saqarTvelos teqnikuri universiteti

xelnaweris uflebiT

beJan kotia

eleqtronebis da polaronebis Zvradobis kvanturi Teoriis zogierTi sakiTxi naxevargamtarebsa da ionur kristalebSi

doqtoris akademiuri xarisxis mosapoveblad
wardgenili disertaciis

avtoreferati

Tbilisi
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samuSao Sesrulebulia saqarTvelos teqnikur universitetis informatikisa da marTvis sistemebis fakultetis
fizikis departamentis
myari sxeulebis fizikis mimarTulebaze.

samecniero xelmZRvanели: ----------

recezentebi: ----------
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dacva Sedgeba ---------- wlis `_____~ ---------- saaTze
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disertaciis gacnoba SeiZleba stu-s biblioTekaSi,
xolo avtoreferatisa stu-s vebgverdze

sadisertacio sabWos mdivani ----------

naSromis zogadi daxasiaTeba

Sesavali kristalebSi eleqtronuli gadatanis movlenebis zonuri Teoria principSi dafuZnebulia sam ZiriTad koncefciaze: 1) denis gadamtanebi warmoadgenen kvazi nawilakebs gansazRvruli kvaziimpulsiT da dispersiis kanoniT. 2) denis gadamtanTa eleqtrogamtaroba da Zvradoba ganisazRvreba maTi gabneviT kristalis idealuri mesris struqturis dinamiur da statikur damaxinjebebze (defeqtebze). 3) denis gadamtanis Tavisufali ganarbenis sigrZe warmoadgens sasrul sidides da is bevrad aRemateba Sesabamisad kvazi nawilakis de-broilis talRis sigrZes. am pirobebis gaTvaliswinebiT denis gadamtanTa gabneva SeiZleba CaiTvalos rogorc “iSviaTi”. am debulebebidan gamomdinare, denis gadamtanTa yofaqceva kristalSi aRiwereba albaTuri ganawilebis funqciiT kvazi impulsebis mixedviT, romelic ganisazRvreba, rogorc bolcman-bloxis kinetikuri gantolebis amoxsna. gadatanis kinetikuri (meqanikuri) koeficientebis (Zvradoba, eleqtrogamtaroba) gamosaTvlelad gamoiyeneba denis gadamtanebis arawonasworuli ganawilebis funqciisTvis kinetikuri gantoleba–bolcmanis gantoleba–romelic iTvaliswinebs denis (muxtis) matarebelTa urTierTqmedebas (gabnevas) kristaluri mesris rxevebze.

ukanasknel wlebSi, eleqtronuli gadatanis movlenebis gamokvlevebSi myari sxeulebis fizikaSi, Zalian farTo gamoyeneba hpova ufro zogadma midgomam, romelic dafuZnebulia kubos wrfivi reaqciis Teoriaze. am TeoriaSi-romelsac gadamwyveti mniSvneloba aqvs wrfiv arawonasworul TermodinamikaSi–gadatanis kinetikuri (meqanikuri) koeficientebi bunebrivad gamoisaxebian (aRiwerebian) droiTi korelaciuri funqciebiT. isini asaxaven sistemis reaqcias hamiltonianis SeSfoTebisas, romlis tipiur magaliTs warmoadgens eleqtrogamtaroba.

amrigad, aRniSnulidan gamomdinare naTelia, rom rogorc samecniero, aseve akademiuri TvalsazrisiT did interess warmoadgens eleqtronuli da polaronuli gadatanis movlenebis koreqtuli kvanturi

Teoriis ageba da gadatanis meqanikuri koeficientebis gamoTvla naxevargamtarebsa da ionur kristalebSi dafuZnebuli kubos wrfivi reaqciis Teoriaze.

Temis aqtualoba Tanamedrove pirobebSi farTod gamokvlevis sagans warmoadgens eleqtronuli da polaronuli gadatanis movlenebis Seswavlis sakiTxi myari sxeulebisa da kondensirebul garemoTa fizikaSi. ukanasknel wlebSi, rTuli molekuluri aRnagobis mqone nivTierebaTa Seqmnis tendencia da maTi eleqtronuli da polaronuli Tvisebebis Seswavla stimuls aZlevda mravali Teoriuli gamokvlevebis Sesrulebas avtolokalizebuli (polaronuli) mdgomareobebis aRsawerad dinamiurad mouwesrigebel sistemebSi. polaronis koncefcias, romelic warmoadgens martiv magaliTs arawrfivi kvazi nawilakisa, Zalian didi mniSvneloba da gamoyeneba aqvs myari sxeulebis (kondensirebul garemoTa) fizikaSi, da kerZod igi mWidrod aris dakavSirebuli kvanturi dinamiuri sistemebis Teoriis funadamentur problemebTan da velis kvanturi Teoriis sakiTxebTan. eleqtronuli da polaronuli movlenebis ganxilvisa da Seswavlisas myar sxeulebSi, Teoriuli gamokvlevebis Zalian didi raodenoba samecniero literaturaSi miZRvnili aris eleqtronebisa da polaronebis eleqtrogamtarobisa da Zvradobis gamoTvlaze naxevargamtarebsa da ionur kristalebSi. es gamokvlevebi dafuZnebuli aris sxvadasxva Teoriul meTodebze–grinis funqciis teqnikaze, bolcmanis kinetikuri gantolebis Seswavlaze, TviTSeTanxmebul meTodebze da sxva. Sedegebi miRebuli sxvadasxva meTodebis gamoyenebiT da Sesabamisad sxvadasxva miaxloebebze dayrdnobiT, Zireulad gansxvavdeba erTmaneTisagan. miuxedavad imisa, rom eleqtronebis da polaronebis eleqtrogamtarobisa da Zvradobis gamoTvla warmoadgens erT-erT uZveles problemas myari sxeulebis fizikaSi, is mainc rCeba erT-erT urTules da Znel amocanad Teoriulad amoxsnis Tvalsazrisi T.

amgvarad, Tanamedrove pirobebSi kvlav aqtualurs warmoadgens sakiTxi eleqtronebis da polaronebis eleqtrogamtarobis da Zvradobis koreqtuli gamoTvlisa naxevargamtarebsa da ionur kristalebSi.

myari sxeulebis fizikisa da arawonasworuli statistikuri meqanikis mravali amocanis ganxilvisas Seiswavleba mcire dinamiuri qvesistemis evolucia droSi, romelic imyofeba kontaqtSi didi Tavisuflebis ricxvis mqone, Termodinamikur wonaswo robaSi myof sistemasTan–TermostatTan.

eleqtronuli da polaronuli gadatanis movlenebis gamokvlevebisas myar sxeulebSi kubos wrfivi gamoZaxilis Teoriaze dayrdnobiT, ZiriTad amocanas warmoadgens zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebis miReba drois ormomentiani wonasworuli korelaciuri funqciebisTvis kvazinawilakebis aRmweri Sesabamisi dinamiuri sidideebisTvis, rodesac xdeba am ukanasknelTa urTierTqmedeba (gabneva) kristaluri mesris rxevebze (fononebze), da rodesac fononuri (bozonuri) veli ganixileba rogorc Termostati. samecniero literaturaSi, aseTi saxis gantolebebis misaRebad, rogorc wesi, gamoiyeneba aprioruli hipoTeza–sawyisi korelaciebis Sesustebis principi, an msgavsi debulebebi–mag. SemTxveviTi fazebis miaxloeba (Sfm)–rodesac drois sawyisi momentisaTvis mTeli sistemis (qvesistema plus Termostati) statistikuri operatori moicema faqtorizebuli saxiT (mTeli sistemis statistikuri operatori ganixileba rogorc qvesistemisa da Termostatis statistikur operatorTa pirdapiri namravli). naTelia, rom aseTi daSvebebis Sedegad miRebuli ganzogadoebuli, kvanturi evoluciuri gantolebebi wonasworuli korelaciuri funqciebisTvis ar aris zusti.

amrigad, eleqtronuli da polaronuli gadatanis movlenebis koreqtuli kvanturi Teoriis asagebad da meqanikuri koeficientebis (mag. Zvradoba, eleqtrogamtaroba) gamosaTvlelad naxevargamtarebsa da ionur kristalebSi da agreTve eleqtron-fononuri sistemis kinetikis sakiTxebis gamosakvlevad kubos wrfivi reaqciis Teoriis CarCo-

ebSi, aqtualurs warmoadgens amocana kvazinawilakebis dinamiuri sidideebisTvis drois ormomentiani wonasworuli korelaciuri funqciebisTvis zusti, ganzogadoebuli, kvanturi evoluciuri gantolebebis miReba–sawyisi korelaciebis Sesustebis principisa da Sfm-is gamoyenebis gareSe.

samuSaos mizani da amocanebi. sadisertacio naSromis mizans warmoadgens: myari sxeulebis fizikis zogierTi kvanturi dinamiuri sistemisTvis, romelic urTierTqmedebs fononur (bozonur) velTan (eleqtron-fononuri sistema, frolixis polaronis modeli, akustikuri polaronis modeli susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi, polaronis feinmanis ganzogadoebuli modeli (fgm)), mowesrigebul operatorTa formalizmsa da T-namravlTa teqnikaze dayrdnobiT, agreTve liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis gamoyenebiT_zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebis miReba da gamokvleva drois ormomentiani wonasworuli korelaciuri funqciebisTvis Sfm-is gamoyenebis gareSe.

–Aam modelebze dayrdnobiT, da am gantolebaTa gamoyenebiT, Tanmimdevruli, srulyofili eleqtronuli da polaronuli gamtarobisa da dabaltemperaturuli dreifuli Zvradobis kvanturi Teoriis ageba naxevargamtarebsa da ionur kristalebSi dafuZnebuli kubos wrfivi gamoZaxilisa da SeSfoTebis Teoriaze. gadatanis meqanikuri koeficientebis (eleqtrogamtaroba, Zvradoba) gamoTvla kvanturi dinamiuri sistemebis zemoTmiTiTebuli modelebisTvis.

sadisertacio naSromis ZiriTadi Sedegebi da mecnieruli siaxle warmodgenil sadisertacio naSromSi gadawyvetilia Semdegi amocanebi:

–mowesrigebul operatorTa formalizmisa da T-namravlTa teqnikis daxmarebiT, sawyisi korelaciebis Sesustebis principisa da Sfm-is gamoyenebis gareSe, gamoyvanilia da gamokvleulia axali, zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebi gamoricxuli bozonuri (fononuri) amplitudebiT drois ormomentiani wona-

sworuli korelaciuri da grinis funqciebisTvis dinamiuri qvesistemisTvis, romelic urTierTqmedebs bozonur TermostatTan. miRebulia agreTve axali, zusti kvanturi kinetikuri gantolebebi korelaciuri funqciebisTvis_liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis daxmarebiT.

–dinamiuri qvesistemis bozonur (fononur) TermostatTan urTierTqmedebis hamiltonianis mixedviT, SeSfoTebis Teoriis meore miaxloebaSi miRebulia axali, ganzogadoebuli kvanturi kinetikuri gantolebebi gamoricxuli bozonuri amplitudebiT, qvesistemis drois ormomentiani wonasworuli korelaciuri funqciebisTvis–rogorc markoviseuli, ise aramarkoviseuli formiT–romelTa dajaxebiTi integralebi Seicaven cxadad gamoyofil sawyisi korelaciebis evoluciur wevrebs.

–kubos wrfivi reaqciisa da SeSfoTebis Teoriis farglebSi, naxevargamtarebisa da ionuri kristalebisTvis agebulia eleqtronuli da polaronuli dabalsixSiruli gamtarobisa da dabaltemperaturuli dreifuli Zvradobis Tanmimdevruli, koreqtuli kvanturi Teoria, dafuZnebuli_kvanturi disipaciuri sistemebis zemoTmiTiTebuli modelebisTvis_ganzogadoebul kvantur kinetikur gantolebebze korelaciuri funqciebisTvis “deni-denze” eleqtronisa da polaronisTvis, romlebic urTierTqmedeben fononebTan Sfm-is gamoyenebis gareSe.

–miRebulia da gamokvleulia analizuri gamosaxulebebi eleqtronisa da polaronis relaqsaciuri maxasiaTeblebisTvis (impulsis relaqsaciis sixSire da sxv.); gamoTvlilia wonasworuli korelaciuri funqciebis–“deni-denze”–milevis dekrementebi da oscilirebadi faqtorebi. napovnia eleqtrogamtarobis tenzoris (disipaciuri nawilis) analizuri saxe eleqtron-fononuri sistemisTvis kristalis dabali temperaturebisa da dabalsixSiruli gareSe eleqtruli velebis SemTxvevaSi da gamoTvlilia gadatanis meqanikuri koeficientebi (Zvradoba, eleqtrogamtaroba) kvanturi disipaciuri sistemebis aR-

niSnul modelTaTvis; napovnia "$\frac{3}{2}\frac{K_B T}{\hbar w_0}$-problemis" nawilobrivi gadawyveta frolixis polaronis dabal temperaturuli Zvradobis TeoriaSi.

–miRebulia temperaturuli Seswo rebebi eleqtronisa da polaronis dreiful Zvradobebze, romlebic ganpirobebulia sawyisi korelaciebis evoluciuri wevrebis arsebobiT kvantur kinetikur gantolebebSi wonasworuli korelaciuri funqciebisTvis "siCqare-siCqareze" ("impulsi-impulsze") eleqtronisa da polaronisTvis. dadgenilia, rom es Seswo rebebi warmoadgenen mcire sidideebs Sesrulebuli miaxloebebisa da ganxiluli TeoriisfarglebSi.

<u>sadisertacio naSromis praqtikuli mniSvneloba</u>

naSromSi dasmuli amocanebis gadawyvetam moiTxova arawonasworuli statistikuri meqanikis zogierTi meTodis Semdgomi ganviTareba. sadisertacio naSromSi miRebuli ZiriTadi Teoriuli Sedegebis praqtikuli mniSvneloba (Rirebuleba) ganisazRvreba imiT, rom miRebuli zusti, ganzogadoebuli kvanturi evoluciuri gantolebebi wonasworuli korelaciuri funqciebisTvis SesaZlebelia gamoyenebuli iqnas gadatanis movlenebis gansaxilvelad da gamosakvlevad_kubos wrfivi reaqciis Teoriis farglebSi, sawyisi korelaciebis Sesustebis principisa da Sfm-is daSvebebis gareSe_myari sxeulebis da kondensirebul garemoTa fizikis dinamiur qvesistemaTa sxva modelTaTvis (kvanturi disipaciuri sistemebisTvis), romlebic urTierTqmedeben bozonur velTan (TermostatTan). (mag. brounis kvanturi nawilakis moZraobis Sesaswavlad, romelic ganixileba rogorc wrfivi, milevadi harmoniuli oscilatori, da romlis dinamika aRiwereba kaldeiralegetis mikroskopuli modeluri hamiltonianiT).

naSromSi ganviTarebuli formalizmi, meTodebi da miRebuli kinetikuri gantolebebi martivad SesaZlebelia ganvrcobil iqnas kinetikuri movlenebis Sesaswavlad da gadatanis meqanikuri koeficientebis (mag. Zvradoba, eleqtrogamtaroba) gamosaTvlelad: eleqtronebis urTi-

erTqmedebisas (gabnevisas) arapolarul optikur fononebze, piezoeleqtrul fononebze, agreTve sxva didi radiusis mqone polaronTa modelTaTvis (mag. akustikuri polaronis modelisTvis-eleqtronis fononebTan Zlieri urTierTqmedebis SemTxvevaSi). gamoyvanili ganzogadoebuli kvanturi kinetikuri gantolebebi korelaciuri funqciebisTvis kvanturi dinamiuri qvesistemisTvis, romelic urTierTqmedebs fononur velTan, SesaZlebelia gamoyenebul iqnas normaluri (arazegamtari) metalebis eleqtrowinaRobis gamosaTvlelad eleqtronebis gabnevisas akustikur fononebze. naSromSi warmodgenili formalizmis daxmarebiT SesaZlebelia temperaturuli Sesworebebis povna metalTa eleqtrowinaRobisTvis (Sesworebebi blox_grunaizenis formulaSi), romlebic agreTve ganpirobebulia eleqtronebis fononebTan urTierTqmedebisas sawyisi korelaciebis gaTvaliswinebiT.

<u>dasacavad gamotanilia Semdegi debulebebi</u>:

1. osakas Sedegis ganzogadoeba dabalsixSirul kuTri eleqtrogamtarobisTvis da "$\frac{3}{2}\frac{K_B T}{\hbar w_0}$-problemis" nawilobrivi gadawyveta frolixis polaronis (eleqtronis) dabal temperaturuli Zvradobis TeoriaSi.
2. eleqtronis dabal temperaturuli statikuri Zvradobis gansxvavebuli (2-jer naklebi) mniSvneloba `bolcmaniseul~ ZvradobasTan SedarebiT akustikuri polaronis modelSi susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi.
3. Zlieri eleqtron_fononuri urTierqmedebis SemTxvevaSi dabaltemperaturuli Zvradobis gansxvavebuli yofaqceva eleqtron-fononuri bmis mudmivas rigis mixedviT polaronis fgm_Si, pekaris modelTan SedarebiT.
4. mcire sididis temperaturuli Sesworebebis arseboba eleqtronis da polaronis dabal temperaturul Zvradobebze ganxilul modelebSi.

<u>naSromis aprobacia</u> disertaciis ZiriTadi Sinaarsi moxsenebuli iyo informatikisa da marTvis sistemebis fakultetis fizikis departa-

mentisa da myari sxeulebis fizikis kolegiis samecniero seminarebis sxdomebze.

disertaciis Sinaarsi da ZiriTadi Sedegebi wardgenili iyo: 1986w. q. TbilisSi Catarebul 24-e sakavSiro TaTbirze_»24-? ?????? ???? ?????????? ?????? ?????? ??????????», Tbilisi, 1986w; 1991w q. xarkovSi (ukraina) Catarebul sakavSiro konferenciaze «?????????????????? ?????????????? ??????», ???????, 14-17??? 1991?; 1992w. q. puSCinoSi (ruseTi) Catarebul saerTaSoriso skolaSi_International Workshop `POLARONS and APPLICATIONS~ May 23-31, 1992, Pushchino, Russia; 1992w. q. berlinSi (germania) Catarebul saerTaSoriso konferenciaze `The 18th IUPAP International Conference on Statistical Physics, Berlin, 2-8 August 1992~; saqarTvelos teqnikuri universitetis profesor_maswavlebelTa samecniero_teqnikur konferenciaze, 16-19 noemberi, Tbilisi, 1993w; 1993w. q. trondhaimSi (norvegia) Catarebul saerTaSoriso simpoziumze `The Lars Onsager Symposium. Coupled Transport Processes and Phase Transitions~, June 2-4 1993, Trondheim, Norway; 1993w. q. florenciaSi (italia) Catarebul saerTaSoriso konferenciaze `EPS9 TRENDS IN PHYSICS~ Firenze, 14-17 September 1993; 1995w. q. qsiamenSi (CineTi) Catarebul saerTaSoriso konferenciaze `The 19th UPAP International Conference on Statisitcal Physics~, Xiamen 31 July-4 August 1995; 1998w. q. parizSi (safrangeTi) Catarebul saerTaSoriso konferenciaze `XXth IUPAP INTERNATIONAL CONFERENCE ON STATISTICAL PHYSICS~, Paris, July 20-24, 1998, UNESCO Sorbonne.

publikaciebi: disertaciis ZiriTadi Sedegebi gamoqveyenebulia Cvidmet samecniero naSromSi, romelTa dasaxeleba moyvanilia avtoreferatis bolos.

naSromis moculoba da struqtura: disertaciis sruli moculoba Seadgens 157 nabeWd gverds; disertacia Sedgeba reziumesagan (or enaze), sarCevisagan, naxazebis nusxisagan, Sesavlisagan, samiTavisagan, ilustraciis saxiT moyvanili sami naxazisgan, daskvnebisa da 125 dasaxelebis mqone gamoyenebuli literaturis siisgan, erTi danarTisa

da avtoris mier gamoqveynebuli samecniero naSromebisgan, romlebSiac asaxulia disertaciis ZiriTadi Sedegebi.

sadisertacio naSromis Sinaarsi

Sesavali dasabuTebulia Temis aqtualoba, Camoyalibebulia naSromis miznebi da amocanebi, da gansazRvrulia kvlevis obieqtebi da meTodebi.

pirveli Tavi ZiriTadad atarebs mimoxilviT xasiaTs

§1.1 (1.1.1-1.1.6)_Si moyvanilia modeluri hamiltonianis saxe dinamiuri sistemebisa, romlebic urTierTqmedeben bozonur TermostatTan da ganxilulia zogierTi aqtualuri magaliTi kvanturi disipaciuri da Ria arawonasworuli modeluri sistemebisa Tanamedrove fizikis sxadasxva dargidan, romlebic gaxdnen intensiuri kvlevisa da Seswavlis sagani ukanaskneli 30-40 wlis ganmavlobaSi. am farTo gamokvlevaTa speqtri moicavda metalTa eleqtrogamtarobisa da zegamtarobis Teoriis, metalTa Senadnobebisa da gadacivebuli `metaluri minebis~ eleqtronuli Teoriis sakiTxebs; susti da Zlieri lokalizaciisa da Zlier araerTgvarovan nivTierebaTa eleqtrogamtarobis Teoriis sakiTxebs mouwesrigebel sistemaTa fizikaSi; lazeruli gamosxivebisa da zegamosxivebis Teoriis aspeqtebs kvantur radiofizikaSi; magnituri polaronebis da fluqtuonebis (fazonebis) Teoriis sakiTxebs magnitur nivTierebebSi (garemoebSi) da sxva.

§1.2 (1.2.1-1.2.2.)_Si ganxilulia dinamiurad mouwesrigebeli sistema eleqtron-fononuri sistema da eleqtronis urTierTqmedeba akustikur da polarul optikur fononebTan; moyvanilia eleqtron-fononuri sistemis hamiltonianis zogadi saxe (frolix-pekaris tipis hamiltoniani), eleqtronis akustikur da polarul optikuri fononebTan urTierTqmedebis hamiltonianTa saxeebi da mokled mimoxilulia agreTve deformaciis potencialis meTodi.

§1.3 (1.3.1-1.3.3)_Si moyvanilia didi radiusis mqone polaronTa modelebi. ganxilulia polaronis frolixisa da pekaris modelebi da polaronis feinmanis erToscilatoriani da feinmanis ganzogadoebu-

li modelebi. amave paragrafSi ganxilulia agreTve ukanasknel wlebSi ganviTarebuli da gamoyenebuli axali midgoma polaronuli sistemebis Termodinamikisa da kinetikis sakiTxebis gamokvlevebisas _ mowesrigebuli operatorTa formalizmi, T_namravlTa meTodi da fononuri operatorebis gamoricxvis teqnika eleqtron-fononuri sistemis maxasiaTebeli fizikuri sidideebis wonasworuli da arawonasworuli saSualo mniSvnelobebidan. aRniSnulia zogierT SemTxvevebSi am axali midgomis upiratesoba, kontinualuri integri-rebis meTodTan SedarebiT, eleqtron-fononuri sistemis kinetikis sakiTxebis Seswavlisas.

$ 1.4._Si ganxilulia fizikuri kinetikis zogierTi principuli sakiTxi dinamiuri sistemebisa, romlebic urTierTqmedeben fononur (bozonur) velTan. mimoxilulia metad mniSvnelovani da principuli sakiTxi, K_tipis dinamiur sistemebSi (rogorc klasikuris, aseve kvanturisTvis), evoluciuri (kinetikuri) gantolebebis gamoyvanis dros Semoklebuli aRweris SesaZleblobaze, romelic ar eyrdnoba hipoTezas_sawyisi korelaciebis Sesustebisa da Sfm-is gamoyenebis Sesaxeb. aRwerilia is ZiriTadi sqemebi da meTodebi, romlebsac mivyavarT bolcmanis saxis kinetikuri gantolebisa da ZiriTadi kinetikuri gantolebis miRebamde. ganxilulia is ZiriTadi principuli xasiaTis sirTuleebi, romlebic warmoiSvebian eleqtron-fononuri sistemisa da polaronTa zemoTmoyvanil modelTaTvis dreifuli Zvradobebis gamoTvlisas, gamomdinare rogorc bolcmanis kinetikuri gantolebidan da kubos wrfivi reaqciis Teoriidan, aseve gamtarobis wrfivi da arawrfivi Teoriebis zogierTi sxva meTodebis (arawonasworuli simkvrivis matricis meTodi, balansis gantolebis meTodi) gamoyenebisas.

meore Tavi sadisertacio naSromSi originaluri xasiaTisaa.

am TavSi dasmulia da gadawyvetilia zogadi saxis amocana_dinamiuri qvesistemisTvis, romelic urTierTqmedebs bozonur (fononur) TermostatTan_axali, zusti ganzogadoebuli kvanturi evoluciuri gantolebebis miReba drois ormomentiani wonasworuli korelciuri

da grinis funqciebisTvis sawyisi korelaciebis Sesustebis principisa da Sfm_is gamoyenebis gareSe.

§2.1_Si ganxilulia mowesrigebuli operatorTa formalizmi da T_namravlTa meTodi.

§2.2_Si am formalizmze dayrdnobiT gamoyvanilia axali, zusti, araCaketili ganzogadoebuli kvanturi kinetikuri gantolebebi wonasworuli korelaciuri funqciebisTvis, rogorc markoviseuli, aseve aramarkoviseuli saxis, saidanac gamoricxulia bozonuri amplitudebi. miRebuli zusti kvanturi kinetikuri gantolebebis dajaxebiTi integralebi Seicaven damatebiT wevrebs, romlebic aRweren sawyisi korelaciebis evolucias droSi, ganpirobebuls qvesistemis urTierTqmedebiT bozonur TermostatTan drois sawyis momentSi. napovnia agreTve msgavsi saxis evoluciuri gantoleba grinis (dagvianebuli) funqciisTvis. sadisertacio naSromis danarTSi detalurad aris aRwerili bozonuri operatorebis (amplitudebis) gamoricxvis teqnika drois ormomentiani wonasworuli korelaciuri funqciebis evoluciuri (kinetikuri) gantolebebidan.

§2.3_Si ganxilulia markoviseuli miaxloeba qvesistemis dinamikisTvis da qvesistemis TermostatTan urTierTqmedebis hamiltonianis mixedviT SeSfoTebis Teoriis meore miaxloebaSi gamoyvanilia axali, ganzogadoebili markoviseuli kvanturi kinetikuri gantoleba drois ormomentiani wonasworuli korelaciuri funqciisTvis $<B_s A_s(-t)>$:

$$\frac{\partial}{\partial t}\left\langle B_s A_s(-t)\right\rangle = \frac{i}{\hbar}\left\langle [H_s B_s]_- \cdot A_s(-t)\right\rangle - \frac{1}{\hbar^2}\sum_k \int_0^t dx \left[\left(1+N_k(b)\right)\times\right.$$
$$\times e^{iw(k)x}\left\langle C_{kH_0}(s,-x)\cdot\left[C_k^+(s),B_s\right]_- A_s(-t)\right\rangle + N_k(b)e^{-iw(k)x}\times$$
$$\left.\times\left\langle C_{kH_0}^+(s_1-x)\cdot\left[C_k(s),B_s\right]_- A_s(-t)\right\rangle\right] + \frac{1}{\hbar^2}\sum_k \int_0^t dx\left[\left(1+N_k(b)\right)\times\right.$$
$$\times e^{-iw(k)x}\cdot\left\langle\left[C_k(s),B_s\right]_- C_{kH_0}^+(s,-x)A_s(-t)\right\rangle + N_k(b)e^{iw(k)x}\times \qquad (1)$$
$$\left.\times\left\langle\left[C_k^+(s),B_s\right]_-\cdot C_{kH_0}(s,-x)A_s(-t)\right\rangle\right] - \frac{i}{\hbar^2}\sum_k \int_0^{\hbar b} dq\left[\left(1+N_k(b)\right)\times\right.$$
$$\times e^{-qw(k)}e^{iw(k)t}\left\langle C_{kH_0}(s,-t-iq)\left[C_k^+(s),B_s\right]_-\cdot A_s(-t)\right\rangle + N_k(b)e^{qw(k)}\times$$
$$\left.\times e^{-iw(k)t}\left\langle C_{kH_0}^+(s,-t-iq)\cdot\left[C_k(s),B_s\right]_-\cdot A_s(-t)\right\rangle\right].$$

sadac H_s_qvesistemis hamiltoniania, A_s, B_s $C_k(s)$, $C_k^+(s)$ –qvesistemis operatorebia, $N_k(\beta)=[e^{\beta\hbar\omega(k)}-1]^{-1}$_warmoadgens bozonebis Sevsebis saSualo ricxvs, xolo operatorebi $C_{kH_0}(S,Z)$ da $C_{kH_0}(S,Z)$ _ gansazRvrulia tolobebiT:

$$C_{kH_0}(S,Z)=e^{\frac{i}{h}H_0 Z}C_k(S)e^{-\frac{i}{h}H_0 Z}\quad C_{kH_0}{}^+(S,Z)=e^{\frac{i}{h}H_0 Z}C_k{}^+(S)e^{-\frac{i}{h}H_0 Z}\quad H_0=H_s+H_\Sigma;$$

da H_Σ- aris bozonuri Termostatis hamiltoniani. analogiuri saxis gantolebebia miRebuli agreTve sxva korelaciuri funqciebisTvis.

§2.4_Si ganxilulia da ganviTarebulia meore (gansxvavebuli) midgoma igive problemisadmi, romelic eyrdnoba liuvilis superoperatorul formalizmsa da proeqciuli operatoris meTods. am formalizmisa da meTodis daxmarebiT napovnia axali, zusti ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebi wonasworuli korelaciuri funqciebisTvis Sfm_is gamoyenebis gareSe. gamoyvanil kinetikur gantolebas $<A_s B_s(-t)>$_korelaciuri funqciisTvis aqvs Semdegi saxe:

$$\frac{\partial}{\partial t}\langle A_s B_s(-t)\rangle = i\langle [\mathrm{P}L_s \mathrm{P}A_s] B_s(-t)\rangle - i\langle \{\mathrm{P}\Im_Q(t,b)\times$$
$$\times\left[1+M_Q(t)\Im_Q(t,b)\right]^{-1} M_Q Q L_i \mathrm{P}A_s\} B_s(-t)\rangle + \int_0^t dt \times$$
$$\times\langle \{\mathrm{P}L_i Q M_Q(t-t)\Im_Q(t,b)\left[1+M_Q(t)\Im_Q(t,b)\right]^{-1}\times \qquad (2)$$
$$\times M_Q(t) Q L_i \mathrm{P}A_s\} B_s(-t)\rangle - \int_0^t dt\,\langle [\mathrm{P}L_i Q M_Q(t-t) Q\times$$
$$\times L_i \mathrm{P}A_s] B_s(-t)\rangle.$$

sadac $L_S \ldots = \frac{1}{\hbar}[H_{S,}\ldots]_-$ _ liuvilis superoperatoria, romelic Seesabameba S–qvesistemis H_S–hamiltonians, P-warmoadgens Termostatis (bozonuri velis) mdgomareobebis mixedviT gasaSualebis proeqciul operators: $P^2 = P$ da $Q = 1 - P$; xolo `masuri~ $M_Q(t)$ da integraluri $\Im_Q(t,b)$ superoperatorebi gansazRvrulia Semdegi tolobebiT:

$$M_Q(t) = \exp[iQLQt]; \qquad \Im_Q(t,b) = \int_0^b d l e^{-iLt} e^{lH} H_{\mathrm{int}} e^{-lH} Q$$

miRebuli aramarkoviseuli saxis zusti, ganzogadoebuli (2) _kinetikuri gantolebis dajaxebiTi integrali Seicavs wevrebs, romlebic aRweren sawyisi korelaciebis evolucias droSi. (sawyisi korelaciebis evolucia drois mixedviT aRiwereba $\Im_Q(t,b)$ _ integraluri superoperatoriT da es evolucia moicema rogorc markoviseuli, aseve aramarkoviseuli formiT).

§2.5_Si, iseve rogorc §2.3_Si, ganxilulia markoviseuli miaxloeba qvesistemis dinamikisTvis da qvesistemis TermostatTan urTierTqmedebis liuvilianis mixedviT _ SeSfoTebis Teoriis meore miaxloebaSi, proeqciuli operatoris meTodis daxmarebiT_napovnia axali, ganzogadoebuli markoviseuli kvanturi kinetikuri gantoleba wonasworuli korelaciuri funqciisTvis $\langle A_s B_s(-t)\rangle$_gamoricxuli bozonuri amplitudebiT:

$$\frac{\partial}{\partial t}\langle A_s B_s(-t)\rangle = -\frac{i}{\hbar}\langle [A_s, H_s]_- B_s(-t)\rangle - \frac{1}{\hbar^2}\int_0^t dx \sum_k \{N_k(b) e^{iw(k)x} \times$$
$$\times \left\langle \left[\left[A_s, C_k^+(s) \right]_- \cdot C_k(s,-x) \right]_{-w(k)} B_s(-t) \right\rangle + (1+N_k(b)) e^{-iw(k)x} \times$$
$$\times \left\langle \left[\left[A_s, C_k(s) \right]_- \cdot C_k^+(s,-x) \right]_{w(k)} B_s(-t) \right\rangle + \frac{i}{\hbar}\int_0^b dl \sum_k \{N_k(b) e^{-iw(k)(t-i\hbar l)} \times \qquad (3)$$
$$\times \left\langle C_k^+(s,-t-i\hbar l) \cdot \left[A_s, C_k(s) \right]_- B_s(-t) \right\rangle + (1+N_k(b)) e^{iw(k)(t+i\hbar l)} \times$$
$$\times \left\langle C_k(s,-t-i\hbar l) \cdot \left[A_s, C_k^+(s) \right]_- B_s(-t) \right\rangle \},$$

$$C_k(s_1 \pm Z) = e^{\pm i L_s Z} C_k(s); \quad C_k^+(s_1 \pm Z) = e^{\pm i L_s Z} C_k^+(s)$$

xolo $[E,D]_{\pm w(k)} = ED - e^{\mp b\hbar w(k)} DE.$

sadac: $C_k(S_, \pm Z) = e^{\pm i L_s Z} C_k(S)$; $C_k{}^+(S_, \pm Z) = e^{\pm i L_s Z} C_k{}^+(S)$; xolo $[E,D]_{\pm w(k)} = ED - e^{\pm b\hbar w(k0} DE$ _ nebismieri E da D_operatorebisTvis.

$$e^{\pm i L_\Sigma t} b_k = e^{\mp i w(k) t} b_k; \quad e^{\pm i L_\Sigma t} b_k^+ = e^{\pm i w(k) t} b_k^+$$
$$\mathrm{P}\left(b_k^+, b_{k'}\right) = N_k(b) d_{k,k'}; \quad \mathrm{P}\left(b_k, b_{k'}^+\right) = (1+N_k(b)) d_{k,k'}$$
$$\mathrm{P}\left(b_k, b_{k'}\right) = \mathrm{P}\left(b_k^+, b_{k'}^+\right) = 0.$$

amrigad, sadisertacio naSromis meore TavSi miRebuli ZiriTadi Sedegebi SesaZlebelia CamovayaliboT Semdegi saxiT: _ dinamiuri qvesistemisTvis, romelic urTierTqmedebs bozonur velTan mowesrigebul operatorTa, liuvilis sauperoperatoruli formalizmisa da proeqciuli operatoris meTodis daxmarebiT, sawyisi korelaciebis Sesustebis proncipisa da Sfm_is gamoyenebis gareSe wonasworuli korelaciuri funqciebisTvis gamoyvanili axali, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebis dajaxebiTi integralebi_Seicaven rogorc wevrebs, romlebic aRweren dajaxebiTi korelaciebis evolucias droSi, aseve sawyisi korelaciebis evoluciur wevrebs, romlebic ganpirobebulia qvesistemis urTierTqmedebiT bozonur velTan drois sawyis momentSi.

<u>mesame TavSi</u> ganxilulia da gamokvleulia eleqtronuli da polaronuli gadatanis wrfivi movlenebis sakiTxebi dinamiur sistemebSi_eleqtron_fononur sistemaSi, frolixis da akustikur polaro-

nTa modelebSi, polaronis fgm_Si. gamokvleva dafuZnebulia kubos wrfivi gamoZaxilisa da SeSfoTebis Teoriaze. gamoTvlilia eleqtronuli da polaronuli gadatanis meqanikuri koeficientebi (dabal temperaturuli Zvradoba, eleqtrogamtaroba) zemoT miTiTebul modelebSi_korelaciuri funqciebisTvis miRebul ganzogadoebul kvantur kinetikur gantolebebze dayrdnobiT.

§3.1_Si gamokvleulia eleqtron-fononuri sistema da gamoTvlilia eleqtronis dabal temperaturuli Zvradoba da dabalsixSiruli eleqtogamtaroba susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi (1) da (3)_gantolebebze dayrdnobiT miRebulia miaxloebiTi kinetikuri gantoleba eleqtronis `siCqare_siCqareze~ wonasworuli korelaciuri funqciisTvis. napovnia am bolcmanis tipis gantolebis amonaxsni kristalis dabali temperaturebis SemTxvevaSi erTi zonisa da relaqsaciis drois miaxloebaSi (rdm) eleqtronisTvis, da fononebis dispersiis nebismieri izotropuli kanonis dros. dadgenilia, rom eleqtronis (qvesistemis) korelaciuri funqciebi miilevian oscilaciebiT didi droebis asimptotur areSi, gamoTvlilia korelaciuri funqciebis milevis dekrementi da oscilirebadi faqtori. gamoyvanilia zogadi formulebi kuTri eleqtrogamtarobis disipaciuri nawilisTvis izotropul SemTxvevaSi da eleqtronis dabal temperaturuli, eleqtruli velis ω_sixSireze damokidebuli ZvradobisTvis (ac mobility). am formulebs aqvs Semdegi saxe:

$$\mathrm{Re}\, s_{mn}^{s} = ne^2 \frac{th\left(\frac{1}{2} b\hbar w\right)}{\hbar w} \int d\vec{\mathrm{P}} r_s(b,\overline{\mathrm{P}}) V_n(\overline{\mathrm{P}}) V_m(\overline{\mathrm{P}}) \left\{ \cos\left[\frac{b\hbar}{2}\Gamma_n^{rel}(b,\overline{\mathrm{P}})\right] \times \right.$$

$$\left. \times \frac{\Gamma_n^{rel}(b,\overline{\mathrm{P}})}{w^2 + \left[\Gamma_n^{rel}(b,\overline{\mathrm{P}})\right]^2} + \cos\left[\frac{b\hbar}{2}\Gamma_m^{rel}(b,\overline{\mathrm{P}})\right] \frac{\Gamma_m^{rel}(b,\overline{\mathrm{P}})}{w^2 + \left[\Gamma_m^{rel}(b,\overline{\mathrm{P}})\right]^2} \right\}, \qquad (4)$$

sadac: $m(w) = m_0(w) - \Delta m(w)$

$$m_0(w)=\frac{eth\left(\frac{1}{2}b\hbar w\right)}{\hbar w}\int d\vec{P}r_s(b,\vec{P})V_V(\vec{P})V_m(\vec{P})\left\{\frac{\Gamma_V^{rel}(b,\vec{P})}{w^2+\left[\Gamma_V^{rel}(b,\vec{P})\right]^2}+\frac{\Gamma_m^{rel}(b,\vec{P})}{w^2+\left[\Gamma_m^{rel}(b,\vec{P})\right]^2}\right\};$$

$$\Delta m(w)=\frac{2eth\left(\frac{1}{2}b\hbar w\right)}{\hbar w}\int d\vec{P}r_S(b,\vec{P})V_V(\vec{P})V_m(\vec{P})\times \qquad (5)$$

$$\times\left\{\sin^2\left[\frac{b\hbar}{4}\Gamma_V^{rel}(b,\vec{P})\right]\frac{\Gamma_V^{rel}(b,\vec{P})}{w^2+\left[\Gamma_V^{rel}(b,\vec{P})\right]^2}+\sin^2\left[\frac{b\hbar}{4}\Gamma_m^{rel}(b,\vec{P})\right]\cdot\frac{\Gamma_m^{rel}(b,\vec{P})}{w^2+\left[\Gamma_m^{rel}(b,\vec{P})\right]^2}\right\};(w<<t_0^{-1}).$$

aq: e-eleqtronis muxtia, n-eleqtronebis koncentraciaa gamtarobis zonaSi, $V_m(\vec{P})$eleqtronis siCqaris μ_komponentia gamtarobis zonidan, $\vec{P}$_eleqtronis kvaziimpulsia, da $r_s(b,\overline{P})=e^{-bT(\overline{P})}/d\vec{p}e^{-bT(\vec{P})}$ naTelia, rom $\Delta\mu(\omega)$_sidide warmoadgens temperaturul Seswo rebas eleqtronis $\mu_0(\omega)$-_dabal temperaturul da sixSirul Zvradobaze, romelic gamowveulia sawyisi korelaciebis arsebobiT eleqtronis urTierTqmedebisas fononebTan arsebul sistemaSi. am paragrafSi moyvanili gamosaxulebebi kuTri eleqtrogamatrobisTvis da dabal temperaturuli ZvradobisTvis warmoadgenen sakmaod zogads ganxiluli modelis CarCoebSi da Sesrulebuli miaxloebebis farglebSi.

§3.2_Si gamokvleulia eleqtronis Zvradobis sakiTxi polaronis frolixis modelSi da napovnia metad mniSvnelovani da principuli sakiTxis: `$\frac{3}{2bhw_0}$problemis~ nawilobrivi gadawyveta polaronis dabaltemperaturuli, Zvradobis TeoriaSi. §3.1_Si eleqtron-fononuri sistemisTvis, miRebul zogad formulebsa da Tanafardobebze dayrdnobiT gamoTvlilia eleqtronis `siCqare_siCqareze~ korelaciuri funqciis milevis dekrementi (eleqtronis impulsis relaqciis sixSire) da oscilirebadi faqtori. `mcire~ siCqariT moZravi eleqtronisTvis kristalis Zalian dabali temperaturebis SemTxvevaSi impu-

lsis relaqsaiciis sixSire ar aris damokidebuli TviT eleqtronis impulsze da warmoidgineba Semdegi saxiT:

$$\Gamma_z^{rel}(g,\tilde{\tilde{P}}) \equiv \Gamma_0^{rel}(g) = \frac{2}{3} a w_0 N_0(g); (\tilde{P}^2 << 1, g = b\hbar w_0 >> 1) \qquad (6)$$

sadac: ω_0_ fononebis rxevis sixSirea, α_ warmoadgens eleqtron-fononuri urTierTqmedebis (frolixis) bmis mudmivas, da $N_0(g) = [e^g - 1]^{-1}$ eleqtronis `siCqare-siCqareze~ korelaciuri funqciisTvis miRebuli bolcmanis tipis miaxloebiTi kinetikuri gantoleba amoxsnilia rdm-Si kristalis dabali temperaturebis SemTxvevaSi, da napovnia eleqtrogamtarobis da Zvradobis mniSvnelobebi frolixis polaronis modelSi_rac faqtiurad warmoadgens osakas Sedegis ganzogadoebas (drudes formulas) dabal sixSiruli eleqtrogamtarobisTvis da dabal temperaturuli ZvradobisTvis, romlebic Seicaven temperaturul Sesworebebs, ganpirobebuls eleqtronis fononebTan arsebuli sawyisi korelaciebiT:

$$\mathrm{Re}\, s(\tilde{w}) = \frac{ne^2}{mw_0}\frac{2}{g\tilde{w}} th\left(\frac{1}{2}g\tilde{w}\right)\left[1 - 2\sin^2\left(\frac{g}{2}\Gamma_0(g)\right)\right]\frac{\Gamma_0(g)}{\tilde{w}^2 + \Gamma_0^2(g)}; \qquad (7)$$
$$(a < 1, g >> 1, \tilde{w}g << 1),$$

sadac: $s(\tilde{w}) = s_{xx}(\tilde{w}) = s_{yy}(\tilde{w}) = s_{zz}(\tilde{w});\ \tilde{w} = \frac{w}{w_{0;}}; \Gamma_0(g) = w_0^{-1}\Gamma_0^{rel}(g) = \frac{2}{3}aN_0(g);$ xolo dabal temperaturuli da dabalsixSiruli ZvradobisTvis Sesabamisad gveqneba:

$$m_0(\tilde{w}) = \frac{e}{mw_0}\frac{2}{g\tilde{w}} th\left(\frac{1}{2}g\tilde{w}\right)\frac{\Gamma_0(g)}{\tilde{w}^2 + \Gamma_0^2(g)}; \qquad (8)$$

$$\Delta m(\tilde{w}) = \frac{e}{mw_0}\frac{4}{g\tilde{w}} th\left(\frac{1}{2}g\tilde{w}\right)\sin^2\left(\frac{g}{2}\Gamma_0(g)\right)\frac{\Gamma_0(g)}{\tilde{w}^2 + \Gamma_0^2(g)}$$
$$(a < 1, g >> 1, \tilde{w}g << 1).$$

dabal temperaturuli statikuri ZvradobisTvis (dc mobility) miRebulia Semdegi mniSvneloba (mcire temperaturuli SeswrebiT).

$$m_0 = \frac{e}{mw_0}\Gamma_0^{-1}(g) = \frac{e}{mw_0}\frac{3}{2a}e^g;$$

$$\Delta m = \frac{2e}{mw_0}\sin^2\left[\frac{g}{2}\Gamma_0(g)\right]\Gamma_0^{-1}(g) \approx \frac{e}{mw_0}\frac{1}{3}ag^2e^{-g}; \qquad (9)$$

$(g >> 1, a < 1).$

gamoTvlilia agreTve eleqtrogamtaroba da eleqtronis Zvradoba eleqtruli velis maRali $\tilde{w}$-sixSireebis SemTxvevaSi. am SemTxvevaSic temperaturuli Sesworeba eleqtronis Zvradobaze warmoadgens Zalian mcire sidides.

sadisertacio naSromis am paragrafSi avtoris mier miRebuli Sedegi (ix. (9) formula) warmoadgens `$\frac{3}{2}\frac{K_BT}{\hbar w_0}$-problemis~ nawilobriv gadawyvetas frolixis polaronis (eleqtronis) dabal temperaturuli Zvradobis TeoriaSi. Zvradobis miRebuli mniSvneloba 3-jer aRemateba `bolcmaniseul~ dabal temperaturul statikur Zvradobas: $m_B = \frac{e}{mw_0}.\frac{1}{2a}e^g; \quad (w = 0, g >> 1);$ da $\frac{1}{2g}$-mamravliT gansxvavdeba fxip-isa (feinmani, xelvorsi, idingsi, platcmani) da tornberg_feinmanis Sedegisgan: $m_{FXIP} = m_{TF} = \frac{e}{mw_0}\frac{3}{2g}\frac{1}{2a}e^g; \quad (w = 0, g >> 1);$ rac Seexeba TviT fxip-isa da tornberg_feinmanis Sedegebis Tanxvedras da $\frac{1}{2g}$_mamravls, maTi warmoSobis buneba (Rrma mizezi) dRevandel dRemde bolomde dadgenili ar aris.

§3.3_Si ganxilulia da gamokvleulia eleqtronis Zvradobis yofaqceva akustikuri polaronis modelSi susti eleqtron-fononuri urTierTqmdebis dros. am SemTxvevaSi adgili aqvs eleqtronis urTierTqmedebas dispersiis mqone akustikur fononebTan: $w(\vec{k}) = V_s.|\vec{k}|$ (V_s _bgeris siCqarea kristalSi), da iseve rogorc polaronis frolixis modelSi, eleqtronis energiisTvis gamtarobis zonaSi gvaqvs dispersiis paraboluri kanoni: $T(\vec{P}) = \vec{P}^2/2m;$ (m-eleqtronis efeqturi masaa). am paragrafSic miRebuli Sedegebi eleqtrogamtarobisa da eleqtronis

Zvradobis yofaqcevis Sesaxeb eyrdnoba $3.1_Si gamoyvanil zogad Tanafardobebsa da formulebs. napovnia eleqtronis `siCqare_siCqareze~_korelaciuri funqciebis milevis dekrementebi (eleqtronis impulsis relaqsaciis sixSire) da oscilirebadi faqtorebi. ganxilulia eleqtronis aradrekadi gabnevis procesebi akustikur fononebze da dadgenilia, rom `mcire~ siCqariT ($\tilde{P} < 1$) moZravi eleqtronisTvis, implsis relaqsaciis sixSire (dro) kristalis Zalian dabali temperaturebis dros ar aris damokidebuli TviT eleqtronis impulsis mniSvnelobebze da warmoidgineba Semdegi saxiT:

$$\Gamma_{Ac}^{rel}(g) = t_{Ac}^{-1rel}(g) = \frac{mV_s^2}{\hbar} 64a \left[e^{4g} - 1\right]^{-1} \qquad (10)$$

$$(\tilde{P} << 1; \quad g >> 1; \quad a < 1).$$

sadac: $\tilde{P} = P / mV_s$: da $g = \frac{mV_s^2}{2K_B T}$: xolo α_eleqtron-fononuri urTierTqmedebis (bmis) mudmivaa: $a = \frac{D^2 m^2}{8p r \hbar^3 V_s} < 1$. D_deformaciis potencialis mudmivaa, ρ_kristalis masuri simkvrive. napovnia `siCqare-siCqareze~ korelaciuri funqciisTvis miRebuli bolcmanis tipis miaxloebiTi kinetikuri gantolebis amonaxsni rdm-Si kristalis dabali temperaturebis dros, da gamoTvlilia dabalsixSiruli kuTri eleqtrogamtaroba da eleqtronis Zvradoba am modelSi izotropul SemTxvevaSi da erTi zonis miaxloebaSi:

$$\mathrm{Res}_{Ac}(w) = \frac{ne^2}{m} \frac{\Gamma_{Ac}^{rel}(g)}{w^2 + \Gamma_{Ac}^{2rel}(g)} \cos\left[\frac{\hbar g}{mV_s^2} \Gamma_{Ac}^{rel}(g)\right] \qquad (11)$$

$$(a < 1; g >> 1; w << \frac{mV_s^2}{\hbar g}).$$

$$m_{Ac} = \lim_{w \to 0} \frac{\mathrm{Re}\, s_{Ac}(w)}{ne} = m_{oAc} - \Delta m_{Ac}$$

$$m_{0Ac} = \frac{\hbar e}{m^2 V_s^2} \frac{1}{64a} e^{4g} \qquad (12)$$

$$\Delta m_{Ac} = \frac{\hbar e}{m^2 V_s^2} \frac{1}{32a} e^{4g} \sin^2\left[32a g e^{-4g}\right]; \qquad (a < 1; g >> 1)$$

naTelia, rom temperaturuli Sesworeba eleqtronis dabal temperaturul Zvradobaze, romelic ganpirobebulia sawyisi korelaciebis gaTvaliswinebiT, warmoadgens Zalian mcire sidides. miRebuli formulebi warmoadgenen Tanmimdevrul da koreqtul Sedegs eleqtronis dabal temperaturuli ZvradobisTvis akustikuri polaronis modelSi susti eleqtron_fononuri bmis SemTxvevaSi.

am paragrafSi gamoTvlilia aseve elqtrogamtaroba da eleqtronis Zvradoba akustikuri polaronis modelSi eleqtruli velis maRali ω_sixSireebis SemTxvevaSi, kristalis rogorc maRali, aseve dabali temperaturebis dros, napovnia am sidideebis ω_sixSiresa da T_temperaturaze damokidebuleba (yofaqceva) am parametrebis sxvadasxva mniSvnelobebis dros. am SemTxvevaSic temperaturuli Sesworeba eleqtronis dabal temperaturul Zvradobaze warmoadgens Zalian mcire sidides.

eleqtronis dabatemperaturuli Zvradobis gamosaTvlelad akustikuri polaronis modelSi susti eleqtron-fononuri bmis SemTxvevaSi (α<1), gamoiyeneba kinetikuri (bolcmanis) gantolebis meTodi. am gantolebis amoxsnisas rdm_Si eleqtronis dabal temperaturuli statikuri ZvradobisTvis (dc-mobility) Sfm_Si miiReba mniSvneloba

$$m_{0BAC} = \frac{\hbar e}{m^2 Vs^2} \cdot \frac{1}{32a} e^{4g}; (g >> 1, a < 1, w = 0). \qquad (13)$$

xolo, fxip-is Teoriisa (miaxloebisa) da balansis gantolebis meTodis (tornberg-feinmanis Teoriis) gamoyenebiT napovni eleqtronis dabal temperaturuli statikuri Zvradobis mniSvneloba tolia sidids:

$$\tilde{m}_{AC}^{FXIP} = \tilde{m}_{AC}^{TF} = \frac{3}{4g} \cdot \frac{1}{64a} e^{4g}; \quad m = \frac{\hbar e}{m^2 V_s^2} \tilde{m}, (g >> 1, a < 1) \qquad (14)$$

avtoris mier napovni dabal temperaturuli statikuri Zvradobis mniSvneloba Sfm_Si (ix. 12 formula). warmoadgens Tanmimdevrul da koreqtul Sedegs akustikuri polaronis modelSi. is 2_jer naklebia

eleqtronis `bolcmaniseul~ dabal temperaturul Zvradobaze da $^{3}/_{4g}$-mamravliT gansxvavdeba fxip-isa da tornberg-feinmanis Sedegasgan. rac Sexeba fxip-isa da tornberg-feinmanis Sedegebis Tanxvedras da $^{3}/_{4g}$-mamravls_iseve, rogorc polaronis froli-xis modelSi, am modelSic maTi warmoSobis Rrma mizezi (buneba) jer-jerobiT dadgenili ar aris.

$3.4_Si ganxilulia polaronis fgm. gamoTvlilia da gamokvleulia kontinualuri optikuri polaronis drefuli Zvradoba da misi yofaqceva am modelSi dabali temperaturebis SemTxvevaSi. gamoyvanilia kvanturi kinetikuri gantolebebi polaronis `impulsi-_impulsze~ (`deni_denze~). wonasworuli korelaciuri funqciebisTvis, ganxilulia markoviseuli miaxloeba polaronis dinamikisaTvis da didi droebis asimpatotur areSi: $t \sim t_{rel} >> t_0 = \max(t_s,\ t_\Sigma);\quad t_{rel} >> b;$ $\hbar = m = w_0 = 1$). (t_s-polaronis dajaxebaTa maxasiaTebeli droa, t_Σ-aris TermostatSi fluqtuaciebis korelaciebis maxasiaTebeli dro), miRebulia miaxloebiTi gamosaxulebebi korelaciuri funqciebisTvis. gamoyvanilia agreTve kinetikuri gantolebebi korelaciuri funqciebis diagonaluri matriculi elementebisTvis. napovnia korelaciuri funqciebis milevis dekrementebi (polaronis impulsis relaqsaciis sixSire) da oscilirebadi faqtorebi.

dabali temperaturebis SemTxvevaSi ($b >> 1,\ b^{-1} << |e_1 - e_0|$) da didi droebis areSi ($t >> |e_i - e_j|^{-1}$)-polaronis $\langle P_z P_z(\pm t)\rangle_{GF^-}$ korelaciuri funqciebis sidide ZiriTadad gansazRvrulia impulsTa im mniSvnelobebiT, romelTaTvisac $\frac{\vec{P}^2}{2M_{GF}} << |e_1 - e_0|$; $\frac{\vec{P}^2}{2M_{GF}} << 1$, (sadac e_l, e_j, e_1, e_0 polaronis agznebuli da ZiriTadi mdgomareobis energiebia, M_{GF}_polaronis masaa). am pirobebSi dadgenilia, rom polaronis impulsis relaqsaciis sixSire $\Gamma^{GF}_{zrel}(b, \vec{P})$_ ar aris damokidebuli TviT

polaronis $\vec{P}$ impulsze (`mcire~ siCqariT moZravi polaroni) da ganisazRvreba Tanafardobi T:

$$\Gamma^{GF}_{zrel}(b,\vec{\hat{P}}) \equiv \Gamma^{GF}_{0rel}(b) = \tfrac{2}{3} a N_0(b)\sqrt{M}\, f(\sqrt{2M}) \qquad (15)$$

$$(b >> 1, \vec{\hat{P}}^2 / 2M << 1)$$

sadac: $f(\sqrt{2M}) = f(k)|_{k=\sqrt{2M}}$; $\qquad f(k) = |<0|\, e^{im_e \vec{k}\vec{x}}\, |0>|^2 \qquad (16)$

$$N_0(b) = \left[e^b - 1\right]^{-1}$$

napovni (dabal sixSiruli) kuTri eleqtrogamtarobisTvis da polaronis dabal temperaturuli ZvradobisaTvis gvaqvs Semdegi saxis gamosaxulebebi:

$$\mathrm{Re}\, s^{GF}(w) = Ne^2 b^{-1} M \frac{2th(\frac{1}{2} bw)}{w} \frac{\Gamma^{GF}_{0rel}(b)}{w^2 + \Gamma^{2GF}_{0rel}(b)} \cos\left[\frac{b}{2}\Gamma^{GF}_{0rel}(b)\right] \qquad (17)$$

$$(w << \Gamma^{GF}_{0rel}(b) << b^{-1} << 1);$$

$$m_0^{GF} = \frac{3}{2} e \frac{\exp(b)}{a} \frac{\sqrt{M}}{f(\sqrt{2M})}; \qquad m^{GF} = m_0^{GF} - \Delta m^{GF}$$

$$\Delta m^{GF} = 3e \frac{\exp(b)}{a} \cdot \frac{\sqrt{M}}{f(\sqrt{2M})} \sin^2\left[\frac{1}{6} a b N_0(b)\sqrt{M} \cdot f(\sqrt{2M})\right]. \qquad (18)$$

$$(w = 0; \quad \Gamma^{GF}_{0rel}(b) << b^{-1} << 1)$$

sadac: N-polaronebis koncentraciaa.

naTelia, rom Δm^{GF} _sidide, romelic warmoadgens temperaturul Sesworebas polaronis Δm_0^{GF} _dabal temperaturul Zvradobaze, warmoadgens mcire sidides TviT am ZvradobasTan SedarebiT.

amave §3.4_Si agreTve ganxilulia da gaanalizebulia sakiTxi polaronis dabal temperaturuli Zvradobis yofaqcevis Sesaxeb eleqtron-fononuri bmis α_mudmivas zRvruli (susti da Zlieri) mniSvnelobebis dros. dadgenilia, rom: 1. susti eleqtron-fononuri bmis zRvrul SemTxvevaSi: (α<1, M_{GF}<<1, $M_{GF} \to 0$), rodesac polaronis fgm

gadadis polaronis frolixis modelSi, polaronis dabal temperaturuli Zvradobis Tvis gvaqvs:

$$m_0^{GF} \Rightarrow m_0 = \frac{3e}{2a} e^b; \quad \Delta m^{GF} \Rightarrow \Delta m = \frac{1}{3} e a b^2 e^{-b}; (a < 1, b >> 1) \qquad (19)$$

romelic emTxveva dabal temperaturuli Zvradobis mniSvnelobas polaronis frolixis modelSi.

2. Zlieri eleqtron-fononuri bmis zRvrul SemTxvevaSi: (α>>1, M_{GF}>>1, $M_{GF} \to 8$), rodesac fgm aRadgens pekaris Teorias, polaronis dabal temperaturuli Zvradobis yofaqceva aRiwereba Tanafardobi T:

$$m_{o\Pi}^{GF} \sim \frac{3e}{2} \exp(b) a^{13}; \quad (a >> 1, b >> 1) \qquad (20)$$

sadisertacio naSromSi avtoris mier ganviTarebuli formalizmi da meTodebi, miRebuli ganzogadoebuli kvanturi kinetikuri gantolebebi wonasworuli korelaciuri funqciebisTvis da mesame Tavis §3.1_§3.4_ebSi ganxilul modelebze dayrdnobiT miRebuli Sedegebi (gamoyvanili formulebi: rogorc zogadi, aseve miaxloebiTi) SesaZleblobas iZleva gadaugvarebel, farTozonian, erTgvarovan (polarul) naxevargamtarebSi, ionur da kovalentur kristalebSi_eleqtronuli da polaronuli gamtarobisa da dabal temperaturuli dreifuli Zvradobis wrfivi kvanturi Teoriis agebas_kvanturi dinamiuri sistemebis sxva modelTaTvisac, romlebic urTierTqmedeben fononebTan (eleqtronebis gabneva arapolarul optikur fononebze, piezoeleqtuli gabneva, polaronis fm. da sxva)._eleqtronebisTvis erTi zonis miaxloebaSi, dispersiis rogorc zogadi, aseve paraboluri kanonis dros da fononebis dispersiis izotropuli kanonis SemTxvevaSi.

daskvnebi

1. sxvadasxva midgomebis-mowesrigebul operatorTa da liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis gamoyenebiT, sawyisi korelaciebis gaTvaliswinebiT_gamoyvanilia axali, zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebi drois ormomentiani wonasworuli korelaciuri funqciebisTvis, dinamiuri qvesistemisTvis romelic urTierTqmedebs bozonur velTan (TermostatTan). miRebul gantolebaTa dajaxebiTi integralebi

Seicaven rogorc wevrebs, romlebic aRweren namdvili korelaciebis evolucias droSi, aseve sawyisi korelaciebis evoluciur wevrebs, romlebic ganpirobebulia qvesistemis urTierTqmedebiT bozonur TermostatTan drois sawyis momentSi.

2. SeSfoTebis Teoriis meore miaxloebaSi – qvesistemis TermostatTan urTierTqmedebis hamiltonianis mixedviT – napovnia ganzogadoebuli kvanturi kinetikuri gantolebebi gamoricxuli bozonuri amplitudebiT korelaciuri funqciebisTvis, rogorc markoviseuli, ise aramarkoviseuli saxiT, romlebic Seicaven cxadad gamoyofil sawyisi korelaciebis evoluciur wevrebs.

3. eleqtron-fononuri sistemisTvis, frolixisa da akustikuri polaronis modelTaTvis, SeSfoTebis Teoriis meore miaxloebaSi, susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi da erTi zonis miaxloebaSi eleqtronisaTvis gamoyvanilia da gamokvleulia markovis saxis kinetikuri gantolebebi eleqtronis siCqaris operatoris komponentebis saSualo mniSvnelobebis diagonaluri matriculi elementebisaTvis, romlebic warmoadgenen bolcmanis tipis gantolebebs, saidanac gamoricxulia fononuri amplitudebi. Gganxilulia eleqtronis aradrekadi gabnevis procesebi fononebze da dadgenilia, rom ganxilul modelebSi adgili aqvs relaqsaciur process korelaciuri funqciebis oscilaciebiT. Nnapovnia eleqtronis impulsis (siCqaris) relaqsaciis sixSireebis analizuri gamosaxulebebi kristalis dabali temperaturebis SemTxvevaSi. gamoTvlilia eleqtronis “siCqaresiCqareze” korelaciuri funqciebis milevis dekrementebi da oscilirebadi faqtorebi.

4. gamokvleulia da dadgenilia, rom eleqtronis siCqaris (impulsis) mcire mniSvnelobebisaTvis, siCqaris relaqsaciis droebi (sixSireebi) ganxilul modelebSi ar aris damokidebuli impulsis sidideze. mcire siCqareebiTYmoZravi eleqtronebisTvis Zalian dabali temperaturebis dros napovnia dabalsixSiruli eleqtrogamtarobisa da eleqtronis dreifuli Zvradobis gamosaTvleli formulebi.

5. frolixis polaronis modelSi miRebuli gamosaxulebebi eleqtronis dabaltemperaturuli dreifuli Zvradobisa da dinamiuri gamtarobiTvis warmoadgens osakas mier napovni Sedegis ganzogadoebas mcire intensivobis mqone dabalsixSirul gareSe eleqtrul velSi, rac faqtiurad SesaZlebelia ganxiluli iqnas, rogorc drudes formula kuTri eleqtrogamtarobisTvis. napovnia agreTve statikuri ($w=0$) eleqtrogamtarobisa da dabaltemperaturuli dreifuli Zvradobis analizuri gamosaxulebebi, rogorc frolixis, aseve akustikuri polaronis modelebSi.

6. rogorc gamoTvlebi gviCvenebs, eleqtronebis gabnevisas polarul optikur fononebze, dabaltemperaturuli dreifuli ZvradobisTvis (dcmobility; $w=0$) miRebuli mniSvneloba 3-jer aRemateba Zvradobis im mniSvnelobas, romelic miiReba bolcmanis kinetikuri gantolebis gamoyenebiT da amoxsniT relaqsaciis drois miaxloebaSi.

miRebuli Sedegi warmoadgens – "$\frac{3}{2}\frac{K_B T}{\hbar w_0}$ problemis" – nawilobriv gadawyvetas frolixis polaronis dabaltemperaturuli Zvradobis TeoriaSi.

7. eleqtronebis gabnevisas akustikur fononebze (akustikuri polaronis modeli) miRebuli dabaltemperaturuli dreifuli Zvradobis $(w = 0)$ mniSvneloba 2-jer naklebia Zvradobis im mniSvnelobaze, romelic aseve miiReba bolcmanis kinetikuri gantolebis amoxsnisas relaqsaciis drois miaxloebaSi.

8. ganxilul modelebSi napovnia agreTve eleqtronis dreiful Zvradobaze temperaturuli Sesworebebi, romlebic ganpirobebulia sawyisi korelaciebis evoluciuri wevrebis arsebobiT gamoyvanili kinetikuri gantolebebis dajaxebiT integralebSi da naCvenebia, rom es Sesworebebi warmoadgenen mcire sidideebs ganxiluli Teoriis farglebSi.

9. polaronis fgm-sTvis miRebuli kvanturi kinetikuri gantolebebi eleqtruli denis operatoris komponentebis (polaronis impulsis) drois ormomentiani wonasworuli korelaciuri funqciebisTvis gamoyenebulia polaronis dreifuli Zvradobisa da eleqtrogamtarobis tenzoris gamosaTvlelad. Gganxilul erTzonian izotropul SemTxvevaSi, markoviseul miaxloebaSi polaronis dinamikisTvis, napovnia miaxloebiTi gamosaxulebebi korelaciuri funqciebisTvis.

10. kristalis Zalian dabali temperaturebis SemTxvevaSi gamoyvanilia bolcmanis tipis kinetikuri gantoleba korelaciuri funqciis diagonaluri matriculi elementisTvis, romelic Seesabameba polaronis ZiriTad mdgomareobas. gamokvleulia polaronis aradrekadi gabnevis procesebi fononebze. napovnia impulsis relaqsaciis sixSiris (drois) analizuri gamosaxuleba da dadgenilia, rom mcire siCqariT moZravi polaronisTvis impulsis relaqsaciis sixSire (dro) ar aris damokidebuli impulsis sidideze.

11. kubos wrfivi reaqciis Teoriis gamoyenebiT miRebulia dabalsixSiruli eleqtrogamtarobis tenzoris analizuri gamosaxuleba eleqtron-fononuri sistemisaTvis erTzonian miaxloebaSi da fononebis dispersiis zogadi (izotropuli) kanonis SemTxvevaSi. gamoTvlilia polaronis dabaltemperaturuli dreifuli Zvradoba fgm-Si. am modelSi napovnia agreTve temperaturuli Sesworeba polaronis dreiful Zvradobaze, romelic ganpirobebulia sawyisi korelaciebis evoluciuri wevrebis arsebobiT miRebuli kinetikuri gantolebebis dajaxebiT integralebSi, da dasabuTebulia, rom es temperaturuli Sesworeba warmoadgens mcire sidides.

12. ganxilulia da gaanalizebulia polaronis dabaltemperaturuli dreifuli Zvradobis yofaqceva susti $(a < 1)$ da Zlieri $(a >> 1)$ eleqtron-fononuri urTierTqmedebis zRvrul SemTxvevebSi. susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi $(M_{GF} \to 0)$, rodesac polaronis fgm gadadis polaronis frolixis modelSi, pola-

ronis dabal temperaturuli dreifuli ZvradobisTvis ($g >> 1$; $w = 0$) vRebulobT iseTive miSvnelobas, rogoric napovnia polaronis frolixis modelSi. Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($M_{GF} \to \infty$), rodesac polaronis fgm aRadgens polaronis pekaris naxevradklasikur Teorias, dabal temperaturuli dreifuli Zvradobis yofaqceva moicema Semdegi Tanafardobit: $m_{GF} \sim \frac{3}{2} e.\exp(g) a^{13}$; ($\hbar = m = w_0 = 1$; $g = b >> 1$; $w = 0$); anu polaronis dabal temperaturuli Zvradoba Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a >> 1$) izrdeba a-bmis mudmivas mecamete rigis proporciulad am mudmivas didi mniSvnelobebis dros, maSin rodesac polaronis pekaris TeoriaSi dabal temperaturuli Zvradoba izrdeba misi mexuTe rigis proporciulad: $m_{\Pi} \sim a^5$; rodesac $a >> 1$; ($\hbar = m = w_0 = 1$; $b >> 1; w = 0$).

13. sadisertacio naSromSi Catarebuli gamokvlevebi gviCvenebs, rom ganviTarebul meTodebs, romlebic dafuZnebulia kinetikuri gantolebebis miRebaze wonasworuli korelaciuri funqciebisTvis da maT gamoTvlaze, gansxvavebiT sxva midgomebisgan, ar mivyavarT ganSladi wevrebisagan Sedgenili usasrulo mwkrivebis ajamvis aucileblobasTan kvazinawilakis (eleqtronis, polaronis) urTierTqmedebis mixedviT fononebTan, kristalze modebuli gareSe eleqtruli velis dabali ($w \to 0$) sixSireebis SemTxvevaSi.

naSromSi dasabuTebulia, rom arsebuli sawyisi korelaciebis evolucia da korelaciuri funqciebis oscilaciebi drois mixedviT, romlebic ganpirobebulia kvazinawilakis (zogad SemTxvevaSi kvanturi dinamiuri qvesistemis) urTierTqmedebiT fononur (bozonur) velTan drois sawyis momentSi, gavlenas ar axdenen relaqsaciur procesebze da isini warmoadgenen Zvradobebze temperaturuli Sesworebebis ZiriTad mizezs (wyaros) ganxilul modelebSi.

SUMMARY

In modern conditions a subject to research is a subject of electron and polaron transport phenomena study in solid states and condensed matter physics. Making electron and polaron mobility and electrical conductivity quantum theory and quasi-particle kinetic features calculation remains one of the actual problem in modern theory of electron and polaron. In the latest years a tendency of making materials of difficult molecular building and studying polaron features gave stimuli to implement a lot of theoretical research for describing autolocalized (polaron) matter. Polaron concepts, which represents a simple example of nonlinear quasi-particle, has great importance and is highly used in solid states and condensed matter physics and especially it is closely connected to the fundamental problems of quantum dynamical systems theory and to the subjects of quantum theory of a field. In the latest period it became actual to research subjects of electron-phonon system and polaron kinetic on the base of Kubo linear response theory and to build correct quantum theory of electron and polaron transfer phenomena and calculation of mechanical coefficients (mobility, electrical conductivity) in semiconductors and ionic crystals.

The aim of thesis work is to receive and research new, exact generalized quantum kinetic equations for time correlation functions for some quantum dynamical systems of solid physics, which interacts with phonon field (electron-phonon system, Frohlich and acoustical polaron models, polaron generalized model of Feynman) and on the base of such models building of consecutive, correct electron and polaron low- frequency conductivity and low-temperature drift mobility quantum theory for non degenerated wide-band semiconductors and ionic crystals based on Kubo linear response and perturbation theory and calculation of mechanical coefficients transport (mobility, electrical conductivity) for above mentioned quantum subsystems models.

The thesis work discusses two method of approach for new, exact generalized quantum kinetic equations for double-time equilibrium correlation functions for quantum dynamical systems, which interacts with boson (phonon) field (thermostat).

The first method of approach is based on ordered operators formalism and chronological and antichronological T-product method; and the second method of approach which is based on Liouville superoperative formalism and projection operator method.

The first chapter of the work generally gives a short brief. In the first paragraph of this chapter deals with model Hamiltonian kind of dynamical systems, which interact with boson (phonon) thermostat and there are discussed some actual examples of quantum dissipative and open nonequilibrium modeling systems and from different fields of modern physics, which became the subject of intensive research and learn in the latest 30-40 years. The spectrum of the wide research contained subjects of metals' electrical conductivity and superconductivity theories, subjects of metal alloy and cold "metal glasses" electronic theory; subjects of week and strong localization and strong inhomogeneous substances electrical conductivity theory in disordered systems physics; aspects of laser radiation and superradiation theory aspects in quantum radiophysics; subjects of magnetic polaron and fluctuon (phason) and etc in magnetic substances (environment) and others. The second paragraph deals with dynamically disordered system - electron-phonon system and electron interaction with acoustical and polar optical phonons and gives general introduction of Hamiltonian of electron-phonon system (Frohlich - Pekar type Hamiltonian), Hamiltonians of electron acoustical and polar optical phonons interaction and short brief of deformation potential method. The third part of the work deals with large radius polaron models. There are reviewed polaron Frohlich and Pekary models and polaron Feynman oscillator and generalized Feynman models there. The same paragraph deals with a new approach for polaron systems thermodynamics and kinetic subjects, developed in latest years – ordered operators formalism, T-product method and phonon operators elimination method from equilibrium and nonequilibrium average value – physical quantity characteristic for electron-phonon system. The advantage of a new method of approach in some occasions to at studying kinetic subjects of electron-phonon system. The fourth paragraph deals with several principal subjects of physical kinetics of dynamical systems, which interact with phonon (boson) field. There is given review of very important and principal subject such as opportunity of shorten description at evolution (kinetic) equation for K-type dynamical systems (for classic and quantum as well), which is not based of a hypothesis about usage of initial correlations weakness and random phase approximation (RPA). There is described those basic schedules and methods, which lead us to Boltzmann type kinetic equation and master equation there. The chapter deals with such basic principal difficulties, which are arisen at calculation of drift mobilities for above mentioned models, as according to Boltzmann kinetic equation and Kubo linear response theory and also at using some methods of linear and nonlinear conductivity theories (nonequilibrium density matrix and balance equation methods).

The second chapter of thesis work deals with general question – to receive exact, generalized, quantum evolutionary equations for equilibrium correlation and Green functions of dynamical subsystems, which interacts with boson (phonon) thermostat. The first paragraph deals with ordered operators formalism and T-product method. The second paragraph deals with new and exact quantum evolutional (kinetic) initial correlations weakness principles equations for without random phase approximation usage and double-time equilibrium correlation and Green retarded functions, with eliminated boson amplitudes. The fourth paragraph deals with new and exact generalized quantum kinetic equations for double-time equilibrium correlation and Green functions been found by using Liouville superoperative formalism and projection operator method. Unlike kinetic equations for correlation functions, received by different authors in scientific literature, integrals of evolutional equations presented in this work contain additional members, which describe initial correlations evolution in the period of time and which are caused by subsystem interaction with boson thermostat in initial moment of time. The third and fifth paragraphs discuss Markov method of approach for subsystem dynamics and accordingly by the help of both formalism and methods there has been found approximately quantum kinetic equations for correlation functions with eliminated boson amplitudes and initial correlation description and additional members in collission integrals. Researches and results have been conducted in this chapter of the work give opportunity for better and wider studying of kinetic phenomena, which take place in dynamical systems and which interact with boson field.

Subjects of electron and polaron transport phenomena quantum theories in solid states – in semiconductors and ionic crystals – have been researched in the third chapter of thesis work. All four paragraphs of the same work are dedicated to electron and polaron low-frequency conductivity and low-temperature drift mobility quantum theory, which is based on the above mentioned models of quantum dynamical systems, Kubo linear response and perturbation theory and on quantum kinetic equations for equilibrium correlation functions presented in the second chapter. The first paragraph researches Markovian type kinetic equations for correlation functions of electron "velocity – on velocity" in relaxation time approximation and there has been found decrements of damping correlation functions and oscillation factors; for electron-phonon systems in the case of weak electron-phonon interaction in one band approximation there has been received analyze image of low-frequency electrical conductivity tensor and low-temperature drift mobility of electron in the case of anisotropy has been calculated there – conductivity band is of electron velocity. The second and third paragraphs deals with several subjects of electronic transport phenomena in Frohlich and acoustical polaron models. There have been found formulas for calculating drift mobility and low-frequency conductivity at low-temperatures for electron in such models. Generalization of Osaka result for electron low-temperature mobility and low-frequency conductivity in electric field are received in polaron Frohlich model. There is given partial decision for "$\frac{3}{2}\frac{K_B \mathrm{T}}{\hbar\omega_0}$ problem" in Frohlich polaron low-temperature mobility theory and is shown, that meaning of mobility given in this work excels three times those meaning of mobility which is received by Boltzmann kinetic equation in relaxation time approximation. In acoustical polaron model (at scattered electron on acoustical phonons) meaning of low-temperature mobility is two times less than the meaning of mobility, which is also received by Boltzmann equation in relaxation time approximation. The fourth paragraph of the same chapter deals researches several subjects of polaron kinetic in generalized Feynman model and kinetic equations are solved for polaron "momentum-on momentum" equilibrium

correlation functions; there is calculated frequency of polaron momentum relaxation (relaxation time) at low temperature crystal and analyze image of low-frequency electrical conductivity tensor (dissipative part) is received; there is found polaron low-temperature drift mobility meaning there. There is analyzed polaron low-temperature mobility behavior in the event of electron phonon interaction there and there is found mobility dependence on coupling constant in the case of strong electron-phonon interaction and different behavior of low-temperature mobility according to the degree of coupling constant by polaron Pekar model is established. The work also calculates temperature corrections on electron and polaron low-temperature mobilitys in the discussed models and there is shown, that these corrections represent small quantities within discussed theory and approaches has been used there.

disertaciis ZiriTadi Sedegebi gamoqveynebulia

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Eelektronebisa da polaronebis Zvradobis kvanturi Teoriis ageba da kvazinawilakebis kinetikuri maxasiaTeblebis gamoTvla kvlav rCeba erT-erT aqtualur amocanad myari sxeulebis fizikaSi. ukanaskneL periodSi did interss iwvevs kubos wrfivi gamoZaxilis meTodze dayrdnobiT eleqtronuli da polaronuli gadatanis movlenebis koreqtuli kvanturi Teoriis ageba da meqanikuri koeficientebisH(Zvradoba, eleqtrogamtaroba) gamoTvla naxevargamtarebsa da ionur kristalebSi.

sadisertacio naSromis mizans warmoadgens-eleqtron-fononuri sistemisTvis kvazinawilakis susti (frolixisa da akustikuri polaronis modelebi) da Zlieri (polaronis feinmanis ganzogadoebuli modeli (fgm)) urTirTqmedebis SemTxvevaSi fononur velTan - axali,zusti, ganzogadoebuli kvanturi kinetikuri gantolebebis miReba da gamokvleva droiTi wonasworuli korelaciuri funqciebisaTvis; am gantolebaTa gamoyenebiT, am modelTaTvis Tanmimdevruli, koreqtuli eleqtronuli da polaronuli dabaltemperaturuli dreifuli Zvradobis kvanturi Teoriis ageba naxevargamtarebsa da ionur kristalebSi.

sadisertacio naSromSi ganxilulia axali, zusti ganzogadoebuli kvanturi kinetikuri gantolebebis miRebis ori midgoma drois ormomentiani wonasworuli korelaciuri funqciebisTvis: pirveli midgoma dafuZnebulia mowesrigebul operatorTa formalizmze da qronologiur da antiqronologiur T-namravlTa meTodze, da meore midgoma eyrdnoba liuvilis superoperatorul formalizmsa da proeqciuli operatoris meTods.

naSromis pirveli Tavis pirvel paragrafSi moyvanilia modeluri hamiltonianis saxe dinamiuri sistemebisa, romlebic urTierTqmedeben bozonur (fononur) TermostatTan da ganxilulia zogierTi aqtualuri magaliTi kvanturi disipaciuri da Ria arawonasworuli modeluri sistemebisa Tanamedrove fizikis sxvadasxva dargidan, romlebic gaxdnen intensiuri kvlevisa da Seswavlis sagani ukanaskneli 30-40 wlis ganmavlobaSi. meore paragrafSi ganxilulia dinamiurad mouwesrigebeli sistema - eleqtron-fononuri sistema da eleqtronis urTierTqmedeba akustikur da polarul optikur fononebTan; moyvanilia eleqtron-fononuri sistemis hamiltonianis zogadi saxe (frolix-pekaris tipis hamiltoniani), eleqtronis akustikur da polarul optikur fononebTan urTierTqmedebis hamiltonianTa saxeebi da mokled mimoxilulia agreTve deformaciis potencialis meTodi. didi radiusis mqone polaronTa modelebi – polaronis frolixisa da pekaris, feinmanis erToscilatoriani da fg modelebi – mimoxilulia mesame paragrafSi.

amave paragrafSi ganxilulia agreTve ukanaskneL wlebSi ganviTarebuli da gamoyenebuli axali midgoma polaronuli sistemebis Termodinamikisa da kinetikis sakiTxebis gamokvlevebisas

– mowesrigebul operatorTa formalizmi, T-namravlTa meTodi da fononuri operatorebis gamoricxvis teqnika eleqtron-fononuri sistemis maxasiaTebeli fizikuri sidideebis wonasworuli da arawonasworuli saSualo mniSvnelobebidan. aRniSnulia zogierT SemTxvevaSi am axali midgomis upiratesoba eleqtron-fononuri sistemis kinetikis sakiTxebis Seswavlisas, kontinualuri integrirebis meTodTan SedarebiT. meoTxe paragrafSi ganxilulia fizikuri kinetikis zogierTi principuli sakiTxi dinamiuri sistemebisa, romlebic urTierTqmedeben fononur (bozonur) velTan. mimoxilulia mniSvnelovani da principuli sakiTxi K-tipis dinamiur sistemebSi (rogorc klasikuris, aseve kvanturisTvis), evoluciuri gantolebebis gamoyvanis dros Semoklebuli aRweris SesaZleblobaze, romelic ar eyrdnoba sawyisi korelaciebis Sesustebisa da SemTxveviTi fazebis miaxloebis (Sfm) hipoTezas. aRwerilia ZiriTadi sqemebi da meTodebi, romlebsac mivyavarT bolcmanis saxis kinetikuri gantolebisa da ZiriTadi kinetikuri gantolebis povnamde. ganxilulia is ZiriTadi principuli xasiaTis sirTuleebi, romlebic warmoiSvebian eleqtron-fononuri sistemisa da polaronis zemoTmoyvanil modelTaTvis dreifuli Zvradobebis gamoTvlisas, gamomdinare rogorc bolcmanis kinetikuri gantolebidan da kubos wrfivi reaqciis Teoriidan, aseve eleqtrogamtarobis wrfivi da arawrfivi Teoriis zogierTi sxva meTodis (arawonasworuli simkvrivis matricis meTodi, balansis gantolebis meTodi) gamoyenebisas.

sadisertacio naSromis meore Tavi originaluri xasiaTisaa. am TavSi dasmulia zogadi amocana –dinamiuri qvesistemisTvis, romelic urTierTqmedebs bozonur (fononur) TermostatTan axali, zusti, ganzogadoebuli kvanturi evoluciuri gantolebebis miReba wonasworuli korelaciuri da grinis funqciebisTvis. pirvel paragrafSi ganxilulia mowesrigebul operatorTa formalizmi da T-namravlTa meTodi. meore da meoTxe paragrafebSi gamoyvanilia axali, zusti ganzogadoebuli kvanturi evoluciuri gantolebebi drois ormomentiani wonasworuli korelaciuri da grinis dagvianebuli funqciebisTvis, liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodisgamoyenebiT, sawyisi korelaciebis Sesustebis principisa da Sfm-s gamoyenebis gareSe. GgansxvavebiT samecniero literaturaSi sxvadasxva avtorTa mier miRebuli kinetikuri gantolebebisagan korelaciuri funqciebisTvis, naSromSi gamoyvanili evoluciuri gantolebebis dajaxebiTi integralebi Seicaven damatebiT wevrebs, romlebic aRweren sawyisi korelaciebis evolucias droSi, da romlebic ganpirobebulia qvesistemis urTierTqmedebiT bozonur TermostatTan drois sawyis momentSi. mesame da mexuTe paragrafebSi ganxilulia markoviseuli miaxloeba qvesistemis dinamikisTvis da Sesabamisad orive formalizmisa da meTodis daxmarebiT napovnia SeSfoTebis Teoriis meore miaxloebaSi kvanturi kinetikuri gantolebebi korelaciuri funqciebisTvis gamoricxuli bozonuri amplitudebiT da sawyisi korelaciebis evoluciis aRmweri damatebiTi wevrebiT dajaxebiT integralebSi.

eleqtronuli da polaronuli gadatanis movlenebis kvanturi Teoriis sakiTxebi – naxevargamtarebsa da ionur kristalebSi – ganxilulia da gamokvleulia sadisertacio naSromis mesame TavSi. am Tavis oTxive paragrafi eZRvneba eleqtronuli da polaronuli dabalsixSiruli gamtarobisa da dabaltemperaturuli dreifuli Zvradobis kvantur Teorias, romelic dafuZnebulia kubos wrfivi reaqciis Teoriaze, kvantur dinamiuri sistemebis zemoTmiTiTebul modelebze, da wina TavSi miRebul kvantur kinetikur gantolebebze. pirvel paragrafSi gamokvleulia da amoxsnilia relaqsaciis drois miaxloebaSi markovis saxis kinetikuri gantolebebi eleqtronis “siCqare-siCqareze” korelaciuri funqciebisTvis; miRebulia dabalsixSiruli gamtarobis tenzoris analizuri gamosaxuleba da gamoTvlilia eleqtronis dabaltemperaturuli dreifuli Zvradoba eleqtron-fononuri sistemisTvis erTi zonis miaxloebaSi izotropul SemTxvevaSi – eleqtronis siCqarisa da fononebis dispersiis nebismieri zogadi, izotropuli kanonis SemTxvevaSi. meore da mesame paragrafebSi napovnia dabalsixSiruli eleqtrogamtarobisa da dabaltemperaturuli dreifuli Zvradobis gamosaTvleli formulebi frolixisa da akustikuri polaronis modelebSi. polaronis frolixis modelSi miRebulia osakas Sedegis ganzogadoeba eleqtronis dabaltemperaturuli dreifuli ZvradobisTvis dabalsixSirul gareSe eleqtrul velSi; moyvanilia “$\frac{3}{2}\frac{K_B\mathrm{T}}{\hbar\omega_0}$ problemis” nawilobrivi gadawyveta frolixis polaronis dabaltemperaturuli Zvradobis TeoriaSi da naCvenebia, rom naSromSi miRebuli Zvradobis mniSvneloba 3-jer aRemateba Zvradobis im mniSvnelobas, romelic miiReba bolcmanis kinetikuri gantolebis amoxsniT relaqsaciis drois miaxloebaSi. akustikuri polaronis modelSi naSromSi napovni eleqtronis dabaltemperaturuli dreifuli Zvradobis mniSvneloba 2-jer naklebia Zvradobis im mniSvnelobaze, romelic aseve miiReba bolcmanis gantolebis amoxsniT relaqsaciis drois miaxloebaSi. meoTxe paragrafSi Ggamoyvanilia da amoxsnilia (relaqsaciis drois miaxloebaSi) kinetikuri gantolebebi polaronis “impulsi-impulsze” wonasworuli korelaciuri funqciebisTvis fgm-Si. miRebulia dabalsixSiruli eleqtrogamtarobis tenzoris analizuri gamosaxuleba da gamoTvlilia polaronis dabaltemperaturuli dreifuli Zvradoba. napovnia Zvradobis damokidebuleba eleqtron-fononuri urTierTqmedebis (bmis) mudmivaze Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi, da dadgenilia dabaltemperaturuli Zvradobis gansxvavebuli yofaqceva (bmis mudmivas rigis mixedviT) polaronis pekaris modelTan SedarebiT. naSromSi gamoTvlilia aseve temperaturuli Sesworebebi eleqtronisa da polaronis dabaltemperaturul dreiful Zvradobebze ganxilul modelebSi, da naCvenebia, rom es Sesworebebi warmoadgenen mcire sidideebs ganxiluli Teoriisa da gamoyenebuli miaxloebebis farglebSi.

Abstract

In modern conditions a subject to research is a subject of electron and polaron transport phenomena study in solid states and condensed matter physics. Making electron and polaron mobility and electrical conductivity quantum theory and quasi-particle kinetic features calculation remains one of the actual problem in modern theory of electron and polaron. In the latest years a tendency of making materials of difficult molecular building and studying polaron features gave stimuli to implement a lot of theoretical research for describing autolocalized (polaron) matter. Polaron concepts, which represents a simple example of nonlinear quasi-particle, has great importance and is highly used in solid states and condensed matter physics and especially it is closely connected to the fundamental problems of quantum dynamical systems theory and to the subjects of quantum theory of a field. In the latest period it became actual to research subjects of electron-phonon system and polaron kinetic on the base of Kubo linear response theory and to build correct quantum theory of electron and polaron transfer phenomena and calculation of mechanical coefficients (mobility, electrical conductivity) in semiconductors and ionic crystals.

The aim of thesis work is to receive and research new, exact generalized quantum kinetic equations for time correlation functions for some quantum dynamical systems of solid physics, which interacts with phonon field (electron-phonon system, Frohlich and acoustical polaron models, polaron generalized model of Feynman) and on the base of such models building of consecutive, correct electron and polaron low-frequency conductivity and low-temperature drift mobility quantum theory for non degenerated wide-band semiconductors and ionic crystals based on Kubo linear response and perturbation theory and calculation of mechanical coefficients transport (mobility, electrical conductivity) for above mentioned quantum subsystems models.

The thesis work discusses two method of approach for new, exact generalized quantum kinetic equations for double-time equilibrium correlation functions for quantum dynamical systems, which interacts with boson (phonon) field (thermostat).

The first method of approach is based on ordered operators formalism and chronological and antichronological T-product method; and the second method of approach which is based on Liouville superoperative formalism and projection operator method.

The first chapter of the work generally gives a short brief. In the first paragraph of this chapter deals with model Hamiltonian kind of dynamical systems, which interact with boson (phonon) thermostat and there are discussed some actual examples of quantum dissipative and open nonequilibrium modeling systems and from different fields of modern physics, which became the subject of intensive research and learn in the latest 30-40 years. The spectrum of the wide research contained subjects of metals' electrical conductivity and superconductivity theories, subjects of metal alloy and cold "metal glasses" electronic theory; subjects of week and strong localization and strong inhomogeneous substances electrical conductivity theory in disordered systems physics; aspects of laser radiation and superradiation theory aspects in quantum radiophysics; subjects of magnetic polaron and fluctuon (phason) and etc in magnetic substances (environment) and others. The second paragraph deals with dynamically disordered system - electron-phonon system and electron interaction with acoustical and polar optical phonons and gives general introduction of Hamiltonian of electron-phonon system (Frohlich - Pekar type Hamiltonian), Hamiltonians of electron acoustical and polar optical phonons interaction and short brief of deformation potential method. The third part of the work

deals with large radius polaron models. There are reviewed polaron Frohlich and Pekary models and polaron Feynman oscillator and generalized Feynman models there. The same paragraph deals with a new approach for polaron systems thermodynamics and kinetic subjects, developed in latest years – ordered operators formalism, T-product method and phonon operators elimination method from equilibrium and nonequilibrium average value – physical quantity characteristic for electron-phonon system. The advantage of a new method of approach in some occasions to at studying kinetic subjects of electron-phonon system. The fourth paragraph deals with several principal subjects of physical kinetics of dynamical systems, which interact with phonon (boson) field. There is given review of very important and principal subject such as opportunity of shorten description at evolution (kinetic) equation for K-type dynamical systems (for classic and quantum as well), which is not based of a hypothesis about usage of initial correlations weakness and random phase approximation (RPA). There is described those basic schedules and methods, which lead us to Boltzmann type kinetic equation and master equation there. The chapter deals with such basic principal difficulties, which are arisen at calculation of drift mobilities for above mentioned models, as according to Boltzmann kinetic equation and Kubo linear response theory and also at using some methods of linear and nonlinear conductivity theories (nonequilibrium density matrix and balance equation methods).

The second chapter of thesis work deals with general question – to receive exact, generalized, quantum evolutionary equations for equilibrium correlation and Green functions of dynamical subsystems, which interacts with boson (phonon) thermostat. The first paragraph deals with ordered operators formalism and T-product method. The second paragraph deals with new and exact quantum evolutional (kinetic) initial correlations weakness principles equations for without random phase approximation usage and double-time equilibrium correlation and Green retarded functions, with eliminated boson amplitudes. The fourth paragraph deals with new and exact generalized quantum kinetic equations for double-time equilibrium correlation and Green functions been found by using Liouville superoperative formalism and projection operator method. Unlike kinetic equations for correlation functions, received by different authors in scientific literature, integrals of evolutional equations presented in this work contain additional members, which describe initial correlations evolution in the period of time and which are caused by subsystem interaction with boson thermostat in initial moment of time. The third and fifth paragraphs discuss Markov method of approach for subsystem dynamics and accordingly by the help of both formalism and methods there has been found approximately quantum kinetic equations for correlation functions with eliminated boson amplitudes and initial correlation description and additional members in collission integrals. Researches and results have been conducted in this chapter of the work give opportunity for better and wider studying of kinetic phenomena, which take place in dynamical systems and which interact with boson field.

Subjects of electron and polaron transport phenomena quantum theories in solid states – in semiconductors and ionic crystals – have been researched in the third chapter of thesis work. All four paragraphs of the same work are dedicated to electron and polaron low-frequency conductivity and low-temperature drift mobility quantum theory, which is based on the above mentioned models of quantum dynamical systems, Kubo linear response and perturbation theory and on quantum kinetic equations for equilibrium correlation functions presented in the second chapter. The first paragraph researches Markovian type kinetic equations for

correlation functions of electron "velocity – on velocity" in relaxation time approximation and there has been found decrements of damping correlation functions and oscillation factors; for electron-phonon systems in the case of weak electron-phonon interaction in one band approximation there has been received analyze image of low-frequency electrical conductivity tensor and low-temperature drift mobility of electron in the case of anisotropy has been calculated there – conductivity band is of electron velocity. The second and third paragraphs deals with several subjects of electronic transport phenomena in Frohlich and acoustical polaron models. There have been found formulas for calculating drift mobility and low-frequency conductivity at low-temperatures for electron in such models. Generalization of Osaka result for electron low-temperature mobility and low-frequency conductivity in electric field are received in polaron Frohlich model. There is given partial decision for "$\frac{3}{2}\frac{K_B \mathrm{T}}{\hbar\omega_0}$ problem" in Frohlich polaron low-temperature mobility theory and is shown, that meaning of mobility given in this work excels three times those meaning of mobility which is received by Boltzmann kinetic equation in relaxation time approximation. In acoustical polaron model (at scattered electron on acoustical phonons) meaning of low-temperature mobility is two times less than the meaning of mobility, which is also received by Boltzmann equation in relaxation time approximation. The fourth paragraph of the same chapter deals researches several subjects of polaron kinetic in generalized Feynman model and kinetic equations are solved for polaron "momentum-on momentum" equilibrium correlation functions; there is calculated frequency of polaron momentum relaxation (relaxation time) at low temperature crystal and analyze image of low-frequency electrical conductivity tensor (dissipative part) is received; there is found polaron low-temperature drift mobility meaning there. There is analyzed polaron low-temperature mobility behavior in the event of electron phonon interaction there and there is found mobility dependence on coupling constant in the case of strong electron-phonon interaction and different behavior of low-temperature mobility according to the degree of coupling constant by polaron Pekar model is established. The work also calculates temperature corrections on electron and polaron low-temperature mobilitys in the discussed models and there is shown, that these corrections represent small quantities within discussed theory and approaches has been used there.

Sinaarsi

Sinaarsi x

naxazebis nusxa xiii

Sesavali xiv

Tavi I. dinamiuri sistemebi, romlebic urTierTqmedeben TermostatTan (bozonur velTan) 23

1.1. kvanturi disipaciuri da Ria arawonasworuli modeluri sistemebi (zogierTi magaliTi) 25

1.1.1. fermionuli sistema 25

1.1.2. Txevadi metalis an Senadnobis modeli 25

1.1.3. nawilaki, romelic urTierTqmedebs garemosTan 27

1.1.4. eleqtron-minarevuli sistema 30

1.1.5. dikes modelebi gamosxivebis TeoriaSi 31

1.1.6. eleqtronebi magnetikSi, romlebic urTierTqmedeben kristalis magnitur qvesistemasTan 33

1.2. eleqtron-fononuri sistema. eleqtronis urTierTqmedeba akustikur da polarul optikur fononebTan 36

1.2.1. eleqtronis urTierTqmedeba kristaluri mesris akustikur rxevebTan. deformaciis potencialis meTodi 37

1.2.2. eleqtronis urTierTqmedeba polarul optikur fononebTan 39

1.3. polaronis amocana. didi radiusis mqone polaronis modelebi 41

1.3.1. polaronis frolixisa da pekaris modelebi 42

1.3.2. polaronis feinmanis modeli 52

1.3.3. polaronis feinmanis ganzogadoebuli modeli..... 60

(latinjer-lus modeli)..... 60

1.4. fizikuri kinetikis zogierTi sakiTxi dinamiuri sistemebisa, romlebic urTierTqmedeben fononur (bozonur) velTan..... 66

Tavi II. ganzogadoebuli kvanturi evoluciuri gantolebebi drois ormomentiani wonasworuli korelaciuri funqciebisa da grinis funqciebisTvis dinamiuri qvesistemisa, romelic urTierTqmedebs TermostatTan (bozonur velTan)..... 82

2.1. mowesrigebul operatorTa formalizmi da T-namravlTa meTodi..... 82

2.2. zusti ganzogadoebuli kvanturi kinetikuri gantolebebi wonasworuli korelaciuri funqciebisa da grinis funqciebisTvis..... 91

2.3. markoviseuli miaxloeba qvesistemis dinamikisTvis miaxloebiTi gantolebebi korelaciuri funqciebisTvis..... 95

2.4. ganzogadoebuli kvanturi evoluciuri gantolebebi korelaciuri funqciebisTvis Sfm-is gamoyenebis gareSe. proeqciuli operatoris meTodi..... 99

2.5. Termostatis bozonuri amplitudebis gamoricxva evoluciuri gantolebidan korelaciuri funqciisaTvis. markoviseuli miaxloeba qvesistemis dinamikisTvis..... 103

Tavi III. naxevargamtarebsa da ionuri kristalebSi eleqtronuli da polaronuli gamtarobisa da dabal temperaturuli Zvradobis kvanturi Teoria dafuZnebuli kubos wrfivi gamoZaxilis Teoriaze..... 108

3.1.eleqtron-fononuri sistema. eleqtronis dabalsixSiruli eleqtrogamtarobisa da dabal temperaturuli Zvradobis gamoTvla susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi 114

3.2. elektronis Zvradoba frolixis polaronis modelSi 117

3.3. elektronis Zvradoba akustikuri polaronis modelSi susti elektron–fononuri urTierTqmedebis SemTxvevaSi 127

3.4 polaronis dabal temperaturuli Zvradoba feinmanis ganzogadoebul modelSi 134

daskvna 143

gamoyenebuli literatura 146

danarTi

bozonuri (fononuri) amplitudebis gamoricxva qronologiur da antiqronologiur T-namravlTa daxmarebiT 153

disertaciis TemasTan dakavSirebiT gamoqveynebulia Semdegi naSromebi 156

naxazebis nusxa

nax.1. potencialuri ormo, energetikuli doneebi da eleqtronis Ψ-talRuri funqcia pekaris polaronis modelSi ---------- **51**

nax.2. polaronis feinmanis modeli. eleqtroni, romelic dakavSirebulia "zambaris" meSveobiT meore nawilakTan masiT M_F ---------- **56**

nax.3. V da W – variaciuli parametrebis yofaqceva, rogorc a-urTierTqmedebis (bmis) mudmivas funqciebi, polaronis feinmanis TeoriaSi ---------- **58**

Sesavali

ukanaskneli 50-60 wlis ganmavlobaSi didi yuradReba eTmoboda denis (muxtis) gadamtanebis dinamiuri da kinetikuri Tvisebebis Seswavlas myar sxeulebSi. zogadad denis aseT gadamtanebs warmoadgens sxvadasxva saxis polaronebi; TiToeuli maTgani moicavs gamtarobis eleqtrons (an xvrels) da maT mier gamowveul mesris struqturis deformacias. aseTi TvalsazrisiT gamtarobis eleqtroni (an xvreli) faqtiurad warmoadgens polarons zRvruli, susti deformaciis SemTxvevaSi. eleqtronebis da polaronebis dinamiuri da kinetikuri yofaqcevis Seswavla stimulirebuli iyo mravali eqsperimentuli masaliT, romelic exeboda gadatanis movlenebis gamokvlevas myar sxeulebSi, romelTa interpretacia mraval SemTxvevaSi standartuli zonuri Teoriis CarCoebSi Zalze rTuli iyo, gansakuTrebiT ionur kristalebSi da polarul naxevargamtarebSi. garda amisa, gadatanis movlenebis zogadi debulebebi kristalebSi arsebiTad iqna ganviTarebuli im fundamentaluri gamokvlevebis safuZvelze, romelic asaxavs disipaciuri sistemebis dinamiur da kinetikur Tvisebebs da romlebSic mimdinareobs Seuqcevadi gadatanis movlenebi. eleqtronuli gadatanis movlenebis Teoriis ganviTarebis aseTma pirobebma gamoiwvia mniSvnelovani zegavlena iseTi kvlevis areebis CamoyalibebaSi, rogoric aris – polaronuli gadatanis movlenebi, eleqtronuli gadatanis movlenebi Zlier (kvantur) magnitur velSi, eleqtronuli gadatanis movlenebis Teoria magnitur kristalebSi da mouwesrigebel garemoebSi (sistemebSi) da sxva.

rogorc cnobilia, kristalebSi eleqtronuli gadatanis movlenebis zonuri Teoria principSi dafuZnebulia sam ZiriTad koncefciaze: 1) denis gadamtanebi warmoadgens kvazinawilakebs gansazRvruli kvaziimpulsiT da dispersiis kanoniT. 2) denis gadamtanTa eleqtrogamtaroba da Zvradoba ganisazRvreba maTi gabneviT kristalis idealuri mesris struqturis dinamiur da statikur damaxinjebebze (defeqtebze). 3) denis gadamtanis Tavi-

sufali ganarbenis sigrZe warmoadgens sasrul sidides da is bevrad aRemateba Sesabamisad kvazinawilakis de-broilis talRis sigrZes. am pirobebis gaTvaliswinebiT denis gadamtanTa gabneva SeiZleba CaiTvalos rogorc “iSviaTi”. am debulebebidan gamomdinare, denis gadamtanTa yofaqceva kristalSi aRiwereba albaTuri ganawilebis funqciiT kvaziimpulsebis mixedviT, romelic ganisazRvreba, rogorc bolcman-bloxis kinetikuri gantolebis amoxsna. ukanaskneli SeiZleba ganxiluli iqnas, rogorc balansis (uwyvetobis) gantoleba, romelSic gaTvaliswinebulia denis gadamtanTa ganawilebis funqciis cvlileba kristalSi, gamowveuli rogorc gareSe modebuli Zalebis zegavleniT, agreTve denis gadamtanTa kvaziimpulsis gadanawilebiT (cvlilebiT) gabnevis procesSi. aseTi gagebiT (Tu mxedvelobaSi ar miviRebT dispersiis kanonis kvantur-meqanikur bunebas da denis gadamtanebis gabnevis albaTurobas), gadatanis movlenebis Teoria, romelsac xSirad uwodeben bolcmaniseuls, arsebiTad warmoadgens klasikurs da igi ar moicavs specifiur kvantur efeqtebs. amrigad, klasikur areebSi gadatanis kinetikuri (meqanikuri) koeficientebis (Zvradoba, eleqtrogamtaroba) gamosaTvlelad gamoiyeneba denis gadamtanebis arawonasworuli ganawilebis funqciisaTvis kinetikuri gantoleba – bolcmanis gantoleba – romelic iTvaliswinebs denis (muxtis) matarebelTa urTierTqmedebas (gabnevas) kristaluri mesris rxevebze.

ukanaskneL wlebSi, eleqtronuli gadatanis movlenebis gamokvlevebSi myari sxeulebis da maxevargamtarebis fizikaSi, Zalian farTo gamoyeneba hpova ufro zogadma, alternatiulma midgomam, romelic dafuZnebulia kubos wrfivi reaqciis Teoriaze. am TeoriaSi - romelsac gadamwyveti mniSvneloba aqvs wrfiv arawonasworul TermodinamikaSi – gadatanis kinetikuri (meqanikuri) koeficientebi bunebrivad gamoisaxebian (aRiwerebian) droiTi korelaciuri funqciebiT. isini asaxaven sistemis reaqcias hamiltonianis SeSfoTebisas, romlis tipiur magaliTs warmoadgens eleqtrogamtaroba. kubo-grinis formulebi gadatanis koeficientebi-

saTvis warmoadgenen kerZo SemTxvevas TanafardobaTa farTo klasisa, romelic cnobilia fluqtuaciur-disipaciuri Teoremebis saxelwodebiT. am Teoremebis amsaxveli maTematikuri formulebi amyareben kavSirs mikroskopul da makroskopul damzerad sidideebs Soris. wrfivi gadatanis movlenebis ganxilvisas kubos formula “deni-denze” droiTi korelaciuri funqciisaTvis warmoadgens arsebiTad zust gamosaxulebas kvantur mravalnawilakovan formalizmSi, im gansxvavebiT bolcmanis kinetikuri gantolebisagan, rom araviTari daSveba ar keTdeba gabnevis kveTis sididis Sesaxeb denis gadamtanebis (eleqtronebis) gabnevisas kristalur mesris rxevebze. unda aRiniSnos, rom tradiciulad eqvivalentobas kubos formulasa da bolcmanis gantolebas Soris mkacrad ikvleven mxolod denis gadamtanebis susti gabnevis zRvrul SemTxvevaSi kristaluri mesris rxevebze. rogorc cnobilia, kubos formula amyarebs kavSirs eleqtrogamtarobasa da droiT wonasworul korelaciur funqcia “deni-dens” Soris, romelic aris ornawilakovani (oTxwertilovani) grinis funqciis msgavsi, maSin, rodesac bolcmanis gantoleba warmoadgens – kinetikur gantolebas arawonasworuli ganawilebis funqciisaTvis, da romelic aris erTnawilakovani (orwertilovani) grinis funqciis saxis.

Teoriuli gamokvlevebis Zalian didi raodenoba samecniero literaturaSi miZRvnili aris eleqtronebisa da polaronebis eleqtrogamtarobisa da Zvradobis gamoTvlaze naxevargamtarebsa da ionur kristalebSi. es gamokvlevebi dafuZnebuli aris sxvadasxva Teoriul meTodebze – grinis funqciis teqnikaze, bolcmanis kinetikuri gantolebis Seswavlaze, TviTSeTanxmebul meTodebze da sxv. rezultatebi miRebuli sxvadasxva meTodebis gamoyenebiT da Sesabamisad sxvadasxva miaxloebebze dayrdnobiT, Zireulad gansxvavdeba erTmaneTisagan. miuxedavad imisa, rom eleqtronebis da polaronebis eleqtrogamtarobisa da Zvradobis gamoTvla warmoadgens erT-erT uZveles problemas myari sxeule-

bis fizikaSi, is mainc rCeba erT-erT urTules da Znel amocanad Teoriulad amoxsnis Tvalsazrisit.

amgvarad, Tanamedrove pirobebSi kvlav aqtualurs warmoadgens sakiTxi eleqtronebis da polaronebis eleqtrogamtarobis da Zvradobis koreqtuli gamoTvlisa naxevargamtarebsa da ionur kristalebSi.

rogorc cnobilia, efeqtur meTods urTierTqmed nawilakTa sistemis kinetikuri maxasiaTeblebis gamoTvlisa warmoadgens wonasworul korelaciur funqciaTa da grinis funqciebis meTodi. kubos wrfivi gamoZaxilis Teoriis upiratesoba arawonasworuli statistikuri meqanikis sxva midgomebTan SedarebiT mdgomareobsimaSi, rom es Teoria saSualebas iZleva uSualod gamoyenebuli iqnas wonasworuli mravalnawilakovani meTodebi gadatanis kinetikuri (meqanikuri) koeficientebis gamosaTvlelad myar sxeulebSi. am midgomis dros ZiriTad problemas warmoadgens wonasworuli korelaciuri funqciebis gamoTvla, romlebisTvisac iwereba kvanturi evoluciuri (kinetikuri) gantolebebi.

myari sxeulebis fizikisa da arawonasworuli statistikuri meqanikis mravali amocanis ganxilvisas Seiswavleba mcire dinamiuri qvesistemis evolucia droSi, romelic imyofeba kontaqtSi didi Tavisuflebis ricxvis mqone, Termodinamikur wonasworobaSi myof sistemasTan – TermostatTan.

eleqtronuli da polaronuli gadatanis movlenebis gamokvlevisas myar sxeulebSi kubos wrfivi gamoZaxilis Teoriaze dayrdnobiT, ZiriTad amocanas warmoadgens zusti ganzogadoebuli. kvanturi evoluciuri (kinetikuri) gantolebebis miReba droiss ormomentiani wonasworuli korelaciuri funqciebisTvis kvazinawilakebis aRmweri Sesabamisi dinamiuri sidideebisaTvis, rodesac xdeba am ukanasknelTa urTierTqmedeba (gabneva) kristaluri mesris rxevebze (fononebze), da rodesac fononuri (bozonuri) veli ganixileba rogorc Termostati. samecniero literaturaSi, aseTi saxis gantolebebis misaRebad, rogorc wesi gamoiyeneba aprioruli hipoTeza – sawyisi korelaciebis Sesustebis

principi, an msgavsi debulebebi – mag. SemTxveviTi fazebis miaxloeba (Sfm) – rodesac drois sawyisi momentisaTvis mTeli sistemis (qvesistema plus Termostati) statistikuri operatori moicema faqtorizebuli saxiT (mTeli sistemis statistikuri operatori ganixileba rogorc qvesistemisa da Termostatis statistikur operatorTa pirdapiri namravli). naTelia, rom aseTi daSvebebis Sedegad miRebuli ganzogadoebuli, kvanturi evoluciuri gantolebebi wonasworuli korelaciuri funqciebisaTvis ar aris zusti. amitom cxadia, rom zogadad kvanturi disipaciuri sistemebis ganxilvisas da kinetikuri movlenebis Seswavlisas mcire dinamiur sistemebSi, romlebic urTierTqmedeben bozonur (fononur) TermostatTan, kubos wrfivi gamoZaxilis Teoriis farglebSi mkacri midgomis gansaviTareblad saWiroa zusti, ganzogadoebuli, kvanturi evoluciuri gantolebebis gamoyvana qvesistemis dinamiuri sidideebis wonasworuli korelaciuri funqciebisTvis.

amrigad, eleqtronuli da polaronuli gadatanis movlenebis koreqtuli Teoriis asagebad da meqanikuri koeficientebis (mag. Zvradoba, eleqtrogamtaroba) gamosaTvlelad naxevargamtarebsa da ionur kristalebSi da agreTve eleqtron-fononuri sistemis kinetikis sakiTxebis gamosakvlevad kubos wrfivi reaqciis Teoriis CarCoebSi, aqtualurs warmoadgens amocana kvazinawilakebis dinamiuri sidideebisTvis drois ormomentiani wonasworuli korelaciuri funqciebisTvis zusti, ganzogadoebuli, kvanturi evoluciuri gantolebebis miReba – sawyisi korelaciebis Sesustebis principisa da Sfm-is gamoyenebis gareSe.

sadisertacio naSromis mizans warmoadgens:

– myari sxeulebis fizikis zogierTi kvanturi dinamiuri sistemisTvis, romelic urTierTqmedebs fononur (bozonur) velTan (eleqtron-fononuri sistema, frolixis polaronis modeli, akustikuri polaronis modeli susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi, polaronis fgm), mowesrigebul opera-

torTa formalizmsa da T-namravlTa teqnikaze dayrdnobiT, agreTve liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis gamoyenebiT zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebis miReba da gamokvleva drois ormomentiani wonasworuli korelaciuri funqciebisTvis Sfm-is gamoyenebis gareSe.

– Aam modelebze dayrdnobiT Tanmimdevruli, srulyofili eleqtronuli da polaronuli gamtarobisa da dabal temperaturuli dreifuli Zvradobiskvanturi Teoriis ageba naxevargamtarebsa da ionur kristalebSi dafuZnebuli kubos wrfivi gamoZaxilisa da SeSfoTebis Teoriaze. gadatanis meqanikuri (kinetikuri) koeficientebis (eleqtrogamtaroba, Zvradoba) gamoTvla kvanturi disipaciuri sistemebis zemoTmiTiTebuli modelebisTvis.

ZiriTadi Sedegebi da mecnieruli siaxle

warmodgenil sadisertacio naSromSi gadawyvetilia Semdegi amocanebi:

– mowesrigebul operatorTa formalizmisa da T-namravlTa teqnikis daxmarebiT, sawyisi korelaciebis Sesustebis principisa da Sfm-is gamoyenebis gareSe, gamoyvanilia da gamokvleulia axali, zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebi gamoricxuli bozonuri (fononuri) amplitudebiT drois ormomentiani wonasworuli korelaciuri da grinis funqciebisTvis dinamiuri qvesistemisTvis, romelic urTierTqmedebs bozonur TermostatTan. aseTive saxis kvanturi kinetikuri gantolebebi korelaciuri funqciebisaTvis miRebulia liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis daxmarebiT.

– dinamiuri qvesistemis bozonur (fononur) TermostatTan urTierTqmedebis hamiltonianis mixedviT, SeSfoTebis Teoriis meore miaxloebaSi miRebulia axali, ganzogadoebuli kvanturi kinetikuri gantolebebi gamoricxuli bozonuri amplitudebiT,

qvesistemis drois ormomentiani wonasworuli korelaciuri funqciebisTvis – rogorc markoviseuli, ise aramarkoviseuli formiT – romelTa dajaxebiTi integralebi Seicaven cxadad gamoyofil sawyisi korelaciebis evoluciur wevrebs.

– kubos wrfivi reaqciisa da SeSfoTebis Teoriis farglebSi, naxevargamtarebisa da ionuri kristalebisTvis agebulia eleqtronuli da polaronuli dabalsixSiruli gamtarobisa da dabaltemperaturuli dreifuli Zvradobis Tanmimdevruli, koreqtuli kvanturi Teoria, dafuZnebuli kvanturi disipaciuri sistemebis zemoTmiTiTebuli modelebisTvis ganzogadoebul kvantur kinetikur gantolebebze korelaciuri funqciebisaTvis "deni-denze" eleqtronisa da polaronisaTvis, romlebic urTierTqmedeben fononebTan Sfm-is gamoyenebis gareSe.

– miRebulia da gamokvleulia analizuri gamosaxulebebi eleqtronisa da polaronis relaqsaciuri maxasiaTeblebisTvis (impulsis relaqsaciis sixSire da sxv.); gamoTvlilia wonasworuli korelaciuri funqciebis – "deni-denze" – milevis dekrementebi. napovnia eleqtrogamtarobis tenzoris analizuri saxe eleqtron-fononuri sistemisTvis kristalis dabali temperaturebisa da dabalsixSiruli gareSe eleqtruli velebis SemTxvevaSi da gamoTvlilia gadatanis meqanikuri koeficientebi (Zvradoba, eleqtrogamtaroba) kvanturi disipaciuri sistemebis aRniSnuli modelebisTvis; napovnia agreTve "$\frac{3}{2}\frac{K_B T}{\hbar w_0}$-problemis" nawilobrivi gadawyveta frolixis polaronis dabaltemperaturuli Zvradobis TeoriaSi.

– miRebulia temperaturuli Sesworebebi eleqtronisa da polaronis dreiful Zvradobebze, romlebic ganpirobebulia sawyisi korelaciebis evoluciuri wevrebis arsebobiT kvantur kinetikur gantolebebSi wonasworuli korelaciuri funqciebisTvis "siCqare-siCqareze" ("impulsi-impulsze") eleqtronisa da polaronisTvis. dadgenilia, rom es Sesworebebi warmoadgenen mcire

sidideebs Sesrulebuli miaxloebebisa da ganxiluli Teoriis farglebSi.

sadisertacio naSromis praqtikuli mniSvneloba:

naSromSi dasmuli amocanebis gadawyvetam moiTxova arawonasworuli statistikuri meqanikis zogierTi meTodis Semdgomi ganviTareba. miRebuli zusti, ganzogadoebuli kvanturi evoluciuri gantolebebi wonasworuli korelaciuri funqciebisTvis SesaZlebelia gamoyenebuli iqnas gadatanis movlenebis gansaxilvelad da gamosakvlevad - kubos wrfivi reaqciis Teoriis farglebSi, sawyisi korelaciebis Sesustebis principisa da Sfm-is daSvebebis gareSe - myari sxeulebis da kondensirebul garemoTa fizikis dinamiur qvesistemaTa sxva modelTaTvis (kvanturi disipaciuri sistemebisTvis), romlebic urTierTqmedeben bozonur velTan (TermostatTan). (mag. brounis kvanturi nawilakis moZraobis Sesaswavlad, romelic ganixileba rogorc wrfivi, milevadi harmoniuli oscilatori, da romlis dinamika aRiwereba kaldeira-legetis mikroskopuli modeluri hamiltonianiT).

naSromSi ganviTarebuli formalizmi, meTodebi da miRebuli kinetikuri gantolebebi martivad SesaZlebelia ganvrcobili iqnas kinetikuri movlenebis Sesaswavlad da gadatanis meqanikuri koeficientebis (mag. Zvradoba, eleqtrogamtaroba) gamosaTvlelad: eleqtronebis urTierTqmedebisas (gabnevisas) arapolarul optikur fononebze, piezoeleqtrul fononebze, agreTve sxva didi radiusis mqone polaronis modelTaTvis (mag. akustikuri polaronis modelisTvis - eleqtronis fononebTan Zlieri urTierTqmedebis SemTxvevaSi). gamoyvanili ganzogadoebuli kvanturi kinetikuri gantolebebi korelaciuri funqciebisTvis kvanturi dinamiuri qvesistemisTvis, romelic urTierTqmedebs fononur velTan, SesaZlebelia gamoyenebul iqnas normaluri (arazegamtari) metalebis eleqtrowinaRobis gamosaTvlelad eleqtronebis gabnevisas akustikur fononebze. naSromSi warmodgenili formalizmis daxmarebiT SesaZlebelia temperaturuli Seswore-

bebis povna metalTa eleqtrowinaRobisTvis (Seswo rebebi blox-grunaizenis formulaSi), romlebic agreTve ganpirobebulia eleqtronebis fononebTan urTierTqmedebisas sawyisi korelaciebis gaTvaliswinebiT.

sadisertacio naSromSi miRebuli ZiriTadi Teoriuli Sedegebis praqtikuli mniSvneloba (Rirebuleba) ganisazRvreba agreTve imiT, rom ukanasknel wlebSi samecniero literaturaSi gamoqveynda mravali Teoriuli naSromi, romelic Seexeba bozonur velTan (TermostatTan) urTierTqmedebaSi myofi kvanturi dinamiuri sistemis kinetikis sakiTxebs, sadac ganixileba msgavsi formalizmi da meTodebi, romelic ganviTarebulia avtoris mier warmodgenil naSromSi.

Tavi I. dinamiuri sistemebi, romlebic urTierTqmedeben TermostatTan (bozonur velTan)

ukanasknel aTwleulebis ganmavlobaSi arsebiTad gaizarda interesi im dinamiuri sistemebis Seswavlasi, romlebic urTierTqmedebaSi imyofebian TermostatTan (bozonur velTan) [1]. amasTan erTad didi yuradReba eTmoboda im procesebis detalur Seswavlas, romlebic mimdinareobdnen im mcire sistemebSi, romlebic urTierTqmedebdnen rogorc sustad, agreTve Zlierad Termodinamikur wonasworobaSi myof didi Tavisuflebis xarisxis mqone sistemasTan – TermostatTan. ZiriTadi meTodi, romlis saSualebiTac xdeboda am procesebis gamokvleva eyrdnoboda midgomebs, romlebic ganviTarebuli iyo arawonasworul statistikur meqanikaSi da stohastikuri (SemTxveviTi) procesebis TeoriaSi [1-2].

ukanasknel periodSi, mkacri midgomebis ganviTarebam arawonasworul statistikur meqanikaSi SesaZlebeli gaxada Camoyalibebuliyo sakmaod sruli da mkacri maTematikuri Teoria arawonasworuli modeluri sistemebisa [3]. Ria arawonasworuli modeluri sistemebis (Ria sistema warmoadgens mcire qvesistemas, romelic urTierTqmedebs TermostatTan) srulyofili maTematikuri Teoriis Seqmna warmoadgens SedarebiT ufro martiv da perspeqtiul problemas (amocanas) arawonasworuli statistikuri meqanikisa [3-4].

arawonasworuli statistikuri meqanikis da fizikuri kinetikis problemaTa farTo wre dakavSirebulia im modeluri hamiltonianebis Seswavlasi, rodesac dinamiuri qvesistema s urTierTqmedebs S TermostatTan, romelic aRiwereba bozonuri veliT; Tanac, rogorc wesi, urTierTqmedeba aiReba wrfivi Termostatis (boze) operatorebis (amplitudebis) mixedviT. zogad SemTxvevaSi, mTliani $(s+S)$ sistemis hamiltoniani SesaZlebelia warmovadginoT Semdegi saxiT:

$$H(t,s,\Sigma) = \Gamma(t,s) + H_{\Sigma} + H_{\text{int}}(t) \qquad (1.1)$$

sadac: $\Gamma(t,s)$ aris s qvesistemis sakuTari hamiltoniani;

H_{Σ} - Termostatis (bozonuri velis) hamiltoniania, xolo

H_{int} warmoadgens urTierTqmedebis hamiltonians s qvesistemisa S TermostatTan.

s qvesistemis urTierTqmedebisas bozonur velTan H_{int}-s aqvs Semdegi saxe:

$$H_{\text{int}}(t) = \sum_k \left[C_k(t,s) b_k + C_k^+(t,s) b_k^+ \right]. \qquad (1.2)$$

operatorebi, romlebic figurireben (1.1) da (1.2) gamosaxulebebSi arian Cveulebriv Sredingeriseul warmodgenaSi Caweruli dinamiuri cvladebi. b_k da b_k^+ warmoadgenen Termostatis boze amplitudebs – gaqrobisa da dabadebis operatorebs Caweruls meoradi dakvantvis warmodgenaSi. bozonur velTan urTierTqmedebis SemTxvevaSi: $H_\Sigma = \sum_k \hbar w(k) b_k^+ b_k$ warmoadgens bozonuri velis sakuTar hamiltonians. k – aris im kvanturi ricxvebis erToblioba, romlebic aRweren s qvesistemis urTierTqmedebas S TermostatTan da TviT Termostatis mdgomareobas. unda aRiniSnos, rom s dinamiuri qvesistemis operatorebis cxadi saxe arsad ar konkretdeba.

gamokvlevaTa Zalian didi raodenoba miZRvnilia kinetikur movlenebisadmi da procesebisadmi, romlebic mimdinareoben kvantur dinamiur sistemebSi, romlebic urTierTqmedeben TermostatTan (bozonur velTan) da aRiwerebian (1.1-1.2) hamiltonianiT [1-21].

ganvixiloT axla Tanamedrove fizikis TvalsazrisiT zogierTi aqtualuri da mniSvnelovani magaliTebi, romlebic farTo Seswavlis sagani gaxda statistikuri fizikis, myari sxeulebisa da kondensirebul garemoTa fizikis, gamosxivebis Teoriis da sxv. - kvanturi dinamiuri sistemebisa, romlebic urTierTqmedeben TermostatTan.

1.1. kvanturi disipaciuri da Ria arawonasworuli modeluri sistemebi (zogierTi magaliTi)

1.1.1. fermionuli sistema

qvesistema s warmoadgens araurTierTqmed fermionTa sistemas, romlebic xasiaTdebian fermi amplitudebiT da adgili aqvs Semdeg Tanafardobebs:

$$\Gamma(t,s)=\sum_{(f)}\Lambda(f)a_f^+a_f;\quad C_k(t,s)=\frac{e^{et}}{\sqrt{V}}L_k\sum_{(f)}a_{f+k}^+a_f$$
$$C_k^+(t,s)=\frac{e^{et}}{\sqrt{V}}L_k^*\sum_{(f)}a_f^+a_{f+k}=\frac{e^{et}}{\sqrt{V}}L_k^*\sum_{(f)}a_{f-k}^+a_f, \tag{1.3}$$

sadac L_k, L_k^* warmoadgenen "C-sidideebs". vinaidan fermionebs gaaCniaT spini, (1.3) gamosaxulebebSi $f\equiv\left(\vec{f},s\right)$ da $\vec{f}$ miekuTvneba kvazidiskretul speqtrs (s - warmoadgens spinis aRmniSvnel maCvenebels). simbolo $(f+k)$ waikiTxeba rogorc $(f+k)\equiv\left(\vec{f}+\vec{k},s\right)$; SesaZlebelia agreTve ganxiluli iqnas SemTxveva, rodesac fermionebi urTierTqmedeben erTmaneTTan. maSin $\Gamma(t,s)$ hamiltonianSi gaTvaliswinebuli unda iqnas agreTve damatebiTi wevrebi, romlebic aRweren fermionebs Soris urTierTqmedebas da maT urTierTqmedebas gareSe velebTan. unda aRiniSnos, rom aseTi saxis dinamiuri sistemebis ganxilvamde mivyavarT amocanebs, romlebic moiTxoven metalTa eleqtrogamtarobis gansazRvras, zegamtarobis movlenis axsnas da sxv. [14-15].

1.1.2. Txevadi metalis an Senadnobis modeli

mravalkomponentiani Txevadi metalis an Senadnobis hamiltoniani SesaZlebelia CavweroT Semdegi saxiT [9]:

$$H=\Gamma(t,s)+H_{\text{int}}:\quad H_{\text{int}}=\sum_{l=1}^{M}\sum_{k}C_{l\vec{k}}(t,s)dr_{l\vec{k}}$$
$$C_{l\vec{k}}^+(t,s)=C_{l,-\vec{k}}(t,s):\quad dr_{l\vec{k}}=N_l^{-1}\sum_{j=1}^{N_l}e^{-i\vec{k}\vec{R}_{lj}}-d_{\vec{k},o} \tag{1.4}$$
$$dr_{l\vec{k}}^*=dr_{l,-\vec{k}}.$$

aq s warmoadgens eleqtronuli sistemis maCvenebels, $\Gamma(t,s)$ aris eleqtronuli sistemis sakuTari hamiltoniani, romelic zogad SemTxvevaSi Seicavs

eleqtron-eleqtronuli urTierTqmedebis wevrebsac; H_{int} warmoadgens eleqtronul da ionur sistemebs Soris urTierTqmedebis hamiltonians, l aris ionuri sistemis maCvenebeli, $1 \le l \le M$; M M- komponentebis ricxvia; R_{lj} warmoadgens l-uri komponentis j-uri ionis koordinatas; $dr_{l\vec{k}}$ aris l-uri komponentis koleqtiuri koordinati, xolo N_l aris l-uri komponentis ionTa ricxvi: ajamva $\vec{k}$ simboloTi xorcieldeba kvazidiskretuli speqtris mixedviT. V-ki warmoadgens sistemis moculobas. magaliTad, araurTierTqmedi eleqtronebis modelisTvis, romlebic imyofebian gareSe eleqtronul velSi $\vec{E}(t)$ daZabulobiT, erTeleqtronian hamiltonians aqvs Semdegi saxe:

$$H = \mathrm{T}(\vec{p}) - e\vec{E}(t)\cdot\vec{r} + V(\vec{r}): \quad V(\vec{r}) = \sum_{l=1}^{M}\sum_{j=1}^{N_l} u_l\left(\vec{r} - \vec{R}_{lj}\right),$$

sadac: e- eleqtruli muxtia, $\mathrm{T}(\vec{p})$- warmoadgens energias (magaliTad, $\mathrm{T}(\vec{p}) = \frac{\vec{p}^{\,2}}{2m}$, m - efeqturi masaa), $\vec{r}$ da $\vec{p}$ aris eleqtronis koordinati da impulsi. $V(\vec{r})$ – eleqtronis ionebTan urTierTqmedebis potencialia, xolo $u_l\left(\vec{r} - \vec{R}_{lj}\right)$ warmoadgens eleqtronis urTierTqmedebis psevdopotencials l-uri komponentis j-ur ionTan. am SemTxvevaSi Cven gveqneba:

$$\Gamma(t,s) = e(\vec{p}) - e\vec{E}(t)\cdot\vec{r}; \quad e(\vec{p}) = \mathrm{T}(\vec{p}) + \overline{V(\vec{r})}$$

$$\overline{V(\vec{r})} = \sum_{l=1}^{M} C_l\tilde{u}_l(0); \quad \tilde{u}_l(\vec{k}) = n\int d\vec{r}e^{-i\vec{k}\vec{r}}u_l(\vec{r})$$

$$C_l = {}^{N_l}\!/_{N}: \quad \sum_{l=1}^{M} C_l = 1; \quad u_l^*(\vec{r}) = u_l(\vec{r}); \quad n = {}^{N}\!/_{V}$$

$$C_{l\vec{k}}(t,s) = e^{i\vec{k}\vec{r}}C_l\tilde{u}_l(\vec{k}).$$

Txevadi metalis an Senadnobis modelSi, romelic aRiwereba (1.4) hamiltonianiT, ionuri sistema ganixileba rogorc klasikuri da aRiwereba koleqtiuri cvladiT $dr_{l\vec{k}}$. Txevadi metalis modelisaTvis ionuri sistemis konfiguraciebis mixedviT gasaSualoeba dafuZnebulia $\tilde{f}\{r_{e\vec{k}}\}$ koleqtiuri cvladebiT gausis ganawilebis funqciiT gasaSualoebaze, romlisTvisac samarTliania Semdegi formula:

$$\left\langle \exp\left\{\sum_{i=1}^{M} a_{l\vec{k}} dr_{l\vec{k}}\right\}\right\rangle_{\tilde{f}} = \exp\left\{\frac{1}{2}\sum_{e,m=1}^{M}\sum_{\vec{k}} a_{l,-\vec{k}}\, a_{m\vec{k}} \left\langle dr^{*}_{l\vec{k}} \cdot dr_{m\vec{k}}\right\rangle_{\tilde{f}}\right\}.$$

aq $\langle ... \rangle_{\tilde{f}} \equiv \int \prod_{l=1}^{M}\prod_{\vec{k}} dd r_{l\vec{k}}\, \tilde{f}\left(\{dr_{l\vec{k}}\}\right)...$; sadac $a_{l\vec{k}}$ warmoadgens $l$da $\vec{k}$-s nebismier funqcias da adgili aqvs Semdeg Tanafardobebs:

$$\left\langle dr^{*}_{l\vec{k}} \cdot dr_{l\vec{k}}\right\rangle_{\tilde{f}} = \frac{1}{C_l N} s_{ll}(k) = \frac{1}{C_l N}\left[1 + C_l n \int d\vec{r} e^{-i\vec{k}\vec{r}}\left(g_{ll}(\vec{r}) - 1\right)\right].$$

$$\left\langle dr^{*}_{l\vec{k}} \cdot dr_{m\vec{k}}\right\rangle_{\tilde{f}} = \frac{1}{N} s_{lm}(k) = \frac{n}{N}\int d\vec{r}\left(g_{lm}(r) - 1\right) e^{-i\vec{k}\vec{r}}: \quad l \neq m,$$

sadac $g_{lm}(r)$ warmoadgenen radialuri ganawilebis funqciebs:

$$g_{lm}(r) = g_{lm}\left(\left|R_{li} - R_{mj}\right|\right),$$

xolo $s_{lm}(k)$ sidideebi warmoadgenen ionuri sistemis struqturul faqtorebs: $s_{lm}(k) = s_{ml}(k)$, $s^{*}_{lm}(k) = s_{lm}(k)$. struqturuli faqtorebi iZlevian srul informacias Txevadi metalis an Senadnobis ionuri sistemis Sesaxeb, romlebic aiReba eqsperimentuli monacemebidan. unda aRiniSnos, rom modelis sruli formulirebisaTvis aucilebelia ionebis R_{lj} SemTxveviTi koordinatebis ganawilebis funqciis miTiTeba, romlis mixedviTac xdeba gasaSualoeba. Txevadi metalis an Senadnobis aRniSnuli modeli xSirad gamoiyeneba metalebis, Senadnobebisa da gadacivebuli "metaluri minebis" kvantur eleqtronul TeoriaSi, romlebic dafuZnebulia am nivTierebaTa atomur da struqturul Taviseburebebze [9].

1.1.3. nawilaki, romelic urTierTqmedebs garemosTan

am modelSi ganixileba qvesistema s (gamoyofili nawilaki), romelic urTierTqmedebaSi imyofeba sxva nawilakebisagan Sedgenil garemosTan. aseTi sistemis hamiltonians aqvs saxe:

$$H = \frac{\vec{\mathrm{P}}^2}{2m} + \sum_{i=1}^{N}\frac{\vec{\mathrm{P}}_i^2}{2M_i} + U\left(\vec{r}_1, \vec{r}_2, \vec{r}_3, ...\vec{r}_N\right).$$

aq: m da $\vec{p}$ warmoadgens masasa da impulss gamoyofili nawilakisa; M_i da $\vec{\mathrm{P}}_i$ arian masebi da impulsebi garemos nawilakebisa. $\vec{r}_i$ – garemos nawilakTa radius-veqtorebia, U warmoadgens mTeli sistemis nawilakTa ur-

TierTqmedebis potenciur energias, xolo $\vec{r}$ – gamoyofili nawilakis radius-veqtoria.

sawyisi hamiltoniani SesaZlebelia warmovadginoT Semdegi formiT:

$$H = \Gamma(s) + H_{\Sigma} + H_{\text{int}},$$

sadac:

$$\Gamma(s) \equiv H_s = \frac{\vec{\mathrm{P}}^2}{2m} + \left(e^{\vec{U}\vec{\nabla}} - 1\right)\left\langle U(\vec{r}, \vec{r}_1, \vec{r}_2 ... \vec{r}_N)\right\rangle_{\Sigma}$$

$$H_{\Sigma} = \sum_{i=1}^{N} \frac{\vec{\mathrm{P}}_i^2}{2M_i} + U(\vec{r}_0, \vec{r}_1, \vec{r}_2 ... \vec{r}_N) \qquad (1.5)$$

$$H_{\text{int}} = \left(e^{\vec{U}\vec{\nabla}} - 1\right)\left[U(\vec{r}_0, \vec{r}_1, \vec{r}_2 ... \vec{r}_N) - \left\langle U(\vec{r}_0, \vec{r}_1, \vec{r}_2 ... \vec{r}_N)\right\rangle_{\Sigma}\right].$$

hamiltonianis aseTi saxiT warmodgenisas igulisxmeba, rom gansaxilvel gamoyofil nawilaks gaaCnia wonasworuli mdebareoba radius-veqtoriT $\vec{r}_0$ raRac saSualo velSi, romelic ganpirobebulia garemos nawilakebTan urTierTqmedebiT da U - potencialuri energia gaSlilia usasrulo mwkrivad nawilakis $\vec{u}$ wanacvlebis mixedviT wonasworuli mdebareobidan: $\vec{r} = \vec{r}_0 + \vec{u}$; $U(\vec{r}, \vec{r}_1, \vec{r}_2 ... \vec{r}_N) = e^{\vec{U}\vec{\nabla}} U(\vec{r}_0, \vec{r}_1, \vec{r}_2 ... \vec{r}_N)$ ($\vec{\nabla}$- warmoadgens gradientis operators gamoyofili nawilakis koordinatebis mixedviT).

amrigad, gamoyofili nawilaki, romelic imyofeba saSualo velSi (H_s hamiltoniani), ganicdis am saSualo velis fluqtuaciebis zemoqmedebas (H_{int} hamiltoniani). simbolo $\langle ... \rangle$ (1.5) formulaSi aRniSnavs gasaSualoebas garemos mdgomareobaTa mixedviT. Tu gavSliT $\vec{u}$ wanacvlebas normaluri koordinatebis mixedviT: $\vec{u} = \sum_c \vec{a}_c a_c + \vec{a}_c^* a_c^+$ da gamoviyenebT formulas:

$e^{\vec{U}\vec{\nabla}} \approx \vec{u}\vec{\nabla} = \quad = \sum_c \left(\vec{a}_c a_c + \vec{a}_c^* a_c^+\right)\vec{\nabla}$ (rac Seesabameba nawilakis mxolod wrfivi urTierTqmedebis gaTvaliswinebas garemosTan, romelic aRiwereba H_{int}-hamiltonianiT), da daviyvanT diagonalur saxeze H_s hamiltonianis im nawils, romelic kvadratulia $\vec{u}$ wanacvlebis mixedviT, maSin SesaZlebelia (1.5) hamiltoniani warmovadginoT (1.1) formiT. simboloebi c aRniSnavs gamoyofil oscilatorebs, xolo a_c da a_c^+ warmoadgenen gaqrobisa da dabadebis operatorebs c oscilatorebisa. amrigad s qvesistemis rolSi gveqneba oscilatorebis erToblioba hamiltonianiT $H_s = \sum_c w_c a_c^+ a_c$, sadac

w_c aris c oscilatoris sixSire. Tu gavSliT $U(\vec{r}_0,\vec{r}_1,\vec{r}_2...\vec{r}_N)$ potenciur energias wanacvlebebis - $\vec{u}_1,\vec{u}_2,...\vec{u}_N$ mixedviT mwkrivad, maSin garemos hamiltoniani H_Σ SesaZlebelia warmovadginoT agreTve rogorc oscilatorebis erToblioba (rasakvirvelia, am SemTxvevaSic unda gamoviyenoT Sesabamisi miaxloebebi). garemos nawilakTa radius-veqtorebisTvis gveqneba: $\vec{r}_1 = \vec{r}_{i0} + \vec{u}_i \ \ (i = 1,2,...N)$, sadac, $\vec{r}_{i0}$ -warmoadgens garemos nawilakTa wonasworuli mdebareobebis Sesabamis radius-veqtorebs.

samecniero literaturaSi xSirad ganixileba magaliTi kvanturi oscilatorisa, romelic urTierTqmedebs TermostatTan (bozonur velTan) [6]. aseTi sistemis hamiltonianisTvis gvaqvs gamosaxuleba:

$$H = \Gamma(t,s) + H_\Sigma + H_{\text{int}},$$

sadac: $$?(t,s) = \hbar w_0 a^+ a + \hbar[f^*(t)a + f(t)a^+];\ \ H_\Sigma = \sum_k \hbar w(k) b_k^+ b_k;$$

$$H_{\text{int}} = \sum_k \left[C_k(t,s)b_k + C_k^+(t,s)b_k^+\right];\ \ C_k(t,s) = \hbar l_k a^+ + \hbar u_k a;$$

$C_k^+(t,s) = \hbar l_k^* a + \hbar u_k^* a^+$ da kvanturi harmoniuli oscilatori imyofeba gareSe, cvladi klasikuri Zalis moqmedebis qveS, romelic wrfivadaa dakavSirebuli (urTierTqmedebs) TermostatTan – araurTierTqmedi kvanturi oscilatorebis sistemasTan. a, a^+, b_k, b_k^+ arian gaqrobis da dabadebis boze operatorebi, l_k, l_k^*, u_k, u_k^* warmoadgenen urTierTqmedebis mudmivebs, romlebic proporciuli arian $\frac{1}{\sqrt{V}}$ sididisa, sadac: V - sistemis moculoba, $\vec{k}$ talRuri veqtoria, romelic iRebs kvazidiskretul mniSvnelobebs, $f(t)$ aris cvladi klasikuri gareSe Zala, xolo w_0, w_k – oscilatorebis sixSireebia.

aseTi saxis dinamiur sistemebs vxvdebiT zogierTi amocanebis ganxilvisas kvanturi radiofizikidan, myari sxeulebisa da kondensirebul garemoTa fizikidan da sxv. magaliTebis saxiT SesaZlebelia moviyvanoT sistemebi, romlebic Sedgebian atomebisa da molekulebisagan da imyofebian lazeris talRis velSi myar sxeulebSi an airebSi, romlebic TamaSoben Termostatis rols [7-8, 10-12].

1.1.4. eleqtron-minarevuli sistema

es modeli warmoadgens sistemas, romelic Sedgeba eleqtronebisagan, romlebic urTierTqmedeben garemoSi SemTxveviT ganlagebul minarevuli centrebTan da gareSe eleqtrul velTan, romlis daZabulobaa - $\vec{E}(t)$. aseTi saxis modeli aRiwereba Semdegi hamiltonianiT:

$$H = \Gamma(t,s) + H_{\text{int}}; \quad \Gamma(t,s) = H_s - e\vec{E}(t)\cdot\vec{r};$$
$$H_s = \frac{\vec{\mathrm{P}}^2}{2m}; \quad H_{\text{int}} = \sum_{l=1}^{N_\Pi} j_e \equiv \sum_{l=1}^{N_\Pi} j\left(\vec{r} - \vec{r}_l\right), \tag{1.6}$$

sadac: $e, m, \vec{r}, \vec{p}$ Sesabamisad warmoadgenen eleqtronis muxts, masas, radius-veqtors da impulss. $j\left(\vec{r} - \vec{r}_l\right)$ aris eleqtronis urTierTqmedebis energia minarevul centrTan, romelic imyofeba wertilSi, romlis radius-veqtoria $\vec{r}_l$, xolo N_Π – minarevuli centrebis ricxvia. xSirad ganixilaven ufro zogad models eleqtron-minarevuli sistemisa, romlis hamiltoniani Caiwereba Semdegi saxiT [22]:

$$H = \Gamma(s) + H_e + H_\Sigma + H_{\text{int}}, \tag{1.7}$$

sadac: $H_{\text{int}} = H_{ie} + H_{e\Sigma}; \quad H_{e\Sigma} = \sum_{e=1}^{N} \frac{\vec{p}_i^{\,2}}{2m} + \frac{e^2}{8pe_0} \sum_{i,j=1}^{N} \frac{1}{\left|\vec{r}_i - \vec{r}_j\right|}$ warmoadgens N eleqtronebis hamiltonians, romlebic urTierTqmedeben erTmaneTTan kulonuri ZaliT, $\vec{r}_i$ da $\vec{p}_i$ aris i-uri eleqtronis koordinata da impulsi masaTa centris mimarT da $\Gamma(s), H_{ie}, H_{e\Sigma}$ moicema Semdegi formulebiT:

$$\Gamma(s) = \frac{\vec{\mathrm{P}}^2}{2Nm} - N\vec{E}\vec{R}; \quad H_{ie} = \sum_{\vec{q},a} U(\vec{q}) e^{-i\vec{q}\vec{R}a}$$
$$H_{e\Sigma} = \sum_{\vec{q},l} M(\vec{q},l)\,\Phi_{\vec{q},l}\, r_{\vec{q}}. \tag{1.8}$$

(1.8) formulebSi H_{ie} da $H_{e\Sigma}$ - eleqtronis urTierTqmedebis hamiltonianebia minarevTan da fononur velTan; $\Gamma(s)$ warmoadgens eleqtronuli sistemis masaTa centris hamiltonians ($\vec{\mathrm{P}}$ da $\vec{R}$ – masaTa centris impulsi da koordinataa Sesabamisad), xolo $r_{\vec{q}} = \sum_{i=1}^{N} e^{i\vec{q}\vec{r}_i}$ aris eleqtronebis simkvrivis operatoris furie saxe (warmodgena); $\Phi_{\vec{q},l} = b_{\vec{q},l} + b^+_{-\vec{q},l}$ fononuri velis operatoria; $b_{\vec{q},l}$, $b^+_{-\vec{q},l}$ - fononebis gaqrobis da dabadebis operatorebia talRuri veqtoriT $\vec{q}$, l warmoadgens fononuri speqtris

Stos, $M(\vec{q},l)$ - eleqtron-fononuri urTierTqmedebis matricauli elementebia, $U(\vec{q})$ - minarevTa potencialis furie saxea, e_0 - dieleqtrikuli SeRwevadobaa, xolo $\vec{R}_a$ - a-uri minarevuli centris koordinatia. (1.7) da (1.8) formulebi faqtiurad warmoadgenen N-urTierTqmedi eleqtronebisa da N_Π - SemTxveviT ganlagebuli minarevuli centrebis modelur hamiltonians, romlebic imyofebian $\vec{E}$ daZabulobis mqone gareSe eleqtrul velSi da urTierTqmedeben TermostatTan, romelic aRiwereba fononuri (bozonuri) velis H_Σ hamiltonianiT.

modeluri hamiltonianebi (1.6)–(1.8) xSirad gamoiyeneba mouwesrigebeli sistemebis speqtraluri da kinetikuri maxasiaTeblebis Seswavlisas da gamokvlevisas. zemoTmiTiTebuli hamiltonianebis SeswavlaSi mivyavarT eleqtronuli gadatanis movlenebis Teoriis mraval amocanas (rogorc wrfivs, aseve arawrfivs) myar sxeulebSi; zogierT sakiTxs susti da Zlieri lokalizaciis Teoriisa, mouwesrigebeli sistemebis eleqtrogamtarobis Teoriis sxvadasxva amocanebs da sxv. [22-23].

1.1.5. dikes modelebi gamosxivebis TeoriaSi

am sistemebSi umartivesi moduri hamiltoniani aRwers qvesistemis urTierTqmedebas fotonebTan (fotonur velTan). urTierTqmedebis hamiltoniani aiReba wrfivi fotonebis (boze) operatorebis mixedviT. am modelis farglebSi ganixileba N raodenobis ori energetikuli donis mqone (ordoniani) gamomsxiveblebi, romelTa sixSirea O. uSveben, rom gamomsxiveblebi urTierTqmedeben erTmaneTTan mxolod velis saSualebiT. rogorc cnobilia, aseTi saxis hamiltoniani pirvelad SemoRebuli iyo atomTa spontanuri koherentuli gamosxivebis movlenis aRsawerad.

Tu ugulvebelvyofT kinetikur efeqtebs, romlebic ganpirobebulia gamomsxivebelTa moZraobiT, gacvliTi da eleqtrostatikuri urTierTqmedebebiT da aRvwerT gamomsxivebelTa dipolur urTierTqmedebas eleqromagnitur velTan “mbrunavi talRis” miaxloebaSi, maSin miviRebT models, romelic aRiwereba hamiltonianiT [10-11]:

$$H(t,s,\Sigma)=\Gamma(s)+H_{\Sigma}+H_{\text{int}}(t,s,\Sigma),$$

sadac: $$\Gamma(s)=\hbar\Omega S_0^z:\quad H_{\Sigma}=\sum_{\vec{k}}\hbar w(k)b_{\vec{k}}^{+}b_{\vec{k}} \qquad (1.9)$$

$$H_{\text{int}}(t,s,\Sigma)=\frac{e^{et}}{\sqrt{V}}\sum_{\vec{k}}g_{\vec{k}}S_{\vec{k}}^{-}b_{\vec{k}}^{+}+\frac{e^{et}}{\sqrt{V}}\sum_{\vec{k}}g_{\vec{k}}^{*}S_{\vec{k}}^{+}b_{\vec{k}}$$

da gamomsxivebeli sistemis spinuri operatorebi S, dakavSirebulia paulis matricebTan standartuli Tanafardobebit:

$$S_k^{\pm}=\sum_j S_j^{\pm}e^{\pm i\vec{k}\vec{r}_j};\ S_k^z=\sum_j S_j^z e^{\pm i\vec{k}\vec{r}_j};$$

$$S_j^{\pm}=S_j^x\pm iS^y;\quad S_j^{(x,y,z)}=\frac{1}{2}s_j^{(x,y,z)}$$

aq: $\vec{r}_j$ aris j-uri gamomsxiveblis radius-veqtori, $b_{\vec{k}}$ da $b_{\vec{k}}^{+}$ - warmoadgenen fotonebis gaqrobis da dabadebis boze operatorebs (amplitudebs) talRuri veqtoriT $\vec{k}$, urTierTqmedebis (bmis) mudmiva $g_{\vec{k}}$ dakavSirebulia $d_{\pm}$ gadasvlis denis dadebiT-sixSiriani operatoris furie-komponentasTan Semdegi TanafardobiT:

$$g_{\vec{k}}=\sqrt{\frac{2p\hbar^3w(\vec{k})}{u}}d_{\pm}(\vec{e}_{\vec{k}}\cdot\vec{e}_{\vec{d}})$$

sadac: u warmoadgens nivTierebis kuTr moculobas, $\hbar$ - plankis mudmivaa, xolo $w(\vec{k})$ – fotonis sixSirea. aq: Σ Termostatis rols TamaSobs fotonuri veli, romelSic “moTavsebulia” gamomsxivebelTa s sistema. calke aRebuli, erTeulovani urTierTqmedebis aqtis Sedegad, romelic xorcieldeba eleqtromagnitur velsa da gamomsxivebels Soris, adgili aqvs fotonuri velis kvantis gamosxivebas (STanTqmas), ris gamoc gamomsxivebeli gadadis ori SesaZlo energetikul mdgomareobidan erT-erTSi. unda aRiniSnos, rom mocemuli modelisTvis SesaZlebelia agreTve sxva midgoma, romlis drosac Termostatis rols TamaSobs gamomsxivebelTa sistema, xolo dinamiuri qvesistemis saxiT gvevlineba bozonuri veli [10]. sakiTxi Termostatisa da dinamiuri sistemis SerCevis Sesaxeb wydeba imisda mixedviT, Tu rogori procesebi ganixileba. ase magaliTad, midgoma romelic ganxilulia [7]-Si Seesabameba eleqtromagnituri velis relaqsaciis procesebis Seswavlas rezonatorSi, xolo midgoma, romelic gaSuqebulia [8]-Si aRwers Tavisufal sivrceSi gamosxivebisas spinuri sis-

temis relaqsaciis procesebs, romlis drosac sivrce ganixileba Termostatis rolSi. xSirad ganixilaven dikes iseT modelebs, romlebic aRiwerebian ufro zogadi hamiltonianiT da romlebic Seicaven agreTve ordoniani obieqtebis kinetikuri energiis operators [ix. mag. [11,24]]. Seswavlili iyo agreTve dikes modelebi, rodesac dinamiuri qvesistema s (gamosxiveba) urTierTqmedebda erTdroulad S atomur da S_1 fononur sistemebTan [12].

aqve unda aRiniSnos, rom aseTi tipis dinamiur sistemebamde (dikes modelebamde) mivyavarT mravali problemis ganxilvas kvanturi radiofizikidan da lazeruli gamosxivebis fizikidan, zegamosxivebis Teoriidan da sxv. amitom dikes tipis modeluri sistemebis Seswavla da gamokvleva, rogorc Ria arawonasworuli kvanturi dinamiuri sistemebisa, warmoadgens did samecniero interess. cxadia, rom dikes modelebis aRmweri hamiltonianebi miekuTvnebian (1.1) da (1.2) formulebiT gamoxatul hamiltonianTa klass.

1.1.6. eleqtronebi magnetikSi, romlebic urTierTqmedeben kristalis magnitur qvesistemasTan

aseTi saxis dinamiur sistemebSi ganixileba eleqtronebis urTierTqmedeba magnetikis atomTa spinebTan S-d modelis farglebSi [25-26]. erTzonian miaxloebaSi sistemis hamiltonians aqvs Semdegi saxe:

$$H = H_e + H_M + H_A$$

$$H_e = \sum_{\vec{c}s} E_{\vec{c}} a^+_{\vec{c}s} a_{\vec{c}s}; \quad H_A = \frac{2A}{N} \sum_{\substack{\vec{c},\vec{c}' \\ s,s'}} a^+_{\vec{c}s} \left(\vec{S}_e \vec{S}_{na}\right) s s' a_{\vec{c}'s} e^{i(\vec{c}-\vec{c}')\vec{R}_{na}} \qquad (1.10)$$

aq H_e – gamtarobis eleqtronebis hamiltoniania, H_A - warmoadgens hamiltonians, romelic aRwers eleqtronebis urTierTqmedebas magnetikis lokalizebul spinebTan (A – spin-eleqtronuli urTierTqmedebis mudmiva, N – magnitur atomTa ricxvia, $\vec{S}_e$ - zonuri eleqtronis spinis operatoria, $\vec{S}_{na}$ - warmoadgens magnituri atomis spinis operators, romelic moTavsebulia kvanZSi, romlis radius-veqtoria $\vec{R}_{na}$; n - kvanZis nomeria, a - qvemesris nomeri). H_M – magnituri qvesistemis hamiltoniania (Cveulebriv, rogorc wesi iReben haizenbergis gacvliTi urTierTqmedebis hamiltonians

lokalizebuli spinebisaTvis). H_A – hamiltonianSi eleqtronis spinis $\langle S_{na} \rangle$ saSualo spinebTan urTierTqmedebis gancalkevebis Semdeg, (1.10) hamiltoniani SesaZlebelia Caiweros Semdegi saxiT:

$$H = H_0 + H_1 + H_M$$

sadac: $$H_0 = \sum_{\vec{c}s} E_c a^+_{\vec{c}s} a_{\vec{c}s} + \frac{2A}{N} \sum_{\substack{\vec{c},\vec{c}' \\ s,s',na}} a^+_{\vec{c}s} \left(\vec{S}_e\right)_{ss'} a_{\vec{c}'s'} \left\langle \vec{S}_a \right\rangle e^{i(\vec{c}-\vec{c}')\vec{R}_{na}} \quad (1.11)$$

$$H_1 = \frac{2A}{N} \sum_{\substack{\vec{c},\vec{c}' \\ s,s',n_a}} a^+_{\vec{c}s} \left(\vec{S}_e\right)_{ss'} a_{\vec{c}'s'} \left(\vec{S}_{na} - \left\langle \vec{S}_a \right\rangle\right) e^{i(\vec{c}-\vec{c}')\vec{R}_{na}}$$

Tu CavatarebT kanonikur gardaqmnas da gadavalT $a^+_{\vec{c}s}$, $a_{\vec{c}s}$ operatorebidan axal C^+_g, C_g operatorebze kristalis mocemuli gansazRvruli magnituri struqturis dros, maSin SesaZlebelia H_0 hamiltonianis dayvana diagonalur saxeze (magaliTad: feromagnetiki-ormesriani antiferomagnetiki da a.S.). magnituri mowesrigebisas magnituri struqturis warmoqmnas mivyavarT eleqtronuli zonis gaxleCamde or zonad (qvezonad) [26], ise rom axali $C^{(+)}_g$ da C_g eleqtronuli operatorebi xasiaTdebian kvanturi ricxvebis erTobliobiT: $\vec{g} = (\vec{c}, s, u)$ da energetikuli speqtriT e_g eleqtronebisTvis (u warmoadgens qvezonis nomers). magaliTad, aseT SemTxvevas aqvs adgili calRerZa helikoidaluri struqturebis SemTxvevaSi, romelTa kerZo SemTxvevas warmoadgenen feromagnetiki da antiferomagnetiki). holstein-primakovis gardaqmnis gamoyenebiT SesaZlebelia $S_{\vec{n},a}$ spinuri operatorebidan gadavideT spinuri talRebis operatorebze da miviRoT hamiltoniani, romelic aRwers eleqtronebis urTierTqmedebas magnonebTan da romelic zogadad Seicavs mravalmagnonian (erTmagnoniani, ormagnoniani da a.S.) wevrebs. (holstein-primakovis gardaqmnis samarTlianoba SesaZlebelia martivad davasabuToT magnetikebisaTvis, romlebic imyofebian mowesrigebul fazaSi Zalian dabali temperaturebis dros: $T < T_e$ (T_e warmoadgens kritikul temperaturas) da didi spinebis mqone atomTa matricis SemTxvevaSi, rodesac $2S >> 1$). zogierT SemTxvevebSi, rogorc wesi, SesaZlebelia SemovisazRvroT mxolod wrfivi operatoruli wevrebiT magnonebis

mixedviT. aseT SemTxvevebSi (1.10)-(1.11) hamiltonianebi erTmagnoniani procesebisaTvis miiReben Semdeg saxes:

$$H = H_s + H_\Sigma + H_{\text{int}}$$
$$H_s = \sum_g e(g) C_g^+ C_g; \quad H_\Sigma = \sum_k \hbar\Omega_k d_k^+ d_k \qquad (1.12)$$
$$H_{\text{int}} = \sum_k \left[B_k(s) d_k + B_k^+(s) d_k^+ \right]; \quad B_k(s) = \frac{1}{\sqrt{N}} \sum_{g,g'} A_{g,g'k} C_g^+ C_{g'},$$

sadac: Ω_k - k magnonuri modis sixSirea; $\left(k = \left(\vec{k}, j\right)\right)$, j - magnonuri Stos nomeria, d_k, d_k^+ - magnonebis gaqrobis da dabadebis boze operatorebia, xolo $A_{gg'k}$ warmoadgens "C-sidides".

magaliTad, antiferomagnetikebSi, sadac eleqtronebis energetikuli doneebi gadagvarebulia spinis mixedviT, SesaZlebelia SemovisazRvroT erTmagnoniani procesebis ganxilviT dabali temperaturebis dros. (ormagnoniani procesebi, romlebic aRiwereba H_1 wevriT (1.11) hamiltonianSi, romelic Seicavs $S_{na}^z - \left\langle S_a^z \right\rangle$ wevrebs, warmoadgenen mcire sidideebs, rodesac $2S >> 1$ da temperatura aris dabali.$(S - \left\langle \vec{S} \right\rangle << S)$. (qvemeserTa damagniteba mimarTulia z RerZis paralelurad, e.i. $\left\langle S_{n_1}^z \right\rangle = -\left\langle S_{n_2}^z \right\rangle$; $\left\langle S_{na}^x \right\rangle = \left\langle S_{na}^y \right\rangle = 0$). SevniSnoT, rom magnitur naxevargamtarebSi S-d urTierTqmedebis A_S parametri principSi ar warmoadgens mcire sidides eleqtronuli energetikuli zonis ΔE siganesTan SedarebiT, ase rom adgili aqvs Zlieri urTierTqmedebis (bmis) SemTxvevas. amitom, am urTierTqmedebam SesaZlebelia migviyvanos magnituri fluqtuonebis da polaronebis warmoqmnamde, rac arsebiT gavlenas axdens kristalis optikur, magnitur da kinetikur Tvisebebze [27-28].

amrigad, Cvens mier ganxiluli (1.12) hamiltoniani formalurad miekuTvneba (1.1)-(1.2) saxis hamiltonianTa klass.

am mokle ganxilvis Semdeg dinamiuri sistemebisa, romlebic urTierTqmedeben TermostatTan (bozonur velTan), an ufro zogadad – kvanturi, disipaciuri da Ria arawonasworuli modeluri sistemebis zogierTi magaliTisa Tanamedrove fizikis sxvadasxva dargidan, gadavideT uSualod im dinamiuri sistemebis mimoxilvasa, Seswavlasa da gamokvlevaze, romlebic Seadgenen mocemuli sadisertacio naSromis ZiriTad Sinaars –

eleqtron-fononur sistemaze da didi radiusis mqone polaronis modelebze.

1.2. eleqtron-fononuri sistema. eleqtronis urTierTqmedeba akustikur da polarul optikur fononebTan

kristalur myar sxeulebSi, magaliTad farTozonian naxevargamtarebSi, eleqtronis fizikuri Tvisebebi, romelic gadaadgildeba kristalSi, ZiriTadad ganisazRvreba perioduli potencialiT, romelsac qmnian kristaluri mesris kvanZebSi ganlagebuli ionebi.

ionTa rxevebs wonasworuli mdebareobebis maxloblobaSi mivyavarT eleqtronebis energiebis praqtikulad myisier cvlilebamde da kristalisaTvis Sredingeris adiabaturi gantolebis hamiltonianSi, romelic aRwers eleqtronebis mdgomareobebs, damatebiTi wevris - H_{int}-is warmoqmnamde. es damatebiTi wevri aRwers eleqtronebis urTierTqmedebas fononebTan. ionebis mcire amplitudebiT rxevebisSemTxvevaSi, fononuri (bozonuri) sistema Σ warmoadgens araurTierTqmedi harmoniuli oscilatorebis erTobliobas. am sistemis energias aqvs Semdegi saxe: $H_{\Sigma} = \sum_{k} \hbar w(k) b_k^{+} b_k$, da igi warmoadgens fononuri velis sakuTriv hamiltonians meoradi dakvantvis warmodgenaSi (nulovani rxevebi mxedvelobaSi ar miiReba). rac Seexeba urTierTqmedebis energias – H_{int} – igi wrfivad aris damokidebuli calkeuli, aRebuli harmoniuli oscilatoris normalur koordinatebze.

im sistemis Tvisebebis Seswavla, romelic Sedgeba kvazinawilakisagan (eleqtronisagan) da fononuri (bozonuri) velisagan, romelTa Soris urTierTqmedeba aris wrfivi fononuri operatorebis mixedviT, warmoadgens myari sxeulebis da kondensirebul garemoTa fizikis da agreTve velis kvanturi Teoriis metad mniSvnelovan amocanas.

amgvarad, eleqtron-fononuri sistema warmoadgens magaliTs eleqtronis urTierTqmedebisa dakvantul fononur velTan kristalSi. am SemTxvevaSi qvesistema S Sedgeba erTi kvazinawilakisagan (eleqtronisagan), xolo Σ Termostatis rolSi gvevlineba fononuri veli.

cnobili gamartivebebis Semdeg, ararelativisturi kvazinawilaki (eleqtroni), romelic urTierTqmedebs kristaluri mesris rxevebis dakva-

ntul skalarul velTan, aRiwereba frolix-pekaris tipis hamiltonianiT [29-31]:

$$H = \frac{\vec{P}^2}{2m} + \sum_{\vec{k}} \hbar w\left(\vec{k}\right) b_{\vec{k}}^{+} b_{\vec{k}} + \sum_{\vec{k}} \left[V_{\vec{k}} e^{i\vec{k}\vec{r}} b_{\vec{k}} + V_{\vec{k}}^{*} e^{-i\vec{k}\vec{r}} b_{\vec{k}}^{+} \right] \qquad (1.13)$$
$$w\left(\vec{k}\right) > 0,$$

sadac $\vec{r}$ – eleqtronis radius-veqtoria, $\vec{P}$ - kvaziimpulsis operatori, $b_{\vec{k}}$, $b_{\vec{k}}^{+}$ - fononebis gaqrobis da dabadebis operatorebia talRuri veqtoriT $\vec{k}$, m - eleqtronis efeqturi masaa kristaluri mesris periodul potencialur velSi, xolo $w\left(\vec{k}\right)$ – warmoadgens fononuri velis kvantis sixSires, romelic aris $\vec{k}$-talRuri veqtoris radialurad simetriuli funqcia: $w\left(-\vec{k}\right) = w\left(\vec{k}\right)$.

1.2.1. eleqtronis urTierTqmedeba kristaluri mesris akustikur rxevebTan. deformaciis potencialis meTodi

rogorc cnobilia, eleqtronebis gabnevisas akustikur fononebze grZeltalRovan miaxloebaSi $ka \ll 1$ (a - mesris mudmivaa) fononebis dispersiis miaxloebiT kanons aqvs Semdegi saxe [32-33]: $w\left(\vec{k}\right) = V_s \left|\vec{k}\right|$, sadac V_s – bgeris siCqarea kristalSi, xolo (1.13) formulis $V_{\vec{k}}$ – mudmivebi, romlebic warmoadgenen eleqtronis fononebTan urTierTqmedebis energiis furie-komponentebs, moicemian Semdegi TanafardobiT:

$$V_{\vec{k}} = \left(\frac{4\pi a}{V} \right)^{1/2} \frac{\hbar^2}{m} k^{1/2}, \qquad (1.14)$$

sadac: V – kristalis moculobaa, xolo $a = \frac{D^2 m^2}{8\pi r \hbar^3 V_s}$ – warmoadgens eleqtron-fononuri urTierTqmedebis uganzomilebo mudmivas; D aris deformaciis potencialis mudmiva da r - kristalis masuri simkvrive. unda aRiniSnos, rom zemoTmoyvanili gamosaxulebebi samarTliania $A^{III}B^{V}$ da $A^{II}B^{VI}$ naxevargamtarebisaTvis, romelTaTvisac adgili aqvs dispersiis izotropul kanons da romlebSic zonis eqstremumi imyofeba briluenis zonis centrSi.

mokled SevexoT deformaciis potencialis meTods. am meTodis idea mdgomareobs SemdegSi: rodesac kristalSi vrceldeba drekadi talRa elementaruli ujredi ganicdis deformacias, icvleba misi moculoba (icvleba kristaluri mesris mudmiva), rac Tavis mxriv iwvevs gamtarobis zonis fskerisa da savalento zonis Weris mdebareobis cvlilebas, vinaidan zonis sigane mgrZnobiarea mesris mudmivas sididis cvlilebis mimarT. gamtarobis zonis fskeris cvlileba ki faqtiurad warmoadgens gamtarobis eleqtronis urTierTqmedebis energias kristaluri mesris rxevebTan. akustikuri rxevebis SemTxvevaSi, rodesac $\vec{k} \to 0$ yvela atomi elementarul ujredSi irxeva sinfazurad. rogorc cnobilia, $\vec{r}$ wertilis $\vec{U}(\vec{r})$ wanacvleba kristalSi grZeltalRovan miaxloebaSi ($ka \ll 1$) SesaZlebelia CavweroT Semdegi saxiT [32]:

$$\vec{U}_{\text{av}}(\vec{r}) = \frac{1}{\sqrt{N}} \sum_{\vec{k},\, j=1}^{3} \vec{e}_{\vec{k}j}(\vec{k}) \left[b_{\vec{j}\vec{k}} e^{i\vec{k}\vec{r}} + b^{+}_{\vec{j}\vec{k}} e^{-i\vec{k}\vec{r}} \right], \qquad (1.15)$$

sadac $\vec{e}_{\vec{k}j}(\vec{k})$ aris polarizaciis veqtori, romlis absoluturi mniSvneloba akustikuri rxevebisaTvis grZeltalRovan miaxloebaSi erTis tolia, xolo N – elementarul ujredTa raodenobaa kristalSi.

vinaidan grZeltalRovan miaxloebaSi akustikuri rxevebisas irxeva mxolod elementaruli ujredis masaTa centri da TviT ujredi ki ar ganicdis deformacias, amitom urTierTqmedebis energia warmoadgens mxolod $\vec{U}_{\text{av}}(\vec{r})$ wanacvlebis koordinatebis mixedviT pirveli warmoebulebis wrfiv funqcias da ar aris damokidebuli TviT wanacvlebis sidideze. amitom urTierTqmedebis energia Caiwereba Semdegi saxiT:

$$H_{\text{int}} = D div \vec{U}_{\text{av}}(\vec{r}). \qquad (1.16)$$

H_{int} sidides uwodeben deformaciis potencials, xolo D proporciulobis koeficients deformaciis potencialis mudmivas, romelic ZiriTadad ganisazRvreba eqsperimentidan. (1.15) da (1.16) formulebis daxmarebiT martivad miviRebT:

$$H_{\text{int}} = \frac{iD}{\sqrt{N}} \sum_{\vec{k},\, j=1}^{3} (\vec{k}\vec{e}_{\vec{k}j}(\vec{k})) \left[b_{\vec{j}\vec{k}} e^{i\vec{k}\vec{r}} - b^{+}_{\vec{j}\vec{k}} e^{-i\vec{k}\vec{r}} \right]. \qquad (1.17)$$

ukanaskneli formulidan Cans, rom im SemTxvevaSi, rodesac gvaqvs izotropuli gabneva gamtarobis eleqtroni urTierTqmedebs mxolod grZiv

grZeltalRovan akustikur fononebTan ($\vec{k} // \vec{e}_{\vec{k}j}(\vec{k})$). zogad SemTxvevaSi, rodesac gabneva anizotropulia da deformaciis potencialis mudmiva warmoadgens tenzorul sidides D_{ab}. $(a,b = 1,2,3)$ - deformaciis potencialisTvis gveqneba gamosaxuleba: $H_{\text{int}} = \sum_{j=1}^{3} D_{ab}^{(j)} U_{ab}^{(j)}$, sadac $U_{ab}^{(j)}$ warmoadgens deformaciis tenzors. am SemTxvevaSi urTierTqmedebis procesSi monawileobas Rebuloben agreTve ganivi fononebic [32-33].

1.2.2. eleqtronis urTierTqmedeba polarul optikur fononebTan

polarul nivTierebebSi (polarul naxevargamtarebsa da ionur kristalebSi) ionTa rxevebisas warmoiqmneba ara marto deformaciis potenciali, aramed garda amisa, adgili aqvs Sorsmqmedi makroskopuli eleqtruli velis warmoSobas da amitom eleqtronis urTierTqmedebas am velTan mivyavarT damatebiTi gabnevis meqanizmis warmoSobamde. es urTierTqmedeba, romelsac uwodeben eleqtronis gabnevas polarul optikur fononebze, bevr kristalebSi ufro arsebiTia, vidre denis (muxtis) gadamtanis gabneva akustikur fononebze. am saxis gabnevac grZeltalRovan miaxloebaSi aRiwereba (1.13) saxis hamiltonianiT. $V_{\vec{k}}$ – sidideebs eleqtronis gabnevisas polarul optikur fononebze aqvs Semdegi saxe [29-31]:

$$V_{\vec{k}} = -i\frac{\hbar w(\vec{k})}{\left|\vec{k}\right|^{1/2} U^{1/2}}\left(\frac{4pa}{V}\right)^{1/2};\quad U = \left(\frac{2mw(\vec{k})}{\hbar}\right)^{1/2}$$
$$a = \frac{1}{2}\left(\frac{1}{e_\infty} - \frac{1}{e_0}\right)\frac{e^2 U}{\hbar w(\vec{k})}. \qquad (1.18)$$

aq V aris sistemis (kristalis) moculoba, e da m – eleqtronis muxti da efeqturi masaa, Sesabamisad; a - eleqtron-fononuri urTierTqmedebis frolixis uganzomilebo bmis mudmivaa, xolo e_0 da e_∞ - warmoadgenen mocemuli nivTierebis statikuri da optikuri dieleqtrikuli SeRwevadobis mudmivebs. eleqtronis urTierTqmedebisas grZiv optikur fononebTan: $\max w(\vec{k}) \equiv w_0$ - warmoadgens dispersiis armqone, kristalis grZivi optikuri rxevebis sixSires. zogierT SemTxvevaSi, eleqtron-

fononuri sistemisTvis: $H_s = \frac{\vec{p}^2}{2m}$ gamosaxulebis nacvlad aucilebelia gamoyenebuli iqnas ufro zogadi saxe eleqtronis energiisa gamtarobis zonidan-$H_s = \mathrm{T}(\vec{p})$. iseve rogorc (1.2) formulaSi, ajamva $\vec{k}$-talRuri veqtoriT (1.13). formulaSi xorcieldeba kvazidiskretuli speqtris mixedviT:

$$\vec{k} = \left(\frac{2p}{L} h_1, \frac{2p}{L} h_2, \frac{2p}{L} h_3 \right); \; L^3 = V, \qquad (1.19)$$

sadac h_1, h_2, h_3 – mTeli ricxvebia (rogorc dadebiTi, aseve uaryofiTi).

amrigad, eleqtron-fononuri sistemisaTvis (1.1), (1.2), (1.13) formulebis Tanaxmad, $C_k(s)$ da $C_k^+(s)$ operatorebs aqvs Semdegi saxe:

$$C_k(s) = V_{\vec{k}} e^{i\vec{k}\vec{r}}; \quad C_k^+(s) = V_k^* e^{-i\vec{k}\vec{r}} \qquad (1.20)$$

(simbolo * aRniSnavs kompleqsurad SeuRlebuls).

rodesac eleqtron-fononuri sistema imyofeba gareSe, erTgvarovan eleqtrul velSi, romlis daZabuloba $\vec{E}(t)$, maSin eleqtronis gareSe eleqtrul velTan urTierTqmedebis hamiltonians aqvs saxe:

$$H_{sext} = -e\vec{E}(t)\vec{r}. \qquad (1.21)$$

im SemTxvevaSi, rodesac gareSe eleqtruli veli icvleba harmoniuli kanoniT eleqtruli velis daZabulobisTvis gvaqvs:

$$\vec{E}(t) = \vec{E}_0 e^{-e|t|} \cos(wt), \qquad (1.22)$$

sadac: w warmoadgens cvladi eleqtruli velis sixSires, xolo $\vec{E}_0$ - aris velis amplituda, $e^{-e|t|}$Tanamamravli aRwers gareSe urTierTqmedebis adiabatur CarTvas (gamorTvas), rodesac $t \to \mp\infty$ da $e \to 0^+ (e > 0)$.

eleqtronis polarul optikur fononebze gabnevisas, eleqtron-fononuri urTierTqmedebis (ufro zogadad polaronis amocanis) specifika mdgomareobs imaSi, rom saerTod, uganzomilebo parametri a, romelic aRwers eleqtron-fononuri urTierTqmedebis siZlieres, ar SeiZleba CaiTvalos rogorc mcire sidide. III-V jgufis naxevargamtarebSi eleqtron-fononuri urTierTqmedeba SesaZlebelia iyos susti ($a < 1$); II-VI jgufis polarul naxevargamtarebsa da dieleqtrikebSi saSualo siZlieris ($a \approx 1$) da ionur kristalebSi Zlieri ($a >> 1$). amitom, zogad SemTxvevaSi, uaryofili unda iqnas daSveba imis Sesaxeb, rom muxtis gadamtanTa

(elektronebis) energetikuli speqtri ganisazRvreba maTi susti urTierTqmedebiT idealuri kristaluri mesris potencialur velTan da kristaluri mesris rxevebis roli mdgomareobs imaSi, rom maT mivyavarT SedarebiT iSviaT gadasvlebTan elektronis mdgomareobebs Soris idealur kristalSi. polarul kristalebSi elektron-fononuri urTierTqmedeba iwvevs elektronuli speqtris arsebiT cvlilebas (polaronuli efeqti), denis gadamtanebis SedarebiT Zlier gabnevas optikur fononebze da am ukanaskneltA dispersiis kanonis cvlilebas. yvelaferi es ki arTulebs poluruli kristalebis eleqtruli da agreTve optikuri Tvisebebis Seswavlas [29-31, 36-39].

amrigad, Zlieri (arasusti) elektron-fononuri urTierTqmedebis SemTxvevaSi, zogadad elektron-fononuri sistemis Termodinamikis sakiTxebis ganxilvisas da kinetikuri movlenebis Seswavlisas Cven bunebrivad davdivarT polaronis amocanis ganxilvamde [29-30, 37-39].

1.3. polaronis amocana. didi radiusis mqone polaronis modelebi

ukanaskneli wlebSi aqtualuri gaxda sakiTxi struqturulad Sedgenili nawilakebis dinamiuri modelebis agebisa. warmodgenebi nawilakis rTuli struqturisa da am nawilakis agznebuli mdgomareobebis arsebobis Sesaxeb yovelTvis warmoadgenda Zlieri urTierTqmedebis (bmis) Teoriis ZiriTad sakiTxs. unda aRiniSnos rom Zlieri bmis Teoriebis siZneleebi Tavidanve ganpirobebuli iyo iseTi cnebebis SemoRebasa da operirebasTan, romlebic arsebiTad gansxvavebodnen Tavisufali velebis Teoriis warmodgenebisagan. n.n. bogolubovis SromebSi ganxiluli da gamokvleuli iyo amocana ararelativisturi nawilakis urTierTqmedebisa dakvantul skalarul velTan adiabaturi miaxloebis zRvrul SemTxvevaSi [35,40].

1.3.1. polaronis frolixisa da pekaris modelebi

pirvelad amocana ararelativisturi nawilakis urTierTqmedebisa dakvantul skalarul velTan dasmuli iyo frolixis mier egreTwodebuli polaronebis problemis gamosakvlevad. polaronebis problema mdgomareobs gamtarobis eleqtronebis yofaqcevis SeswavlaSi polarul kristalebSi. eleqtroni, romelic imyofeba kristalSi, Tavisi kulonuri veliT waanacvlebs ionebs TavianTi wonasworuli mdebareobebidan; Tavis mxriv warmoqmnili ionuri polarizacia moqmedebs eleqtronze da iwvevs misi energiis Semcirebas. kristalSi gadaadgilebisas, eleqtrons Tan gadaaqvs kristaluri mesris damaxinjebis are. eleqtroni da masTan erTad aRebuli TviTSeTanxmebuli polarizaciuli veli SesaZlebelia ganxiluli iqnes rogorc kvazinawilaki, romelsac uwodeben polarons [29,38]. unda aRiniSnos, rom TviT polaronis koncepcia SemoRebuli iqna pekaris mier, romelic ganixilavda zRvrul SemTxvevas eleqtronisa da kristaluri mesris rxevebis Zlieri urTierTqmedebisa da mis aRsawerad iyenebda adiabatur miaxloebas, romelic warmoadgens naxevradklasikur meTods [29-30].

istoriulad pirveli da yvelaze gavrcelebuli midgoma polaronuli amocanis amoxsnisaTvis dafuZnebuli iyo or ZiriTad miaxloebaze, romlebic arsebiTad gansazRvraven polaronuli mdgomareobebis Tvisebebs: 1) efeqturi masis miaxloeba, romlis Tanaxmadac eleqtronis urTierTqmedeba xisti kristaluri mesris periodul potencialTan gaTvaliswinebulia m efeqturi masiT, rogorc parametriT. aseT SemTxvevaSi eleqtronis kinetikuri energia $T(\vec{p}) = \frac{\vec{P}^2}{2m}$ gamtarobis zonaSi da TviT zonis sigane formalurad warmoadgenen SemousazRvrel sidideebs da amitom ar TamaSoben parametrebis rols polaronis amocanisaTvis; 2) kontinualuri miaxloeba, romlis drosac ar gaiTvaliswineba kristaluri mesris diskretuli struqtura. am miaxloebaTa CarCoebSi, polaronis amocana warmoadgens velis kvanturi Teoriis tipiur magaliTs ferminawilakis urTierTqmedebisa dakvantul fononur velTan, da amitom, rogorc aseTi, igi gaxda erT-erTi magaliTi velis Teoriis meTodebis gamoyenebisa myari sxeulebis fizikaSi.

polaronis ZiriTadi mdgomareobis Tvisebebis Seswavla arsebiTad martivdeba susti da Zlieri eleqtron-fononuri urTierTqmedebis zRvrul SemTxvevebSi. susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi polaronis fizikuri maxasiaTeblebi kargad aRiwereba Cveulebrivi SeSfoTebis Teoriis gamoyenebiT, xolo Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi polaronuli mdgomareoba aRiwereba TviTSeTanxmebuli midgomiT, romelic pirvelad ganxiluli iyo pekaris mier da romelic eyrdnoboda adiabatur miaxloebas [30-31, 39].

velis Teoriis lagranJiseuli formulirebisa da standartuli da-kvantvis proceduris gamoyenebiT, frolixisa da pekaris mier miRebuli da ganxiluli iyo polaronuli sistemis hamiltoniani (1.13-1.18) saxiT. vinaidan Sredingeris gantolebis zusti amoxsna (1.13) saxis hamiltonianiT ver iqna napovni, amitom sxvadasxva dros mravali avtoris mier gamoyenebuli iyo miaxloebiTi meTodebi, romlebsac susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi mivyavarT an standartuli tipis SeSfoTebis TeoriasTan, an sxvadasxva saxis variaciul midgomebTan, romlebic faqtiurad warmoadgenen hartri-fokis miaxloebis ama Tu im modifikacias [30, 37-38]. am gamokvlevebis Sedegebi gviCvenebs, rom uZravi eleqtronis energia mcirdeba sididiT: $\Delta E = -\hbar w_0 a$, romelic SesaZlebelia ganxilul iqnas, rogorc polaronis sakuTari energia. garda amisa icvleba eleqtronis efeqturi masa: $m^* = m(1-a/6)^{-1}$.

susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi polaroni pirvel miaxloebaSi SesaZlebelia warmovidginoT rogorc kvazinawilaki (eleqtroni), romelic garemoculia fononuri velis arakorelirebuli kvantebis RrubliT, romelTa saSualo ricxvi proporciulia bmis mudmivasi (polaronis frolixis modeli) [29].

fizikis TvalsazrisiT bevrad ufro saintereso da aqtualuria Zlier urTierTqmedebis SemTxveva mawilakisa fononur velTan. Zlier eleqtron-fononur urTierTqmedebas mivyavarT fononuri vakumis polarizaciaze, rac iwvevs sabolood Sedgenili kvazinawilakis struqturis Camoyalibebas. cxadia, rom nebismier gamoTvliT sqemas

(algoriTms) unda Seswevdes unari am Camoyalibebuli struqturis modelirebisa ukve pirvel miaxloebaSi [38-40].

pekaris Tanaxmad, Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi, kristaluri mesris deformacias, romelic gamowveulia gamtarobis eleqtroniT, mivyavarT efeqturi potencialuri ormos Camoyalibebamde da eleqtronis CaWeramde diskretul energetikul doneze, romelsac Seesabameba ukanasknelis finituri moZraoba. GaerTianebuli sistema (eleqtroni plus deformaciis are), rogorc mTliani gadaadgileba kristalSi efeqturi masiT, romelic sagrZnoblad aRemateba eleqtronis masas (efeqturs) gamtarobis zonaSi [30,37,39].

amgvarad, Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi pekaris mier ganviTarebuli Teoria iTvaliswinebs ionuri kristalis dieleqtrikul polarizacias gamowveuls gamtarobis eleqtronis eleqtruli veliT. warmoqmnili lokaluri polarizacia dakavSirebulia ionTa wanacvlebasTan da amitom is aris inerciuli; mas ar SeuZlia "mxari aubas" SedarebiT ufro swrafad moZrav eleqtrons da amitom es lokaluri inerciuli polarizacia, rogorc ukve iTqva, eleqtronisTvis qmnis potencialur ormos. sakmarisad Rrma ormoSi xdeba eleqtronis avtolokalizacia da am warmoqmnili potencialuri ormos siRrme sakmarisia, raTa masSi arsebobdes diskretuli energetikuli doneebi eleqtronisTvis. kristalTa didi umravlesobisTvis ormos siRrme 0,5-1 eleqtron-voltis rigisaa. eleqtroni, romelic imyofeba avtolokalizebul mdgomareobaSi erT-erT aseT energetikul doneze Tavisi eleqtruli veliT "iWers" kristaluri mesris lokalur polarizacias. ionebi TavianTi inerciulobis gamo "aRiqvamen" eleqtronis ara myisier, aramed saSualo eleqtrul vels. eleqtronis aseTi avtolokalizebuli mdgomareoba anu kristalis aseTi mdgomareobebi polarizaciuli potencialuri ormoTi, romelSiac lokalize-bulia eleqtroni, iwodeba polaronul mdgomareobebad (polaronis pekaris modeli) [30,39-40].

erT-erT mniSvnelovan da ZiriTad parametrs, romelic axasiaTebs polaronul mdgomareobas, warmoadgens polaronis radiusi, romelic aRwers maxasiaTebel zomebs kristaluri garemos deformaciis arisa. Tu eleqtron-fononuri urTierTqmedeba aris susti, maSin polaronis radiusi SesaZlebelia Sefasebuli iqnas ganusazRvrelobis Tanafardobidan: $r_{\mathrm{P}} \approx \hbar^{1/2}/(mw_0)^{1/2}$, rogorc maxasiaTebeli zoma eleqtronis fluqtuaciebisa

sivrceSi, romelic ganpirobebulia virtualuri fononebis gamosxivebisa da STanTqmis procesebiT. Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi polaronis radiusis sidide arsebiTadaa damokidebuli am urTierTqmedebis xasiaTze. frolix-pekaris polaronis modelSi, rodesac $a >> 1$, martivi Tvisobrivi Sefaseba polaronis radiusisaTvis iZleva Semdeg mniSvnelobas: $r_{\mathrm{P}} \approx \hbar^{1/2}/(mw_0)^{1/2} a$, rac Seesabameba polaronis radiusis Semcirebas bmis mudmivas zrdasTan erTad [37,41].

didi radiusis mqone polaronis adiabatur TeoriaSi polaronis zoma ganisazRvreba optimaluri balansis pirobidan gamomdinare eleqtronis kinetikuri energiis dadebiTi wvlilisa, romelic lokalizebulia SemosazRvruli sivrceSi, dadebiTi wvlilisa deformirebuli kristaluri mesris energiisa da uaryofiTi wvlilisa eleqtron-fononuri urTierTqmedebis energiisa. yvela es wvlili erTi da igive rigisaa sididis mixedviT, rac jamSi iZleva mogebas polaronis energiisaTvis, SedarebiT Tavisufali eleqtronis mdgomareobisaTvis aradeformirebuli kristaluri mesrisaTvis (polaronuli wanacvleba) [37,42-43]. unda aRiniSnos, rom principSi polaronuli mdgomareobebis Tvisebebi arsebiTad ganisazRvreba sami masStaburi energetikuli parametriT: D, $\hbar w$, E_{P}, sadac E_{P} warmoadgens polaronul wanacvlebas – energiis Semcirebas eleqtron-fononuri sistemisaTvis polarizaciuli saxis urTierTqmedebis gamo da warmoadgens im energetikul masStabs, romelic axasiaTebs am urTierTqmedebis intensivobas. D aris eleqtronebis gadaunomrvi zonis sigane, xolo w warmoadgens fononebis maxasiaTebel rxevebis saSualo six-Sires. didi radiusis mqone polaronis piroba moicema Semdegi Tana-fardobiT: $r_{\mathrm{P}} > a$, sadac a aris kristaluri mesris mudmiva. SesaZlebelia naCveneb iqnas, rom didi radiusis mqone polaronisaTvis adgili aqvs utolobas: $E_{\mathrm{P}}/D < 1$, romelic faqtiurad ekvivalenturia zemoT moyvanili utolobisa [37,41].

polaronuli mdgomareobebis mdgradobisTvis aucilebelia, rom eleqtronis bmis energia potencialur ormoSi aRematebodes ionTa siTburi moZraobis saSualo energias kristalSi. variaciuli meTodis daxmarebiT pekarma ganaviTara mkacri Teoria eleqtronis Zlieri urTierTqmedebisa

izotropul ionur dieleqtrikTan, rodesac kristali ganixileboda rogorc uwyveti garemo.

pekaris Tanaxmad eleqtronis energia polarizebul kristalSi (dieleqtrikSi), romlis polarizaciis veqtoria - $\vec{P}(\vec{r})$, warmoidgineba Semdegi saxiT [29-30] (nulovan adiabatur miaxloebaSi, rodesac ar gaiTvaliswineba ionTa moZraobis kinetikuri energia).

$$E\left[\Psi,\vec{P}\right]=-\frac{\hbar^2}{2m}\int\Psi^*(\vec{r})\Delta\Psi(\vec{r})d\vec{r}+2pe^*\int\vec{P}^2(\vec{r})d\vec{r}-\int\vec{P}(\vec{r})D(\vec{r})d\vec{r}, \qquad (1.23)$$

sadac: $D(\vec{r})=e\int\left|\Psi(\vec{r}_1)\right|^2\frac{\vec{r}_1-\vec{r}}{\left|\vec{r}_1-\vec{r}\right|^3}d\vec{r}_1$ warmoadgens eleqtruli velis induqciis veqtors dieleqtrikis wertilSi, romlis radius-veqtoria $\vec{r}$, xolo $e^{*-1}=e_\infty^{-1}-e_0^{-1}$ aris polarizebuli garemos efeqturi dieleqtrikuli SeRwevadoba (ix. (1.18) formula). (1.23) formulis pirveli ori wevri aRwers eleqtronisa da polarizaciuli velis energiebs, xolo ukanaskneli wevri - maT Soris urTierTqmedebis energias. (1.23) gamosaxuleba ganixileba rogorc funqcionali – $\Psi(\vec{r})$ da $\vec{P}(\vec{r})$ funqciebis mimarT. rodesac kristali imyofeba ZiriTad mdgomareobaSi, maSin am funqcionals unda gaaCndes absoluturi minimumi,$\Psi(\vec{r})$ da $\vec{P}(\vec{r})$ funqciebis damoukidebeli variaciebis dros, im pirobiT rom adgili eqneba talRuri funqciis normirebis Senaxvis pirobas:

$$\int\left|\Psi(\vec{r})\right|^2d\vec{r}=1. \qquad (1.24)$$

Tu gavutolebT nuls (1.23) funqcionalis variacias, romelic ganpirobebulia $\vec{P}(\vec{r})$ polarizaciis cvlilebiT, rodesac $\Psi(\vec{r})$ talRuri funqcia fiqsirebulia, maSin martivad davadgenT kavSirs $\vec{P}(\vec{r})$ da $D(\vec{r})$ sidideebs Soris:

$$\vec{P}(\vec{r})=\frac{1}{4pe^*}D(\vec{r}), \qquad (1.25)$$

sadac: $D(\vec{r})$ - induqcia (1.23) formulis Tanaxmad ganisazRvreba $\Psi(\vec{r}_1)$ talRuri funqciis saSualebiT. (1.25) gamosaxulebis daxmarebiT, martivad vpoulobT (1.23) funqcionalis saxes, romelic damokidebulia mxolod $\Psi(\vec{r})$ talRur funqciaze:

$$\Im[\Psi]=\frac{\hbar^2}{2m}\int\left|\nabla\Psi(\vec{r})\right|^2d\vec{r}-\frac{1}{8pe^*}\int\vec{D}^2(\vec{r})d\vec{r}. \qquad (1.26)$$

$\Im[\Psi]$ funqcionali gansazRvravs polarizebuli kristalis (dieleqtrikis) energias, romlisTvisac polarizacia SeTanxmebulia eleqtronis mdgomareobasTan, romelic aRiwereba $\Psi(\vec{r})$-funqciiT. polarizebuli kristalis aseTi mdgomareobisaTvis, eleqtronisTvis ufro "xelsayrelia" energetikuli Tvalsazrisi T imyofebodes ara gamtarobis zonaSi, aramed mdgomareobaSi, romelic Seesabameba eleqtronis moZraobas kristalis SemosazRvrul (finitur) areSi da romelic ganisazRvreba - $\Psi(\vec{r})$ talRuri funqciiT. eleqtronisTvis es energetikulad ufro xelsayreli mdgomareoba SesaZlebelia ganisazRvros (1.26) funqcionalis minimumis pirobidan, (1.24) Tanafardobis gaTvaliswinebiT, $\Psi(\vec{r})$ funqciis mixedviT. (1.26) funqcionalis minimizaciisaTvis pekarma gamoiyena pirdapiri variaciuli meTodi [29-30]. ZiriTadi mdgomareobis (polaronuli mdgomareobis) funqciis - $\Psi(\vec{r})=\Psi_0(\vec{r})$. aproqsimacia xdeboda ramodenime parametris saSualebiT. am funqcias hqonda Semdegi saxe:

$$\Psi_0(\vec{r}) = A[1+a'r+br^2]e^{-a'r} \qquad (1.27)$$

sadac: A mudmiva ganisazRvreboda normirebis pirobidan (talRuri funqciisTvis) da igi toli iyo sididis:

$$A^2=\frac{2a^3}{p\left(14+168g+720g^2\right)};$$

$$g=\frac{b}{4a'^2};\quad \Psi_0(x)=A(1+\frac{1}{2}x+gx^2)e^{-\frac{1}{2}x};\quad x=2a'g\ , \qquad (1.28)$$

sadac x warmoadgenda uganzomilebo cvlads. variaciuli gaTvlebi a' da g parametrebisaTvis iZleoda Semdeg mniSvnelobebs: $a'=0{,}6585\frac{me^2}{\hbar^2e^*}$,, $g=0{,}1129$; (1.28) formulebis daxmarebiT polaronis ZiriTadi mdgomareobis energiisaTvis miRebuli iyo Semdegi gamosaxuleba [30]:

$$\mathrm{E}_0(a,g)=\frac{3}{2}\frac{p\hbar^2A^2}{ma}\left(1+4g+24g^2\right)-\frac{p^2e^2A^4}{e^*a^5}\left(10{,}494+209{,}88g+\right.$$
$$\left.+1884g^2+8507{,}8g^3+16727g^4\right). \qquad (1.29)$$

SedarebiT ufro uxeSi gaTvlebisTvis, pekaris mier gamoyenebuli iyo agreTve talRuri funqcia, romelic Seicavda erT variaciul parametrs. saerTod polaronis ZiriTadi mdgomareobis energia ar iyo Zalian "mgZnobiare" SerCeuli variaciuli parametrebis raodenobis mimarT.

magaliTad, erTi damoukidebeli meore parametris damateba talRur funqciaSi saSualebas iZleoda ZiriTadi mdgomareobis energiis mxolod 2%-iT Semcirebas. erTi variaciuli parametris mqone normirebul talRur funqcias hqonda Semdegi saxe:

$$\Psi_0(\vec{r}) = \frac{a'^{3/2}}{\sqrt{7p}}\left(1 + a'r\right)e^{-a'r}, \qquad (1.30)$$

sadac $a' \equiv \frac{1}{r_0} = \frac{me^2}{2\hbar^2 e^*}$, a' parametris (1.30) mniSvneloba ganisazRvreboda (1.23), (1.26) da (1.30) formulebis daxmarebiT – (1.26) funqcionalis minimumis pirobidan. TviT (1.30) talRur funqcias Seesabameboda (1.26) funqcionalis Semdegi mniSvneloba:

$$\Im[\Psi_0] = -0{,}054\frac{me^4}{\hbar e^{*2}} \equiv -2 \cdot 0{,}054\hbar w_0 a^2, \qquad (1.31)$$

sadac: a - aris eleqtron-fononuri urTierTqmedebis frolixis uganzomilebo mudmiva (ix. (1.18) formula). (1.31) gamosaxuleba faqtiurad gansazRvravs polarizebuli kristalis srul energias. (1.23) da (1.25) gamosaxulebebis daxmarebiT SesaZlebelia ganisazRvros kristalis polarizacia, romelic Seesabameba (1.30) mdgomareobas.

$$\vec{P}_0(\vec{r}) = \frac{e}{4pe^x}\int\left|\Psi_0(\vec{r}_1)\right|^2 \frac{\vec{r}_1 - \vec{r}}{\left|\vec{r}_1 - \vec{r}\right|^3} d\vec{r}_1, \qquad (1.32)$$

xolo (1.32) formulisa da $V_0(r) = -\int \frac{div\vec{P}_0(\vec{r})}{\left|\vec{r} - \vec{r}\,'\right|} d\vec{r}_1$ Tanafardobis daxmarebiT vipoviT sferuli polarizaciuli potencialuri ormos formas (saxes), romelSiac moZraobs eleqtroni (ix. nax.1). eleqtronis talRuri funqcia (ix. 1.28) napovni a' variaciuli parametris saSualebiT Caiwereba Semdegi saxiT:

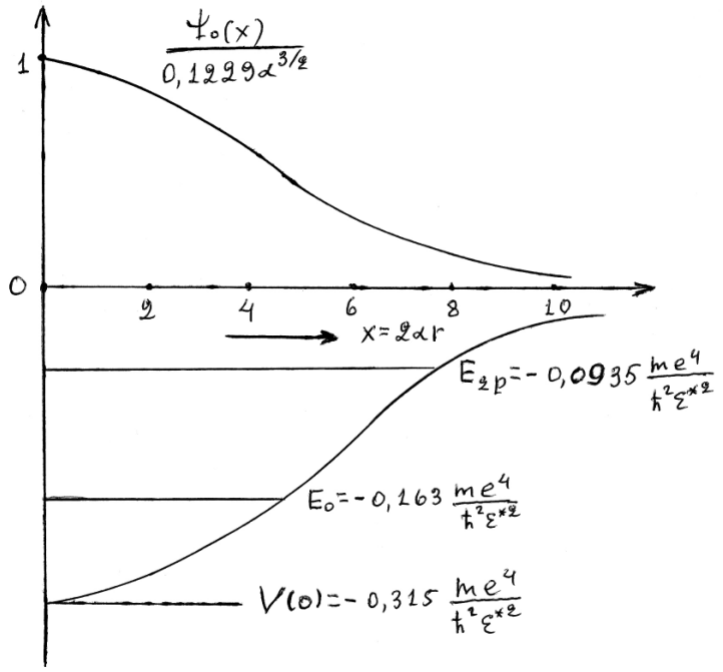
$$\Psi_0(r) = 0{,}1229a^{3/2}\left(1 + ar + 0{,}4516 \cdot a^2 r^2\right)e^{-ar}.$$

TviT $V_0(r)$ potencials aqvs Semdegi analizuri saxe:

$$V_0(r) = -\frac{2a\,e^2}{e^*}\left[\frac{1}{x} - e^{-x}\left(\frac{1}{x} + 0{,}7605 + 0{,}2605x + 0{,}05087x^2 + \right.\right. \qquad (1.33)$$
$$\left.\left. + 0{,}005703x^3 + 0{,}0003024x^4\right)\right],$$

sadac, x ganisazRvreba (1.28) formuliT. rodesac $x >> 1$, maSin eqsponencialuri Tanamamravli aris Zalian mcire da $V_0(r)$ potencialis saxe aris

kulonuri: $V_0(r) \to -\frac{e^2}{e^* r}; (r >> 1)$; xolo $r = 0$ wertilSi potencials gaaCnia paraboluri tipis minimumi. polaronis ZiriTadi mdgomareobis energia (1.33) fiqsirebul potencialur ormoSi gamoiTvleba (1.23), (1.30) da (1.32) formulebis daxmarebiT. gamoTvlebi iZleva eleqtronis energiis Semdeg mniSvnelobas: $E_0 = -0{,}163\frac{me^4}{\hbar^2 e^{*2}} = -2 \cdot 0{,}163\hbar w_0 a^2$; Tu polarizaciuli potencialuri ormo aris sakmaod Rrma, maSin masSi SesaZlebelia agreTve sxva diskretuli energetikuli doneebis arseboba eleqtronisaTvis (ix. nax.1).



nax.1. potencialuri ormo, energetikuli doneebi da eleqtronis Υ-talRuri funqcia pekaris polaronis modelSi

amrigad, pekaris polaronuli mdgomareobebi SesaZlebelia ganxiluli iqnes rogorc eleqtronisa da kristalis lokaluri polarizaciis bmuli (avtolokalizebuli) mdgomareobebi. es mdgomareobebi xasiaTdebian erTi an ramodenime diskretuli Sinagani energetikuli doneebis arsebobiT avtolokalizebuli eleqtronisTvis. gansxvavebiT polaronis frolixis modelisagan, romelic aRiwereba susti eleqtron-fononuri urTierTqmedebis a mudmivaTi $(a < 1)$, pekaris polaronuli mdgomareobebi xorcieldeba mxolod a bmis mudmivas didi mniSvnelobebis dros $(a >> 1)$. aseTi avtolokalizebuli mdgomareobebi – polaronebi SesaZlebelia

gadaadgildnen kristalSi, rogorc erTiani mTliani struqtura (kvazinawilaki), raRac efeqturi masiT – polaronis masiT.

pekaris mier gamoTvlili iyo agreTve polaronis masa, rodesac polaroni asrulebda gadataniT moZraobas kristalSi mcire siCqareebiT: $V << w_0 r_0$, sadac r_0 ganisazRvreba (1.30) tolobiT. miRebuli polaronis efeqturi masis mniSvneloba pekaris TeoriaSi SesaZlebelia warmovadginoT Semdegi saxiT [30]:

$$M = 5{,}8 \cdot 10^{-3} \left(\frac{me^2}{\hbar^2 e^*} \right)^3 e^2 C_2 = 9{,}08 \cdot 10^3 \left(\frac{m}{m_e} \right)^3 \frac{1}{e^{*3}} C_2, \qquad (1.34)$$

sadac $C_2 = \frac{1}{e^* w_0^2}$ da m_e warmoadgens eleqtronis masas.

zogadad, polaronis efeqturi masa M bevrad aRemateba eleqtronis efeqtur masas gamtarobis zonidan. ase magaliTad, $NaCl$ ionuri kristalisTvis, gamoTvlebi gviCvenebs, rom $M \approx 391m$.

pekaris modelSi, polaronis Zvradobisa da eleqtrogamtarobis gamosaTvlelad gamoiyeneboda bolcmanis kinetikuri gantoleba. ionebi ganixileboda rogorc siTbur wonasworobaSi myofi. am gantolebis daxmarebiT gamoTvlili iyo polaronis dabaltemperaturuli ($K_B T << \hbar w_0$) Zvradoba, rodesac xdeboda eleqtronis gabneva polarul optikur fononebze da gabnevis procesSi monawileobas iRebda fononis erTi kvanti (erTfononiani procesebi). polaronis dabaltemperaturuli ZvradobisTvis miRebuli iyo Tanafardoba:

$$m = \frac{e}{M} t, \qquad (1.35)$$

sadac: Tavisufali ganarbenis saSualo dro t toli iyo sididis:

$$t = \left[W_{\vec{k},\vec{k}'} \right]^{-1}. \qquad (1.36)$$

aq: $W_{\vec{k},\vec{k}'}$ - warmoadgens polaronis $\vec{k}$-dan $\vec{k}'$ mdgomareobaSi gadasvlis albaTobas drois erTeulSi (gadasvlis sixSires) da ganisazRvreba Semdegi TanafardobiT ($\vec{k}$ da $\vec{k}'$-talRuri veqtorebia):

$$W_{\vec{k},\vec{k}'} = \frac{e^2}{4p\hbar^{3/2}} \frac{\sqrt{2Mw_0}\left(1+\frac{1}{7}Z\right)^2}{\left(1+Z\right)^8} N;$$
$$N = \left[e^{\frac{\hbar w_0}{K_B T}} - 1\right]^{-1}; \quad Z = \frac{\left|\vec{k}' - \vec{k}\right|^2}{4a'^2}, \tag{1.37}$$

sadac: a' - sidide moicema (1.30) formuliT. mcire siCqareebiT moZravi polaronisTvis, rodesac $\frac{\hbar^2\vec{k}^2}{2M} << \hbar w_0$ (1.34) formulis gaTvaliswinebiT gveqneba:

$$Z \approx \frac{Mw_0}{2\hbar a'^2} = 0{,}0116\frac{me^4}{\hbar^3 w_0 e^{*2}}. \tag{1.38}$$

(1.35) - (1.37) Tanafardobebis daxmarebiT martivad miviRebT polaronis ZvradobisaTvis Semdeg gamosaxulebas kristalis dabali temperaturebis dros:

$$m = m_0 N; \qquad m_0 = \frac{\hbar^{3/2} e^*}{M^{3/2} e\sqrt{2w_0}} \frac{\left(1+Z\right)^8}{\left(1+\frac{1}{7}Z\right)^2}. \tag{1.39}$$

xolo, Tu visargeblebT polaronis M masis (1.34) mniSvnelobiT, maSin dabal temperaturuli Zvradoba warmoidgineba Semdegi saxiT [30]:

$$m_0 = 5{,}8\cdot 10^{-38} \frac{w_0^{5/2}\left(1+Z\right)^8 e^{*7}}{\left(\frac{m}{m_e}\right)\left(1+\frac{1}{7}Z\right)^2}. \tag{1.40}$$

aqve unda aRiniSnos polaronis M masisa da m_0 dabal temperaturuli Zvradobis damokidebuleba a-bmis mudmivaze polaronis pekaris TeoriaSi. rogorc (1.18) da (1.34) formulebi gviCveneben polaronis masis yofaqceva moicema TanafardobiT: $M \sim a^4 (a >> 1)$, xolo (1.18), (1.34) da (1.39)-is Tanaxmad dabal temperaturuli Zvradobis yofaqceva aisaxeba damokidebulebiT: $m_0 \sim a^5 (a >> 1)$ (rodesac ganixi-leba mxolod erTfononiani procesebi polaronis gabnevisas optikur fononebze). amrigad, pekaris polaronis modelSi miRebuli yvela fizikuri sididis (polaronis masa, Zvradoba da sxv.) mniSvneloba, gansxvavebiT polaronis frolixis modelisagan, samarTliania mxolod Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a >> 1$).

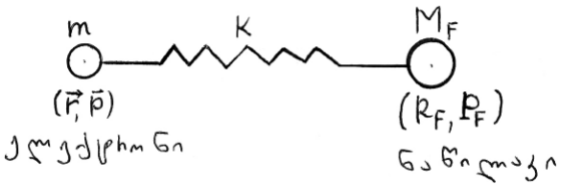
ganvixiloT axla dinamiuri modeli struqturulad Sedgenili kvazinawilakis–polaronis, romelic aRiwereba eleqtron-fononuri bmis α-mudmivas nebismieri mniSvnelobis dros, e.w. polaronis feinmanis modeli.

1.3.2. polaronis feinmanis modeli

eleqtron-fononuri sistemisTvis da polaronis amocanaSi farTo gamoyeneba hpova feinmanis kontinualuri integrebis meTodma (integralebi traeqtoriebis gaswvriv) [44-45]. am meTodis warmateba polaronis Termodinamikis sakiTxebis ganxilvisas dakavSirebulia Semdeg mTavar teqnikur momentebTan: 1) es meTodi SesaZlebels xdis, raTa moxdes zusti gamoricxva fononuri amplitudebisa polaronis amocanidan (problemidan), ris Sedegadac mravalnawilakovani amocana daiyvaneba erTnawilakovani amocanis ganxilvamde, romelic aRiwereba aralokaluri funqcionaliT da romelic damokidebulia mxolod eleqtronis traeqtoriebze. polaronis feinmanis modelis formulirebisas fononuri operatorebi (amplitudebi) gamoiricxeba zustad eleqtron-fononuri sistemis qmedebidan. amgvarad, miRebuli qmedeba, romelic ar aris lokaluri fononuri operatorebis gamoricxvis Semdeg eleqtron-fononuri sistemidan, aRwers eleqtronis iseT moZraobas, rodesac amocana erTi nawilakis urTierTqmedebisa nawilakTa usasrulo ricxvTan, daiyvaneba erTi nawilakis (eleqtronis) urTierTqmedebaze Tavis TavTan (TviTqmedebaze). 2) amocanis aseTi arsebiTi gamartivebis Sedegad advili xdeba amoxsnebisTvis variaciuli meTodebis formulireba, dafuZnebuli iensenis utolobaze, romelic warmoadgens funqcionalur analogs n.n. bogolubovis variaciuli principisa kvanturstatistikuri sistemebis Tavisufali energiisTvis [25]. 3) miRebul funqcionalTa daxmarebiT, SesaZlebeli xdeba zustad amoxsnad modelTa klasis ageba, romlebic Seesabamebian kvadratul funqcionalebs da romlebic gamoiyenebian rogorc miaxloebiTi modelebi variaciuli gamoTvlebisaTvis.

feinmanis modelis (miaxloebis) arsi polaronis amocanisTvis mdgomareobs imaSi, rom ganixileba zusti, aralokaluri qmedebis aprosimireba aralokaluri kvadratuli qmedebiT. aralokalurobis gaTvaliswineba anu “maxsovrobis” efeqtis CarTva qmedebaSi, aZlevs feinma-nis midgomas polaronis amocanisadmi unikalobis Tvisebas, polaronis sxva

Teoriebisagan gansxvavebiT [46]. feinmanis sacdeli qmedeba aRwers eleqtrons, romelic urTierTqmedebs meore fiqtiur nawilakTan, romlis koordinatebis gamoricxva xdeba qmedebidan–mas Semdeg, rac ganixileba eleqtronis moZraoba ionur kristalSi da kristaluri me-sris rxevebis (fononebis) gavlena eleqtronze modelirdeba meore nawilakiT–romlis masaa M_F da romelic urTierTqmedebs kvadratulad, k-urTierTqmedebis mudmivaTi eleqtronTan. aseTi saxis sistemas, romelic aRwers eleqtronis urTierTqmedebas polarul optikur fononebTan, urTierTqmedebis (bmis) a mudmivas nebismieri mniSvnelobis dros, uwodeben polaronis feinmanis (erToscilatorian) models, romelic aris translaciurad invariantuli [44,46] (ix. nax. 2).



nax.2. polaronis feinmanis modeli. eleqtroni, romelic dakavSirebulia "zambaris" meSveobiT meore nawilakTan masiT M_F

amrigad, polaronis feinmanis modelSi eleqtronisa da masTan dakavSirebuli virtualuri, korelirebuli fononebis "Rrublis" moZraoba aRiwereba eleqtronis urTierTqmedebiT fiqtiur nawilakTan. am modelis hamiltonians aqvs Semdegi saxe [44,46]:

$$H_s^F = \frac{\vec{P}^2}{2m} + \frac{\vec{P}_F^2}{2M_F} + \frac{1}{2}k(\vec{r} - \vec{r}_F)^2, \qquad (1.41)$$

sadac: $\vec{P}$ da $\vec{P}_F$ - warmoadgenen eleqtronisa da fiqtiuri nawilakis impulsis operatorebs, Sesabamisad; xolo $\vec{r}$ da $\vec{r}_F$ arian eleqtronisa da fiqtiuri nawilakis radius-veqtorebi, m aris eleqtronis efeqturi masa gamtarobis zonidan, xolo M_F – fiqtiuri nawilakis masa. (1.41) polaronis feinmanis modeluri hamiltoniani aRwers nulovan miaxloebaSi polaronis aradisipaciur yofaqcevas eleqtron-fononuri urTierTqmedebis (bmis) a mudmivas nebismieri mniSvnelobis dros. Tu SemoviRebT axal kanonikur cvladebs, (1.41) hamiltoniani SesaZlebelia daviyvanoT diagonalur saxeze. marTlac gveqneba:

$$H_s^F = \frac{\vec{P}^2}{2(m+M_F)} + \frac{M_F+m}{2mM_F}\vec{P}_{os}^2 + \frac{k}{2}\vec{r}_{os}^2. \qquad (1.42)$$

aq: $\vec{P} = \vec{P} + \vec{P}_F$ - warmoadgens mTliani impulsis operatorsistemisa, romelic kanonikurad SeuRlebulia masaTa centris radius-veqtorTan:

$$\vec{R} = \frac{m\vec{r} + M_F\vec{r}_F}{m+M_F};$$

xolo $\vec{r}_{os} = \vec{r} - \vec{r}_F$ - warmoadgens fardobiT koordinatas.

$\vec{P}_{os} = \frac{M_F\vec{P} - m\vec{P}_F}{m+M_F}$ aris $\vec{r}_{os}$ koordinatis kanonikurad SeuRlebuli impulsi. (1.42) hamiltonianis energetikul spektrs aqvs Semdegi saxe:

$$E_{\vec{P},\vec{h}} = \frac{\vec{P}^2}{2(m+M_F)} + \hbar n(h_x + h_y + h_z + 3/2); \qquad (1.43)$$
$$(h_x, h_y, h_z = 0,1,2,...),$$

xolo: $n = \sqrt{k\frac{M_F+m}{mM_F}}$ warmoadgens harmoniuli oscilatoris sixSires da $\frac{mM_F}{M_F+m}$ aris sistemis dayvanili masa. $M_F + m$ - sidide mocemul modelSi warmoadgens polaronis efeqtur masas.

Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi, rodesac $a >> 1$, adgili aqvs utolobebs: $M_F >> m$ da $n >> w_0$. feinmanis mier SemoRebuli iyo uganzomilebo parametrebi V da W, romlebic dakavSirebulia M_F da n sidideebTan Semdegi tolobebiT: $M_F = m\left[\left(\frac{V}{W}\right)^2 - 1\right]$; $n = Vw_0$; V da W parametrebi ganisazRvrebodnen polaronis Tavisufali energiis minimizaciiT [44,46]. modelis yvela sxva danarCeni parametri, rogorebicarian: k, $M_F + m$, $\frac{mM_F}{m+M_F}$ da sxv. SesaZlebelia ganisazRvron (m, w_0) da (V, W) parametrebis daxmarebiT. susti da saSualo siZlieris (intensivobis) eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a < 1$): $V >> W; M_F \to 0; n \geq w_0$; $V \geq 1; V \approx 1 + a/12$ [47]. (V da W variaciuli parametrebis yofaqcevis Sesaxeb polaronis feinmanis modelSi ix. nax. 3).

polaronis problemisadmi variaciuli meTodis gamoyenebiT, feinmanis mier napovni iyo polaronis ZiriTadi mdgomareobis energiis zeda

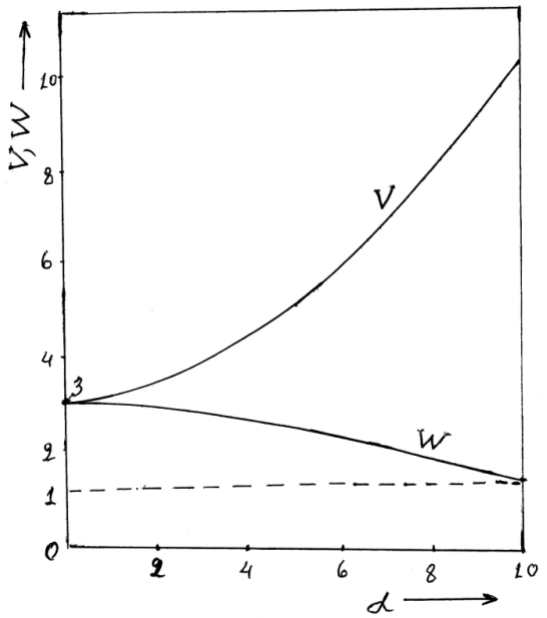
sazRvari, kristaluri mesris (fononebis) nulovani temperaturis ($T = 0$) dros:

$$E \le \frac{3}{4V}(V-W)^2 - \frac{aV}{\sqrt{p}}\int_0^\infty \frac{dUe^{-U}}{\left\{W^2U + \left[\left[\left(V^2-W^2\right)/V\right]\left(1-e^{-UV}\right)\right]\right\}^{1/2}}. \qquad (1.44)$$

$$(\hbar = w_0 = m = 1)$$

fononuri operatorebis (amplitudebis) gamoricxvis Sedegad miRebul zust qmedebas hqonda Semdegi saxe (gamoiyeneboda feinmanis meTodi integralebi traeqtoriebis gaswvriv kristaluri mesris nulovani temperaturis pirobebSi):

$$S = \frac{1}{2}\int\left(\frac{d\vec{r}}{dt}\right)^2 dt - \frac{a}{\sqrt{8}}\int_0^\infty\int_0^\infty \frac{e^{-|t-s|}}{|\vec{r}(t)-\vec{r}(s)|}dtdS. \qquad (1.45)$$



nax.3. V da W – variaciuli parametrebis yofaqceva, rogorc a-urTierTqmedebis (bmis) mudmivas funqciebi, polaronis feinmanis TeoriaSi

(1.44) da (1.45) Tanafardobebis ganzogadoeba kristaluri mesris nebismieri temperaturebis dros Sesrulebuli iyo [48] naSromSi. V da W parametrebis varirebis Sedegad (1.44) formulidan miiReboda polaronis ZiriTadi mdgomareobis energiis yvelaze saukeTeso umciresi zeda sazRvris Sefaseba a-bmis mudmivas sxvadasxva mniSvnelobebis dros:

1) a-s mcire mniSvnelobebis dros ($a<1$), V da W-s saukeTeso mniSvnelobebia: $V=3\left[1+2a\,(1-\mathrm{P})/3W\right]$, sadac $\mathrm{P}=\frac{2}{W}\left[(1-W)^{1/2}-1\right]$ da W = 3. V da W-s am mniSvnelobebisaTvis polaronis E-energiisaTvis gveqneba Semdegi Sefaseba:

$$E\le -a-\frac{1}{81}a^2+\mathrm{O}(a^3)=-a-0.0123a^2+\mathrm{O}(a^3). \qquad (1.46)$$

xolo SeSfoTebis Teoriis Sedegad miRebuli rezultati tolia sididis

$$E=-a-0.0126a^2+... \qquad (1.47)$$

2) a-s didi mniSvnelobebis SemTxvevaSi, rodesac ($a>>1$), V da W-s saukeTeso mniSvnelobebisTvis gvaqvs: $V=\frac{4}{9p}a^2 4\left(\ln 2+\frac{C}{2}\right)+1$, sadac C - eilermaskeronis mudmivaa: $C=0{,}5772...$ da $W=1$. am SemTxvevaSi polaronis energiisTvis gveqneba Sefaseba:

$$E\le -\frac{a^2}{3p}-\frac{3}{2}(2\ln 2+C)-\frac{3}{4}+\mathrm{O}\left(\frac{1}{a^2}\right)+... \qquad (1.48)$$

rogorc me-3 nax. naTlad Cans, V da W variaciuli parametrebi, polaronis feinmanis modelSi, warmoadgenen bmis a-mudmivas uwyvet funqciebs. ricxviTi gamoTvlebis Sedegad miRebuli iyo polaronis ZiriTadi mdgomareobis energiis damokidebuleba bmis mudmivaze. GgamoTvlebma aCvena, rom polaronis ZiriTadi mdgomareobis energiis mniSvneloba pekaris TeoriaSi: $E_0=-0.326a^2$ ($\hbar w_0$-erTeulebSi) – ufro mcire sididisaa, vidre polaronis feinmanis TeoriaSi, rodesac $a>34.29$. saerTod ki unda aRiniSnos, rom polaronis ZiriTadi mdgomareobis energiis Sefaseba feinmanis TeoriaSi bevrad ufro mcirea yvela sxva SefasebebTan SedarebiT, romlebic miiReba polaronis sxva Teoriebis saSualebiT; garda amisa, unda aRiniSnos agreTve is garemoebac, rom feinmanis meTods gaaCnia didi upiratesoba sxva meTodebTan SedarebiT polaronis TeoriebSi, vinaidan es meTodi (integralebi traeqtoriebis gaswvriv) iZleva saSualebas rom vipovoT polaronis energiis Sefasebebi bmis a-mudmivas rogorc mcire, aseve saSualedo da didi mniSvnelobebis dros; Tanac es meTodi iZleva erTaderT saimedo Sedegebs a-bmis mudmivas saSualedo ($5<a<10$) mniSvnelobebisaTvis [46,49].

funqcionalur-variaciuli meTodis daxmarebiT feinmanis mier gamoTvlili iyo agreTve polaronis efeqturi masis sidide [44,46]. integralebiT traeqtoriebis gaswvriv miaxloebiT gamoTvlas – polaronis feinmanis modelis qmedebisTvis _ mivyavarT polaronis efeqturi masis Semdeg gamosaxulebamde:

$$m_F^* = 1 + \frac{aV^3}{3\sqrt{p}} \int_0^\infty dt\, e^{-t} t^{\,2} \left[t + \frac{V^2 - 1}{VW} \left(1 - e^{-VWt} \right) \right]^{-3/2} \quad (m = 1). \qquad (1.49)$$

(1.49) formulaSi V da W variaciuli parametrebis optimaluri mniSvnelobebis CasmiT SesaZlebelia Sefasebuli iqnas m_F^* efeqturi masa a-bmis parametris mniSvnelobaTa mTel intervalSi. mcire siCqareebiT moZravi feinmanis polaronis efeqturi masis (1.49) mniSvneloba susti da Zlieri eleqtron-fononuri urTierTqmedebis zRvrul SemTxvevebSi warmoidgineba Semdegi saxiT:

$$m_F^* = 1 + \frac{a}{6} + \frac{2a^2}{81}; \quad a << 1$$

$$(m = 1) \qquad (1.50)$$

$$m_F^* = \left(\frac{4a^2}{9p} \right)^2 - \frac{4a^2}{p} (1 + 2\ln 2 + C); \quad a >> 1.$$

rasakvirvelia, (1.49-1.50) gamosaxulebebi samarTliania kristalis nulovani temperaturis (T=0) SemTxvevaSi. (1.50) gamosaxulebebi efeqturi masisaTvis ZiriTadi rigiT a-parametris mixedviT emTxveva, Sedegebs gamomdinare rogorc SeSfoTebis Teoriidan ($a << 1$), aseve adiabaturi miaxloebidan ($a >> 1$).

sainteresoa aRiniSnos is garemoeba, rom m_F^* efeqturi masis mniSvnelobebi, romlebic napovnia (1.49) gamosaxulebidan mxolod umniSvnelod (ramodenime procentiT) gansxvavdeba sacdeli modelis sruli masis mniSvnelobisagan: $M_F + 1 = \left(\frac{V}{W} \right)^2$ (*m* – eleqtronis efeqturi masis erTeulebSi). sasruli temperaturebis dros, polaronis feinmanis Teoriis formulirebisas gamoiTvleboda gibsis operatoris kvali, traeqtoriebis gaswvriv integralebis meTodis gamoyenebiT, Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi [48]. eleqtron-fononuri sistemis mdgomareobaTa erToblioba dakavSirebulia helmholcis Tavisufali energiis

mniSvnelobebTan, romlis minimizacia xdeboda V da W parametrebis mixedviT mocemuli, fiqsirebuli temperaturis pirobebSi; amgvarad ganisazRvreboda polaronis saSualo energia, rogorc temperaturis funqcia. temperaturis zrdasTan erTad (a-parametris fiqsirebuli mniSvnelobis dros), polaronis saSualo energiisa da misi efeqtur masis mniSvnelobebi mcirdeba. polaronis saSualo energiisa da efeqturi masis aseTi yofaqceva, rodesac $T \to \infty$, $E \to 0$ da $m_F \to 0$ [48] naSromSi aixsneba imiT, rom vinaidan Zalian dabali temperaturebis dros fononebi arian “Tavisufali”, maTi entropia izrdeba im fononebis entropiasTan SedarebiT, romlebic dakavSirebuli arian eleqtronTan.

eleqtronuli da polaronuli gadatanis movlenebis TeoriaSi arsebul im mravalricxovan gamokvlevaTa Soris, romelic miZRvnilia polaronis feinmanis modelis kinetikis sakiTxebisadmi, gansakuTrebuli mniSvneloba eniWeba naSromebs, romlebSiac gamokvleulia polaronis Zvradoba da eleqtrogamtaroba. es gamokvlevebi damyarebulia grinis funqciaTa meTodze [50] bolcmanis kinetikuri gantolebis Seswavlaze [51-52], TviTSeTanxmebuli da feinmanis kontinualuri integrebis meTodebis gamoyenebaze [53-54], kubos wrfivi gamoZaxilis Teoriaze [55-56] da sxv. rogorc wesi, rezultatebi miRebuli am sxvadasxva meTodebis daxmarebiT, romlebSiac gamoiyeneba sxvadasxva miaxloebebi, aris sxvadasxva (zogjer arsebiTadac gansxvavdeba erTmaneTisagan). unda aRiniSnos, rom zogadad polaronis kinetikis ganxilvisas yvela zemoT CamoTvlili meTodi iTvaliswinebs ZiriTadi mdgomareobis energiis Semcirebas da kvazinawilakis maxis gazrdas fononebTan urTierTqmedebis Sedegad, romelic gamowveulia eleqtron-fononuri urTierTqmedebis didi nawilis gaTvaliswinebiT. darCenili eleqtron-fononuri urTierTqmedeba (e.w. “nar-Ceni” urTierTqmedeba) aRwers polaronis gabnevas realur (siTbur) fononebze da iZleva Sesworebebs polaronis ZiriTadi mdgomareobis energiisaTvis da efeqturi masisTvis.

amgvarad, TviT sakuTriv polaronis feinmanis modelSi, eleqtronis urTierTqmedebas polarizaciul velTan mivyavarT arsebiTad or, erTmaneTisagan gansxvavebul movlenasTan (efeqtTan):

1) eleqtroni garSemortymulia virtualuri fononebis “RrubliT”. sakmarisad Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi,

struqturulad Sedgenil kvazinawilaks – polarons gaaCnia Sinagani mdgomareoba. es “Cacmis” efeqti, romelic aris Sedegi virtualuri fononebis gamosxivebisa da STanTqmisa, nulovan miaxloebaSi aRiwereba feinmanis moduluri hamiltonianiT (1.41).

2) disipaciis efeqti. es efeqti, romelic arsebiTad gansxvavdeba pirvelisagan, aRwers polaronis disipaciis movlenas; eleqtroni, fononur velTan urTierTqmedebis Sedegad - asxivebs da STanTqavs realur (siTbur) fononebs, ris gamoc gadadis erTi stacionaruli mdgomareobidan meoreSi, magaliTad gareSe velis zemoqmedebis Sedegad. TviT polaronis urTierTqmedeba realur fononebTan am modelSi moicema frolix-pekaris (1.13) urTierTqmedebis hamiltonianiT, sadac $V_{\vec{k}}$ sidideebi ganisazRvreba (1.18) TanafardobebiT.

amgvarad, feinmanis kontinualuri integrebis formalizmisa da funqcionaluri-variaciuli meTodis gamoyenebiT SesaZlebeli xdeba erTiani midgomis farglebSi aRweril iqnas polaronis amocana α-bmis mudmivas nebismieri mniSvnelobis dros, Tanac α-mudmivas mniSvnelobaTa farTo intervalSi vRebulobT polaronis ZiriTadi mdgomareobis energiis Sefasebas bevrad ufro zusts, vidre sxva cnobili meTodebis da miaxloebebis gamoyenebisas; am formalizmis daxmarebiT SesaZlebelia gamoTvlil iqnas TiTqmis yvela statikuri (Termodinamikuri) da dinamiuri sidide, romelic ki warmoadgens interess polaronis amocanisTvis didi radiusis mqone polaronis TeoriaSi. rasakvirvelia, ar arsebobs winaswar garantia imisa, rom kargi miaxloeba polaronis Tavisufali energiisTvis aseve kargad aRwers polaronis sxva fizikur maxasiaTeblebs (zogierT SemTxvevaSi, marTlac es ase ar aris), magram zogadad unda iTqvas, rom funqcionalur-variaciuli midgoma SesaZlebels xdis polaronuli sistemis yofaqcevis erTiani suraTis Camoyalibebas α-bmis parametris mniSvnelobaTa farTo intervalSi, kristalis sxvadasxva temperaturis dros, gareSe velebis sxvadasxva daZabulobebisa da sixSireebis SemTxvevaSi da sxv.

magram miuxedavad polaronis feinmanis modelis unikalobisa, am modelsac gaaCnia erTgvari SemosazRvruloba. rogorc ukve iyo aRniSnuli, feinmanis polaronis TeoriaSi xdeba zusti, aralokaluri qmedebis miaxloeba aralokaluri kvadratuli qmedebiT, rac adebs erTgvarad Sez-

Rudvas urTierTqmedebis potencialis formas, romelic Semoifargleba mxolod harmoniuli urTierTqmedebiT. Ggarda amisa, Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi naTlad ar Cans kavSiri polaronis feinmanis Teoriasa da polaronis pekaris models Soris.

polaronis feinmanis modelis ganzogadoeba Sesrulebuli iyo [57-58] naSromebSi. gansxvavebiT polaronis feinmanis modelisagan, ganzogadoebul modelSi ar xdeboda qmedebis aproqsimireba araloKaluri kvadratuli qmedebiT, anu urTierTqmedebis potenciali fiqtiur nawilakTan ar iyo harmoniuli tipis; ufro metic, eleqtronis urTierTqmedebis potenciali fiqtiur nawilakTan ar iyo fiqsi-rebuli saxis - am potencialis povna xdeboda variaciuli meTodis gamoyenebiT [57-58]. mimovixiloT axla SedarebiT ufro dawvrilebiT polaronis feinmanis ganzogadoebuli modeli (fgm).

1.3.3. polaronis feinmanis ganzogadoebuli modeli (latinjer-lus modeli)

polaronis feinmanis modelisagan gansxvavebiT fgm-Si, eleqtronisa da masTan dakavSirebuli virtualuri, korelirebuli, optikuri fononebis "Rrublis" moZraobis aproqsimireba xdeba eleqtronis traeqtoriiT, romlis drosac eleqtroni urTierTqmedebs M_{GF} masis mqone fiqtiur nawi-lakTan V_{GF} potencialis meSveobiT. SedarebiT yvelaze ufro martiv SemTxvevaSi aseTi sistemis (eleqtroni+fiqtiuri nawilaki) hamiltoniani aiReba Semdegi saxiT [57]:

$$H_{GF}^{s}=\frac{\vec{\mathrm{P}}^{2}}{2}+\frac{\vec{\mathrm{P}}_{GF}^{2}}{2M_{GF}}+V_{GF}\left(\vec{r}-\vec{R}_{GF}\right), \qquad (1.51)$$

sadac: $\vec{\mathrm{P}}_{GF}, \vec{R}_{GF}$ da M_{GF} warmoadgenen impulsis operators, radius-veqtors da masas fiqtiuri nawilakisa, Sesabamisad. gamoTvlebis gamartivebis mizniT, Cven SemovisazRvrebiT erTeulTa sistemiT, romelSiac: $\hbar=m=w_0=1$.. (1.51) formulaSi, daSvebulia, rom eleqtroni urTierTqmedebs fiqtiur nawilakTan $V_{GF}\left(\vec{r}-\vec{R}_{GF}\right)$ - centraluri, Zaluri potencialiT. Tu SemoviRebT axal kanonikur cvladebs, SesaZlebelia (1.51) hamiltonianis dayvana diagonalur saxeze da misi warmodgena Semdegi formiT:

$$H_{GF}^{s}=\frac{\vec{\mathrm{P}}^{2}}{2\left(M_{GF}+1\right)}+\frac{M_{GF}+1}{2M_{GF}}\vec{\mathrm{P}}_{1GF}^{2}+V_{GF}\left(\vec{x}\right). \qquad (1.52)$$

aq: $\vec{\mathrm{P}}=\vec{\mathrm{P}}+\vec{\mathrm{P}}_{GF}$ aris sistemis sruli impulsis operatori, romelic kanonikurad SeuRlebulia masaTa centris radius-veqtorTan: $\vec{R}=\frac{\vec{r}-\vec{R}_{GF}M_{GF}}{M_{GF}+1}$; $\vec{x}=\vec{r}-\vec{R}_{GF}$ warmoadgens fardobiT koordinatas, xolo $\vec{\mathrm{P}}_{1GF}=\frac{M_{GF}\vec{\mathrm{P}}-\vec{\mathrm{P}}_{GF}}{M_{GF}+1}$ aris Sesabamisi impulsi. unda aRiniSnos, rom sidide $M_{GF}+1$ mocemul miaxloebaSi warmoadgens polaronis efeqtur masas fgm-Si; TviT V_{GF} potenciali zogadad ar aris fiqsirebuli, misi forma (saxe) moiZebneba variaciuli principidan mocemul modelSi (SevniSnavT, rom polaronis feinmanis modelSi Teoriis variaciul parametrebs warmoadgenen k da M_F sidideebi).

[57-58] naSromebSi ganzogadoebuli iqna feinmanis kontinualuri integrebis meTodi (feinmanis formalizmi – integralebi traeqtoriebis gaswvriv), romlis daxmarebiTac da iensenis utolobis gaTvaliswinebiT, miRebuli iyo optikuri polaronisTvis energiis mniSvneloba E_0^{GF}, rogorc qveda sazRvari variaciuli energiisa E_V^{GF}, ise rom ar iyo fiqsirebuli forma (saxe) V_{GF} variaciuli potencialisTvis.

$$\mathrm{E}_0^{GF}\le\mathrm{E}_V^{GF}=\left\langle u_0\left|\frac{\vec{\mathrm{P}}_{1GF}^{2}}{2m}\right|u_0\right\rangle-\frac{a}{\sqrt{2}m}\sum_{n=0}^{\infty}\int\int d\vec{x}\,d\vec{x}\,'\times$$

$$\times\frac{u_0^{*}(\vec{x}\,')u_0(\vec{x})u_n^{*}(\vec{x})u_n(\vec{x}\,')}{\left|\vec{x}-\vec{x}\,'\right|}\left\{\frac{1-\exp\left[-2C(1+\Delta e_n)^{1/2}\left|\vec{x}-\vec{x}\,'\right|\right]}{1+\Delta e_n}\right\}, \qquad (1.53)$$

sadac: $m=\frac{M_{GF}}{M_{GF}+1}$; $\Delta e_n=e_n-e_0$; $C=\frac{M_{GF}}{\sqrt{2(M_{GF}+1)}}$ da: $u_n(\vec{x})$ da e_n warmoadgenen sakuTar funqciebs da sakuTar mniSvnelobebs Sredingeris gantolebisa, arafiqsirebuli (ganusazRvreli) variaciuli potencialiT V_{GF}:

$$\left[-\frac{1}{2m}\Delta_{\vec{x}}+V_{GF}(\vec{x})\right]u_n(\vec{x})=e_nu_n(\vec{x});$$
$$(n=0,1,2,...). \qquad (1.54)$$

(1.52) hamiltonianis cxadi saxe gviCvenebs, rom Sredingeris gantoleba sistemisaTvis (eleqtroni+fiqtiuri nawilaki) SesaZlebelia ganvacalkevoT

da CavweroT rogorc (1.54) Sredingeris gantoleba $V_{GF}(\vec{x})$ potencialiT, da agreTve Semdegi saxis Sredingeris gantoleba $\Psi_{\vec{P}}(\vec{R})$ talRuri funqciisTvis:

$$\left[-\frac{1}{2}\frac{1}{M_{GF}+1}\Delta_{\vec{R}}\right]\Psi_{\vec{P}}(\vec{R})=\mathrm{E}_{\vec{P}}\Psi_{\vec{P}}(\vec{R}), \qquad (1.55)$$

sadac: sistemis sruli energia $\mathrm{E}^{GF}_{\vec{P},n}$ moicema TanafardobiT $\mathrm{E}^{GF}_{\vec{P},n}=\mathrm{E}_{\vec{P}}+e_n\equiv\frac{\vec{P}^2}{2(M_{GF}+1)}+e_n$, xolo $\Psi_{\vec{P}}(\vec{R})=\frac{1}{\sqrt{V}}e^{i\vec{P}\vec{R}}$ warmoadgens brtyel talRas, romelic normirebulia sistemis V moculobaze.

vinaidan (1.53) gantolebis yvela wevri, romelic figurirebs ajamvis simbolos qveS, warmoadgens dadebiT sidides, amitom cxadia, rom Tu Cven SemovisazRvrebiT mxolod ZiriTadi wevriT (h=0) (1.53) gantolebis marjvena nawilSi, maSin am gantolebis marjvena mxare gaxdeba zeda sazRvari polaronis energiisTvis. ZiriTadi mdgomareobis miaxloebaSi Cven gveqneba:

$$\mathrm{E}_0^{GF}\le\mathrm{E}_V^{GF}=\int d\vec{x}\,u_0^*(\vec{x})\frac{\vec{\mathrm{P}}_{1GF}^2}{2m}u_0(\vec{x})-\frac{a}{\sqrt{2}m}\int\int d\vec{x}\,d\vec{x}'\cdot$$
$$\cdot\frac{\left|u_0(\vec{x})u_0(\vec{x}')\right|^2}{\left|\vec{x}-\vec{x}'\right|}\left\{1-\exp\left[-2C\left|\vec{x}-\vec{x}'\right|\right]\right\}. \qquad E_v^{GF}=E_v^{0GF} \qquad (1.56)$$

vinaidan (1.56) funqcionali Seicavs m da $u_0(\vec{x})$ sidideebs, SesaZlebelia am sidideebis varireba, imisaTvis, rom vipovoT $\mathrm{E}_V^{0GF}(m,u_0)$ energiis minimaluri mniSvneloba. Tu gamoviyenebT ritcis variaciul princips (meTods) pekaris tipis sacdeli talRuri funqciebiT, romelsac aqvs Semdegi saxe:

$$u_0(\vec{x})=N\left(1+bmx+ab^2m^2x^2\right)e^{-bmx};\ N^2=\frac{2b^3m^3}{p\,(14+42a+45a^2)}, \qquad (1.57)$$

sadac a da b warmoadgenen variaciul parametrebs, maSin SesaZlebelia gamoTvlil iqnas $E_V^{0GF}(m,a,b)$ - polaronis ZiriTadi mdgomareobis energiis minimaluri mniSvneloba. SesaZlebelia agreTve gamoyenebuli iqnas variaciuli meTodi pirdapiri integrirebisa. vinaidan E_V^{0GF} warmoadgens m (dayvanili masis) parametris funqcias da $u_0(\vec{x})$ funqciis funqcionals, da Seicavs damatebiTi pirobis saxiT mxolod $u_0(\vec{x})$ funqciis normirebas:

$\int d\vec{x}\left|u_0(\vec{x})\right|^2 = 1$, amitom moTxovna saukeTeso (optimaluri) urTierTqmedebis potencialis SerCevisa (romelic ganapirobebs polaronis ZiriTadi mdgomareobis - $E_V^{0GF}(m,a,b)$ energiis minimaluri mniSvnelobis miRebas) ekvivalenturia Semdeg gantolebaTa sistemisa:

$$\begin{aligned}&\frac{d}{du_0(\vec{x})}\left\{E_V^{0GF} - l\int d\vec{x}'\left|u_0(\vec{x}')\right|^2\right\} = 0;\\ &\frac{d}{dm}E_V^{0GF} = 0.\end{aligned} \tag{1.58}$$

amrigad, amocana faqtiurad daiyvaneba m sididis TiToeuli mniSvnelobisaTvis, hartris saxis TviTSeTanxmebuli Sredingeris gantolebis amoxsnamde:

$$\frac{\vec{P}_{1GF}^2}{2m}u_0(\vec{x}) - \frac{a\sqrt{2}}{m}\int d\vec{x}'\frac{\left|u_0(\vec{x}')\right|^2}{\left|\vec{x}-\vec{x}'\right|}\left[1-\exp(-2C\left|\vec{x}-\vec{x}'\right|)\right]\times \tag{1.59}$$
$$\times u_0(\vec{x}) = e_0 u_0(\vec{x}).$$

amitom, aseTi miaxloebis dros V_{GF} TviTSeTanxmebuli variaciuli potencialisTvis gveqneba Semdegi saxis gamosaxuleba:

$$V_{GF}^0(\vec{x}) = -\frac{a\sqrt{2}}{m}\int d\vec{x}'\frac{\left|u_0(\vec{x}')\right|^2}{\left|\vec{x}-\vec{x}'\right|}\left[1-\exp(-2C\left|\vec{x}-\vec{x}'\right|)\right]. \tag{1.60}$$

(1.56-1.57) da (1.59) gantolebebis daxmarebiT SesaZlebelia aRdgenili (miRebuli) iqnas pekaris naxevradklasikuri Teoria [30,58]. Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a >> 1$), rodesac $M_{GF} >> 1$, ($e_0 >> \hbar w_0$) da $C \to \infty$. (1.60) gantolebis Tanaxmad $V_{GF}^0(\vec{x})$ potencialisTvis gveqneba gamosaxuleba:

$$V_{GF}^0(\vec{x}) = -\frac{a\sqrt{2}}{m}\int d\vec{x}'\frac{\left|u_0(\vec{x}')\right|^2}{\left|\vec{x}-\vec{x}'\right|}. \tag{1.61}$$

susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a < 1$), rodesac $M_{GF} \to 0$, $m \to 0$, $C \to 0$, Tu (1.56), (1.60) formulebis, integralqveSa gamosaxulebebSi gavSliT eqsponentas mwkrivad, maSin martivad davrwmundebiT, rom am zRvrul SemTxvevaSi polaronis energia fgm-Si SemosazRvrulia mniSvnelobiT: $-a$, anu $E_0 \le -a$. zogad SemTxvevaSi, polaronis

$E_V^{0GF}(m,a,b)$ energiis mniSvneloba SesaZlebelia gamoTvlil iqnas analizurad Tu gamoviyenebT Semdeg cnobil formulebs:

$$\frac{\exp\left(ik\left|\vec{x}-\vec{x}'\right|\right)}{4p\left|\vec{x}-\vec{x}'\right|} = ik\sum_{l=1}^{\infty} I_e(kx<)h_l^{(1)}(kx>)\sum_{m=-l}^{+e} Y_{lm}(q,j)Y_{lm}^*(q,j);$$

$$\int_0^Z t^n e^{-bt}dt = \frac{n!}{b^{n+1}} - e^{-bZ}\sum_{k=0}^{n}\frac{n!}{k!}\frac{Z^k}{b^{n-k+1}}; \qquad (1.62)$$

$$\int_Z^{\infty} t^n e^{-bt}dt = e^{-bZ}\sum_{k=0}^{\infty}\frac{n!}{k!}\frac{Z^k}{b^{n-k+1}}.$$

polaronis energiis $E_V^{0GF}(m,a,b)$ mniSvneloba gamoTvlili iyo [58] naSromSi. Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a >>1$) polaronis energiis zeda sazRvris mniSvneloba tolia sididis: $-0{,}108504a^2$ [57-58].

ricxviTi meTodebis gamoyenebiT, TviTSeTanxmebuli (1.60) potenciali rogorc sawyisi potenciali, saSualebas iZleva rom gamovTvaloT $u_n(\vec{x})$ aRgznebuli talRuri funqciebi, Sredingeris (1.59) gantolebis daxmarebiT. polaronis fgm-Si, TviTSeTanxmebul potencialis yofaqceva did manZilze aris kulonuri tipis, xolo mcire manZilze (areSi, sadac eleqtronis talRuri funqcia aris didi) potenciali aris paraboluri saxis (harmoniuli oscilatoris potencialis tipis) [30,57-58]. gansxvavebiT polaronis feinmanis modelisagan, am modelSi martivad xerxdeba miRebuli Sedegebis (magaliTad: polaronis ZiriTadi mdgomareobis energiis) dakavSireba SedegebTan, romlebic gamomdinareoben polaronis pekaris Teoriidan, Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi. [58] naSromSi naCvenebia, rom midgoma, romelic eyrdnoba variaciuli meTodis gamoyenebas optimaluri, TviTSeTanxmebuli potencialis sapovnelad, ukeTes Sedegs iZleva polaronis ZiriTadi mdgomareobis energiis gamoTvlisas, vidre harmoniuli aproqsimacia urTierTqmedebis potencialisTvis.

iseve rogorc polaronis feinmanis modelSi, polaronis fgm-Si (1.51) modeluri hamiltoniani aRwers nulovan miaxloebaSi polaronis aradisipaciur yofaqcevas, a-parametris nebismieri mniSvnelobis dros. amrigad, polaronis fgm-Sic, eleqtronis urTierTqmedebas polarul optikur fononebTan mivyavarT or gansxvavebul efeqtTan. erTi efeqti ganapirobebs polaronis - rogorc kvazinawilakis struqturis Camoya-

libebas, romelic aris Sedegi virtualuri fononebis gamosxivebisa da STanTqmisa da romelsac adgili aqvs Zlieri eleqtron-fononuri urTierTqmedebis dros da meore efeqti, romelic gansxvavdeba pirvelisagan da romelic aRwers polaronis disipaciis movlenas, ganpirobebuls eleqtronis urTierTqmedebiT siTbur polarul optikur fononebTan. es ukanasknели efeqti, iseve rogorc polaronis feinmanis modelSi, aRiwereba frolix-pekaris tipis - (1.13) urTierTqmedebis hamiltonianiT.

miuxedavad kontinualuri integrirebis (integralebi traeqtoriebis gaswvriv) meTodis upiratesobisa sxva meTodebTan SedarebiT da funqcionalur-variaciuli midgomis dadebiTi mxareebisa, romlebsac Cven SevexeT polaronis feinmanis modelisa da fgm-is ganxilvis dros, wonasworul da arawonasworul statistikur meqanikaSi da, kerZod polaronuli sistemebis Termodinamikisa da kinetikis sakiTxebis Seswavlisas farTo gamoyeneba hpova mowesrigebul operatorTa formalizmma da T-namravlTa meTodma, romelic agreTve emyareba fononuri amplitudebis gamoricxvis teqnikas [59-62]. ufro metic, SeiZleba iTqvas, rom zogierTi Sedegi polaronis TeoriaSi pirvelad miRebul iqna swored am midgomis gamoyenebiT. garda amisa, mowesrigebul operatorTa formalizmsa da T-namravlTa meTods eniWeba upiratesoba zogierTi sakiTxis ganxilvisas, gansakuTrebiT maSin, rodesac saWiroa rezultatebis marTebulobis safuZvlianobisa da zogierTi Teoremebis damtkiceba statistikur meqanikaSi, da kerZod, polaronis TeoriaSi [60-62].

gasuli saukunis 80-ian wlebSi n.n. bogolubovisa da n.n. bogolubov (umc.) mier ganviTarebul iqna axali midgoma eleqtron-fononuri sistemisaTvis da polaronis wonasworul TeoriaSi (ganixileboda eleqtronis urTierTqmedeba polarul optikur fononebTan), romelic samarTliania nebismieri temperaturebisa da eleqtron-fononuri urTierTqmedebis α-parametris nebismieri mniSvnelobis dros. am midgomas safuZvlad edo T-namravlTa teqnikis gamoyeneba fononebis Tavisuflebis xarisxis gamosaricxad eleqtron-fononuri sistemidan, da Sesabamisad eleqtron-fononuri sistemis maxasiaTebeli fizikuri sidideebis wonasworuli saSualo mniSvnelobebis gamoTvla [62]. T-namravlTa teqnika saSualebas iZleva mkacri maTematikuri sizustiT da SedarebiT martiv doneze daasabuTos kontinualuri integrebis meTodis safuZvlianobis idea

[14-15]. zustad amoxsnadi hamiltonianisa da agreTve variaciuli principis gamoyenebam polaronis TeoriaSi, SesaZlebeli gaxada polaronis Tavisufali energiis zeda sazRvris Sefaseba sasruli temperaturebisa da α-bmis mudmivas nebismieri mniSvnelobis dros [40,62]. unda aRiniSnos, rom mowesrigebul operatorTa formalizmi da T-namravlTa teqnika gansakuTrebiT efeqturi aRmoCnda polaronis Tavisufali energiis gamosaTvlelad SeSfoTebis Teoriis meTodebis gamoyenebisas sasruli temperaturebis SemTxvevaSi da agreTve eleqtron-fononuri sistemis (polaronis) kinetikis sakiTxebis ganxilvisas [5,14-16,62].

axla gadavideT fizikuri kinetikis zogierTi principuli sakiTxis mimoxilvaze dinamiuri sistemebisa, romlebic urTierTqmedeben bozonur (fononur) TermostatTan.

1.4. fizikuri kinetikis zogierTi sakiTxi dinamiuri sistemebisa, romlebic urTierTqmedeben fononur (bozonur) velTan

rogorc cnobilia, kinetikuri gantolebebis miRebis Cveulebrivi procedura dakavSirebulia korelaciebis Sesustebis hipoTezasTan an ekvivalentur daSvebebTan, magaliTad Sfm-Tan. es hipoTeza an miaxloeba saSualebas iZleva rom moxdes sistemis Semoklebuli aRwera kinetikuri gantolebis saxiT. magram, rogorc cnobilia, dinamiur sistemebSi mimdinare stohastikuri procesebis Teoriidan, Tu dinamiuri sistema warmoadgens K tipis sistemas (a.n. kolmogorovis saxis sistemebi) [20,63], maSin araviTari hipoTeza ar aris saWiro kinetikuri gantolebis misaRebad, Semoklebuli aRwera warmoiqmneba avtomaturad dinamiuri sistemis evoluciis procesSi fazur sivrceSi Serevis procesebis arsebobis gamo erT-erTi an ramdenime dinamiuri cvladis mixedviT. swored am cvladis an cvladebis mixedviT xdeba korelaciebis swrafi Sesusteba. analogiuri debuleba samarTliania agreTve kvanturi - K sistemebisaTvis. tradiciulad, rogorc wesi, kinetikuri gantolebis gamoyvanas Tan axlavs specifiuri tipis aprioruli hipoTeza. kargad aris cnobili, rom kinetikuri gantolebis forma da struqtura ganisazRvreba im procesebis albaTuri bunebiT da TvisebebiT, romlebsac aRwers TviT es gantoleba. Tu gamovalT liuvilis gantolebidan ganawilebis funqciisTvis (kvantur-meqanikuri midgomisas

fon-neimanis gantolebidan statistikuri operatorisTvis), Cven SegviZlia vipovoT kinetikuri gantolebis saxe, Tu ugulvebelvyofT wevrebs romelTa gamo moZraobis dinamiuri xasiaTi arsebiTad gansxvavdeba SemTxveviTi procesebisagan. amis gamo kinetikuri gantolebis miRebas ama Tu im formiT Tan axlavs raime principis an aprioruli hipoTezis formulireba, da amitom aseTi hipoTezis arsi (datvirTva) mdgomareobs imaSi, rom mocemuli dinamiuri sistemisTvis SemoaqvT SemTxveviTobis (qaosis) esa Tu is elementi [3,20].

im meTodebs Soris, romlebsac mivyavarT kinetikuri gantolebis miRebamde, yvelaze ufro srulyofili ganviTareba da gamoyeneba hpova n.n. bogolubovis meTodma, romelic gadabmuli gantolebebis ierarqiuli jaWvis daxmarebiT saSualebas iZleva ganawilebis funqciis agebisa, da romelic gamomdinareobs liuvilis gantolebidan. es meTodi cnobilia, rogorc – bbgki-is (bogolubovi-borni-grini-kirkvudi-ivoni) saxelwodebiT. bbgki-is jaWvi sabolood mTavrdeba bolcmanis tipis gantolebis miRebiT. am meTodSi gamoiyeneba sivrculi korelaciebis Sesustebis principi, romelic mdgomareobs imaSi, rom nawilakebi romlebic sakmao manZiliT arian dacilebuli erTmaneTisagan sivrceSi, asruleben arakorelirebad moZraobas [4,34,64-65].

unda aRiniSnos, rom fundamenturi miRwevebi bolcmanis tipis kinetikuri gantolebis (rogorc klasikuris, aseve kvanturis) da ZiriTadi kinetikuri gantolebis gamoyvanaSi, miuZRvis n.n. bogolubovs. bolcmanis saxis kvantur-kinetikuri gantoleba mkacri saxiT miRebuli iqna n.n. bogolubovis mier, romelic eyrdnoboda korelaciebis Sesustebis hipoTezas [36,66]. mis mier damuSavebuli iyo formaluri sqemebi zogadad kinetikuri gantolebebis miRebisa da formulirebuli iyo mkacri maTematikuri formiT is daSvebebi, romlebic avseben damatebiT am gamoyvanebis meTodebs. kvanturi kinetikuri gantolebis sxva formac – ZiriTadi kinetikuri gantoleba (master equation), romelic pirvelad SemoTavazebuli iyo paulis mier – gamoyvanili iyo n.n. bogolubovis mier Sfm-Si, romlis miRebis drosac gamoyenebuli iyo SeSfoTebis operatoris speqtraluri Tvisebebi [36,66].

K-tipis dinamiuri sistemebisaTvis (rogorc klasikuris, aseve kvanturisTvis), SesaZlebelia paulis saxis kvanturi kinetikuri gantole-

bis miReba Sfm-is gamoyenebis gareSe. aseTi saxis gantolebis miReba demonstrirebuli iyo [20] naSromSi, kvanturi arawrfivi oscilatoris magaliTze, romelzedac moqmedebda gareSe perioduli Zala. meTodis ZiriTadi idea, romelic gamoyenebuli iyo [20] naSromSi mdgomareobda imaSi, rom kvanturi K sistemebis ergodiul Tvisebebs klasikur zRvrul SemTxvevaSi mivyavarT statistikuri operatoris aradiagonaluri matriculi elementebis swraf milevamde. Sedegi miRebuli iyo kvaziklasikur miaxloebaSi, romelsac mivyavarT kvanturi dinamiuri sistemis Semoklebuli aRweris SesaZleblobaze (fazur sivrceSi) da rogorc Sedegi - napovni iyo paulis saxis kinetikuri gantoleba.

ukanasknel wlebSi, dinamiuri sistemebis TeoriaSi, farTo ganviTareba hpova mkacrma meTodebma kvanturi dinamiuri qvesistemis dinamikis aRwerisa, romelic urTierTqmedebs dakvantul bozonur velTan (TermostatTan). es meTodebi gamoirCeva im TaviseburebiT, rom saSualebas iZleva, raTa miRebuli iqnas Tanafardobebi, romlebic aRweren qvesistemis dinamikas, romelic samarTliania bozonur velTan urTierTqmedebis (bmis) mudmivas nebismieri mniSvnelobebis dros, nebismieri temperaturebisa da nebismieri gareSe moqmedi Zalebis SemTxvevaSi. am midgomebis dros ar gamoiyeneba daSveba mTeli dinamiuri sistemis statistikuri operatoris gamartivebis Sesaxeb didi droebis SemTxvevaSi: $t >> t_0$ (sadac: t_0-warmoadgens qaotizaciis maxasiaTebel dros), rodesac am daSvebis Tanaxmad, mTeli kvanturi dinamiuri sistemis statistikuri operatori xdeba qvesistemis dayvanili (reducirebuli) statistikuri operatoris funqcionali.

pirvelad aseTi saxis evoluciuri gantoleba qvesistemis statistikuri operatorisaTvis, rodesac qvesistema urTierTqmedebs bozonur velTan (fononebTan), romlebic imyofebian statistikuri wonasworobis mdgomareobaSi T temperaturiT, miRebuli iyo [15-16] naSromebSi, bozonuri amplitudebis zusti gamoricxviT am evoluciuri gantolebidan. evoluciuri gantoleba Sfm-is gamoyenebiT qvesistemis statistikuri operatorisTvis, romelic urTierTqmedebs TermostatTan, miRebuli iyo [67-71] SromebSi, romelic gansxvavebiT [5-6, 14-16] naSromebSi miRebuli gantolebebisagan aris Caketili. sivrculi erTgvarovnebis SemTxvevaSi, qvesistemis (eleqtronis) TermostatTan susti urTierTqmedebis dros

SeSfoTebis Teoriis meore miaxloebaSi am evoluciuri gantolebidan gamomdinareobs bolcmanis gantoleba eleqtronisaTvis [57,69-71]. ganzogadoebuli kvanturi kinetikuri gantolebebis mkacri gamoyvana eleqtron-fononuri sistemisaTvis Sesrulebuli iyo [6,14-15] SromebSi, sadac ganxiluli iyo agreTve am gantolebebis gamoyeneba sxvadasxva modelisTvis. Seqmnili iyo meTodi kinetikuri gantolebebis miRebisa, romelic eyrdnoboda ganviTarebul specifiur teqnikas – velis kvanturi Teoriisa da T-namravlTa formalizmis daxmarebiT, – bozonuri amplitudebis gamoricxvisa Sesabamisi kinetikuri gantolebebidan [5-6]. Sesabamisi miaxloebebis SesrulebiT, gamoyvanili kinetikuri gantolebebidan miRebuli iyo konkretuli fizikuri Sedegebi, romlebic aRweren eleqtronisa da polaronis kinetikas [27,29-31,38]. amrigad, fundamenturi midgoma, romelic ganviTarebuli da gamoyenebuli iyo [14-15] SromebSi, saSualebas iZleoda Sfm-Si ganzogadoebuli kvanturi evoluciuri gantolebebis miRebas sistemis statistikuri operatorisTvis, gamoricxuli bozonuri amplitudebiT.

ukanaskneL periodSi, arawonasworuli da Seuqcevadi procesebis aRsawerad da Sesabamisi adekvaturi Teoriis Sesaqmnelad, myari sxeulebis fizikaSi farTo gamoyeneba da ganviTareba hpova arawonasworuli statistikuri meqanikis sxvadasxva meTodebma. arawonasworul sistemebSi relaqsaciuri procesebis Sesaswavlad didi mniSvneloba eniWeba korelaciuri da grinis funqciebis meTods [4,34,64-65,72-73]. ukanaskneL wlebSi, arawonasworuli movlenebis gamosakvlevad xSirad gamoiyeneba agreTve proeqciuli operatoris meTodi [74]. Gganzogadoebuli kvanturi kinetikuri gantoleba statistikuri operatorisaTvis qvesistemisa, romelic urTierTqmedebs bozonur TermostatTan, SesaZlebelia miRebul iqnas aseve arawonasworuli statistikuri operatoris meTodis gamoyenebiT [4,34].

[68] naSromSi, proeqciuli operatorisa da grinis superoperatoris meTodi gamoiyeneboda Caketili evoluciuri gantolebis misaRebad qvesistemis statistikuri operatorisaTvis, romelic urTierTqmedebda bozonur velTan, saidanac gamoricxuli iyo bozonuri operatorebi. am naSromSi, liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis daxmarebiT, gamoyvanili iyo moZraobis ganzo-

gadoebuli, kvanturi gantoleba grinis dagvianebuli superoperatorisTvis. grinis superoperatorebis meTodi gamoiyeneboda agreTve [75-76] naSromebSi, sadac miRebuli iyo kvanturi evoluciuri gantolebebi qvesistemis operatorebis drois ormomentiani wonasworuli korelaciuri funqciebisTvis. Sesabamisi miaxloebebis ganxilvisas qvesistemis (eleqtronis) dinamikisTvis, am gantolebebidan martivad miiReboda cnobili Sedegebi eleqtron-fononuri sistemisTvis da, kerZod polaronis kinetikaSi [29,77]; magram, miuxedavad amisa, xazi unda gaesvas im garemoebas, rom yvela zemoT moyvanil naSromSi, qvesistemis statistikuri operatoris-Tvis ganzogadoebuli kvanturi evoluciuri gantolebis gamoyvanisas, da grinis superoperatorebisTvis moZraobis gantolebebis miRebisas, gamoiye-neboda aproqsimacia – Sfm, da amitom am naSromebSi yvela miRebuli gantoleba – rogorc qvesistemis statistikuri operatorisTvis, ise qvesistemis operatorebis wonasworuli korelaciuri funqciebisTvis – ar aris zusti.

rogorc cnobilia, wrfivi gadatanis movlenebis Sesaswavlad myar sxeulebSi, erT-erT efeqtur xerxs warmoadgens meTodi, romelic damyarebulia bolcmanis kinetikuri gantolebis gamoyenebaze. Ggadatanis movlenebis kvanturi Teoria, romlis aRsawerad gamoiyeneba bolcmanis gantoleba, faqtiurad warmoadgens kvaziklasikur Teorias, romelic dafuZnebulia adiabatur miaxloebasa da SeSfoTebis Teoriaze. eleqtronuli da polaronuli gadatanis movlenebis kvantur TeoriaSi bolcmaniseuli midgomisas igulisxmeba, rom gamtarobis eleqtronebi (an polaronebi) imyofebian stacionarul da TiTqmis “Tavisufal” mdgo-mareobebSi kvaziimpulsebis gansazRvruli mniSvnelobebiT. kristaluri mes-ris periodulobis darRveva ganpirobebuli, magaliTad fononebiT, iwvevs eleqtronebis mdgomareobaTa arastacionarobas. eleqtronebis fononebze gabnevisas igulisxmeba, rom gabnevis procesebis aqtebi kargad aris gan-calkevebuli sivrcesa da droSi, da amitom, faqtiurad, adgili ar aqvs interferenciis movlenas eleqtronebis erTi mdgomareobidan meoreSi gadasvlis dros. kristalze modebuli gareSe eleqtruli veli ganixileba rogorc susti intensivobisa (mcire amplitudebis mqone) da mdored cv-ladi sivrcesa da droSi. rogorc Sedegi, aseTi gareSe eleqtruli velis moqmedeba iwvevs mxolod muxtis matarebelTa aCqarebas da maT gadasvlebs

sxvadasxva mdgomareobebSi ise, rom ar xdeba TviT am mdgomareobebis arsebiTi cvlileba. aseT SemTxvevebSi eleqtronis gabnevis kveTebi ar iReben did mniSvnelobebs. amgvarad, bolcmaniseuli aRwera SeiZleba CaiTvalos rogorc kvaziklasikuri, specifiuri kvantur-meqanikuri efeqtebis gareSe.

eleqtron-fononuri sistemisaTvis bolcmanis ganzogadoebuli gantoleba da polaronis frolixis modelisaTvis bolcmanis gantoleba miRebuli iyo susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi [14-15] naSromebSi. bolcmanis gantolebis miRebisa da gamoyenebis safuZvlianoba eleqtronebis drekadi gabnevis SemTxvevaSi minarevul centrebze, rodesac es ukanasknelni ganlagebulni arian qaosurad sivrceSi, ganxiluli iyo [78-79] naSromebSi. rogorc ukve aRvniSneT, bolcmanis gantoleba SesaZlebelia miRebuli iqnas agreTve qvesistemis (eleqtronis) simkvrivis matricis zusti, Caketili kinetikuri gantolebidan, rodesac adgili aqvs eleqtronis sust urTierTqmedebas polarul optikur fononebTan, romelic ganxiluli iyo [67,69-71] naSromebSi. magram miuxedavad amisa unda aRiniSnos, rom gadatanis movlenebis wrfiv TeoriaSi, gadatanis meqanikuri koeficientebis gamosaTvlelad bolcmanis kinetikuri gantolebis gamoyenebis are SezRudulia. ase magaliTad, eleqtron-fononuri sistemis SemTxvevaSi, Tu eleqtronebis fononebze gabnevis sxvadasxva aqtebi erTmaneTTan ganicdian interferencias, maSin cxadia, rom bolcmanis kinetikuri gantoleba ukve ar gamoiyeneba [80].

gasuli saukunis 70-ian wlebSi, gadatanis arawrfivi movlenebis aRsawerad da meqanikuri koeficientebis (mag. Zvradoba) gamosaTvlelad, tornbergisa da feinmanis mier ganviTarebuli iyo axali midgoma, romelic Tavisufali iyo im SezRudvebisagan rasac moicavda gadatanis movlenebis bolcmaniseuli aRwera. gamoyenebul iqna ra kontinualuri integrebis meTodi, tornbergisa da feinmanis mier dadgenili iyo arawrfivi damokidebuleba kristalze modebul gareSe eleqtrul velsa da muxtis matareblis (eleqtronis) damyarebul saSualo siCqares Soris polarul nivTierebebSi [84]. tornberg-feinmanis Teoriis sqemaSi eleqtron-fononuri sistemis statistikuri operatorisTvis, romelic ganisazRvreboda liuvil-fon neimanis evoluciuri gantolebidan, gamoyenebuli iyo Zalian rTuli

maTematikuri formalizmi dafuZnebuli feinmanis integralebze traeqtoriebis gaswvriv [53,84]. unda aRiniSnos, rom feinmanis traeqtoriebiT integralebis gamoTvla ar xerxdeboda zustad da amitom zemoTmiTiTebuli avtorebi iyenebdnen sxvadasxva miaxloebebs fizikuri Sedegebis misaRebad. am midgomis farglebSi, eleqtron-fononuri sistemis simkvrivis matricidan xdeboda fononuri operatorebis gamoricxva.

amgvarad, tornberg-feinmanis midgoma da meTodi amyarebda arawrfiv Tanafardobas gareSe sasrul (Zlier) eleqtrul velebsa da eleqtronis saSualo siCqareebs Soris polarul kristalSi, rac faqtiurad saSualebas iZleoda myar sxeulebSi gadatanis arawrfivi movlenebis Seswavlis SesaZleblobas [84-85]. xazi unda gaesvas im garemoebas, rom tornberg-feinmanis mier miRebuli zemoTnaxsenebi Sedegebi samarTliania rogorc Zlieri, aseve susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi. samecniero literaturaSi tornberg-feinmanis midgoma cnobilia rogorc balansis gantolebis meTodi. aqve unda aRvniSnoT, rom balansis gantolebis meTodi awydeba siZneleebs eleqtronis (an polaronis) Zvradobis gamoTvlisas polarul nivTierebebSi Zalian dabali temperaturebis dros. am meTodSi miCneulia, rom arc Tu ise Zlieri eleqtruli velebisas miiRweva stacionaruli mdgomareoba, rodesac eleqtroni moZraobs mudmivi siCqariT. [84] naSromSi daxatuli fizikuri suraTi, eleqtronis damyarebuli siCqaris damokidebulebisa Zlier statikur eleqtrul velze, principSi samarTliania a, T da E-s nebismieri mniSvnelobebisaTvis, magram avtorebi aRniSnaven or ZiriTad sirTules, romelic jer kidev ar aris gadalaxuli dRevandel dRemde:

1) impulsis balansis gantolebaze dayrdnobiT miRebuli Sedegebi ar emTxveva im Sedegebs, romlebic miiReba energiis balansis gantolebidan.

2) susti intesivobis eleqtruli velebis SemTxvevaSi, Zvradoba gamoTvlili balansis gantolebis daxmarebiT ar emTxveva Zvradobis im mniSvnelobas, romelic miiReba bolcmanis gantolebis amoxsniT (gansxvavdeba misgan $\frac{3}{2}\frac{K_B T}{\hbar\omega_0}$-faqtoriT).

rogorc mogvianebiT gairkva [15-16], tornbergisa da feinmanis Teoriis Sedegi (mxolod susti eleqtron-fononuri urTierTqmedebis zRvrul SemTxvevaSi) SeiZleba miviRoT bolcmanis gantolebidan, Tu vivaraudebT,

rom mis stacionarul amoxsnas aqvs kvazimaqsvelis ganawilebis funqciis saxe. marTlac, erTis mxriv eleqtron-fononuri sistemis qmedebis aproqsimacias kvadratuli funqcionaliT (feinmanis meTodSi – integralebi traeqtoriebis gaswvriv) yovelTvis mivyavarT kvazimaqsvelis tipis impulsis ganawilebis funqciasTan [53,85] da amave dros, meores mxriv bolcmanis gantolebis amonaxsnTa gamokvlevebi [86] da eleqtronis dreifuli siCqaris gamoTvlis eqsperimentaluri monacemebi Zlier eleqtrul velebSi dabali temperaturebisas [87] cxadad gviCveneben, rom impulsis ganawilebis funqcia mkveTrad gansxvavdeba maqsveliseulisagan. Tvisobrivad es dakavSirebulia im faqtTan, rom dabali temperaturebisa da Zlieri velebis SemTxvevaSi, relaqsaciis dominirebul meqanizmad gvevlineba polaruli optikuri fononebis gamosxiveba, romelic aris Zlier aradrekadi da anizotropuli xasiaTis procesi da romelsac mivyavarT denis matareblebis specifiur yofaqcevamde, romelic cnobilia, rogorc “Streaming motion” movlena. miuxedavad zemoT aRniSnuli sirTuleebisa, [84-85] naSromebSi mocemuli Teoria warmoadgens jerjerobiT erTaderT mikroskopul Teorias eleqtronisa, nebismieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi Zlier gareSe eleqtrul velSi.

imisaTvis, rom daeZliaT eleqtronuli da polaronuli gadatanis movlenebis siZneleebi naxevargamtarebsa da ionur kristalebSi, romlebic dafuZnebuli iyo bolcmanis gantolebis gamoyenebaze, da im mizniT, rom aegoT impendansis erTiani wrfivi Teoria polaronisTvis (eleqtronisTvis) gareSe eleqtruli velis nebismieri sixSireebis, kristalis nebismieri temperaturebisa da eleqtron-fononuri bmis mudmivas nebismieri mniSvnelobis dros, feinmanis, xelvorsis, idingsisa da platcmanis (fxip) mier ganviTarebuli iyo midgoma, romelic dafuZnebuli iyo eleqtron-fononuri sistemisTvis arawonasworuli simkvrivis matricis gamoTvlaze feinmanis meTodiT – integralebi traeqtoriebis gaswvriv. fxip-is mier miRebuli iyo wrfivi gamoZaxilis funqciis zusti mniSvneloba ormagi kontinualuri integralis saxiT traeqtoriebis gaswvriv, romelic Semdeg aproqsimirebuli iyo feinmanis erToscilatoriani modelis farglebSi [88]. fxip-is midgomam Semdgomi ganviTareba hpova [47,89-90] SromebSi. fxip-is mier miRebuli impendansis zogadi gamosaxulebidan gamoyvanili iyo polaronis efeqturi masisTvis zogadi formula, napovni iyo polaronis optikuri

STanTqmis koeficienti da sxv. miRebuli iyo agreTve polaronis Zvradobis zogadi formula bmis mudmivas nebismieri mniSvnelobisa da nebismieri temperaturis dros. unda aRiniSnos, rom fxip-is mier miRebuli yvela Sedegi samarTliania agreTve eleqtronisTvisac, bmis mudmivas mcire ($a < 1$) mniSvnelobebisas. magram miuxedavad fxip-is midgomis universalobisa, am midgomasac gaaCnia sirTuleebi, romlebic dRemde ar aris gadawyvetili. erT-erTi ZiriTadi sirTule mdgomareobs imaSi, rom iseve rogorc tornberg-feinmanis TeoriaSi, aqac napovni dreifuli Zvradobis mniSvneloba kristalis dabali temperaturebis dros $\frac{3}{2}\frac{K_B T}{\hbar\omega_0}$-Tanamamravli T gansxvavdeba Zvradobis im mniSvnelobisagan, romelic miiReba bolcmanis gantolebis amoxsniT dabali temperaturebisas da bmis mudmivas rogorc mcire, aseve didi mniSvnelobis dros. Aarawonasworuli simkvrivis matricis meTodis sirTule mdgomareobs agreTve imaSi, rom arsebobs garkveuli ganusazRvreloba impendansis miaxloebiTi mniSvnelobis SerCevaSi, romelic aiReba maTematikurad aramkacri mosazrebebisa da fizikis TvalsazrisiT gonivruli aproqsimaciis ganxilvaSi. saerTo jamSi unda iTqvas, rom fxip-is mier napovni eleqtrogamtarobis tenzoris gamosaxuleba ZiriTadad sworad da erTiani TvalsazrisiT misaRebad aRwers polaronul efeqtebs optikaSi, galvanomagnitur movlenebs da ciklotronul rezonans myari sxeulebis fizikaSi da sxv.

rogorc ukve aRniSnuli iyo sadisertacio naSromis SesavalSi, eleqtronuli da polaronuli gadatanis movlenebis gamosakvlevad naxevargamtarebsa da ionur kristalebSi, garda bolcmanis kinetikuri gantolebisa da zemoTmoyvanili midgomebisa da meTodebisa, SesaZlebelia gamoyenebuli iqnas sruliad gansxvavebuli (alternatiuli) midgoma, romelic dafuZnebulia kubos wrfivi gamoZaxilis Teoriaze [4,64,72-73]. am midgomis farglebSi araviTari SezRudva ar edeba eleqtronis gabnevis aqtebs (gabnevis kveTebs) fononebze, gansxvavebiT bolcmaniseuli aRwerisagan. magram miuxedavad amisa, eleqtrogamtarobis gamoTvlisas kubos meTodiT warmoiSveba sirTuleebi, romlebic dakavSirebulia ganSladobebTan $s(?)$-eleqtrogamtarobis gaSlisas mwkrivad eleqtronis urTierTqmedebis hamiltonianis mixedviT fononebTan (gambnevebTan), gareSe eleqtruli velis dabali $?\to 0$ – sixSireebis SemTxvevaSi. susti eleqtron-

fononuri urTierTqmedebis SemTxvevaSic, $s(?)$-eleqtrogamtarobisTvis swori Sedegis misaRebad, rodesac $?\to 0$, aucilebelia ganSladi wevrebisgan Sedgenili usasrulo mwkrivis ajamva [80]. kubos wrfivi reaqciis Teoriam – eleqtronuli da polaronuli gadatanis movlenebis aRsawerad – Semdgomi ganviTareba hpova [91,93-95] SromebSi. [91] naSromSi liuvilis gantolebaze dayrdnobiT da proeqciuli operatoris meTodis gamoyenebiT, eleqtron-fononuri sistemisTvis miRebuli iyo eleqtrowinaRobis zogadi formula. SeSfoTebis Teoriis gamoyenebiTa da Sesabamisi miaxloebebis ganxilviT (e.w. kenkre-drezdenis aproqsimacia) am zogadi gamosaxulebidan napovni iyo eleqtrowinaRobis (impendansis) miaxloebiTi formula. mogvianebiT [101]-naSromSi naCvenebi iyo, rom kenkre-drezdenis aproqsimacia impendansisTvis da kubos formulisTvis ekvivalenturia fxip-is mier gamoyvanili impendansis (eleqtrowinaRobis) miaxloebiTi mniSvnelobisa susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi. kubos wrfivi gamoZaxilis Teoria da proeqciuli operatoris meTodi [94]-naSromSic gamoyenebuli iyo eleqtruli winaRobis Teoriis asagebad. miRebuli iyo zogadi gamosaxuleba eleqtrowinaRobisTvis da naCvenebi iyo, rom iseve rogorc eleqtrogamtarobisTvis, eleqtrowinaRobis swori mniSvnelobis misaRebad aucilebelia calkeuli wevrebisgan Sedgenili usasrulo mwvrivis ajamva. zogadi saxiT dadgenili iyo martivi kavSiri kompleqsur eleqtrogamtarobasa da impendans Soris. [95]-naSromSi kubos Teoriisa, fonneimanis gantolebisa da cvancigis tipis proeqciuli operatoris daxmarebiT miRebuli iyo araerTgvarovani ZiriTadi kinetikuri gantoleba, romelic saSualebas iZleoda gamoZaxilis funqciis povnisa kubos formalizmSi. gamoyvanili iyo agreTve formulebi ganzogadoebuli amTviseblobisa da eleqtrogamtarobisTvis. ZiriTadi kinetikuri gantolebis daxmarebiT napovni iyo bolcmanis tipis gantoleba pirveli momentisTvis, romelic Seicavda rogorc disipaciur, aseve nakadisebr wevrebs.

kubos formalizmi da grinis funqciaTa meTodi [83], [93] naSromSi gamoyenebuli iyo polaronis dabaltemperaturuli Zvradobis gamosaTvlelad SeSfoTebis Teoriis meoTxe miaxloebaSi. avtorTa mier am naSromSi, eleqtronis siCqaris drois ormomentiani korelaciuri funqcia gamosaxuli iqna grinis ornawilakovani funqciis saSualebiT, xolo grinis ornawilakovani funqcia warmodgenili iqna grinis erTnawilakovani

funqciisa da eleqtron-fononuri urTierTqmedebis mixedviT mwkrivis saxiT. sabolood, maT mier napovni dabaltemperaturuli Zvradobis mniSvneloba iZleoda karg miaxloebas [55]-naSromSi miRebul polaronis dabaltemperaturuli Zvradobis sididesTan, rodesac $\alpha<1$. grinis funqciaTa meTodi da kubos wrfivi reaqciis Teoria polaronis Zvradobis gamosaTvlelad ganxiluli iyo agreTve [96] naSromSi. am naSromSi kubos formalizmisa da ornawilakovani temperaturuli grinis funqciis daxmarebiT, SeSfoTebis Teoriisa da feinmanis diagramuli teqnikis wesebis gamoyenebiT, napovni iyo eleqtronis dabaltemperaturuli Zvradobis mniSvneloba, am ukanasknelis rogorc polarul optikur fononebze, aseve akustikur fononebze gabnevisas susti eleqtron-fononuri bmis SemTxvevaSi. avtoris mier, eleqtronis dreifuli Zvradobis aRmwer dajaxebiT integralebSi, nawilobriv ajamuli iyo mniSvnelovani wevrebi SeSfoTebis Teoriis miaxloebis yvela rigis mixedviT feinmanis diagramis wverosaTvis (vertex terms, ladder diagrams). naCvenebi iyo, rom am wevrTa wvlili mniSvnelovania eleqtronis gabnevisas akustikur (piezoeleqtrul) fononebze. dadgenili iyo agreTve, rom eleqtronis Zvradobis gamoTvlisas polarul optikur fononebze gabnevisas, es wevrebi ar TamaSoben mniSvnelovan rols dabali temperaturebis dros. [96]-naSromSi faqtiurad dadasturebuli iqna [93]-naSromi miRebuli Sedegebis marTebuloba eleqtronis dabaltemperaturuli dreifuli Zvradobis yofaqcevis Sesaxeb.

rogorc ukve iyo aRniSnuli, mravali gamokvleva iqna Catarebuli bolcmanis kinetikuri gantolebis miRebaze polaronis feinmanis modelSi da am gantolebaze dayrdnobiT polaronis dreifuli Zvradobis gamoTvlaze. [97]- naSromSi feinmanis modelisTvis gamoyvanili bolcmanis gantoleba gamoyenebuli iyo polaronis dabaltemperaturuli Zvradobis gamosaTvlelad. bolcmanis gantolebis daxmarebiT polaronis dreifuli Zvradoba feinmanis modelSi ganxiluli da gamoTvlili iyo [51-52,98] SromebSic. [51]- naSromSi miRebuli iyo bolcmanis gantoleba, napovni iyo statikuri da dinamiuri (sixSireze damokidebuli) dreifuli Zvradobebi da dadasturebuli iyo [97]- naSromSi miRebuli Sedegis samarTlianoba polaronis dabaltemperaturuli statikuri ZvradobisTvis. [98]- naSromSi, iseve rogorc [97]- naSromSi, bolcmanis gantolebis gamoyvanisas, ganxiluli da gaanalizebuli iyo polaronis drekadi gabnevis procesi

fononebze, e.w. polaronis rezonansuli urTierTqmedeba (gabneva) fononebTan, da am procesis gaTvaliswinebiTa da bolcmanis gantolebis amoxsniT, napovni iyo dabaltemperaturuli Zvradobis mniSvneloba polaronisTvis. [52]- naSromSi, polaronis Zvradoba feinmanis modelSi gamoTvlili iyo sasruli temperaturebisa da arasusti eleqtron-fononuri bmis SemTxvevaSi. [52]- naSromi faqtiurad warmoadgenda [51,55-56] Sromebis (osakas Sedegebis) ganzogadoebas – oRond gansxvavebiT yvela sxva zemoT miTiTebuli naSromebisgan, am naSromSi bolcmanis gantoleba amoxsnili iyo variaciuli meTodis gamoyenebiT (zemoTaRniSnul SromebSi bolcmanis gantolebis amosaxsnelad ZiriTadad gamoiyeneboda relaqsaciis drois miaxloeba, an am meTodis esa Tu is modificirebuli forma). ricxviTi gamoTvlebi Catarebuli iyo TlBr-kristalebis nimuSTa monacemebis mixedviT da karg Tanxvedrasi iyo eqsperimentis SedegebTan. aqve unda aRiniSnos, rom zemoTmoyvanil naSromebSi da saerTod kinetikuri gantolebis meTodSi, bolcmanis gantolebis amoxsnisas (saubaria gawrfivebul gantolebaze) gamoiyeneba sxvadasxva saxis miaxloebebi (ix. mag. [106]), da amitom eleqtronis da polaronis dabaltemperaturuli ZvradobebisTvis miRebuli mniSvnelobebi ar aris Tanmimdevruli da zusti. zogadad Zalian rTulia mkafiod dadgindes bolcmaniseuli midgomis gamoyenebis sazRvrebi saSualo da Zlieri eleqtron-fononuri bmis SemTxvevebSi. mosalodnelia, rom es midgoma samarTliani iqneba kristalis dabali temperaturebis dros, rodesac dajaxebaTa xangrZlivobis dro (romelic aris $\hbar b = \hbar / K_B \mathrm{T}$-s rigis) bevrad naklebia t-relaqsaciis droze. variaciuli meTodi [106]- bolcmanis kinetikuri gantolebis amosaxsnelad polaronis frolixis modelSi ganixileboda agreTve [99]- naSromSi. gamoTvlili iyo frolixis polaronis dabaltemperaturuli dreifuli Zvradobis sidide, romelic emTxveoda relaqsaciis drois miaxloebaSi frolixis mier napovn dabaltemperaturuli statikuri Zvradobis mniSvnelobas polaronisTvis [43]. amrigad, rogorc zemoTmoyvanili naSromebis mimoxilva gviCvenebs, arsebobs arsebiTi gansxvaveba polaronis Zvradobis mniSvnelobebs Soris, romelic erTis mxriv miiReba bolcmanis gantolebis amoxsnisas relaqsaciis drois miaxloebaSi da meores mxriv feinmanis meTodis – integralebi traeqtoriebis gaswvriv gamoyenebisas polaronis frolixisa da feinmanis modelebSi [100]. susti gareSe

eleqtruli velebisa da susti eleqtron-fononuri bmis SemTxvevaSi, polaronis Zvradobis gamoTvlisas relaqsaciis drois miaxloeba SedarebiT ufro realuri Cans, vidre balansis gantolebis meTodi [84-85,100]. [84,88] -naSromebSi polaronis Zvradoba gamoTvlili iyo feinmanis meTodiT – integralebi traeqtoriebis gaswvriv, xolo [15,85,101] SromebSi Zvradobis gamoTvlisas gamoiyeneboda eleqtronis impulsebis mixedviT maqsvelis wanacvlebuli ganawilebis funqcia. [101] - naSromSi naCvenebi iyo, rom meTodebi romlebic ganviTarebuli da gamoyenebuli iyo [91-92,84,88] SromebSi, susti eleqtron-fononuri bmisa da susti gareSe eleqtruli velebis SemTxvevaSi, polaronis dabaltemperaturuli ZvradobisTvis iZleodnen faqtiurad erTnair mniSvnelobebs; rac Seexeba gamoTvlebs, romlebic dafuZnebulia bolcmanis kinetikuri gantolebis gamoyenebaze, optikuri polaronis dabaltemperaturuli dreifuli ZvradobisTvis mivyavarT sxva mniSvnelobebTan. [97,100]. kritikuli analizi, polaronis ZvradobisTvis miRebuli sxvadasxva mniSvnelobebis Tanxvdenis Sesaxeb, Catarebuli iyo [102,103]- SromebSi, da dadgenili iyo, rom optikuri polaronis Zvradobis sidide damokidebulia zRvruli gadasvlebis $\alpha\to 0$, $?\to 0$ operaciebis Tanmimdevrobaze (am SromebSi naCvenebi iyo, rom zRvruli gadasvlebis swori Tanmimdevrobaa: $\lim_{\alpha\to 0}\lim_{\omega\to 0}$).

polaronis fgm-Si[57-58]-bolcmanis tipis kinetikuri gantoleba Zlieri eleqtron-fononuri bmisa da kristalis dabali temperaturebis SemTxvevaSi, miRebuli iyo [70-71]- SromebSi. bolcmanis gantolebis miRebisas, avtorebi eyrdnobodnen maT mier [68-69]- naSromebSi gamoyvanil Caketil kinetikur gantolebas qvesistemis (polaronis) statistikuri operatorisaTvis, romelic napovni iyo Sfm-Si. Gganixileboda mcire siCqariT moZravi polaroni dabali temperaturebis dros da miRebuli iyo kinetikuri gantoleba qvesistemis statistikuri operatoris, rogorc diagonaluri matriculi elementisaTvis (polaronis ganawilebis funqciisTvis, polaronis ZiriTadi mdgomareobisTvis), aseve aradiagonaluri matriculi elementebisaTvis (polaronis agznebuli, gadagvarebuli mdgomareobebisTvis). rac Seexeba TviT sakuTriv polaronis Zvradobas, igi gamoTvlili ar iyo am modelSi. aqve, erTxel kidev unda aRiniSnos da xazi gaesvas im garemoebas, rom TviT bolcmanis kinetikuri gantolebis sxvadasxva meTodebiT gamoyvanisas da misi amoxsnisas gamo-

iyeneba sxvadasxva saxis miaxloebebi, da amitom eleqtronis da polaronis Zvradobis Tanmimdevruli da koreqtuli gamoTvlis problema sxvadasxva modelSi moiTxovs Semdgomi damatebiTi gamokvlevebis Catarebas.

kovalentur (araionur) kristalebSi, magaliTad germaniumisa da siliciumis tipis naxevargamtarebSi, eleqtronebis urTierTqmedeba fononebTan aRiwereba deformaciis potencialis meTodiT, romelic moqmedebs zonur eleqtronze da romelic warmoadgens axlomqmed SeSfoTebas kristalis perioduli potencialisTvis [39,42,107]. eleqtronis moZraobis SeSfoTeba, gamowveuli am urTierTqmedebiT, warmoadgens kvazinawilakis gabnevas deformaciis potencialze. Tavisi bunebidan gamomdinare, es urTierTqmedeba damaxasiaTebelia yvela naxevargamtarebis-Tvis da saerTod myari sxeulebisTvis. rogorc cnobilia, eleqtronis urTierTqmedeba (gabneva) akustikur fononebTan SesaZlebelia iyos rogorc susti, aseve Zlieri [41,104]. eleqtronis susti urTierTqmedebisas akustikur fononebTan, eleqtronis gadaadgilebas kovalenturi kristalebis gamtarobis zonaSi Tan axlavs kristalis lokaluri deformaciis gadanacvleba, romelic aRiwereba SeSfoTebis Teoriis enaze, rogorc eleqtronis mier virtualuri fononebis gamosxivebisa da STanTqmis procesi; xolo kristalebSi, romlebsac gaaCniaT mcire drekadobis modulebi da gamtarobis zonaSi eleqtronebis didi efeqturi masebi – eleqtronis urTierTqmedeba grZiv akustikur fononebTan aris Zlieri, rasac mivyavarT kristalis lokalur deformaciasTan, romelic sakmarisia potencialuri ormos warmosaqmnelad da romelSiac eleqtroni asrulebs stacionarul moZraobas diskretuli energiiT (e.w. akustikuri polaronis modeli) [39,41-42,104-105]. Aakustikuri polaronis modelTan, da saerTod kvazinawilakis lokalizaciis problemasTan myar sxeulebSi, mWidrod aris dakavSirebuli sakiTxi eleqtronis e.w. TviTCaWerisa, romelic gamowveulia Zlieri eleqtron-fononuri urTierTqmedebiT [41-42,104-105]. akustikuri polaronis modeli – feinmanis meTodiT, integralebi traeqtoriebis gaswvriv – Seswavlili iyo [41,104-105] SromebSi. dadgenili iyo, rom Zlieri eleqtron-fononuri bmis SemTxvevaSi adgili aqvs eleqtronis TviTCaWeras, romelic ganpirobebulia deformaciis potencialiT gamowveuli axlomqmedi urTierTqmedebiT. saerTod unda aRiniSnos, rom eleqtronebis TviTCaWeris amocanis Seswavlas didi mniSvneloba aqvs eleqtronuli

(polaronuli) gadatanis movlenebis aRsawerad myar sxeulebSi, vinaidan kristaluri mesris deformaciis Sedegad TviTCaWerili kvazinawilaki ar iZleva wvlils eleqtrogamtarobaSi (ZvradobaSi).

susti eleqtron-fononuri bmis SemTxvevaSi, eleqtronuli gadatanis movlenebis Sesaswavlad akustikuri polaronis modelSi kristalis dabali temperaturebis dros, gamoiyeneba kinetikuri (bolcmanis) gantolebis meTodi. dabali temperaturebisas eleqtronis Zvradoba ZiriTadad ganisazRvreba misi gabneviT kristalSi arsebul minarevebze da akustikur fononebze. sufTa kristalebSi dabali temperaturebisas- rodesac optikuri fononebi sustad arian aRgznebuli – dominirebs eleqtronis gabneva akustikur fononebze. eleqtronis urTierTqmedebis energia grZeltalRovan grZiv akustikur fononebTan mcire sididisaa, vidre misi urTierTqmedebis energia polarul optikur fononebTan da, garda amisa, eleqtronis energiis cvlileba akustikur fononebze gabnevisas, warmoadgens mcire sidides (kvazidrekadi gabneva). amis gamo, eleqtronis gabneva akustikur fononebze SesaZlebelia ganxilul iqnas relaqsaciis drois miaxloebaSi [29,32-33,107]. vinaidan am SemTxvevaSic bolcmanis kinetikuri gantolebis amoxsnisas gamoiyeneba sxvadasxva saxis miaxloeba (magaliTad, Sfm), eleqtronis Zvradobis gamoTvla mis akustikur fononebze gabnevisas, moiTxovs damatebiTi gamokvlevebis Catarebas [29,108].

sadisertacio naSromSi ganviTarebulia da gamoyenebulia midgoma, eleqtronuli da polaronuli gadatanis movlenebis gamosakvlevad kvanturi dinamiuri sistemebis zemoTmoyvanili modelebisTvis (romlebic urTierTqmedeben fononur velTan), romelic damyarebulia kubos wrfivi gamoZaxilisa da SeSfoTebis Teoriaze [109-122, 125].

mowesrigebul operatorTa formalizmi da proeqciuli operatoris meTodi, T-namravlTa meTodi (teqnika) da fononuri (bozonuri) operatorebis gamoricxvis procedura wonasworuli, droiTi korelaciuri funqciebisaTvis aRwerili da gamoyenebuli iqneba sadisertacio naSromis II da III TavSi. III TavSi ganxilulia eleqtronuli da polaronuli gadatanis movlenebis sakiTxebi kvantur disipaciur sistemebSi – eleqtron-fononur sistemaSi, polaronis frolixis modelSi, akustikuri polaronis modelSi, polaronis fgm-Si– dafuZnebuli kubos wrfivi gamoZaxilis Teoriaze; kerZod, III TavSi gamoTvlilia eleqtronuli da po-

laronuli gadatanis meqanikuri (kinetikuri) koeficientebi (Zvradoba, eleqtrogamtaroba) zemoT miTiTebul modelebSi, zemoT naxseneb formalizmsa da meTodze, da korelaciuri funqciebisaTvis ganzogadoebul kvantur kinetikur gantolebebze dayrdnobiT.

Tavi II. ganzogadoebuli kvanturi evoluciuri gantolebebidrois ormomentiani wonasworuli korelaciuri funqciebisa da grinis funqciebisTvis dinamiuri qvesistemisa, romelic urTierTqmedebs TermostatTan (bozonur velTan)

2.1. mowesrigebul operatorTa formalizmi da T-namravlTa meTodi

ganvixiloT mcire dinamiuri qvesistema s, romelic urTierTqmedebs bozonur (fononur) velTan S. mTliani (s + S) sistemis hamiltoniani aviRoT Semdegi saxiT:

$$H = H_s + H_\Sigma + H_{\text{int.}}, \tag{2.1}$$

sadac H_s aris s qvesistemis sakuTari hamiltoniani; H_Σ- warmoadgens bozonuri (fononuri) velis hamiltonians; xolo $H_{\text{int.}}$- aris s qvesistemis urTierTqmedebis hamiltoniani – bozonur velTan.

$$H_\Sigma = \sum_k \hbar w(k) b_k^+ b_k; \quad H_{\text{int.}} = \sum_k \left[C_k(s) b_k + C_k^+(s) b_k^+ \right], \tag{2.2}$$

$C_k(s)$ da $C_k^+(s)$ – warmoadgenen operatorebs, romlebic miekuTvnebian s qvesistemas. mTliani (2.1) – hamiltoniani ar aris damokidebuli droze. A_s, B_s .... aRvniSnoT operatorebi Sredingeris warmodgenaSi, romlebic damokidebuli arian mxolod s qvesistemis dinamiur cvladebze da romlebic ar arian damokidebuli droze. operatorebi, romlebic damokidebuli arian mxolod s-is an S-s cvladebze, komutireben erTmaneTTan. bozonuri (fononuri) sistema S ganixileba rogorc Termostati. davuSvaT, rom $A_s(t)$ da $B_s(t)$ – warmoadgenen s qvesistemis operatorebs haizenbergis warmodgenaSi:

$$A_S(t) = e^{\frac{i}{\hbar}Ht} A_S e^{\frac{-i}{\hbar}Ht}; \qquad B_S(t) = e^{\frac{i}{\hbar}Ht} B_S e^{\frac{-i}{\hbar}Ht};$$

am operatorebis sawyisi mniSvnelobebisaTvis gveqneba

$$A_s = A_s(t)\big|_{t=0}, \quad B_s = B_s(t)\big|_{t=0}$$

drois ormomentiani wonasworuli korelaciuri funqciebi da grinis funqciebi (dagvianebuli, winmswrebi da mizezobrivi) ganisazRvrebian Semdegi tolobebiT (ix. mag. [25,34,64]).

$$F_{A_s B_s}(t-t) = < A_s(t) B_s(t) >.$$

$$G^r(t-t) = q(t-t) < \left[A_s(t) B_s(t) \right]_h >;\ G^a(t-t) = -q(t-t) < \left[A_s(t) B_s(t) \right]_h >$$

$$G^c(t-t) = \frac{1}{i\hbar} < T_h \left\{ A_s(t) B_s(t) \right\} >, \qquad (2.3)$$

sadac: $q(x) = \begin{cases} 1; x > 0 \\ 0; x < 0 \end{cases}$; $\left[A_s(t) B_s(t) \right]_h = A_s(t) B_s(t) - h B_s(t) A_s(t)$;

$$T_h \left\{ A_s(t) B_s(t) \right\} = q(t-t) A_s(t) B_s(t) + h q(t-t) B_s(t) A_s(t).$$

$h = 1$ - boze operatorebisaTvis da $h = -1$ Ffermi operatorebisaTvis, da

$$< \ldots >= Z^{-1}(b) SP_{s\Sigma}(e^{-bH} \ldots);\ b^{-1} = k_B T, \qquad (2.4)$$

sadac: $Z(b) = SP_{s\Sigma}(e^{-bH})$ - warmoadgens statjams mTeli (s + S) sistemisaTvis; k_B - aris bolcmanis mudmiva; T - absoluturi temperatura, xolo $\hbar$ –plankis mudmiva; gasaSualoeba (2.4) formulaSi xorcieldeba gibsis kanonikuri ansamblis wonasworuli statistikuri operatoris mixedviT.

ganixileba Semdegi saxis zogadi amocana [109-113] – agebuli unda iqnas Teoria, romlis saSualebiTac SesaZlebeli iqneba miviRoT zusti, ganzogadoebuli (albaT araCaketili), kvanturi evoluciuri (kinetikuri) gantolebebi drois ormomentiani wonaworuli korelaciuri da grinis funqciebisaTvis A_s da B_s – operatorebisaTvis, s – dinamiuri qvesistemisaTvis, romelic urTierTqmedebs S sistemasTan – bozonur velTan. am Teoriis agebisas, gamoyenebuli unda iqnas mowesrigebul operatorTa meTodi [5-6,59-61], (s + S) -sistemis (2.1) hamiltonianis cxadi saxe da gibsis kanonikuri ansamblis statistikuri operatori. gamoviyvanoT jer ganzogadoebuli kvanturi, evoluciuri gantoleba wonasworuli korelaciuri funqciisaTvis:

$$F_{B_s A_s}(t) = < B_s(t) A_s > = < B_s A_s(-t) >. \qquad (2.5)$$

dasmuli amocanis gadasawyvetad CavweroT (2.5) korelaciuri funqcia Semdegi saxiT:

$$< B_s(t) A_s > = Z^{-1}(b) SP_{s\Sigma} \left[e^{-bH} B_s(t) A_s \right] = Z^{-1}(b) SP \left[A_s G_{B_s}(t,b) \right] \qquad (2.6)$$

(2.6) formulaSi, Cven SemoviReT damxmare operatori $G_{B_s}(t,b)$, romelic ganisazRvreba tolobiT:

$$G_{B_s}(t,b) = SP_{\Sigma} \left[e^{-bH} B_s(t) \right]. \qquad (2.7)$$

Tu gavawarmoebT (2.5) – korelaciur funqcias t-droiTi cvladis mixedviT, maSin Cven miviRebT gantolebas, romelic gansazRvravs mis evolucias droSi:

$$\frac{\partial}{\partial t}F_{B_sA_s}(t)=\frac{i}{\hbar}<[H,B_s(t)]_-\cdot A_s>, \qquad (2.8)$$

sadac [...,...] – warmoadgens komutatoris agebuls ori operatorisagan.

ganvsazRvroT, agreTve evoluciis wrfivi operatorebi: $W^+(t,0)$, $W(t,0)$, $W^+(b,0)$, $W(b,0)$ - Semdegi Tanafardobebi T:

$$\begin{aligned} e^{\frac{i}{\hbar}Ht}&=W^+(t,0)e^{\frac{i}{\hbar}H_0t}, \quad e^{-\frac{i}{\hbar}Ht}=e^{-\frac{i}{\hbar}H_0t}W(t,0),\\ e^{-bH}&=W^+(b,0)e^{-bH_0}, \quad e^{-bH}=e^{-bH_0}W(b,0) \end{aligned}, \qquad (2.9)$$

sadac: $H_0=H_s+H_\Sigma$.

Tu SemoviRebT T-namravlTa cnebas [5-6], maSin es operatorebi formalurad SesaZlebelia warmovadginoT Semdegi saxiT:

$$W^+(t,0)=\begin{cases} \mathrm{T}_a\exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}(t)\right] & t>0\\ \mathrm{T}\exp\left[-\frac{i}{\hbar}\int_t^0 dt\,\tilde{H}_{\mathrm{int}}(t)\right] & t<0 \end{cases}$$

$$W(t,0)=\begin{cases} \mathrm{T}\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}(t)\right] & t>0\\ \mathrm{T}_a\exp\left[\frac{i}{\hbar}\int_t^0 dt\,\tilde{H}_{\mathrm{int}}(t)\right] & t<0, \end{cases} \qquad (2.10)$$

sadac: $\tilde{H}_{\mathrm{int}}(t)=e^{\frac{i}{\hbar}H_0t}H_{\mathrm{int}}e^{-\frac{i}{\hbar}H_0t}$ da:

$$W^+(b,0)=\mathrm{T}_a\exp\left[-\int_0^b dl\,\tilde{H}_{\mathrm{int}}(l)\right];\quad b>0$$

$$\tilde{H}_{\mathrm{int}}(l)=e^{-lH_0}H_{\mathrm{int}}e^{lH_0}$$

$$W(b,0)=\mathrm{T}\exp\left[-\int_0^b dl\,\tilde{H}_{\mathrm{int}}(l)\right];\quad b>0 \qquad (2.11)$$

$$\tilde{H}_{\mathrm{int}}(l)=e^{lH_0}H_{\mathrm{int}}e^{-lH_0}$$

am operatorebis sawyisi mniSvnelobebisaTvis gveqneba:

$$W^+(t,0)\big|_{t=0}=W(t,0)\big|_{t=0}=1;\quad W^+(b,0)\big|_{b=0}=W(b,0)\big|_{b=0}=1.$$

SemoRebul operatorebs gaaCniaT agreTve jgufuri Tvisebebi:

$$W^+(t,0)=W(0.t)=W^{-1}(t,0);\qquad W(t,t)W(t,0)=W(t,0) \qquad (2.12)$$

da $W^{+}(b,0)=W(0,b)=W^{-1}(b,0);\ \ W(b,l)W(l,0)=W(b,0)$

nebismieri t, t da b, l ($b>0$, $l>0$) mniSvnelobebisaTvis.

(2.10) formulebSi T - qronologiurad mowesrigebis simboloa (operatorTa mowesrigeba xdeba drois mixedviT marjvenidan marcxniv drois momentis zrdasTan erTad, rodesac t>0), xolo T_a - warmoadgens antiqronologiurad mowesrigebis simbolos drois mixedviT (operatorTa mowesrigeba xdeba drois mixedviT marcxnidan marjvniv drois momentis zrdasTan erTad, rodesac t>0). analogiurad, (2.11) formulebSi T da T_a warmoadgens qronologiurad da antiqronologiurad mowesrigebis simboloebs operatorebisaTvis l temperaturuli cvladis mixedviT. unda aRiniSnos, rom $W^{+}(t,0)$, $W(t,0)$, $W^{+}(b,0)$, $W(b,0)$ operatorebisaTvis droiTi da temperaturuli cvladebi $\tilde{H}_{\mathrm{int}}(t)$ da $\tilde{H}_{\mathrm{int}}(l)$ operatorebs aniWeben ara marto raRac mniSvnelobebs, aramed gansazRvraven agreTve maT mowesrigebul Tanmimdevrobas T namravlebSi.

Tu gamoviyenebT $W(t,0)$, $W^{+}(t,0)$ da $W(b,0)$ evoluciis operatorebs, maSin $G_{Bs}(t,b)$ operatori SesaZlebelia warmovadginoT Semdegi saxiT:

$$\begin{aligned} G_{Bs}(t,b) &= S\mathrm{P}_{\Sigma}\left[e^{-bH_0}W(b,0)W(t,0)B_{SH_s}(t)W(t,0)\right]= \\ &= e^{-bH_s}SP_{\Sigma}\left[e^{-bH_{\Sigma}}W(b,0)W^{+}(t,0)B_{SH_s}(t)W(t,0)\right]= \\ &= Z_{\Sigma}(b)e^{-bH_s}\mathrm{P}_{\Sigma}(b)\left[W(b,0)W^{+}(t,0)B_{SH_s}(t)W(t,0)\right] \end{aligned} \quad , \qquad (2.13)$$

sadac: $P_{\Sigma}(b)...=Z_{\Sigma}^{-1}(b)S\mathrm{P}_{\Sigma}\left[e^{-bH_{\Sigma}}...\right]$ - warmoadgens bozonuri velis mdgomareobebis mixedviT gasaSualoebis operators (proeqciul operators); $Z_{\Sigma}(b)$ - bozonuri velis statjamia da $B_{sH_s}(t)$ operatori ganisazRvreba Semdegi formuliT:

$$B_{sH_s}(t)=e^{\frac{i}{\hbar}H_s t}B_s e^{-\frac{i}{\hbar}H_s t}. \qquad (2.14)$$

cxadia, rom adgili aqvs Tanafardobas:

$$B_{sH_0}(t)=B_{sH_s}(t),\ \text{sadac}\ B_{sH_0}(t)=e^{\frac{i}{\hbar}H_0 t}B_s e^{-\frac{i}{\hbar}H_0 t}.$$

SemoviRoT axla specialuri operacia, romelic aRiniSneba simboloTi $\mathrm{T}^{L,R,s}_{F_s(t)}$ (ix. mag. [5-6,109]). $\mathrm{T}^{L,R,s}_{F_s(t)}$ operacia garkveuli wesiT awesrigebs operatorTa namravls, romelic Sedgeba erTi $F_s(t)$- operatorisagan da mis

gverdiT mdgomi $A_j(t_j, s)$ da $A_k(b_k, s)$ operatorebisagan. $t_1, t_2, \ldots t_n$ warmoadgenen $(0,t)$-droiTi intervalis sxvadasxva wertilebs. ($j = 1,2,\ldots n$), da $b_1, b_2, \ldots b_m$ arian $(0, b)$ – temperaturuli intervalis sxvadasxva wertilebi ($k = 1,2,\ldots m$).

vTqvaT simbolo aRniSnavs erTi $F_s(t)$ operatoris namravls sxva $A_j(t_j, s)$ ($j = 1,2,\ldots n$) da $A_k(b_k, s)$ ($k = 1,2,\ldots m$) operatorebze, romlebic aRniSnuli (moniSnuli) arian indeqsebiT: L (left) da R (right).

aRniSnuli operatorebis Tanmimdevruli ganlageba -Si nebismieria.

$$t_j \in (o,t);\ \ j \in 1,2,\ldots,n;\ b_k \in (o,b);\ k \in 1,2,\ldots m.$$

operacia $\mathrm{T}^{L,R,s}_{F_s(t)}$ ganisazRvreba Semdegnairad: yvela $A^L_j(b_j, s)$ – operatoris movaTavsebT $F_s(t)$ – operatoris marcxniv da ganvalagebT anti-qronologiurad droiTi momentebis mixedviT; yvela $A^L_k(b_k, s)$ operators movaTavsebT $A^L_j(t_j, s)$ operatorTa marcxniv da ganvalagebT qronologiuri wesis mixedviT da bolos yvela $A^R_{j'}(t_{j'}, s)$ - ($j' = 1,2,\ldots$) operators movaTavsebT marjvniv $F_s(t)$ operatoridan da ganvalagebT qronologiurad droiTi momentebis mixedviT. am proceduris Sesrulebis Semdeg CamovacilebT L da R indeqsebs.

amrigad, am gansazRvris Tanaxmad Cven gveqneba

$$T^{L,R,s}_{F_s(t)} = T\left[\prod_k A^L_k(b_k, s)\right] \times T_a\left[\prod_j A^L_j(t_j, s)\right] \times F_s(t) T\left[\prod_{j'} A^R_{j'}(t_{j'}, s)\right] \qquad (2.15)$$

cxadia, rom $\mathrm{T}^{L,R,s}_{F_s(t)}$ operaciis niSnis qveS, Semavali yvela operatori SegviZlia gadavanacvloT nebismierad ise, rom ar SevcvaloT Sedegi – TiTqos es operatorebi warmoadgendnen C sidideebs – vinaidan TviT es operacia avtomaturad amyarebs wesrigs sabolood operatorTa ganlagebaSi. Cvens mier SemoRebuli operacia bunebrivad SegviZlia agreTve ganvazogadod operatorebisagan Sedgenil transcendentul funqcionalebzec. unda aRiniSnos, rom Cvens mier SemoRebuli specialuri operacia $T^{L,R,s}_{F_s(t)}$ warmoadgens adre SemoRebuli $\mathrm{T}^{F}_{s(L)s(R)}$ operaciis bunebriv ganzogadoebas droiT da temperaturul intervalebze [5-6,109,111-113].

axla ganvixilOT (2.13) formula da CavweroT is Semdegi saxiT:

$$G_{B_s}(t,b) = Z_\Sigma(b)\, e^{-bH_s} \tilde{G}_{B_s}(t,b): \quad t>0$$

sadac:

$$\begin{aligned}
&G_{Bs}(t,b) = \mathrm{P}_\Sigma(b)\left[W(b,0)W^+(t,0)B_{sH_s}(t)W(t,0)\right] = \\
&= P_\Sigma(b)\left\{\mathrm{T}\exp\left[-\int_0^b dl\,\tilde{H}_{\mathrm{int}}(l)\right]\cdot \mathrm{T}_a \exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}(t)\right]\cdot B_{sH_s}(t)\times\right. \\
&\left.\times\mathrm{T}\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}(t)\right]\right\} = \mathrm{T}^{L,R,S}_{B_{sHs}}(t)\left\{\mathrm{P}_\Sigma(b)\left[\mathrm{T}_\Sigma \exp\left[-\int_0^b dl\,\tilde{H}^L_{\mathrm{int}}(l)\right]\times\right.\right. \\
&\left.\left.\times\mathrm{T}_{a\Sigma}\exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^L_{\mathrm{int}}(t)\right]\cdot B_{sH_s}(t)\mathrm{T}_\Sigma \exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^R_{\mathrm{int}}(t)\right]\right]\right\}; \quad t>0
\end{aligned} \tag{2.16}$$

(2.16) formulaSi $\tilde{H}_{\mathrm{int}}(l)$ da $\tilde{H}_{\mathrm{int}}(t)$ operatorebi gansazRvrulia (2.10-2.11) tolobebiT: T_Σ da $\mathrm{T}_{a\Sigma}$ simboloebi awesrigeben mxolod im operatorebs, romlebic moqmedeben bozonur (fononur) velis cvladebze. Tu gaviTvaliswinebT (2.10-2.11) tolobebs $\tilde{H}^L_{\mathrm{int}}(l)$ da $\tilde{H}^{L,R}_{\mathrm{int}}(t)$ operatorebisaTvis gveqneba:

$$\begin{aligned}
\tilde{H}^L_{\mathrm{int}}(l) &= \sum_k\left[\tilde{C}^L_{kH_0}(s,l)b_{kH_0}(l) + \tilde{C}^{+L}_{kH_0}(s,l)b^+_{kH_0}(l)\right] \\
\tilde{H}^{L,R}_{\mathrm{int}}(t) &= \sum_k\left[\tilde{C}^{L,R}_{kH_0}(s,t)b_{kH_0}(t) + \tilde{C}^{+L,R}_{kH_0}(s,t)b^+_{kH_0}(t)\right]
\end{aligned} \tag{2.17}$$

sadac:

$$\begin{aligned}
b_{kH_0}(l) &= e^{lH_0}b_k e^{-lH_0} = e^{-l\hbar w(k)}b_k; \\
b^+_{kH_0}(l) &= e^{lH_0}b^+_k e^{-lH_0} = e^{l\hbar w(k)}b^+_k; \\
b_{kH_0}(t) &= e^{\frac{i}{\hbar}H_0 t}b_k e^{\frac{i}{\hbar}H_0 t} = e^{-iw(k)t}b_k; \\
b^+_{kH_0}(t) &= e^{\frac{i}{\hbar}H_0 t}b^+_k e^{-\frac{i}{\hbar}H_0 t} = e^{iw(k)t}b^+_k.
\end{aligned} \tag{2.18}$$

$$\begin{aligned}
\tilde{C}_{kH_0}(s,t) &= \tilde{C}_{kH_s}(s,t) = e^{\frac{i}{\hbar}H_0 t}C_k(s)e^{-\frac{i}{\hbar}H_0 t} = e^{\frac{i}{\hbar}H_s t}C_k(s)e^{-\frac{i}{\hbar}H_s t} \\
\tilde{C}^+_{kH_0}(s,t) &= \tilde{C}^+_{kH_s}(s,t) = e^{\frac{i}{\hbar}H_0 t}C^+_k(s)e^{-\frac{i}{\hbar}H_0 t} = e^{\frac{i}{\hbar}H_s t}C^+_k(s)e^{-\frac{i}{\hbar}H_s t}.
\end{aligned}$$

gamosaxuleba, romelic mocemulia (2.16) formuliT $P_\Sigma(b)$ gasaSualoebis simbolos qveS $\tilde{G}_{Bs}(t,b)$ operatorisaTvis, gamoiTvleba danarTSi miRebul formulis daxmarebiT (ix. danarTi, (1.4) formula). am yvelafris gaTvaliswinebiT gveqneba:

$$\tilde{G}_{B_s}(t,b)=T^{L,R,s}_{B_sH_s}(t)\left\{B_{sH_s}(t)\exp\left[\Phi_{L,R,S}(t,b)\right]\right\},\quad t>0, \tag{2.19}$$

sadac $\Phi_{L,R,S}(t,b)$ funqcionali ganisazRvreba Semdegi gamosaxulebiT:

$$\Phi_{L,R,S}(t,b)=-\frac{1}{\hbar^2}\int_0^t dt\int_0^t dx\sum_k\Big[\big(1+N_k(b)\big)e^{iw(k)(t-x)}\tilde{C}^{L}_{kH_0}(s,x)\times$$

$$\times\tilde{C}^{+L}_{kH_0}(s,t)+N_k(b)e^{-iw(k)(t-x)}\tilde{C}^{+L}_{kH_0}(s,x)\tilde{C}^{+L}_{kH_0}(s,t)\Big]-\frac{1}{\hbar^2}\int_0^t dt\times$$

$$\times\int_0^t dx\sum_k\Big[\big(1+N_k(b)\big)e^{-iw(k)(t-x)}\tilde{C}^{R}_{kH_0}(s,t)\tilde{C}^{+R}_{kH_0}(s,x)+N_k(b)\times$$

$$\times e^{iw(k)(t-x)}\tilde{C}^{+R}_{kH_0}(s,t)\tilde{C}^{R}_{kH_0}(s,x)\Big]+\frac{1}{\hbar^2}\int_0^t dt\int_0^t dx\sum_k\Big[\big(1+N_k(b)\big)\times$$

$$\times e^{-iw(k)(t-x)}\tilde{C}^{L}_{kH_0}(s,t)\tilde{C}^{+R}_{kH_0}(s,x)+N_k(b)e^{iw(k)(t-x)}\tilde{C}^{+L}_{kH_0}(s,t)\times$$

$$\times\tilde{C}^{R}_{kH_0}(s,x)\Big]-\frac{i}{\hbar}\int_0^t dt\int_0^b dl\sum_k\Big[\big(1+N_k(b)\big)e^{w(k)(it-\lambda l)}\tilde{C}^{L}_{kH_0}(s,l)\times$$

$$\times\tilde{C}^{+L}_{kH_0}(s,t)+N_k(b)e^{-w(k)(it-\lambda l)}\tilde{C}^{+L}_{kH_0}(s,l)\tilde{C}^{L}_{kH_0}(s,t)\Big]+\frac{i}{\hbar}\int_0^t dt\times$$

$$\times\int_0^b dl\sum_k\Big[\big(1+N_k(b)\big)e^{w(k)(it-\lambda l)}\tilde{C}^{L}_{kH_0}(s,l)\tilde{C}^{+R}_{k}(s,t)+N_k(b)\times \tag{2.20}$$

$$\times e^{-w(k)(it-\lambda l)}\tilde{C}^{+L}_{kH_0}(s,l)\tilde{C}^{R}_{kH_0}(s,t)\Big]+\int_0^b dg\int_0^g dl\sum_k\Big[\big(1+N_k(b)\big)\times$$

$$\times e^{-\hbar w(k)(g-l)}\tilde{C}^{L}_{kH_0}(s,g)\tilde{C}^{+L}_{kH_0}(s,l)+N_k(b)e^{\hbar w(k)(g-l)}\tilde{C}^{+L}_{kH_0}(s,g)\times$$

$$\times\tilde{C}^{L}_{kH_0}(s,l)\Big];\qquad t>0.$$

aq: $N_k(b)=P_\Sigma(b)\left(b_k^+b_k\right)=\left[e^{b\hbar w(k)}-1\right]^{-1}$ warmoadgens bozonebis (fononebis) Sevsebis ricxvebis saSualo mniSvnelobas k mdgomareobaSi; (2.18) formulebis msgavsad $\tilde{C}_{kH_0}(s,l)$ da $\tilde{C}^{+}_{kH_0}(s,l)$ – operatorebisaTvis gvaqvs Semdegi gamosaxulebebi:

$$\tilde{C}_{kH_0}(s,l)=\tilde{C}_{kH_s}(s,l)=e^{lH_0}C_k(s)e^{-lH_0}=e^{lH_s}C_k(s)e^{-lH_s};$$

$$\tilde{C}^{+}_{kH_0}(s,l)=\tilde{C}^{+}_{kH_s}(s,l)=e^{lH_0}C^{+}_k(s)e^{-lH_0}=e^{lH_s}C^{+}_k(s)e^{-lH_s}.$$

Tu gavawarmoebT (2.19) gamosaxulebas t droiTi cvladis mixedviT da gamoviyenebT (2.16) formulas, maSin martivad vipoviT $\tilde{G}_{B_s}(t,b)$ operatorisaTvis evoluciur gantolebas (moZraobis gantolebas):

da

$$\frac{\partial}{\partial t}\tilde{G}_{B_s}(t,b)=\frac{i}{\hbar}T^{L,R,S}_{B_sH_s(t)}\left\{\left[H_s,B_{sH_s}(t)\right]\exp\left[\Phi_{L,R,S}(t,b)\right]\right\}+$$
$$+T^{L,R,S}_{B_sH_s(t)}\left\{B_{sH_s}(t)\frac{\partial}{\partial t}\Phi_{L,R,S}(t,b)\cdot\exp\left[\Phi_{L,R,S}(t,b)\right]\right\};\ \ t>0$$
$$\frac{\partial}{\partial t}\tilde{G}_{B_s}(t,b)=\frac{i}{\hbar}\mathrm{P}_{\Sigma}(b)\left[W(b,0)W^{+}(t,0)\left[H_s,B_{sH_s}(t)\right]W(t,0)\right]+$$
$$+\frac{i}{\hbar}\mathrm{P}_{\Sigma}(b)\left[W(b,0)W^{+}(t,0)\left[\tilde{H}_{\mathrm{int}}(t),B_{sH_s}(t)\right]W(t,0)\right];\ \ t>0 \qquad (2.21)$$

xolo TviT $\Phi_{L,R,S}(t,b)$ funqcionalis warmoebulisaTvis miviRebT Semdeg gamosaxulebas:

$$\frac{\partial}{\partial t}\Phi_{L,R,S}(t,b)=\frac{1}{\hbar^2}\int_0^t dx\sum_k\left\{\left(1+N_k(b)\right)e^{iw(k)(t-x)}\left[\tilde{C}^{L}_{kH_0}(s,x)\times\right.\right.$$
$$\times\tilde{C}^{+R}_{kH_0}(s,t)-\tilde{C}^{L}_{kH_0}(s,x)\tilde{C}^{+L}_{kH_0}(s,t)\Big]+N_k(b)e^{-iw(k)(t-x)}\left[\tilde{C}^{+L}_{kH_0}(s,x)\times\right.$$
$$\left.\left.\times\tilde{C}^{R}_{kH_0}(s,t)-\tilde{C}^{+L}_{kH_0}(s,x)\tilde{C}^{L}_{kH_0}(s,t)\right]\right\}+\frac{1}{\hbar^2}\int_0^t dx\sum_k\left\{\left(1+N_k(b)\right)\times\right.$$
$$\times e^{-iw(k)(t-x)}\left[\tilde{C}^{L}_{kH_0}(s,t)\tilde{C}^{+R}_{kH_0}(s,x)-\tilde{C}^{R}_{kH_0}(s,t)\tilde{C}^{+R}_{kH_0}(s,x)\right]+N_k(b)\times$$
$$\left.\times e^{iw(k)(t-x)}\left[\tilde{C}^{+L}_{kH_0}(s,t)\tilde{C}^{R}_{kH_0}(s,x)-\tilde{C}^{+R}_{kH_0}(s,t)\tilde{C}^{R}_{kH_0}(s,x)\right]\right\}+\frac{i}{\hbar}\int_0^b dl\times$$
$$\times\sum_k\left\{\left(1+N_k(b)\right)e^{w(k)(it-\hbar l)}\left[\tilde{C}^{L}_{kH_0}(s,l)\tilde{C}^{+R}_{kH_0}(s,t)-\tilde{C}^{L}_{kH_0}(s,l)\tilde{C}^{+L}_{kH_0}(s,t)\right]+\right.$$
$$\left.+N_k(b)e^{-w(k)(it-\hbar l)}\left[\tilde{C}^{+L}_{kH_0}(s,l)\tilde{C}^{R}_{kH_0}(s,t)-\tilde{C}^{+L}_{kH_0}(s,l)\tilde{C}^{L}_{kH_0}(s,t)\right]\right\};\ \ t>0 \qquad (2.22)$$

Tu visargebleblebT (2.16, 2.22) formulebiT, da agreTve $W(t,0)$, $W^{+}(t,0)$, $W(b,0)$ evoluciis wrfivi operatorebis (2.9) gansazRvrebiT da (2.12) jgufuri TvisebebiT, maSin $G_{B_s}(t,b)$ operatorisaTvis evoluciuri gantoleba SesaZlebelia warmovadginoT Semdegi saxiT [109]:

$$\frac{\partial}{\partial t}G_{B_s}(t,b)=\frac{i}{\hbar}SP_\Sigma\left\{e^{-bH}e^{\frac{i}{\hbar}}[H_s,B_s]e^{\frac{i}{\hbar}Ht}\right\}-\frac{1}{\hbar^2}\int_0^t dx\sum_k\{(1+N_k(b))\times$$

$$\times e^{iw(k)x}SP_\Sigma\left[e^{-bH}e^{\frac{i}{\hbar}Ht}C_k(s,-x)C_k^+(s)e^{-\frac{i}{\hbar}Ht}B_s(t)\right]+N_k(b)e^{iw(k)x}\times$$

$$\times SP_\Sigma\left[e^{-bH}e^{\frac{i}{\hbar}Ht}C_k^+(s,-x)C_k(s)e^{-\frac{i}{\hbar}Ht}B_s(t)\right]\Big\}-\frac{1}{\hbar^2}\int_0^t dx\sum_k\{(1+N_k(b))\times$$

$$\times e^{-iw(k)x}SP_\Sigma\left[e^{-bH}B_s(t)e^{\frac{i}{\hbar}Ht}C_k(s)C_k^+(s,-x)e^{-\frac{i}{\hbar}Ht}\right]+N_k(b)e^{iw(k)x}\times \qquad (2.23)$$

$$\times SP_\Sigma\left[e^{-bH}B_s(t)e^{\frac{i}{\hbar}Ht}C_k^+(s)C_k(s,-x)e^{-\frac{i}{\hbar}Ht}\right]\Big\}+\frac{1}{\hbar^2}\int_0^t dx\sum_k\{(1+N_k(b))\times$$

$$\times e^{-iw(k)x}SP_\Sigma\left[e^{-bH}C_k(s,t)B_s(t)e^{\frac{i}{\hbar}Ht}C_k^+(s,-x)e^{-\frac{i}{\hbar}Ht}\right]+N_k(b)e^{iw(k)x}\times$$

$$\times SP_\Sigma\left[e^{-bH}C_k^+(s,t)B_s(t)e^{\frac{i}{\hbar}Ht}C_k(s,-x)e^{-\frac{i}{\hbar}Ht}\right]\Big\}+\frac{1}{\hbar^2}\int_0^t dx\sum_k\{(1+N_k(b))\times$$

$$\cdot e^{iw(k)x}SP_\Sigma\left[e^{-bH}e^{-\frac{i}{\hbar}Ht}C_k(s_1-x)e^{-\frac{i}{\hbar}Ht}B_s(t)C_k^+(s,t)\right]+N_k(b)e^{-iw(k)x}\times$$

$$\times SP_\Sigma\left[e^{-bH}e^{-\frac{i}{\hbar}Ht}C_k^+(s,-x)e^{-\frac{i}{\hbar}Ht}B_s(t)C_k(s,t)\right]\Big\}-\frac{1}{\hbar}\int_0^b dl\sum_k\{(1+N_k(b))\times$$

$$\times e^{-w(k)(it+\hbar l)}SP_\Sigma\left[C_k^+(s,-l)e^{-bH}C_k(s,t)B_s(t)\right]+N_k(b)e^{w(k)(it+\hbar l)}\times$$

$$\times SP_\Sigma\left[C_k(s,-l)e^{-bH}C_k^+(s,t)B_s(t)\right]\Big\}+\frac{i}{\hbar}\int_0^b dl\sum_k\{(1+N_k(b))e^{-w(k)(it+\hbar l)}\times$$

$$\times SP_\Sigma\left[C_k^+(s,-l)e^{-bH}B_s(t)C_k(s,t)\right]+N_k(b)e^{w(k)(it+\hbar l)}SP_\Sigma\left[C_k(s,-l)\times\right.$$

$$\left.\times e^{-bH}B_s(t)C_k^+(s,t)\right]\Big\};\quad t>0$$

(2.23) gantolebaSi Semavali: $C_k(s,\pm x)$, $C_k^+(s,\pm x)$, $C_k(s,-l)$ da $C_k^+(s,-l)$ operatorebi ganisazRvrebian Semdegi tolobebiT:

$$C_k(s,\pm x)=e^{\pm\frac{i}{\hbar}Hx}C_k(s)e^{\pm\frac{i}{\hbar}Hx};\ C_k^+(s,\pm x)=e^{\pm\frac{i}{\hbar}Hx}C_k^+(s)e^{\mp\frac{i}{\hbar}Hx}$$
$$C_k(s,-l)=e^{-lH}C_k(s)e^{lH};\qquad C_k^+(s,-l)=e^{-lH}C_k^+(s)e^{lH}. \qquad (2.24)$$

amrigad, rogorc vxedavT $G_{B_s}(t,b)$ operatorisTvis (2.23) evoluciur gantolebaSi bozonuri amplitudebi ar gvaqvs. bozonuri amplitudebis gamoricxva moxerxda $T^{L,R,S}_{B_sH_s(t)}$ specialuri operaciisa da bozonuri veliT gasaSualoebis $P_\Sigma(b)$ operatoris gamoyenebis Sedegad (naTelia, rom bozonuri cvladebi (amplitudebi) gveqneba $e^{\pm\frac{i}{\hbar}Ht}$ evoluciis operatorebSi

da e^{-bH} gibsis faqtorSi). Semdeg paragrafSi (2.23) evoluciuri gantoleba $G_{B_s}(t,b)$ operatorisaTvis gamoyenebuli iqneba zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebis misaRebad $F_{B_sA_s}(t)$ korelaciuri funqciisTvis da grinis funqciebisTvis [110].

2.2. zusti ganzogadoebuli kvanturi kinetikuri gantolebebi wonasworuli korelaciuri funqciebisa da grinis funqciebisTvis

gamoviyvanoT axla zusti ganzogadoebuli kvanturi kinetikuri gantolebebi korelaciuri funqciebisTvis. amisTvis ganvixiloT (2.6) formula $F_{B_sA_s}(t)$ korelaciuri funqciisTvis da (2.5)-is daxmarebiT CavweroT is Semdegi saxiT:

$$F_{B_sA_s}(t)=\langle B_s(t)A_s\rangle=\langle B_sA_s(-t)\rangle=Z^{-1}(b)SP_s\left[A_sG_{B_s}(t,b)\right]= \\ =Z^{-1}(b)SP_s\left[B_sG_{A_s}(-t,b)\right] \tag{2.25}$$

sadac: $G_{A_s}(-t,b)$ operatorisTvis gansazRvris Tanaxmad gvaqvs Semdegi gamosaxuleba:

$$G_{A_s}(-t,b)=SP_\Sigma\left[A_s(-t)e^{-bH}\right]. \tag{2.26}$$

Tu gavawarmoebT (2.25) Tanafardobas t-droiTi cvladis mixedviT, maSin miviRebT:

$$\frac{\partial}{\partial t}F_{B_sA_s}(t)=\frac{\partial}{\partial t}\langle B_sA_s(-t)\rangle=Z^{-1}(b)SP_s\left[A_s\frac{\partial}{\partial t}G_{B_s}(t,b)\right]= \\ =Z^{-1}(b)SP_s\left[B_s\frac{\partial}{\partial t}G_{A_s}(-t,b)\right] \tag{2.27}$$

Tu CavsvamT (2.27) gantolebaSi $\frac{\partial}{\partial t}G_{B_s}(t,b)$ operatoris gamosaxulebas (2.23) formulidan da visargeblebT $SP_{s,\Sigma}(...)$ operaciis qveS operatorTa cikliuri gadanacvlebis SesaZleblobiT, maSin martivi gamoTvlebis Semdeg vipoviT saZiebel zust, ganzogadoebul kvantur kinetikur gantolebas $\langle B_sA_s(-t)\rangle$ korelaciuri funqciisTvis [110-111,113]:

$$\frac{\partial}{\partial t}\left\langle B_s A_s(-t)\right\rangle = \frac{i}{\hbar}\left\langle [H_s B_s]_- \cdot A_s(-t)\right\rangle - \frac{1}{\hbar^2}\sum_k \int_0^t dx \left[\left(1+N_k(b)\right)\cdot\right.$$
$$\cdot e^{iw(k)x}\left\langle C_k(s,-x)\cdot\left[C_k^+(s),B_s\right]_-\cdot A_s(-t)\right\rangle + N_k(b)e^{-iw(k)x}\cdot$$
$$\left.\left\langle C_k^+(s,-x)\cdot\left[C_k(s),B_s\right]_-\cdot A_s(-t)\right\rangle\right] + \frac{1}{\hbar^2}\sum_k \int_0^t dx \left[\left(1+N_k(b)\right)\cdot\right.$$
$$\cdot e^{-iw(k)x}\cdot\left\langle\left[C_k(s),B_s\right]_-\cdot C_k^+(s_1-x)\cdot A_s(-t)\right\rangle + N_k(b)e^{iw(k)x}\cdot \qquad (2.28)$$
$$\left.\left\langle\left[C_k^+(s),B_s\right]_-\cdot C_k(s,-x)\cdot A_s(-t)\right\rangle\right] - \frac{i}{\hbar^2}\sum_k \int_0^{\hbar b} dq \left[\left(1+N_k(b)\right)\cdot\right.$$
$$\cdot e^{-qw(k)}e^{iw(k)t}\left\langle C_k(s,-t-iq)\cdot\left[C_k^+(s),B_s\right]_-\cdot A_s(-t)\right\rangle +$$
$$\left. + N_k(b)e^{qw(k)}e^{-iw(k)t}\left\langle C_k^+(s,-t-iq)\cdot\left[C_k(s),B_s\right]_-\cdot A_s(-t)\right\rangle\right]; \qquad t>0.$$

analogiurad SesaZlebelia miviRoT zusti, ganzogadoebuli kvanturi kinetikuri gantoleba $F_{A_s B_s}(-t) = \left\langle A_s B_s(t)\right\rangle = \left\langle A_s(-t)B_s\right\rangle$ korelaciuri funqciisTvis. am gantolebis gamoyvana principulad ar gansxvavdeba zemoTmoyvanili gamoTvlebisagan da amitom moviyvanT mxolod saboloo Sedegs:

$$\frac{\partial}{\partial t}\left\langle A_s(-t)B_s\right\rangle = \frac{i}{\hbar}\left\langle A_s(-t)\cdot[H_s B_s]_-\right\rangle - \frac{1}{\hbar^2}\sum_k \int_0^t dx \left[\left(1+N_k(b)\right)\cdot\right.$$
$$\cdot e^{iw(k)x}\left\langle A_s(-t)\cdot C_k(s,-x)\cdot\left[C_k^+(s),B_s\right]_-\right\rangle + N_k(b)e^{-iw(k)x}\cdot$$
$$\left.\left\langle A_s(-t)\cdot C_k^+(s,-x)\cdot\left[C_k(s),B_s\right]_-\right\rangle\right] + \frac{1}{\hbar^2}\sum_k \int_0^t dx \left[\left(1+N_k(b)\right)\cdot\right.$$
$$\cdot e^{-iw(k)x}\cdot\left\langle A_s(-t)\cdot\left[C_k(s),B_s\right]_-\cdot C_k^+(s,-x)\right\rangle + N_k(b)e^{iw(k)x}\cdot \qquad (2.29)$$
$$\left.\left\langle A_s(-t)\cdot\left[C_k^+(s),B_s\right]_-\cdot C_k(s,-x)\right\rangle\right] - \frac{i}{\hbar^2}\sum_k \int_0^{\hbar b} dq \left[\left(1+N_k(b)\right)\cdot\right.$$
$$\cdot e^{qw(k)}e^{iw(k)t}\left\langle A_s(-t)\cdot\left[C_k(s),B_s\right]C_k^+(s,-t+iq)\right\rangle +$$
$$\left. + N_k(b)e^{qw(k)}e^{iw(k)t}\left\langle A_s(-t)\cdot\left[C_k^+(s),B_s\right]_- C_k(s,-t+iq)\right\rangle\right]; \qquad t>0.$$

martivi SesamCnevia, rom (2.28) da (2.29) evoluciuri gantolebebi korelaciuri funqciebisTvis arian araCaketili da markoviseuli. t<0 SemTxvevaSi ganzogadoebul evoluciur (kinetikur) gantolebebs korelaciuri funqciebisTvis aqvT igive saxe, rogorc (2.28) da (2.29) gantolebebs. magram, unda aRiniSnos, rom t>0 da t<0 SemTxvevebisTvis $W(t,0)$ da $W^+(t,0)$ - evoluciis operatorebis warmodgena iqneba sxvadasxva Tanaxmad (2.10) gansazRvrebisa. am gantolebaTa miReba t<0 SemTxvevaSi ar gansxvavdeba

zemoTwarmodgenili gamoyvanisagan da amitomac aq ar moiyvaneba. aRvniSnavT mxolod imas, rom am gantolebaTa miRebisas saWiroa $T^{L,R,S}_{B_s A_s(t)}$ operaciis xelaxali gansazRvra $W(t,0)$ da $W^{+}(t,0)$ operatorebis (2.10) warmodgenis Sesabamisad. ($T^{L,R,S}_{B_s A_s(t)}$ operaciis xelaxali gansazRvra aucilebelia agreTve $F_{A_s B_s}(-t)$ korelaciuri funqciisTvis zusti, ganzogadoebuli kinetikuri gantolebis misaRebadac, rodesac $t>0$). naTelia, rom ganzogadoebuli kvanturi kinetikuri gantolebebi $\langle B_s A_s(t)\rangle$ da $\langle A_s(t) B_s\rangle$ - korelaciuri funqciebisTvis miiReba (2.28) da (2.29) gantolebebidan t droiTi cvladis formaluri cvlilebiT: $t \to -t$. kinetikuri gantolebebi: $\langle B_s A_s(t)\rangle$ da $\langle A_s(t) B_s\rangle$ korelaciuri funqciebisTvis SesaZlebelia warmovadginoT agreTve aramarkoviseuli saxiT. Tu SevasrulebT (2.28) da (2.29) gantolebebSi t sididis cvlilebas: $t \to -t$, visargeblebT operatoruli tolobiT: $A_s(t) = e^{\frac{i}{\hbar}Hx} A_s(t-x) e^{-\frac{i}{\hbar}Hx}$; $(x \in [0,t])$, da $SP_{s\Sigma}(...)$ operaciis qveS operatorTa cikliuri gadanacvlebis SesaZleblobiT, maSin miviRebT Semdeg zust, ganzogadoebul kvantur kinetikur gantolebebs $\langle B_s A_s(t)\rangle$ da $\langle A_s(t) B_s\rangle$ korelaciuri funqciebisTvis [110]:

$$
\begin{aligned}
&\frac{\partial}{\partial t}\langle B_s A_s(t)\rangle = -\frac{i}{\hbar}\langle [H_s B_s] A_s(t)\rangle - \frac{1}{\hbar^2}\sum_k \int_0^t dx \Big[\big(1+N_k(b)\big)\times \\
&\times e^{-iw(k)x}\Big\langle C_k(s)\cdot\big[C_k^{+}(s,-x), B_s(-x)\big]_{-} A_s(t-x)\Big\rangle + N_k(b) e^{iw(k)x}\times \\
&\times\Big\langle C_k^{+}(s)\big[C_k(s,-x), B_s(-x)\big]_{-} A_s(t-x)\Big\rangle + \frac{1}{\hbar^2}\sum_k \int_0^t dx \Big[\big(1+N_k(b)\big)\times \\
&\times e^{iw(k)x}\cdot\Big\langle\big[C_k(s,-x), B_s(-x)\big]_{-} C_k^{+}(s) A_s(t-x)\Big\rangle + N_k(b) e^{-iw(k)x}\times \qquad (2.30)\\
&\times\Big\langle\big[C_k^{+}(s,-x), B_s(-x)\big]_{-}\cdot C_k(s) A_s(t-x)\Big\rangle\Big] + \frac{i}{\hbar^2}\sum_k \int_0^{\hbar b} dq \Big[\big(1+N_k(b)\big)\times \\
&\times e^{-qw(k)} e^{-iw(k)t}\Big\langle C_k(s,t-iq)\cdot\big[C_k^{+}(s), B_s\big]_{-} A_s(t)\Big\rangle + N_k(b) e^{qw(k)}\times \\
&\times e^{iw(k)t}\Big\langle C_k^{+}(s,t-iq)\cdot\big[C_k(s), B_s\big]_{-}\cdot A_s(t)\Big\rangle\Big];
\end{aligned}
$$

$$\frac{\partial}{\partial t}\left\langle A_s(t)B_s\right\rangle=-\frac{i}{\hbar}\left\langle A_s(t)\cdot[H_sB_s]_-\right\rangle-\frac{1}{\hbar^2}\sum_k\int_0^t dx\left[\left(1+N_k(b)\right)\times\right.$$
$$\times e^{-iw(k)x}\left\langle A_s(t-x)\cdot C_k(s)\left[C_k^+(s,-x),B_s(-x)\right]_-\right\rangle+N_k(b)e^{iw(k)x}\times$$
$$\times\left\langle A_s(t-x)\cdot C_k^+(s)\left[C_k(s,-x),B_s(-x)\right]_-\right\rangle+\frac{1}{\hbar^2}\sum_k\int_0^t dx\left[\left(1+N_k(b)\right)\times\right. \qquad (2.31)$$
$$\times e^{iw(k)x}\cdot\left\langle A_s(t-x)\left[C_k(s,-x),B_s(-x)\right]_-C_k^+(s)\right\rangle+N_k(b)e^{-iw(k)x}\times$$
$$\times\left\langle A_s(t-x)\left[C_k^+(s,-x),B_s(-x)\right]_-\cdot C_k(s)\right\rangle\Big]+\frac{i}{\hbar^2}\sum_k\int_0^{\hbar b}dq\left[\left(1+N_k(b)\right)\times\right.$$
$$\times e^{-qw(k)}e^{-iw(k)t}\left\langle A_s(t)\left[C_k(s),B_s\right]_-\cdot C_k^+(s,t+iq)\right\rangle+N_k(b)e^{qw(k)}\times$$
$$\times e^{-iw(k)t}\left\langle A_s(t)\cdot\left[C_k^+(s),B_s\right]_-\cdot C_k(s,t+iq)\right\rangle\Big];$$

(2.28) da (2.29) gantolebebisagan gansxvavebiT, (2.30) da (2.31) evoluciuri (kinetikuri) gantolebebi arian araCaketili da aramarkoviseuli formis. (2.3) gamosaxulebebi da (2.28)-(2.29) evoluciuri gantolebebi gansazRvraven gantolebebs grinis funqciebisTvis. ase magaliTad, gantolebas dagvianebuli grinis funqciisTvis: $G^r(t)=q(t)\left\langle\left[A_s(t),B_s\right]_h\right\rangle$ aqvs Semdegi saxe:

$$\frac{\partial}{\partial t}G^r(t)=d(t)\left\langle\left[A_s,B_s\right]_h\right\rangle+q(t)\frac{\partial}{\partial t}\left\langle\left[A_s(t),B_s\right]_h\right\rangle. \qquad (2.32)$$

amdagvarad SesaZlebelia ganisazRvros agreTve evoluciuri gantolebebi sxva danarCeni grinis funqciebisTvis (winmswrebisa da mizezobrivisTvis). (2.30)–(2.31) formulebis daxmarebiT evoluciuri (kinetikuri) gantoleba $G^r(t)$ – grinis dagvianebuli funqciisTvis SesaZlebelia warmovadginoT Semdegi saxiT [110-111]:

$$\frac{\partial}{\partial t}G^r(t)=d(t)\left\langle[A_s,B_s]_h\right\rangle-\frac{i}{\hbar}q(t)\left\langle\left[A_s(t),[B_s,H_s]_-\right]_h\right\rangle+$$
$$+\frac{1}{\hbar^2}\sum_k\int_{-\infty}^{+\infty}dxq(x)q(t-x)\Big\{\big(1+N_k(b)\big)e^{-iw(k)x}\left\langle\left[A_s(t-x)C_k(s)\times\right.\right.$$
$$\left.\left.\times\left[B_s(-x)C_k^+(s,-x)\right]_-\right]_h\right\rangle+N_k(b)e^{iw(k)x}\left\langle\left[A_s(t-x)C_k^+(s)\times\right.\right.$$
$$\left.\left.\times\left[B_s(-x),C_k(s,-x)\right]_-\right]_h\right\rangle\Big\}-\frac{1}{\hbar^2}\sum_k\int_{-\infty}^{+\infty}dxq(x)q(t-x)\Big\{\big(1+N_k(b)\big)\times \qquad (2.33)$$
$$\times e^{iw(k)x}\left\langle\left[A_s(t-x)\left[B_s(-x),C_k^+(s,-x)\right]_-C_k^+(s)\right]_h\right\rangle+N_k(b)\times$$
$$\times e^{-iw(k)x}\left\langle\left[A_s(t-x)\left[B_s(-x),C_k^+(s,-x)\right]_-C_k(s)\right]_h\right\rangle-\frac{i}{\hbar^2}\sum_k\int_0^{\hbar b}dq\times$$
$$\times\Big\{\big(1+N_k(b)\big)e^{-qw(k)}q(t)\Big\{e^{iw(k)t}\left\langle A_s(t)\left[B_s,C_k(s)\right]_-C_k^+(s,t+iq)\right\rangle-$$
$$-he^{-iw(k)t}\left\langle C_k(s,t-q)\left[B_s,C_k^+(s)\right]_-A_s(t)\right\rangle\Big\}+N_k(b)\cdot e^{qw(k)}q(t)\times$$
$$\times\Big\{e^{-iw(k)t}\left\langle A_s(t)\left[B_s,C_k^+(s)\right]_-C_k(s_1t+iq)\right\rangle-he^{iw(k)t}\left\langle C_k^+(s,t-iq)\times\right.$$
$$\left.\times\left[B_s,C_k(s)\right]_-A_s(t)\right\rangle\Big\}\Big\}.$$

miRebuli (2.28–2.31) da (2.33) kvanturi evoluciuri (kinetikuri) gantolebebi warmoadgenen zust, ganzogadoebul gantolebebs drois or momentiani wonasworuli korelaciuri funqciebisa da grinis funqciisTvis [25,34,64]. gansxvavebiT kinetikuri gantolebebisagan, romlebic miRebulia [5-6,75-77] SromebSi, gamoyvanili evoluciuri gantolebebis dajaxebiTi integralebi Seicaven rogorc maRali rigis korelaciur da grinis funqciebs, aramed aseve sawyisi korelaciebis evoluciis amsaxvel wevrebs (ukanaskneli wevrebi (2.28–2.31 da 2.33) gantolebebis marjvena mxareSi). SevniSnavT agreTve, rom (2.28–2.31) gantolebebis marjvena mxareebis pirveli wevrebi aRweren korelaciuri funqciebis Tavisufal (aradajaxebiT) dinamikas.

2.3. markoviseuli miaxloeba qvesistemis dinamikisTvis. miaxloebiTi gantolebebi korelaciuri funqciebisTvis

davuSvaT, rom (2.2) urTierTqmedebis hamiltoniani s qvesistemasa da S bozonur Termostats Soris Seicavs mcire parametrs ($C_k(s)$ da $C_k^+(s)$ urTierTqmedebis operatorebi Seicaven mcire parametrs). aseT SemTxvevaSi,

s qvesistemasa da S bozonur vels Soris susti urTierTqmedebis gamo, adgili eqneba droTa ierarqias:

$$t_{ree} >> t_0 = \max\left(t_s, t_\Sigma\right), \tag{2.34}$$

sadac: t_{ree} - warmoadgens s qvesistemis relaqsaciis maxasiaTebel dros, xolo $t_s \cdot \hbar b$ aris s qvesistemis dajaxebiTi (gabnevis) dro; $t_\Sigma \cdot \frac{1}{\tilde{w}}$- aris korelaciebis fluqtuaciebis milevis dro TermostatSi ($\tilde{w}$ - bozonebis rxevebis maxasiaTebeli sixSirea). (2.34) utoloba saSualebas iZleva SemovifargloT SeSfoTebis Teoriis meore miaxloebiT (H_{int}- urTierTqmedebis hamiltonianis mixedviT) (2.28–2.31) evoluciur gantolebebSi korelaciuri funqciebisTvis. ase magaliTad, Tu SevasrulebT (2.28) evoluciur gantolebaSi Semdegi saxis miaxloebebs:

$$\begin{aligned} &C_k\left(s,-x\right) \Rightarrow C_{kH_0}\left(s,-x\right); \quad C_k^+\left(s,-x\right) \Rightarrow C_{kH_0}^+\left(s,-x\right); \\ &C_k\left(s,-t-iq\right) \Rightarrow C_{kH_0}\left(s,-t-iq\right); \quad C_k^+\left(s,-t-iq\right) \Rightarrow C_{kH_0}^+\left(s,-t-iq\right). \end{aligned} \tag{2.35}$$

maSin miviRebT, drois ormomentiani wonasworuli korelaciuri funqciisTvis: $\left\langle B_s A_s\left(-t\right)\right\rangle$ _ ganzogadoebul, markoviseul kvantur kinetikur gantolebas SeSfoTebis Teoriis meore miaxloebaSi [110-111]:

$$\begin{aligned} &\frac{\partial}{\partial t}\left\langle B_s A_s\left(-t\right)\right\rangle = \frac{i}{\hbar}\left\langle\left[H_s B_s\right]_- \cdot A_s\left(-t\right)\right\rangle - \frac{1}{\hbar^2}\sum_k \int_0^t dx\left[\left(1+N_k\left(b\right)\right)\times\right. \\ &\times e^{iw(k)x}\left\langle C_{kH_0}\left(s,-x\right)\cdot\left[C_k^+\left(s\right),B_s\right]_- A_s\left(-t\right)\right\rangle + N_k\left(b\right)e^{-iw(k)x}\times \\ &\left.\times\left\langle C_{kH_0}^+\left(s_1-x\right)\cdot\left[C_k\left(s\right),B_s\right]_- A_s\left(-t\right)\right\rangle\right] + \frac{1}{\hbar^2}\sum_k \int_0^t dx\left[\left(1+N_k\left(b\right)\right)\times\right. \\ &\times e^{-iw(k)x}\cdot\left\langle\left[C_k\left(s\right),B_s\right]_- C_{kH_0}^+\left(s,-x\right)A_s\left(-t\right)\right\rangle + N_k\left(b\right)e^{iw(k)x}\times \\ &\left.\times\left\langle\left[C_k^+\left(s\right),B_s\right]_- \cdot C_{kH_0}\left(s,-x\right)A_s\left(-t\right)\right\rangle\right] - \frac{i}{\hbar^2}\sum_k \int_0^{\hbar b} dq\left[\left(1+N_k\left(b\right)\right)\times\right. \\ &\times e^{-qw(k)}e^{iw(k)t}\left\langle C_{kH_0}\left(s,-t-iq\right)\left[C_k^+\left(s\right),B_s\right]_-\cdot A_s\left(-t\right)\right\rangle + N_k\left(b\right)e^{qw(k)}\times \\ &\left.\times e^{-iw(k)t}\left\langle C_{kH_0}^+\left(s,-t-iq\right)\cdot\left[C_k\left(s\right),B_s\right]_-\cdot A_s\left(-t\right)\right\rangle\right]. \end{aligned} \tag{2.36}$$

analogiurad miiReba evoluciuri gantolebebi sxva korelaciuri funqciebisa da grinis funqciisTvis (ix. (2.29), (2.30–2.31) da (2.33) formulebi).

rogorc cnobilia, xelsayrel da efeqtur meTods sustadarawonasworuli mdgomareobebisa, relaqsaciuri procesebisa da kinetikuri movlenebis Seswavlisa – romlebic mimdinareoben mcire dinamiur qvesistemaSi,

romelic urTierTqmedebs TermostatTan da gareSe velTan, - warmoadgens korelaciuri funqciebisa da grinis funqciis meTodi.

drois ormomentiani wonasworuli korelaciuri funqciebi da grinis funqciebi warmoadgenen ZiriTad sidideebs kubos wrfivi gamoZaxilis (reaqciis) TeoriaSi [4,34,64,72-73]. (2.28–2.29) gantolebebi gansxvavdebian msgavsi gantolebebisagan, romlebic gamoyvanili iyvnen SemTxveviTi fazebis miaxloebaSi [5-6,68,75-77], ukanasknели wevrebiT gantolebebis marjvena mxareebSi, romlebic aRweren sawyisi korelaciebis evolucias da gavlenas dajaxebiT procesebze gabnevis (dajaxebiT) integralebSi (ix. agreTve (2.36) gantoleba). unda aRiniSnos agreTve is garemoeba, rom sawyisi korelaciebis evolucia droSi moicema markoviseuli formiT ((2.28–2.29), (2.30–2.31)) kinetikur gantolebebSi korelaciuri funqciebisTvis, da isini ar Seicaven maxsovrobis efeqtebs. Sfm-Si, rodesac t=0 drois sawyis momentSi mTeli $(s+\Sigma)$ sistemis wonasworuli statistikuri operatori (gibsis kanonikuri ganawileba) aiReba faqtorizebuli saxiT:

$$r_{eq}(b)=Z^{-1}(b)\cdot e^{-bH}\Rightarrow r_s(b)\, r_\Sigma(b):\quad r_s(b)=Z_s^{-1}(b)\cdot e^{-bH_s}$$
$$r_\Sigma(b)=Z_\Sigma^{-1}(b)\cdot e^{-bH_\Sigma}. \qquad (2.37)$$

sadac: $Z_s(b)=S\mathrm{P}_s\left[e^{-bH_s}\right]$ da $Z_\Sigma(b)=S\mathrm{P}_\Sigma\left[e^{-bH_\Sigma}\right]$ – warmoadgenen statjamebs s-qvesistemisa da Σ bozonuri velisa, Sesabamisad; (anu ugulvebelvyofT H_{int} urTierTqmedebis hamiltonians e^{-bH} gibsis faqtorSi da $Z(b)$ statjamSi, magram vinarCunebT $e^{\pm\frac{i}{\hbar}Ht}$- operatorebSi, ris gamoc $W(b,0)=W^{+}(b,0)=1$ (ix. (2.9); (2.11) formulebi)); _ sawyisi korelaciebis evoluciis wevrebi (2.28)–(2.29) da (2.30)–(2.31); (2.36) gantolebebSi xdeba nulis toli da, rogorc Sedegi am miaxloebaSi vRebulobT ganzogadoebul kvantur-kinetikur gantolebebs korelaciuri funqciebisTvis, romlebic miRebuli iyo [6,68,75-77] SromebSi.

sawyisi korelaciebis Sesustebis principis (postulatis) Tanaxmad “xelovnurad” Seqmnili sawyisi korelaciebi, romlebic ganpirobebulia t=0 drois sawyisi momentisTvis s-qvesistemis urTierTqmedebiT Σ TermostatTan, unda miilion drois mixedviT, rodesac $t\to\infty$, Tu isini ar miekuTvnebian Senaxvad sidideebs, da unda moxdes dajaxebiTi (namdvili) korelaciebis aRdgena, romlebic aRiwerebian maRali rigis korelaciuri funqciebiTa da

grinis funqciebiT (2.28), (2.29), (2.30), (2.31), (2.36) – gantolebebis dajaxebiT integralebSi.

amrigad, $r_{eq}(b) = Z^{-1}(b) \cdot e^{-bH}$ - sawyisi wonasworuli ganawilebis “detalebi” TiTqos ar unda iyos arsebiTi [4]; magram, miuxedavad amisa cxadia, rom principSi sawyisi korelaciebis evoluciis wevrebis arseboba ganzogadoebul kvantur kinetikur gantolebebSi korelaciuri funqciebisa da grinis funqciebisTvis gavlenas axdenen evoluciur procesze, romelic mimdinareobs s qvesistemaSi. s qvesistemis da S Termostatis (bozonuri velis) sustiurTierTqmedebis SemTxvevaSic, sawyisi korelaciebis evoluciuri wevrebi korelaciuri funqciebisTvis kinetikur gantolebebSi ar miilevian nulisaken didi droebis asimptotur areSi, rodesac $(t \sim t_{rel} >> t_0; t \to \infty)$ da iZlevian TavianT wvlils gadatanis kinetikur (meqanikur) koeficientebSi (Zvradoba, eleqtrogamtaroba) s qvesistemisTvis (ix. III Tavi). Kkinetikuri koeficientebis [34], gamoZaxilis funqciis (impedansi, admitansi) [72-73] da dinamiuri amTviseblobis [4] gamoTvlisas; garda amisa, relaqsaciuri procesebis Seswavlisas, romlebic mimdinareoben Ria modelur sistemebSi, da myari sxeulebis fizikis kvanturi disipaciuri sistemebis ganxilvisas, ganzogadoebul kvantur kinetikur gantolebebSi sawyisi korelaciebis evoluciuri wevrebis gaTvaliswinebas aqvs principuli mniSvneloba da maTi ugulvebelyofa ar SeiZleba. miuxedavad amisa unda aRiniSnos, rom kinetikuri movlenebis Seswavlisas am sistemebSi “namdvili” (dajaxebiTi) korelaciebi TamaSoben dominirebul rols sawyis korelaciebTan SedarebiT [4].

axla ganvixiloT gansxvavebuli midgoma igive amocanisadmi, romelic eyrdnoba liuvilis superoperatorul formalizmsa da proeqciuli operatoris meTods [114-122].

2.4. ganzogadoebuli kvanturi evoluciuri gantolebebi korelaciuri funqciebisTvis Sfm-is gamoyenebis gareSe. proeqciuli operatoris meTodi

ganvixiloT drois ormomentiani wonasworuli korelaciuri funqcia $\langle A_s(t)B_s\rangle$ da warmovadginoT is Semdegi saxiT:

$$\langle A_S(t)B_S\rangle = Z^{-1}(b)SP_{s\Sigma}\left[B_s e^{-bH}e^{iLt}A_s\right] \qquad (2.38)$$

(2.38) formulaSi Cven SemoviReT liuvilis superoperatoris (L) cneba, romelic moqmedebs nebismier D-operatorze Semdegi wesiT: $LD=\frac{1}{\hbar}[H,D]_-$: $e^{\pm iLt}D = e^{\pm\frac{i}{\hbar}Ht}De^{-\frac{i}{\hbar}Ht}$, anu $e^{\pm iLt}D = D(\pm t)$ da $D=D(t)\big|_{t=0}$.

liuvilis sruli L superoperatori Caiwereba Semdegi saxiT: $L = L_s + L_\Sigma + L_i$, sadac $L_s\ldots=\frac{1}{\hbar}[H_s,\ldots]$, $L_\Sigma\ldots=\frac{1}{\hbar}[H_\Sigma,\ldots]$ da $L_i\ldots=\frac{1}{\hbar}[H_{\text{int}},\ldots]_-$; (2.1)–(2.2) hamiltonianis TiToeuli wevris Sesabamisad. (2.38) formulidan gamomdinare cxadia, rom korelaciuri funqciebis dinamika xelsayrelia ganvixiloT Semdegi superoperatorebis daxmarebiT, romlebic moqmedeben D D-operatorze Semdegi wesiT:

$$\begin{aligned} R(t)D &= Z^{-1}(b)S\mathrm{P}_\Sigma\left[e^{-bH}e^{iLt}\mathrm{P}D\right]\\ I(t)D &= Z^{-1}(b)S\mathrm{P}_\Sigma\left[e^{-bH}e^{iLt}QD\right], \end{aligned} \qquad (2.39)$$

sadac: P warmoadgens Termostatis (bozonuri velis) mdgomareobebis mixedviT gasaSualebis proeqciul operators:

$$\begin{gathered} \mathrm{P}^2=\mathrm{P};\ \mathrm{P}=\mathrm{P}_\Sigma(b);\ \mathrm{P}D = S\mathrm{P}_\Sigma(r_\Sigma D)=\langle D\rangle_\Sigma;\ r_\Sigma = Z_\Sigma^{-1}(b)e^{-bH_\Sigma}\\ \mathrm{Z}_\Sigma(b)=S\mathrm{P}_\Sigma\left(e^{-bH_\Sigma}\right);\ \ Q=Q_\Sigma(b)=1-\mathrm{P}. \end{gathered} \qquad (2.40)$$

(2.38) gamosaxuleba $\langle A_s(t)B_s\rangle$ korelaciuri funqciisaTvis CavweroT Semdegi formiT:

$$\langle A_S(t)B_S\rangle=\langle A_SB_S(-t)\rangle = SP_s[B_sR(t)A_s]. \qquad (2.41)$$

P da Q – proeqciuli operatorebis daxmarebiT martivad miviRebT Semdeg zust moZraobis gantolebebs $R(t)$ da $I(t)$ superoperatorebisaTvis:

$$\begin{aligned} \frac{\partial}{\partial t}R(t) &= iR(t)\mathrm{P}LP + iI(t)QL\mathrm{P};\\ \frac{\partial}{\partial t}I(t) &= iI(t)QLQ + iR(t)\mathrm{P}LQ. \end{aligned} \qquad (2.42)$$

Tu CavatarebT (2.42) gantolebis integrebas $I(t)$ superoperatorisaTvis, maSin Cven miviRebT Semdeg gamosaxulebas:

$$I(t)=I(0)M_Q(t)+i\int_0^t dt\,R(t)\mathrm{P}LQM_Q(t-t'), \tag{2.43}$$

sadac:

$$I(0)=Z^{-1}(b)S\mathrm{P}_\Sigma e^{-bH}Q \tag{2.44}$$

aris $I(t)$-superoperatoris sawyisi mniSvneloba da $M_Q(t)=\exp[iQLQt]$ warmoadgens "masur" superoperators.

Tu CavsvamT $I(t)$-superoperatoris (2.43) gamosaxulebas (2.42) formulis pirvel gantolebaSi, maSin Cven vipoviT zust, araerTgvarovan evoluciur gantolebas $R(t)$-superoperatorisaTvis:

$$\frac{\partial}{\partial t}R(t)=iR(t)\mathrm{P}LP+iI(0)M_Q(t)QL\mathrm{P}-\int_0^t dt\,R(t)\mathrm{P}LQM_Q(t-t')QL\mathrm{P}. \tag{2.45}$$

miRebuli gantoleba gansazRvravs evoluciur gantolebas (2.41) korelaciuri funqciisaTvis. marTlac, Tu visargeblebT (2.39) gansazRvrebiTa da $S\mathrm{P}_{s,\Sigma}$ operaciis qveS operatorTa cikliuri gadanacvlebis SesaZleblobiTa da (2.41)–(2.45) formulebiT, maSin martivad vipoviT Semdeg evoluciur gantolebas korelaciuri funqciisTvis [119]:

$$\begin{aligned}\frac{\partial}{\partial t}\langle A_sB_s(-t)\rangle &= i\langle[\mathrm{P}LPA_s]B_s(-t)\rangle+i\langle[QM_Q(t)QLPA_s]B_s\rangle-\\ &-\int_0^t dt\,\langle[\mathrm{P}LQM_Q(t-t')QLPA_s]B_s(-t')\rangle.\end{aligned} \tag{2.46}$$

(2.45) da (2.46) gantolebebi warmoadgenen zust, aramarkoviseul evoluciur gantolebebs $R(t)$ superoperatorisa da $\langle A_sB_s(-t)\rangle$ korelaciuri funqciisTvis. am gantolebaTa araerTgvarovani wevrebi (meore wevrebi (2.45), (2.46) ganatolebaTa marjvena nawilSi) aRweren sawyisi korelaciebis evolucias drois mixedviT, romlebic ganapirobebulia s qvesistemis urTierTqmedebiT S TermostatTan (bozonur velTan) drois sawyis momentSi: t=0. amis gamo, sawyisi amocanis (koSis amocana) amoxsnisas (2.45) gantolebisaTvis (da korelaciuri funqciis povnisaTvis) saWiroa codna ara marto superoperatorisa – $R(0)$, aramed agreTve $I(0)$ sididisa. Tu maxsovroba sawyisi korelaciebisa drois mixedviT miileva, maSin evoluciis procesSi dominirebs dajaxebaTa gavlena. magram, miuxedavad amisa, principSi sawyisi

korelaciebis wevrebis arseboba evoluciur gantolebebSi, romelic ganapirobebulia $I(0)$-is arsebobiT, gavlenas moaxdens relaqsaciur process-ze, romelic aRiwereba korelaciuri funqciiT, qvesistemis sustiurTierT-qmedebis SemTxvevaSiac TermostatTan. mogvianebiT Cven vaCvenebT, rom sawyis korelaciebs SeaqvT TavianTi wvlili s qvesistemis (mag. eleqtronis) gadatanis kinetikur koeficientSi (eleqtrogamtaroba) [115-122].

bevrad ufro efeqturi da xelsayrelia, Tu Cven ganvixilavT evoluciis zust da erTgvarovan gantolebas, romelSiac sawyisi korelaciebi moicema aracxadi saxiT. imisaTvis, rom vipovoT aseTi saxis gantoleba, visargebloT cnobili integraluri operatoruli igiveobiT:

$$e^{-bH} = e^{-bH_0} - \int_0^b dl\, e^{-bH} e^{lH} H_{\text{int}} e^{-lH_0}, \tag{2.47}$$

sadac H_0 moicema (2.9) formuliT. am igiveobis gamoyenebiT, advilia imis Cveneba, rom adgili aqvs Semdeg gantolebaTa sistemas $I(t)$ da $I(0)$-superoperatorebisaTvis, romlebic gamomdinareoben (2.43) da qvemoT moyvanili gantolebidan:

$$I(0) = -R(t)\Im_Q(t,b) - I(t)\Im_Q(t,b) \tag{2.48}$$

da romelic miiReba (2.47) gamosaxulebisa da $I(t)$-superoperatorisTvis (2.44) sawyisi pirobidan. (2.48) gantolebaSi Cven SemoviReT integraluri superoperatori, romelic ganisazRvreba Semdegi tolobiT:

$$\Im_Q(t,b) = \int_0^b dl\, e^{-iLt} e^{lH} H_{\text{int}} e^{-lH} Q. \tag{2.49}$$

Tu amovxsniT (2.43) da (2.48) gantolebebs $I(0)$-is mimarT da CavsvamT (2.45) gantolebaSi, maSin Cven miviRebT saZiebel zust, erTgvarovan Caketil gantolebas $R(t)$-superoperatorisaTvis:

$$\begin{aligned}
&\frac{\partial}{\partial t} R(t) = iR(t)\mathrm{P}LP - iR(t)\mathrm{P}\Im_Q(t,b)\left[1 + M_Q(t)\Im_Q(t,b)\right]^{-1} \times \\
&\times M_Q(t)QL\mathrm{P} + \int_0^t dt\, R(t)\mathrm{P}LQM_Q(t-t')\Im_Q(t,b)\left[1 + M_Q(t) \times\right. \\
&\left.\times \Im_Q(t,b)\right]^{-1} M_Q(t)QL\mathrm{P} - \int_0^t dt\, R(t)\mathrm{P}LQM_Q(t-t')QL\mathrm{P}.
\end{aligned} \tag{2.50}$$

unda aRvniSnoT, rom miRebuli gantolebebi SesaZlebelia gavamartivoT, Tu visargeblebT Semdegi TanafardobebiT:

$$L_\Sigma \mathrm{P} = 0;\ \ \mathrm{P}L_s Q = QL_s \mathrm{P} = 0;\ \ \mathrm{P}L_i \mathrm{P} = 0. \tag{2.51}$$

dabolos, Tu gamoviyenebT (2.50)–(2.51) formulebs, (2.46) gantolebis nacvlad miviRebT Semdeg zust kvanturevoluciur (kinetikur) gantolebas korelaciuri funqciisTvis [119]:

$$\begin{aligned}\frac{\partial}{\partial t}\left\langle A_s B_s(-t)\right\rangle &= i\left\langle [\mathrm{P}L_s \mathrm{P}A_s] B_s(-t)\right\rangle - i\left\langle \{\mathrm{P}\Im_Q(t,b)\times\right.\\ &\times\left.\left[1+M_Q(t)\Im_Q(t,b)\right]^{-1} M_Q Q L_i \mathrm{P}A_s\right\} B_s(-t)\Big\rangle + \int_0^t dt\,\times\\ &\times\left\langle \{\mathrm{P}L_i Q M_Q(t-t')\Im_Q(t,b)\left[1+M_Q(t)\Im_Q(t,b)\right]^{-1}\times\right.\\ &\times\left. M_Q(t) Q L_i \mathrm{P}A_s\right\} B_s(-t')\Big\rangle - \int_0^t dt\,\Big\langle\Big[\mathrm{P}L_i Q M_Q(t-t') Q\times\\ &\times L_i \mathrm{P}A_s\Big] B_s(-t')\Big\rangle.\end{aligned} \tag{2.52}$$

(2.50)–(2.52) evoluciur gantolebebs gaaCniaT sakmarisad rTuli operatoruli struqtura. sawyisi korelaciebis evolucia droSi aRiwereba (2.49) integraluri superoperatoriT; igi Sedis evoluciur gantolebebSi rogorc markoviseuli, ise aramarkoviseuli formiT (meore da mesame wevrebi (2.50) da (2.52) gantolebebis marjvena nawilSi). Sfm-is dros, rodesac (2.38) korelaciuri funqciis gansazRvrebaSi Cven viRebT e^{-bH_0}– operators, nacvlad e^{bH}-gibsis statistikuri operatorisa, vRebulobT, rom $I(0)=0$, rogorc es naTlad Cans (2.39) da (2.40) formulebidan (vinaidan $PQ=0$). am garemoebas mivyavarT im Sedegamde, rom integraluri superoperatori xdeba nulis toli ($\Im_Q(t,b)\equiv 0$), rac Tavis mxriv iwvevs sawyisi korelaciebis evoluciis amsaxveli wevrebis gaqrobas (isini xdebian nulis toli) (2.50) da (2.52) evoluciur gantolebebSi. rogorc Sedegi da kerZo SemTxveva Cven vRebulobT evoluciur gantolebas korelaciuri funqciisTvis, romelic gamoyvanilia [75-77] SromebSi.

evoluciuri gantolebebi (2.3)-grinis funqciebisTvis gamomdinareoben (2.52)-gantolebidan. ase magaliTad, grinis dagvianebuli funqciisTvis gveqneba gantoleba:

$$\begin{aligned}\frac{\partial}{\partial t}G^r(t) &= d(t)\left\langle [A_s B_s]_h\right\rangle + q(t)\frac{\partial}{\partial t}\left\langle A_s B_s(-t)\right\rangle -\\ &\quad - hq(t)\frac{\partial}{\partial t}\left\langle B_s A_s(t)\right\rangle.\end{aligned} \tag{2.53}$$

naTelia, rom evoluciuri gantoleba $\left\langle A_s B_s(t)\right\rangle$ korelaciuri funqciisTvis miiReba (2.52) gantolebidan, Tu gamoviyenebT Casmas $t \to -t$ [119, 121-122].

2.5. Termostatis bozonuri amplitudebis gamoricxva evoluciuri gantolebidan korelaciuri funqciisaTvis. markoviseuli miaxloeba qvesistemis dinamikisTvis

ganvixiloT axla ufro detalurad (2.52) evoluciuri gantoleba korelaciuri funqciisTvis. advili misaxvedria, rom (2.52) gantoleba Seicavs Termostatis (bozonuri velis) amplitudebs, romlebic ar arian gamoricxuli am gantolebidan. davuSvaT, rom hamiltoniani H_{int} (liuviliani L_i) Seicavs mcire parametrs (susti urTierTqmedebis SemTxveva qvesistemasa da Termostats Soris); maSin (2.52)-gantolebidan principSi SesaZlebelia bozonuri amplitudebis gamoricxva. am amocanis gadasawyvetad gavSaloT mwkrivebad superoperatorebi, romlebic figurireben (2.52)-gantolebaSi $L_i(H_{\text{int}})$ liuvilianis (hamiltonianis) mixedviT. gveqneba:

$$\left[1+M_Q(t)\Im_Q(t,b)\right]^{-1}=\sum_{k=0}^{\infty}(-1)^k\left[M_Q(t)\Im_Q(t,b)\right]^k$$

$$M_Q(t)=\sum_{k=0}^{\infty}M_Q^{(n)}(t);\quad M_Q^{(0)}(t)=e^{iL_0t}$$

$$M_Q^{(n)}(t)=\int_0^t dt_1\int_0^{t_1}dt_2\ldots\int_0^{t_{n-1}}dt_n e^{iL_0(t-t_1)}iQL_ie^{iL_0(t_1-t_2)}iQL_i\ldots\times$$
$$\times e^{iL_0(t_{n-1}-t_n)}iQL_ie^{iL_0t_n};\quad (n=1,2,\ldots)$$
$$e^{-iLt}=e^{-iL_0t}\,\mathrm{T}\exp\left[-i\int_0^t L_i(x)\,dx\right] \qquad (2.54)$$
$$e^{lH}=e^{lH_0}\,\mathrm{T}'\exp\left[\int_0^l H_{\text{int}}(g)\,dg\right]$$
$$L_i(x)=e^{iL_0x}L_ie^{-iL_0x};\quad H_{\text{int}}(g)=e^{-gH_0}H_{\text{int}}e^{gH_0}$$
$$L_0=L_s+L_\Sigma,$$

sadac T da T' simboloebi aRniSnaven operatorTa mowesrigebas Sesabamisad x da g cvladebis mixedviT.

s qvesistemis S TermostatTan susti urTierTqmedebis SemTxvevaSi (2.54) gaSlebi formalurad SegviZlia ganvixiloT rogorc SeSfoTebis Teoriis mwkrivebi da gamovTvaloT wevrebi (2.50)–(2.52) gantolebebis marjvena nawilebSi mocemuli sizustiT. martivi saCvenebelia, rom aseTi gaSlebisas urTierTqmedebis mixedviT im SemTxvevaSi, rodesac H_Σ da H_{int} aqvT (2.2) saxe, nulisgan gansxvavebuli iqnebian mxolod iseTi saSualo

sidideebi – $\langle ... \rangle_{\Sigma}$, romlebic Seicaven bozonebis dabadebisa da gaqrobis operatorebis erTnair raodenobas. amitom aseTi saxis saSualoebi toli iqneba sidideebis, romlebic proporciuli iqnebian bozonebis Sevsebis saSualo ricxvebis namravlebis. amrigad, bozonuri (fononuri) operatorebi (amplitudebi) mTlianad gamoiricxeba (2.52) evoluciuri gantolebidan wonasworuli korelaciuri funqciisaTvis.

davuSvaT, rom susti urTierTqmedebis gamo, romelsac adgili aqvs s qvesistemasa da S Termostats Soris, gvaqvs droTa ierarqia mTel $(s+\Sigma)$ sistemaSi, romelic aRiwereba (2.34) utolobiT. (2.34) utolobis samarTlianoba gvrTavs nebas CavataroT markoviseuli miaxloeba (2.50)–(2.52) gantolebebSi; Tu SemovisazRvrebiT SeSfoTebis Teoriis meore miaxloebiT urTierTqmedebis $H_{\text{int}}(L_i)$ hamiltonianis (liuvilianis) mixedviT, visargeblebT (2.54) gaSlebiT da Sevasrulebt Semdeg miaxloebebs:

$$\begin{gathered}
\left[1+M_Q(t)\Im_Q(t,b)\right]^{-1} \Rightarrow 1 \\
M_Q(t) \Rightarrow M_Q^{(0)}(t) = e^{iL_0 t} \\
\Im_Q(t,b) \Rightarrow \Im_Q^0(t,b) = \int_0^b d\,l\, e^{-iL_0 t} e^{l H_0} H_{\text{int}} e^{-l H_0} Q \\
B_s(-t) \Rightarrow e^{iL_0(t-t)} B_s(-t).
\end{gathered} \tag{2.55}$$

maSin (2.52) evoluciuri gantoleba martivdeba da igi iRebs saxes markoviseuli, ganzogadoebuli kvanturi kinetikuri (evoluciuri) gantolebisa wonasworuli korelaciuri funqciisTvis $\langle A_s B_s(-t)\rangle$ [119]:

$$\begin{aligned}
&\frac{\partial}{\partial t}\langle A_s B_s(-t)\rangle = i\langle [L_s A_s] B_s(-t)\rangle - i\int_0^b d\,l\,\langle \Big[\mathrm{P} e^{-iL_0 t} e^{l H_0} \times \\
&\times H_{\text{int}} e^{-l H_0} e^{iL_0 t} L_i A_s \Big] B_s(-t)\rangle - \int_0^t d\,t\,\langle \Big[\mathrm{P} L_i e^{iL_0(t-t)} L_i A_s \Big] \times \\
&\times e^{iL_0(t-t)} B_s(-t)\rangle.
\end{aligned} \tag{2.56}$$

miRebuli (2.56) gantoleba korelaciuri funqciisTvis jer kidev Seicavs gamouricxav bozonur amplitudebs. Tu visargeblebT H_{Σ} da H_{int} hamiltonianebis – (2.2) cxadi saxiT da gamovricxavT bozonur operatorebs zemoT aRwerili proceduris daxmarebiT, maSin (2.56) evoluciuri gantoleba korelaciuri funqciisTvis Caiwereba Semdegi saboloo saxiT [119]:

$$\frac{\partial}{\partial t}\langle A_s B_s(-t)\rangle = -\frac{i}{\hbar}\langle [A_s, H_s]_- B_s(-t)\rangle - \frac{1}{\hbar^2}\int_0^t dx \sum_k \{N_k(b) e^{iw(k)x} \times$$
$$\times \left\langle \left[\left[A_s, C_k^+(s)\right]_- \cdot C_k(s,-x)\right]_{-w(k)} B_s(-t)\right\rangle + (1+N_k(b)) e^{-iw(k)x} \times$$
$$\times \left\langle \left[\left[A_s, C_k(s)\right]_- \cdot C_k^+(s,-x)\right]_{w(k)} B_s(-t)\right\rangle + \frac{i}{\hbar}\int_0^b dl \sum_k \{N_k(b) e^{-iw(k)(t+i\hbar l)} \times \qquad (2.57)$$
$$\times \left\langle C_k^+(s,-t-i\hbar l)\cdot \left[A_s, C_k(s)\right]_- B_s(-t)\right\rangle + (1+N_k(b)) e^{iw(k)(t+i\hbar l)} \times$$
$$\times \left\langle C_k(s,-t-i\hbar l)\cdot \left[A_s, C_k^+(s)\right]_- B_s(-t)\right\rangle\},$$

sadac: $N_k(b) = \left[e^{b\hbar w(k)} - 1\right]^{-1}$ - warmoadgens bozonebis (fononebis) Sevsebis saSualo ricxvs, da

$$C_k(s_1 \pm Z) = e^{\pm i L_s Z} C_k(s); \;\; C_k^+(s_1 \pm Z) = e^{\pm i L_s Z} C_k^+(s)$$
$$\text{xolo} \quad [E, D]_{\pm w(k)} = ED - e^{\mp b\hbar w(k)} DE. \qquad (2.58)$$

nebismieri E da D operatorebisaTvis.

(2.57) gantolebis gamoyvanisas, Cven visargebleT agreTve Semdegi Tanafardobebi T:

$$e^{\pm i L_2 t} b_k = e^{\mp iw(k)t} b_k; \;\; e^{\pm i L_2 t} b_k^+ = e^{\pm iw(k)t} b_k^+$$
$$\mathrm{P}\left(b_k^+, b_{k'}\right) = N_k(b) d_{k,k'}; \;\; \mathrm{P}\left(b_k, b_{k'}^+\right) = \left(1+N_k(b)\right) d_{k,k'} \qquad (2.59)$$
$$\mathrm{P}\left(b_k, b_{k'}\right) = \mathrm{P}\left(b_k^+, b_{k'}^+\right) = 0.$$

Tu SevasrulebT $t \to -t$ Casmas (2.57) evoluciur gantolebaSi, maSin martivad miviRebT ganzogadoebul kvantur kinetikur gantolebas $\langle A_s B_s(t)\rangle$ korelaciuri funqciisTvis:

$$\frac{\partial}{\partial t}\langle A_s B_s(t)\rangle = \frac{i}{\hbar}\langle [A_s, H_s]_- B_s(t)\rangle - \frac{1}{\hbar^2}\int_0^t dx \cdot \sum_k \{N_k(b) \times$$
$$\times e^{-iw(k)x} \left\langle \left[\left[A_s, C_k^+(s)\right]_- \cdot C_k(s,x)\right]_{-w(k)} B_s(t)\right\rangle + \left(1+N_k(b)\right) \times$$
$$\times e^{iw(k)x} \left\langle \left[\left[A_s, C_k(s)\right]_- \cdot C_k^+(s,x)\right]_{w(k)} B_s(t)\right\rangle\} - \frac{i}{\hbar}\int_0^b dl \times \qquad (2.60)$$
$$\times \sum_k \{N_k(b) e^{iw(k)(t-i\hbar l)} \left\langle C_k^+(s,t-i\hbar l)\cdot \left[A_s, C_k(s)\right]_- B_s(t)\right\rangle +$$
$$+ \left(1+N_k(b)\right) e^{-iw(k)(t-i\hbar l)} \left\langle C_k(s,t-i\hbar l)\cdot \left[A_s, C_k^+(s)\right]_- B_s(t)\right\rangle\}.$$

(2.57)–(2.60) gantolebebi gansxvavdeba Sfm-Si miRebuli gantolebebisagan [75-77]. mesame wevrebis arsebobiT gantolebaTa marjvena nawilSi, romlebic aRweren sawyisi korelaciebis evolucias [114, 119,121-122].

dabolos, unda aRiniSnos erTi principuli sakiTxi, romelic exeba sawyisi korelaciebis evoluciis wevrebis gaTvaliswinebas ganzogadoebuli kvanturi kinetikuri gantolebebis dajaxebiT integralebSi, wonasworuli korelaciuri da grinis funqciebisTvis. Sfm – mTeli (s + S)-kvanturi dinamiuri sistemis statistikuri operatorisTvis – dafuZnebulia im daSvebaze da aRwers iseT situacias, rodesac drois sawyisi t = 0 momentisTvis adgili ar aqvs korelaciebs s-kvanturi dinamiuri qvesistemisa da S-Termostatis mdgomareobebs Soris, da drois am momentisTvis xdeba "CarTva" urTierTqmedebisa, rogorc qvesistemasa da Termostats Soris, aseve qvesistemasa da gareSe velebs Soris. cxadia, rom aseT SemTxvevaSi mTliani (s + S)-kvanturi dinamiuri sistemis sawyisi statistikuri ganawileba (statistikuri operatori drois sawyis momentSi) aiReba faqtorizebuli saxiT (ix. (2.37) formula). amitom, rogorc ukve iyo aRniSnuli, rogorc Sedegi vRebulobT ganzogadoebul kinetikur gantolebebs korelaciuri da grinis funqciebisTvis, romelTa dajaxebiTi integralebi ar Seicaven sawyisi korelaciebis evoluciis wevrebs [75-77].

yvela im realur modelebSi fizikuri sistemebisa (kvanturi disipaciuri sistemebi, Ria arawonasworuli modeluri sistemebi da sxv.), romlebsac ganixilavs statistikuri fizika (meqanika) da Termodinamika, fizikuri kinetika da a.S., qvesistemis urTierTqmedebis gamo TermostatTan, s dinamiuri qvesistemac da S Termostatic erTad Seadgenen ganuyofel nawilebs erTiani mTliani dinamiuri sistemisa - (s + S) (qvesistema plus Termostati). ufro metic, SeiZleba iTqvas, rom qvesistemasa da Termostats Soris urTierTqmedebis gamo, eqsperimentebze faqtiurad SeuZlebelia maTi erTmaneTisagan gancalkeveba. aseT situaciaSi, kinetikuri movlenebis srul da adekvatur aRwerasa da gamokvlevas, romlebic mimdinareoben mcire kvantur dinamiur qvesistemaSi, Seesabameba – mTeli (s + S) dinamiuri sistemis statistikuri operatoris sawyisi mniSvneloba – ara Sfm-is tipis, aramed iseTi saxis sawyisi mniSvnelobebi mTeli sistemis statistikuri operatorisa, romlebic iTvaliswineben korelaciebs kvanturi dinamiuri qvesistemisa da Termostatis mdgomareobebs Soris drois sawyisi momentisaTvis (t = 0) (arafaqtorizebuli sawyisi statistikuri ganawilebebi mTeli (s + S)-sistemisa) [19,21].

Cvens mier dasmuli amocanis Tanaxmad, mTeli (s + S) dinamiuri sistema drois sawyisi t = 0 momentisaTvis imyofeba statistikuri wonasworobis mdgomareobaSi, romelic aRiwereba gibsis kvanturi kanonikuri (an didi kanonikuri) ganawilebiT mTeli (s + S) sistemisTvis: $r_{eq}(b) = Z^{-1}(b)e^{-bH}$, da drois amave t = 0 momentSi xdeba urTierTqmedebis "CarTva" mTel (s + S) sistemasa da gareSe wyaroebs (velebs) Soris. amis gamo, kinetikuri procesebis mkacrad, zustad da koreqtulad aRsawerad da Sesaswavlad, romlebic mimdinareoben mcire kvantur dinamiur qvesistemaSi, romelic urTierTqmedebs TermostatTan (mag. bozonur (fononur) velTan), sawyisi korelaciebisa da sawyisi korelaciebis evoluciis wevrebis gaTvaliswinebas - ganzogadoebuli kvanturi kinetikuri gantolebebis dajaxebiT integralebSi, wonasworuli korelaciuri da grinis funqciebisTvis s-qvesistemis dinamiuri sidideebisaTvis– aqvs principuli mniSvneloba, da maTi apriori ugulvebelyofa (ignorireba) dauSvebelia [19, 21, 110, 114-115, 119-122].

miRebuli ganzogadoebuli kvanturi kinetikuri gantolebebi drois ormomentiani wonasworuli korelaciuri funqciebisTvis, sadisertacio naSromis III TavSi gamoyenebuli iqneba eleqtronuli da polaronuli gadatanis movlenebis gamosakvlevad myar sxeulebSi – naxevargamtarebsa da ionur kristalebSi [114-118, 120-122,125].

Tavi III. naxevargamtarebsa da ionuri kristalebSi eleqtronuli da polaronuli gamtarobisa da dabal temperaturuli Zvradobis kvanturi Teoria dafuZnebuli kubos wrfivi gamoZaxilis Teoriaze

rogorc ukve aRniSnuli iyo Sesavalsa da literaturis mimoxilvaSi, myar sxeulebSi gadatanis wrfivi movlenebis Sesaswavlad da denis matareblebis gadatanis kinetikuri (meqanikuri) koeficientebis gamosaTvlelad, SesaZlebelia gamoyenebuli iqnas ori gansxvavebuli midgoma: 1) dafuZnebuli kubos wrfivi gamoZaxilis (reaqciis) Teoriaze, da 2) damyarebuli kinetikur gantolebaze denis gadamtanebis ganawilebis funqciisTvis, romelic cnobilia rogorc bolcmanis gantoleba.

rogorc ukve araerTxel iyo xazgasmuli, eleqtronuli da polaronuli gadatanis movlenebis Teoriis Seswavla myar sxeulebSi da maTi kinetikuri maxasiaTeblebis gamoTvla, warmoadgens erT-erT aqtualur amocanas eleqtronisa da didi radiusis mqone polaronis kinetikis Tanamedrove TeoriaSi [29-30,37-38]. gamoviyenoT axla wina TavSi gamoyvanili ganzogadoebuli kvanturi kinetikuri gantolebebi eleqtronuli da polaronuli gadatanis movlenebis Sesaswavlad naxevargamtarebsa da ionur kristalebSi; kerZod – ganvixiloT konkretuli magaliTebi kvanturi dinamiuri qvesistemebisa, romlebic urTierTqmedeben fononur velTan: eleqtron-fononuri sistema (eleqtronis urTierTqmedeba (gabneva) polarul optikur da akustikur fononebTan), polaronis latinjer-lus (fg) modeli da maTze dayrdnobiT avagoT denis gadamtanebisTvis eleqtrogamtarobisa da Zvradobis wrfivi kvanturi Teoria da gamovTvaloT kinetikuri maxasiaTeblebi (korelaciuri funqciebis milevis devrementebi, relaqsaciis droebi (sixSireebi) da sxv.) da gadatanis meqanikuri koeficientebi (kuTri eleqtrogamtaroba, dabal temperaturuli Zvradoba, da sxv.) kvanturi disipaciuri (qve) sistemebis am kerZo modelebisTvis. ganixileba midgoma, romelic eyrdnoba kubos wrfivi reaqciisa da SeSfoTebis Teorias.

3.1. eleqtron-fononuri sistema. eleqtronis dabalsixiruli eleqtrogamtarobisa da dabal temperaturuli Zvradobis gamoTvla susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi

ganvixilоT SemTxveva nawilakis (eleqtronis) urTierTqmedebisa dakvantul fononur velTan (eleqtron-fononuri sistema), rodesac mTeli sistemis hamiltoniani moicema (1.13) formuliT da eleqtronis energias gamtarobis zonidan aqvs Semdegi zogadi saxe: $H_s = \mathrm{T}(\overline{\mathrm{P}})$.

rogorc cnobilia, kubos wrfivi reaqciis Teoriis Tanaxmad sistemaze moqmedi susti intensivobisa da ω-sixiris mqone gareSe eleqtruli velis SemTxvevaSi, eleqtrogamtarobis tenzori SesaZlebelia gamovsaxoT “deni-denze” korelaciuri funqciis saSualebiT. kubos formulis Tanaxmad eleqtrogamtarobis tenzori Caiwereba Semdegi saxiT [4,25,64,72,83]:

$$s_{mn}(w) = -\frac{i}{p\hbar}\int_{-\infty}^{+\infty} d\Omega \frac{\left(th\frac{1}{2}b\hbar\Omega\right)}{\Omega} I\{m,n\}(\Omega)\frac{1}{\Omega - w - ie} \qquad (3.1)$$

$$e > 0;\ e \to 0^{+} \qquad (m,n = x,y,z),$$

sadac: $I\{m,n\}(\Omega) = \frac{1}{2}\int_{-\infty}^{+\infty} dt e^{i\Omega t}\left[\left\langle j_n(0)J_m(t)\right\rangle + \left\langle j_m(t)J_n(0)\right\rangle\right].$

(3.1) formulis Tanaxmad eleqtrogamtarobis tenzoris disipaciuri nawilisTvis gveqneba:

$$\mathrm{Re}\, s^{s}_{mn}(w) \equiv \frac{2th(\frac{1}{2}b\hbar w)}{\hbar w}\int_{0}^{\infty} dt\cos(wt)\Psi^{s}_{mn}(t), \qquad (3.2)$$

sadac: $s^{s}_{mn}(w)$ da $\Psi^{s}_{mn}(t)$ warmoadgenen gamtarobis $s_{mn}(w)$ tenzorisa da $\Psi_{mn}(t)$ korelaciuri funqciis simetriul nawilebs:

$$s^{s}_{mn}(w) = \frac{1}{2}\left[s_{mn}(w) + s_{nm}(w)\right];$$

$$\Psi^{s}_{mn}(t) = \frac{1}{2}\left[\Psi_{mn}(t) + \Psi_{nm}(t)\right] = \frac{1}{2}\left[\Psi_{mn}(t) + \Psi_{mn}(-t)\right]; \qquad (3.3)$$

$$\Psi_{mn}(t) = \frac{1}{2}\left[\left\langle j_n(0)j_m(t)\right\rangle + \left\langle j_m(t)j_n(0)\right\rangle\right] = \frac{1}{2}\left[\left\langle j_n(0)j_m(t)\right\rangle + \left\langle j_m(0)j_n(-t)\right\rangle\right]$$

da $j_m(t) = e^{iLt}j_m(0)$ aris $\vec{j}$-eleqtruli denis operatoris m komponenti haizenbergis warmodgenaSi. amrigad, eleqtrogamtarobis gamosaTvlelad

saWiroa vipovoT: $\Psi_{mn}(t)=\frac{e^2}{2}\left[\left\langle V_n(0)V_m(t)\right\rangle+\ +\left\langle V_m(0)V_n(-t)\right\rangle\right]$ korelaciuri funqciis mniSvneloba. $\vec{V}$ warmoadgens eleqtronis siCqaris operators gamtarobis zonaSi. imisaTvis, rom vipovoT $\Psi_{mn}(t)$ korelaciuri funqciis sidide, gamoviyenoT naSromis II-TavSi miRebuli (2.57) da (2.60) miaxloebiTi evoluciuri gantolebebi wonasworuli korelaciuri funqciebisTvis eleqtron-fononuri sistemisTvis, da visargebloT mTeli sistemis hamiltonianis (1.13) gamosaxulebiT. miaxloebiT evoluciur (kinetikur) gantolebas eleqtronis drois ormomentiani wonasworuli korelaciuri funqciisTvis "siCqare-siCqare" eqneba Semdegi saxe $\left(H_s=\mathrm{T}(\bar{\mathrm{P}});\ A_s=V_n;\ B_s=V_m\right)$.[120-122]:

$$\begin{aligned}
&\frac{\partial}{\partial t}\left\langle V_n(0)V_m(t)\right\rangle=\frac{i}{\hbar}\left\langle\left[V_n,\mathrm{T}(\bar{\mathrm{P}})\right]_-V_m(t)\right\rangle-\frac{1}{\hbar^2}\int_0^t dx\sum_{\bar{k}}\left|V_{\bar{k}}\right|^2\left\{\left[e^{-iw(\bar{k})x}\ N_k(b)+\right.\right.\\
&\left.+e^{iw(\bar{k})x}\left(1+N_k(b)\right)\right]\left\langle\left[V_n,e^{i\bar{k}\bar{r}}\right]_-e^{-i\bar{k}\bar{r}(x)}V_m(t)\right\rangle-\left[e^{iw(\bar{k})x}\ N_k(b)+e^{-iw(\bar{k})x}\times\right.\\
&\left.\left.\times\left(1+N_k(b)\right)\right]\left\langle e^{-n\bar{k}\bar{r}(x)}\left[V_n,e^{i\bar{k}\bar{r}}\right]_-V_m(t)\right\rangle\right\}-\frac{i}{\hbar}\int_0^b dl\sum_{\bar{k}}\left|V_{\bar{k}}\right|^2\left[e^{iw(\bar{k})(t-i\hbar l)}\ N_k(b)+\right.\\
&\left.+e^{-iw(\bar{k})(t-i\hbar l)}\left(1+N_k(b)\right)\right]\left\langle e^{-i\bar{k}\bar{r}(t-i\hbar l)}\left[V_n,e^{i\bar{k}\bar{r}}\right]_-V_m(t)\right\rangle,
\end{aligned}\tag{3.4}$$

sadac: $V_m(t)=e^{iLt}V_m(0)$, $\bar{r}(x)=e^{\frac{i}{\hbar}\mathrm{T}(\bar{\mathrm{P}})x}\bar{r}e^{-\frac{i}{\hbar}\mathrm{T}(\bar{\mathrm{P}})x}\equiv e^{iL_sx}\vec{r}$ da $\bar{r}(x)$ aris eleqtronis Tavisufali moZraobis "traeqtoria". analogiurad Caiwereba kinetikuri gantoleba $\left\langle V_m(0)V_n(-t)\right\rangle$ korelaciuri funqciisTvis. (3.4) gantolebis gamoyvanisas Cven visargeblebT agreTve Semdegi Tanafardobebi: $w(-\bar{k})=w(\bar{k})$; $V_{-\bar{k}}=V_{\bar{k}}$.

Cven SemovifarglebiT mxolod erTi zonis miaxloebiT eleqtronisTvis, rodesac eleqtronis siCqaris operatori diagonaluria impulsur (kvaziimpulsis) warmodgenaSi da amitom adgili aqvs Semdeg tolobebs:

$$V_m(\bar{\mathrm{P}})=\frac{\partial}{\partial \mathrm{P}_m}\mathrm{T}(\bar{\mathrm{P}});\ \left[V_m(\bar{\mathrm{P}}),\mathrm{T}(\bar{\mathrm{P}})\right]_-=0,\ (m=x,y,z).$$

Cven viyenebT agreTve aRniSvnas $V_m(\bar{\mathrm{P}})$ eleqtronis siCqaris operatoris matriculi elementisTvis $\left\langle\bar{\mathrm{P}}\left|V_m\right|\bar{\mathrm{P}}\right\rangle$, romelic gamoiTvleba eleqtronis kvaziimpulsis operatoris sakuTari funqciebis $\left|\bar{\mathrm{P}}\right\rangle$ meSveobiT.

Tu SemoviRebT Semdeg relevantur (damxmare) operators (Sedarebis Tvis ix. (2.39)) $G_m(t,b)$; sawyisi mniSvnelobiT, rodesac $t=0$; $G_m(b)=G_m(t,b)\big|_{t=0}$ da ganvsazRvravT tolobebiT:

$$G_m(t,b)=Z^{-1}(b)S\mathrm{P}_\Sigma\left[V_m(t)e^{-bH}\right];\ G_m(b)=V_m\frac{Z^s(b)}{S\mathrm{P}_s\left[Z^s(b)\right]}, \tag{3.5}$$

sadac: $Z^s(b)=S\mathrm{P}_\Sigma\left[e^{-bH}\right]$ - dayvanili (reducirebuli) statjamia eleqtron-fononuri sistemisTvis; maSin SemoRebuli (3.5) operatoris daxmarebiT SesaZlebelia $\left\langle V_n(0)V_m(\pm t)\right\rangle$ - korelaciuri funqciebi da maTi Sesabamisi kinetikuri gantolebebi gamovsaxoT Semdegi formiT:

$$\begin{aligned}&\left\langle V_n(0)V_m(\pm t)\right\rangle=S\mathrm{P}_s\left[V_n(0)G_m(\pm t,b)\right]\\ &\frac{\partial}{\partial t}\left\langle V_n(0)V_m(\pm t)\right\rangle\equiv S\mathrm{P}_s\left[V_n(0)\frac{\partial}{\partial t}G_m(\pm t,b)\right]=\pm S\mathrm{P}_s\left[V_n(0)\Gamma_n(\pm t,b)G_m(\pm t,b)\right],\end{aligned} \tag{3.6}$$

sadac: operatori $\Gamma_n(t,b)$ uSualod ganisazRvreba (3.4) gantolebidan da aqvs Semdegi saxe:

$$\begin{aligned}&\Gamma_n(t,b)=-\frac{1}{\hbar^2}\int_0^t dx\sum_{\bar k}\left|V_{\bar k}\right|^2\left\{\left[e^{-iw(\bar k)x}N_{\bar k}(b)+e^{iw(\bar k)x}\left(1+N_{\bar k}(b)\right)\right]V_n^{-1}\times\right.\\ &\times\left[V_n,e^{i\bar k\bar r}\right]_-e^{-i\bar k\bar r(x)}-\left[e^{iw(\bar k)x}N_{\bar k}(b)+e^{-iw(\bar k)x}\left(1+N_{\bar k}(b)\right)\right]V_n^{-1}e^{-i\bar k\bar r(x)}\times\\ &\left.\times\left[V_n,e^{i\bar k\bar r}\right]_-\right\}-\frac{i}{\hbar}\int_0^b dl\sum_{\bar k}\left|V_{\bar k}\right|^2\left[e^{iw(\bar k)(t-i\hbar l)}N_{\bar k}(b)+e^{-nw(\bar k)(t-i\hbar l)}\left(1+N_{\bar k}(b)\right)\right]\times\\ &\times V_n^{-1}e^{-i\bar k\bar r(t-i\hbar l)}\left[V_n,e^{i\bar k\bar r}\right]_-,\end{aligned} \tag{3.7}$$

sadac: $V_n^{-1}\cdot V_n=V_n\cdot V_n^{-1}=1.$

(3.6) kinetikur gantolebebSi kvali eleqtronis (qvesistemis) mdgomareobebis mixedviT gamovTvaloT eleqtronis kvaziimpulsis operatoris $\left|\bar{\mathrm{P}}\right\rangle$ sakuTari funqciebis saSualebiT. amis gaTvaliswinebiT (4.6) Tanafardobebi SesaZlebelia CavweroT Semdegi saxiT:

$$\begin{aligned}&\left\langle V_n(0)V_m(\pm t)\right\rangle=\int d\bar{\mathrm{P}}V_n(\bar{\mathrm{P}})G_m(\pm t,b,\bar{\mathrm{P}})\\ &\int d\bar{\mathrm{P}}V_n(\bar{\mathrm{P}})\frac{\partial}{\partial t}G_m(\pm t,b,\bar{\mathrm{P}})=\pm\int d\bar{\mathrm{P}}V_n(\bar{\mathrm{P}})\Gamma_n(\pm t,b,\bar{\mathrm{P}})G_m(\pm t,b,\bar{\mathrm{P}}).\end{aligned} \tag{3.8}$$

(3.8) gantolebebis miRebisas Cven gaviTvaliswineT, rom eleqtronis siCqaris operatori diagonaluria kvaziimpulsis warmodgenaSi da, vinaidan ganixileba sivrculad erTgvarovani sistema, amitom mxolod diagonaluri

matriculi elementebi – $\left\langle \overline{\mathrm{P}}\left|\Gamma_n(t,b)\right|\overline{\mathrm{P}}\right\rangle \equiv \Gamma_n(t,b,\overline{\mathrm{P}})$; $\Gamma_n(t,b)$ - operatoris aris gansxvavebuli nulisagan. Tu visargeblebt Semdegi Tanafardobebit:

$$\left\langle \overline{\mathrm{P}}_1\left|e^{\pm i\overline{k}\overline{r}}\right|\overline{\mathrm{P}}_2\right\rangle = d\left(\overline{\mathrm{P}}_2 \pm \hbar\overline{k} - \overline{\mathrm{P}}_1\right);$$
$$e^{\pm i\overline{k}\overline{r}} f\left(\overline{\mathrm{P}}\right) = f\left(\overline{\mathrm{P}} \mp \hbar\overline{k}\right) e^{\pm i\overline{k}\overline{r}};$$
$$f\left(\overline{\mathrm{P}}\right) e^{\pm i\overline{k}\overline{r}} = e^{\pm i\overline{k}\overline{r}} f\left(\overline{\mathrm{P}} \pm \hbar\overline{k}\right),$$

sadac: $f\left(\overline{\mathrm{P}}\right)$ warmoadgens $\overline{\mathrm{P}}$ kvaziimpulsis (impulsis) nebismier funqcias da visargeblebt (3.7) gantolebit, maSin $\Gamma_n(t,b)$ operatoris $\Gamma_n(t,b,\overline{\mathrm{P}})$ matriculi elementisaTvis miviRebT Semdeg gantolebas [120]:

$$\Gamma_n(t,b,\overline{\mathrm{P}}) = \frac{2}{\hbar}\sum_{\overline{k}}\left|V_{\overline{k}}\right|^2 \frac{V_n(\overline{\mathrm{P}}+\hbar\overline{k}) - V_n(\overline{\mathrm{P}})}{V_n(\overline{\mathrm{P}})}\left\{ N_{\overline{k}}(b)\frac{\sin\left[\frac{t}{\hbar}\Delta^-(\overline{k},\overline{\mathrm{P}})\right]}{\Delta^-(\overline{k},\overline{\mathrm{P}})} + \right.$$
$$+\left(1+N_{\overline{k}}(b)\right)\frac{\sin\left[\frac{t}{\hbar}\Delta^+(\overline{k},\overline{\mathrm{P}})\right]}{\Delta^+(\overline{k},\overline{\mathrm{P}})} + \frac{i}{2}\left[N_{\overline{k}}(b)e^{-\frac{i}{\hbar}t\Delta^-(\overline{k},\overline{\mathrm{P}})}\frac{e^{-b\Delta^-(\overline{k},\overline{\mathrm{P}})}-1}{\Delta^-(\overline{k},\overline{\mathrm{P}})} + \right. \qquad (3.9)$$
$$\left.\left.+\left(1+N_{\overline{k}}(b)\right)e^{-\frac{i}{\hbar}t\Delta^+(\overline{k},\overline{\mathrm{P}})}\frac{e^{-b\Delta^+(\overline{k},\overline{\mathrm{P}})}-1}{\Delta^+(\overline{k},\overline{\mathrm{P}})}\right]\right\},$$

sadac: $\Delta^{\pm}(\overline{k},\overline{\mathrm{P}}) = \mathrm{T}(\overline{\mathrm{P}}+\hbar\overline{k}) - \mathrm{T}(\overline{\mathrm{P}}) \pm \hbar w(\overline{k})$.

ganvixiloT axla izotropuli SemTxveva, rodesac eleqtrogamtarobis tenzors da simetrizebul korelaciur funqcias aqvT Semdegnairi saxe:

$$s^s_{mn}(w) = s^s(w)d_{mn};\ \Psi^s_{mn}(t) = \Psi^s(t)d_{mn}$$

da visargebloT miaxloebiTi gantolebiT, romelic gamomdinareobs (3.8) gantolebidan:

$$\frac{\partial}{\partial t}G_m(\pm t, b, \overline{\mathrm{P}}) = \pm\Gamma_m(\pm t, b, \overline{\mathrm{P}})G_m(\pm t, b, \overline{\mathrm{P}}). \qquad (3.10)$$

cxadia, rom (3.10) kinetikuri gantoleba warmoadgens relaqsaciis drois miaxloebis (rdm) saxis aproqsimacias. naTelia, rom (3.10) miaxloebiTi gantoleba xdeba zusti, rodesac $\Gamma_m(\pm t, b, \overline{\mathrm{P}})$ funqcia ar aris damokidebuli $\overline{\mathrm{P}}$ kvaziimpulsze. magaliTad, aseT SemTxvevas aqvs adgili frolixis polaronisTvis dabali temperaturebis areSi [116-118, 120].

Tu CavatarebT (3.10) gantolebis integracias da gaviTvaliswinebT (3.5) sawyis pirobebs, maSin Cven miviRebT:

$$G_m(\pm t,b,\vec{P})=\exp\left[\tilde{\Gamma}_m(\pm t,b,\vec{P}\right]G_m(b,\vec{P});\quad \tilde{\Gamma}_m(t,b,\vec{P})=\int_0^t dt\Gamma_m(t,b,\vec{P});$$

$$G_m(b,\overline{\mathrm{P}})=\left\langle\overline{\mathrm{P}}\middle|G_m(b)\middle|\overline{\mathrm{P}}\right\rangle=\frac{V_m(\overline{\mathrm{P}})Z^s(b,\overline{\mathrm{P}})}{\int d\overline{\mathrm{P}}Z^s(b,\overline{\mathrm{P}})};\quad Z^s(b,\overline{\mathrm{P}})=\left\langle\overline{\mathrm{P}}\middle|Z^s(b)\middle|\overline{\mathrm{P}}\right\rangle. \tag{3.11}$$

Tu CavsvamT $\Gamma_m(t,b,\overline{\mathrm{P}})$-s (3.9) mniSvnelobas (3.11) formulaSi, maSin integraciis Sedegad $\tilde{\Gamma}_m(t,b,\overline{\mathrm{P}})$-Tvis Cven miviRebT gamosaxulebas:

$$\tilde{\Gamma}_m(t,b,\overline{\mathrm{P}})=\mathrm{Re}\,\tilde{\Gamma}_m(t,b,\overline{\mathrm{P}})+i\mathrm{Im}\,\tilde{\Gamma}_m(t,b,\overline{\mathrm{P}});$$

$$\mathrm{Re}\,\Gamma_m(t,b,\overline{\mathrm{P}})=\sum_{\overline{k}}\left|V_{\overline{k}}\right|^2\frac{V_m(\overline{\mathrm{P}}+\hbar\overline{k})-V_m(\overline{\mathrm{P}})}{V_m(\overline{\mathrm{P}})}\left\{N_{\overline{k}}(b)\left[1+e^{-b\Delta^-(\overline{k},\overline{\mathrm{P}})}\right]\times\right.$$

$$\left.\times\frac{1-\cos\left[\frac{t}{\hbar}\Delta^-(\overline{k},\overline{\mathrm{P}})\right]}{\left[\Delta^-(\overline{k},\overline{\mathrm{P}})\right]^2}+\left(1+N_{\overline{k}}(b)\right)\left[1+e^{-b\Delta^+(\overline{k},\overline{\mathrm{P}})}\right]\frac{1-\cos\left[\frac{t}{\hbar}\Delta^+(\overline{k},\overline{\mathrm{P}})\right]}{\left[\Delta^+(\overline{k},\overline{\mathrm{P}})\right]^2}\right\}; \tag{3.12}$$

$$\mathrm{Im}\tilde{\Gamma}_m(t,b,\overline{\mathrm{P}})=-\sum_{\overline{k}}\left|V_{\overline{k}}\right|^2\frac{V_m(\overline{\mathrm{P}}+\hbar\overline{k})-V_m(\overline{\mathrm{P}})}{V_m(\overline{\mathrm{P}})}\left\{N_{\overline{k}}(b)\frac{1-e^{-b\Delta^-(\overline{k},\overline{\mathrm{P}})}}{\left[\Delta^-(\overline{k},\overline{\mathrm{P}})\right]^2}\times\right.$$

$$\left.\times\sin\left[\frac{t}{\hbar}\Delta^-(\overline{k},\overline{\mathrm{P}})\right]+\left(1+N_{\overline{k}}(b)\right)\frac{1-e^{-b\Delta^+(\overline{k},\overline{\mathrm{P}})}}{\left[\Delta^+(\overline{k},\overline{\mathrm{P}})\right]^2}\sin\left[\frac{t}{\hbar}\Delta^+(\overline{k},\overline{\mathrm{P}})\right]\right\}.$$

(3.11) da (3.12) gamosaxulebebi asaxaven (3.6) korelaciuri funqciebis droze damokidebulebas da principSi saSualebas iZlevian, rom gamoTvliliqnes eleqtrogamtarobis tenzori (3.2)-(3.3) formulebis daxmarebiT. vinaidan Cven SemovifarglebiT SeSfoTebis Teoriis mxolod meore miaxloebiT (3.4) kinetikur gantolebaSi eleqtron-fononuri urTierTqmedebis $H_i\left(V_{\overline{k}}\right)$ hamiltonianis mixedviT, amitom Tanmimdevrobis dacvis mizniT SevasruloT miaxloeba: $e^{-bH}\Rightarrow e^{-bH_0}=e^{-bH_s}e^{-bH_\Sigma}$ - korelaciuri funqciebis (3.5)-(3.11) – sawyisi mniSvnelobebisaTvis. Aamrigad Cven gvaqvs:

$$G_m(b)=\frac{e^{-bH_s}}{S\mathrm{P}_s\left[e^{-bH_s}\right]}V_m;\quad G_m(b,\overline{\mathrm{P}})=\frac{e^{-b\Gamma(\overline{\mathrm{P}})}}{\int d\overline{\mathrm{P}}e^{-b\Gamma(\overline{\mathrm{P}})}}V_m(\overline{\mathrm{P}}). \tag{3.13}$$

(3.8), (3.11) da (3.13) gantolebebs mivyavarT Semdeg gamosaxulebamde $\Psi_{mn}(t)$ korelaciuri funqciisaTvis:

$$\Psi_{mn}(t)=\frac{e^2}{2}\frac{\int d\overline{\mathrm{P}}e^{-b\Gamma(\overline{\mathrm{P}})}V_n(\overline{\mathrm{P}})V_m(\overline{\mathrm{P}})\left\{\exp\left[\tilde{\Gamma}_n(t,b,\overline{\mathrm{P}})\right]+\exp\left[\tilde{\Gamma}_m(-t,b,\overline{\mathrm{P}})\right]\right\}}{\int d\overline{\mathrm{P}}e^{-b\Gamma(\overline{\mathrm{P}})}}, \tag{3.14}$$

sadac: $\tilde{\Gamma}_n(t,b,\bar{\mathrm{P}})$ da $\tilde{\Gamma}_m(-t,b,\bar{\mathrm{P}})$ ganisazRvrebian (3.12) formulebiT.

(3.12) da (3.14) tolobebis Tanaxmad, eleqtronis (qvesistemis) korelaciuri funqciebi miilevian oscilaciebiT imis gamo, rom relaqsaciis $\tilde{\Gamma}_n(t,b,\bar{\mathrm{P}})$-faqtori warmoadgens kompleqsur sidides, da rogorc Cven mogvianebiT vaCvenebT, es oscilaciebi "sicocxlis unariani" arian didi droebis asimptotur areSi $t>>t_0$ da iZlevian wvlils gadatanis kinetikur koeficientebSi (eleqtrogamtaroba, Zvradoba) [117-118, 120-122]. es daskvna gamomdinareobs im martivi garemoebidan, rom wonasworuli droiTi korelaciuri funqciebis gansazRvrebaSi (ix. mag. (2.6) formula) figurirebs gibsis ganawileba, romelic Seicavs sawyisi korelaciebis wevrs (H_{int}) da romlis zusti gaTvaliswinebac xdeba evoluciur (kinetikur) gantolebebSi am funqciebisTvis. Sfm-Si $\Gamma_n(t,b,\bar{\mathrm{P}})$ _ relaqsaciis faqtoris warmosaxviTi nawili nulis tolia, da, amitom zemoT miTiTebul oscilaciebs adgili ar eqneba [75,77]. unda aRiniSnos, rom ganxiluli msjeloba samarTliania im SemTxvevaSi, rodesac adgili aqvs droTa ierarqias (ix. (2.34) formula); rogorc (3.12) formulidan naTlad Cans, im SemTxvevaSi, rodesac ganixileba eleqtronis urTierTqmedeba fononebTan: $t_s \sim \hbar b$ da $t_\Sigma \sim \dfrac{1}{v}$, sadac $\bar{w}$- warmoadgens fononTa maxasiaTebel sixSires. ufro metic, (3.12) gamosaxulebidan gamomdinareobs, rom energiis Senaxvis kanoni eleqtronis fononebTan gabnevis procesis dros samarTliania didi droebis SemTxvevaSi: $t>>t_0$, $t_0=\max(t_s,t_\Sigma)$; Tu ganvixilavT droTa did intervals $t>>t_0$, maSin Cven SegviZlia SevasruloT zRvruli gadasvla $t\to\infty$ (3.12) gamosaxulebaSi da, rogorc Sedegi miviRebT [120]:

$$\lim_{t\to\infty}\mathrm{Re}\tilde{\Gamma}_n(t,b,\bar{\mathrm{P}})=-\Gamma_n^{rel}(b,\bar{\mathrm{P}})|t|=-\frac{1}{t^{rel}(b,\bar{\mathrm{P}})}|t|;$$

$$\Gamma_n^{rel}(b,\bar{\mathrm{P}})=-\frac{2p}{\hbar}\sum_{\bar{k}}|V_{\bar{k}}|^2\frac{V_n(\bar{\mathrm{P}}+\hbar\bar{k})-V_n(\bar{\mathrm{P}})}{V_n(\bar{\mathrm{P}})}\Big\{N_{\bar{k}}(b)d\left[\Delta^-(\bar{k},\bar{\mathrm{P}})\right]+$$

$$+\left(1+N_{\bar{k}}(b)\right)d\left[\Delta^+(\bar{k},\bar{\mathrm{P}})\right]\Big\}; \qquad (3.15)$$

$$\lim_{t\to\infty}\mathrm{Im}\tilde{\Gamma}_n(t,b,\bar{\mathrm{P}})=-bp\sum_{\bar{k}}|V_{\bar{k}}|^2\frac{V_n(\bar{\mathrm{P}}+\hbar\bar{k})-V_n(\bar{\mathrm{P}})}{V_n(\bar{\mathrm{P}})}\Big\{N_{\bar{k}}(b)d\left[\Delta^-(\bar{k},\bar{\mathrm{P}})\right]+$$

$$+\left(1+N_{\bar{k}}(b)\right)d\left[\Delta^+(\bar{k},\bar{\mathrm{P}})\right]\Big\}Signt.$$

(3.15) formulebis gamoyvanisas Cven visargebleT Tanafardobebi T:

$$\lim_{t\to\infty}\frac{1-\cos(wt)}{w^2}=p\,|t|d(w);\ \ \lim_{t\to\infty}\frac{\sin(wt)}{w}=pd(w)Signt.$$

aRvniSnavT, rom (3.15) gamosaxulebebSi $\lim_{t\to\infty}$ zRvrul gadasvlamde unda Sesruldes Termodinamikuri zRvruli gadasvla (T-zRvari):

$$\sum_{\bar{k}}(...)=\frac{V}{(2p)^3}\int d\bar{k}(...).$$

cxadia, rom Zalian didi droebis asimptotur areSi, rodesac $(t>>t_0,t\to\infty)$ (3.15) Tanafardobebi Cven gvaZlevs Semdeg tolobas:

$$\lim_{t\to\infty}\mathrm{Im}\tilde{\Gamma}_n(t,b,\bar{\mathrm{P}})=\frac{1}{2}b\hbar\Gamma_n^{rel}(b,\bar{\mathrm{P}})Signt. \qquad (3.16)$$

amrigad, $\Gamma_n^{rel}(b,\bar{\mathrm{P}})$ - sidide, romelic faqtiurad warmoadgens eleqtronis “siCqare-siCqare” – korelaciuri funqciis milevis dekrements – SesaZlebelia ganxilul iqnas rogorc eleqtronis $V_n(\bar{\mathrm{P}})$ siCqaris ? – komponentis relaqsaciis sixSire ($t_n^{rel}(b,\bar{\mathrm{P}})$- warmoadgens Sesabamis relaqsaciis dros).

dabolos, Tu visargeblebT (3.2)-(3.3) da (3.14)-(3.15) TanafardobebiT, sabolood vpoulobT gamosaxulebas kuTri eleqtrogamtarobis disipaciuri nawilisTvis [120]:

$$\mathrm{Re}\,s_{mn}^{s}=ne^2\frac{th\left(\frac{1}{2}b\hbar w\right)}{\hbar w}\int d\vec{\mathrm{P}}r_s(b,\bar{\mathrm{P}})V_n(\bar{\mathrm{P}})V_m(\bar{\mathrm{P}})\left\{\cos\left[\frac{b\hbar}{2}\Gamma_n^{rel}(b,\bar{\mathrm{P}})\right]\times\right.$$

$$\left.\times\frac{\Gamma_n^{rel}(b,\bar{\mathrm{P}})}{w^2+\left[\Gamma_n^{rel}(b,\bar{\mathrm{P}})\right]^2}+\cos\left[\frac{b\hbar}{2}\Gamma_m^{rel}(b,\bar{\mathrm{P}})\right]\frac{\Gamma_m^{rel}(b,\bar{\mathrm{P}})}{w^2+\left[\Gamma_m^{rel}(b,\bar{\mathrm{P}})\right]^2}\right\}, \qquad (3.17)$$

sadac: n - warmoadgens eleqtronebis koncentracias gamtarobis zonaSi, xolo $r_s(b,\bar{\mathrm{P}})=e^{-b\Gamma(\bar{\mathrm{P}})}\Big/\int d\vec{\mathrm{P}}e^{-b\Gamma(\bar{\mathrm{P}})}$.

eleqtronis dabal temperaturuli Zvradoba, romelic damokidebulia gareSe eleqtruli velis ? sixSireze (ac-mobility), SesaZlebelia warmodgenili iqnas Semdegi saxiT (saubaria dreiful Zvradobaze):

$$m(w)=m_0(w)-\Delta m(w),$$

sadac:

$$m_0(w)=\frac{eth\left(\frac{1}{2}b\hbar w\right)}{\hbar w}\int d\vec{P}r_s(b,\vec{P})V_V(\vec{P})V_m(\vec{P})\left\{\frac{\Gamma_V^{rel}(b,\vec{P})}{w^2+\left[\Gamma_V^{rel}(b,\vec{P})\right]^2}+\frac{\Gamma_m^{rel}(b,\vec{P})}{w^2+\left[\Gamma_m^{rel}(b,\vec{P})\right]^2}\right\};$$

$$\Delta m(w)=\frac{2eth\left(\frac{1}{2}b\hbar w\right)}{\hbar w}\int d\vec{P}r_S(b,\vec{P})V_V(\vec{P})V_m(\vec{P})\times \qquad (3.18)$$

$$\times\left\{\sin^2\left[\frac{b\hbar}{4}\Gamma_V^{rel}(b,\vec{P})\right]\frac{\Gamma_V^{rel}(b,\vec{P})}{w^2+\left[\Gamma_V^{rel}(b,\vec{P})\right]^2}+\sin^2\left[\frac{b\hbar}{4}\Gamma_m^{rel}(b,\vec{P})\right]\cdot\frac{\Gamma_m^{rel}(b,\vec{P})}{w^2+\left[\Gamma_m^{rel}(b,\vec{P})\right]^2}\right\};(w<<t_0^{-1}).$$

rogorc naTlad Cans (3.17) da (3.18) gamosaxulebebidan, sawyisi korelaciebi, romlebic gamowveulia eleqtronis urTierTqmedebiT fononebTan, figurireben am formulebSi $\cos\left[\frac{b\hbar}{2}\Gamma_n^{rel}(b,\overline{P})\right]$ da $\sin^2\left[\frac{b\hbar}{4}\Gamma_n^{rel}(b,\overline{P})\right]$ Tanamamravlebis saxiT; magram, vinaidan adgili aqvs droTa ierarqias (ix. (2.34)), amitom $b\hbar\Gamma_n^{rel}(b,\overline{P})<<1;(t^{rel}(b,\overline{P}),\sim 1/\Gamma_n^{rel}(b,\overline{P}),t_s\sim b\hbar)$. unda aRiniSnos, rom sawyisi korelaciebi ar axdenen gavlenas $t_n^{rel}(b,\vec{p})$ relaqsaciis droze. $\Delta m(w)$-sidide warmoadgens temperaturul Sesworebas eleqtronis $m_0(w)$ dabal temperaturul da sixSirul Zvradobaze, romelic gamowveulia sawyisi korelaciebis arsebobiT eleqtronis urTierTqmedebisas fononebTan arsebul sistemaSi [120].

Sfm-Si droiTi wonasworuli korelaciuri funqciebisTvis Cven ugulvebelvyofT H_{int} urTierTqmedebas e^{-bH} gibsis faqtorSi [75-77], magram vinarCunebT am urTierTqmedebas $e^{\pm\frac{i}{\hbar}Ht}$ evoluciis operatorebSi, ris Sedegadac aseT miaxloebas mivyavarT Semdegi aproqsimaciebis Sesrulebamde (3.17)-(3.18) gamosaxulebebSi: $\cos\left[\frac{b\hbar}{2}\Gamma_m^{rel}(b,\overline{P})\right]\Rightarrow 1;\ \cos\left[\frac{b\hbar}{2}\Gamma_n^{rel}(b,\overline{P})\right]\Rightarrow 1.$ anu $b\hbar\Gamma_m^{rel}(b,\overline{P})\Rightarrow 0;\quad b\hbar\Gamma_n^{rel}(b,\overline{P})\Rightarrow 0;$ amgvarad, Sfm-Si Sesworeba Zvradobaze $\Delta m(w)\Rightarrow 0.$

amrigad, Cvens mier napovni gamosaxulebebi kuTri eleqtrogamtarobisTvis, dabal temperaturuli Zvradobisa da eleqtronis “siCqare-siCqare” korelaciuri funqciebisTvis warmoadgenen yvelaze ufro zogads ganxiluli modelis CarCoebSi da Sesrulebuli miaxloebebis farglebSi [112-113,120].

3.2. eleqtronis Zvradoba frolixis polaronis modelSi ("$\frac{3}{2b\hbar w_0}$ problema" polaronis dabal temperaturuli Zvradobis TeoriaSi)

ganvixiloT axla eleqtroni, romelic moZraobs polarul naxevargamtarSi an ionur kristalSi, romlis moZraoba aRiwereba (1.13)-(1.18) hamiltonianiT da romelic sustad urTierTqmedebs polarul optikur fononebTan: ($a<1$) (e.w. frolixis polaronis modeli) [29-30]. ganixileba eleqtronis urTierTqmedeba dispersiis armqone optikur fononebTan, rodesac $w(\bar{k})\equiv w_0$. vinaidan eleqtronis energiisTvis gamtarobis zonidan gvaqvs gamosaxuleba $T(\vec{P})=\frac{\vec{P}^2}{2m}$, amitom eleqtronis siCqaris m-komponentisTvis gveqneba Semdegi formula:

$$V_m(\vec{P})=\frac{P_m}{m} \tag{3.19}$$

rogorc (3.14), (3.15) da (3.17) gamosaxulebebidan Cans, sakiTxi daiyvaneba eleqtronis relaqsaciis sixSiris: $\Gamma_m^{rel}(b,\vec{P})$- gamoTvlaze, romelic zogad SemTxvevaSi damokidebulia eleqtronis $\vec{P}$ impulsze.

davuSvaT, rom eleqtruli veli mimarTulia z RerZis dadebiTi mimarTulebis gaswvriv, da, gansazRvrulobisaTvis ganvixiloT $\Gamma_z^{rel}(b,\vec{P})$. Tu SevasrulebT Termodinamikur zRvrul gadasvlas da CavatarebT integracias $|\vec{k}|$ cvladis mixedviT, maSin (1.18) da (3.15) gamosaxulebebidan miviRebT:

$$\Gamma_0^{rel}(b,\tilde{\tilde{P}})=\frac{a w_0}{2p}\frac{1}{\tilde{\tilde{P}}_z}\left\{N_0(g)\int_0^{2p}dj\int_0^{p}dq\sin q\cos q\,\frac{\tilde{P}\cos\Phi}{\sqrt{\tilde{P}^2\cos^2\Phi+1}}+\right.$$

$$\left.+(1+N_0(g))\int_0^{2p}dj\int_0^{p}dq\sin q\cos q\,\frac{\tilde{P}\cos\Phi}{\sqrt{\tilde{P}^2\cos^2\Phi-1}}\right\}(\tilde{P}^2\cos^2\Phi\geq 1). \tag{3.20}$$

aq Cven SemoviReT eleqtronis uganzomilebo impulsi:

$\tilde{P}_i=\frac{P_i}{\sqrt{2m\hbar w_0}}; i=(x,y,z)$ da $N_0(g)=\left[e^g-1\right]^{-1}$; $g=b\hbar w_0$.

Φ - warmoadgens kuTxes $\vec{k}$ da $\tilde{\tilde{P}}$ veqtorebs Soris, romelic dakavSirebulia q da j kuTxeebTan (q da j kuTxeebi gansazRvraven $\vec{k}$ veqtoris mimarTulebas) Semdegi Tanafardobit:

$$\tilde{\mathrm{P}}\cos j = \sin q\cos j\tilde{\mathrm{P}}_x + \sin q\sin j\tilde{\mathrm{P}}_y + \cos q\tilde{\mathrm{P}}_z.$$

(3.20) gamosaxulebis gamosaTvlelad SemovisazRvroT dabali temperaturebis SemTxveviT, rodesac

$$g >> 1 \qquad (3.21)$$

da (3.14) korelaciuri funqciebi gansazRvrulia eleqtronis impulsis mcire mniSvnelobebiT:

$$\tilde{\mathrm{P}}^2 << 1. \qquad (3.22)$$

am SemTxvevaSi, eleqtroni moZraobs “mcire” siCqariT da mas ar SeuZlia gamoasxivos fononebi, vinaidan ar eqneba adgili energiisa da impulsis Senaxvis kanonebs eleqtronis gabnevisas fononebze (ix. (3.15) da (3.20)). amgvarad, rodesac sruldeba (3.21) da (3.22) pirobebi, (3.20) gamosaxulebis meore wevri mis marjvena nawilSi xdeba nulis toli. Tu gaviTvaliswinebT, rom $\tilde{\mathrm{P}}^2\cos^2\Phi << 1$, maSin (3.20) gamosaxuleba SesaZlebelia warmovadginoT Semdegi saxiT:

$$\Gamma_z^{rel}(g,\tilde{\tilde{\mathrm{P}}}) \equiv \Gamma_0^{rel}(g) = \frac{2}{3}a w_0 \mathrm{N}_0(g);(\tilde{\mathrm{P}}^2 << 1). \qquad (3.23)$$

amrigad, “mcire” siCqareebiT moZravi eleqtronis impulsis relaqsaciis sixSire (dro) ar aris damokidebuli eleqtronis impulsze da ganpirobebulia mxolod im procesebiT, romlis drosac xdeba fononebis STanTqma mis mier. Tu gaviTvaliswinebT (3.23) Tanafardobas, maSin (3.14)-dan Cven miviRebT:

$$\left\langle V_z(0)V_z(\pm t)\right\rangle = \frac{\hbar w_0}{mg}\exp\left[-\Gamma_0^{rel}(g)|t|\right]\exp\left[\pm\frac{ig}{2w_0}\Gamma_0^{rel}(g)\right]$$

$$(g >> 1, t >> \frac{g}{w_0}). \qquad (3.24)$$

(3.24) gamosaxulebis gamoTvlisas Cven visargebleT Semdegi formulebiT:

$$\int d\tilde{\tilde{P}}e^{-g\tilde{\tilde{P}}^2}\tilde{P}_z^2 = \frac{1}{2g}\left(\frac{p}{g}\right)^{\frac{3}{2}};\quad \int d\tilde{\tilde{P}}e^{-g\tilde{\tilde{P}}^2} = \left(\frac{p}{g}\right)^{\frac{3}{2}} \qquad (3.25)$$

amrigad, rogorc (3.24) gamosaxulebidan Cans, eleqtronis “siCqare-siCqare” korelaciuri funqciebi eqsponencialurad miilevian drois mixedviT dabali temperaturebis ganxilul SemTxvevaSi. (3.24)-is Tanaxmad relaqsaciis droisTvis gveqneba Semdegi gamosaxuleba: $t^{rel}(g) = \left[\Gamma_0^{rel}(g)\right]^{-1}$.

cxadia, rom Cvens mier miRebuli rezultati napovnia Sfm-is gamoyenebis gareSe [120]. (3.24) gamosaxuleba gansxvavdeba Sedegisagan, romelic napovnia Sfm-Si [77] eqsponencialuri faqtoriT $\exp\left[\pm\frac{ig}{2w_0}\Gamma_0^{rel}(g)\right]$.

gamovTvaloT axla eleqtrogamtaroba da dabaltemperaturuli Zvradoba eleqtronisTvis frolixis polaronis modelSi susti eleqtron-fononuri urTierTqmedebis dros: $(a<1)$. Tu gaviTvaliswinebT (3.19) da (3.23)–(3.25) gamosaxulebebs, (3.17) formulidan kuTri eleqtrogamtarobisTvis miviRebT [120]:

$$\mathrm{Re}\, s(\tilde{w}) = \frac{ne^2}{mw_0}\frac{2}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)\left[1-2\sin^2\left(\frac{g}{2}\Gamma_0(g)\right)\right]\frac{\Gamma_0(g)}{\tilde{w}^2+\Gamma_0^2(g)}; \qquad (3.26)$$

$$(a<1, g>>1, \tilde{w}g<<1),$$

sadac: $s(\tilde{w}) = s_{xx}(\tilde{w}) = s_{yy}(\tilde{w}) = s_{zz}(\tilde{w});\ \tilde{w} = \frac{w}{w_{0;}};\ \Gamma_0(g) = w_0^{-1}\Gamma_0^{rel}(g) = \frac{2}{3}aN_0(g)$ xolo dabaltemperaturuli da dabalsixSiruli ZvradobisaTvis Sesabamisad gveqneba:

$$m_0(\tilde{w}) = \frac{e}{mw_0}\frac{2}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)\frac{\Gamma_0(g)}{\tilde{w}^2+\Gamma_0^2(g)}; \qquad (3.27)$$

$$\Delta m(\tilde{w}) = \frac{e}{mw_0}\frac{4}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)\sin^2\left(\frac{g}{2}\Gamma_0(g)\right)\frac{\Gamma_0(g)}{\tilde{w}^2+\Gamma_0^2(g)}$$

$$(a<1, g>>1, \tilde{w}g<<1).$$

(3.26) da (3.27) gamosaxulebebi warmoadgenen osakas Sedegis ganzogadoebas [55-56] susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi; (3.26) gamosaxuleba faqtiurad warmoadgens drudes formulas dabaltemperaturuli da dabalsixSiruli eleqtrogamtarobisTvis, romelic Seicavs temperaturul Sesworebas, romelic ganpirobebulia eleqtronis fononebTan arsebuli sawyisi korelaciebiT (meore wevri (3.26) formulaSi. Zvradobaze Sesworeba – $\Delta m(\tilde{w})$ moicema (3.27) formuliT). pirveli wevri (3.26) formulaSi da $m_0(w)$-s gamosaxuleba Seesabameba Sfm-s. vinaidan $\tilde{w}g<<1$ (romelic gamomdinareobs $t>>t_0$ pirobidan) da $g.\Gamma_0(g)<<1$ (ix. (2.34) piroba), Cven SegviZlia gavSaloT $\frac{2}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)$ da $\sin^2\left(\frac{g}{2}\Gamma_0(g)\right)$ wevrebi mwkrivebad (3.26) da (3.27) gamosaxulebebSi. naTelia, rom Sesworebebi, romlebic ganpirobebulia sawyisi korelaciebiT, warmoadgenen

mcire sidideebs ($g >> 1$). (3.27) gamosaxulebebidan eleqtronis dabaltemperaturuli statikuri ZvradobisTvis (dc-mobility) frolixis polaronis modelSi gveqneba [120]:

$$m_0 = \frac{e}{mw_0}\Gamma_0^{-1}(g) = \frac{e}{mw_0}\frac{3}{2a}e^g;$$
$$\Delta m = \frac{2e}{mw_0}\sin^2\left[\frac{g}{2}\Gamma_0(g)\right]\Gamma_0^{-1}(g) = \frac{e}{mw_0}\frac{1}{3}ag^2e^{-g}; \qquad (3.28)$$
$$(g >> 1, a < 1).$$

napovni (3.28) gamosaxulebebi warmoadgens Tanamimdevrul da swor rezultats eleqtronis dabaltemperaturuli Zvradobisa, frolixis polaronis modelSi, mcire temperaturuli SesworebiT susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi [114-118,120].

ganvixiloT axla eleqtronis gamtaroba da Zvradoba polaronis frolixis modelSi eleqtruli velis maRali sixSireebis SemTxvevaSi, rodesac adgili aqvs Semdeg Tanafardobas:

$$\Gamma_m^{rel}(b,\vec{\mathrm{P}}) << w << t_0^{-1}. \qquad (3.29)$$

izotropul SemTxvevaSi, (3.17) formulis Tanaxmad gveqneba (ix. agreTve (3.18)):

$$w^2\mathrm{Re}s_{0z}^s(w) = ne^2\frac{th(\frac{1}{2}b\hbar w)}{\hbar w}\int d\vec{\mathrm{P}}r_s(b,\vec{\mathrm{P}})V_z^2(\vec{\mathrm{P}})\Gamma_z^{rel}(b,\vec{\mathrm{P}});$$
$$w^2\mathrm{Re}\Delta s_z^s(w) = 2ne^2\frac{th(\frac{1}{2}b\hbar w)}{\hbar w}\int d\vec{\mathrm{P}}r_s(b,\vec{\mathrm{P}})V_z^2(\vec{\mathrm{P}})\Gamma_z^{rel}(b,\vec{\mathrm{P}})\times \qquad (3.30)$$
$$\times\sin^2\left[\frac{b\hbar}{2}\Gamma_z^{rel}(b,\vec{\mathrm{P}})\right].$$

sadac: $r_s(b,\vec{\mathrm{P}})$ moicema Semdegi gamosaxulebiT:

$$r_s(b,\vec{\mathrm{P}}) = \mathrm{e}^{-\frac{b\vec{\mathrm{P}}^2}{2m}}\Big/\int d\vec{\mathrm{P}}\mathrm{e}^{-\frac{b\vec{\mathrm{P}}^2}{2m}}. \qquad (3.31)$$

izotropulobis gamo, eleqtronis impulsis relaqsaciis sixSire $\Gamma^{rel}(b,\vec{\mathrm{P}})$ warmoadgens skalarul sidides da is SesaZlebelia warmovadginoT Semdegi saxiT (ix. SedarebisTvis (3.15) formula):

$$\Gamma^{rel}(b,\vec{\mathrm{P}}) = -\frac{2p}{\hbar}\sum_{\vec{k}}\left|V_{\vec{k}}\right|^2\frac{(\vec{k}\cdot\vec{\mathrm{P}})}{\vec{\mathrm{P}}^2}\left\{(1+N_0(b))d\left[\Delta^+(\vec{k},\vec{\mathrm{P}})\right]+\right.$$
$$\left.+N_0(b)d\left[\Delta^{(-)}(\vec{k},\vec{\mathrm{P}})\right]\right\}. \qquad (3.32)$$

gamovTvaloT axla (3.32)-is daxmarebiT eleqtronebis kuTri eleqtrogamtaroba da Zvradoba eleqtruli velis maRali $\tilde{w}$-sixSireebis SemTxvevaSi. vipovoT jer $s_0(\tilde{w})$-kuTri eleqtrogamtarobis mniSvneloba. Tu CavsvamT $\Gamma^{rel}(b,\tilde{\mathrm{P}})$-s (3.32) gamosaxulebas (3.30)-is pirvel formulaSi, CavatarebT martiv gardaqmnebs da gamoviyenebT (3.19) da (3.31) formulebs, maSin $\tilde{\mathrm{P}}$-impulsuri cvladiT integraciisa da Termodinamikuri zRvruli gadasvlis Semdeg, $s_0(\tilde{w})$-eleqtrogamtarobisTvis miviRebT Semdeg gamosaxulebas:

$$
\begin{aligned}
& s_0(\tilde{w}) = \frac{ne^2}{mw_0}\tilde{s}_0(\tilde{w}); \\
& \tilde{w}^2\tilde{s}_0(\tilde{w}) = \frac{2}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)\frac{2}{3\sqrt{p}}ag^{3/2}N_0(g)\int_0^\infty dk\left[e^g\left(k+\frac{1}{k}\right)\times\right. \\
& \left.\times e^{-\frac{g}{4}\left(k+\frac{1}{k}\right)^2}+\left(k-\frac{1}{k}\right)e^{-\frac{g}{4}\left(k-\frac{1}{k}\right)^2}\right]; \qquad \mathrm{Re}\, s_0(\tilde{w}) \equiv s_0(\tilde{w}),
\end{aligned}
\tag{3.33}
$$

sadac: $\tilde{s}_0(\tilde{w})$ warmoadgens uganzomilebo dinamiur (sixSireze damokidebul) gamtarobas, xolo uganzomilebo parametrebi: g, $\tilde{w}$ da $N_0(g)$ moicema (3.20) da (3.26) formulebiT. SevniSnoT, rom sixSireze damokidebul eleqtronis ZvradobisaTvis (3.33)-is msgavsad gveqneba: $m_0(\tilde{w}) = \frac{e}{mw_0}\tilde{m}_0(\tilde{w})$ da $\tilde{m}_0(\tilde{w}) \equiv \tilde{s}_0(\tilde{w})$.

eleqtronis dinamiuri gamtarobisTvis miRebuli (3.33) gamosaxuleba frolixis polaronis modelSi SesaZlebelia CavweroT kompaqturi formiT, Tu CavatarebT integracias k-cvladiT (3.33) gamosaxulebaSi. gveqneba:

$$
\tilde{w}^2\tilde{s}_0(\tilde{w}) = \frac{2}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)\frac{2}{3\sqrt{p}}ag^{3/2}e^{\frac{g}{2}}N_0(g)K_1\left(\frac{1}{2}g\right), \tag{3.34}
$$

sadac: $K_1(z)$ warmoadgens pirveli gvaris makdonaldis funqcias.

(3.32) formula saSualebas iZleva, rom gamoTvlili iqnas eleqtronis impulsis relaqsaciis sixSire, $\vec{k}$-cvladiT integraciis Semdeg. (3.32) gamosaxuleba: $\Gamma^{rel}(b,\tilde{\mathrm{P}})$-sididisTvis miiRebs Semdeg saxes:

$$
\Gamma_0^{rel}(g,\tilde{\mathrm{P}}) = w_0 a\frac{1}{\tilde{\mathrm{P}}^2}\left\{(1+\mathrm{N}_0(g))q(\tilde{\mathrm{P}}-1)\left[\sqrt{\tilde{\mathrm{P}}^2-1}+\frac{1}{\tilde{\mathrm{P}}}arcch\tilde{\mathrm{P}}\right]+\mathrm{N}_0(g)\left[\sqrt{\tilde{\mathrm{P}}^2+1}-\frac{1}{\tilde{\mathrm{P}}}arcsh\tilde{\mathrm{P}}\right]\right\} \tag{3.35}
$$

cxadia, rom eleqtronis impulsis mcire mniSvnelobebisaTvis, rodesac: $\tilde{P} << 1$, $\tilde{P} \to 0$. (3.35) formulidan avtomaturad miviRebT (3.23) gamosaxulebas eleqtronis impulsis (siCqaris) relaqsaciis sixSirisaTvis. eleqtrogamtarobis (3.34) gamosaxuleba samarTliania (3.29) pirobebis dacviT. (3.29) utolobebs uganzomilebo sidideebis saxiT Cawerils, eqneba Semdegi saxe:

$$\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << \tilde{w} << \min\left(\frac{1}{g};1\right) \qquad (3.36)$$

sadac: $\Gamma_0^{rel}(g,\tilde{P}) = w_0\tilde{\Gamma}_0^{rel}(g,\tilde{P})$ da $\Gamma_0^{rel}(g,\tilde{P})$ aris uganzomilebo, eleqtronis impulsis relaqsaciis sixSire. unda aRiniSnos, rom dinamiuri gamtarobis (3.34) gamosaxuleba samarTliania kristalis, rogorc dabali, aseve maRali temperaturebis mniSvnelobebisaTvis. GgamovikvlioT axla $\tilde{s}_0(\tilde{w})$ eleqtrogamtarobis $\tilde{w}$ sixSiresa da T-temperaturaze damokidebuleba am sidideebis sxvadasxva mniSvnelobebis dros.

I) dabali temperaturebis SemTxveva, rodesac $\Gamma_0^{rel}(g,\tilde{P}) << \frac{1}{g} << 1$ (3.36) utolobis Tanaxmad Cven gvaqvs: $\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << \tilde{w} << \frac{1}{g} << 1$.vinaidan $g\tilde{w} << 1$ da $N_0(g) \Rightarrow e^{-g}$; $\frac{2}{g\tilde{w}} th\left(\frac{1}{2}g\tilde{w}\right) \Rightarrow 1$; $K_1\left(\frac{1}{2}g\right) \Rightarrow \sqrt{\frac{p}{g}}e^{-\frac{g}{2}}$, $(g >> 1)$; amitom eleqtronis gamtarobisaTvis (ZvradobisTvis) gveqneba yofaqceva:

$$\tilde{w}^2 \operatorname{Re}\tilde{s}(\tilde{w}) = \tilde{w}^2\tilde{m}_0(\tilde{w}) \approx \frac{4}{3}ag\,e^{-g} \qquad (3.37)$$
$$g \to \infty.$$

amrigad kristalis dabali temperaturebis areSi eleqtronis Zvradoba ukuproporciulia sixSiris kvadratisa SedarebiT maRali sixSireebis SemTxvevaSi da eqsponencialurad mcirdeba temperaturis SemcirebasTan erTad. ganvixiloT axla kristalis SedarebiT maRali temperaturebis SemTxveva.

II) maRal temperaturaTa are, rodesac $\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << 1 << \frac{1}{g}$ kristalis temperaturaTa am areSi gamoiyofa $\tilde{w}$-sixSireTa ori are, ganvixiloT TiToeuli maTgani cal-calke.

1). SedarebiT dabal sixSiruli are, rodesac: $\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << \tilde{w} << 1 << \frac{1}{g}; g \to 0$. aseT SemTxvevaSi Cven gveqneba Semdegi Tanafardobebi (utolobebi): $g\tilde{w} << 1; \frac{2}{g\tilde{w}} th\left(\frac{1}{2}g\tilde{w}\right) \Rightarrow 1; \qquad K_1\left(\frac{1}{2}g\right) \Rightarrow \frac{2}{g}, (g << 1)$ amitom eleqtronis ZvradobisTvis gveqneba Semdegnairi yofaqceva T-temperaturisa da $\tilde{w}$ sixSiris mixedviT:

$$\tilde{w}^2 \tilde{m}_0(\tilde{w}) \approx \frac{8}{3\sqrt{p}} a g^{-1/2}; \quad (g \to 0). \tag{3.38}$$

2). SedarebiT maRalsixSiruli are, rodesac: $\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << 1 << \tilde{w} << \frac{1}{g}$ naTelia, rom SedarebiT maRalsixSirul areSi eleqtronis ZvradobisTvis gveqneba iseTive yofaqceva, rogoric SedarebiT dabalsixSirul areSi, romelic moicema (3.38) gamosaxulebiT. (3.30)- gamosaxulebis daxmarebiT martivad gamoiTvleba temperaturuli Sesworeba eleqtronis Zvradobaze maRalsixSirul areSi da kristalis dabali temperaturebis SemTxvevaSi:

$$\frac{\Delta\tilde{m}(\tilde{w})}{\tilde{m}_0(\tilde{w})} = 2\sin^2\left[\frac{g}{2}\tilde{\Gamma}_0^{rel}(g)\right]; \qquad \frac{\Delta\tilde{m}(\tilde{w})}{\tilde{m}_0(\tilde{w})} \approx \frac{2}{9} a^2 g^2 e^{-2g};$$

$$(\tilde{\Gamma}_0^{rel}(g) << \tilde{w} << \frac{1}{g} << 1; a < 1) \tag{3.39}$$

rogorc (3.39) formulidan Cans temperaturuli Sesworeba eleqtronis Zvradobaze warmoadgens Zalian mcire sidides.

ganvixiloT @"$\frac{3}{2}\frac{K_B T}{\hbar w_0}$ problema" frolixis polaronis (eleqtronis) dabal temperaturuli Zvradobis TeoriaSi [114-116,120,123-124]. Ffxip-is mier miRebuli Sedegi eleqtronis impendansisTvis (kompleqsuri eleqtro-winaRobisaTvis da gamtarobisTvis) SesaZlebelia warmodgenili iqnas Semdegi saxiT [47, 88-90, 101-103]: .

$$\tilde{s}(\tilde{w}) = \frac{i}{\tilde{w}} + i\frac{2a}{3\sqrt{p}}\frac{1}{\tilde{w}^3}\int_0^\infty dt(1-e^{i\tilde{w}t})\,\mathrm{Im}[S(t)];$$

$$\tilde{Z}(\tilde{w}) = \frac{1}{\tilde{s}(\tilde{w})} \approx -i\tilde{w} + i\frac{2a}{3\sqrt{p}}\frac{1}{\tilde{w}}\int_0^\infty dt(1-e^{i\tilde{w}t})\,\mathrm{Im}[S(t)] \tag{3.40}$$

sadac: $S(t)$-"maxsovrobis" funqcias aqvs Semdegi saxe:

$$S(t) = D^{-\frac{3}{2}}(t)\left[(1+N_0(g))e^{it} + N_0(g)e^{-it}\right]; \quad \text{da} \quad D(t) = \frac{t^2}{g} - it; \tag{3.41}$$

Ffxip-is TeoriaSi (miaxloebaSi) eleqtronis dreifuli Zvradoba Mmoicema (ganisazRvreba) Semdegi Tanafardobit:

$$\frac{1}{\tilde{m}_{FXIP}} = \lim_{\tilde{w}\to 0} \tilde{w}^2 \operatorname{Re} \tilde{s}(\tilde{w}) = \lim_{\tilde{w}\to 0} \operatorname{Re} \tilde{Z}(\tilde{w}); \tag{3.42}$$

sadac: (3.40)-formulis Tanaxmad, eleqtronis impendansis realuri nawili ganisazRvreba Semdegi tolobiT:

$$\operatorname{Re} \tilde{Z}(\tilde{w}) = \frac{2a}{3\sqrt{p}} \int_0^\infty dt \frac{\sin(\tilde{w}t)}{\tilde{w}} \operatorname{Im}[S(t)] = \frac{4}{3\sqrt{p}} a g^{\frac{3}{2}} e^{\frac{1}{2}g} N_0(g) K_1(\frac{1}{2}g). \quad (\tilde{w} \to 0) \tag{3.43}$$

(3.43)-gamosaxulebidan martivad miiReba eleqtronis dabal temperaturuli statikuri $(w = 0)$ dreifuli Zvradobis mniSvneloba (ix. SedarebisaTvis (3.37)-formula) fxip-is miaxloebaSi:

$$m_{FXIP} = \frac{3}{2g}\frac{1}{2a} e^g; \qquad (g >> 1, g \to \infty) \tag{3.44}$$

Bbalansis gantolebis meTodze dayrdnobiT tornberg-feinmanis mier miRebuli eleqtronis statikuri dreifuli Zvradobis mniSvneloba moicema Semdegi gamosaxulebiT: [53, 84-85, 101-103];

$$\frac{1}{\tilde{m}_{TF}} = \frac{2a}{3\sqrt{p}} \int_0^\infty dt \cdot t \cdot \operatorname{Im}[S(t)] = \frac{4}{3\sqrt{p}} a g^{\frac{3}{2}} e^{\frac{1}{2}g} N_0(g) K_1(\frac{1}{2}g) \tag{3.45}$$

romelic emTxveva fxip-is mier miRebul dreifuli Zvradobis (3.43)-mniSvnelobas. Aamitom cxadia, rom frolixis polaronis (eleqtronis) dabal temperaturuli ZvradobisTvis gvaqvs igive saxis gamosaxuleba, rogoric fxip-is TeoriaSi:

$$\tilde{m}_{TF} = \frac{3}{2g}\frac{1}{2a} e^g; (g >> 1, g \to \infty) \tag{3.46}$$

[15] - naSromSi gamokvleuli da naCvenebi iyo, rom tornberg-feinmanis midgomaSi eleqtronis dreifuli Zvradobis gamoTvlisas gamoiyeneboda maqsvelis wanacvlebuli ganawilebis funqcia eleqtronisaTvis; xolo fxip-is TeoriaSi eleqtronis Zvradobis gamosaTvlelad gamoiyeneba eleqtrogamtarobis (eleqtrowinaRobis) mniSvneloba SeSfoTebis Teoriis meore miaxloebaSi. (a -bmis mudmivas rigis mixedviT).

rogorc aRniSnuli iyo literaturis mimoxilvaSi, frolixis polaronis dabal temperaturuli Zvradobis gamosaTvlelad mravali gamokvleva

iqna Catarebuli bolcmanis kinetikur gantolebaze dayrdnobiT [55, 91, 93, 98]. aRniSnuli gamokvlevebis Sedegad miRebuli dabaltemperaturuli Zvradobis mniSvneloba moicema Semdegi gamosaxulebiT:

$$\tilde{m}_B = \frac{1}{2a} e^{g}; \qquad (\tilde{w} = 0, g >> 1; g \to \infty) \tag{3.47}$$

(3.47)- formulis miRebis dros, bolcmanis gawrfivebuli (gareSe eleqtruli velis mixedviT) kinetikuri gantolebis amoxsnisas gamoiyeneboda relaqsaciis drois miaxloeba da Tanac dajaxebiT integralebSi gadasvlis sixSireebis da TviT integralebis gamoTvlisas gaTvaliswinebuli iyo mxolod “danaklisis” wevrebi. Aam miaxloebebis farglebSi - eleqtronis ganawilebis funqciis relaqsaciis sixSirisaTvis (droisTvis) miiReboda Semdegi saxis gamosaxuleba:

$$\Gamma_B^{rel}(b, \vec{p}) = \frac{1}{t_B^{rel}(b, \vec{p})} = \frac{2p}{\hbar^2} \sum_{\vec{K}} |V_{\vec{K}}|^2 \left\{ (1 + N_0(b)) d\left[\Delta^{+}(\vec{k}, \vec{p})\right] + N_0(b) d\left[\Delta^{-}(\vec{k}, \vec{p})\right] \right\} \tag{3.48}$$

(SedarebisTvis ix. (3.31) formula).

saidanac, mcire siCqareebiT moZravi eleqtronisaTvis $\tilde{\mathrm{P}}^2 << 1$, dabali temperaturebis SemTxvevaSi $(g >> 1)$, Tu CavatarebT martiv ga-moTvlebs dgindeba, rom relaqsaciis sixSire $\Gamma_B^{rel}(g, \tilde{\vec{\mathrm{P}}})$ – warmoidgineba Semdegi formiT:

$$\Gamma_B^{rel}(g, \tilde{\vec{\mathrm{P}}}) = \Gamma_{0B}(g) = 2aN_0(g); \qquad (g >> 1, \tilde{\mathrm{P}}^2 << 1). \tag{3.49}$$

(ix.SedarebisTvis (3.26)-formula). (3.49)-gamosaxulebidan ukve martivad miiReba eleqtronis dabaltemperaturuli Zvradobis (3.47)- mniSvneloba. rogorc (3.44), (3.46) da (3.47) – formulebidan Cans, fxip-isa da tornberg-feinmanis Sedegi $\frac{3}{2g}$ mamravliT gansxvavdeba dabaltemperaturuli Zvradobis (3.47)- mniSvnelobisagan, romelic miiReba bolcmanis kinetikuri gantolebis amoxsniT (e.w.” $\frac{3}{2}\frac{K_B T}{\hbar w_0}$ – problema”). rogorc araerTgzis iyo aRniSnuli samecniero literaturaSi [31,101-103], fxip-is mier $\tilde{Z}(\tilde{w})$ - impedansis da Zvradobis gamoTvlisas, rodesac $\tilde{w} \to 0$- gamoiyeneba arakoreqtuli maTematikuri procedura. Aavtoris mier naSromSi miRebuli eleqtrogamtarobis (3.34)- formula, romelic faqtiurad warmoadgens fxip-is miaxloebas adebs pirobas fxip-is Teoriis gamoyenebis (samarTlianobis)

sazRvrebs: $\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << \tilde{w} << \min(\frac{1}{g};1)$. Aamis gamo eleqtrogamtarobis (3.34)-gamosaxuleba, anu rac igivea fxip-is Teoria (miaxloeba) samarTliania $\tilde{w}$-maRali sixSireebis SemTxvevaSi da $\tilde{w} \to 0$-zRvruli gadasvla (3.42) – formulaSi ar aris koreqtuli. Ggarda amisa, $\tilde{s}(\tilde{w})$- eleqtrogamtarobis gaSlisas mwkrivad da $\tilde{Z}(\tilde{w})$- impendansis mniSvnelobis gamoTvlisas, ar gaiTvaliswineba maRali rigis wevrebi a -bmis mudmivas rigis mixedviT. (unda aRiniSnos, rom fxip-is miaxloeba samarTliania agreTve maRal temperaturul areSi, rodesac: $(\tilde{\Gamma}_0^{rel}(g,\tilde{P}) << 1 << \tilde{w} << \frac{1}{g})$. rac Seexeba tornberg-feinmanis midgomas, am TeoriaSi bolcmanis kinetikuri gantolebis stacionarul SemTxvevaSi amoxsnisas da eleqtronis dabal temperaturuli Zvradobis gamoTvlisas gamoiyeneba maqsvelis saxis wanacvlebuli ganawilebis funqcia eleqtronisaTvis, romelic araadekvaturad asaxavs eleqtronis yofaqcevas kristalis dabali temperaturebisa da Zlieri eleqtruli velebis SemTxvevaSi (ix. literaturis mimoxilva) da amitomac ar aris moulodneli, rom miRebuli Sedegi $\frac{3}{2g}$ TanamamravliT gansxvavdeba eleqtronis “bolcmaniseuli” (3.47)-dabal temperaturuli Zvradobisagan.

sadisertacio naSromSi, avtoris mier miRebuli Sedegi frolixis polaronis (eleqtronis) dabal temperaturuli ZvradobisaTvis (ix.(3.28) – formula) warmoadgens “$\frac{3}{2g}$ problemis” nawilobriv gadawyvetas [116,120]. is 3-jer aRemateba “bolcmaniseul” (3.47)- dabal temperaturul Zvradobas da $\frac{1}{2g}$DA- mamravliT gansxvavdeba fxip-isa da tornberg-feinmanis Sedegisagan. Mmamravli 3-ianis warmoSoba ganpirobebulia im faqtiT, rom: $\Gamma_0(g)/\Gamma_{0B}(g) = \frac{1}{3}$; da TviT $\Gamma_0(g)$- eleqtronis siCqaris (impulsis) relaqsaciis sixSiris gamoTvlisas, korelaciuri funqciebisaTvis kinetikuri gantolebebis dajaxebiTi integralebi da $\Gamma_n^{rel}(b,\vec{p})$ sixSire Seicaven Tanamamravls:

$\frac{V_n(\vec{p}+\hbar\vec{k})-V_n(\vec{p})}{V_n(\vec{p})}$ (ix. (3.9), (3.12), (3.15)), romelic aRwers eleqtronis siCqaris cvlilebas misi gabnevisas fononebze, maSin rodesac eleqtronis ganawilebis funqciis relaqsaciis sixSire: $\Gamma_B^{rel}(b,\vec{p})$ (ix. (3.48))-aseTi saxis Tanamamravls ar Seicavs. swored es faqtori ganapirobebs am damatebiTi mamravlis warmoqmnas [120]. rac Seexeba fxip-isa da tornberg-feinmanis Sedegebis Tanxvedras $\tilde{m}_{FXIP}=m_{TF}=\frac{1}{2g}\frac{3}{2a}e^g;\quad (g>>1)$ da $\frac{1}{2g}$ - mamravls, maTi warmoSobis buneba dRevandel dRemde bolomde garkveuli ar aris.

3.3. eleqtronis Zvradoba akustikuri polaronis modelSi susti eleqtron–fononuri urTierTqmedebis SemTxvevaSi

ganvixiloT eleqtroni, romelic moZraobs kovalentur (araionur) kristalSi an naxevargamtarSi, romlis moZraoba aRiwereba (1.13)-(1.14) hamiltonianiT. davuSvaT, rom eleqtroni sustad urTierTqmedebs akustikur fononebTan; $a=\frac{D^2m^2}{8\pi r\hbar^3V_s}<1.$ Aam SemTxvevaSi adgili aqvs eleqtronis urTierTqmedebas dispersiis mqone akustikur fononebTan: $w(\vec{k})=V_s\cdot k;\quad k\equiv|\vec{k}|.$ eleqtronis energiisaTvis gamtarobis zonidan gvaqvs dispersiis standartuli paraboluri kanoni da eleqtronis siCqaris $m-$komponenti moicema (3.19) formuliT. eleqtronis Zvradobis gamosaTvlelad akustikuri polaronis modelSi visargebloT (3.17)–(3.18) formulebiT, xolo $\Gamma_{vac}^{rel}(b,\vec{p})$- relaqsaciis sixSiris gamosaTvlelad ki – (3.15) gamosaxulebiT. Tu gamoviyenebT (1.14) da (3.15) – formulebs, mivmarTavT eleqtrul vels Z–RerZis dadebiTi mimarTulebis gaswvriv, SevasrulebT Termodinamikur zRvrul gadasvlas da CavatarebT integrebas K-cvladiT, maSin $\Gamma_{zac}^{rel}(g,\vec{\mathrm{P}})-$ relaqsaciis sixSirisaTvis miviRebT gamosaxulebas:

$$\Gamma_{zac}^{rel}(g,\tilde{\vec{\mathrm{P}}})=-\frac{mV_s^2}{\hbar}\frac{16a}{\tilde{\mathrm{P}}_z}\int d\Omega_{\vec{k}}\cos q\,(1-\tilde{\mathrm{P}}\cos\Phi)^3\frac{1}{\exp\left[4g\,(1-\tilde{\mathrm{P}}\cos\Phi)\right]-1}-$$

$$-\frac{mV_s^2}{\hbar}\frac{16a}{\tilde{\mathrm{P}}_z}\int d\Omega_{\vec{k}}\cos q\,(1+\tilde{\mathrm{P}}\cos\Phi)^3\frac{1}{\exp\left[4g\,(1+\tilde{\mathrm{P}}\cos\Phi)\right]-1};\qquad (3.50)$$

$$(a<1.)$$

sadac: $g = \frac{mV_s^2}{2K_BT-}$ - warmoadgens modelis maxasiaTebel uganzomilebo fizikur parametrs, $\tilde{\vec{P}}-$ uganzomilebo impulsia: $\tilde{P} = \vec{P}/mV_s$

$$d\Omega_{\tilde{k}} = \sin q dq dj; \qquad \tilde{P}\cos\Phi = \sin q\cos j\tilde{P}_x + \sin q\sin j\tilde{P}_y + \cos q\tilde{P}_z,$$

sadac q da j - sferuli kuTxeebia, xolo Φ - warmoadgens kuTxes $\vec{K}$da $\vec{P}$ veqtorebs Soris. gamovTvaloT (3.50) – formulis daxmarebiT eleqtronis impulsis relaqsaciis sixSire kristalis dabali temperaturebis SemTxvevaSi, rodesac $g >> 1$. amisaTvis ganvixiloT “mcire“ siCqariT moZravi eleqtroni: $\tilde{P} << 1\ (P << mV_s)$. aseT SemTxvevaSi eleqtrons ar Seswevs unari gamoasxivos fononebi, vinaidan adgili ar eqneba energiisa da impulsis Senaxvis kanonebs misi gabnevisas fononebze (ix. (3.15)-formula). Aamis gamo, (3.50)- gamosaxuleba martivdeba da SesaZlebelia Cawerili iqnas Semdegi saxiT:

$$\Gamma_{Ac}^{rel}(g) = t_{Ac}^{-1rel}(g) = \frac{mV_s^2}{\hbar}64a\left[e^{4g} - 1\right]^{-1} \tag{3.51}$$

$$(\tilde{P} << 1; \quad g >> 1; \quad a < 1\ ).$$

Aamrigad, mcire siCqariT moZravi eleqtronisTvis, rodesac eleqtronis siCqare gacilebiT naklebia kristalSi bgeris gavrcelebis siCqareze ($(P/m << V_s)$, eleqtronis siCqaris (impulsis) relaqsaciis sixSire (dro) ganpirobebulia mxolod eleqtronis mier fononebis STanTqmis procesiT da ar aris damokidebuli eleqtronis $\tilde{P}-$impulsze. cxadia, rom aseT SemTxvevas adgili aqvs kristalis Zalian dabali temperaturebis dros ($g >> 1$). miRebuli (3.51) – formulis daxmarebiT eleqtronis “siCqare–siCqareze“- korelaciuri funqciebi warmoidgineba Semdegi formiT. (ix. SedarebisaTvis (3.14) da (3.24) – formulebi):

$$< V_z(0)V_z(\pm t) >= \frac{V_s^2}{2g}\exp\left[-\Gamma_{Ac}^{rel}(g)\,|t|\right]\exp\left[\pm i\frac{\hbar g}{mV_s^2}\Gamma_{Ac}^{rel}(g)\right]; \tag{3.52}$$

$$(a < 1; g >> 1; t \geq t_{Ac}^{rel})$$

(3.52)–korelaciuri funqciebis asimptoturi gamosaxulebebis gamoyva-nisas Cven visargebleT (3.25) – Tanafardobebi T.

Aamgvarad, rogorc (3.52) –formulebidan Cans, “siCqare – siCqareze” – korelaciuri funqciebi eqsponencialurad miilevian drois mixedviT

dabali temperaturebis dros $(g >> 1), \Gamma_{Ac}^{rel}(g)$ – milevis dekrementiT. naTe-lia, rom miRebuli Sedegi napovnia Sfm-is gamoyenebis gareSe, da gan-sxvavdeba. Sedegisagan, romelic miiReba Sfm-Si eqsponencialuri Tana-mamravliT: $\exp\left[\pm\frac{i\hbar g}{mV_s^2}\Gamma_{Ac}^{rel}(g)\right]$. [121-122].

vipovoT axla eleqtrogamtaroba da dabaltemperaturuli Zvradoba eleqtronisTvis erTzonian miaxloebaSi da izotropul SemTxvevaSi akustikuri polaronis modelSi susti eleqtron- fononuri bmis dros. Tu visargeblebT (3.17), (3.19) da (3.25) – formulebiT, maSin kuTri ele-qtrogatarobisaTvis miviRebT gamosaxulebas [121-122]:

$$\mathrm{Res}_{Ac}(w) = \frac{ne^2}{m}\frac{\Gamma_{Ac}^{rel}(g)}{w^2 + \Gamma_{Ac}^{2rel}(g)}\cos\left[\frac{\hbar g}{mV_s^2}\Gamma_{Ac}^{rel}(g)\right] \qquad (3.53)$$

$$(a < 1; g >> 1; w << \frac{mV_s^2}{\hbar g}).$$

sadac: n-warmoadgens eleqtronebis koncentracias; xolo dabaltemperaturuli statikuri $(w = 0)$ ZvradobisaTvis Sesabamisad gveqneba:

$$m_{Ac} = \lim_{w\to 0}\frac{\mathrm{Re}\, s_{Ac}(w)}{ne} = m_{oAc} - \Delta m_{Ac}$$

$$m_{0Ac} = \frac{\hbar e}{m^2V_s^2}\frac{1}{64a}e^{4g}$$

$$\Delta m_{Ac} = \frac{\hbar e}{m^2V_s^2}\frac{1}{32a}e^{4g}\sin^2\left[32a g e^{-4g}\right]; \qquad (a < 1; g >> 1) \qquad (3.54)$$

rogorc (3.54) – formulebidan Cans, temperaturuli Sesworeba eleqtronis dabaltemperaturul, dreiful, statikur (dc) – Zvradobaze, romelic ganpiribebulia sawyisi korelaciebis gaTvaliswinebiT am modelSi warmoadgens Zalian mcire sidides:

$$\Delta m_{Ac} \approx \frac{\hbar e}{m^2V_s^2}32a g^2 e^{-4g}; \qquad \frac{\Delta m_{Ac}}{m_{Ac}} \approx 2048\cdot a^2 g^2 e^{-8g}; \qquad (3.55)$$

$$(a < 1; g >> 1)$$

miRebuli (3.54- 3.55)– formulebi warmoadgenen Tanmimdevrul da koreqtul Sedegs eleqtronis dabaltemperaturuli Zvradobisa akustikuri polaronis modelSi susti eleqtron – fononuri bmis SemTxvevaSi [121-122].

gamovTvaloT axla eleqtrogamtaroba da dreifuli Zvradoba akustikuri polaronis modelSi eleqtruli velis maRali sixSireebis

SemTxvevaSi, rodesac srulDeba (3.29)–Tanafardoba romelic akusti-kuri polaronis modelSi miiRebs Semdeg saxes:

$$\tilde{\Gamma}^{rel}_{Ac}(g,\tilde{\mathrm{P}}) << \tilde{w} << \frac{1}{2g};\ \text{sadac:}\qquad \tilde{w} = \frac{\hbar}{mV_s^2}w;\ \text{da}\ \Gamma^{rel}_{AC}(g,\tilde{\mathrm{P}}) = \frac{mV_s^2}{\hbar}\tilde{\Gamma}^{rel}_{AC}(g,\tilde{\mathrm{P}}); \qquad (3.56)$$

($\tilde{w}$ da $\tilde{\Gamma}^{rel}_{AC}(g,\tilde{\mathrm{P}})$– uganzomilebo sixSireebia). Tu gaviTvaliswinebT (3.17) – formulas, izotropul SemTxvevaSi gveqneba Tanafardoba: (ix. agreTve (3.18) da (3.30) – formulebi):

$$\tilde{w}^2\,\mathrm{Re}\,\tilde{s}_{AC}(\tilde{w}) = \frac{2}{g\tilde{w}}th\left(\frac{1}{2}g\tilde{w}\right)\frac{128}{3\sqrt{p}}ag^{3/2}\int_{-1}^{\infty}dK(K+1)^4\frac{e^{-gK^2}}{e^{4g(K+1)}-1} \qquad (3.57)$$

$$s_{AC}(w) = \frac{ne^2\hbar}{m^2V_s^2}\tilde{s}_{AC}(w).$$

Dda relaqsaciis (uganzomilebo) sixSire $\tilde{\Gamma}^{rel}_{AC}(g,\tilde{\mathrm{P}})$ am modelSi warmoidgineba Semdegi saxiT:

$$\tilde{\Gamma}^{rel}_{AC}(g,\tilde{\mathrm{P}}) = \frac{16a}{p}\int d\vec{K}\cdot K\frac{(\vec{K}\cdot\tilde{\vec{\mathrm{P}}})}{\tilde{\mathrm{P}}^2}\left\{[1+N(4gK)]d(K^2+\vec{K}\cdot\tilde{\vec{\mathrm{P}}}+K)+N(4gK)d(K^2+\vec{K}\cdot\tilde{\vec{\mathrm{P}}}-K)\right\};$$

$$N(4gK) = \left[e^{4gK}-1\right]^{-1};\qquad (a<1). \qquad (3.58)$$

(3.57) da (3.58) – gamosaxulebebis miRebisas gaTvaliswinebuli iyo fononebis dispersiis kanoni, Sesrulebuli iyo Termodinamikuri zRvruli gadasvlebi (3.17) da (3.15) – formulebSi da Catarebuli iyo integracia $\vec{\mathrm{P}}$ – impulsuri cvladiT (3.17)-Si (3.31)–gamosaxulebis gamoyenebiT. naTelia, rom eleqtronis impulsis mcire mniSvnelobebisaTvis: $\tilde{\mathrm{P}}<<1;\quad \tilde{\mathrm{P}}\to 0$ (3.58) – formulidan martivad miviRebT (3.51)–gamosaxulebas ele-qtronis impulsis relaqsaciis sixSirisaTvis.

dinamiuri gamtarobis (3.57) formula principSi samarTliania kristalis nebismieri temperaturis dros am modelSi im pirobiT, rom daculia (3.56) utoloba. ganvixiloT axla eleqrogamtarobis (Zvra-dobis) $\tilde{w}$ sixSiresa da T-temperaturaze damokidebuleba am parametre-bis sxvadasxva mniSvnelobebis dros.

1) dabal temperaturaTa are, rodesac $\tilde{\Gamma}^{rel}_{AC}(g,\tilde{p}) << \frac{1}{2g} << 1$. aseT SemTxvevaSi, (3.56) utolobis gaTvaliswinebiT gveqneba: $\tilde{\Gamma}^{rel}_{AC}(g,\tilde{p}) << \tilde{w} << \frac{1}{2g} << 1$. vinaidan

$g >> 1; \frac{2}{g\tilde{w}} th(\frac{1}{2} g\tilde{w}) \Rightarrow 1$. amitom (3.57) formulidan gamomdinare (Tu CavatarebT martiv gardaqmnebsa da gamoTvlebs) dinamiuri gamtarobisTvis gveqneba Semdegnairi (asimptoturi) yofaqceva:

$$\tilde{w}^2 \operatorname{Re} \tilde{s}_{0AC}(\tilde{w}) \approx \frac{128}{3} a \; g \; e^{-4g}; \qquad (g >> 1, g \to \infty); a < 1 \tag{3.59}$$

amrigad, am areSi eleqtrogamtaroba ukuproporciulia sixSiris kvadratisa (maRali sixSireebis SemTxvevaSi) da miileva eqsponencia-lurad T temperaturis SemcirebasTan erTad.

II) maRal temperaturaTa are, rodesac $\tilde{\Gamma}_{AC}^{rel}(g, \tilde{p}) << 1 << \frac{1}{2g}$; kristalis temperaturaTa am areSi gamoiyofa $\tilde{w}$-sixSireTa ori diapazoni: 1) $\tilde{\Gamma}_{AC}^{rel}(g, \tilde{p}) << \tilde{w} << 1 << \frac{1}{2g}$; da 2) $\tilde{\Gamma}_{AC}^{rel}(g, \tilde{p}) << 1 << \tilde{w} << \frac{1}{2g}$; naTelia, rom maRali temperaturebis SemTxvevaSi $\tilde{w}$-sixSireTa am orive diapazonSi dinamiuri gamtarobisTvis gveqneba erTnairi yofaqceva. radgan $g << 1, g\tilde{w} << 1, \frac{2}{g\tilde{w}} th(\frac{1}{2} g\tilde{w}) \Rightarrow 1$; amitom (3.57) formulidan gamomdinare martivi gamoTvlebiT davadgenT, rom maRali temperaturebis SemTvevaSi gamtarobisaTvis gveqneba Semdegi saxis yofaqceva:

$$\tilde{w}^2 \operatorname{Re} \tilde{s}_{0AC}(\tilde{w}) \Rightarrow \frac{32}{3} a; \qquad (g << 1, \quad g \to 0); a < 1. \tag{3.60}$$

cxadia, rom eleqtronis sixSireze damokidebuli ZvradobisTvis - $\tilde{m}_{0AC}(\tilde{w})$Sfm-Si, rogorc dabali aseve maRali temperaturebis SemTxvevaSi gvaqvs iseTive saxis yofaqcevis suraTi, rogorc dinamiuri gamtarobisTvis vinaidan$\operatorname{Re} \tilde{s}_{AC}(\tilde{w}) \equiv \tilde{m}_{0AC}(\tilde{w})$. amgvarad, (3.60)-is Tanaxmad maRal temperaturaTa areSi dinamiuri gamtaroba (eleqtronis Zvradoba) ar aris damokidebuli kristalis temperaturaze.

rogorc (3.53) da (3.55) formulebidan Cans temperaturuli Seswo-reba eleqtronis Zvradobaze, romelic ganpirobebulia eleqtronis fononebTan arsebuli sawyisi korelaciebis gaTvaliswinebiT, maRalsixSirul areSic da kristalis dabali temperaturebis SemTxvevaSi moicema (3.55) Tanafardobebis aRmweri meore formulis saSualebiT.

rogorc ukve aRniSnuli iyo naSromis I TavSi, eleqtronis daba-l-temperaturuli Zvradobis gamosaTvlelad akustikuri polaronis modelSi susti eleqtron-fononuri bmis SemTxvevaSi ($a<1$), gamoiyeneba kinetikuri (bolcmanis) gantolebis meTodi [99,108]. gareSe eleqtruli velis mixedviT gawrfivebuli bolcmanis gantolebis amoxsnisas relaqsaciis drois miaxloebaSi, dajaxebiT integralebSi gadasvlis sixSireebisa da TviT am integralebis gamoTvlisas, gaiTvaliswineba mxolod `danaklisis" wevrebi. aseTi saxis miaxloebis Sesruleba (araferi rom ar vTqvaT Sfm-ze) warmoadgens sakmaod uxeSs da zogadad arasrulyofilad asaxavs eleqtronuli gadatanis movlenebs eleqtron-fononur sistemaSi. warmodgenil modelSi, zemoT Tqmuli miaxloebebis farglebSi, eleqtronis ganawilebis funqciis relaqsaciis sixSires aqvs Semdegi saxe:

$$\Gamma^{rel}_{BAC}(b,\vec{p})=\frac{2p}{\hbar^2}\sum_{\vec{k}}\left|V_{\vec{k}}\right|^2\left[\mathrm{N}_{\vec{k}}(b)d\left(\frac{\hbar\vec{k}^2}{2m}+\frac{\vec{k}\vec{p}}{m}-V_s k\right)+(1+N_{\vec{k}}(b))\mathrm{x}\right.$$

$$\left.\mathrm{x}\ d\left(\frac{\hbar\vec{k}^2}{2m}+\frac{\vec{k}\vec{p}}{m}+V_s k\right)\right];\ \Gamma^{rel}_{BAC}(g,\tilde{\vec{p}})=\frac{mV_s^2}{\hbar}\tilde{\Gamma}^{rel}_{BAC}(g,\tilde{\vec{p}}); \qquad (3.61)$$

$$\tilde{\Gamma}^{rel}_{BAC}(g,\tilde{\vec{p}})=\frac{8a}{p}\int d\vec{K}K\left[(1+N(4g\ K)d(\vec{K}^2+\vec{K}\tilde{\vec{p}}+\vec{K})+N(4g\ K)d(\vec{K}^2+\vec{K}\tilde{\vec{p}}-K)\right]$$

sadac: uganzomilebo talRuri veqtori $\vec{K}$ (iseve rogorc (3.57) da(3.58) formulebSi) ganisazRvreba Tanafardobit: $\vec{K}=\frac{\hbar}{2mVs}\cdot\vec{k}$;

martivad dgindeba, rom dabali temperaturebis SemTxvevaSi ($g>>1$) da `mcire~ siCqariT moZravi eleqtronisTvis $\left(\tilde{P}^2<<1\right)$, (3.61) formulebi gvaZleven eleqtronis albaTobis ganawilebis funqciis relaqsaciis sixSirisaTvis Semdeg mniSvnelobas:

$$\Gamma^{rel}_{BAC}\left(g,\tilde{\vec{p}}\right)=\Gamma^{rel}_{0BAC}(g)=\frac{mVs^2}{\hbar}32a\left[e^{4g}-1\right]^{-1} \qquad (3.62)$$

$$\left(\tilde{P}<<1,\ g>>1,\ a<1\right).$$

(3.62)-is daxmarebiT ki martivad vpoulobT eleqtronis dabal temperaturul Zvradobas (Sfm-Si) akustikuri polaronis modelSi:

$$m_{0BAC}=\frac{\hbar e}{m^2Vs^2}\cdot\frac{1}{32a}e^{4g};\left(g>>1,a<1\right). \qquad (3.63)$$

amrigad, sadisertacio naSromSi avtoris mier miRebuli Sedegi akustikuri polaronis modelSi eleqtronis dabaltemperaturuli (statikuri) dreifuli Zvradobis Tvis (ix. (3.54) formula) Sfm-Si 1/2-jer naklebia eleqtronis `bolcmaniseul~ dabaltemperaturul dreiful Zvradobaze (ix. 3.63)). mamravli 1/2-is warmoSoba ganpirobebulia im garemoebiT, rom $\Gamma^{rel}_{AC}(g)/\Gamma^{rel}_{0BAC}(g)=2$, da TviT eleqtronis siCqaris (impu-lsis) relaqsaciis sixSiris (3.58)-gamosaxulebis integralqveSa wevrebi Seicaven $(\overline{K}\cdot\vec{\tilde{P}})/\vec{\tilde{P}}^2$ _Tanamamravls, maSin rodesac (3.61) relaqsaciis sixSiris gamosaxulebis integralqveSa wevrebi aseT Tanamamravls ar Seicaven; xolo TviT am Tanamamravlis warmoSoba ganpirobebulia korelaciuri funqciebisTvis kinetikuri gantolebebis dajaxebiT integralebSi eleqtronis siCqaris cvlilebis wevris arsebobiT misi gabnevisas fononebze (ix. (3.9), (3.12, (3.15) da 3.2 paragrafi)). swored am garemoebis gamo miiReba eleqtronis dabaltemperaturuli Zvrado-bisTvis 2-jer naklebi mniSvneloba am modelSi, romelic warmoadgens Tanamimdevrul da swor Sedegs gansxvavebiT kinetikuri gantolebis gamoyenebiT miRebuli Sedegisagan (`bolcmaniseuli~ midgomisagan) [121-122].

rac Seexeba eleqtronis dabaltemperaturul (statikur) Zvradobebs am modelSi romlebic miiRebian fxip-is Teoriisa (miaxloebisa) da balansis gantolebis meTodis (tornberg-feinmanis Teoriis) gamoyenebiT, avtoris mier Catarebuli gamokvlevebis safuZvelze napovnia am dabaltemperaturuli Zvradobebis mniSvneloebebi da dadgenilia, rom isini emTxvevian erTmaneTs:

$$\tilde{m}^{FXIP}_{AC}=\tilde{m}^{TF}_{AC}=\frac{3}{4g}\cdot\frac{1}{64a}e^{4g};\quad (g>>1, a<1) \qquad (3.64)$$

iseve rogorc polaronis frolixis modelSi, am modelSic $\frac{3}{4g}$-mamravlis warmoSobis Rrma mizezi (buneba) jer-jerobiT dadgenili ar aris.

amrigad sadisertacio naSromis am Tavis (3.1_3.3) paragrafebSi avtoris mier ganxilul modelebze dayrdnobiT miRebuli Sedegebi (gamoyvanili formulebi: rogorc zogadi, aseve miaxloebiTi) SesaZleblobas iZleva gadaugvarebel, farTozonian, erTgvarovan (polaruli) naxevargamtarebSi, ionur da kovalentur kristalebSi eleqtronuli gadatanis meqanikuri koe-

ficientebis (dreifuli Zvradoba, dinamiuri gamtaroba) gamoTvlisa erTi zonis miaxloebaSi kvazinawilakebis (eleqtronebis) dispersiis rogorc zogadi, aseve paraboluri kanonis dros, fononebis dispersiis izotropuli kanonisa da susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi.

3.4 polaronis dabal temperaturuli Zvradoba feinmanis ganzogadoebul modelSi

polaronuli gadatanis meqanikuri koeficientebis (dreifuli Zvradoba, eleqtrogamtaroba) gamosaTvlelad polarul naxevargamtarebsa an ionur kristalebSi SemovifargloT polaronis fgm-iT, romelic aRwerili iyo naSromis I Tavis 1.3.3 paragrafSi da romlis modeluri hamiltoniani H^{S}_{GF} moicema (1.52)-tolobiT. polaronis dreifuli Zvradobis sapovnelad visargeblоT kubos wrfivi gamoZaxilis TeoriiT da gamoTvlebis gasamartiveblad SemovifargloT 1.33 paragrafSi warmodgenil erTeulTa sistemiT: ($\hbar = m = w_0 = 1$). CavTvaloT, rom deni romelic figurirebs (3.2)-formulaSi, ganpirobebulia eleqtronisa, da fiqtiuri nawilakis (polaronis) masaTa centris gadaadgilebiT, vinaidan isini dakavSirebuli arian erTmaneTTan. amgvarad, ganixileba sistema, romelic aRiwereba hamiltonianiT [57-58,125]:

$$H_{GF} = H^{S}_{GF} + H_{\Sigma} + H_{\text{int}} \tag{3.65}$$

sadac: H_{Σ} -fononuri velis hamiltoniania, xolo H_{int} urTierTqmedebis hamiltoniani ganisazRvreba (1.2), (1.18) da (1.20)-tolobebiT. eleqtron-fononuri urTierTqmedeba ganixileba rogorc mcire SeSfoTeba. naTelia, rom eleqtronis $\bar{r}$-koordinati dakavSirebulia axal kanoni-kur cvladebTan TanafardobiT (ix. 1.33. paragrafi):

$$\vec{r} = \vec{R} + m_e \vec{x}; \quad m_e = \frac{M_{GF}}{M_{GF} + 1}, \qquad m \equiv m_e \tag{3.66}$$

SemovifargloT erTi zonis miaxloebiT da izotropuli SemTxveviT da ganvixiloT, magaliTad polaronis `impulsi-impulsze~-korelaciuri funqciis z-komponenti.

$$\left\langle \hat{P}_z\,\hat{P}_z(t)\right\rangle_{GF} = Z_{GF}^{-1}(b)\,SP_{GF\Sigma}\left[e^{-bH_{GF}}\hat{P}_z e^{\frac{i}{\hbar}H_{GF}t}\hat{P}_z e^{-\frac{i}{\hbar}H_{GF}t}\right] =$$

$$SP_{GF}^{s}\left[\hat{P}_z G_z^{GF}(t,b)\right];\; G_z^{GF}(t,b) = Z_{GF}^{-1}(b)\,SP_{\Sigma}\left[(e^{t^{"}L_{GF}t}\hat{P}_z)e^{-bH_{GF}}\right] \qquad (3.67)$$

$$Z_{GF}(b) = SP_{GF\Sigma}\,(e^{-bH_{GF}}) \quad \hat{P}_z \equiv$$

sadac: Cven SemoviReT damxmare (relevanturi) operatori $G_z^{GF}(t,b)$. msgavsi gamosaxuleba gveqneba agreTve korelaciuri funqciisTvis: $\left\langle \hat{P}_z(t)\hat{P}(t)\right\rangle_{GF}$. rogorc (3.67)-tolobebidan Cans kvali korelaciuri funqciis gamoTvlisas aiReba $\left|\hat{P}\right> = \left|n\right> - .$ orTonormirebul sakuTar funqciebze Sredingeris (1.54) da (1.55)-gantolebebisa;

$$\left|n\right> \equiv u_n(\vec{x});.\;\; SP_{GF}^{s}\left[\hat{\vec{P}}_z G_z^{GF}(t)\right] = \sum_h \int d\vec{\hat{P}}\,\hat{P}_z G_z^{GF}(\vec{\hat{P}},n,t,b)$$

$$\text{da} \quad G_z^{GF}(\vec{\hat{P}},n,t,b) = \left\langle \vec{\hat{P}}\right| < n\left|G_z^{GF}(t,b)\right|n\left\rangle \vec{\hat{P}}\right\rangle \qquad (3.68)$$

martivad SesaZlebelia naCvenebi iqnas, rom korelaciuri funqcia $\left\langle \hat{P}_z(t)\hat{P}(t)\right\rangle$ da $G_z^{GF}(t,b)$-operatori akmayofileben Semdegi saxis kinetikur gantolebas (ix. SedarebisaTvis (3.4)-gantoleba):

$$\frac{\partial}{\partial t}\left\langle \hat{P}_z\hat{P}_z(t)\right\rangle = SP_{GF}^{s}\left[\hat{P}_z\frac{\partial}{\partial t}G_z^{GF}(t,b)\right] = \frac{i}{\hbar}SP_{GF}^{s}\left\{\left[\hat{\hat{P}}_z, H_{GF}^{s}\right].G_z^{GF}(t,b)\right\} -$$

$$-\int_0^t dt\sum_{\vec{k}}\left|V_{\vec{k}}\right|^2\left[e^{-it}N_0(b)+e^{it}(1+N_0(b)\right]SP_{GF}^{S}\left\{\left[\hat{P}_Z, e^{i\vec{k}\vec{r}}\right]_{-}\cdot e^{-i\vec{k}\vec{r}(t)}G_Z^{GF}(t,b)\right\}+$$

$$+\int_0^{t-ib} dz\sum_{\vec{k}}\left|V_{\vec{k}}\right|^2\left[e^{iz}N_0(b)+e^{-iz}(1+N_0(b)\right]\cdot SP_{GF}^{S}\left\{e^{-i\vec{k}\vec{r}(z)}\left[\hat{P}_Z, e^{i\vec{k}\vec{r}}\right]\cdot G_Z^{GF}(t,b)\right\}; \qquad (3.69)$$

sadac: $\vec{r}$ – ganisazRvreba (3.66) – tolobiT da $\vec{r}(t) = e^{iH_{gf}^{s}t}\vec{r}e^{-iH_{GF}^{S}t}$ warmoa-dgens polaronis Tavisufali moZraobis “traeqtorias” fgm-Si. analogiurad Caiwereba kinetikuri gantoleba $<\hat{P}_Z(t)\hat{P}_Z>_{GF} = <\hat{P}_Z\hat{P}_Z(-t)>_{GF}$ korelaciuri funqciisaTvis. Tu gaviTvaliswinebT (3.66) – tolobas, CavatarebT integrebas t da z- cvladebiT, maSin martivi gardaqmnebisa da gamoTvlebis Semdeg miviRebT kinetikur (moZraobis) gantolebas $G_Z^{GF}(t,b)$- operatoris diagonaluri matriculi elementebisaTvis- $G_Z^{GF}(\vec{\hat{P}},n,t,b)$:

$$\frac{\partial}{\partial t}G_Z^{GF}(\vec{\hat{P}},n,t,b) = i\sum_{\vec{k},n_1,n_2}\left|V_{\vec{k}}\right|^2\frac{K_Z}{\hat{P}_z}\times$$

$$\times\left\{N_0(b)\frac{1-\exp\left[it\Delta^-(\vec{k},\vec{\tilde{P}},n_1n_2)\right]}{\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n_2)}+(1+N_0(b))\frac{1-\exp\left[it\Delta^+(\vec{k},\vec{\tilde{P}},n_1n_2)\right]}{\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n_2)}\right\}\times$$

$$<n|e^{im_e\vec{k}\vec{x}}|n_1><n_1|e^{-im_e\vec{k}\vec{x}}|n_2>G_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b)-i\sum_{\vec{k},n_1,n_2}|V_{\vec{k}}|^2\frac{k_Z}{\tilde{P}_Z}\times$$

$$\times\left\{N_0(b)\frac{1-\exp\left[-i(t-ib)\Delta^-(\vec{k},\tilde{P},n_1,n)\right]}{\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)}+(1+N_0(b))\frac{1-\exp\left[-i(t-ib)\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n)\right]}{\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n)}\right\}\mathrm{P}$$

$$\times<n|e^{-im_e\vec{k}\vec{x}}|n_1><n_1|e^{im_e\vec{k}\vec{x}}|n_2>G_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b) \qquad (3.70).$$

aq $\Delta^{\pm}(\vec{k},\vec{\tilde{P}},n_1,n_2)=\frac{\vec{k}^2}{2M}+\frac{\vec{k}\vec{\tilde{P}}}{M}\pm1+e_{n_1}-e_{n_2}$ – sidide warmoadgens fononebze gabne-visas polaronis energiis cvlilebas misi erTi aRgznebuli energe-tikuli mdgomareobidan meore aRgznebul mdgomareobaSi gadasvlis dros; $M\equiv M_{GF}+1$-ki polaronis masaa. Tu (3.70) – gantolebaSi Sevasru-lebT Casmas $t\to -t$ martivad vpoulobT gantolebas $G_Z^{GF}(\vec{\tilde{P}},n,-t,b)$ sididisaTvis. cxadia, rom (3.70)- kinetikuri gantoleba ar warmoadgens bolcmanis tipis gantolebas, vinaidan am gantolebis dajaxebiTi inte-gralebi Seicaven aradiagonalur matricul elementebs $G_Z^{GF}(t,b)$ operatorisa: $G_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b)=<\vec{\tilde{P}}|<n_2|G_Z^{GF}(t,b)|n>|\vec{\tilde{P}}>$. naTelia, rom ajamva (3.70) – gantolebis marjvena mxareSi xorcieldeba Sredingeris (1.54)–gantolebis yvela $|n>\equiv u_n(\vec{x})$ – orTonormirebuli ZiriTadi da aRgznebuli (zogadad gadagvarebuli) mdgomareobebis mixedviT. (Cven vTvliT, rom ZiriTadi mdgomareobis $|0>$ – energetikuli done e_0 – ar aris gadagvarebuli).

bolcmanis tipis kinetikuri gantolebis misaRebad $G_Z^{GF}(\vec{\tilde{P}},n,t,b)$ sididisaTvis warmovadginoT $G_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b)$ – aradiagonaluri matriculi elementebi Semdegi formiT:

$$G_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b)=G_Z^{GF}(\vec{\tilde{P}},n,t,b)d_{n_2n}+\exp\left[it(e_{n_2}-e_n)\right]\tilde{G}_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b)\left[1-d_{n_2n}\right]: \qquad (3.71)$$

sadac d_{n_2n} – warmoadgens kronekeris simbolos da SemoRebuli sidide $\tilde{G}_Z^{GF}(\vec{\tilde{P}},n_2,n,t,b)$ – SedarebiT mdored icvleba t – didi droebis asimptotur areSi ($t\geq t_{rel}$). ganvixiloT did droTa mniSvnelobebi, rodesac

$$t>>|e_{n_i}-e_{n_j}|^{-1};(n_i,n_j=0,1,2,...) \qquad (3.72)$$

Tu CavsvamT (3.71)–tolobas (3.70)–kinetikuri gantolebis marjvena mxareSi da gaviTvaliswinebT (3.72)–utolobas, maSin miviRebT bolcmanis saxis kinetikur gantolebas $G_Z^{GF}(\vec{\tilde{P}},n,t,b)$–sididisaTvis. (Cven ugulvebelyaviT dajaxebiTi integralebi aradiagonaluri matriculi elementebiT, vinaidan isini warmoadgenen swrafad oscilirebad funqciebs didi droebis SemTxvevaSi) [125]:

$$\frac{\partial}{\partial t}G_Z^{GF}(\vec{\tilde{P}},\vec{n},t,b)=i\sum_{\vec{k},n_1}|V_{\vec{k}}|^2\frac{k_Z}{\tilde{P}_Z}\left\{N_0(b)\frac{1-\exp\left[it\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)\right]}{\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)}+(1+N_0(b)\frac{1-\exp\left[it\Delta^+(\vec{k},\vec{\tilde{P}},n_1n\right]}{\Delta^+(k,\vec{\tilde{P}},n_1,n)}\right\}\times$$

$$\times<n|e^{im_e\vec{k}\vec{x}}|n_1><n_1|e^{-im_e\vec{k}\vec{x}}|n>\cdot G_Z^{GF}(\vec{\tilde{P}},n,t,b)-i\sum_{\vec{k},n_1}|V_{\vec{k}}|^2\frac{k_Z}{\tilde{P}_Z}\times$$

$$\times\left\{N_0(b)\frac{1-\exp\left[-i(t-ib)\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)\right]}{\Delta^-(k,\vec{\tilde{P}},n_1,n)}+(1+N_0(b))\frac{1-\exp\left[-i(t-ib)\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n)\right]}{\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n)}\right\}\times$$

$$\times<n|e^{-im_e\vec{k}\vec{x}}|n_1>\times<n_1|e^{im_e\vec{k}\vec{x}}|n>G_Z^{GF}(\vec{\tilde{P}},n,t,b);\quad t>>|e_{n_i}-e_{n_j}|^{-1} \tag{3.73}$$

(3.73) gantolebaSi ajamva n_1–simboloTi moicavs agreTve yvela im mdgomareobebs, romelTaTvisac $e_{n_2}=e_{n_1}$, vinaidan zogadad aRgznebuli $|n>$–mdgomareobebis energetikuli speqtri gadagvarebulia. msgavsi saxis gantolebebi gveqneba agreTve $G_Z^{GF}(\vec{\tilde{P}},n,-t,b)$ da $G_Z^{GF}(\vec{\tilde{P}},0,t,b)$–ZiriTadi mdgomareobis $(e_{0,}|0>)$ matriculi elementebisaTvis. Tu CavatarebT (3.73)-gantolebisa da misi msgavsi gantolebis $G_Z^{GF}(\vec{\tilde{P}},n,-t,b)$–sididisaTvis integrebas t–droiTi cvladis mixedviT, gaviTvaliswinebT $G_Z^{GF}(\pm t,b)$–operatorebisaTvis sawyis pirobebs $t=0$–drois momenti-saTvis: $G_Z^{GF}(0,b)=Z^{-1}{}_{GF}(b)\vec{\tilde{P}}_Z SP_\Sigma(e^{-bH_{GF}});<\hat{P}_Z\hat{P}_Z(t)>_{GF}$ da $<\hat{P}_Z\hat{P}_Z(-t)>_{GF}$ korelaciuri funqciebisTvis (3.68) formulebs, maSin am korelaciuri funqciebisTvis miviRebT Semdegi saxis gamosaxulebebs:

$$<\hat{P}_Z\hat{P}_Z(\pm t)>_{GF}=\frac{(\frac{b}{2pM})^{3/2}}{\sum_n e^{-be_n}}\sum_n e^{-be_n}\int d\vec{\tilde{P}}P_Z^2\exp\left[-\frac{b\vec{\tilde{P}}^2}{2M}\right]\times$$

$$\times\exp\left[\mathrm{Re}\,\Gamma_Z^{GF}(t,b,\hat{P},n)\right]\exp\left[\pm i\,\mathrm{Im}\,\Gamma_Z^{GF}(t,b,\vec{\tilde{P}},n)\right]; \tag{3.74}.$$

sadac, $$\mathrm{Re}\,\Gamma_Z^{GF}(t,b,\vec{\tilde{P}},n)=-\sum_{\vec{k},n_1}\frac{k_Z}{\tilde{P}_Z}|V_{\vec{k}}|^2\left\{N_0(b)\frac{1-\cos\left[t\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)\right]}{\Delta^{2-}(\vec{k},\vec{\tilde{P}},n_1,n)}\left[1+e^{-b\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)}\right]+\right.$$

$$\left.+(1+N_0(b))\frac{1-\cos\left[t\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n)\right]}{\Delta^{2+}(\vec{k},\vec{\tilde{P}},n_1,n)}\times\left[1+e^{-b\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n)}\right]\right\}<n|e^{im_e\vec{k}\vec{x}}|n_1><n_1|e^{-im_e\vec{k}\vec{x}}|n>$$

da $$\mathrm{Im}\,\Gamma_Z^{GF}(t,b,\vec{\tilde{P}},n)=\sum_{\vec{k},n_1}\frac{k_Z}{\tilde{P}_Z}|V_{\vec{k}}|^2\left\{N_0(b)\frac{\sin\left[t\Delta^-(\vec{k},\vec{\tilde{P}},n_{1n}\right]}{\Delta^{2-}(\vec{k},\vec{\tilde{P}},n_1,n)}\times\right\}$$

$$\left[1-e^{-b\Delta^-(\vec{k},\vec{\tilde{P}},n_1,n)}\right]+(1+N_0(b))\frac{\sin\left[t\Delta^+(\vec{k},\vec{\tilde{P}},n_1n\right]}{\Delta^{2+}(\vec{k},\vec{\tilde{P}},n_1,n)}\left[1-e^{-b\Delta^+(\vec{k},\vec{\tilde{P}},n_1,n}\right]\}<n|e^{im_e\vec{k}\vec{x}}|n_1>\times$$

$$\times<n_1|e^{-im_e\vec{k}\vec{x}}|n> \qquad (3.75)$$

xolo, TviT korelaciuri funqciebis milevis dekrementisaTvis (polaronis impulsis $Z-$komponentis relaqsaciis sixSirisTvis) da oscilirebadi faqtorisaTvis gveqneba Semdegi Tanafardobebi:

$$((t>>|e_{n_i}-e_{n_j}|^{-1});\ \Gamma_{Zrel}^{GF}(b,\tilde{\mathrm{P}},n)=\lim_{|t|\to\infty}\frac{\mathrm{Re}\,\Gamma_z^{GF}(t,b,\vec{\tilde{\mathrm{P}}},n)}{|t|}=-2p\sum_{k,\vec{n}_1}\frac{k_z}{\tilde{\mathrm{P}}_z}|V_{\vec{k}}|^2\times$$

$$\times\left\{N_0(b)\cdot d\left[\Delta^-(\vec{k},\vec{\tilde{\mathrm{P}}},n_1,n)\right]+(1+N_0(b))d\left[\Delta^+(\vec{k},\vec{\tilde{\mathrm{P}}},n_1,n)\right]\right\}<n|e^{im_e\vec{k}\vec{x}}|n_1><n_1|e^{-im_e\vec{k}\vec{x}}|n>; \qquad (3.76)$$

$$\mathrm{Im}\,\Gamma_Z^{GF}(b,\vec{\tilde{\mathrm{P}}},n)=\lim_{|t|\to\infty}\mathrm{Im}\,\Gamma_Z^{GF}(t,b,\vec{\tilde{\mathrm{P}}},n)=\frac{b}{2}\Gamma_{Zrel}^{GF}(b,\vec{\tilde{\mathrm{P}}},n)Signt$$

napovni (3.74) formulisa da (3.2)–(3.3) Tanafardobebis daxmarebiT martivad vRebulibT polaronisTvis eleqtrogamtarobis tenzoris disipaciuri nawilis mniSvnelobas ganxilul izotropul SemTxvevaSi [125]:

$$\mathrm{Re}\,s_{zz}^{GFS}(w)=\frac{Ne^2}{M^2}\frac{2th(\frac{1}{2}bw)}{w}\int_0^\infty dt\cos(wt)\frac{(\frac{b}{2pM})^{\frac{3}{2}}}{\sum_n e^{-be_n}}\cdot\sum_n e^{-be_n}\int d\vec{\tilde{\mathrm{P}}}\tilde{\mathrm{P}}_Z^2\cdot\exp\left[-\frac{b\vec{\tilde{\mathrm{P}}}^2}{2M}\right]\times$$

$$\times\exp\left[\mathrm{Re}\,\Gamma_Z^{GF}(t,b,\vec{\tilde{\mathrm{P}}},n)\ \right]\cos\left[\mathrm{Im}\,\Gamma_Z^{GF}(t,b,\vec{\tilde{\mathrm{P}}},n)\right] \qquad (3.77)$$

sadac: $N-$warmoadgens polaronebis koncentracias gamtarobis zonaSi.

polaronis dabal temperaturuli dreifuli Zvradobis gamosaTvlelad fgm-Si ganvixiloT kristalis Zalian dabali temperaturebis zRvruli SemTxveva, rodesac:

$$b>>1;b^{-1}<<|e_1-e_0| \qquad (3.78)$$

sadac e_1 – warmoadgens polaronis pirveli aRgznebuli mdgomareobis energias; (3.78) – pirobebis dacvis SemTxvevaSi ZiriTad wvlils (3.67)-(3.74) korelaciur funqciebSi (ix. agreTve (3.77)) iZlevian polaronis mdgomareobebi, romelTaTvisac: $E^{GF}_{\vec{\tilde{P}},n} \approx b^{-1} << |e_1 - e_0|$; davuSvaT, agreTve, rom $w_0 = 1 << |e_1 - e_0|$. aRniSnuli pirobebis gaTvaliswinebis dros (3.74), (3.75), (3.76) da (3.77) – gamosaxulebebis gamoTvlisas arsebiTi wvlili Seaqvs polaronis impulsis mniSvnelobebs, romlebic akmayofileben pirobas: $\frac{\vec{\tilde{P}}^2}{2M} << |e_1 - e_0|$; Tu mxedvelobaSi miviRebT yvela zemoTaRniSnul pirobas da agreTve Tanafardobas: $t >> |e_{n_i} - e_{n_j}|^{-1}$, maSin (3.74), (3.76) formulebi martivdeba da warmoidgineba Semdegi formiT:

$$< \hat{P}_z \hat{P}_z(\pm t) >_{GF} = \left(\frac{b}{2pM}\right)^{3/2} \int d\vec{\tilde{P}} \hat{P}_z^{\,2} \exp\left[-\frac{b\vec{\tilde{P}}^2}{2M}\right] \cdot \exp\left[-\Gamma^{GF}_{zrel}(b,\vec{\tilde{P}}) \cdot |t|\right] \times \exp\left[\pm i \frac{b}{2} \Gamma^{GF}_{zrel}(b,\vec{\tilde{P}})\right] \qquad (3.79)$$

$$\Gamma^{GF}_{zrel}(b,\vec{\tilde{P}}) = -2p \sum_{\vec{k}} \frac{k_z}{\tilde{P}_z} |V_{\vec{k}}|^2 \left\{ N_0(b) d\left[\Delta^-(\vec{k},\vec{\tilde{P}})\right] + (1 + N_0(b)) d\left[\Delta^+(\vec{k},\vec{\tilde{P}})\right] \right\} \times$$

$$\times |< 0 | e^{im_e \vec{k}\vec{x}} | 0 >|^2; \qquad \mathrm{Im} \cdot \Gamma^{GF}_z(b,\vec{\tilde{P}}) = \frac{b}{2} \Gamma^{GF}_{zrel}(b,\vec{\tilde{P}})$$

sadac: $\Delta^{\pm}(\vec{k},\vec{\tilde{P}}) = \frac{\vec{k}^2}{2M} + \frac{\vec{k} \cdot \vec{\tilde{P}}}{M} \pm 1.$

$$(b >> 1; b^{-1} << |e_1 - e_0|; \frac{\vec{\tilde{P}}^2}{2M} << |e_1 - e_0|)$$

dabali temperaturebis SemTxvevaSi ($b >> 1, b^{-1} << |e_1 - e_0|$), (3.79) korelaciuri funqciebis sidide ZiriTadad ganisazRvreba polaronis impulsebis im mniSvnelobebiT, romelTaTvisac $\frac{\vec{\tilde{P}}^2}{2M} << 1$. dabali temperaturebis dros polaronis impulsis Z – komponentis relaqsaciis sixSire $\Gamma^{GF}_{zrel}(b,\vec{\tilde{P}})$ – martivad gamoiTvleba "impulsTa sferul koordinatTa sistemaSi." $\vec{k}$ – cvladiT integrebisas (3.79) formulidan martivad dgindeba, rom kristalis dabali temperaturebis dros, "mcire siCqariT" moZravi ($\frac{\vec{\tilde{P}}^2}{2M} << 1$) polaronis $\Gamma^{GF}_{zrel}(b,\vec{\tilde{P}})$ – impulsis relaqsaciis sixSire ar aris da-

mokidebuli TviT polaronis $\vec{\tilde{P}}$–impulsis sidideze da ganisazRvreba Semdegi Tanafardobit:

$$\Gamma^{GF}_{zrel}(b,\vec{\tilde{P}}) \equiv \Gamma^{GF}_{0rel}(b) = \tfrac{2}{3} a N_0(b)\sqrt{M}\, f(\sqrt{2M}) \qquad (3.80)$$

$$(b >> 1, \vec{\tilde{P}}^2 / 2M << 1)$$

sadac: $f(\sqrt{2M}) = f(k)|_{k=\sqrt{2M}}$; $\qquad f(k) = |<0|\, e^{im_e \vec{k}\vec{x}}\, |0>|^2 \qquad (3.81)$

$$N_0(b) = \left[e^b - 1\right]^{-1}$$

polaronis dabalsixSiruli eleqtrogamtarobisa da dabaltemperaturuli Zvradobis sapovnelad fgm-Si visargebloT (3.77), (3.79) da (3.80) – formulebiT. martivi gamoTvlebis Sesrulebis Semdeg Cven vRebulobT Semdegi saxis gamosaxulebebs polaronis kuTri eleqtrogamtarobisa da ZvradobisTvis [125]:

$$\mathrm{Re}\, s^{GF}(w) = Ne^2 b^{-1} M \frac{2th(\frac{1}{2} bw)}{w} \frac{\Gamma^{GF}_{0rel}(b)}{w^2 + \Gamma^{2GF}_{0rel}(b)} \cos\left[\frac{b}{2}\Gamma^{GF}_{0rel}(b)\right] \qquad (3.82)$$

$$(w << \Gamma^{GF}_{0rel}(b) << b^{-1} << 1);$$

$$m_0^{GF} = \frac{3}{2} e \frac{\exp(b)}{a} \frac{\sqrt{M}}{f(\sqrt{2M})}; \qquad m^{GF} = m_0^{GF} - \Delta m^{GF}$$

$$\Delta m^{GF} = 3e \frac{\exp(b)}{a} \cdot \frac{\sqrt{M}}{f(\sqrt{2M})} \sin^2\left[\frac{1}{6} a b N_0(b)\sqrt{M} \cdot f(\sqrt{2M})\right]. \qquad (3.83)$$

$$(w = 0; \quad \Gamma^{GF}_{0rel}(b) << b^{-1} << 1)$$

rogorc (3.83) formulidan Cans, Δm^{GF}–sidide warmoadgens temperaturul Sesworebas polaronis m_0^{GF}-dabaltemperaturul Zvradobaze fgm-Si romelic ganpirobebulia arsebuli sawyisi korelaciebiT polaronisa fononebTan. naTelia, rom temperaturuli Sesworeba Zvradobaze war-moadgens m_0^{GF}–ZvradobasTan SedarebiT mcire sidides.

gamovikvlioT da davadginoT kavSiri polaronis dabaltemperaturul Zvradobebs Soris fgm-Si da pekaris naxevrad klasikur TeoriaSi. am programis gansaxorcieleblad pirvelyovlisa vipovoT matricul elementis mniSvneloba $e^{im_e \vec{k}\vec{x}}$–eqsponencialur faqtorze pekaris saxis talRuri funqciebis meSveobiT. martivi gamoTvlebis Catarebis Semdeg vRebulobT Semdegi saxis gamosaxulebas:

$$f(k) \equiv <0|e^{im_e \vec{k}\vec{x}}|0>|^2 = \frac{F_1(k)}{F_2(k)};\ \text{sadac}\ F_2(k) = B_0^2(a)(k^2+4b^2)^{12};$$

$$\text{da}\ F_1(k) = 16384b^8\left[b^4B_1^2(a)k^{12} + 2b^6B_1(a)B_2(a)k^{10} + b^8(B_2^2(a) + 2B_1(a)B_3(a)k^8 + \right.$$

$$+2b^{10}(B_1(a)B_4(a) + B_2(a)B_3(a))k^6 + b^{12}(B_3^2(a) + 2B_2(a)B_4(a))k^4 +$$

$$\left. + 2b^{14}B_3(a)B_4(a)k^2 + b^{16}B_4^2(a)\right] \qquad (3.84)$$

aq: $B_0(a) = 14 + 42a + 45a^{2;}$; $B_1(a) = 1 - 3a$; $B_2(a) = 36 - 132a + 90a^2$

$B_3(a) = 240 - 144a - 1200a^2$; $B_4(a) = 448 + 1344a + 1440a^2 = 32B_0(a)$

xolo, a da b- sidideebi (mudmivebi) warmoadgenen variaciul parametrebs fgm-Si. ganvixiloT polaronis fgm-is zRvruli SemTxvevebi:

I. Zlieri eleqtron-fononuri urTierTqmedeba:

Zlieri eleqtron-fononuri bmis zRvrul SemTxvevaSi, rodesac

$a >> 1,\quad M_{GF} >> 1;\quad (M_{GF} \to \infty, C \to \infty), m_e \to 1$ (ix. 1.33 – paragrafi) fgm-is talRuri funqcia gadadis pekaris talRur funqciaSi:

$$u_0(\vec{x}) \Rightarrow N_\Pi\left[1 + b_\Pi x + a_\Pi b_\Pi^2 x^2\right]e^{-b_\Pi x};\ a' = b_\Pi;\ b \equiv b_\Pi = a_\Pi b_\Pi^2;$$

da manormirebeli mamravli tolia: $N_\Pi = \dfrac{2b_\Pi^3}{p(14 + 42a_\Pi + 45a_\Pi^2)}$ – sididis,

xolo a_Π da b_Π-pekaris variaciuli parametrebia, romlebic SerCeul erTeulTa sistemaSi moicemian Semdegi saxiT: $b_\Pi = 0{,}6585\sqrt{2a}$; $a_\Pi = 0{,}4516$. (ix. 1.3.1 paragrafi). vinaidan f – funqcia warmoadgens ori mravalwevris Sefardebas da fgm-Si da $M = M_{GF} + 1$- aris polaronis efeqturi masa, amitom Tu SevinarCunebT wamyvan wevrs a–s rigis mixedviT f – funqciaSi, maSin Cven miviRebT:

$$f(\sqrt{2M}) \approx \frac{16384b_\Pi^{12}B_1^2(a_\Pi)k^{12}}{(k^2 + 4b_\Pi^2)^{12}};\quad k = \sqrt{2M};\quad (a >> 1) \qquad (3.85).$$

vinaidan pekaris TeoriaSi $M_\Pi \approx a^4$ da $M = M_{GF} + 1 \to M_\Pi$, amitom xarisxTa rigis gamoTvla gviCvenebs, rom: $f(\sqrt{2M}) \approx a^{-12};(a >> 1)$. amrigad, dabal-temperaturuli ZvradobisTvis polaronis fgm-Si vRebulobT Semdegi saxis yofaqcevas a–bmis mudmivas xarisxis rigis mixedviT [125]:

$$m_{o\Pi}^{GF} = \frac{3e}{2a}\exp(b)\frac{\sqrt{M}}{f(\sqrt{2M})} \approx \frac{3e}{2}\exp(b)a^{13};\quad (a >> 1, b >> 1) \qquad (3.86)$$

maSin rodesac polaronis pekaris TeoriaSi (ix. 1.3.1- paragrafi) dabal-temperaturuli Zvradobis yofaqceva $a-$bmis mudmivas xarisxis rigis mixedviT moicema Semdegi damokidebulebiT:

$m_0 \equiv m_{0\Pi} \approx a^5; (a >> 1, b >> 1)$ (SevniSnavT, rom Zlieri eleqtron-fononuri bmis SemTxvevaSi $(a >> 1)$ polaronis fgm-i gadadis polaronis pekaris modelSi).

II. susti eleqtron-fononuri urTierTqmedeba:

susti eleqtron-fononuri bmis zRvrul SemTxvevaSi, rodesac

$a < 1, M_{GF} << 1, (M_{GF} \to 0, c \to 0),$ $m_e = \frac{M_{GF}}{M_{GF}+1} \Rightarrow 0$ (ix.1.3.3-paragrafi),

$M = M_{GF} + 1 \Rightarrow 1,$ da $f(k) \Rightarrow 1.$ (ix.3.81- formula). (susti eleqtron-fono-nuri bmis SemTxvevaSi, $(a < 1)$; polaronis fgm gadadis polaronis frolixis modelSi). am SemTxvevaSi (3.83) da (3.28) formulebidan gamo-mdinare martivad vpoulobT [125]:

$$m_0^{GF} \Rightarrow m_0 = \frac{3e}{2a} e^b; \quad \Delta m^{GF} \Rightarrow \Delta m = \frac{1}{3} e a b^2 e^{-b}; (a < 1, b >> 1) \qquad (3.87)$$

amrigad, polaronis dabal temperaturuli dreifuli ZvradobisTvis vRebulobT iseTive mniSvnelobas, rogoric napovnia polaronis frolixis modelSi.

dabolos unda aRiniSnos, rom sadisertacio naSromSi avtoris mier ganviTarebuli formalizmi (meTodebi) da miRebuli ganzogadoebuli kvanturi kinetikuri gantolebebi korelaciuri funqciebisaTvis SesaZlebelia gamoyenebuli iqnas wrfivi eleqtronuli da polaronuli gadatanis meqanikuri koeficientebis (dreifuli Zvradoba, dinamiuri gamtaroba) gamosaTvlelad urTierTqmedebis rigis mixedviT SeSfoTebis Teoriis maRal miaxloebebSi zemoTganxiluli modelebisTvis, da myari sxeulebis fizikis ((polaruli) naxevargamtarebi, ionuri da kovalenturi kristalebi da sxva). kvantur dinamiuri sistemebis sxva modelTaTvisac, romlebic urTierTqmedeben fononebTan (eleqtronebis gabneva arapolarul optikur fononebze, piezoeleqtruli gabneva, polaronis feinmanis modeli da sxva).

daskvna

1. sxvadasxva midgomebis-mowesrigebul operatorTa da liuvilis superoperatoruli formalizmisa da proeqciuli operatoris meTodis gamoyenebiT, sawyisi korelaciebis gaTvaliswinebiT- gamoyvanilia axali, zusti, ganzogadoebuli kvanturi evoluciuri (kinetikuri) gantolebebi drois ormomentiani wonasworuli korelaciuri funqciebisTvis, dinamiuri qvesistemisTvis romelic urTierTqmedebs bozonur velTan (TermostatTan). miRebul gantolebaTa dajaxebiTi integralebi Seicaven rogorc wevrebs, romlebic aRweren namdvili korelaciebis evolucias droSi, aseve sawyisi korelaciebis evoluciur wevrebs, romlebic ganpirobebulia qvesistemis urTierTqmedebiT bozonur TermostatTan drois sawyis momentSi.

2. SeSfoTebis Teoriis meore miaxloebaSi – qvesistemis TermostatTan urTierTqmedebis hamiltonianis mixedviT – napovnia ganzogadoebuli kvanturi kinetikuri gantolebebi gamoricxuli bozonuri amplitudebiT korelaciuri funqciebisTvis, rogorc markoviseuli, ise aramarkoviseuli saxiT, romlebic Seicaven cxadad gamoyofil sawyisi korelaciebis evoluciur wevrebs.

3. ganviTarebuli midgoma da formalizmi gamoyenebulia gadaugvarebel farTozonian, erTgvarovan naxevargamtarebsa da ionur kristalebSi eleqtronuli da polaronuli gamtarobisa da dabaltemperaturuli dreifuli Zvradobis wrfivi kvanturi Teoriis asagebad. ganxilul kvantur dinamiur qvesistemebis modelTaTvis, romlebic urTierTqmedeben fononur velTan - eleqtron-fononuri sistemisTvis, frolixisa da akustikuri polaronis modelTaTvis, polaronis fgm–sTvis gamoyvanilia ganzogadoebuli kvanturi evoluciuri gantolebebi wonasworuli korelaciuri funqciebisTvis – “deni-denze” (“siCqare-siCqareze”) – eleqtronisa da polaronisTvis Sfm-is gamoyenebis gareSe.

4. eleqtron-fononuri sistemisTvis, frolixisa da akustikuri polaronis modelTaTvis, SeSfoTebis Teoriis meore miaxloebaSi, susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi da erTi zonis miaxloebaSi eleqtronisaTvis gamoyvanilia da gamokvleulia markovis saxis kinetikuri gantolebebi eleqtronis siCqaris operatoris komponentebis saSualo mniSvnelobebis diagonaluri matriculi elementebisaTvis, romlebic warmoadgenen bolcmanis tipis gantolebebs, saidanac gamoricxulia fononuri amplitudebi. Gganxilulia eleqtronis aradrekadi gabnevis procesebi fononebze da dadgenilia, rom ganxilul modelebSi adgili aqvs relaqsaciur process korelaciuri funqciebis oscilaciebiT. Nnapovnia eleqtronis impulsis (siCqaris) relaqsaciis sixSireebis analizuri gamosaxulebebi kristalis dabali temperaturebis SemTxvevaSi. gamoTvlilia eleqtronis “siCqare-siCqareze” korelaciuri funqciebis milevis dekrementebi da oscilirebadi faqtorebi.

5. gamokvleulia da dadgenilia, rom eleqtronis siCqaris (impulsis) mcire mniSvnelobebisaTvis, siCqaris relaqsaciis droebi (sixSireebi) ganxilul modelebSi ar aris damokidebuli impulsis sidideze. mcire siCqareebiTYmoZravi eleqtronebisTvis Zalian dabali temperaturebis dros napovnia dabalsixSiruli eleqtrogamtarobisa da eleqtronis dreifuli Zvradobis gamosaTvleli formulebi.

6. frolixis polaronis modelSi miRebuli gamosaxulebebi eleqtronis dabaltemperaturuli dreifuli Zvradobisa da dinamiuri gamtarobiTvis warmoadgens osakas mier napovni Sedegis ganzogadoebas mcire intensivobis mqone dabalsixSirul gareSe eleqtrul velSi, rac

faqtiurad SesaZlebelia ganxiluli iqnas, rogorc drudes formula kuTri eleqtrogamtarobisTvis. napovnia agreTve statikuri ($w=0$) eleqtrogamtarobisa da dabaltemperaturuli dreifuli Zvra-dobis analizuri gamosaxulebebi, rogorc frolixis, aseve akustikuri polaronis modelebSi.

7. rogorc gamoTvlebi gviCvenebs, eleqtronebis gabnevisas polarul optikur fononebze, dabaltemperaturuli dreifuli ZvradobisTvis (dcmobility; $w=0$) miRebuli mniSvneloba 3-jer aRemateba Zvradobis im mniSvnelobas, romelic miiReba bolcmanis kinetikuri gantolebis gamoyenebiT da amoxsniT relaqsaciis drois miaxloebaSi. miRebuli Sedegi warmoadgens – "$\frac{3}{2}\frac{K_B\mathrm{T}}{\hbar w_0}$ problemis" – nawilobriv gadawyvetas frolixis polaronis dabaltemperaturuli Zvradobis TeoriaSi.

8. eleqtronebis gabnevisas akustikur fononebze (akustikuri polaronis modeli) miRebuli dabaltemperaturuli dreifuli Zvradobis ($w=0$) mniSvneloba 2-jer naklebia Zvradobis im mniSvnelobaze, romelic aseve miiReba bolcmanis kinetikuri gantolebis amoxsnisas relaqsaciis drois miaxloebaSi.

9. ganxilul modelebSi napovnia agreTve eleqtronis dreiful Zvradobaze temperaturuli Seswor ebebi, romlebic ganpirobebulia sawyisi korelaciebis evoluciuri wevrebis arsebobiT gamoyvanili kinetikuri gantolebebis dajaxebiT integralebSi da naCvenebia, rom es Seswor ebebi warmoadgenen mcire sidideebs ganxilul Teoriis farglebSi.

10. polaronis fgm-sTvis miRebuli kvanturi kinetikuri gantolebebi eleqtruli denis operatoris komponentebis (polaronis impulsis) drois ormomentiani wonasworuli korelaciuri funqciebisTvis gamoyenebulia polaronis dreifuli Zvradobisa da eleqtrogamtarobis tenzoris gamosaTvlelad. Gganxilul erTzonian izotropul SemTxvevaSi, markoviseul miaxloebaSi polaronis dinamikisTvis, napovnia miaxloebiTi gamosaxulebebi korelaciuri funqciebisTvis.

11. kristalis Zalian dabali temperaturebis SemTxvevaSi gamoyvanilia bolcmanis tipis kinetikuri gantoleba korelaciuri funqciis diagonaluri matriculi elementisTvis, romelic Seesabameba polaronis ZiriTad mdgomareobas. gamokvleulia polaronis aradrekadi gabnevis procesebi fononebze. napovnia impulsis relaqsaciis sixSiris (drois) analizuri gamosaxuleba da dadgenilia, rom mcire siCqariT moZravi polaronisTvis impulsis relaqsaciis sixSire (dro) ar aris damokidebuli impulsis sidideze.

12. kubos wrfivi reaqciis Teoriis gamoyenebiT miRebulia dabalsixSiruli eleqtrogamtarobis tenzoris analizuri gamosaxuleba eleqtron-fononuri sistemisaTvis erTzonian miaxloebaSi da fononebis dispersiis zogadi (izotropuli) kanonis SemTxvevaSi. gamoTvlilia polaronis dabaltemperaturuli dreifuli Zvradoba fgm-Si. am modelSi napovnia agreTve temperaturuli Sesworeba polaronis dreiful Zvradobaze, romelic ganpirobebulia sawyisi korelaciebis evoluciuri wevrebis arsebobiT miRebuli kinetikuri gantolebebis dajaxebiT integralebSi, da dasabuTebulia, rom es temperaturuli Sesworeba warmoadgens mcire sidides.

13. ganxilulia da gaanalizebulia polaronis dabaltemperaturuli dreifuli Zvradobis yofaqceva susti ($a<1$) da Zlieri ($a>>1$) eleqtron-

fononuri urTierTqmedebis zRvrul SemTxvevebSi. susti eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($M_{GF} \to 0$), rodesac polaronis fgm gadadis polaronis frolixis modelSi, polaronis dabal temperaturuli dreifuli Zvradobis Tvis ($g >> 1$; $w = 0$) vRebulobT iseTive miSvnelobas, rogoric napovnia polaronis frolixis modelSi. Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($M_{GF} \to \infty$), rodesac polaronis fgm aRadgens polaronis pekaris naxevradklasikur Teorias, da-bal temperaturuli dreifuli Zvradobis yofaqceva moicema Semdegi Tanafardobi T: $m_{GF} \sim \frac{3}{2} e.\exp(g) a^{13}$; ($\hbar = m = w_0 = 1$; $g = b >> 1$; $w = 0$); anu polaronis dabal temperaturuli Zvradoba Zlieri eleqtron-fononuri urTierTqmedebis SemTxvevaSi ($a >> 1$) izrdeba a-bmis mudmivas mecamete rigis proporciulad am mudmivas didi mniSvnelobebis dros, maSin rodesac polaronis pekaris TeoriaSi dabal temperaturuli Zvradoba izrdeba misi mexuTe rigis proporciulad: $m_{\Pi} \sim a^5$; rodesac $a >> 1$; ($\hbar = m = w_0 = 1$; $b >> 1; w = 0$).

14. sadisertacio naSromSi Catarebuli gamokvlevebi gviCvenebs, rom ganviTarebul meTodebs, romlebic dafuZnebulia kinetikuri gantolebebis miRebaze wonasworuli korelaciuri funqciebisTvis da maT gamoTvlaze, gansxvavebiT sxva midgomebisgan, ar mivyavarT ganSladi wevrebisagan Sedgenili usasrulo mwkrivebis ajamvis aucilebl obasTan kvazinawilakis (eleqtronis, polaronis) urTierTqmedebis mixedviT fononebTan, kristalze modebuli gareSe eleqtruli velis dabali ($w \to 0$) sixSireebis Sem-TxvevaSi.

naSromSi dasabuTebulia, rom arsebuli sawyisi korelaciebis evolucia da korelaciuri funqciebis oscilaciebi drois mixedviT, romlebic ganpirobebulia kvazinawilakis (zogad SemTxvevaSi kvanturi dinamiuri qvesistemis) urTierTqmedebiT fononur (bozonur) velTan drois sawyis momentSi, gavlenas ar axdenen relaqsaciur procesebze da isini warmoadgenen Zvradobebze temperaturuli Seswor ebebis ZiriTad mizezs (wyaros) ganxilul modelebSi.

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bozonuri (fononuri) amplitudebis gamoricxva qronologiur da antiqronologiur T-namravlTa daxmarebiT

ganvixilοT axla ufro dawvrilebiT bozonuri (fononuri) cvladebis gamoricxvis meTodi (teqnika) qronologiur da antiqronologiur T-namravlTa daxmarebiT Cvens mier warmodgenili im klasis sistemebisaTvis, romlebic aRiwerebian (2.1), (2.2) saxis hamiltonianiT [109].

fononuri cvladebis (amplitudebis) gamoricxva CavataroT H_{int} hamiltonianisTvis, romelic warmoadgens wrfiv formas boze-amplitudebisgan. cxadia, rom komutatorebi: $\left[\tilde{H}_{\text{int}}(x),\tilde{H}_{\text{int}}(t)\right]_-$, $\left[\tilde{H}_{\text{int}}(x),\tilde{H}_{\text{int}}(l)\right]_-$, $\left[\tilde{H}_{\text{int}}(g),\tilde{H}_{\text{int}}(l)\right]_-$ - warmoadgenen C sidideebs (ricxvebs) bozonuri (fononuri) velis mimarT.

Tu gamoviyenebT magnusis formulas [6,81] da veilis igiveobas [6,82] Cven gveqneba:

$$
\begin{aligned}
&\mathrm{T}_{\Sigma}\exp\left[-\int_0^b d\,l\,\tilde{H}^{L}_{\text{int}}(l)\right]=\exp\left[\frac{1}{2}\int_0^b dg\int_0^g d\,l\left[\tilde{H}^{L}_{\text{int}}(g),\tilde{H}^{L}_{\text{int}}(l)\right]_-\right]\times\\
&\qquad\times\exp\left[-\int_0^b d\,l\,\tilde{H}^{L}_{\text{int}}(l)\right];\\
&\mathrm{T}_{a\Sigma}\exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^{L}_{\text{int}}(t)\right]=\exp\left[\frac{1}{2\hbar^2}\int_0^t dx\int_0^x dt\left[\tilde{H}^{L}_{\text{int}}(x),\tilde{H}^{L}_{\text{int}}(t)\right]_-\right]\times\\
&\qquad\times\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^{L}_{\text{int}}(t)\right];\\
&\mathrm{T}_{\Sigma}\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^{R}_{\text{int}}(t)\right]=\exp\left[\frac{1}{2\hbar^2}\int_0^t dx\int_0^x dt\left[\tilde{H}^{R}_{\text{int}}(t),\tilde{H}^{R}_{\text{int}}(x)\right]_-\right]\times\\
&\qquad\times\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^{R}_{\text{int}}(t)\right].
\end{aligned}
\tag{1.1}
$$

ganvixilοT axla Semdegi gamosaxuleba:

$$
\begin{aligned}
&\mathrm{P}_{\Sigma}(b)\left[\mathrm{T}_{\Sigma}\exp\left[-\int_0^b d\,l\tilde{H}_{\mathrm{int}}^{L}(l)\right]\cdot\mathrm{T}_{a\Sigma}\exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}^{L}(t)\right]\times\right.\\
&\left.\times\mathrm{T}_{\Sigma}\exp\left[\frac{i}{\hbar}\int_0^t d\,l\tilde{H}_{\mathrm{int}}^{L}(t)\right]\right]=\exp\left[\frac{1}{2}\int_0^b dg\int_0^g d\,l\left[\tilde{H}_{\mathrm{int}}^{L}(g),\tilde{H}_{\mathrm{int}}^{L}(l)\right]_{-}\right]\times\\
&\times\exp\left[\frac{1}{2\hbar^2}\int_0^t dg\int_0^x dt\left[\tilde{H}_{\mathrm{int}}^{L}(x),\tilde{H}_{\mathrm{int}}^{L}(t)\right]_{-}\right]\cdot\exp\left[\frac{1}{2\hbar^2}\int_0^t dx\int_0^x dt\times\right.\\
&\left.\times\left[\tilde{H}_{\mathrm{int}}^{R}(t),\tilde{H}_{\mathrm{int}}^{R}(x)\right]_{-}\right]\cdot I(t,b),
\end{aligned}
\tag{1.2}
$$

sadac, gansazRvris Tanaxmad, $I(t,b)$ funqcionalisTvis gvaqvs Semdegi mniSvneloba:

$$
\begin{aligned}
I(t,b)=\mathrm{P}_{\Sigma}(b)\Big\{&\exp\left[-\int_0^b d\,l\tilde{H}_{\mathrm{int}}^{L}(l)\right]\cdot\exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}^{L}(t)\right]\cdot\\
&\cdot\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}_{\mathrm{int}}^{R}(t)\right]\Big\}.
\end{aligned}
$$

da bolos, Tu gamoviyenebT Tanafardobebs:

$$
\left[\frac{1}{2}\int_0^b dg\int_0^g d\,l\left[\tilde{H}_{\mathrm{int}}^{L}(g),\tilde{H}_{\mathrm{int}}^{L}(l)\right]_{-}\right]+\frac{1}{2}\int_0^b d\,l\int_0^b dg\,\tilde{H}_{\mathrm{int}}^{L}(l),\tilde{H}_{\mathrm{int}}^{L}(g)=
$$

$$
=\int_0^b dg\int_0^g d\,l\tilde{H}_{\mathrm{int}}^{L}(g),\tilde{H}_{\mathrm{int}}^{L}(l);
$$

$$
\frac{1}{2\hbar^2}\int_0^t dx\int_0^x dt\left[\tilde{H}_{\mathrm{int}}^{L}(x),\tilde{H}_{\mathrm{int}}^{L}(t)\right]_{-}-\frac{1}{2\hbar^2}\int_0^t dt\int_0^t dx\,\tilde{H}_{\mathrm{int}}^{L}(t)\tilde{H}_{\mathrm{int}}^{L}(x)=
$$

$$
=-\frac{1}{\hbar^2}\int_0^t dt\int_0^t dx\tilde{H}_{\mathrm{int}}^{L}(x)\tilde{H}_{\mathrm{int}}^{L}(t);
$$

$$
\frac{1}{2\hbar^2}\int_0^t dx\int_0^x dt\left[\tilde{H}_{\mathrm{int}}^{R}(t),\tilde{H}_{\mathrm{int}}^{R}(x)\right]_{-}-\frac{1}{2\hbar^2}\int_0^t dt\int_0^t dx\,\tilde{H}_{\mathrm{int}}^{R}(t)\tilde{H}_{\mathrm{int}}^{R}(x)=
$$

$$
=-\frac{1}{\hbar^2}\int_0^t dt\int_0^t dx\tilde{H}_{\mathrm{int}}^{R}(t)\tilde{H}_{\mathrm{int}}^{R}(x);
$$

$$
\frac{1}{2\hbar^2}\int_0^t dt\int_0^t dx\left[\tilde{H}_{\mathrm{int}}^{L}(t),\tilde{H}_{\mathrm{int}}^{R}(x)\right]_{-}+\frac{1}{2\hbar^2}\int_0^t dt\int_0^t dx\tilde{H}_{\mathrm{int}}^{L}(t)\tilde{H}_{\mathrm{int}}^{R}(x)+
$$

$$
+\frac{1}{2\hbar^2}\int_0^t dt\int_0^t dx\,\tilde{H}_{\mathrm{int}}^{R}(x)\tilde{H}_{\mathrm{int}}^{L}(t)=\frac{1}{\hbar^2}\int_0^t dt\int_0^t dx\,\tilde{H}_{\mathrm{int}}^{L}(t)\tilde{H}_{\mathrm{int}}^{R}(x);
$$

$$
-\frac{i}{2\hbar}\int_0^b d\,l\int_0^t dt\left[\tilde{H}_{\mathrm{int}}^{L}(l),\tilde{H}_{\mathrm{int}}^{L}(t)\right]_{-}-\frac{i}{2\hbar}\int_0^b d\,l\int_0^t dt\,\tilde{H}_{\mathrm{int}}^{L}(l)\tilde{H}_{\mathrm{int}}^{L}(t)-
$$

$$
-\frac{i}{2\hbar}\int_0^b d\,l\int_0^t dt\,\tilde{H}_{\mathrm{int}}^{L}(t)\tilde{H}_{\mathrm{int}}^{L}(l)=-\frac{i}{\hbar}\int_0^b d\,l\int_0^t dt\,\tilde{H}_{\mathrm{int}}^{L}(l)\tilde{H}_{\mathrm{int}}^{L}(t);
$$

$$\frac{i}{2\hbar}\int_0^b d\,l\int_0^t dt\left[\tilde{H}^L_{\rm int}(l),\tilde{H}^R_{\rm int}(t)\right]_- + \frac{i}{2\hbar}\int_0^b d\,l\int_0^t dt\,\tilde{H}^L_{\rm int}(l)\tilde{H}^R_{\rm int}(t)+$$
$$+\frac{i}{2\hbar}\int_0^b d\,l\int_0^i dt\,\tilde{H}^R_{\rm int}(t)\tilde{H}^L_{\rm int}(l)=\frac{i}{\hbar}\int_0^b d\,l\int_0^t dt\,\tilde{H}^L_{\rm int}(l)\tilde{H}^R_{\rm int}(t).$$

da SevasrulebT gasaSualoebas bozonuri (fononuri) velis mdgomareobebis mixedviT, Cven miviRebT [109]:

$$\mathrm{P}_\Sigma(b)\left[\tilde{H}^L_{\rm int}(g)\tilde{H}^L_{\rm int}(l)\right]=\sum_k\left[(1+N_k(b))e^{-\hbar w(k)(g-l)}\tilde{C}^L_{kH_0}(s,g)\times\right.$$
$$\left.\times\tilde{C}^{+L}_{kH_0}(s,l)+N_k(b)e^{\hbar w(k)(g-l)}\tilde{C}^{+L}_{kH_0}(s,g)\tilde{C}^L_{kH_0}(s,l)\right];$$
$$\mathrm{P}_\Sigma(b)\left[\tilde{H}^L_{\rm int}(x)\tilde{H}^L_{\rm int}(t)\right]=\sum_k\left[(1+N_k(b))e^{-iw(k)(x-t)}\tilde{C}^L_{kH_0}(s,x)\times\right.$$
$$\left.\times\tilde{C}^{+L}_{kH_0}(s,t)+N_k(b)e^{iw(k)(x-t)}\tilde{C}^{+L}_{kH_0}(s,x)\tilde{C}^L_{kH_0}(s,t)\right];$$
$$\mathrm{P}_\Sigma(b)\left[\tilde{H}^R_{\rm int}(t)\tilde{H}^R_{\rm int}(x)\right]=\sum_k\left[(1+N_k(b))e^{-iw(k)(t-x)}\tilde{C}^R_{kH_0}(s,t)\times\right.$$
$$\left.\times\tilde{C}^{+R}_{kH_0}(s,x)+N_k(b)e^{iw(k)(t-x)}\tilde{C}^{+R}_{kH_0}(s,t)\tilde{C}^R_{kH_0}(s,x)\right];\qquad(1.3)$$
$$\mathrm{P}_\Sigma(b)\left[\tilde{H}^L_{\rm int}(t)\tilde{H}^R_{\rm int}(x)\right]=\sum_k\left[(1+N_k(b))e^{-iw(k)(t-x)}\tilde{C}^L_{kH_0}(s,t)\times\right.$$
$$\left.\times\tilde{C}^{+R}_{kH_0}(s,x)+N_k(b)e^{iw(k)(t-x)}\tilde{C}^{+L}_{kH_0}(s,t)\tilde{C}^R_{kH_0}(s,x)\right];$$
$$\mathrm{P}_\Sigma(b)\left[\tilde{H}^L_{\rm int}(l)\tilde{H}^L_{\rm int}(t)\right]=\sum_k\left[(1+N_k(b))e^{w(k)(it-\hbar l)}\tilde{C}^L_{kH_0}(s,l)\times\right.$$
$$\left.\times\tilde{C}^{+L}_{kH_0}(s,t)+N_k(b)e^{-w(k)(it-\hbar l)}\tilde{C}^{+L}_{kH_0}(s,l)\tilde{C}^L_{kH_0}(s,t)\right];$$
$$\mathrm{P}_\Sigma(b)\left[\tilde{H}^L_{\rm int}(l)\tilde{H}^R_{\rm int}(t)\right]=\sum_k\left[(1+N_k(b))e^{w(k)(it-\hbar l)}\tilde{C}^L_{kH_0}(s,l)\times\right.$$
$$\left.\times\tilde{C}^{+R}_{kH_0}(s,t)+N_k(b)e^{-w(k)(it-\hbar l)}\tilde{C}^{+L}_{kH_0}(s,l)\tilde{C}^R_{kH_0}(s,t)\right].$$

martivi gamoTvlebis Catarebis Semdeg advilad vipoviT $\exp\left[\Phi_{L,R,S}(t,b)\right]$ funqcionalis saboloo gamosaxulebas [109]:

$$\mathrm{P}_\Sigma(b)\left[\mathrm{T}_\Sigma\exp\left[-\int_0^b d\,l\,\tilde{H}^L_{\rm int}(l)\right]\cdot\mathrm{T}_{a\Sigma}\exp\left[\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^L_{\rm int}(t)\right]\times\right.$$
$$\left.\times\mathrm{T}_\Sigma\exp\left[-\frac{i}{\hbar}\int_0^t dt\,\tilde{H}^R_{\rm int}(t)\right]\right]=\exp\left[\Phi_{L,R,S}(t,b)\right];\ \ t>0,\ \ b>0\qquad(1.4)$$

da (1.4) formuliT gamoxatuli $\Phi_{L,R,S}(t,b)$ funqcionalis mniSvneloba ganisazRvreba (2.20) gamosaxulebiT.

disertaciis temasTan dakavSirebiT gamoqveynebuli a

Semdegi naSromebi:

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