22652790 12713192.217949 23894098650 31139540172 199759379 134404168177 16711684180 7567956.5890411 36002345.431034 143525751357 38662161.756098 1205765508 6699098700 70024579652 67138537956 39153639.16129 115189804.66667 31253259342 2903204661 89687449.904762 39281116.977273 19688397.395833 90432820696 165675452 53144908.675676 81214516075 3004060.2619048 19061832.674157 36791622978 73587081915 25522833378

# Quantum theory of solids charles kittel pdf online download full word

D., 339 Mean free path, 116 Meissner effect, 169 Metallic sodium, 115 Metals, electrodynamics, 308 electron-ion hamiltonian, 144 INDEX Metals, electron-phonon interaction, 142 velocity of sound, 143 Migdal, 397 Miller, A., 24 Miller, P. When more than two electrons are present, other types of graphs are possible. Forward scattering by an unexcited particle. You're Reading a Free Preview Pages 501 to 511 are not shown in this preview. A. The evaluation of the nth order term in the perturbation expansion of G is usually accomplished with the help of Wick's theorem which gives a systematic reduction procedure to products of expectation values involving one c and one c. PARTICLE FIELD EQUATION OF MOTION METHOD FOR THE HARTREE-FOCK EQUATION We consider a system of electrons described by the field operator $\psi(x)$ = L Cj$\varphi_j$(x) ... The fluctuation in the number of phonons is given by the expansion of motion (102) and the definitions of F and G: (10) (t : ·~ )Gaj(x · x') · iVF';y( +O)F'~(x - t' ) x· o(x - x')(cL't), ... x' ... One electron scattering. (8) We now show that the ground state of the system in terms of the quasiparticle operator ak is (88) na·ka k4~vee, 4>0 k or vk2 == (89) el·Vk(Uk + vkcT~-k)4~vae. Terms with exponents! and! arise from the use of full 'Yk rather than the leading k 2 term in the expansion of 1 - 'Yk' However, if one includes the Tl/l, - T:z/2 terms, but numerical significance the integral over d3k should be taken only over the actual range of k space and not to oo. li. 1 with those of the ring structure. ·Fig. Now u(xt) satisfies the differential equation as at (4) = Dv 2u' + with I 1- D=· (5) 2m Further, at the origin, (6) u(Ot) = c;P(O)cpk(O)e-i-el) ep: cp(O)'F!:(O)g(Ek)e-ekl It 340 QUANTUM THEORY OF SOLIDS is the laplace transform of the probability density 1t'~(Oh~k(O)g(Ck) per unit energy range per unit volume. (a) Discuss the form in relative coordinate space of the ground-state Cooper-pair wavefunction. This energy is to be compared with e1 = -0.38 ry, the ionization energy of a neutral sodium atom. This is not surprising because the phase shift (105) from the delta-function potential is seen to be of the order of 0.1 (atomic exchange energy/fermi energy), whereas the Friedel rule for d states and Z = 1 demands '12 = '11°/10, which is much larger. The reason for the dominance of the ring graphs at high densities may be understood from an example. The theorem states that any function of more than one independent variable which, as w(k), is periodic in all its variables has at least a certain number of saddle points. 4. The gauge invariance of the theory has been demonstrated from several approaches. U. S., 326 Boltzmann equation, 29, 313, 328 Born approximation, 344, 368 Born, M., 37 Boson gas, 23 Bouckaert, L., 206 Bound electron pairs, fermi gas, 153 1-1 1-2 Boundary condition, Wigner-Seitz, 253 Bowers, R., 320, 371 Bragg condition, 255, 374 Breakthrough, magnetic, 229 Brillouin zone, 199 Hexagonal close-packed structure, 211 face-centered cubic lattice, 213 hexagonal close-packed structure, 214 linear lattice, 202 simple cubic lattice, 205 simple square lattice, 203 Brockhouse, B. Thus in the Hartree-Fock approximation the magnetic moment is made that, for fermions, (97) {1234} ''' G(13)G(24) - G(14)G(23). S., 114 Indirect exchange interaction, 360, 364 Lattice, empty, 208 reciprocal, 1 Indirect optical transitions, 295 Lattice displacement operator, 23 Indium antimonide, 277, 278, 283 Lattice series, fourier, 3 Ineffectiveness concept, 311 Inelastic neutron scattering, 27, 53, 375 Laue theorem, 393 Law, B., 298, 305 Interaction, coulomb, 117 Lax, M., 216 deformation potential, 130, 134 Lead, 255 electron-phonon, 130 Lee, T., 393 Harrison, W. c2 + (1 ... The normal conductor that the flux is not energetically advantageous in the normal state ... the 2 of the velocities of first and second sound is approximately satisfied in liquid helium at T ~ 0, but the attainable experimental accuracy is poor because second sound becomes highly damped at very low temperatures as the phonon mean free path increases relative to the wavelength of the second sound. You're Reading a Free Preview Pages 304 to 323 are not shown in this preview. As the quasiparticle transformation (13) H0B = Akata' The energies of the excited states are given directly as the sum of the roots Ak of the equations of motion for the quasiparticle creation operators. (75) to (79) ; (109) E = ... The free particle states ... The sum over spin states in the result for the product the term in k'. The quantity n is the total electron concentration. J., 194 Body-centered cubic lattice, Brillouin zone, 211 Bogoliubov, N., 23, 26, 59, 151 Bohm, H. Sodium is a convenient example because it has an effective electronic mass close to the free electron mass: here we neglect differences between m and m*. Suppose the impurity is at the center of a large empty sphere of radius R; the electron is free within the sphere except for the impurity potential. E., III, 128 Gold, A. To O(A) the expectation value of the diamagnetic current operator is, letting q → 0, (122) jO(X) = ... The gauge ... PROBLEMS 1. (Schiff, 1955) ... (13C and (13) if SUPERCONDUCTIVITY, CH. 8 Thus the indirect exchange interaction between the nuclear spins is not the ... term ... (1955) ... The factor ... H is the magnetic energy. Thus the chemical potential, with the ... term ... Hence the magnetic moment ... The ground state energy of the (unpaired) electron system may be found by the methods of field theory ... (1958) ... the first order energy ... This is a ... equation ... so that the ... Plasmons in metals have been observed as discrete peaks in plots of energy loss versus voltage for fast electrons transmitted through thin metal films. 21 405 We now exhibit an important result known as the Lehmann representation: (48) G(kw) = lim ... (m) M 1 (Ukx ... 1 ... Magnon ... Inside R we have V1 = 0, so the wave functions are ... The relative rate and number of the term ... x ... in a ... the normal ... in magnon ... magnetic ... spectra ... In the ... approximation ... the ... here ... the gauge transformation. ... magnetization, 56 Rigid band theorem, 344 Ring graphs, 129, 421, 424 Rocher, Y. In the same way it is a trivial matter to show that the average over a canonical ensemble of two arbitrary operators A and B satisfies the relation (A(t)B(0)) = (B(0)A(t + iβ)) + (13). (a) If S refers to the total spin S = L Sj and ... (167) ... is ... Th ... the ... (2) ... (19) Laff: ... The effective ... In the limit the result ... where ... CONDUCTIVITY OF METALS, CH. ... 120 ... electrons, 284 Hartree, H. dw e... (4) ... (26) ... . The fact that w(k) is periodic is shown in the chapter on Bloch functions; we have seen an example of the periodicity in (26) above. Estimate in a one-dimensional metal the range of the interaction (11), subject to (10), for a Debye energy of 10-14 ergs. We then treat several representative alloy problems. We now seek ... ir ... (37) ... A. ... (39) ... superconducting ... 18 ... ... a) ... (85) ... (18) The electric current density ... electron ... transitions ... (12) ... The ... conductivity ... of ... ... for the ... of the ... in the ... We note that ... is ... in Fig ... 1 ... A ... is an ... electrons ... the ... with ... order ... : ... 10 ... Coherence effects ... (1958) ... (20) ... Thus ... in ... of ... ... This is ... a ... of the ... energy ... The first term on the right-hand side is the same ... is ... of the ... magnetic ... at ... The approximate value ... is ... interactions ... electron ... Fig ... Brillouin ... In ... G... The nuclear spin ... ... density of states ... The ... expression ... equation (28) ... thermodynamic ... Collective ... phonon ... (34) ... electrons ... one ... spin ... the ... Green's ... We ... 178 ... ... Note that the ... of ... temperature ... 2 ... . The first term ... in ... ... energy ... the Fermi ... is ... plasma ... 114 ... the ... 186 ... ... 100 ... The ... of ... is ... = ... Thus ... Cooper ... QUANTUM THEORY OF SOLIDS ... ... It is ... 

THEORY OF SOLIDS where all quantities are in the interaction representation. Let gJ be the current per unit length in the solenoid. Abrahams [Phys. The oscillatory character of the indirect exchange interaction leads to a large variety of possible ordered spin structures in magnetic crystals, including spirals. 14wDe- 1/ Pl'V ; (66) combined with (55) for PF V «1. Piing is much stronger than that of the deformation potential at the frequencies of interest in experiments. {if(x'),if(x)} Note the mixture of commutators and anticommutators in (40). Screening is a very impor tant feature of the electron gas. ..59 4 The sum for c is over the N atoms j on sublattice a, and for dover atoms l on b. p.) g ~~(~w~ I . Let 0 denote the ground state of H 0, denoted by 10) in Chapter 1. 128, 1618 (1962), and papers cited there. CHAPTER 16 1. We note that Vq - V: is the external potential, and (Vq - V:) + V: V q is the effective potential. The structure of perturbation theory requires that all terms in the energy be constructed to get particles back to their initial states. - -, Z - c2 aEt/az +0 kc 2 (11) ELEC . peip P - pe- 2 - tT iP 2 P - -oc 2 } tT with p k'r and tT = kr. Graph for 1 l' ~ I I 2' 2 third-order energy correction involving two electrons. 5. The ~o outside the integral remains unchanged. Steinman, PhY8. B., 319 Mirror planes, 213J Mitchell, A., 289 Modes, magnetostatic, 48, 72 Momentum, crystal, 15 density, 19 representation, 184 Monster, 261 MontroU, E., 30 Moore, 318 Morel, P., 163 Morse, M., 31 Mossbauer effect, 386 Mott exciton, 298 n C C 0 0 0 0 0 10 p, Nagamiya, T., 58 Nakamura, T., 58 Nearly free electrons, 255, 256 model, 262 N eel temperature, 62 Nettel, S. Va (1958). Ho =--'\72_-, H' = y tz2 ' 3 = - (~'\72- 3 ~) 2 2 Ell e 2 Je.l Ell/x + y2 + Z2 e EO/;;2 + y2 + Z2 3 2 az 2 2 2 ytz2(1 a 1 a a ) 3/l 2 ax 2 + 2 a y 2'- az 2 ' o Y = Y'/lo· QUANTUM THEORY OF SOLIDS A-56 From Ho1/1 = E1/1, (this is just the hydro genic Schrodinger equa tion), En = -E l /n 2 , E1 = l'oe4/2E~/i2. We write the many-particle state ~ of the system as ~ = ~o (118) where ~o + ~1 (A) + . te d: og he 68. 11m (48) 8-++0 x 1 . We observe that {'lr(x),'lr+(x')} = o(x (29) because (30) r = {'lr(x),'lr+(x')} x'), {cj,cdIP;Cx)IPt(x') = LIP;Cx)IPj(x'), fi and by closure r (31) i IP/x)IPj(x') = o(x - x'). This is exact. Thus for the saturation magneti zation, with the same assumptions as for the heat capacity, and taking unit volume, (36) }y[ 8 = 2JLoSz ~ btbk ), = 2JLO (NS - and (37) M 8(0} - M8(T) == !:&M = 2JLO f~ (nk) = At low temperatures such that Dk max 2 » (38) !:&M = JL02 27r 2JLO (27r)3 J 3 d k T, (!..-)% («> dx x~ -z_I_, D Jo e - 1 where the integral is equal to r(l-)r(I-;I). This fur nishes an excellent and important check on the accuracy of the usual methods of finding the eigenvalues of the BCS reduced hamiltonian. E., 365 Donor states, 286 Doppler shift, 319 Double group, 216 Dresselhaus, G., 186,215,273,277,278, 301,318 Drift velocity, 238, 239 Dynamic structure factor, 33, 110, 129 Dyson, F. We recall that the term involves a product of four operators, such as Cit+qCk/Ct_qCk; in terms of the a and 13 there are 16 possible combinations. The Bloch theorem states that if V(x) is periodic with the periodicity of the lattice, then the solutions cp(x) of the wave equation THEOREM (1) H",(x) = C~ p' + V(X») ",(x) = E",(x) are of the form V - - __ ,' •r , "-.... 243). == p-(kw). The sum over electron spin states is carried out with the help of a standard relation (Schiff, p. The actual consequences of small concentra tions of impurities are often much less serious than might be imagined· from this formal statement, particularly if the impurity atom has the same valence as the atoms of the host crystal. 1 { T ~ k + q involves 2 + .!1 ) 1+ XX • k k+q SkSk+q This is the result for photon absorption and for nuclear spin relaxation in a superconductor. We shall see that the configuration with each sublattice saturated is not the true ground state. The Vet) in (13I) are in the illteraction representation. PI Pl Pl Pl Pi Pi NDEx' INDEX >n,142 OPW method, 263 generalized, 254 Orbach, R., 164 Orbits, aperiodic open, 233, 234 closed, 229 electron, 230, 232, 258 extended, 234 hole, 230, 232, 258 magnetic field, 229 open, 230,238, 244, 245, 247 periodic open, 232, 233, 234 quantization, 228 Orthogonalized plane wave, 263 Oscillations, free, 37 Oscillator, harmonic, 293 Oscillatory magnetoabsorption, 296 Overhauser, A. specimens of yttrium iron garnet measured by Shinozaki gave 0.81 X 10-28 erg-cm 2 and 0.85 X 10- 28 erg-cm 2, leading to m */m con Two D = "'' 6. In the following development we consider only terms linear in the external perturbation v(w,q), but we are interested in all Pq orders of the coulomb interaction. 150 screening, 112 Lifetime, electron-electron, 115 James, R. We define f G(kt) = (19) d 3x e-ik·XO(xt); the inverse transformation is (20) G(xt) = (2:)3 f 3 d k eik-XO{kt). ~ V ~ V) is now more complicated. The usual definition relates the polarization component P q to the longi a For a review ijee D. " be the d3x at (106) where omitt the a wavelt that ( (107) No (l08) Beca collisi (l09) Thus (110) and 0 (111) liFo menta ,F SOLIDS sfied will limum of iVill have positive l particle be zero. tion is destroyed by umklapp processes. A discussion of second sound in liquid helium is given by R. JETP 6, 1174 (1957); which is based on the work of V. For photon energies less than the gap the only inelastic photon process which can occur is the scattering of a quasiparticle in an excited state. G., 57 Basis vectors, 1 Baym, G., 397 BCS equation, 160,414 equation-of-the-motion method, 164 spin-analog method, 157 BCS operators, 178 Beliaev, 397 Bethe, H. The components which contribute to (6) at time te are principally those for which cktc < 1, or, using (8), 1 (9) But ck ck < 2m~2' k2/2m, so that if 1 (10) 3 or 4. me k Ek +q - Ek - FlW - III 2 2 e) '" e 1i- ( -;me lW 2{ Eq~kX k tk Ek+q - Ek -liw ------i~} , 2 2 -e - 1i me (~)Eq~'" k{ g; k x where Eq is electric field. Vosko, J. 6 125 the times of the interactions in an unlinked part be tI, t2,' , t" (0 > tl > t2 > ... The second-order interaction between the two nuclear spins is given by H"(x) = (121) Sk - Sk' H"(x) = ' 2; (8· In)(8· Im)m*J 2 (211")-6p • s.h de< thl of Fr lar r'd 3k Jo roo Jkr d 3k' e-i(k-k')'x -k--:;;2-_-k-''''''''2 + cc. The minimum value of k for which the k min = l(q + qc), db IS trl gr (3 = 0 reduces to k min = lqc (31) so m *c s • For this value of k the electron group velocity Vg = kminlm * is equal to cs , the velocity of sound. Soc. R., 249 electron-electron interaction, 151 Relaxation time, 135 frequency distribution, 30 ~presentation, small, 201 longitudinal optical, 137 Residual resistivity, 346 optical, 34, 37 Resistivity, electrical, 345 Photon absorption, 294 residual, 346 surface, 311 Piezoelectric semiconductor, 149 tensor, 241 Pincherle, L., 250 1-8 Resonance, cyclotron, 217, 226, 234 geometrical, 334 open-orbit, 335 Response, dielectric, 116 Reuter, G. We first discuss two results of wide application in the theory of alloys, the Laue theorem and the Friedel sum rule. I., 57 Allowed transitions, 294 Alloys, 338 Almost-free electron approximation, 254 Aluminum, 262 fermi surface, 260 Analysis, graphical, 116 Anderson, P. The first term on the 82 QUANTUM THEORY OF SOLIDS right-hand side of (45) is the direct coulomb term, and the second term is the exchange term. N,_E.N", L l(nlckI0)12ei(EnN-l-EoNlt, t > 0; t < O. as in Fig. The critical magnetic field at absolute zero is obtained by equating Eg to He 2/8rr for a specimen of unit volume. kl = -qkl~l; q • k2 = qk2~2, where the limits imply that ~l, ~2 are positive. 8 163 excitation of the same Ikl, according to (167) and (168). A gauge transformation from the cou lomb gauge means that one adds to our vector potential a longitudinal part iq~(q). Appl. II J. V~' L, B k*" k' w SUPERCONDUCTIVITY, CH. We consider the absorption of ultrasonic waves by quasiparticles, with the deformation potential interaction hamiltonian (2): tol fror (14: (14~ Ad (14L QUA 11 duc (14: We (14! whe V nel ma~ prOl surf the (15( wh€ pho regi 11 n SUPERCONDUCTIVITY, CH. The experimental verification of this, particularly of the factor j, is strong evidence of the importance of BCS pairing in the ground state. -w where we have used the symmetry property l(nlpqI0)\2 From (42) we have the exact result 1) + WnO ~8. The thickness of the shell in the direction normal to a bounding surface is given by IVkWI dk n (115) = dw, so that (116) Vo [ dS, g(w) = Zl JSew) IVJtw[ where Vo is the volume of the primitive cell; Z denotes the number of atoms per cell; and l is the dimensionality of the space. The acoustic phonons themselves possess many of the attributes of particles. The number of such pairs is a variable of the problem, so that we should add to the right-hand side of (103) the term + 2}{N + 21 T('lr:;(Xa)'lrt(X4) )IN). Here Eo(g) is the exact eigenvalue and cI»o(g) the exact eigenfunction. We note that we are concerned with the product of probability density CPk(X)CPE(X) and the density of states geE). = Thus we oCt' - t)o(x' - x) - i f d y V(y 3 x')K(yt';x't';yt~;xt). Thus, from (151) and (152), (155) ~ it'(x) t v it'(x) exp (iell>/c), on carrying one electron once around the ring. e.l yEn e e E.l x2 y2 E.l f.l E.l~ -+ e Je.l Ell 1/ x 2 y2 + + ( E.l ) Ell 32 + ' _f!i V-;; 3· Z = V(r) = e2 eolx 2 + y2 + Z2 tz2 e2 2/l0 Eor . Morel and P. K., 142 transitions, 296, 297 Impedance, surface, 309, 315 Langenberg, D., 318 Impurity states, 286 Langer, J. G., 371 Silicon, 234, 275 Simple cubic lattice, Brillouin zone, 205 Simple square lattice, Brillouin zones, 257 Singwi, K. 126, 1263 (1962). The ground state (69) is only an approximation to the exact ground state, because we have assumed a product form for (69) and the true eigenstate is bound to be much more complicated. The theoretical values of the curie temperature in the following table were calculated by Rocher using the value rs= 5.7 ev-A3 which fits the observed curie tempera ture of Gd. T.(exp) Tc(theo) Gd 300 300 Tb Dy 237 154 200 135 Ho 85 85 Er 41 48 Tm 20 25 Yb 0 0 Lu 0 0 degK degK The agreement is quite satisfying. An unlinked graph: the part 3,4 is not connected to the part 1,:6. J., 262 Shinozaki, S., 56 Shirkov, D. We employ the identities (82) lim 8 ..... We are concerned with the behavior of the integrand for small q,~because we want to examine the convergence here. In m ~) , :t.s )r an ,he ~ge 2 8 Z k----k r e ·. If Uk(X) does uti (x) V p(x)uo(x). The BCS integral equation (49) is modified accordingly at a finite temperature to take account of this decrease in Uk; with ek unchanged: (62) tan Ok = (V/ 2ek) L' tanh (Xk,/T) sin Ok' = .1/ek, k' with, from (56), (63) Xk = {ek 2 + .1 2(T) } ~. But, and this is the most important feature, the ring graphs may be summed to all orders to give a convergent sum even at low q. Doubling the number of excitations doubles the entropy, which is exactly equivalent in the free energy to doubling the temperature. 2 ACOUSTIC PHONONS, CH. r 38 ] ] ] ] 1 1 1 1 INDEX Hexagonal close-packed structure, Brillouin zone, 214 field limit, magneto resistance, 241 Hole annihilation, 117 creation, 117 operators, 84 orbits, 230, 232, 258 Holstein-Primakoff transformation, 49, 58,64 Holstein, T., 320, 329 Hopfield, J. 13 261 r ,......---- ....... This is Thu: magna '11\ I[ ~'] LIDS MAGNONS, CH. kk' The hamiltonian transformed to magnon variables is, if there are z nearest neighbors, (49) H -2NzJS 2 = - 4Np. oH AS + Xo + Xl, where the term bilinear in magnon variables is (50) + Ckdk) + Xo = 2JzS _L ['Yk(ctdt k (CtCk + dtdk)] + 2p.oHA L(CtCk + dtdk), k with (51) 'Yk Z -1" '-' 6 ik·O e 'Y -k' assuming a center of symmetry. - i grad, (35) d''', ~ cjcIl"j(x) :~ I'''(x), For free particles, with p = H= '1'\"(k/) + 2m cicI' 80 QUANTUM THEORY OF SOLIDS where the factor cici automatically arranges that we count the energy of occupied states only in a representation in which the cici are diagonal. We may define the dielectric constant in various equivalent ways. We expect the Thomas-Fermi dielectric constant (34) to be a special case of the self-consistent field dielectric constant (23) for w = 0 and for q/kp «1. Acoustical and optical magnon dispersion relations in magnetite, as determined from inelastic neutron scattering by Brockhouse and Watanabe (IAEA Symposium, Chalk River, Ontario, 1962). We consider a circular ring R with a tun FIG. At high densities ring graphs are dominant; they are also divergent in each order at low q, as we saw explicitly for the second-order energy correction, which corresponds to a ring graph. Woll, Jr., and W. (8) It is convenient to make a transformation from the atomic at,aj to the magnon variables bt,bk defined by bk = N-YA (9) L eik,xjaj; b+ k j here Xj is the position vector of the atom j. B., 30 Direct optical transitions, 294 Dirty superconductors, 183 Dispersion relations, 405 Distribution function, pair, 110 Divalent metals, 242 Donath, W. L., 173 Glauber, R. (126) Thus 0 p+( +0) = vp+( +3 ) f d 3k 1 2(211') Ak = l Vp+( +0) 2: k 1 (Ck + or (127) L m a p 1 =j-V2: k 1 - H' (I This is just the fundamental BCS equation, as in (8.53). (b) Estimate the range of the function for a representative superconductor, taking L1 :;: : : kBTc, where To is the critical temperature for a superconductor. The integral over dw need include only positive w because Wn is always positive. We consider, to illustrate the notation, an unperturbed system containing only two electrons, in states kl' k 2 • The first-order perturbation energy is (9) = e(1) (V) = (12IVd12) = (12IVI12), where, for convenience, we drop the electron indices from V. The quantity H A is positive and is a fictitious magnetic field, which approximates the effect of the crystal anisotropy energy, with the property of tending for positive JJ.o to align the spins on a in the +z direction and the spins on b in the - z direction. From (3), (4), and (5) we may calculate the transformation for SZ' Now, dropping the subscript j, (6) Sz2 + 1) = S(S + 1) - = S(S Sx 2 - Sy2 = S(S + 1) - i(S+S- + S-S+) S[(l - a+a/2S)Haa+(l - a+a/2S)~fl a+(1 - a+a/2S)a]. HAMILTONIAN IN SPIN-WAVE VARIABLES Using the transformation of S+, S-, Sz to spin-wave variables, the hamiltonian H = -J L8 j • Sj+i- 2p.oHo j6 LSjz ~ .: ~ VI c: ~ :>. C., 141, 142 Brownian motion, 396 Brueckner, K. G., 232, 246 Classical skin depth, 308 Classification of plane wave states, 208 Clogston, A. Supplement 3t 446-507 J. From (91) we form (93) / (aat' f - i \T i -i (p')2) 'li(x't')'li+(xt)/ \ 2m d 3 y V(y - x')(T('li+(yt')'li(yt')'li(x't')'li+(xt» = f d~y V(y x')K(yt';x't';yt~;xt), with the two-particle Green's function K defined by (12). 2 It is generally helpful to express the prop~rties of the interacting electron gas in terms of the longitudinal dielectric constant E(W,q). If the elementary excitations had a free particle dispersion relation-", a: k 2-then the critical velocity would be zero. The screening of the coulomb potential by the electron gas is an important effect. n We also encounter the notation A(kw) With our notation (41) becomes == p+(kw)j B(kw) fo" dwp+(kw)e-i(w+l'lt, i fo" dw p-(kw)ei(w-l'lI, l -i (44) G(kt) = t > OJ t < O. This number is determined by topological considerations and depends only on the number of independent variables. 2 Phil 2mhll + 2 P hJ. For sodium with l8 as estimated by Pines, the result is 0"0 171raH 2 , where aH is the bohr radius. 12 that the magnetic flux through a supercon ducting ring or toroid is quantized in units of 1 ch (148) - - = 2.07 X 10-7 gauss/cm 2 • 2 e We note that the unit may be written as (149) 2 ! 2dc = 21r eli mc = 21r/oLB, 2 e 2mc e2 ae where ae is the classical radius of the electron. (After Shinozaki.) The intercept at T = 0 measures the magnon contribution. rqe-tMt test charge We now calculate (Pq), the response of the system to the test charge. J., 392 Glide plane, 213 Glover, R. - nm [ i1l"O(W e/l(II-",..ft l ) wmn)(l- + (1 (S> Wmn - + cfJ(II-"'",,,l)]. (b) H artree A pproximation. We now consider the screening in several approximations. For t > 0 the states n are excited states of a system of (N + 1) particles; for t < 0 the states n refer to excited states of a system of (N - 1) particles. Sondheimer, Proc. The fact that the curie temperatures are much higher in the metals than in the oxides is consistent with the role we ascribe to the conduc tion electrons. Schrieffer, The many-body problem, Wiley, 1959, pp. By operating on (101) from the right with 'Itt, we obtain the equation (117) ( a p2 + 2p, ) P+(x -i- - at 2m - x') = o. (++ grad 'lr - 'lr grad 'lr+) 2m~ = .&jp(x) e2 (123: - - 'lr+A'lr mc + .&jD(X), in terms of the paramagnetic and diamagnetic parts. = &E/iJN. (28) beca and (31) Tl (32) + ... Thus the scattering term is, from (143) with the appropriate change of sign, (147) (Uk+qUk - VkVk+q) 2 1 = T I+ 1 SkSk+q - AA 6 2 } • k k+q A discussion of experiments involving coherence effects of the type of (144) and (147) is given in reference 4. Phys. ± ~s (P (, tl (J iE o 1 - . Note that (30) may be checked by an elementary argument: for phase shift 1'/ L(kF) the quantized values of k near k F in a sphere of radius R are shifted by Ilk = -1'/L(k F)/Rj but there are 2(2L + l)R/r states of given L for a unit range of k, so that the total change in the 344 QUANTUM: THEORY OF SOLIDS T: L (2£ + l)71L(kF), 1 number of states below the fermi level is just (2/11') 1, which must equal Z if the excess charge is to be screened. E ELECTRODYNAMICS OF SUPERCONDUCTORS The first objective of a theory of superconductivity is to explain the Meissner effect, the exclusion of magnetic flux from a supercon ductor. On the nearly free electron model the presence of a band gap at a zone boundary is related to an appropriate fourier component of the periodic crystalline potential; the "partial" destruction of the periodicity by the admixture of a weak spectrum of other fourier components associ ated with a low concentration of impurity atoms does not destroy the 338 Thi energ, at dis wavel scree note '!O~(x) think subst was s Pr (1) Weir (2) wher (3) Now (4) (5) Furt (6) THEOHY OF ALLOYS, 339 elf. In two dimensions the singularity is logarithmic; in three dimensions g(w) is continuous, but dgldw has infinite discontinuities. We now wish to express Sj, and SZj in terms of the spin-wave variables. The density of states g(w) dw is directly proportional to f dk, where the integral is over the volume in k space bounded by the constant energy surfaces at wand w + dw. +0 Thus (84) ('" dx c'(a+i 8 l., h = 1I"o(a) + i ~; a f o dx et(a-isl., 1I"o(a) _ i = -'" G(kw) (S> a L cll (!!+IIN..-E"li(n!ckim>i 2. We observe that an interaction independent of k may be represented by a delta function potential. 2 the incident particles can be chosen in N 3 ways and q in a number of ways proportional to Q. by (52) and (86): (93) (94) Thus the normalized I Uk 2 2 = 2 COS }Ok = The values of Uk, Vk are given -HI + cos Ok) = l[l + (Ck/Ak)]; 2 Vk = sin lOk = l(l - cos Ok) = l[1 - (Ck/Ak)]. Jd V(y - x)if+(y)if(y)if(x) = - r Jd V(y 3 Here y)if(y)if(x'),if(x)] 3 y y 3y CtClC m x),°k(y),Ol(y),om(x). (85) = ek2uk2 + 42Vk2 + 2ek 4UkVk = (ek 2 + 42)Uk2, Thus 4 2 (Uk 2 - Vk2) = 2ek 4UkVk' O. For slowly varying A the Pippard expression (137) reduces to the London form (112), with A as defined there. (24) C) -I . Ziman, Proc. Now (3) k p2 2qk 1h (4) +k (k p - k1)(k p 1 ) "'" APP wh{ (fro stat 2k p (k p - k 1 ), or V (5) con per1 kp > kl > k p q~l, - and similarly for h We use these relations, valid for small q, to express the limits on the integrations over kl and k 2_ For a part of (1) evaluated at small q, recalling that h, ~2 are positive, (6) f f:1 1 d k2 - c - - - d 3k1 = (2~)2 (2~)2 10o d~l 101 d~2 1 ~ -4- k p 4 q 0 11 11 dh 0 0 dk 1 kp-q~l l kP kP-q~. 422 A QUANTUM THEORY OF SOLIDS iJ c In third order there are terms of the structure (17) V12 !I'2') '" 1 T.J (34!V 34 !34) '" 1 '" (1'2'! 12), n d involving four electrons, as illustrated by Fig. The ion cores are too far apart in relation to their radii for direct exchange to be significant. J., 326 Eddy current equation, 308 Effective carrier charge, 336 Effective conductivity, 312 Effective mass, 292 mass, cyclotron resonance, 227 mass tensor, 185, 283 Elastic line, 13, 18 Electric dipole transitions, 302 1-3 Electrical resistivity, 345 Electric field, 190 hall,241 Electrodynamics, metals, 308 superconductors, 169 Electron annihilation, 117 creation, 117 crystal,99 -electron interaction, virtual phonons, 149, 151 -electron lifetime, 115 gas, 86, ll8, 126 exchange integral, 91 perturbation theory, 417 self-energy, 93 -ion hamiltonian, metals, 144 operators, 84 orbits, 230, 232, 258 -phonon interaction, 130 metals, 142 Elliott, R. 7. We write 11 = H 0 + V, and choose II 0 so that the one-particle Green's function appropriate to H 0 can be found explicitly. The solution for k = 0 of the one-electron periodic potential problem for sodium gives e(k = 0) "-' -0.60 ry, according to calcula tions described in the references cited in Chapter 13. A., 335 Parallel pumping, 69 Process, normal, 132 Paramagnetic scattering, 382 umklapp, 133 Parameter ~, energy-gap, 161 Proton, 147 Particle density fluctuation operator, 95 Pseudopotential, 361, 372 Pekar, S., 141 Pumping, parallel, 69 Periodic open orbits, 232, 233, 234 Perturbation expansion, Green's func Quantization, field, 19 orbits, 228 tions, 415 Quantized flux, 175 varying, 196 theory, degenerate, 187 Quantum equations, summary, 5 Quasimomentum, 15 k· p, 188 Quasiparticles, fermion, 84 electron gas, 417 k . contributions. The evaluation of G(xt) for the ground state \0) of a noninteracting fermi gas in one dimension is the subject of Problem 1. If ~ < -"'L, as in certain alloy super conductors, the superconductor is said to be a hard or Type II super, conductor; its behavior in strong magnetic fields is changed drastically, see in particular A. We make the adiabatic hypothesis, so that 80 can differ from 0 only by a phase factor. Dyson [PhY8. We can do the arithmetic another way. We expect a singularity when (117) IVJtwl = iJw)2 [(iJk x + (iJw)2]~ iJk = 0, ll written for two dimensions. Langer and S. Because N n = N m (81) G(kt) = i - 21 409 1, this may be written as L e8(1l+IINn-E"le/l(""..+lIli(nickim)i2cw"",t, t nm < O. Even in simple metals V is expected to depend somewhat on M, which should spoil the agreement of observation with the simple theory; see, for example, P. We label the intermediate states as 1'; 2', 3. 96, 839 (1954)] by calculating phase shifts-the Born approximation is not accurate. With our factor - i the Green's function for a free-electron gas satisfies, using (14), (17), and (18), (i -ata + -21maxat) Go(xt} .. kv)r] I ~ 1. The first step is to find cxx , Cyy ' cxy ' and eyX ; then use Eq. (79) to find w. 1 there are N 2 ways of picking the incident particles, but q and q' are independent and may be picked in Q2 ways. (39) MAGNO Therefore I!:&M = 0.117JLo(kBT/D)~2 = 0.117(JLo/a 3 )(kBT/2SJ)*, 1 Keff T4 ter 8 for S nearest expand we get magno depend temper' Letters We metals the ba shown a low-t electro magno Revi are: F.K A. l Nagamiya, Yosida, and Kubo, Advance8 in Physics 4, 97 (1955); J. It is apparent that the singularities of g(w) originate from the critical points of w(k), where all the deriva· tives in (117) vanish. The equivalent spinor hamiltonian (if V is constant for N' states 178 QUANTUM THEORY OF SOLIDS and zero otherwise) is (166) H = -tv L' (O'kzO"k'z + O'kUO'k'U), kk' where k, k' run over the N' states. The electron density corresponding to (113) is, to O(J), (114) cos kr + m*J21I'r cos kx I~ p(kt) = 1 - m*J;;S kr cos kx I~ p(kj) = 1 also (115) It is interesting to sum p(kj) over the ground state fermi sea: (116) 1 p(j) = (211')3 f k]i'3 3 d kp(kj) = 611'2 m*JI· (2kl'r + 4(2r)3;4 10 dx x sin:v, or (117) k]i'3 {3m*JI~k]i' p(n = 611'2 1- 11' } F(2k]i'r) , where (118) F(x) = x cos x - sin x X 4 • If the electron concentration is 2n, of which n are of each spin, we may summarize (117) and the corresponding result for p(!) by* (119) P:l;(x) = n [1 + ~ 1I'JF(2kFT)I~ r We see that the nuclear moment perturbs the electron spin polariza tion in an oscillatory fashion. This term is linked in the sense that the diagram may not be split into two parts with no interaction lines between the parts. (+i) lim (V x ' 2mz x'-+x Vx)Gap(x't',xt). Kaganov, Soviet Physics-Uspekhi 3, 567 (1961); original in Russian, Usp. If 11E(O,q) has poles, there will be oscillations in space of the screening charge density. We now examine the contribution of the surface to the inductance of a magnetizing circuit: consider a flat solenoid with inside it a flat slab of conductor of thickness 2d. a e '] e T (. Then UIO} = (2'; terms from unlinked parts) X (2'; linked parts). 176 QUANTUM THEORY OF SOLIDS s' Then curl A = 0 and A = grad x, where X cannot be a constant because it must ensure that on going once around '1 (151) ~x = ~ grad x . C., 315, 318, 365 Mattuck, R. You're Reading a Free Preview Pages 442 to 447 are not shown in this preview. Heat capacity of yttrium iron garnet, showing magnon and phonon con tributions. The total displaced charge A involved in screening is (71) a = f (2!)' d'x ap(x) = = f f ('(;'q) - 1) e,q·· d'q d'x Zfd 3q o(q) (_1_ - 1) E(O,q) =Z (.(;'0) - I} The value of E(O,O) is sometimes not well-defined, but may depend on the order in which ~ and q are allowed to approach zero. R., 220 Free electron, magnetic field, 217 Frenkel exciton, 298 Frequency, cyclotron, 218, 235, 2:~6 distribution, phonons, 30 plasma, 36, 105 Friedel, J., 339, 346, 360, 365 Friedel sum rule, 341, 343 f-sum rule, 128, 186, 198, 301 Galitskii, 397 Gas, boson, 23 Gauge invariance, 172 transformation, 172 Gavenda, J. tm ' • The sum is therefore the product of the expressions obtained separately from the two parts. Such a term in the potential is coupled strongly to plasmon excitations and in fact shifts the plasmon coordinate. 111, 1214 (1958). 2 involves three electrons in initial states 1, 2, 3. nm Note now that 1+ (87) ~~II-'" .. JETP 7, 505 (1958)] as described in Chapter 21. T by pai xz the the (68, but sta1 (69 ' SUPERCONDUCTIVITY, CH. If we extend the space to allow single particle excitations, as in (102), p. T i - 1 (00 (27) c; = Tl ... There is a further, but approximate, simplification at high densities (ra < 1) in the electron gas problem. (104) T('lr ,,(XI)'lr/l(X2) )IN hi (l o " (l w (J s( (: We may write the factors in (104) in the form (105) (NIT('lr,,(x)'lr/l(x'lnIN (106) (N + 2) + 2IT('lr;;(x)'lrt(x'»IN) 2i v = e- l'tF"/l(x - x'), = e2il't~(x x'). HOLSTEIN-PRIMAKOFF TRANSFORMATION The hamiltonian involves the three components Sjz, SjYJ SjZ of each spin S j. R., 150, 151, 172 Schultz, T. This statement appears to contradict (31). C., 284 Harmonic oscillator, 218, 253, 293 Harrison, M. Nabauer, Phys. EXCITED STATES With (100) ~o IIa-kak~vac, 168 QUANTUM THEORY OF SOLIDS the products fOJ cf!kl ... Thus the threshold for the emission of phonons by electrons in a crystal is that the electron group velocity should exceed the acoustic velocity; this requirement resembles the Cerenkov threshold for the emission of photons in crystals by • There is a simple connection between the fust..-order renormalization of the electron energy and the relaxation rate (28). M., 228, 237 JeIlium, 142 Line shape, dysonian, 323 Jones, H., 200 Linear lattice, band structure,256 Brillouin zone, 202 Kadanoff, L. dl = JJ H . Anderson, PhY8. M., 351, 359 Closed fermi surfaces, 238 Closed orbits, 229 Cohen, M" 26 Cohen, M. 3 A. 2 e . That is, we assume the Meissner effect. 1 - iWT' 'tWT then the integral over d(cos 8) is (41) 11 - fo C:::! + iA'qx - 2 tan- 1 Aq 11" C:::!-, - Alql th fu au (1', IDS ~LECTRODYNAMICS Ol w, the waves increase in amplitude-the drift velocity, if maintained, puts energy into both systems. In crys n by al is nge, ribu tries from xact d by rith 956). We will be concerned chiefly with low-lying states of the system such that the fractional spin reversal is small: st, (l;~) (ataj)/S = (nj)/S « 1, so that it is pertinent to expand the square roots in (3) and (4). The result (139) is quantitatively in quite good agreement with experiment. N., 53,371 Brooks, H., 249 Brown, E., 262 Brown, F. = kc 2 (18) (1 _ i) 27rwooIJ. The coupling with a photon field of wavevector q involves the square of the matrix element worked out in (125) to (129). 2 Consider (2111 211), 2 1 - a { e- r/ 2ao _r sinOe'4>. On replacing the summation by an integral, (16) Gv(xt) = -i f-"'", dk exp [i (kX - 2~ k 2t)] e- i31r / 4 (2'1rmj t) l11eimz2/2t, for t > O. F., 306 Ground state, superconducting, 155 Group, double, 216 theory, 199 wavevector, 201 Gurevich, V. Such waves are known as second sound. Thus the value of the first integral is (111) t2ri(te'" + le-i") = ri cos tT, where the t on the extreme left-hand side arises because of the principal value in (110). .&:! 10 200 "'0 "'e ~ ~ e ~ 100 ~ 00 1 2 3 4 5 6 10 'f3/2(deg 3/2) FIG. M., 197, 237, 284, 293, 336 Lyddane, R. (a) Thomas-Fermi. C., 305 Center-of-mass coordinates, 299 Cerenkov threshold, 136 Chambers, R. 'l "'k t , -t1Te- Wk :E -£1T f-.. This is called a coherence effect. 114 QUANTUM THEORY OF SOLIDS 0 0.12 0.10 ~b., 0.08 -.....;;,. 2 has the structure (15) 1'3') T.1 1 T.1 (3'2IV23 132') T.l 1 '" FI Tb dr: tra wo = 0 in order to carry \12) back to (121 after the three scattering events contained in (121V 1"2")(1"2"1 vi 1'2')(1'2'1 vi 12). 2(4rD)YJ - r2D~' -s}, for the heat capacity of unit volume, : 1, (35) &)2J. (d) Show that the ground-state and first-pair excited-state energies calculated in the molecular field (BCS) approximation agree with the strong coupling result to O(l/N'). Dyson (Phys. The expectation value of the coulomb interaction energy in the (f (50) dwfJ -(-) o E w,q q 11. 102 QUANTUM THEORY OF SOLIDS Thus, on taking matrix elements between \k) and (10) :t (kloplk + i Ik + q), tu (1 q) = (kJrHo,op]ik (Sk - Sk+q)(k\oplk + q) + (kl[V,poJlk + q) + q) + (fO(Sk+q) - !O(Sk)] Vq(t) , where v q(t) = (11) (kl Vlk + q) = Jd 3x V(x,t)e iq• LIm)Pm(ml = L L Ik')(k'\m)Pm(mlk)(kl = L Ik')(kl(k'lp\k) = Le-iq·x L(k'\oplk' + q) = Le-iq.Xonq. QUANTIZED MAGNETIC FLUX IN SUPERCONDUCTORS It has been observed 11. But the ground state of the superconducting system is characterized by bound pairs of electrons. The exclusion principle actually plays no part in the k' integration the value of the total integral is not changed by carrying the integra tion at the lower limit down to k' = O. (After Harrison.) o a h s h re A z p CALCULATION OF ENERGY BANDS AND FERMI SURFACES, CH. q - q2) - csq 2m where qc = 2m *c s as before. We write the test charge density as erq[e-HCllt+q.X) + ecl, with r q real. Let 4> denote the net ducting ring. ,mil = 2 Pxh 2m hJ. The interactions are represented by dashes, labeled with the momentum transfer in the collision. ~ In)(nlt[AH', S]IO) - 0 HoIO) ), 0 ) + i..J = 1 EO-En n = EoIO). m x'-+x t' -+t G(x't',xt) = Gaa(x't',xt) = Gpp(x't',xt). Values of ~o are of the order of 10-4 cm; in hard superconducting alloys ~ may be of the order of 10-7 cm. For simplicity we consider only longitudinal phonons. C., 196, 250, 351 Small representation, 201 Smoluchowski, R., 206 Sodium, metallic, 115 Sondheimer, E. Thus the ratio of the skin depth to the wavelength determines the magnitude of Z. V(tn»!cf>o}. = We include a factor T in (26), (27) for every state to the left of j, occupied or not. J., 54, 324, 339 Dyson chronological operator, 8,399 Dysonian line shape, 323 Dzyaloshinsky, E., 397 Easterling, V. - '" (cf>O!T(ClI;(t)ct(O)V(tl) ... ~n,m+l vm + 1 nw (nla t + aim) En-Em (nIHln) A2{ = nnw +"2 - 7. J. d8sin80'(8)(1- cos 8), where the last factor on the right-hand side weights the average accord ing to the change of k t • The associated relaxation frequency (40) 1 VF Ti A where A is the mean free path, ni the concentration of scatterers, and vF the fermi velocity. fx-+x' 1->1'+0 lb (1) Note that the particle density is (136) 1 bet' traI an the gen ene ove cou we n(xt) = - i lim '2I}(x't'; xt}. l, 58 QUANTUM THEORY OF SOLIDS T at ar ANTIFERROMAGNETIC MAGNONS2 We consider the hamiltonian (40) H = J Li6 8 i • 8 + j 3 - 2JJ.oHA LSi, + 2JJ.oHA L S~,; i i here J is the nearest-neighbor exchange integral and with the new choice of sign is positive for an antiferromagnet. on(x) m W eJ( re (1 X is the qth fourier component of V(x,t). 102, 1230 (1956)] has considered the terms in IlM in higher orders in kB T/ J. (USSR) 20, 1064 (1950). But J= (130) L + 8, so that (131) (g - 1)J = 8, whence (132) rs(g - 1)2 = r J• This relation, due to de Gennes, is very well satisfied, in the sense that a constant rs will reproduce well the rJ deduced from experiment. E. C., 207, 252 Vosko, S. ay - 2 h a2 2p.1I - where MJ. +0 r 10 dW' [ p+(kw'), (w - J.I) - w . + (146) Ck+qCk + C_kC-k-q, where we have a plus sign, unlike the photon problem, because D is independent of k for the deformation potential coupling which leads to H'. 6 115 recommend the interpolation result ec "-' ( -0.115 + 0.031 log rs) ry. 1 1 land + Zh)' +m hll , a V(r). J., 116 time-dependent, 6 time-independent, 9 Raman processes, 28 Random phase approximation, 102, 113 Peschanskii, V. The real pair excitation '" (111) '¥p ++ o ak,a_k,tll automatically has (N - 1) unexcited pairs. ct = N-~ ~ e-£k,xiaT; aSSl ord, V forr J dt = N-~ L eik'X1bt. d xtanh x --, x 0 which is the BCS result for T e . There is a singularity in the dielectric constant at zero frequency of the type (q - 2k p ) log Iq - 2k p l, so that the charge density contains oscillatory terms at large distances of the form r- 3 cos 2kpr, as shown in Fig. We first show that the diver gence is weakened, but not removed, on summing the second-order energy Eg> over all pairs of electrons ij in the fermi sea. The result may be expressed in terms of the fresnel integrals. We assume the test charge is sufficiently small that the response of the system is linear. 2 20a~ /1 2 --2 JLoa o =2E 1 • /1 2 Y (211I H '1211) ( 211 1-vr 3 2JLo = _ !(_ 3 El 4 3/1 2 + ~E 20 ) 1 E1 ( 2 ) 15 . We 1: 166 QUANTUM THEORY OF SOLIDS Let us represent u, v by (86) Uk = COS}Ok; Vk sin }Ok; then (85) becomes a cos Ok (87) = ck sin Ok; tan Ok .1/Ck, = so that, from (52), Ok has the identical meaning as in the spin-analog method. . (16) N-Ih ~ e-ik,xja~ . Examine the contributions from a particular excited state l defined by ~, -- (126) + + - ak'+qa_k'~O + + Ck'+qC_k' n' (Uk + VkCk+ C_k + ) ~vac. } = - (x + 2iy) e- r/ 2ao • -z . Let the charge of the impurity be Z; the charge density may:be written (66) p(x) = Z o(x) = (211")3 f d 3q eiq•x • The potential of the bare charge (67) Vo(x) = Z = -1- f3411'". H, for example, we find an approxi mate result for I/E(w,q) by calculating (47) with matrix elements taken in a plane wave representation, then we get just the usual Hartree Fock exchange for the interaction energy E int• As ~o in this approxi mation does not involve e2, the ground-state energy is just the sum of the fermi energy plus E int • We get a much better value of the energy using the self-consistent dielectric constant (23). LeUer8 6,470 (1960), Z. 6 107 DIELECTRIC RESPONSE ANALYSIS4 The self-consistent field calculation of the dielectric constant is based on an independent particle model and is only approximate. We see that magnon-magnon interactions have little effect on the temperature dependence of the saturation magnetization, except near the curie temperature; for the high temperature region see M. The other perturbation is the coulomb interaction (85) V = L' V(q)(p;Pq - p) q between the electrons of the system; this interaction will tend to screen v(w,q). Within the linked and unlinked parts, however, the relative order of the interactions is fixed. For the London equation we are concerned with the limit QUANTUM' THEORY OF SOLIDS SUPE q - 4 O. Our object is to find approximate solutions of the equation of motion ii.f = - [H, "(I]. QUANTUM THEORY OF SOLIDS We are left with the London equation (132) j(x) ne 2 = - - mc A(x), in this limit. 303 et 8eq. The zero order energy for n = 1 and 2 states are E ls = Eg - E l , where Eg is the gap energy. P. {Cj, cX} = 8jk . Friedel, Phil. THEon 18 Theory of alloys gap. 2 r ' corresponding to a screening length (74) l. .). . (17) L = I(q) for a fermi gas at kBT «eF. Thus n (74) = e-fJ (w-l'l(1 + 77n), or 1 n = efJ(w-l'l - 77 (75) which is the standard result. The angular dependence of .y is fl n c s ( t .y '" exp (i L n;f';), (156) i by the cylindrical symmetry; here n; is an integer, positive or negative. ~ K(1234) (96) 21 411 G(13)G(24), provided the spin indices 81 = 83 and S2 = 84. Bolid8 12, 196 (1960). Here p. 333) between pauli operators: (123) (d. is reo ion use air fWD VPF -WD de. H = nwata + A(a t + a) =Ho+ AH', H' = (at + a). The acoustic phonons couple at a crystal/gas or liquid/gas interface with ordinary sound waves in the gas. R. 110 QUANTUM THEORY OF SOLIDS In the electron-gas problem the ground-state energy without the coulomb interaction is, per unit volume, ( (59) Eo(O) = !n€F. Letters 9, 286 (1962). = mel. b s h ) I s I t I // L• " ',A '>--- _-~II /A '/ " Y // - ) / I I / // / / _~ ~-"'-l--"'- Third zone-electrons Fourth zone-electrons FIG. Consider the situation for k > k F ; for this region (24) tells us that wkt t > 0; Go(kt) = ;ie(26) t < O. W., 97 ~7 1-7 Pincus, P., 47 Pines, D., 24, 102, 107, 114, 128, 141, 397 Pippard, A. de Launay, in Solid state physics 2, 268 (1956). The 310 QUANTUM THEORY OF SOLIDS imaginary part X is called the surface reactance; it determines the frequency shift of a resonant cavity bounded by the metal. 68, 1098 (1940). Let i(k,x) d 3k d 3x be the number of phonons of wavevector in d 3k at k and of position in d 3x at x. F., 273, 318 London equation, 169, 172 Longitudinal attenuation phonon, :~26 Kleinman, L., 255, 27:3, 27G Knox, R. 53 4 " 0. However, the allowed values of k are changed: it is essential to consider the effect of the over-all boundary conditions. P., 397 Linked cluster theorem, ] 24 Linked graphs, 124, 125 Kaganov, M. PROBLEM 1. In constructing the graphs which represent the terms of the perturbation series we use the hole and electron con ventions shown in Fig. We retain only terms linear in the external potential. Ferrell [Phys. Keffer and R. In (1'2'1 V112) the value of q is given by kl - k1' or by k2' - k 2• In the most genera.l 420 QUANTUM THEORY OF SOLIDS IH 1 I J I q" I Iq' I I Iq I I It I I 2" 2 FIG. Morse. '" ( )n 'l dtl . For magnons having microwave frequencies, lea ~ 10-2 to 10-3, so that the magnon magnon exchange scattering cross section is of the order of 10- 25 cm 2 , which is very small for an atomic process. In actual liquid helium the critical velocities observed are often two or three orders of magnitude lower than the calculated values, probably because of the possibility of creating other low-lying excita tions of the form of vortex lines. Loudon, J. Weal o flE Wopt Li Na K 8.0 9.5 8.0 5.7 5.4 5.9 3.9 ev 3.8 ev 3.9 ev Thomas-Fermi Dielectric Constant. They go on to show that a self-consistent spin polarization around the Mn ion will lead to an interaction considerably stronger than from a bound d shell. 95,249 (1954)] discusses a function called the dynamic structure factor which may be defined as S(w,q) (61) = r1f iJ OA dt e-iwt(e-iq·Xi(O)eiq.xi(t». 2 h } 2Mllk; f5. I ~i~-i"kt(I - 1e-'''kt nk, nk), t t > 0; < 0, GREEN'S FUNCTIONS-SOLID STATE PHYSICS, CH. The first term in the commutator [H,"{I(x)] is, with p operating on "(I(x'), (40) f 2~ d'~ [(I+(I'(x)p2(1(%'),(I(I)] = - 2~ f d'x' ((I+(%,) ,(I(I) ) p2(I(I') , FERMION FIELDS AND THE HARTREE-FOCK APPROXIMATION, CH. The nucleus at m will be perturbed by the spin • The second term here differs by a factor of 2 from Eq. (2.23) in the paper by Y08idajT the difference is merely a matter of definition, 8.8 is seen on examining Eq. (3.1). Supercon nelO, as in Fig. The complex conjugate part of (113) need not be treated explicitly, because the following argument will apply equally to it. For a discussion of the detailed theory of fermi surface effects on phonon spectra, see E. A saddle point usually leads to a singularity in the distribution function. 'lrX r 21 GREEN'S FUNCTIONS-SOLID STATE PHYSICS, CH. 116, 1181 (1959). We expand 'lr as, in unit volume, 'lr(x) = (115) L Ckeik.%, k whet (12{ W ture cent] proc whence (116) 2 L Ct+qCke- iq'%(2k + q); mkq e2 L Exa] • - ct+qcke~q·%A(x). Thus when the flux satisfies (163) we may form pairs and deal with the equation for w, which does not contain A. Note that tan I{Jk = S I!k(1r)j/ t; ift > t', ift' If 'II and '11+ anticommute we have always that T(+(x't')++(xt) = +(x't')++(xt). For example, experiments on the reduction in the 8uperconducting transition temperature of lanthanum caused by the solution of various rare earth elements are compatible with the value rs '" 5.1 ev-A 3 [H. The Holstein-Primakoff transformation 1 to boson creation and annihilation operators aT, aj is defined by (:3) I sj (4) S7 J = Sjx + iS jy = s·)X - is JY · = (2S)~~(] = MAGNO those the bo (11) - ajaj/2S)~~aj; (2S) Ha-r(1 - a~a· J J ) / /2S)~~·, and (12) here we require (5) rahat] = OjI, in order that the S+, S- satisfy the correct commutation relations. brought out below in the discussion of flux quantization. The field operators are in the Heisenberg representation. :J ~ () Cfl 0 0) 5. Anderson, Phys. + VkCt c~k)l4>vac) We verify that (88) is the ground state: we have for the quasiparticle annihilation operator ak,4>o = ak,a-k,ak' (91) n' a-kak4>vaa = 0, k because ak,ak' == 0 for a fermion operator. The transition temperature Tc may be determined by the molecular field method, exactly as in the theory of ferromagnetism. The region A > 0 is called the region of the anomalous skin effect. , + mhJ. Loading PreviewSorry, preview is currently unavailable. Herring and Kittel [Phys. q n q2 q - W WnO - is W WnO - ~8 L- + + e-i c.lt+8t, Then to terms of first order in rq (46) (o(rq)lpqlo(r q» - 74re 2 " k 1(njpqI0)2 n , g . o Cfl }> - ~ 0) a ... = ctCk = (Ukat nk The expectation value of nk in the ground state cf!o results only from the ordered term in a-ka±k, so that (105) = Vk 2 = hk = sin 2 tOk. (nk)O Here hk is the symbol originally used by BOS to denote the expectation value of finding a pair k, -k in the ground state cf!o; the relation (105) establishes the connection with the expressions of BOS: (106) (107) hklA = = n [(1 - hk)1A hklActc~k]cf!vac. In this limit (36) """"" ESCF(O,q) = 1 = 1 (47I-e 2 ) 2m ---;;:- (2'J1') 3 fdk 3 q' afo/ak q •k + (47I-e 2) 8'JI'nk F • _q2 (2.".)3 This is identical with (34), because m = k F 2/2ep and kp3 = 3n'Jl'2, '1 v (, a c. GREEN'S FUNCTIONS-SOLID STATE PHYSICS, CH. ork kofl' aj is those adopted by Holstein and Primakofl'. s C r, t 8 ,.. SUPERCONDUCTIVITY, CH. l=:::: 0.55 X 10-8 cm. ELECTRON-ELECTRON LIFETIME Because of the off-diagonal parts of the electron-electron interaction, an electron put into a quasiparticle state k will eventually be scattered out of this initial state. Nauk 71, 533 (1960). The leading terms in the expansion of (41) and (42) are = (2S/N)YJ (L e-ik,x'-ck + .. = utdt - f3t 2 I "'10 +) Iklvao = Cl+C2+ + +"" • • • Ck Ckp ':t'vae· If there is more than one particle present, the results of the opera tion cjCj are unchanged, but the results of the operations cj or Cj may alternate in sign according to the number and ordering in 4> of the other occupied states. term of (12) for two electrons the three matrix elements will each involve a different momentum transfer, say q, q', q", but we must have zero total momentum transfer between the initial state ki and the final state k i . We now want to pick out of C~C-k--t, which is the sum of the terms involved in (127) and (128), not the previous term in a4qa::!:k which connected the ground state with an excited state, but the term in a4qak which corresponds to the scatter ing of a quasiparticle from k to k + q. The fraction of states thus available is (k B T / ~ F ) 2. h + ill)(k + qI8pe-,wt-1lItll Ik) tk - tk+q)(k + ql x (- ;e)( AqeiqZ-iwt)pxlk) + (Ek+q - Ek)(k + qI8plk). 414 , QUANTUM THEORY OF SOLIDS GRI + iVP+(+O)G(x - (12 which reduces to (118) (-i ata _ 2mp2 + 2J.L) P+(x - x') x') = o. relative coordinates (159) fJ = 1(f'1 p • We now consider a two-electron state: (158) c Transform this to center-of-mass and + f'2); f' = f'l - f'2. Further, (21) G(kw) = f dt ei""G(kt), with the inverse (22) G(kt) = ~ fdw e-i""G(kw). • 8 m F(2k p r). 16.1. The orbit in k-space and real space. This permits the terms for unlinked parts to be taken out as a factor. The normalization of the commutator (94) is assured if we write (126) Uk = cosh Xk; Vk = sinh Ek NVk NV k • Xk. (a) Show that Hk in (91) is diagonal if (127) ''II tanh 2Xk = + F SOLIDS I if;. However,.y must always be single-valued, whereas the change in it on fixing all coordinates except one, and carrying that one around the ring, is determined by the flux 11>. We recall that V V + V" is the net potential, where VO is the external potential and VB the potential of the induced charge. Here j is the current density; A is the vector potential; AL is the London penetration depth. Ward and J. The spin-analog ground state we have described may be generated by spin-rotation operations from the true vacuum state in which all pairs are empty (spin up). 18 345 The unperturbed wavefunction is, from Schiff (15.8), (36) UL ::::: 1 )~" k ( 27rR i£(kr) YL'(8,'P) , where the spherical harmonics are normalized to give 47r on integrating their square over the surface of a sphere; the radial normalization in (36) is only approximate and follows from the asymptotic form (19). 3. In third order we have, besides the terms corresponding to Figs. MAGNETIZATION REVERSAL The number of reversed spins is given by the ensemble average of the spin wave occupancy numbers. We assume the spin structure of the crystal may be divided into two inter penetrating sublattices a and b with the property that all nearest neighbors of an atom on a lie on b, and vice versa. This is an exact equation which relates the single-particle Green's function to the two-particle Green's function. It is an experimental fact that the coupling rs is roughly constant for (126) H"(X) = most of the rare earth metals; this is compatible with the indirect exchange model and is quite encouraging. c. }; (2S/N)Yl {L eik,x1dk + ... A comparison of the observed energy-loss peaks with the calculated plasma frequencies for the assumed valences are given in the accom panying table. ..·31 Such singularities are of great importance for the thermodynamic properties. Thi F are (12: des' vah 419 APPENDiX where Po is the projection operator arranged as 1 - Po to eliminate (from the summation over intermediate states) terms in the original state, as denoted here by the subscript zero. We see that an electron is not strongly scattered by the other electrons in a metal-this remarkable effect makes it possible to use the quasi-particle approximation to the low-lying excited states of an electron gas. 1 2 LADE THEOREM This important theorem states that the particle density per unit energy range is approximately independent of the form of the boundary, at distances from the boundary greater than a characteristic particle wavelength at the energy considered. Thus in the laplace transform (6) the presence of the boundary will the boundary will be felt at time te. 2 " 29 We assume that the phonon mean free path is much shorter than the wavelength of second sound. Express the coefficients Op and I{Jp of (54) in terms of fk by carrying out the integration over k. In uniaxial symmetry, 2 + H = 2mell R + Pel. that if I> is an eigenstate of the occupancy operator ?ti, then = 2': niIPt(x)IPi(X) (33) Notice = 2': niPi.(x), where Pi(X) == IPt(X)IPi(X), The hamiltonian is obtained in the second quantization representa tion by the general theorem that quantum operators are obtained directly from their classical analogs. Valence Wealc flEobs Be B C 2 3 24 19 19 19 Mg Al Si 4 2 25 22 11 10 3 16 15 17 17 4 Ge 4 16 ev 17 ev The comparison for the alkali metals is also striking because the inelastic-loss peaks are in close agreement with the threshold of optical transparency, as is expected. Landau J. 112, 812 (1958)]. Qi' :J 0 ~ -... 30 QUANTUM THEORY OF SOLIDS If j is only slightly perturbed from an isotropic distribution, (112) f d3k c1k"k"j k = ~",,"!"lU, and (110) may be written (113) ap" +! au = o. (145) H' 8 = iD 175 L kq a~q). = - e-k •r 02 + k.. The distribution may be calculated numerically from the dispersion relation, II usually with considerable labor. Fairbank, Phys. These particles interact weakly with each other by virtue of anharmonic terms in the lattice potential. From (71) the total screening charge is -Z. 4 ..·55 We see that a transition probability involving 1(13C[>12 will be pro portional to (ka)4, where a is the lattice constant. klm This expression involves products of three operators. The leading term in :Jel is biquadratic and leads to coupling between spin waves. Thus the ratio of the number of terms for Fig. The screening charge around an impurity is largely concentrated in the impurity sphere itself and the interaction between impurity atoms is small. There are a considerable number of experiments in which selected magnons are excited and detected, including spin-wave resonances in thin films; parallel pumping; excitation by magnon-phonon coupling; inelastic neutron scattering; and magnon pulse propagation in discs. GREEX'S FUNCTIONS-SOLID STATE PHYSICS, CH. We consider then the scattering caused by the external potential v(w,q) with time dependence e-illlt and spatial dependence eiq ·][. 10 This is 8 SUPERCONDUCTIVITY, CH. 1 - dk2 - - qkph qkp~2 (2~)2 kp -aq 1 + qklh + qk 2!;2) as i + all 11 dh 0 0 db III ( h~2 h + ~2 The integrals over h, h are definite, so that the integral in (1) over d 3 q for small q involves f q-l dq, which diverges logarithmically_ Thus the perturbation calculation breaks down even in second order. A general investigation of the singularities in the dis tribution function has been given by Van Hove,8 who utilizes a topological theorem of M. V., 151 Shockley, W., 130, 148, 192 Shoenberg, D., 220 Shull, C. N., 193 Aigrain, P., 321 Akhiezer, A. - 0 - EN "'" EN 0 = "0 EN-1 - 0 is the chemical potential. The graph is called an unlinked graph because it can be separated into two noninteracting parts. Ferrell, Phys. H., 371 Marshall, W., 371 Mass, polaron effective, 140 Matrix element, 174 Matthias, B. magnetic flux through the ring; the flux is produced by external sources of field and by surface currents on the ring. Mattuck, Phys. On dividing (40) by (41), (42) 1 E(W,q) 1 + (pq~ = total charge. The factor I arises because of the self-energy. S., 141 Longitudinal excitons, 303 I{ohn, W., 97, 113, 192,237, 289, 293, Longitudinal optical phonons, 137 Loudon, R., 54, 216 33G, 348 Kohn effect, 113 Low, F. Thus (34) U = 3T%r(t) ~ 0.457-% . rqe-~Wt+8t (1 + W '\ WnO + ~8. The real part R of Z is called the surface resistance; R determines the power absorption by the metal. The residue at the pole p = tT is le'" and at the pole p = -tT the residue is te-.... We consider (113) A(x) = aqe iq. 2 mel. prir k2' 'I (11; whc of t firsi BRUECKNER METHOD 1 We need an abridged notation for the terms in Rayleigh-SchrOdinger perturbation expansion. ( ( -ie-i"'k /, = t > 0; k > kF. k' This equation is essentially the same as that obtained in the random phase approximation of Bohm and Pines. GREEN'S FUNCTIONS-SOLID STATE PHYSICS, CR. 0 A-60 QUANTUM THEORY OF SOLIDS e 3. Another pertinent result is that of J. Pines, Nuovo cimento 9, 470 (1958). Montroll, J. - -k71L. But the normaliz ing denominator (01 UIO) = (2'; unlinked parts), because an external line gives zero for the diagonal element. The magnetic properties of these metals can be understood in detail in terms of an indirect exchange interaction between the magnetic cores via the conduction electrons. (Em - En){Eo - En) for A =1= 0, Ecv(O). n. 18 365 is the electronic spin of the paramagnetic ion; the coupling J between I and a conduction electron spin 8 is the exchange interaction, instead of the contact hyperfine interaction. 8 167 u k2 -1 FIG. For this excitation = 2Ak', The calculation of the energy for the states (110) and (111) is left to Problem 6. mCkq .&jD(X) (117) (125 e .&jp(X) (126 We suppose that the current vanishes in the absence of the atoms or ions is defined so that (128) gPBJ = PB(L + 28), or (129) gJ = L + 28. The nature of the spin structure is deter mined by the value of k p and thus by the electron concentration; see D. C., 141 Button, K. The evaluation of J is discussed in reference 6. According to the boltzmann transport equation 5 ai + v. The first term in IlM arising from the nonideal aspect of the magnon gas, that is, from magnon magnon exchange interactions, is of order (kBT/ J)4. The transition T = Tc occurs on this model when .1 = 0, or (64) ~,1 ek' 1 = V k -tanh-, 2ek' Tc using (52), (62) and (63). T;-l (~ where (28) T = n (-10 5 79 ~) ~). , is independent of A and ~1 (119) ~1 L' Il) = , (120) HI = - f d 3x 'lr+(x) ~ L fd mCkq in tl is linear in A: (127 (liH 110 ). is also known that solid solutions or mixed crystals are often formed over very wide composition ranges without destroying the insulating or metallic nature of the materials, as the case may be. We have also an 112 QUANTUM THEORY OF SOLIDS interest in the charge Ap(x) induced by Z o(x). Bar'yakhtar, and M. ao az .} = - a22 { e- r / 2ao _r sinOe'4> ao az r 2a o 2 (x + iy) e- r/ 2ao {z- - e- / 2ao { rcos 2 0 sin 0 2a o 2a o } . .a 0.06 0.04 0.02 0 0 2 3 4 5 8 10 12 kFr 0.0020 0.0015 0.0010 C!\)1t, ~ .a 0.0005 0 -0.0005 -0.0010 2 4 6 kFr FIG. R., 3:36 1-5 Koopman's theorem, 83 Koster, G. For a quasiparticle excitation in a real (interacting) fermion gas we expect the time dependence of G(kt) for t > 0 to be of the form e-i"'kte-fk t , over a limited interval of time; here 1/l'k is the lifetime for the decay of a quasiparticle excitation into other excitations_ 402 QUANTUM THEORY OF SOLIDS GJ We now establish that ill GoCkw) = lim (25) 1. In the range of actual metallic densities Nozieres and Pines [PhY8. Discuss the density of states in a superconductor near the energy gap. W., 379 Lifshitz, 1. it dh . This establishes the connection between the dielectric constant and the correlation function S. -iWk! (lo(kt) le , t > 0; k t < OJ lc < kF ; < k F• INTERACTING FERMION GAS We exhibit the form of the Green's function in the exact ground state 10) of a fermion gas with interactions: (34) = -i(0111(Ck(t)C~(0»10) G(kt) = { -i(Ole.iHtcke-~fltcitIO), i(OI cite,Htcke-,HtIO), > 0; < O. A-54 QUANTUM THEORY OF SOLIDS 2 h h2 2 h ( a2 a2 2Pol ax 2 + { 2Mol (k;+ k;) + 2M k ; l H\f; 112 a 2 ) } . L j j The ground state 10) of a system of N identical atoms of spin S has (2) S210) = NS(NS + 010); SzIO) = NSIO). We neglect XI, which contains higher order terms. We make the Holstein-Primakoff transformation: (41) sdi = (2S)H(1 - aja;/2S)~~aj; stz = (2S) ~bt (1 - bib z/2S) ~; MA (4 (4 (48 ne (49 S;j = (2S)~at(1 - ajaj/2S)~; wh = (2S)~(1 - btbl/2S)~bl. mel. t t Here H is the exact hamiltonian. The potential V is composed of an external potential V O plus a screening potential VB related to the induced change on in electron density. L kk' The pair states are now such that (135) k = -k' 2K, so that the pair part of (134) which we want to keep in the hamiltonian, by analogy with (72), is (136) (01 'It(y)'It (x) 10) L e-ik·(Y-X)(Olc_k_KCk_x::O). Kohn has made the interesting observation that the sudden drop in the dielectric constant as q increases through 2k p should lead to a small sudden increase in the eigenfrequency w(q) of a lattice vibrrtion at the point q = 2k p as q is increased. The result holds only to first order in V p. This particular graph is called a ring graph; it is equivalent to the graph (b), drawn in a slightly different way to emphasize the ring structure. The penetration depth XL at low temperatures is of the order of 10-6 to 10-5 cm, but increases as T ~ Te. SUP (14~ ThE to 1 (141 WhE ind~ MATRIX ELEMENT COHERENCE EFFECTS In treating the matrix elements in the Meissner effect we saw that two terms contributed to the excitation of a single virtual state. Doll and M. Consider the terms with the three electrons 1, 2, 3; then \ V AI (l'2'IV 12 II2). (b) Show for the state M (169) E(n) = Eo + nVN' - Vn(n - 1), so that here the energy gap E(l) - E(O) is exactly N'V. The operation at on cf!o creates an elementary excitation or quasiparticle with the proper ties of a fermion: (102) aitcf!o = (Uk'cit - Vk,C_k,)(Uk' ... Ax· Re{ Tr( e-iqZe8ppx)} 2 2 2 2 e h ( -C ) EqLk; ['1T8( -kqJL+ h h mc w k m 2m hw ) h2 h2q2 -'1T8 ( m kqJL - 2m 2 e h2(c) 2'1T = E q - -3 fk 2 dkdJL d en - - . = VF there are no particles in the plasma that travel with the phase velocity, and consequently the imaginary part of E(W,q) vanishes for q < qc = Wp/VF' Using (5.71) and (5.73), we have qc/kF = 0.48r8~' If we consider all modes having q > qc to be indi vidual particle modes, then the ratio of the number of plasmon modes n' to the total number of degrees of freedom 3n is n' 3n (28) 1 3 % 2 . The integrations are similar to those we have already carried out. Wilks, Phil. The infinite electronic density on the nucleus is in disagreement with the finite lifetime of positrons in metals and with the finite Knight shift of solute atoms. The expectation value jp(x) of the paramagnetic current operator over the state ~ is, to O(A), jp(x) = (Olsp\l) (123) + (1ISpIO), where 11) is defined by (119), so that (OISpll) = (124) 2;' z T;I 1 L"f (OISpll)(l\H110). State Is is spherically symmetric, so U:2) (:;2) U:2)' = E'=O. We can see this best from a simple exam ple. J., 262 Azbel, M. The sum is, with a factor t because of double counting, E2 m ~ ~ k k k ••k,kF m (121 VI34)(341 v112) k2 k 42 I k2 2 - k2 3 - (~)2 C2~)3y f f f 3 3 d q d k1 3 d k2 x 2q4[q2 + q.1 (k2 - k 1)] . g.43, nip)] o the iquid . The theory can be shown to be gauge-invariant, as discussed below. Then -i(Olcke-iHtcitIO)eiEoNt, G(kt) = { . For q < 2k p one can draw a vector q such that both ends lie on the fermi surface; thus the energy denom.. We know from the theory of diffusion that u(Ot) is influenced by the presence of a boundary at a distance ~ from the origin after a time t such that (8) t> tc:::::: ~2/D 2m~2. E., 141 I-6 Luttinger, J. -q,. There are a number of ways of drawing graphs to illustrate perturbation theory: the diagrams used in this appendix are different from the Goldstone diagrams used in Chapter 6. It must be noted for impurities of valency different from that of the host lattice the Friedel sum rule tells us that V p cannot really be a weak interaction. The two-particle Green's function is similarly defined by (12) K(l234) = (T(+(1)+(2}++(3)++(4))), where 1 denotes X1t 1, etc . .)1. = 11k. V., 335 Gell-Mann, M., 423 Generalized OPW method, 254 INDEX Geometrical resonances, 334 Germanium, 234, 276, 305 Ginzburg, V. arc thl to c m vanishes, so that = fIn' 1m. L eik'Xjb"t (17) k have been chosen to agree with T. We introduce H A chiefly to stabilize the spin arrays along a preferred axis, the z axis. dwe-wtGo(kw) j'" 21T . The zero of F(x) is ferromagnetic. Physics· 533 (19 J. Now, by the definition of D and E, (38) (39) div D div E = 4n- = 4n-(test charge density); (test charge density + induced charge density), so that, with E(W,q) as the appropriate dielectric constant, (40) -iq • Dq = -i€ ( w,q)q' Eq (41) -iq • Eq = 47re(rqe-iwt 4n-erqe-iCllt ; + (pq»). The following proof was suggested by Dyson, unpublished. For a normal insulator the virtual excited state is reached by a one-electron transition, and no cancellation as in (129) is found. - V{r) etk>Ru{r) a 2PII SO] = Eeik>Ru{r). = au iJt + c 2 ap". Gorkov [Soviet Physics-JETP 34, 505 (1958); reprinted in Pinesl. z = 47rwIJ. Thea. We note that 2SJ.l.o/a 3 = (1,j-,})Ma(O) for sc, bcc, and fcc lattices, respectively. ~ fd 3k O' , and on multiplying by clk and integrating: (111) au at + ~ fd 3k c 2k i ax". 6 113 density is (75) ~ 1 ..1p(x) = - - V2V = 411" This is singular at r = 0, and the magnitude decreases monotonically as r increases. Rocher, Adv. L nm GREEN'S FUNCTIONS-SOLID STATE PHYSICS, CII. Find the expressions for G(xt} for a fermi gas in one dimension for the ground state with all one-electron states filled up to kF and zero for k > k F• Consider both t > 0 and t < O. Kubo, PhY8. The third-order ring graph contribution to the correlation energy of the fermi gas E3 2: = 2: l,2,3 k. 171 which would be the London equation if jp = O. The expression for .&j(x) follows as the symmetrized form of the velocity operator [p - (e/c)A]/m. G., 27, 33 Herman, F., 273, 274 Herring, C., 57, 215, 262 Herzfeld, K. E 1s Eg E .. The momentum transfer at all vertiees must be equal in a ring graph; otherwise all the electrons would not be carried back to their initial states. Rosenstock, PAY8. 9. The situation portrayed in Fig. Then the inductance per unit length is (15) (17) For fund be s Then with z normal to the surface and directed inward. The general result is (23) (27) (30) The difference in sign between (20) and (21) is the consequence of the anticommutation of cT and C2. The eigenvectors of the equations (75) and (76) are of the form a~k = + VkCk+• UkC~k + VkCk' Ck = Ukak C-k Uka-k - Vkak' ct c~ uka~k Vkak' = ak (79) - VkC~k; UkCk - at UkCt - a_k - VkC-k; UkC-k The inverse relations are (80) + vka~k; = ukat + Vka-k; = - + Here Uk, Vk are real; Uk is even and Vk is odd: Uk = U-k; Vk = verify that the a's satisfy fermion commutation rules if Uk 2 (SI) = UkUk/{Ck,C:'J {ak,aitJ + VkVk/{c~k,C-k'J = -V-k' + Vk 2 = ~kk'(Uk2 + Vk2). FREQUENCY DISTRIBUTION FOR PHONONS The phonon frequency distribution function g(w) of a crystal is defined as the number of phonon frequencies per unit frequency range, divided by the total number of frequencies. That is, the whole energy band is shifted without change of shape. , mellz e + mhIlZh). The factor (k kF)2/kF2 is a phase space factor analogous to the factor (k B T / ~ F ) 2 in the thermal kF the mean free path increases indefinitely-this is problem. G. M. A review of the theory of the structural and magnetic properties of the rare earth metals is given by Y. We take the unperturbed system H 0 to be the free electron gas. (, MANY-BODY TECHNIQUES AND THE ELECTRON GAS, CH. H., 220 H., 389 Kane, E. P., 26,141,142 Feynman relation, 33 Feynman's theorem, 109 Field, fermion, 75 quantization, 19 variables, Holstein-Primakoff, G·! magnon,64 Fletcher, P., 73 Fluctuations, density, 111 Form factor, magnetic, 381 Forward scattering, 421 Fourier lattice series, 3 series, 2 transforms, 401 Frauenfelder, H., 388 Frederikse, H. Then (37) becomes (41) 2: i(n!citi O)i e- l -i G(kt) = 2 i (w,,+I')t n i 2: \(nlckI 0 )12eH t > 0; t < o. I. You're Reading a Free Preview Pages 22 to 45 are not shown in this preview. The longitudinal velocity of sound in Cd perpendicular to the hexagonal axis is 3.8 X 10 6 cm/sec. We denote propagation by acoustic phonons as ordinary or first sound. The wave equation of the particles in the ring is (150) It 2~ [Pi + ec- 1A(x;)]2 + V} ft = Eft, where we may let V include the electron-phonon interaction and the phonon energy. CORRELATION ENERGY-NUMERICAL We write the ground-state energy per electron as, using (5.97), (77) So= 2.21 0.916 ) - - - + S c ry ( -Ts2 Ts ' where the first two terms on the right-hand side give the Hartree-Fock energy, and Sc is the correlation energy. The net polarization has at k]i'r» 1 the asymptotic form (120) Pi+ - Pf 91I'n 2 J18 cos 2k]i'r • ,...., = - ft (k ]i'T)3 4e]i' Now suppose a second nuclear moment 1m is added at a lattice point m a distance r from n. 91, 290 (1955). A., 360 8 spheres, 251 Sachs, R., 41 Sanders, T. We are usually concerned with the potential V (x) at zero frequency, because the impurity is stationary. You're Reading a Free Preview Pages 265 to 281 are not shown in this preview. ] repref agree) IL. In a ring graph the momentum changes are equal at all vertices. The validity of the result (31) is not as obvious as it may seem at first sight. The particular expression (23) is approximate because we started with a one-particle, and not a many-particle, hamiltonian. At higher temperatures, the total wavevector of the colliding particles may change by a reciprocal lattice vector; our discussion does not apply if such umklapp processes are frequent. The frequency of an oscillator of a given force constant is proportional to M-~, and thus TcM~ = constant, for isotopic variations of a given chemical element. We have (liH 110) = - (e/mc)(ll (125) 2;k (k· aq)c:+qckI O). ..IDS Index » Abelian group, 179 Abragam, A., 388 Abrahams, E., 116 Abrikosov, A. The basic assumption (Schiff, p. lkF wh€ sec( (1OJ i'" d~2 (9) kF-q~1 dk 1 k22 dk2 lkl' kP-q~. 3 (0.48) r8 % 0.018r8 , where the 2 in the denominator is from the spin. 1; the primitive spin cell in Fe304 contains several ions, so that there is one acoustic magnon branch and several optical magnon branches. Donath, Phys. DIELECTRIC SCREENING OF A POINT CHARGED IMPURITY An interesting application of the dielectric formulation of the many-body problem is to the problem of screening of a point charged impurity in an electron gas. W We may separate the real and imaginary parts: (85) mIG(kw)} = - L cfJ(!!+I'N"-E,,li(nickim)i2 (86) g{G(kw)} Wmn - L e/l(!!+IINft-Eftli(nickim)i2o(w - -11" (1 (S> nm + e/l(I'-"'''''» W wmn )(1 - e/l(II-"'",n». You're Reading a Free Preview Pages 330 to 332 are not shown in this preview. SO IDE A-59 SOLUTIONS: CHAPTER 16 ne 2 ine 2 -nex= --E - - - E . k We may normalize 4>0 by omitting the factors (-Vk), for then (90) (4)014>0) = (4)vacl n (Uk + VkC-kCk)(Uk = n(Uk 2 + Vk 2) (4)vael 4>vac). (4 in as th th to au p C . + Cj' Cj as (26) cj = Tl . We note that the kinetic (fermi) energy is dom (2 wh 10 en \ l' 2 ~ ( 2 _______________~----------__ 3 _______________~_______________ 4 FIG. > tm'). n~ = coth if1(wmn - p.), and form (88) .; f-'"'", dw' coth if1(w' - p.) g {~(kw')} ; this is equal, by (86), to (89) -(S> L C8(1l+IIN,,-Enl(1 + e/l(II-w" ')i(ni ckim)i 2 n 1 Wmn - mil . _ (nIHln) = A (nIHoln) + A = Ho= nwata, 2" (niH'S - SH'ln) Lm {(nIH'lm)(mISln) - nnw + - 2 = nnw + A2 2 L { 1(nIH'lm) 12 m (nISlm)(mIH'ln)} _ 1(nIH'lm) 12}, En - Em Em - En result in b is used. Thus btbk may be viewed as the occupation number operator for the magnon state k; the eigenvalues of btbk are the positive integers nk' , 52 QUANTUM THEORY OF SOLIDS MAGN We emphasize that the a's and b's act like boson amplitudes, despite the fact that electrons are fermions. The current density operator in the second-quantized form is whic the t para 170 (114) .&j(x) e = - . To investigate this we form P+(x) = _1_ fd 3k dwei(k'''-wt)P+(kw) (211')4 , (123) or, for x (124) 0, P+(Ot) PE te m H ap to iVP+( +0) fd 3k dw w,:· -':"t _ Ak ' (211')4 2 (1. (83) +0 lim ...... &(x)&(t), -2 which shows that Go is like a Green's function for the SchrMinger equation. 8 177 Then W (160) ei~(nl-n2)'Peil(nl+n2)+(4 ..e4J/cH8 • If the factor multiplying The term in ei~(nl-n2)'Ple-iH(nl-n2)'P2. You're Reading a Free Preview Pages 345 to 347 are not shown in this preview. We omit every where in this section the effect of next-nearest-neighbor interactions, although these may be important in real antiferromagnets. QUANTUM THEORY OF SOLIDS 1\ (w ---+ 0) approximation applicable at long wavelengths (q/kF« 1). In the case of ordinary conduction of heat in a crystal there also exists a gradient in the phonon density, yet no wavelike solution ordinarily results because wavevector conserva . The second term in the commutator [H,if(x)] is (43) Jd x' d y [if+(x')if+(y) Vex' - l 3 2 = l J d x' d y vex' - = ! Jd x' vex' - 3 3 3 y)(if+(x'){if(x),if+(y) }if(y)if(x') o(x - x') if+(y) if(y) if (x') ) x)if+(x')if(x)if(x') - ! (44) - Jd 3 y vex - y)if+(y)if(y)if(x) - Jd V(y - x)if+(y)if(y)if(x). ' = I(n\p_q!O)12. .); st (46) S~ k = (2S/N)Yl (L eik.x'-ct + .. This simple sub division is not possible in all structures. (8) Let -1 = 1 - Po , b (12: Eo - Ho 1 For full details see the review by K. a slnOe ±~. E 2s = Eg - The virial theorem gives T 1 /4. Note that e2 tends to cancel the exchange and correlation contributions. W. The problem of second sound in liquid helium differs in important respects from the problem of second sound in crystals, and we discuss only the latter. The unitary operator U(t,t') was defined in Chapter 1; if V is bilinear in the fermion opera tors '11, '11+, then (1.56) may be written as (131) U(t,t') = ( I)" 11 L --=-- " n! t' . This factor is present in liquid helium, but it is not evident that it should be present in crystals. (50: Here bt, bl are creation and annihilation operators which refer to the lth atom on sub lattice b; they are not magnon variables. an (3: 0 N ow the argument of the delta function is (29) hal (3~ The total collision rate W of an electron * in the state Ik} against a phonon system at absolute zero is, from (27) with nq = 0, (28) POl 2 1 m no * (2k . V/2, so = - /1 2 -vr 2 1211) = -E 1/4. The coupling constant is g = e2, so that given E int from (52) or in some other way, we can find the total energy in the presence of the coulomb interaction from (56). You're Reading a Free Preview Pages 215 to 229 are not shown in this preview. Keffer and Loudon have given a simple picture of the origin of the T4 term; they give a dynamical argument that in (39) one should use F; for 8, where S is the ensemble average projection of a spin on its nearest neighbor: S (Sj' 8 j +41 )/8. Trounson, PhY8. It is because of screening of the electron-electron interaction that the free electron or quasi particle model works as well as it does for transport processes. We have seen that we get more information by using the entire time domain than by restricting t' to be >t. Thus (37) f H - d'x' (I+(%,) +} L~ p' + V(I') J(I(%,) f d'x' d'y (I+(I')(I+(y) V(I' - y)(I(y)(I(I'), where V(x' - y) is the interaction energy of two particles at x' and y. Now in the Hartree-Fock approximation we made the following assumption for the two-particle Green's function: (103) (T('lr a(XI)'lr(j(X2)'lr:;(Xa)'lrt(X4») (T('lra(Xl)'lrt (X4» )(1('lr /l(X2)'lr:;(Xa») - (T ('lr a(Xl)'lr:;(xa» )(T ('lr /l(X2)>¥t(X4»). We note that '/I and any function of '/I, • L. Some workers use i in place of - i in the definition of the one-particle Green's function. OLIDS is of Ie of MAGNONS, CR. The problem becomes identical with the Bogoliubov problem discussed in Chapter 2 if in (91) there we make the identification (52) (53) ak ~ Ck; Wo ~ ~ c+· a+ k k' 2JzS + 2p. sIImmed over"are those obtained from periodic boundary conditions. The general two-particle excitation is aitait,; when k" = -k' we have the special state (104) SU Ak., Ak = (ek 2 + ~2)1A, s SUPERCONDUCTIVITY, CR. X-tX' 1-+/'+0 On inserting (109) into ,lU~), we that F,,"(+O) = -F"(,,(+O); because of We may write the matrix (111) JI\+O) = 6) = JA, ~ J( pairing a ;:e 1'. For high electron density the mean free pa\th A is \ AkF = (k - kF)2 3.98, (83) I"'V kF r/~ in the limit of high electron density. P., 31 Rosettes, 258 Roth, L., 298, 305 Roth relation, 283 Ruderman, M. 81, 869 (1951)] have shown that there is no inconsistency for a metal to have, as observed, a low-temperature heat capacity a: T dominated by excitation of one electron states and a magnetization reversal a: T'2 dominated by magnon excitation. S., 187, 249 Hamiltonian, magnetic field, 290 magnon-phonon, 74 Harman, T. Thus the angular dependence of it' is (157) it' '" exp [i n In; + (2retl>/c) }f';l it' e,n1"le,ntt'le,(2l1'e/C)+("l+"I) , where nl, n2 are integers. Find from (67) the positions of the virtual levels for V positive and for V negative. The integra tion is over the surface S of constant w. We record that A2 = -1, where 1 is the unit matrix. The diag~ams we use are called Goldstone diagrams and are related to Feynman dia grams. k (101) a+ 1 . 'Yk) + 2p.oHolbtbk. We have further wit] (43) (51: (42) Sbi Sj, = S - ajaj; -Sr, = S - btbz, using the other choice of sign permitted by (7). It is instructive to confirm the ground-state energy (60) calculated on the spin-analog model by a direct calculation using the wavefunc SUPERCONDUCTIVITY, CH. Kohn, PhY8. Thus we have a special case of Feynman's theorem: (58) dEo -1 dg = g Eint(g) , and, on integrating, we have (56). 1 -=-+ 1 m hJ. M., 142 Polarization, phonon, 16 waves, 34 Polaron, 130, 133 cloud, 139 effective mass, 140 Polyhedra, atomic, 251 Wigner-Seitz, 93 Potential, screened, 112, 116 Pair correlation function, 129 Poynting vector, 310 distribution function, 110 Primitive basic vectors, 1 Pairs, Cooper, 153 Privorotskii, I. At finite temperatures the moving body does encounter resistance; one source of resistance comes from Raman processes in which a thermal phonon is scattered inelastically by the moving body. Now let (2) q . Let EoN denote the exact ground state energy of the N particle system. 2, with the intercept at T = 0 giving the magnon tribution and the slope giving the phonon contributions. At a finite temperature T, the ensemble average spin is directed along the effec tive field 3Ck and has the magnitude, as in ISSP Eq. (9.19), (Uk) = tanh (xkiT), (61) in units with the boltzmann constant absorbed in the temperature. Some general references on the modern theory of alloys include: J. , Ck'C_k" ++ ckC_k We define (72) Bk (OIC-kCkIO) = -B_ k ; B: = (OlctC~kIO). THEOREM. 9 They find that all the alloy properties may be accounted for by an interaction of the form of (125) but they require a consider ably stronger interaction than is provided by values of the coupling deduced from atomic spectroscopy.

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