PHASE TRANSITIONS INDUCED IN A CRYSTAL BY THE FIELD OF A STRONG ELECTROMAGNETIC WAVE

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It was demonstrated recently, with several models as an example [1 - 3], that solids with close energy bands (levels) can be unstable when account is taken of the Coulomb or electron-phonon interaction of the quasiparticles, and tend to become realigned at a definite temperature T_k in such a way that the bands move farther apart or come closer together. Depending on the form of the initial bands and on the character of the interaction, this gives rise to different phase transitions.

It is possible to bring the bands together artificially and to produce a phase transition by using high pressures. We wish to call attention to the fact that a strong electromagnetic wave with frequency Ω close to Δ (Δ - distance between the filled band and one of the empty bands or the exciton level) can play the same role as pressure, by effectively bringing together the levels of the system and producing conditions favorable for the occurrence of an electronic phase transition.

We shall consider for concreteness the phase transitions connected with a strong electron-phonon interaction, described in [2, 3]. These investigations are closely related, although the models differ somewhat. It is shown in these papers that when account is taken of the intraband or interband interaction of the electrons with the optical phonons, if the criterion

$$V^2 / M\omega_0^2 \Delta > 1 \tag{1}$$

is satisfied (V - matrix element of the electron-phonon interaction, ω_0 - phonon frequency, M - ion mass), then phase transitions are produced in the system and are connected with the change of the electron spectrum and with the displacements of the atoms in the crystal lattice.

All the parameters of these phase transitions are determined by the extent to which the inequality (1) is stronger or weaker.

The indicated models are used to describe real phase transitions in compounds of the V_2O_3 type and in a number of ferroelectrics of the displacement type.

It is seen from the criterion (1) that an artificial bringing together of the bands is indeed an effective method of leading the system to a phase transition.

Assume that an intense monochromatic wave with $\Omega \lesssim \Delta$ is incident on the crystal, and there is an electron-phonon interaction with one of the optical phonon modes.

In the narrow-band approximation, in the node representation, if all the transitions occur without a change in the number of electrons at the node, the Hamiltonian of the system has the form given in [2], to which a term corresponding to the interaction with the field wave is added:

$$H = \sum_m \frac{\Delta}{2}(a^+_{1m} a_{1m} + b^+_{2m} b_{2m}) + \sum_q \omega_q c^+_q c_q +$$

$$+ \lambda \sum_m \{a^+_{1m} b^+_{2m} e^{-i\Omega t} + b_{2m} a_{1m} e^{i\Omega t}\} +$$

$$+ \sum_{mj} \mathbf{u}_{jm}\{w_{jm11} a^+_{1m} a_{1m} + w_{jm22} b_{2m} b^+_{2m}\} +$$

$$+ \sum_{mj} \mathbf{u}_{jm}\{\tilde{w}_{jm} a^+_{1m} b^+_{2m} + (\tilde{w}_{jm})^* b_{2m} a_{1m}\}, \qquad (2)$$

where $\vec{u}_{jm}$ are the displacements of the j-th atom in the m-th cell, $\lambda = E_0 \vec{P}_{12}$, $\vec{P}_{12}$ is the matrix element of the dipole moment, w are different matrix elements of the electron-phonon interaction, and $\vec{E}_0$ is the intensity of the wave field. The operators a, b, and c describe the electrons and holes at the levels 1 and 2 respectively and the phonons.

We take into account here only the resonant part of the interaction with the wave field, and assume satisfaction of the condition $|\lambda| > \tau^{-1}$, where τ is the minimal relaxation time of the electrons.

For an exact account of the electromagnetic wave, we carry out a cannonical transformation of the Hamiltonian with the aid of the operator

$$U(t) = \exp\{-(i\Omega t/2)\sum_m a^+_{1m} a_{1m} + b^+_{2m} b_{2m}\},$$

and also the Bogolyubov u-v transformation, which mixes the states 1 and 2 [4]. As a result we arrive at a system of new quasiparticles with excitation energy $\varepsilon = \{[\Delta - \Omega)/2]^2 + \lambda^2\}^{1/2}$ and with a distance between levels $\tilde{\Delta} = 2\varepsilon$. The phonon part of the Hamiltonian also changes. The last term in (2) can be omitted, since following the U(t) transformation it acquires a time dependence with frequency Ω, and consequently, the direct interaction of the quasiparticles via the phonons, associated with this term, contains an additional small parameter $\omega_0/\Omega << 1$.

The remaining part of the Hamiltonian is given by

$$H = \sum_m \epsilon(a^+_{1m} a_{1m} + \beta^+_{2m}\beta_{2m}) + \frac{1}{2}\sum_{mj}\mathbf{u}_{jm}(w_{jm11} - w_{jm22})\frac{\lambda}{\epsilon}(a^+_{1m}\beta^+_{2m} + \beta_{2m} a_{1m}) +$$

$$+ \frac{1}{2}\sum_{mj}\mathbf{u}_{jm}\left\{\left[(w_{jm11} + w_{jm22}) + (w_{jm11} - w_{jm22})\frac{\Delta - \Omega}{2\epsilon}\right] a^+_{1m} a_{1m} + \right.$$

$$\left. + \left[(w_{jm11} + w_{jm22}) - (w_{jm11} - w_{jm22})\frac{\Delta - \Omega}{2\epsilon}\right]\beta_{2m}\beta^+_{2m}\right\}. \qquad (3)$$

When $(\Delta - \Omega)/2 > \lambda$, the second term in (3) can be discarded compared with the third. Then the Hamiltonian (3) is equivalent to that used in [2], the only difference being that the role of the effective distance between the levels is played by the quantity $\tilde{\Delta} << \Delta$.

When $(\Delta - \Omega)/2 < \lambda$, we can omit the third term in (3) compared with the second, and then the problem reduces to that considered in [3], again with Δ replaced by $\tilde{\Delta}$. Consequently, when the wave is applied, it is necessary to replace Δ by $\tilde{\Delta}$ in the foregoing conditions and in the criterion (1). If the initial distance $\Delta \sim 1$ eV between the levels is effectively reduced in this manner by one or two orders of magnitude, then the probability of an instability associated with the phase transition increases rapidly, even if the initial system was far from unstable.

To satisfy the condition $\lambda > \tau^{-1}$ at the values $\tau \sim 10^{-12} - 10^{-14}$ sec characteristic of solids, the required field intensity of the light wave is $E_0 \sim 10^4 - 10^6$ V/cm.

Suitable substances in which one can attempt to produce a phase transition are, for example, semiconductors and dielectrics containing ions of rare-earth and transition elements (see the reviews [5, 6]). In such substances there exist narrow exciton lines corresponding to transitions with energy 0.1 - 1 eV in the d- or f-shells of the indicated ions. Generally speaking, these transitions are parity- or spin-forbidden. In crystals, however, such a forbiddenness is frequently violated, and many transitions are allowed in the dipole approximation [6].

Transitions in d- and f-shells frequently occur with optical phonons taking part, thus indicating a sufficiently strong electron-phonon interaction.

Illumination with a strong wave can maintain the system at a temperature comparable with T_k.

The phase transition can be revealed by displacements in the lattice (in some cases by the appearance of a spontaneous dipole moment), by shifts of the energy levels of the electrons, and also by the change of the electric conductivity of the system.

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INFLUENCE OF INHOMOGENEITY OF PLASMA ON THE RELAXATION OF AN ULTRARELATIVISTIC ELECTRON BEAM

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An experiment for producing and heating plasma by ultrarelativistic electrons using a beam interacting with a solid target was proposed in [1]. The preliminary estimates given in that paper lead to the following two conclusions: 1) An acceptable beam deceleration length ($L \lesssim 1$ cm) can be reached only if the relaxation of the beam is caused by collective processes which result from the