FEASIBILITY OF HIGH-TEMPERATURE SUPERCONDUCTIVITY IN NONEQUILIBRIUM SYSTEMS WITH REPULSION

V. M. Galitskii, V. F. Elesin, and Yu. V. Kopaev
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 8 May 1973
ZhETF Pis. Red. 18, No. 1, 50 - 53 (5 July 1973)

We examine the feasibility of obtaining high-temperature superconductivity in nonequilibrium systems with repulsion between the electrons. We show that in a metal containing a source that transfers electrons with energies lower than the Fermi energy to a state with higher energy it is possible to obtain, besides the trivial solution with zero gap, also a new solution with nonzero superconducting gap and inverted electron distribution.

1. It was shown recently [1] that the equation for the superconducting gap can have a solution in systems with repulsion ($g > 0$) if an inverted population[1]) is produced for the quasiparticles $n_p$, i.e., $2n_p - 1 > 0$

$$1 = g \int \frac{d\xi (2n_p - 1)}{\sqrt{\xi^2 + \Delta_o^2}}, \tag{1}$$

where $\xi = p^2/2m - \mu_0$ and $\mu_0$ is the Fermi level.

The main difficulty lies in maintaining the "inverted population" in the interval $|\xi| \leq \tilde{\omega}$ of the interaction. In [1] it was proposed to get around this difficulty in a "semiconducting medel," in which it is assumed that the dielectric gap makes an inverted distribution possible. In this case the gap is produced near the extrema of the bands, and not on the Fermi surface.

2. Another possibility is to use a gap $\lambda = d_{cv}\mathcal{E}$ ($d_{cv}$ is the dipole moment of the interband transition); this gap is produced by the action of a strong electromagnetic field $\mathcal{E}$ of frequency $\omega_\lambda$ [2], which causes resonant transitions between the bands.

From the structure of the kinetic equations for the quasiparticles, it follows that when

$$2\lambda \geq \omega_{ph} \tag{2}$$

(where $\omega_{ph}$ is a frequency on the order of the Debye frequency), the transition of the quasiparticles through the gap is possible only via multiphonon processes. The time $\tau_A$ of this process is therefore much shorter than the time of energy relaxation of the quasiparticles under (over) the gap.

If we now turn on a source that transfers the quasiparticles from a state below the gap into a state above it, then the quasiparticles will be blocked in such a way that their distribution will take the form

$$n_p = \left[\exp\left(\frac{E_p - \mu}{T}\right) + 1\right]^{-1}, \quad E_p = \sqrt{\xi^2 + \lambda^2}, \tag{3}$$

where $\mu$ is the quasiparticle Fermi quasilevel determined by the source intensity and by the time $\tau_A$.

Such a quasiparticle distribution will lead to the appearance of a superconducting gap $\Delta$ equal to (cf. [3])

$$\Delta = \begin{cases} \sqrt{\Delta_o^2 - \lambda^2}, & \Delta_o > \lambda, \quad \Delta_o = \dfrac{2\mu^2}{\tilde{\omega}} e^{-1/g}(1 - e^{-2/g})^{-1}. \\ 0, & \Delta_o < \lambda \end{cases} \tag{4}$$

The energy of the quasiparticles in this state is given by

$$\epsilon_p = \sqrt{\xi^2 + \Delta^2 + \lambda^2} = \sqrt{\xi^2 + \Delta_o^2}. \tag{5}$$

3. In expression (4) we can let $\lambda$ tend to zero while retaining the condition

$$2\Delta_0 > \omega_{ph}. \tag{6}$$

This means that a solution with a gap $\Delta_0$ in a nonequilibrium state, in the presence of a source that transfers the quasiparticles from a state below the gap into a state above the gap, is self-maintaining, viz., the gap leads to an inverted particle distribution, which in turn leads to the existence of the gap. Such a self-consistent solution is possible not only in the saturation state, when the electrons in the conduction bands are produced by a strong field $\mathcal{E}$, as was assumed above, but also near the Fermi surface of a metal or of a doped semiconductor. It is possible to go over into this state by turning the strong field off adiabatically.

4. We can note also that the processes of the transition of the quasiparticles through the gap can also be caused by electron-electron collisions. However, in view of the limitation imposed on the volume of the phase space by the Pauli principle, the probability of this process decreases by a factor $(\mu_0/\mu)^2$ and at $\mu/\mu_0 \simeq 10^{-1} - 10^{-2}$ it turns out to be small in comparison with the reciprocal relaxation time $1/\tau_{ph}$ of the quasiparticles on the phonons.

If $\mu/\mu_0 \sim 1$, when the electron-electron collisions become predominant, $\omega_{ph}$ in (6) must be replaced by $\tilde{\omega}$; therefore, taking (4) into account, we obtain

$$\sinh(1/g) < 2. \tag{7}$$

5. Let us calculate the response of the system to an external weak field. The current in a constant magnetic field at $qv_0 \ll \Delta$ and $T \ll \mu$ is given by

$$\mathbf{j}_q \simeq + \frac{e^2 n_0}{mc} \mathbf{A}_q; \quad n_0 = \frac{p_0^3}{3\pi^2\hbar^3}, \quad \frac{p_0^2}{2m} = \mu_0, \tag{8}$$

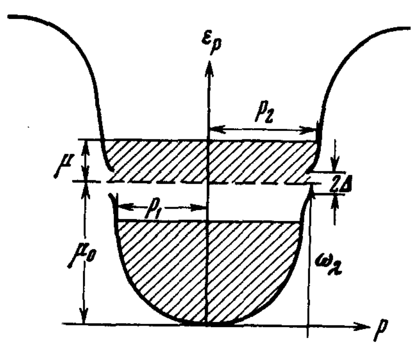
i.e., it is equal to the current in an equilibrium superconductor, but with opposite sign. This means that the system under consideration has an anomalous paramagnetism that leads to the onset of an electromagnetic field in the sample, and the magnetic field oscillates with a period $(4\pi n_0 e^2/mc^2)^{1/2}$.

The physical meaning of this result can be easily understood by turning to Fig. 1. Contributions to the paramagnetic current are made by the electrons near $p \simeq p_1$ and $p \simeq p_2$, whereas the contribution at $p \simeq p_0$ is equal to zero because of the gap.

The paramagnetic current is thus doubled, so that the total current with allowance for the diamagnetic one is given by (8).

6. Let us find the current in an alternating field $\vec{F} = \vec{F}_0 e^{i\omega t}$, with allowance for the elastic scattering by the impurities. We present the simplest equation, when the period of the oscillations is much shorter than the correlation length, $\omega \to 0$, and $T \ll \mu$:

$$\mathbf{j} \simeq \mathbf{F}\left(2\sigma_N + i\frac{\pi\Delta}{\hbar\omega}\sigma_N\right), \quad \sigma_N = \frac{2e^2 n_0 \tau}{3m}. \tag{9}$$




Spectrum and energy distribution of electrons in the conduction band, $p_{1,2}^2 = p_0^2 \mp \sqrt{\mu^2 - \Delta^2}\cdot 2m$.

The first term in (9) corresponds to double the normal conductivity $2\sigma_N$ connected with the contributions from the surfaces with $p \simeq p_0$ and $p = p_2$. The second term corresponds to the undamped current, which becomes infinite at $\omega \to 0$ and is connected with the contribution from the surface with $p = p_0$, where the superconducting gap hinders the momentum scattering (see Fig. 1). We note that the sign of the second term is opposite that of the current of the equilibrium superconductor, and this explains the existence of the anomalous paramagnetism. This "negative superconductivity" has a definite analogy with the effect of negative conductivity in semiconductors [4].

The temperature leads to smearing of the distribution (3), i.e., to a decrease of $n_p$. The transition temperature at which ghe gap tends to zero is approximately equal to

$$T_c \simeq \mu. \quad (10)$$

The stability of the considered superconducting state and the role of multiphonon processes in the kinetic phenomena call for a separate study.

The authors are grateful to Yu. A. Bykovskii, L. V. Keldysh, and D. A. Kirzhnits for useful remarks and discussions.

---

1) Analogous considerations were advanced also by A. G. Aronov and V. L. Gurevich.

[1] D. A. Kirzhnits and Yu. V. Kopaev, ZhETF Pis. Red. 17, 379 (1973) [JETP Lett. 17,270(1973)]
[2] V. M. Galitskii, S. P. Goreslavskii, and V. F. Elesin, Zh. Eksp. Teor. Fiz. 57, 207 (1969) [Sov. Phys.-JETP 30, 117 (1970)].
[3] V. F. Elesin and Yu. V. Kopaev, Fiz. Tverd. Tela 14, 669 (1972) [Sov. Phys.-Solid State 14, 570 (1972)].
[4] V. F. Elesin and E. A. Manykin, Zh. Eksp. Teor. Fiz. 50, 1381 (1966) [Sov. Phys.-JETP 23, 917 (1966)].

## SPONTANEOUS POSITRON PRODUCTION BY THE COULOMB FIELD OF A HEAVY NUCLEUS

V. S. Popov
Institute of Theoretical and Experimental Physics, USSR Academy of Sciences
Submitted 21 May 1973
ZhETF Pis. Red. 18, No. 1, 53 - 58 (5 July 1973)

The spontaneous production of positrons in a Coulomb field with $Z > Z_c$ (where $Z_c \simeq 170$ is the critical charge of the nucleus [1 - 3] is of interest as an example of $e^+e^-$ pair production via an unusual static mechanism [4 - 9]. The most realistic way of searching for this phenomenon is in collisions of heavy nuclei with $Z_1 + Z_2 > Z_c$, for example uranium or californium nuclei. It is not necessary that both colliding nuclei be "bare" (i.e., have no electron shells). When a beam of bare nuclei $Z_1$ is incident on an ordinary heavy target $Z_2$, vacant places are produced in the K shell of the combined atom if $Z_1 > Z_2$. The cross section $\sigma$ for the production of $e^+$ has in this case practically the same value as for bare nuclei [8, 9].

A detailed discussion of this process, as well as an estimate of the background effects, can be found in [9]. There, however, the cross section $\sigma$ was calculated using a threshold formula valid only for $E \to E_t$ (i.e., where the cross section itself is exponentially small). In view of the strong dependence of $\sigma$ on the energy E of the colliding nuclei, extrapolation of this formula to the region $E \gtrsim 1.5E_t$ is not valid[1]. At the same time, calculation of the cross section $\sigma$ in the entire range of energies and the energy spectrum of the produced positrons is needed for an experiment on the spontaneous production of $e^+$ in nuclear collisions, which is being planned for the near future. The results of such a calculations are presented below.

Since the velocity of the nuclei is much lower than the velocity of the electron on the K orbit (at $Z\alpha \sim 1$), the process of $e^+$ production can be regarded in the adiabatic approximation. The cross section $\sigma$ is then expressed in terms of the imaginary part $\gamma$ of the energy of the quasistationary level that has gone to the lower continuum at $R < R_c$ ($\varepsilon = \varepsilon_0 + i\gamma/2$, $\varepsilon_0 < -1$). Exact calculation of $\varepsilon_0$ and $\gamma$ as functions of the internuclear distance R calls for a solution of the Dirac equation for the two-center problem and entails considerable mathematical difficulties. We have used the fact that in the region $Z \sim 90 - 100$ there is satisfied the condition of "low supercriticality"

$$\delta = (Z_1 + Z_2 - Z_c)/Z_c << 1 \quad (1)$$

(we put for simplicity $Z_1 = Z_2 = Z$). Consequently, the solution of the relativistic two-center problem can be obtained in analytic form by using the method of matching the asymptotic forms [10]. The energy $\varepsilon$ of the ground level of the quasimolecule $1s\sigma$ is determined by the asymptotic equation

$$\ln\frac{R_c}{R} = \psi\left(-\frac{\epsilon}{\lambda}\right) + \ln\lambda + \frac{1+\epsilon}{1+\epsilon+\lambda} \quad , \quad (2)$$