Feasibility of superfluidity of paired spatially separated electrons and holes; a new superconductivity mechanism

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Systems with dielectric pairing of spatially separated electrons and holes are considered. Superfluid motion of the charges, corresponding to undamped electric currents, is possible in such systems. The role of interband transitions is discussed.

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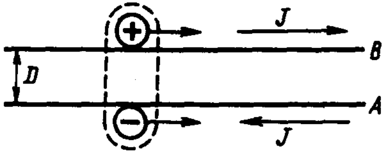
As shown in[1], the transitions between bands of paired quasiparticles, which were hitherto unaccounted for by the theory of the "excitonic dielectric,"[2–6] lift the degeneracy of the state of the system with respect to the phase of the order parameter $\Delta(\mathbf{p})$, and by disturbing the coherence make it impossible for an electron-hole liquid to be superfluid. In this article we discuss systems in which dielectric pairing is produced between spatially separated electrons and holes, so that the transitions between the bands of the paired quasiparticles are tunneling processes and can be negligibly weak. The pairing interaction not connected with tunneling remains appreciable and causes the system to go over to the superfluid state of an excitonic dielectric. The superfluid motion of "Cooper" pairs of spatially-separated electrons and holes corresponds to undamped currents flowing through different regions of the system in opposite directions (see the figure).

I. We consider two1) thin ($d \leq l$) superconducting films separated by a dielectric layer of thickness D (see the figure), in one of which (A) there are2) excess electrons, and in the other (B) holes (d is the film thickness, l is



the average distance between like charges). Let $l \ll \rho_0$ (ρ_0 is the radius of the "quasi-two-dimensional" bound state of the electron on the film *A* and the hole on the film *B*; the inequality corresponds to weak *e–h* binding), and then in the case of sufficiently close[6–9] Fermi surfaces of the electrons and holes the system is unstable with respect to dielectric pairing of the quasiparticles. By determining in the Thomas-Fermi approximation the two-dimensional Fourier component of the potential of the screened interaction between the electrons and holes

$$V(p) = \frac{2\pi e^2 \exp(-pD)}{p + \dfrac{4}{a_0^*} + \dfrac{4}{p_{02} a_0^{*2}}\left[1 - \exp(-2pD)\right]},$$

($a_0^* = \epsilon/m^* e^2$, where ϵ is the dielectric constant of the medium surrounding the film, $\hbar = 1$, m^* is the effective mass, assumed for simplicity to be isotropic and the same for electrons and holes, and p_{02} is the Fermi momentum), we obtain in the usual manner[2,4,8] the value of the gap Δ in the spectrum of the single-particle excitations of the altered state of the system:

$$\Delta = \frac{a_0^*}{l} Ry^* \begin{cases} \exp\left[-\dfrac{\pi p_{02} a_0^*}{\ln(p_{02} a_0^*)}\right], & D \ll l \ll a_0^* \\ \exp\left[-\dfrac{\pi p_{02} a_0^*}{\ln\left(\dfrac{a_0^*}{D}\right)}\right], & l \ll D \ll a_0^* \end{cases}, \quad (1)$$

where $Ry^* = m^* e^4/\epsilon^2$. At $D \gg a_0^*$, the gap decreases very rapidly, $\sim \exp[(-32/\pi)(D^2 p_{02}/a_0^*)]$. The maximum value of the gap $\Delta \sim Ry^*$ is reached at $D \lesssim a_0^* \sim l$ (region of strong interaction, where (1) is only an estimate). If, for example, $m^* = 0.2 m_0$ (m_0 is the electron mass) and $\epsilon = 10$, then $a_0^* = 100$ Å and at $D \sim l \sim 100$ Å we have $\Delta \sim 100$ °K. The tunneling probability $\sim \exp[-0.4 D\sqrt{W}]$ (*D* is in Å and *W* is the height of the barrier in eV) at $W \sim 2$ eV and $D \sim 100$ Å is negligibly small ($\sim e^{-60}$). It can be shown rigorously that transitions of electrons between bands of one and the same film do not affect the coherence in this case. Thus, superfluid joint motion of the electrons and holes along the film is possible in this system. This motion of the charges corresponds to antiparallel undamped electric currents *J* flowing through the film (see the figure). This system turns out to be equivalent to a two-conductor superconducting "electric transmission line." Similar properties are possessed by a system of "charged" filaments. For this system, in the strong-interaction region of greatest interest, corresponding to values $l \sim a_0^*$, one must expect the gap Δ to be comparable in magnitude with the binding energy $\Delta \sim Ry^* \ln^2(a_0^*/a)$ of the "one-dimensional" exciton (*a* is the filament diameter, $a \ll a_0^*$).

Returning to the two-dimensional system, we discuss now the case of low ($l \gg \rho_0$) density of a quasiparticle gas. Each electron is bound in this case with an oppositely located hole, forming a "quasi-two-dimensional" exciton with radius ρ_0 ($\rho_0 \sim a_0^*$ at $D \lesssim a_0^*$; $\rho_0 \sim a_0^{*1/4} D^{3/4}$ at $D \gtrsim a_0^*$).[10] We note that these excitons are repelled at large ($\rho \gtrsim \rho_0$) distances in accord with the expression

$$V(\rho) \simeq \frac{2e^2}{\epsilon}\left(\frac{1}{\rho} - \frac{1}{\sqrt{\rho^2 + D^2}}\right).$$

The potential barrier produced by the repulsion interaction (in constrast to the three-dimensional case) ensures stability of the rarefied exciton gas to coalescence into biexcitons, drops, etc. A transition to the superfluid state is possible in this gas, with a transition temperature $k_B T_c \sim 1/m^* l^2 \sim Ry^* (a_0^*/l)^2$.

II. We consider two semimetallic films (or filaments) *A* and *B* (see the figure), which are individually stable with respect to a transition into an excitonic dielectric. This can be ensured[6–9] by sufficiently large differences between the Fermi surfaces of the electrons and holes in each film, caused by anisotropy (in the case of films) or inequality of the electrons and holes (see footnote 2). Neglecting the interactions of the electrons and holes of the same semimetal, which does not lead to instability, and the interaction of like quasiparticles, we can investigate the "electrons *A* + holes *B*" subsystem independently of the "holes *A* + electrons *B*" subsystem. If the Fermi surfaces in any of these subsystems are close, then the attraction interaction of the quasiparticles leads to a restructuring of this subsystem into an excitonic dielectric, and this restructuring is described in exactly the same manner as in the system considered in Sec. I. Depending on the geometry of the Fermi surfaces, one of the following variants is realized: 1) there is no pairing in either subsystem; 2) pairing occurs in only one subsystem—"superfluid" and "normal" liquids are present in the system; 3) pairing occurs in both subsystems, and the system consists of two interpenetrating superfluid liquids with order parameters Δ_1 and Δ_2; it can be shown that those terms of the Hamiltonian which describe the interaction of these subsystems and the interband transitions within each of the semimetals fix the difference between the phases Δ_1 and Δ_2, but preserve degeneracy with respect to the absolute values of the phases. This means that when account is taken of the interaction the liquids cannot move independently of one another, but, as before, their joint motion is superfluid. If the electron and hole densities in each semimetal are equal, then in case 3) there are no electric currents in *A* and *B*, owing to the local electroneutrality of the system. On the other hand, in case 3) (if the concentrations of the unlike quasiparticles in each semimetal are different) and in case 2) the superfluid motion of the charges is accompanied by undamped electric currents that flow in opposite directions along *A* and *B*.

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[1] The effects predicted in the article can take place also in quasi-two-dimensional and quasi-one-dimensional periodic structures.

[2] For example, owing to doping, to differences in the work functions, to charge transport, etc.

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