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Possible parity violation in superconductors

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If an interaction leading to spontaneous breaking of the reflectional symmetry exists in a metal, the critical current in a long superconducting sample of this metal in a longitudinal magnetic field may be different for parallel and antiparallel orientations of the current and the field. The difference is linear in the magnetic field and has a specific temperature dependence.

It has recently been suggested by Akhiezer and Chudnovsky[1] that the reflectional symmetry (P) may be violated spontaneously as a result of a spin-dependent effective electron interaction in metals. This violation has nothing to do with weak interactions. It belongs to a class of phenomena where the symmetry of the ground state is lower than that of the interaction involved. The idea has been worked out further by Chudnovsky and Vilenkin[2] who suggested a microscopic model for a system of interacting electrons where a state with a nonzero average helicity $\langle \vec{\sigma}\cdot\vec{k}\rangle$ can be energetically favorable ($\vec{\sigma}$ is the electron spin and $\vec{k}$ is its momentum).

According to Ref. 2, the state of the broken P symmetry arises if the interaction g is strong enough and the temperature does not exceed a critical value T_c ($g\nu_0 > 3$ with ν_0 being the density of states at the Fermi level). The usual energy band then splits into two subbands with different helicities. The subbands are shifted with respect to each other by an energy 2λ. However, phenomena associated with the broken P symmetry are hard to observe in a normal metal.[2]

Let us consider, for the sake of simplicity, the situation where the split 2λ is big enough so that only one of the subbands is occupied. If the temperature drops down, the system undergoes the normal-superconducting phase transition. The helicity does not interfere with a possibility to apply Bogolubov's transformation. Indeed, the counterparts in a Cooper pair are of the same helicity: $\vec{\sigma}\cdot\vec{k}=(-\vec{\sigma})\cdot(-\vec{k})$. In other words, the helicity remains unchanged while the metal undergoes the normal-superconducting transition. Thus the superconducting phase can arise with a fixed nonzero helicity built in. This argument holds also if the subbands are partially overlapped.

The very existence of an interaction, which would be responsible for an energy split between states with different helicities, is subject to experimental verification. We suggest here a simple idea for an experiment to answer the question: The critical current in a long superconductor situated in a longitudinal magnetic field should be different for parallel and antiparallel orientation of the current and the field.

Let us consider a long thin superconducting strip (or a long microbridge) of a thickness d smaller than both the correlation length ξ and the penetration depth λ. We now estimate the critical-current density j_c, taking for simplicity the Ginzburg-Landau (GL) domain ($T \lesssim T_c$). One has here for the order parameter Δ and for the current $\vec{j}$:

$$-\xi^2\Pi^2\Delta=\Delta(1-|\Delta/\Delta_0|^2) \ , \quad (1)$$

$$\vec{j}=C\,\mathrm{Im}(\Delta^*\vec{\Pi}\Delta) \ , \quad (2)$$

where $\vec{\Pi}=\vec{\nabla}-2ei\vec{A}/\hbar c$ and $\vec{A}$ is the vector potential. The order parameter of the bulk material in the absence of the field is denoted by Δ_0. The constant C depends upon material characteristics.

To find the critical current in the absence of a magnetic field, we look for a solution of Eqs. (1) and (2) in the form $\Delta=f\exp(iqz)$ with z being the longitudinal coordinate. Both $f=|\Delta|$ and j_z can be taken as constants due to the condition $d \ll (\xi,\lambda)$. Then Eqs. (1) and (2) yield a cubic equation for $y\equiv f^2$:

$$F(y)=y^3-ay^2+(\xi j\Delta_0/C)^2=0 \ , \quad (3)$$

with $a=\Delta_0^2$. The function $F(y)$ has a maximum at $y_1=0$ and a minimum at $y_2=2a/3$. In order to have a positive root, $F(y)$ must obey the condition $F(y_2)<0$. This gives the known result[3]

$$j<j_c=\frac{2C\Delta_0^2}{3\sqrt{3}\xi} \quad (4)$$

for the critical-current density. We point out the $(1-T/T_c)^{3/2}$ temperature dependence of j_c.

To take account of the magnetic field H_z, we choose the gauge $A_x=A_z=0$, $A_y=Hx$, where x is the coordinate normal to the strip surface and changing from 0 to d. The self-field of the current is assumed to be small with respect to the external field H. As above, the order parameter $\Delta=f\exp(iqz)$ depends only weakly on x. The magnetic field term in

$$\Pi^2\Delta=\left[\frac{\partial^2}{\partial z^2}-\left(\frac{2eH}{c\hbar}x\right)^2\right]\Delta$$

can be considered small if $q^2 >> (2eHd/c\hbar)^2$ or if

$$q\xi >> \frac{H}{H_{c2}}\frac{d}{\xi} \ , \tag{5}$$

with $H_{c2}=\phi_0/2\pi\xi^2$ and ϕ_0 being the flux quantum. The condition (5) is satisfied if $Hd/H_{c2}\xi << 1$; indeed, the term $q\xi\sim j_c\xi/Cf^2\sim\Delta_0^2/f^2>1$. Replacing now x^2 by $\langle x^2\rangle=d^2/3$ in Eq. (1) and taking f as x independent, one obtains from Eq. (1): $\xi^2q^2+\frac{1}{3}(Hd/H_{c2}\xi)^2=1-(f/\Delta_0)^2$. We now combine this with $j=Cqf^2$ to get again Eq. (3) for $y=f^2$ with $a=\Delta_0^2[1-\frac{1}{3}(Hd/H_{c2}\xi)^2]$. The same simple analysis as above gives

$$j_c(H)=j_c(0)[1-\tfrac{1}{2}(Hd/H_{c2}\xi)^2] \ , \tag{6}$$

where $j_c(0)$ is given in Eq. (4). Note that $j_c(H)-j_c(0)\propto H^2$, i.e., $j_c(H)$ is the same for the field parallel or antiparallel to the current. This must be so in a system where parity is conserved.

In a superconductor without the reflectional symmetry a term of the form

$$\gamma|\Delta|^2\vec{j}\cdot\vec{H} \tag{7}$$

in the free-energy density is no longer forbidden by the symmetry. Here the constant γ characterizes an interaction responsible for the broken P symmetry. The term (7) is a pseudoscalar. It is invariant with respect to time inversion, but it changes sign under spatial inversion (or under reflection in the plane normal to $\vec{H}$, in particular).

As in shown in Ref. 2, the current associated with the broken P symmetry is absent in the thermal equilibrium of the normal phase. Therefore the contribution (7) should vanish in the normal state. This is why the term (7) should contain some positive power of $|\Delta|$. Further, all terms in the GL free energy expansion are proportional to $(1-T/T_c)^2\propto|\Delta|^4$, while the current density $j\propto|\Delta|^2$. This gives the factor $|\Delta|^2j$ in Eq. (7); a smaller power of $|\Delta|$ would have destroyed the second-order phase transition at T_c; a higher one would have been out of the accuracy range of the GL method.

The contribution (7) to the free-energy density affects the GL equation (1) which is obtained by varying the free energy with respect to Δ^*:

$$-\xi^2\Pi^2\Delta=\Delta(1-|\Delta/\Delta_0|^2)-\gamma_1\Delta\vec{j}\cdot\vec{H} \ . \tag{8}$$

The new constant $\gamma_1=\gamma/|\alpha|$, where α comes from the term $\alpha|\Delta|^2$ in the GL free-energy density; note that $\gamma_1\propto(1-T/T_c)^{-1}$. The variation of (7) with respect to $\vec{A}$ yields a correction to the GL Eq. (2) proportional to $\vec{\nabla}\times(\vec{H}\times\vec{\nabla}|\Delta|^2)$. In our case $|\Delta|=$const and this correction vanishes.

To find the critical current in the new conditions we again look for a solution of Eq. (8) in the form $\Delta=f\exp(iqz)$ and treat the magnetic field term in Π^2 perturbatively. Then

$$\xi^2q^2+\tfrac{1}{3}(Hd/H_{c2}\xi)^2=1-(f/\Delta_0)^2-\gamma_1\vec{j}\cdot\vec{H} \ .$$

Taking into account $j=Cqf^2$ we obtain again the cubic Eq. (3) for $f^2=y$ with $a=\Delta_0^2[1-\frac{1}{3}(Hd/H_{c2}\xi)^2-\gamma_1\vec{j}\cdot\vec{H}]$. Then, after some simple algebra,

$$j_c=j_c(0)[1-\tfrac{1}{2}(Hd/H_{c2}\xi)^2]\mp\tfrac{3}{2}\gamma_1Hj_c^2(0) \ . \tag{9}$$

The last term here is a result of the broken P symmetry. The $\mp$ signs correspond to the parallel and antiparallel orientation of the current and field. We emphasize the linear dependence of this term upon the magnetic field and its $(1-T/T_c)^2$ dependence on temperature. The "symmetric" contribution to j_c is quadratic in H and has $(1-T/T_c)^{1/2}$ temperature behavior in the GL domain. These differences allow one to distinguish, in principle, a parity-violating contribution from the symmetric one.

It is interesting enough that the asymmetry of the critical current in thick ($d >> \xi, \lambda$) type-II superconducting wires placed in a longitudinal field has been observed by Leblanc[4] quite a time ago (see also Ref. 5). The results were "independent of the sequence of application of field and current, and independent of previous history (i.e., no training occurs)."[4] Still, the author of Ref. 4 ascribed the effect to the irreversibility of the samples. In this respect the critical-current measurements in a microbridge situated in a longitudinal field seem to be more appropriate in a search for a broken P symmetry in superconductors.

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