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Bogoliubov Fermi surface revealed

Discovery of segmented Fermi surface induced by Cooper pair momentum
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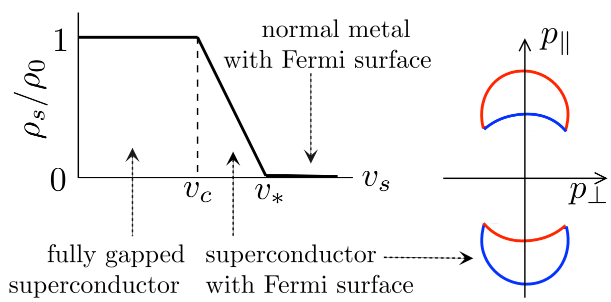
Recommended with a Commentary by Carlo Beenakker, Instituut-Lorentz, Leiden University

The Fermi surface of a metal separates electronic states that are occupied at zero temperature from states that remain empty. It is obtained by solving for zero excitation energy, $E(\boldsymbol{p}) = 0$, to produce a $d-1$ dimensional surface in d-dimensional momentum space. Can a superconductor have a Fermi surface, a surface of zero excitation energy for Bogoliubov quasiparticles? That question was addressed theoretically by Volovik many years ago, and an experimental demonstration is now reported by Zhu *et al.* (arXiv:2010.02216).

A figure from Volovik's 2006 paper (arXiv:cond-mat/0601372) explains the mechanism for the emergence of a Bogoliubov Fermi surface. The excitation gap Δ closes if the velocity v_s of the Cooper pairs exceeds a critical velocity $v_c = \Delta/p_{\rm F}$. This is the Doppler effect first pointed out for superfluids by Landau, which shifts the quasiparticle energy by an amount

$$\delta E(\boldsymbol{p}) = \boldsymbol{p} \cdot \boldsymbol{v}_s. \qquad (1)$$

The gap remains open for momentum directions $p_\perp$ perpendicular to the superflow, producing the segmented Fermi surface shown in the figure — provided that v_s remains below the depairing velocity v_* at which the superconductor becomes a normal metal.



Upon increasing the velocity v_s of the superconducting condensate, the excitation gap closes at a critical velocity $v_c = \Delta/p_{\rm F}$ and a Bogoliubov Fermi surface appears. The left panel shows the drop in the Cooper pair density ρ_s, which vanishes at the depairing velocity v_*. The right panel shows the contours of zero excitation energy: a Fermi surface formed out of electron-like states (red) and hole-like states (blue) appears for $v_c < v_s < v_*$. [Adapted from Volovik (2006).]

In a bulk superconductor $v_* \approx v_c$ so Volovik's mechanism is not operative, but if superconductivity is induced by the proximity effect in a 2D electron gas one may have $v_c = \Delta_{\rm induced}/p_{\rm F}$ small compared to the depairing velocity in the bulk. This is the approach taken by Zhu *et al.*, following up on a proposal by Yuan and Fu (arXiv:1801.03522). The 2D electron gas on the surface of the topological insulator Bi_2Te_3 is proximitized by the superconductor $NbSe_2$. An in-plane magnetic field B induces a screening supercurrent over a London penetration depth λ, which boosts the Cooper pair momentum by an amount $p_s \simeq eB\lambda$, in-plane and perpendicular to B. The proximity induced gap is reduced below the bulk gap, and thus only a small magnetic field is needed to significantly affect the quasiparticle spectrum without strongly impacting the parent superconductor.

The 2D electrons on the surface of a 3D topological insulator are massless Dirac fermions, which requires a modification of the usual expression (1) for the Doppler shift of massive Schrödinger electrons. In the ideal case of an isotropic dispersion, $\varepsilon(\boldsymbol{p}) = v_{\rm F}|\boldsymbol{p}|$, the Doppler shift due to a Cooper pair momentum p_s is given by

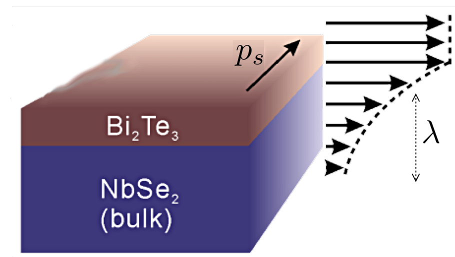
$$\delta E(\boldsymbol{p}) = \frac{v_{\rm F}}{|\boldsymbol{p}|}\boldsymbol{p}\cdot\boldsymbol{p}_s. \tag{2}$$

For Bi_2Te_3 the dispersion relation is anisotropic,

$$\varepsilon(\boldsymbol{p}) = v_{\rm F}\sqrt{|\boldsymbol{p}|^2 + \alpha^2 p_x^2(p_x^2 - 3p_y^2)^2}, \tag{3}$$

and a more general expression is needed:[1]

$$\delta E(\boldsymbol{p}) = \frac{\partial\varepsilon(\boldsymbol{p})}{\partial\boldsymbol{p}}\cdot\boldsymbol{p}_s. \tag{4}$$



Heterostructure studied by Zhu *et al.* The Bi_2Te_3 topological insulator film is sufficiently thin that the $NbSe_2$ superconductor can induce a pair potential in the 2D electron gas on the top surface. An in-plane magnetic field B gives a nonzero Cooper pair momentum $p_s \simeq eB\lambda$.

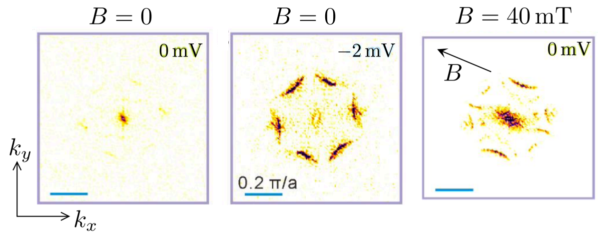
The corresponding critical momentum depends on the direction of the supercurrent,

$$p_c = \begin{cases} \Delta/v_{\rm F} & \text{in the } y\text{-direction,} \\ (\Delta/v_{\rm F})(1 - \frac{5}{2}\alpha^2 p_{\rm F}^4) & \text{in the } x\text{-direction.} \end{cases} \tag{5}$$

To observe the Bogoliubov Fermi surface Zhu *et al.* use the technique of Fourier-Transform Scanning Tunneling Microscopy (Petersen *et al.*, 1998). Surface electrons scattered by defects produce an oscillatory interference pattern in the local density of states (Friedel oscillations), with a spatial periodicity set by the difference of wave vectors on the Fermi surface. The Fourier transform of the spatial dI/dV map measured at low bias voltages with a scanning probe reveals these periodicities.

[1] Eq. (4) holds to first order in $\boldsymbol{p}_s$ for a time-reversally-symmetric single-electron Hamiltonian $H_0(\boldsymbol{p})$ and an s-wave pair potential Δ. The Cooper pair momentum enters in the Bogoliubov-De Gennes Hamiltonian $\mathcal{H}(\boldsymbol{p}) = H_0(\boldsymbol{p})\tau_z + \Delta\tau_x$ as an offset $\boldsymbol{p} \mapsto \boldsymbol{p} + \tau_z\boldsymbol{p}_s$, with τ_z a Pauli matrix in the electron-hole degree of freedom. The linearized energy shift is $\delta E = \tau_z\boldsymbol{p}_s\cdot\langle\partial\mathcal{H}/\partial\boldsymbol{p}\rangle = \tau_0\boldsymbol{p}_s\cdot\langle\partial H_0/\partial\boldsymbol{p}\rangle = \tau_0\boldsymbol{p}_s\cdot\partial\langle H_0\rangle/\partial\boldsymbol{p}$, in view of Hellmann-Feynman and $\tau_z^2 = \tau_0$. Because $\tau_0 H_0$ and $\mathcal{H}$ commute, they can be jointly diagonalized and the expectation value $\langle H_0\rangle$ in the basis of eigenstates of $\mathcal{H}$ is equal to an eigenvalue $\varepsilon(\boldsymbol{p})$ of $H_0(\boldsymbol{p})$, hence $\delta E = \boldsymbol{p}_s\cdot\partial\varepsilon/\partial\boldsymbol{p}$. I have not found this simple formula in the literature and thank Yaroslav Herasymenko for the derivation.

Zhu *et al.* present a detailed numerical analysis of their experimental data, but the key features are evident upon inspection: In the absence of a magnetic field the hexagonally warped Fermi surface of Eq. (3) is visible in the dI/dV map for voltages outside of the superconducting gap, while at $V = 0$ the dI/dV map is featureless. Application of an in-plane magnetic field reintroduces the segments of the Fermi surface with wave vectors in the perpendicular direction.



Fourier transformed dI/dV maps, measured at different bias voltages V and magnetic fields B. At $B = 0$ the hexagonal Fermi contour of the Bi_2Te_3 surface electrons is visible outside of the superconducting gap ($e|V| = 2\,\mathrm{meV} > \Delta_{\mathrm{induced}} = 0.5\,\mathrm{meV}$), while it vanishes inside the gap. An in-plane magnetic field of 40 mT closes the gap in the perpendicular direction. Only the electron-like segments of the Bogoliubov Fermi surface are probed by the STM for $V = 0^+$.

Volovik's supercurrent mechanism is not the only way to create an extended Bogoliubov Fermi surface (a gapless $d-1$ dimensional manifold in d-dimensional momentum space). In a multiband superconductor with a nodal pair potential the pairing of mismatched Fermi surfaces can expand a nodal point or nodal line into a 2D surface segment. This mechanism could be operative in a $d_{x^2-y^2}$ superconductor in a Zeeman field (Yang and Sondhi, 1998) or in a chiral pair potential with intrinsically broken time-reversal symmetry (Agterberg, Brydon, and Timm, 2017; Link and Herbut, 2020). I am not aware of any experimental demonstration along these lines.

The simplicity of the realization of Zhu *et al.* promises much follow-up work. Papaj and Fu (arXiv:2006.06651) propose to confine the gapless superconducting state to a narrow 1D channel, surrounded by 2D regions with a full superconducting gap. Majorana bound states may emerge at the end points of the channel, providing an alternative platform to existing semiconductor nanowire based systems.