Discovery of segmented Fermi surface induced by Cooper pair momentum

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A sufficiently large supercurrent can close the energy gap in a superconductor and create gapless quasiparticles through the Doppler shift of quasiparticle energy caused by finite Cooper pair momentum. In this gapless superconducting state, zero-energy quasiparticles reside on a segment of the normal-state Fermi surface, whereas the remaining Fermi surface is still gapped. We use quasiparticle interference to image the field-controlled Fermi surface of bismuth telluride (Bi$_2$Te$_3$) thin films under proximity effect from the superconductor niobium diselenide (NbSe$_2$). A small applied in-plane magnetic field induces a screening supercurrent, which leads to finite-momentum pairing on the topological surface states of Bi$_2$Te$_3$. We identify distinct interference patterns that indicate a gapless superconducting state with a segmented Fermi surface. Our results reveal the strong impact of finite Cooper pair momentum on the quasiparticle spectrum.

In the presence of supercurrent flow, Cooper pairs in a superconductor acquire finite momentum ($\mathbf{q}$, 2). This Cooper pair momentum $\mathbf{q}$ results in a Doppler shift of the energy of the Bogoliubov quasiparticle excitations (Fig. 1A)

$$E(\mathbf{k}) = \sqrt{\left(\varepsilon_k - \mu\right)^2 + \Delta^2 + \frac{1}{2} v_k \cdot \mathbf{q}}$$

which is characterized by the Doppler shift energy scale $E_D = v_k q / 2$, where $v_k = \partial \varepsilon_k / \partial \mathbf{k}$ is the velocity at momentum $\mathbf{k}$, $\varepsilon_k$ is the normal-state dispersion, $\mu$ is the chemical potential, and $\Delta$ is the superconducting gap in the absence of supercurrent. This Doppler shift changes the energy of the quasiparticles that move parallel or antiparallel to the supercurrent but does not affect the quasiparticles that move in the perpendicular direction, resulting in an anisotropic quasiparticle energy dispersion.

When the Doppler energy shift $E_D$ exceeds $\Delta$, the superconducting gap closes, and a segmented Fermi surface appears with zero-energy quasiparticles that are a superposition of electrons and holes (2–4). A schematic example of this behavior for a system with a circular Fermi surface in the normal state is shown in Fig. 1B. The supercurrent decreases the energy of quasiparticles moving parallel to it. With sufficiently large current, zero-energy quasiparticles first appear on a segment of the normal-state Fermi surface in the direction of the current. As the current increases, the momentum-space contour of these zero-energy quasiparticles grows, forming a banana-like shape and contributing to finite density of states (DOS) at $E = 0$. The solid and dashed lines in Fig. 1B indicate whether the excitation is more electron- or hole-like, respectively, in a given part of the contour. At the same time, the rest of the normal-state Fermi surface remains fully gapped because the Doppler shift energy has not overcome the superconducting gap there. Although the existence of supercurrent-induced gapless quasiparticles, known as the Volovik effect (5), has been established by tunneling (6, 7) and specific heat measurements (8, 9) on d- and s-wave superconductors, the Fermi surface of a current-carrying superconductor has not been observed directly. Detection of the segmented Fermi surface of Bogoliubov quasiparticles requires spectroscopic techniques with both energy and momentum resolution. Furthermore, the supercurrent that is necessary to close the superconducting gap is often larger than the depairing current at which the superconductor switches to a resistive state (6).

In this work, we overcome the aforementioned difficulty with an alternative approach and material platform. Instead of passing a transport current directly through a superconductor, we apply a small external magnetic field $B_{\perp}$ to produce a screening current near the surface by means of the Meissner effect. Then, the superconducting order parameter on the surface develops a spatially varying phase $\Delta(\mathbf{r}) = \Delta \exp(i \mathbf{q} \cdot \mathbf{r})$ at position $\mathbf{r}$, with $\mathbf{q}$ in the direction of the screening current that is perpendicular to the field $B_{\text{ext}}$. Our platform of choice (Fig. 1C) consists of a thin film of Bi$_2$Te$_3$, the quintessential topological insulator (10, 11), grown by molecular beam epitaxy on top of bulk crystal NbSe$_2$, an s-wave superconductor. The superconducting proximity effect from NbSe$_2$ induces a hard gap in Bi$_2$Te$_3$ at zero field, as demonstrated in previous scanning tunneling microscopy (STM) measurements (12). This material combination provides ideal synergy for creating and detecting the gapless superconducting state. NbSe$_2$ is a clean s-wave superconductor with a large superconducting gap and long London penetration depth $\lambda_L$ that exceeds 100 nm (13). Notably, this means that a small in-plane magnetic field can create a large screening current and Cooper pair momentum on the surface, without introducing vortices in the measurement region.

Our platform is ideal to observe formation of the segmented Fermi surface, owing to a combination of two factors. A Bi$_2$Te$_3$ film under the proximity effect has a simple Fermi pocket surrounding the $\Gamma$ point (14) that originates from the topological surface states. The proximity-induced gap in the top layer of Bi$_2$Te$_3$ is reduced compared with the bulk gap of NbSe$_2$, and the topological surface state has a substantially higher Fermi velocity (~2.6 eVÅ) (14) than the states of the parent superconductor (0.65 to 1.95 eVÅ, depending on the pocket and crystalline axis) (15). Therefore, although both NbSe$_2$ and the proximitized surface state of Bi$_2$Te$_3$ share the same Cooper pair momentum $q$, the substantial differences in Fermi velocities and superconducting gaps make it possible to choose a small magnetic field that closes the gap of the proximitized surface state but not that of the parent superconductor NbSe$_2$. The Bi$_2$Te$_3$/NbSe$_2$ heterostructure has previously been investigated for the presence of Majorana zero modes in vortex cores (12, 16–19). A recent theory predicts that topological superconductivity hosting Majorana end states may be formed when field-induced quasi-particles in proximitized topological insulators are confined into a quasi-one dimensional (1D) channel (4).

In the insets of Fig. 1C, we present the topography of our thin film with regions of varying thickness (top inset) and an atomic-resolution image of the Bi$_2$Te$_3$ lattice (bottom inset), demonstrating its high quality. The properties of Bi$_2$Te$_3$ films are appreciably affected by the number of quintuple layers (QLs), the 1-nm-thick basic building blocks of this crystal. Topological surface states are formed for thicknesses above three QLS (20); previous results show that a proximity-induced superconducting energy gap is present in the top surface for films up to 11 QLS thick (12).
Fig. 1. Topography and characterization of proximitized Bi$_2$Te$_3$ thin films.

(A) Quasiparticle dispersion around the superconducting gap without magnetic field (blue curves) and with magnetic field above $B^*$ (red curves) that induces the gapless superconducting state (for parabolic dispersion $B^* \approx d/ev$, where $e$ is the electron charge and $v$ is the Fermi velocity). (B) Schematic depiction of a segmented Fermi surface that arises as a result of the magnetic field $B$ along the $x$ axis. Solid red lines indicate electron-dominated states, whereas dashed red lines denote hole-dominated states. The pink line indicates the Fermi surface of the normal state. (C) Structure of the samples with four or five quintuple layers (QLs) of Bi$_2$Te$_3$ on top of NbSe$_2$. An external in-plane magnetic field $B_{\text{ext}}$ induces a perpendicular screening supercurrent and Cooper pair momentum $\mathbf{q}$. Insets show the topography of a large area (320 nm by 320 nm) of the thin film, with regions of varying thickness (top inset) and an atomic-resolution image (10 nm by 10 nm) of the Bi$_2$Te$_3$ lattice (bottom inset). The dotted white square indicates the area where the $dI/dV$ maps in Fig. 3 are measured. (D) Differential conductance $dI/dV$ spectra taken across the yellow line cut in (C) for a wide range of energies. The set point is at 0.1 V and 0.5 nA. CBM and VBM denote the conduction band minimum and valence band maximum, respectively, of the Bi$_2$Te$_3$ bulk bands. (E) The proximity-induced superconducting gap along the yellow line cut from (C). The set point is at 2.5 mV and 0.5 nA. From the position of the coherence peaks, we determine a superconducting gap $\Delta \approx 0.5$ meV. All STM measurements were conducted at a temperature of 40 mK. a.u., arbitrary units.

Fig. 2. DOS on the Bi$_2$Te$_3$/NbSe$_2$ surface under in-plane magnetic field.

(A) Differential conductance $dI/dV$ spectra and (B) theoretical DOS curves for increasing magnetic field along the $\Gamma K$ direction. (C) Differential conductance $dI/dV$ spectra and (D) theoretical DOS curves for increasing magnetic field along the $\Gamma M$ direction. For both (A) and (C), the spectra are acquired at a set point of 2.5 mV and 0.5 nA and a temperature of 40 mK. The characteristic energy scale for theoretical calculations is $E_A = evA_x$, where $A_x$ is the magnetic vector potential (22). Arrowheads indicate in-gap features attributed to pockets of segmented Fermi surface, as depicted in movies S1 and S2. Dotted rectangles indicate regions magnified in the insets.
To optimize the superconductivity in the topological surface states, we perform all of our measurements on a four-QL area of the sample, denoted in Fig. 1C by the dotted white square of area 120 nm by 120 nm, away from the step edges. Figure 1, D and E, shows differential conductance \( dI/dV \) curves (\( I \), current; \( V \), voltage) along the line cut inside this region. These curves display a high degree of spatial uniformity over a wide range of energy scales from 0.1 to \(-0.43\) eV (Fig. 1D). We identify the valence band maximum (VBM) and conduction band minimum (CBM) from \( dI/dV \) peaks at \(-0.3\) and \(-0.07\) eV, respectively. This allows us to infer the Fermi-level position at \(-360\) meV above the surface Dirac point (14). Near the Fermi level, we observe a hard, U-shaped superconducting energy gap \( \Delta \approx 0.5\) meV at zero magnetic field, with no visible in-gap features across the line cut.

We now apply an in-plane magnetic field to the thin film and measure the differential conductance \( dI/dV \) to investigate the gapless superconducting state. Considering the strong hexagonal warping effect of Bi\(_2\)Te\(_3\) surface states (21), we orient the magnetic field along two different high-symmetry directions \( \Gamma K \) and \( \Gamma M \). The \( dI/dV \) spectra (Fig. 2) reveal a rich set of in-gap features, indicated by arrowheads. As the magnetic field is increased in small steps of 10 mT, multiple distinct peaks and shoulders appear and change rapidly. The in-gap spectrum depends on the field direction. This behavior is in contrast to that of the surface of pristine NbSe\(_2\) (fig. S7) (22), where the in-gap spectrum is featureless under the same magnetic field, displaying a hard gap with only minimal changes to the coherence peaks. Moreover, these observations contrast sharply with the tunneling spectra of conventional superconductors such as aluminum or lead, for which the magnetic field also causes the filling of the superconducting gap in a featureless manner (7), as do magnetic impurities (23). To understand the microscopic origin of the observed tunneling spectra, we perform theoretical calculations of the DOS at various field-induced Cooper pair momenta. The distinctive in-gap features and their evolution with the field in both directions are reproduced by our calculation that is based on the established model Hamiltonian for Bi\(_2\)Te\(_3\) surface states including hexagonal warping (22). We can rule out the Zeeman effect as the primary origin of these effects because in order for the Zeeman energy to close the superconducting gap \( (\mu_B B_{\text{ext}}/2 = \Delta \sim 0.5\) meV, where \( \mu_B \) is the Bohr magneton) at 20 mT, the effective g-factor would have to be \(-800\)—much higher than the values expected in various topological materials (24–27). On the other hand, the Doppler shift energy due to the screening current at 20 mT, estimated from the Fermi velocity and London penetration depth of NbSe\(_2\), is close to the measured gap on the proximitized surface of Bi\(_2\)Te\(_3\) at zero field (22). The observed in-gap features are therefore a consequence of supercurrent-induced quasiparticles. The evolution of spectral function at energies around the Fermi level with the field is calculated and depicted in movies S1 and S2.

To detect the segmented Fermi surface directly within momentum space, we scan the constant energy local DOS over the whole region of interest and perform a Fourier transform to obtain the quasiparticle interference (QPI) patterns (28, 29). At energies far outside the superconducting gap, we observe strong and equal intensities at six segments, which are symmetrically placed along three equivalent \( \Gamma M \) directions (fig. S5E). This QPI pattern is independent of the direction or magnitude of magnetic field (fig. S6E) and is similar to those observed in Bi\(_2\)Te\(_3\) without superconductivity (30–32).

However, the QPI pattern becomes markedly different at the energies inside the superconducting gap. Pairs of real- and momentum-space images at zero energy are presented in Fig. 3 for six different orientations of magnetic field along high-symmetry directions at \( B_{\text{ext}} = 40\) mT. In the real-space images, we observe 1D standing wave patterns, whose orientation changes with the magnetic field direction. These real-space patterns yield two distinct classes of Fourier images, respectively showing four and two of the six original high-intensity segments. When the field is applied along \( \Gamma K \), two bright segments are found along the perpendicular \( \Gamma M \) direction, whereas the remaining four are strongly suppressed. When the field is directed along \( \Gamma M \), the corresponding two segments are dark, whereas the other four segments are bright.

These QPI patterns can be understood directly from the picture of a segmented Fermi surface in the superconducting state under an in-plane magnetic field. Because of the direction-dependent pair-breaking effect, only a portion of the normal-state Fermi surface becomes gapless, and thus only the hotspots located in this gapless segment are activated for scattering at zero energy. To illustrate this, in Fig. 4, G to I, we present the spectral function of the normal state, the superconducting state with magnetic field along \( \Gamma K \), and the superconducting state with magnetic field along \( \Gamma M \), respectively. In the normal state, we observe a hexagonally warped contour, which gives rise to six symmetric segments in the QPI pattern (Fig. 4A) associated with scattering between the hotspots at the neighboring tips of the star. In the superconducting
state at zero field, there is no Fermi surface, owing to the hard gap. Nevertheless, it re-emerges at $B_{\perp} = 40 \text{ mT}$, as a result of the gap being filled with quasiparticle states. However, this new Fermi surface consists of only segments of the normal-state Fermi surface, whose size and location are controlled by the field strength and orientation (Fig. 4, H and I). Scattering between the available hot-spots on the segmented Fermi surface gives rise to those bright segments in the observed QPI pattern (Fig. 4, B and C), as represented by the indicated momentum transfer vectors $\mathbf{Q}_3$. By contrast, the gapped hotspots cannot participate in quasiparticle scattering processes, leading to suppression of QPI intensity at corresponding wave vectors.

Notably, scattering between Bogoliubov quasiparticles on the segmented surface is strongly dependent on the superconducting coherence factors. Zero-energy quasiparticles that originate from the $E > 0$ and $E < 0$ branches at zero field are the symmetric and anti-symmetric superpositions of electron and hole states, respectively. In the presence of nonmagnetic impurities, scattering between the two opposite branches is constructively enhanced, whereas scattering within each branch is destructively suppressed. For this reason, even though the wave vector $\mathbf{Q}_3$ connects the same pair of hotspots in both Fig. 4H and Fig. 4I, quasiparticle scattering at this wave vector is present in the former case but suppressed by coherence factors in the latter. This can be clearly seen in Fig. 4, B and C, indicating that the gapless excitations are Bogoliubov quasiparticles rather than normal electrons. To further substantiate the above theoretical analysis, we perform a full numerical simulation of the proximitized topological surface state under an in-plane magnetic field. By using recursive Green’s functions (22), we calculate the local DOS in the presence of random disorder and construct its Fourier image.

Our numerical QPI patterns (Fig. 4, D to F) show good agreement with the experimental data. Our results reveal the strong impact of Cooper pair momentum caused by screening supercurrent on the quasiparticle energy dispersion. The observation of the segmented Fermi surface of Bogoliubov quasiparticles paves the way for further STM study of pair density wave and Fulde-Ferrell-Larkin-Ovchinnikov states in unconventional superconductors (33–36).

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SUPPLEMENTARY MATERIALS

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