Angle-Resolved Mapping of the Fermi Velocity in a Quasi-Two-Dimensional Conductor

A. Kovalev, University of Florida, Physics
S. Hill, University of Florida, Physics and NHMFL

Microwave spectroscopy has been utilized as a means of studying the electrodynamic properties of metals for well over half a century, especially resonant absorption in an external DC magnetic field. Quasiparticles in such conductors usually move on closed periodic trajectories in reciprocal (k-) space, or cyclotron orbits in real space. When any period associated with this motion matches the period of the external electromagnetic field, so-called cyclotron resonance (CR) occurs if the condition $\omega_c\tau > 1$ is satisfied, where ω_c is the cyclotron frequency and τ is the relaxation time; ω_c depends on the magnetic field strength, and on the cyclotron mass (m_c)—a characteristic of the Fermi surface (FS).

In layered conductors, the FS may be either quasi-two-dimensional (Q2D), quasi-one-dimensional (Q1D), or a combination of both.[1] In the Q2D case, the FS is a warped cylinder with its axis perpendicular to the layers (see Figure 1) while, in the Q1D case, the FS consists of a pair of warped sheets at $\pm k_F$. Because of this reduced dimensionality (and reduced $v_F \sim 10^5$ m/s), several new effects in the microwave conductivity have been reported, one of which is the observation of multiple periodic orbit resonances (POR) in Q1D systems.[2] In this report, we detail a new magnetic resonance phenomenon that enables angle-resolved mapping of the in-plane Fermi velocity for a Q2D conductor.[3] As such, this technique is complementary to Angle-Resolved Photo-Electron Spectroscopy (ARPES[4]), i.e., it can provide information concerning the in-plane momentum dependence of the density-of-states ($\propto v_F$) and quasiparticle scattering rate (τ^{-1}). We illustrate the utility of this method for the κ-(BEDT-TTF)$_2$I$_3$ (BEDT-TTF≡bis-ethylenedithio-tetrathiafulvalene) organic superconductor, which has a relatively simple and well characterized FS (see Figure 1).[1] This technique, however, could equally be applied to more exotic Q2D conductors (e.g. Sr_2RuO_4). As many ARPES investigations have shown, angle-resolved FS spectroscopies have the potential to reveal critical information concerning the various instabilities that give rise to unusual magnetic and superconducting states in low-dimensional correlated electron systems.[4]

High-field measurements (up to 33 T) in the conventional geometry (field ⊥ layers) performed at Tallahassee reveal a form of closed orbit POR. The new open orbit effect appears when one aligns the magnetic field within the layers.[3] In this case, the quasiparticle motion is *principally* open and periodic (except for a small fraction of the total electrons—see Figure 1a); this is due to the underlying periodicity of the crystal which leads to the FS warping. The period depends on the magnetic field strength, B, and on the velocity component ($v_\perp$) perpendicular to the field. Averaging over the FS leads to the result that the extremal perpendicular velocity ($v_\perp^{ext}$) dominates the electrodynamic response, giving rise to a resonance in the interlayer conductivity (σ_{zz}) when the period of the electromagnetic field matches the periodicity of the extremal quasiparticle trajectories, i.e., when $\omega = \omega_c^{ext}$ ($\equiv eBa\, v_\perp^{ext}/\hbar$, a is the interlayer spacing). Measurement of ω_c^{ext}, as a function of the field orientation ψ within the xy-plane, yields a polar plot of $v_\perp^{ext}(\psi)$. The procedure for mapping $v_F(\phi)$ is then identical to that of reconstructing the FS of a Q2D conductor from the measured periods of Yamaji oscillations.[1] Analytically, assuming one can measure $v_\perp^{ext}(\psi)$, it is possible to generate the Fermi velocity $v_F(\phi)$ using the following transformations (see also Figure 1b):

$$v_F = \sqrt{\left(v_\perp^{ext}\right)^2 + v_\parallel^2}; \qquad \phi = \psi + \arctan\left(\frac{v_\perp^{ext}}{v_\parallel}\right); \qquad v_\parallel = -\frac{dv_\perp^{ext}}{d\psi} \quad (1)$$

A small platelet shaped (0.7×0.4×0.12 mm^3) single crystal of κ-(BEDT-TTF)$_2$I$_3$ was studied using a phase sensitive cavity perturbation technique described elsewhere.[5] The FS of κ-(BEDT-TTF)$_2$I$_3$ may be calculated using a 2D tight binding model, resulting in a network of overlapping Fermi cylinders,[1] as shown in Figure 1c. All measurements were carried out at 4.5 K, above the superconducting transition temperature (T_c = 3.5 K), and at a frequency of 53.9 GHz.

In Figure 2, we plot the experimentally determined $v_\perp^{ext}(\psi)$ on a polar diagram. The dashed line is a fit to Equation 1, and the

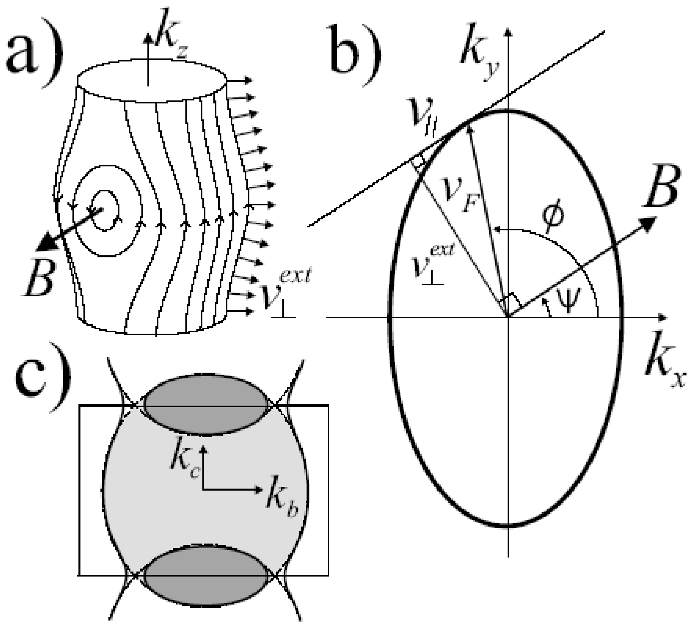

Figure 1. (a) An illustration of the quasiparticle trajectories on a warped Q2D FS cylinder for a field oriented perpendicular to the cylinder axis. The resulting trajectories lead to a weak modulation of the quasiparticle velocities parallel to k_z and, hence, to a resonance in σ_{zz}. (b) The thick line shows $v_F(\phi)$ according to Equation 1; the right angle triangle illustrates the relationship between $v_\perp^{ext}(\psi)$ and $v_F(\phi)$. (c) The Fermi surface of κ-(BEDT-TTF)$_2$I$_3$.[1]

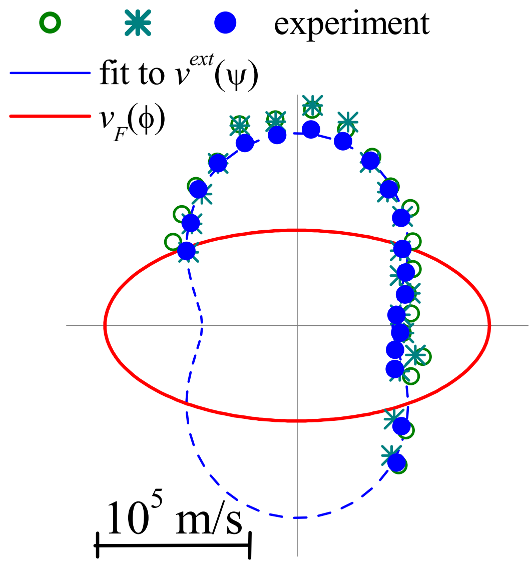

Figure 2. Polar plot of experimentally obtained $v_\perp^{ext}(\psi)$; the dotted line is a fit and the solid line is the resultant $v_F(\phi)$.

solid line is the corresponding Fermi velocity; the extremal values are $v_{xm} = 1.3 \times 10^5$ m/s and $v_{ym} = 0.62 \times 10^5$ m/s. This anisotropy is in good agreement with the known anisotropy of the small Q2D FS for κ-(BEDT-TTF)$_2$I$_3$ (dark shaded region in Figure 1c). If one assumes a parabolic dispersion, it is possible to compare our data with the band parameters determined for the large Q2D β-orbit from optical data by Tamura *et al.*[6] In particular, we may estimate the effective mass along the *c*-direction as $m_{c\beta} = 2.5\ m_e$, which compares to the value of 2.4 m_e determined from the optical measurements.[6] Based on the known value for the area of the small Q2D section of the FS (α) in *k*-space, we may estimate the momentum averaged cyclotron mass to be $m_{c\alpha} = 1.7\ m_e$, while the experimental value deduced from the SdH and dHvA effects is ~1.9 m_e.[7] Thus, our findings appear to be in excellent agreement with published data.

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