de Haas-van Alphen Oscillations in the Underdoped High-Temperature Superconductor YBa$_2$Cu$_3$O$_{6.5}$

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The de Haas-van Alphen effect was observed in the underdoped cuprate YBa$_2$Cu$_3$O$_{6.5}$ via a torque technique in pulsed magnetic fields up to 59 T. Above a field of ~30 T, the magnetization exhibits clear quantum oscillations with a single frequency of 540 T and a cyclotron mass of 1.76 times the free electron mass, in excellent agreement with previously observed Shubnikov-de Haas oscillations. The oscillations obey the standard Lifshitz-Kosevich formula of Fermi-liquid theory. This thermodynamic observation of quantum oscillations confirms the existence of a well-defined, closed, and coherent, Fermi surface in the pseudogap phase of cuprates.

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Progress towards a more complete understanding of the high temperature superconductors involves a few key questions, one of which is to understand the nature of the pseudogap phase in the underdoped region of the phase diagram. Angle-resolved photoemission spectroscopy (ARPES) shows an apparent destruction of the Fermi surface (FS): below the pseudogap temperature $T^*$, a gap opens up along the $(\pi, 0)$ direction, producing a set of disconnected Fermi arcs. Recently, quantum oscillations, a clear signature of a Fermi-liquid ground state, were observed in the Hall resistance of YBa$_2$Cu$_3$O$_{6.5}$. Since quantum oscillations are a direct consequence of the quantization of closed orbits in a magnetic field, this result suggests that the FS consists of small pockets, rather than Fermi arcs. Very recently, Shubnikov-de Haas oscillations have also been observed in the stoichiometric compound YBa$_2$Cu$_4$O$_8$, suggesting that they are generic to the CuO$_2$ planes rather than some feature of the band structure specific to YBa$_2$Cu$_3$O$_{6.5}$. The frequency of the oscillations gives the area of the FS, but neither the location in $k$-space, nor the number of pockets are known. A comparison with ARPES measurements (assuming only half of each pocket is detected) suggests a four nodal pockets scenario. However, when the density of carriers is estimated from the Luttinger sum rule, an obvious violation of the data obey the standard Lifshitz-Kosevich theory, there is no indication of any deviation from Fermi-liquid theory.

We used a detwinned single crystal of YBa$_2$Cu$_3$O$_{6.5}$ flux-grown in a non-reactive BaZrO$_3$ crucible. The dopant oxygen atoms were ordered into an ortho-II superstructure of alternating full and empty CuO chains, yielding a superconducting transition temperature $T_c=57.5$ K. The sample used for the torque experiment is a
FIG. 1: (color on line) Torque versus magnetic field at different temperatures. Both up (50 ms) and down (250 ms) field sweeps are shown, as indicated by the arrows. Lower inset: schematic of the cantilever. Upper inset: Magnetic fields dependence of the torque ($\theta \approx 5^\circ$) at $T=1.4$ K and of the Hall resistance ($\theta = 0^\circ$) measured in the same sample at $T=1.5$ K.

Small part (140*140*40 $\mu$m$^3$) of the sample studied in ref. [2]. The Hall effect of the original piece was measured at different orientations of the magnetic field with respect to the CuO$_2$ planes, in order to study the angular dependence of the SdH frequency. Torque measurements were performed with commercial piezoresistive micro-cantilever [11] down to 0.4 K at the LNCMP in Toulouse, using pulsed magnetic fields up to 59 T. The sample was glued with Araldite epoxy to the cantilever. A one-axis rotating sample holder allowed the angle ($\theta \approx 5^\circ$) to be varied between the normal to the CuO$_2$ planes and the magnetic field at ambient temperature. The cantilever was set inside a vacuum tight resin capsule filled at room temperature with $^{3}$He gas to ensure thermalization of the sample. This capsule sits in the $^3$He/$^4$He mixture of the dilution fridge. The temperature gradient between the sample located at the end of the cantilever and the thermometer located in the mixing chamber was estimated by measuring the critical field of a known compound under the same experimental conditions. The temperature gradient is about 0.2±0.1 K at 0.4 K and negligible above 1 K. This uncertainty does not affect the value of the physical parameters extracted from the data. The variation of the piezoresistance of the cantilever is measured with a Wheatstone bridge with an AC excitation at a frequency of 63 kHz (see lower inset of Fig. [1]).

Raw data of torque $\tau = |\mathbf{M} \times \mathbf{B}|$ versus magnetic field are shown in Fig. [1] for the up and down field sweeps between $T=1.1$ K and $T=0.4$ K. As observed in the mixed state of other type-II superconductor at low field, there is a strong hysteresis effect, which reflects the penetration (expulsion) of magnetic field into (out of) the sample when the magnetic field increases (decreases). In this regime, “flux jumps” are clearly observed and are associated with a thermal instability corresponding to a reorganization of the magnetic flux as it enters (exits) the sample. [12, 13] The hysteresis disappears above $B_{irre}$ and the torque becomes almost linear with magnetic field. $B_{irre}$ marks the field where the electrical resistance starts to rise and corresponds to the vortex liquid phase. The upper inset of Fig. [1] shows the torque and the (normalized) Hall resistance versus magnetic field measured in the same sample at $T \approx 1.5$ K. Above a field of ~30 T, clear dHvA oscillations are observed. [14] We have checked that the amplitude of oscillations is identical for the up and down field sweeps, which shows that no detectable self-heating occurs in the sample during the measurement.

In the following, we will discuss only the oscillatory part of torque, obtained by subtracting a monotonic background from the raw data. The amplitude of the first harmonic of the dHvA oscillations is interpreted using the Lifshitz-Kosevich (LK) theory for a two-dimensional Fermi liquid:

$$\tau_{osc} = BA \tan \theta \sin[2\pi(F/B - \gamma)]$$

(1)

where $F$ is the oscillation frequency and $\gamma$ is a phase factor. We neglect any contribution from magnetic breakdown, spin damping or any additional damping coming from the effect of superconductivity on the dHvA amplitude. The amplitude of the fundamental frequency is given by $A \propto R_T R_D$ where $R_T$ and $R_D$ are the thermal $(R_T = \alpha T m^*/B \sinh[\alpha T m^*/B])$ and Dingle $(R_D = \exp[-\alpha T D m^*/B])$ damping factors, respectively, where $\alpha = 2\pi^2 k_B m_0/\hbar c$ ($\approx 14.69$ T/K) and $TD$ is the Dingle temperature. [14]

Fig. [2] displays the temperature dependence of the amplitude of the oscillations (“mass plot”) for different field windows. The usual behavior expected for thermal damping of the dHvA oscillations is observed. Solid lines are fits of Eq. [1] from which we deduce an effective mass $m^* = 1.76 \pm 0.07 m_0$, in agreement with the value obtained from Shubnikov-de Haas measurements [2]. No significant variation of the effective mass with magnetic field is observed, which confirms that the LK model is adequate to describe the data. Using $v_F = \hbar k_F/m^*$ and the Onsager relation (assuming a circular orbit) $\pi k_F^2 = 2\pi^2 F/\Phi_0$, the average Fermi velocity is $8.4 \times 10^4$ m s$^{-1}$. This value is in fact very similar to that found by ARPES at the anti-node in both La$_2-x$Sr$_x$CuO$_4$ [15] and Bi$_2$Sr$_2$CuO$_{6+\delta}$. [16] This may indicate that the pockets detected by dHvA are not located at the same
position in \( k \)-space as the Fermi arcs seen by ARPES [1].

Fig. 3(a) displays the oscillatory torque versus \( 1/B \) between \( T=5.2 \) K and \( T=0.4 \) K. At the lowest temperatures, 8 periods can be resolved, corresponding to the Landau levels \( n=9 \) to \( n=16 \). Oscillations can be observed down to a field of \( \sim 30 \) T, in particular in the resistive superconducting transition (see upper panel of Fig. 3). Fig. 3(b) displays the corresponding field dependence of the amplitude of the dHvA oscillations divided by the \( R_T \) factor ("Dingle plot"). Within our experimental resolution, it is not possible to resolve an extra attenuation corresponding to the effect of superconductivity on the dHvA amplitude. [17, 18] By neglecting any additional damping factor coming from the mixed state, the solid line in Fig. 3(b) yields an upper limit of \( T_D = 6.2 \pm 1.2 \) K (using \( m^*=1.76 \pm 0.07 \) \( m_0 \)), which converts to \( \omega_c \tau = 0.7 \pm 0.2 \) at \( B=35 \) T. Assuming a cylindrical FS, we can deduce a mean free path \( \ell=16 \) nm. Black solid lines in Fig. 3(a) are fits to Eq. 1 obtained by setting \( m^*=1.76 \) \( m_0 \) and \( T_D = 6.2 \) K for all temperatures. The deduced oscillation frequency and phase factor are \( F = 540 \pm 4 \) T and \( \gamma = 0.15 \pm 0.05 \), respectively. This fitting procedure confirms that the LK formula, which describes the dHvA oscillations for a 2D Fermi liquid is appropriate. This conclusion is at odds with recent theories that invoke mechanisms other than the Landau quantization of quasi-particles. [19, 20]

Fig. 4(a) shows the oscillatory Hall resistance versus magnetic field measured in the same sample at \( T=3 \) K for different angles \( \theta \). Several measurements have been done at different temperatures for each orientation, from which we have deduced an oscillation frequency \( F \) plotted in Fig. 4(b). Within the error bars, \( F \) increases as \( 1/\cos(\theta) \) as expected for a quasi-2D part of the FS [14]. It simply reflects the increase of the area of the cyclotron orbit when the magnetic field is tilted from the normal of the CuO\(_2\) plane.

dHvA measurements have been widely used to study the FS of metals. [14] As a thermodynamic measurement, it firmly confirms the existence of well-defined quasi-particles at the FS with a substantial mean free path. Quantum oscillations are detected with torque starting at a field corresponding to the onset of the electrical resistance, but there is no clear evidence in the amplitude of the oscillations of a transition from the mixed state to the normal state. [21] It may be due to the fact that, in order to resolve an additional damping, the dHvA signal have to be measured in a field range much larger...
In summary, we have observed the first direct evidence of dHvA oscillations in YBa$_2$Cu$_3$O$_6.5$. The frequency and the effective mass are in excellent agreement with previous SdH measurements in the same compound. This observation confirms the existence of a coherent closed Fermi surface at low temperature in the underdoped side of the phase diagram of cuprates and suggests that the ground state obeys Fermi-liquid theory.

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than than in Fig. 3(b). dHvA oscillations have been observed in the mixed state of many superconductors, and in all cases the oscillations have the same frequency as in the normal state. In particular, dHvA and SdH effects have been observed in the organic superconductor $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ which shares many characteristics with high Tc superconductors such as low dimensionality and short coherence length, but which has a much lower $H_{c2}$. The striking similarity between the data in $\kappa$-salt (see Fig. 2 of ref. [20]) and that in the upper inset of Fig. 1 suggests that the normal state could be reached around our maximum field in YBa$_2$Cu$_3$O$_6.5$. This value is lower than the one given by the extrapolation of the Nernst data to higher fields, which suggest that $H_{c2}$ could be as large as 150 T (corresponding to the field scale associated with the short coherence length in cuprates). However, one should keep in mind that in such a layered superconductor, there is no true phase transition between the vortex liquid and the normal state, but a cross-over with an extended range of fluctuating superconductivity. In this cross-over regime, one can expect the electrical resistance to be representative of the normal state.

Finally, the frequency $F=540$ T converts to a carrier density 0.038 carrier per planar Cu atom. Independently of whether there are 2 or 4 pockets, it gives a number of carriers which is not in agreement with the doping level (10 %). However, a scenario based on a $(\pi, \pi)$ reconstruction of the FS can explain both the negative Hall effect (electron pocket) in the normal state and the apparent violation of the Luttinger sum rule. It assumes that the frequency observed with SdH and dHvA effects corresponds to an electron pocket, whose mobility is much higher than that of a larger hole pocket not seen in the measurements. To validate this scenario, however, the detection of another frequency corresponding to a total hole density of 0.138 hole per planar Cu atom, is still required.
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