Quantum oscillations in underdoped $YBa_2Cu_3O_{6.5}$

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Shubnikov-de Haas and de Haas-van Alphen effects have been measured in the underdoped high temperature superconductor $YBa_2Cu_3O_{6.51}$. Data are in agreement with the standard Lifshitz-Kosevitch theory, which confirms the presence of a coherent Fermi surface in the ground state of underdoped cuprates. A low frequency $F = 530 \pm 10$ T is reported in both measurements, pointing to small Fermi pocket, which corresponds to 2% of the first Brillouin zone area only. This low value is in sharp contrast with that of overdoped $Tl_2Ba_2CuO_{6+\delta}$, where a high frequency $F = 18$ kT has been recently reported and corresponds to a large hole cylinder in agreement with band structure calculations. These results point to a radical change in the topology of the Fermi surface on opposing sides of the cuprate phase diagram.

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The first unambiguous observation of quantum oscillations (QO) in underdoped $YBa_2Cu_3O_{6.5}$ [1] has created a lot of interest concerning the exact nature and the origin of the Fermi surface (FS) in the pseudogap phase of cuprates. If QO are interpreted as the usual consequence of the quantization of closed orbits in a magnetic field, they show that the FS consists of small pockets. It contrasts with angle-resolved photoemission spectroscopy (ARPES) which shows an apparent destruction of the FS producing a set of disconnected Fermi arcs [2]. The apparent contradiction between the two sets of measurements is not yet resolved [3–5]. Shubnikov-de Haas effect has been confirmed in the stoichiometric compound $YBa_2Cu_4O_8$ [6, 7], indicating that QO are generic to the CuO_2 planes rather than some feature of the band structure specific to $YBa_2Cu_3O_{6.5}$ [6, 8]. More recently, de Haas-van Alphen effect (dHvA) has been reported in underdoped $YBa_2Cu_3O_{6.5}$ [9, 10], which confirmed the existence of a well-defined, closed, and coherent, FS via a thermodynamic probe.

In this paper we report a set of new data of Shubnikov-de Haas (SdH) in an underdoped cuprate $YBa_2Cu_3O_{6.51}$ obtained both in the in-plane and Hall resistances. We compare the results with measurements of the dHvA at the same doping level published in ref. [9].

Transverse magnetoresistance (R_{xx}) and Hall resistance (R_{xy}) were measured down to 1.5 K in pulsed magnetic fields up to 60 T. Current and field were applied along the **a** axis and normal to the CuO_2 planes, respectively. A commercial piezoresistive microcantilever [11] was used for torque measurements in a dilution fridge down to 0.5 K in pulsed magnetic fields up to 59 T. The crystal was glued to the beam of the cantilever with an angle of approximately $\theta \sim 5^o$ between the direction of the magnetic field and the normal to the CuO_2 planes [9].

We used two detwinned single crystals of $YBa_2Cu_3O_{6.51}$ flux-grown in a non-reactive $BaZrO_3$ crucible [12]. The dopant oxygen atoms are ordered into an ortho-II superstructure of alternating full and empty CuO chains which corresponds to a superconducting temperature of $T_c = 57.5$ K and therefore a doping of about $p \sim 0.1$[13].

Fig. 1(a) shows raw data of torque (defined as $\tau = |\overrightarrow{M} \times \overrightarrow{B}|$ where M is the magnetization) in one sample of $YBa_2Cu_3O_{6.51}$ at different temperatures. The torque signal displays clear dHvA oscillations in high magnetic fields. Above 30 T, the torque varies almost linearly with magnetic field which allow us to subtract a monotonic background from the data in order to derive the oscillatory part. Eight oscillations can be resolved at $T = 0.5$ K.

Fig. 1(b) and Fig. 1(c) show raw data of the Hall resistance and of the transverse magnetoresistance, respectively, in another sample of $YBa_2Cu_3O_{6.51}$ at different temperatures. Oscillatory parts of R_{xy} and R_{xx} are obtained after substraction of a polynomial background.

The oscillatory part of the resistance (ΔR) and of the magnetization (ΔM) are analyzed in the framework of the standard Lifshitz-Kosevich (LK) theory for a two-dimensional generalized Fermi liquid [14]:

$$\Delta R, \Delta M \propto R_T R_D cos\Big[2\pi\big(\frac{F}{B} - \gamma\big)\Big] \qquad (1)$$

where F is the oscillation frequency and γ a phase factor. The amplitude is given by $A \propto R_T R_D$, where $R_T = \alpha T m^*/B \sinh[\alpha T m^*/B]$ and $R_D = \exp[-\alpha T_D m^*/B]$ are the thermal and Dingle damping factors, respectively. m^* is the cyclotron effective mass, T_D is the Dingle tem-