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Slow quantum oscillations without fine-grained Fermi surface reconstruction in cuprate superconductors

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In the last decade, following their first observation in cuprate high-temperature superconductors,[1] magnetic quantum oscillations (MQO) are extensively used to investigate the electronic structure of cuprates. The MQO in the underdoped yttrium barium copper oxide (YBCO) compounds $YBa_2Cu_3O_{6+\delta}$, reviewed in [2–5]). have a prominent peak at frequency $F_\alpha \approx 530\,T$ with two smaller shoulders at $F_\pm = F_\alpha \pm \Delta F_\alpha$, where $\Delta F_\alpha \approx 90\,T$. All these frequencies are much smaller than expected from closed pockets of the Fermi surface (FS). To explain such a set of frequencies, many different theoretical models have been proposed, which are based on FS reconstruction due to the periodic potential created by a charge density wave (CDW) (see [2–4] for review). A weak and inhomogeneous or fluctuating CDW order has been detected in $YBa_2Cu_3O_{6+\delta}$, e.g., by X-Ray scattering [6–8]. High magnetic fields suppress superconductivity and lead to long-range CDW coherence [7, 8]. Static CDW order can indeed lead to FS reconstruction, seen in new MQO frequencies, but only if the CDW potential is sufficiently strong: the CDW energy gap must be larger than the magnetic-breakdown gap $\Delta_{\rm mb} \sim \sqrt{\hbar\omega_c E_{\rm F}}$, where $\hbar\omega_c$ is the cyclotron energy, and $E_{\rm F} \sim 1\,eV$ is the Fermi energy of the unreconstructed electron dispersion. The oscillations in cuprates are measured in magnetic fields $\mathbf{B}$ higher than $30\,T$, where $\Delta_{\rm mb} \gtrsim 40\,meV$ is rather large and a weak CDW ordering may not be enough to form new frequencies with amplitudes sufficient for experimental observation. Moreover, a frequency pattern similar to that of $YBa_2Cu_3O_{6+\delta}$ is observed in $YBa_2Cu_4O_8$, where there is no experimental indication of a static CDW. Even if this CDW is sufficiently strong, it is hard to explain the observed three-peak frequency pattern of MQO in YBCO without additional frequencies of similar amplitude for the CDW wave vector seen in X-ray experiments [6–8]. Moreover, if FS reconstruction really is the origin of the observed F_α, F_+, and F_-, they should depend strongly on doping. In $YBa_2Cu_3O_{6+\delta}$ the observed doping dependence of the three low frequencies is rather weak: frequency changes by only 10 %, from 515 T to 570 T, as the doping p varies from 0.09 to 0.14 [9]. In this paper, we propose a simple alternative picture, which is consistent with the observed three equidistant MQO peaks in $YBa_2Cu_3O_{6+\delta}$ and other features of the measurements.

Our explanation is somewhat analogous to "slow oscillations" (SlO), observed in organic superconductors and attributed not to new small FS pockets, but to the interplay (mixing) of two close frequencies $F_\beta \pm \Delta F$, where the frequency splitting ΔF is due to FS warping, originating from the interlayer electron transfer integral t_z [10]. As a result, magnetoresistance (MR) oscillations with a new frequency $F_{\rm slow} = 2\Delta F = 4t_z B/\hbar\omega_c$ arise. The amplitudes of the emergent slow oscillations may be even higher than those of the oscillations with the original frequencies $F_\beta \pm \Delta F$, because the SlO are damped neither by temperature nor by long-range disorder or sample inhomogeneities [10, 11]. The latter feature is especially important, because even in high-quality monocrystals of organic metals this long-range disorder makes the major contribution to the Dingle temperature [10]. In the notoriously inhomogeneous cuprates such disorder is much stronger, and MQO from closed pockets should be strongly damped, whereas the proposed SlO are insensitive to this form of disorder and can easier be observed.

In contrast to organic metal β-(BEDT-TTF)$_2$IBr$_2$, the YBCO compounds have bilayer crystal structures. The resulting electron energy spectrum is approximately given by

$$\epsilon_\pm\left(k_z, \mathbf{k}_\parallel\right) \approx \epsilon_\parallel\left(\mathbf{k}_\parallel\right) \pm t_\perp\left(\mathbf{k}_\parallel\right) \pm 2t_z\left(\mathbf{k}_\parallel\right)\cos\left[k_z c^*\right]. \quad (1)$$

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In YBCO there are thus at least two types of splitting of the original frequencies: the larger bilayer splitting $\Delta F_{\perp} = t_{\perp}B/\hbar\omega_c$, and the smaller splitting $\Delta F_c = 2t_zB/\hbar\omega_c \ll \Delta F_{\perp} \ll F_{\beta}$ due to the k_z electron dispersion. These two splittings result in *four* underlying MQO frequencies $F_{\beta}\pm\Delta F_{\perp}\pm\Delta F_c$ of similar amplitudes, instead of only *two* $F_{\beta}\pm\Delta F_c$ for organic metals without bilayers [10]. The SlO of MR originate from these *four* frequencies in a similar way as before [10, 12] but result in a much richer set of frequencies.

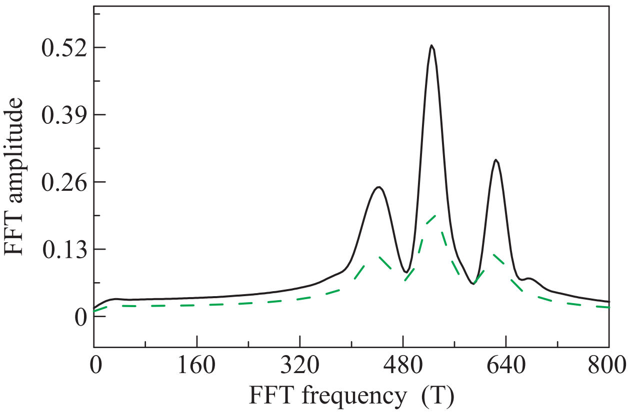

Fig. 1. (Color online) The Fourrier transform of slow oscillations of magnetoresistance given by Eq. (5) at two Dingle temperatures: $\Gamma/\hbar\omega_c(B_z = 1T) = 8$ (black line) and 16 (dashed green line)

Each pocket β contributes to total conductivity

$$\sigma = \sum_{\beta}\sigma_{\beta} = \sum_{\beta} e^2 g_{\mathrm{F}\beta} D_{\beta}. \qquad (2)$$

via the product of a density of electron states (DoS) $g_{\mathrm{F},\beta} = g_{\beta}(\varepsilon = E_{\mathrm{F}})$ and an electron diffusion coefficient $D_{i,\beta}$. Both contribute to oscillations, since they vary with the magnetic field B_z perpendicular to the conducting x-y layers as:

$$\frac{g_{\mathrm{F}\beta}}{g_{0\beta}} = 1 + A_{\beta}\sum_{j,l=\pm1}\cos\left(2\pi\frac{F_{\beta}+j\Delta F_{\perp}+l\Delta F_c}{B_z}\right), \quad (3)$$

with $g_{0\beta}$ the average DoS at the Fermi level, and

$$\frac{D_{\beta}}{D_{0,\beta}} = 1 + B_{\beta}\sum_{j,l=\pm1}\cos\left(2\pi\frac{F_{\beta}+j\Delta F_{\perp}+l\Delta F_c}{B_z}\right), \quad (4)$$

with $D_{0,\beta}$ the non-oscillating part of the diffusion coefficient. Coefficients A_{β} and B_{β} contain Dingle factor. Combining Eqs. (2)–(4), in addition to fast oscillations with frequencies $\sim F_{\beta}$ or $\sim 2F_{\beta}$, we obtain the terms

$$A_{\beta}B_{i,\beta}\left[2\cos\left(\frac{4\pi\Delta F_{\perp}}{B_z}\right) + \sum_{l=\pm1}\cos\left(4\pi\frac{\Delta F_{\perp}+l\Delta F_c}{B_z}\right)\right], \quad (5)$$

which contain only the differences of fundamental MQO frequencies and thus are not damped by the smearing of Fermi level. The amplitude of the central frequency $2\Delta F_{\perp}$ in Eq. (5) is twice as large as the amplitudes of the side frequencies $2\Delta F_{\perp}\pm 2\Delta F_c$, and in Fig. 1 the amplitudes of side peaks are additionally damped by the finite Dingle factor. This resembles closely the experimental data in YBCO [2, 3]. We therefore propose an alternative interpretation of the observed oscillations at low frequency $F_{\alpha}\approx 530$ T in $YBa_2Cu_3O_{6+\delta}$ (and, possibly, in $YBa_2Cu_4O_8$), in which three equidistant harmonics are not due to the small pockets of the FS reconstructed by CDW order, but originate from mixing, according to Eq. (5), of four frequencies $F_{\beta}\pm\Delta F_{\perp}\pm\Delta F_c$, formed by a fundamental frequency F_{β} split by bilayer and inter-bilayer electron hopping integrals $t_{\perp}$ and t_z.

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