Competing types of quantum oscillations in the 2D organic conductor \((\text{BEDT-TTF})_8\text{Hg}_4\text{Cl}_{12}(\text{C}_6\text{H}_5\text{Cl})_2\)

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I. INTRODUCTION

In some organic conductors, the Fermi surface (FS) presents quasi 2D pieces connected with small enough gaps, which offers the very attractive opportunity to investigate still interesting questions of fermiology such that the ’competing coexistence’ between different types of quantum oscillations. This is the case of e. g. the quasi-2D charge transfer salt \(\kappa-(\text{ET})_2\text{Cu(NCS)}_2\), where ET stands for the donor molecule BEDT-TTF (bisethylenedithia-tetrathiofulvalene). Indeed, the FS of this compound appears to be adequately described by the textbook model of a chain of coupled orbits introduced by Pippard.\(^1\) In this compound, conventional Shubnikov de Haas effect (SdH) results from magnetic flux quantization inside semiclassical closed orbits and quantum interference (QI) between open electron paths, which can be both induced by magnetic breakdown (MB)\(^2\) or quantum interference (QI).\(^3\) These phenomena yield frequencies resulting from linear combinations of the two basic frequencies \(a\) and \(b\) as observed in the oscillatory spectrum of the magnetization and of the longitudinal magnetoresistance,\(^4\) although some of these combinations are forbidden in the semiclassical picture. Similar frequency mixing induced by oscillation of the chemical potential of a 2D-electron gas may also contribute to the observed data. More recently, numerical computation of the de Haas-van Alphen (dHvA) oscillation spectrum has been achieved.\(^5\) Based on a realistic tight-binding model of quasi-2D organic conductors, these computations also evidenced, although at quite high \(B/T\) ratios, significant frequency mixing including the forbidden frequencies. They occur as well for a fixed number of particles as for a fixed chemical potential and are due to the field-dependent interplay of electronic states from the different bands crossing the Fermi level.\(^6\)

The main still open question lies in the relative weight of these different contributions to the data.

The room temperature FS of \((\text{ET})_8\text{Hg}_4\text{Cl}_{12}(\text{C}_6\text{H}_5\text{Cl})_2\) results from the hybridization of two pairs of hidden quasi-1D sheets, parallel to the \((a^*, b^* + c^*)\) and \((a^*, c^*)\) planes.\(^7\) The resultant FS, obtained after raising of degeneracy is built up with one hole and one elongated electron tube (see Figure 1). Although the cross section area of both electron and hole tubes amounts to 13 percent of the FBZ area,\(^8\) the resulting orbits do not share the same topology and are separated from each other by two unequal gaps labeled E\(_1\) and E\(_2\) in Figure 1. Provided these gaps are not too large, MB between electron and hole orbits can occur in magnetic field, leading to a two-dimensional network of coupled orbits. This may give rise, besides quantum oscillations linked to the electron and hole closed orbits, to additional oscillation frequencies that can be accounted for either by the semiclassical model of Falicov and Stachowiak\(^9\) or by QI. Regarding the FS topology at low temperature, it is worth to notice that a metallic groundstate is stabilized in \((\text{ET})_8\text{Hg}_4\text{Cl}_{12}(\text{C}_6\text{H}_5\text{Cl})_2\). Indeed, the conductivity exhibits a metallic behavior down to the lowest temperatures with a residual resistivity ratio equal to 100 and without any sign of (even imperfect) nesting of neither electron nor hole tubes.\(^10\)

Previous magnetoresistance experiments performed up to 15 teslas on \((\text{ET})_8\text{Hg}_4\text{Cl}_{12}(\text{C}_6\text{H}_5\text{Cl})_2\) crystals with the
made to the crystal using annealed gold wires of 20 mm in diameter glued with graphite paste. Alternating current (400 mA, 50 kHz) was injected parallel to the a* direction (interlayer configuration). A lock-in amplifier with a time constant of 100 ms was used to detect the signal across the potential leads. If the measurements, performed during the decay of the pulsed fields of the LNCMP (36 T, 1.2 sec) were noiseless, this should allow to derive reliable oscillatory data down to e. g. 11 T and 1 T for a frequency of 2200 T and 150 T, respectively (see Ref.14).

Data analysis is based on Fourier transforms (FT) calculated with an elevated cosine window in a given field range from B_{min} to B_{max}. In the following, the amplitude of a given oscillation series at the mean field value B = 2 / (1/B_{min} + 1/B_{max}) is determined by the ratio of the amplitude of the FT to (1/B_{min} - 1/B_{max}). The orientation of the magnetic field is defined by the angle θ between the field direction and the normal to the conducting bc-plane. The sign of θ is arbitrary.

III. RESULTS AND DISCUSSION

A. Oscillatory spectrum

Fig. 3 displays the oscillatory magnetoconductance for different orientations of the magnetic field at a temperature of ~ 1.7 K. FT deduced from data in Fig. 3 are displayed in Fig. 4. A complex oscillatory behavior is observed since up to 6 fundamental frequencies - without counting some harmonics - are displayed in Fig. 3. Moreover, these 6 frequencies follow the orbital behavior expected for a two-dimensional FS in the explored angle range from -21° to +72°, as demonstrated in Fig. 3 for some angles. In the field range between 10 and 30 teslas (see Figure 3a), the observed frequencies can be regarded as linear combinations of F_a and F_b with F_a = (241.5 ± 2.0) T and F_b = (149 ± 2) T. In addition, an oscillation series with a frequency F_δ = (2185 ± 15) T and up to 3 harmonics are observed in the higher field range between 20 and 35.2 T (see Figure 3b). These three frequencies correspond to cross section area of 11.0 ± 0.1, 6.8 ± 0.1 and 100 ± 1 percent of the FBZ area, respectively. According to band structure calculations, the cross section area of the electron and the hole orbits corresponds to approximately 13 % of the FBZ area. Keeping in mind that a discrepancy of few percents between experimental data and band structure calculations is an usual feature, it can be assumed that the calculated FS is in qualitative agreement with the experimental data. Hence F_a is associated to the closed electron and hole orbits (referred to as the a orbits in the following) and F_δ to the δ orbit. F_b which corresponds to the whole FBZ area, accounts for an orbit that involves 2a + ∆ + δ. Owing to the experimental values of the frequencies F_a and F_δ, the cross section of the ∆ orbit amounts to 71 % of the FBZ area. Finally, it is important to notice that more than ten
frequency combinations involving $F_b$ are also observed in FT performed in the high field range (see Fig. 3). In particular, the frequency linked to $b-2a-\delta$, which corresponds to the $\Delta$ orbit is clearly evidenced in the figure. In order to assign the above reported frequencies to k-space SdH orbits or QI paths, it is important to keep in mind that, following Falicov and Stachowiak and Shoenberg, areas enclosed by electron and hole parts of a MB orbit bears opposite sign. One of the possible consequence is that very large SdH orbits and QI paths including both electron and hole parts may account for a given (even rather low) frequency, although with a reduced damping factor and a large effective mass, as discussed in the next section. For example, $F_5$ can be attributed, among others, to both the semiclassical MB closed orbit (a b c d e b f g h m i h l a) and the QI path (a k l)-(a b c d e b f g h l) (see Fig. 2). It is worth to note that magnetic interaction MI can also induce frequency combinations in dHvA oscillations spectrum when the FS is composed of several orbits. However, recent measurements have revealed that, as it is usually the case for most organic conductors, the value of the magnetization of the isostructural compound $(ET)_8\text{Hg}_4\text{Cl}_{12}(C_6\text{H}_5\text{Cl})_2$ remains rather weak even at high magnetic field. This latter result makes unlikely a significant contribution of MI to the oscillation spectrum. In the following, we will examine the possible contribution of QI and conventional SdH effect to the observed oscillatory behavior through the temperature and magnetic field dependencies of the oscillation amplitude. Unfortunately, the oscillation series resulting from frequency combinations involving the $F_b$ frequency (see Fig. 3) will not be considered due to too small amplitude and/or too steep field and temperature dependencies.

FIG. 2: Oscillatory part of the magnetoconductance at $\sim 1.7$ K for different orientations of the magnetic field. $\sigma_{bg}$ is the field-dependent background part of the conductivity. $\theta$ is the angle between the magnetic field direction and the normal to the conducting plane.

FIG. 3: Fourier transforms deduced from data in Figure 2. The magnetic field window is 10 - 30 T and 20 - 35.2 T for Fig. 3a and Fig. 3b, respectively.
where \((u_0 = 14.694 \text{ T/K})\); \(T_D(i)\) and \(m_e(i)\) are the Dingle temperature and the effective cyclotron mass, respectively. \(R_T(i)\) is given by:

\[
R_T(i) \propto \frac{T m_e(i)/B^n}{\sinh[-u_0 T m_e(i)/B]} \tag{4}
\]

In the two- and three-dimensional case, \(n\) is equal to 1 and 1/2, respectively.\[1\]

Following Falicov and Stachowiak\[1\], the effective mass linked to electron and hole orbits can be expressed as \(m^*_{e} = 2(m_{e1} + m_{e2})\) and \(m^*_{h} = 2(m_{h1} + m_{h2})\), respectively. The weight factors \(m_{e1}, m_{e2}, m_{h1}\) and \(m_{h2}\), which can be regarded as absolute values of partial cyclotron mass parameters, are defined in Fig.\[1\]. Since the oscillation series with frequency \(F_a\) results from the contribution of the electron and hole orbits, the resultant effective cyclotron mass has been assumed equal to \(m^*_{e} = (m^*_{e} + m^*_{h})/2\), i.e. \(m_{a} = m_{e1} + m_{e2} + m_{h1} + m_{h2}\). Same type of calculation has been performed for the other \(\text{SdH}\) orbits as reported in Table 1.

In the framework of the \(\text{QI}\) model\[1\], the effective mass is given by the energy derivative of the phase difference \((\varphi_i - \varphi_j)\) between the two different routes \(i\) and \(j\) of a two-arm interferometer. Within this model, \(\partial(\varphi_i - \varphi_j)/\partial \epsilon = \hbar B \partial S_k/\partial \epsilon\), where \(S_k\) is the reciprocal space area bounded between the two arms. Since \(\partial(\varphi_i - \varphi_j)/\partial \epsilon\) is proportional to the difference between the effective mass of the two arms of the interferometer, the associated effective mass is given by \(m^* = |m^*_{e} - m^*_{h}|\) where \(m^*_{e}\) and \(m^*_{h}\) are the partial effective masses of the routes \(i\) and \(j\). The calculated values for the \(\text{QI}\) orbits are given in Table 1. It should be kept in mind that a given oscillation series can be accounted for by several types of \(\text{QI}\) paths or \(\text{SdH}\) orbits with different damping factors. Data in Table 1 is restricted to orbits yielding the highest damping factors i.e. with the lowest number of \(\text{MB}\) junctions and the lowest effective mass.

For a given oscillation series, noticeable differences between effective masses linked to either \(\text{SdH}\) or \(\text{QI}\) can be observed. E.g. \(m^*_{2n+\delta}\) is equal to \(2 m^*_{a}\) in the case of \(\text{SdH}\) while \(m^*_{2n+\delta}\) is equal to \(2 |m_{e2} - m_{h2}|\) in the case of \(\text{QI}\) which is certainly much lower than \(m^*_{a}\).

We discuss now the damping factor \(R_{MB}\) entering Eq. (2). According to Falicov and Stachowiak\[1\], the damping factor for a \(\text{SdH}\) orbit can be written as:

\[
R_{\text{SdH}}^g(i) = \prod_{g=1,2} p_{g}^{n_{pg}} q_{g}^{n_{qg}} \exp \{i (n_{pg} \varphi_p + n_{qg} \varphi_q)\} \tag{5}
\]

The indices \(g\) stand for the two different gaps between electron and hole orbits (see Fig.\[1\]). \(\varphi_p\) and \(\varphi_q\) are phase factors \((\varphi_p + \varphi_q = \pm \pi/2)\). The integers \(n_{pg}\) and \(n_{qg}\) are respectively equal to the number of \(\text{MB}\) and \(\text{Bragg}\) reflections encountered along the path of the quasiparticle. The \(\text{MB}\) and \(\text{Bragg}\) reflection probabilities are given by \(p_{g}^{n_{pg}} = \exp(-B_{g}/B)\) and \(| q_{g} |^2 = 1 - p_{g}^{n_{pg}}\), respectively.
TABLE I: Experimental data and calculated parameters relevant to the observed oscillation series. F(θ = 0°) is the oscillation frequency deduced from experimental data for the magnetic field applied perpendicular to the conducting plane. m* and m, are the calculated effective mass and the experimental effective cyclotron mass deduced from the conventional LK model (in the temperature range below 8 K for b and δ oscillations), respectively relevant to the considered oscillation series. The field-dependent part of the damping factors K_{SDH} and K_{QI} are defined in Eq. (5) and (6), respectively. Only the SdH orbits and QI paths yielding the highest damping factors are considered in the table.

| Orbit | Experimental data | SdH oscillations | Calculations |
|-------|-------------------|------------------|--------------|
|       | F(θ = 0°) | m_e | m_e/m_c(a) | m*/m_c(a) | K_{SDH} | m*/m_c(a) | K_{QI} |
| δ    | 149 ± 2 | 0.50 ± 0.15 | 0.43 ± 0.18 | 4 | q_1 q_2^2 p_1^2 p_2^2 | 2 | q_1 q_2^2 p_1^2 p_2^2 |
| a    | 241.5 ± 2 | 1.17 ± 0.13 | 1 | 1 | q_1^2 q_2^2 | not relevant | not relevant |
| a+δ  | 391 ± 4 | 1.02 ± 0.08 | 0.87 ± 0.17 | 3 | q_1 q_2^2 p_1^2 p_2^2 | 1 | q_1 q_2 p_1 p_2^2 |
| 2a+δ | 633 ± 4 | 1.95 ± 0.10 | 1.67 ± 0.27 | 2 | q_1 q_2^2 p_1^2 p_2^2 | 2 | m_{c2} - m_{h2} | m* (a) |
| 3a+δ | 875 ± 15 | 0.73 ± 0.15 | 0.62 ± 0.20 | 3 | q_1 q_2^2 p_1^2 p_2^2 | 0 | q_1 q_2 p_1 p_2^2 |
| b    | 2185 ± 15 | 0.5 ± 0.1 | 0.43 ± 0.13 | 4 | q_1 q_2^2 p_1^2 p_2^2 | 0 | q_1 q_2 p_1 p_2^2 |

where B_g is the gap-dependent MB field. In the following, the field-dependent part of R_{SDH}^{MB}(i) is expressed as K_{SDH}(i) = \sum_{j=1,2} \rho_{j}^{n_{pg} n_{gg}} g_{pg}.

In the case of a two-arm interferometer, the damping term for QI is given, according to Harrison et al[8], by:

\[ R_{MB}^{QI}(i) \propto \prod_{k,g=1,2} \rho_{kg}^{n_{pg} n_{gg}} \exp \left( -\frac{\pi}{\omega_i \tau} \right) \]  (6)

In this expression, i and g indices have the same meaning as in Eq. (5) while k indices stands for each of the two arms of the interferometer. n_{pg} and n_{gg} are the number of MB and Bragg reflections, respectively encountered by each of the arms of the interferometer. As stated in[13], the relevant effective mass m_i entering \omega_i = \hbar c B/m_i is the sum of the partial effective masses of the two branches of the interferometer. In addition, as pointed out by Stark and Friedberg[9] and contrary to the scattering time involved in the Dingle damping factor, which is usually assumed temperature-independent, the quantum state lifetime \tau includes the temperature-dependent electron-phonon interaction. Assuming that 1/\tau is proportional to the zero field resistivity \rho_0(T) yields:

\[ R_{MB}^{QI}(i) \propto K_{QI}(i) \exp \left( -\alpha(i) \rho_0 \right) \]  (7)

where \alpha(i) and \rho_0 are field- and temperature-dependent, respectively.

As pointed out above and contrary to the case of e.g. κ-(ET)$_2$Cu(NCS)$_2$, several QI paths or SdH orbits with different topologies may contribute to a given oscillation series, even restricting ourselves to the orbits or paths with the highest damping factor. As an example, the a+δ series can be accounted for by the QI paths with the arms (a k l) - (a b f g h l) and (e b c) - (e b k m i j c) (see Fig. 1). Nevertheless, both of them include the same four MB and four Bragg reflections involving the small and the large gap between electron and hole orbit. This leads to the field-dependent part of the damping factor K_{QI}(a+δ) = q_1^2 q_2^2 p_1^2 p_2^2 (see Eq. (6) and (7)). In addition to SdH orbits which may present either hole (c d e k m i j c orbit) or electron (a b f g h l a orbit) character, the 2a+δ series can be accounted for by the two interferometers with the arms (a k m i j) - (a b f g j) and (b f g h m) - (b c d e k m). However, contrary to the case of the a+δ series, these two QI orbits yield different damping factors, namely q_1^2 q_2^2 p_1^2 p_2^2 and q_1^2 q_2^2 p_1^2 p_2^2, respectively. Regarding the b oscillation series, it can be accounted for by semiclassical MB orbits, such as the one marked with shaded area in Fig. 2, with large effective mass and reduced MB damping factors (see Table 1). A lot of QI paths can also account for F_b, even without taking into account the interferometers which involve QI paths with strongly different arms length and bear reduced MB damping factors (12 MB junctions) and large effective mass (m^b = 2m^*(a)). Among those with a zero effective mass, some interferometers also involve a large number of MB junctions. Since they are the most probable, only those which involve 10 MB junctions (see the hatched area in Fig. 2) are considered in Table 1.

C. Data analysis

The oscillatory part of the magnetoconductance is displayed in the field range 22 to 36 T for θ = -13° in Fig. 3. The temperature dependence of the amplitude of the oscillations for the a, a+δ, 2a+δ and 3a+δ series observed in the oscillatory spectrum is displayed in Fig. 3 in the temperature range up to 10 K. A good agreement with the conventional LK model is observed as it is the case for the δ and b oscillations below ~ 8K (see Fig. 3). However, Fig. 3 displays strong downward deviations from above ~ 8 K for these latter series. These deviations from LK model are discussed later on. The cyclotron effective masses have been determined for different directions and mean values of the magnetic field. In the main, slight variations of the measured effective cyclotron mass parameter can be observed at high magnetic field, likely due to the strongly two-dimensional character of the FS[19]. Stronger downward deviations are neverthe-
less observed in some cases e.g. for $m_c(a)$ at $\theta = 33^\circ$ and $m_c(a+\delta)$ at $\theta = 22^\circ$. The values deduced from experimental data are given in Table 1, assuming that reliable values of the effective cyclotron mass are obtained at low magnetic field.

In the framework of the Fermi liquid theory, effective cyclotron masses are renormalised by electron-phonon interactions and electron correlation, accounted for by multiplicative factors $(1 + \lambda_{e-ph})$ and $(1 + \lambda_{e-e})$, respectively where $\lambda_{e-ph}$ and $\lambda_{e-e}$ are the strength of the interactions. Assuming this model holds in the present case, allows us to compare experimental values of $m_c((i)/m_c(a)$ to calculated values of $m^*_i/m^*_a$.

Effective cyclotron mass $m_c(a+\delta)$ is close to $m_c(a)$ (see Table 1) which is in agreement with QI phenomenon. Similarly, $m_c(2a+\delta)$ value is in between $m_c(a)$ and $2m_c(a)$ which suggests a significant contribution of conventional SdH. Oppositely, $m_c(\delta)$ and $m_c(3a+\delta)$ are lower than $m_c(a)$ which invalidates both the conventional SdH and the QI models. It must be pointed out that, the a+\delta series is not observed in dHvA experiments performed at low magnetic field, although these dHvA data present a better signal-to-noise ratio than the present conductivity data. This result suggests that QI do contribute to the oscillatory behavior. Otherwise, the 2a+\delta frequency combination, which mainly results

FIG. 5: Oscillatory part of the magnetoconductance at different temperatures in the field range 21.7 to 36 T. The angle between the magnetic field direction and the normal to the conducting plane is $\theta = -13^\circ$.

FIG. 6: Temperature dependence of the oscillation amplitude of some of the series observed in Fig. 5. The angle between the magnetic field direction and the normal to the conducting plane is $\theta = -13^\circ$. The mean field value is 29.57 T, 28.29 T, 29.57 T and 27.66 T, respectively for the a, a+\delta, 2a+\delta and 3a+\delta series. Solid lines are best fits to Eq. (4).

FIG. 7: Temperature dependence of the amplitude of the b (full circles) and $\delta$ (full squares) oscillations. The mean field value is 22.66 T and 29.57 T, respectively for the $\delta$ and b series. The angle between the magnetic field direction and the normal to the conducting plane is $\theta = -13^\circ$. Dashed lines are best fits to the LK model (see Eq. (4)) as done in Fig. 6. Full lines are best fits to the LK model, assuming a zero effective cyclotron mass and taking into account the temperature dependence of the quantum state lifetime according to Eq. (7). The temperature dependence of the zero field resistance (empty circles) is also displayed. Dotted line is a guide for the eye and accounts for a $T^2$ dependence (see text).
from SdH, is still visible in the dHvA experiment. Nevertheless, the frequencies linked to the \( \delta \) and to the 3a+\( \delta \) orbits which are not accounted for by neither conventional SdH nor QI are also not detected in the dHvA data. Owing to the large cross section of the b orbits, \( m_c(b) \) deduced from the low temperature part of the data is low when compared to \( m_c(a) \) since \( m_c(b) / m_c(a) \sim 0.4 \) (see dashed lines in Fig. 8). This rules out the conventional SdH model and suggests that the b oscillation series may result from QI. Nevertheless, only the interferometers with a zero effective mass should significantly contribute to the oscillatory behavior. Such a discrepancy has already been observed in the case of the 3D LaB\(_6\) compound which also exhibits a QI orbit with an extremal cross section equal to the FBZ area and for which a zero effective mass is predicted. This discrepancy can be accounted for by Eq. (7) which assumes that the relevant lifetime arising in Eq. (6) is proportional to the interlayer conductivity in zero-field. This is demonstrated in Fig. 8 where solid lines are best fits to Eq. (2) assuming a zero effective cyclotron mass (i.e. \( R_T(b) \) defined in Eq. (4) is temperature-independent) and a temperature dependence of \( R_T^{SI} \) given by Eq. (7). Even better agreement between data and Eq. (7) is obtained assuming \( 1/\tau_1 \) is proportional to \( T^2 \), which constitutes a signature of the Fermi liquid behavior. It can be noticed in Fig. 8 that Eq. (7) also holds for the \( \delta \) oscillation series although there is no theoretical justification for this behavior in the framework of the SdH and QI models since much higher values of \( m_c(\delta) \) are predicted in both cases (see Table 1).

Additional information can be derived from the field dependence of the oscillation amplitude. Fig. 8 displays conventional Dingle plots of the various oscillation series at 1.6 K (see Fig. 8). Data at \( \theta = -13^\circ \) have been chosen since no significant field dependence of the various effective cyclotron masses has been observed for this field direction. The b series has not been considered since reliable data can be derived for the b oscillations in a very narrow field range only, likely due to their weak amplitude. The two-dimensional case (\( n = 1 \) in Eq. (4)) is considered. Dashed lines in Fig. 8 are best fits to Eq. (2) to the data without taking into account any contribution of MB damping factor. Downward deviations from linearity are observed at high magnetic fields. Solid lines in the figure are best fits to the data including MB damping factor (see Table 1) relevant to either SdH (a and 2a+\( \delta \) series) or QI (a+\( \delta \) series). It is worth to note that the same damping factor holds for SdH and QI in the case of the 3a+\( \delta \) oscillation series. Generally speaking, a very large uncertainty in the derived values of MB fields is obtained. Assuming same MB fields for the two gaps reduces the uncertainty and yields \( B_1 = B_2 = (55 \pm 20) \) T for the a series. This value might also account for the data relevant to the 2a+\( \delta \) series for which MB fields between 30 T and 160 T are obtained. Nevertheless, a negative Dingle temperature is obtained assuming MB field in this range even though the Dingle temperature for the a oscillation series is \( T_D(a) = 0.4 \) K. In addition, Dingle plot for the a+\( \delta \) series can only be accounted for by lower MB fields i.e. between 0.2 T and 19 T (above 19 T, negative \( T_D \) values are obtained). Hence, the data in Fig. 8 cannot be accounted for by a unique set of MB field values. This may suggest that, in addition to SdH and QI, other contribution should play a role in the oscillatory data.

### IV. SUMMARY AND CONCLUSION

The oscillatory behavior of the interlayer magnetoconductance of the quasi-two dimensional organic metal (BEDT-TTF)\(_8\)Hg\(_4\)Cl\(_{12}\)(C\(_6\)H\(_5\)Cl)\(_2\) can be described on the basis of linear combinations of three basic frequencies arising from the compensated closed hole and electron orbits and from the two orbits located in between. It can be remarked first that the various MB-induced SdH orbits and QI paths responsible for the observed oscillation spectrum are not independent but do constitute an interlinked network which has been considered in the framework of the coupled orbits model of Falicov and Stachowiak. On the basis of the derived values of the effective cyclotron masses linked to the various oscillation series, it can be inferred that a strong contribution of conventional SdH accounts for the 2a+\( \delta \) series while data for a+\( \delta \) and b, are consistent with QI. Oppositely, the low values of \( m_c(\delta) \) and \( m_c(3a + \delta) \) dis-
agree with both SdH and QI. In addition, the field dependence of the oscillation amplitude of the various series cannot be consistently accounted for by a unique set of MB gaps $E_1$ and $E_2$. These features suggest that additional contribution, such as frequency mixing due to oscillation of the chemical potential or interplay of electronic states from the different bands crossing the Fermi level, strongly influence the oscillatory behavior. From the experimental point of view, further enlightenment could be given by dHvA experiments in high magnetic field. Indeed, contrary to conductivity, magnetization, as a thermodynamic parameter, is not sensitive to QI. In addition, the configuration of measurement (in-plane vs. interlayer) should also be considered since, up to now, no frequency combinations has been observed in conductivity data recorded in the in-plane configuration.

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