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Authors
Harrison, N
Goodrich, RG
Vuillemin, JJ
et al.

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Quantum Interference in LaB$_6$

N. Harrison, R. G. Goodrich, J. J. Vuillemin, Z. Fisk, and D. G. Rickel

1National High Magnetic Field Laboratory, LANL, MS-E536, Los Alamos, New Mexico 87545
2Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803
3Department of Physics, University of Arizona, Tucson, Arizona 85721
4National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310

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Quantum interference effects in the induced currents in metallic LaB$_6$ are investigated in pulsed magnetic fields extending to 60 T and to temperatures of up to 70 K. One of the quantum interference frequencies, corresponding to an area in $k$ space equal to the Brillouin zone, has an effective mass precisely equal to zero. The attenuation of this and other frequencies at high temperatures requires the scattering effects of phonons to be considered within the Boltzmann transport equation.

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The quantum interference (QI) of electrons within magnetic breakdown (MB) networks is a rare phenomenon in metals [1–3]. The Stark interferometer concept was originally devised to explain transport phenomena in pure Mg [1–3]. The effect has since been found to readily manifest itself in low-dimensional (LD) organic charge-transfer salts [4–6], but there have been no further reports in conventional three-dimensional (3D) metals. When interference occurs, the $k$-space area $A_j$ enclosed by the interferometer appears as a "virtual" Onsager phase within the Boltzmann transport equation, leading to new frequencies in addition to the conventional Shubnikov–de Haas (SdH) oscillations [2–4,7]. It is generally understood that QI does not manifest itself in thermodynamic properties of the system [2–4,7] and so cannot contribute to magnetic oscillations giving rise to the de Haas–van Alphen (dHvA) effect. In spite of this, QI oscillations in the magnetotransport behave in a manner that is in remarkable concordance with the Lifshitz-Kosevich (LK) theory [8] of Landau quantum (LQ) oscillations. As with LQ oscillations, the effective mass $m_j^*$ associated with the enclosed area $A_j$ is proportional to the energy derivative $\partial A_j / \partial \epsilon_k$ [2–4], where $\epsilon_k$ is electron energy. An unusual situation arises when $A_j$ has a weak or negligible dependence on $\epsilon_k$ so that $m_j^*$ is anomalously small, as has been shown to occur both in pure Mg [1–3] and in the organic superconductor $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ under hydrostatic pressure [9]. Because the net effective mass is small, QI oscillations persist to high temperatures where the conventional SdH oscillations with much higher effective masses are completely damped.

In this Letter we report a particularly novel situation in LaB$_6$ where not only are QI oscillations observed in a 3D metal, but where one of the QI frequencies corresponds exactly to the cross-sectional area of the Brillouin zone (BZ) with an effective mass precisely equal to zero. The Fermi surface (FS) of LaB$_6$ primarily consists of prolate electron ellipsoids centered at the X points of the cubic BZ, connected together by short necks [10,11]. The extremal cross-section area of these ellipsoids within the XMR plane of the BZ (referred to as the $\alpha_3$ branch in Ref. [11]) accounts for the majority of the dHvA signal at low magnetic fields. Weaker signals originate from closed hole orbits within the $\Gamma XM$ plane (which we will refer to as $e$ and $y$ following common usage); all of these orbits are illustrated in Fig. 1. A second sheet of the FS consists of a set of eight smaller electron ellipsoids located within the necks [12]. At sufficiently strong magnetic fields, MB through the necks, involving the smaller ellipsoids, leads to a multitude of new frequencies. The simplest MB orbit $\alpha_{1,2} + 2\rho$ within the $\Gamma XM$ plane is illustrated

FIG. 1. A cross section of the Fermi surface of LaB$_6$ through the $\Gamma XM$ plane in the extended zone representation. The hole orbits $e$ and $y$ are shown together with the simplest MB orbit $\alpha_{1,2} + 2\rho$. The intersection of the $\alpha_3$ extremal orbit, which occurs within the XMR plane, is indicated by a heavy line. In addition, we schematically illustrate possible orbits for the three principal QI areas. The heavy circles indicate the points at which the QI paths divide (A) and recombine (B).
in Fig. 1; each small ellipsoid contributes only ~2.5 T, and is therefore too small to be seen in Fig. 1. The three principal areas enclosed between two interfering electrons on trajectories within this plane are also illustrated in Fig. 1. Of these, the $\alpha_{1,2} + \epsilon$ and $\alpha_{1,2} + \gamma$ combination frequencies are expected to have finite effective masses as listed in Table I; note that the contributions from the smaller electron ellipsoids cancel for the two branches. Since the BZ contains exactly two $\alpha_{1,2}$ areas, an $\epsilon$ orbit and a $\gamma$ orbit, it is evident from the QI paths shown in Fig. 1 that the $2\alpha_{1,2} + \gamma + \epsilon$ combination frequency corresponds to the area $A_{BZ}$ of the BZ. The absence of an associated effective mass for this QI area originates from the fact that this area is independent of $\epsilon_j$. This situation, where $m_j^* = 0$, is presently unique to LaB$_6$.

While QI should be a universal feature of all MB networks, the lack of observation of QI in 3D high conductivity metals primarily concerns the difficulty in measuring the SdH effect in such systems. The SdH effect represents only a tiny fraction of the total magnetoresistance, which certainly falls within the category of high conductivity metals [13], possessing large FS sheets and low quasiparticle effective masses [10]. In such metals where conventional resistance measurements may lack the required sensitivity, the inductive technique in pulsed magnetic fields provides an alternative [14]. In a pulsed field experiment, induced eddy currents in the sample contribute to its measured magnetic moment $m$ in addition to the dHvA effect. The total induced voltage in the detection coils $V = \eta (\partial m / \partial t)$ is apparent from the oscillations measured by means of a Lakeshore Cernox resistor mounted close to the sample.

A Fourier transformation (FT) of the oscillatory magnetization on the falling field at 1.5 K is shown in Fig. 2(a). At low temperatures, where the dHvA effect dominates, the rich spectrum of frequencies originates not only from direct extremal orbits and their harmonics, but also from MB and the Shoenberg magnetic interaction (MI) effect [15]. Frequencies originating solely from MI can be identified as those corresponding to combinations of frequencies from planes intersecting the cubic BZ at different values of $k_z$; $k_z$ being the $k$ vector parallel to $B$. It should be noted that the frequencies identified with QI in Fig. 1 can also be generated by MI. Only at higher temperatures, where the dHvA oscillations become significantly damped, is MI no longer a factor. The FT of the oscillations at 50 K in Fig. 2(b) clearly indicates that the amplitudes of the dHvA contributions are considerably attenuated. The three principal frequencies that remain correspond to the QI trajectories illustrated in Fig. 1. We can discriminate between oscillations in the induced eddy currents and dHvA oscillations by observing their phase on the rising and falling magnetic fields. The dHvA magnetization is a static effect (independent of $\partial B / \partial t$), but since $\nabla \times \partial B / \partial t$, the phase of the dHvA signal reverses between rising and falling fields. This is apparent in the inset of Fig. 2(a) in which the dHvA effect dominates. On the other hand, the voltage induced from oscillations in the magnetoresistance is proportional to $(\partial B / \partial t)^2$. In this case, the induced voltage oscillations maintain the same phase irrespective of the direction of sweep of the magnetic field, as is apparent from the oscillations measured at 50 K in the inset of Fig. 2(b).

In spite of the fact that the BZ frequency is predicted to have an effective mass of zero, it is evident from Fig. 3 that all of the QI frequencies have notable temperature dependences. The amplitudes of all three frequencies change by more than 2 orders of magnitude between 20 and 70 K. Clearly this cannot be accounted for by renormalizing by the temperature dependence of $\rho$ alone. Even in the absence of a magnetic field, the resistivity changes by little more than 1 order of magnitude between

<table>
<thead>
<tr>
<th>QI frequency</th>
<th>$m^*$</th>
<th>$m'$</th>
</tr>
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<tbody>
<tr>
<td>$\alpha_{1,2} + \epsilon$</td>
<td>$m^<em>_\epsilon - m^</em><em>{\alpha</em>{1,2}} = 0.18$</td>
<td>$m^<em>_\epsilon + \frac{1}{2} m^</em><em>{\alpha</em>{1,2}} = 1.21$</td>
</tr>
<tr>
<td>$\alpha_{1,2} + \gamma$</td>
<td>$m^<em>_\gamma - m^</em><em>{\alpha</em>{1,2}} = 0.18$</td>
<td>$\frac{1}{2} m^<em>_\epsilon + m^</em><em>{\alpha</em>{1,2}} = 1.03$</td>
</tr>
<tr>
<td>$2\alpha_{1,2} + \epsilon + \gamma = BZ$</td>
<td>$2m^<em><em>{\alpha</em>{1,2}} - m^</em><em>\epsilon - m^*</em>\gamma = 0$</td>
<td>$\frac{5}{4} m^<em>_\epsilon + \frac{5}{4} m^</em><em>{\alpha</em>{1,2}} = 1.87$</td>
</tr>
</tbody>
</table>
features of the SdH effect depend on the velocity 

The essential of the energy levels is determined by the quantum lifetime is a function of the density of states. Since the broadening 

\[ \theta \propto e^2 \int \frac{d^3k}{4\pi^3} \left( -\frac{\partial f}{\partial E} \right) \nu_k \Lambda_k \] 

(2)

for the transverse conductivity, as derived from the linearized Boltzmann transport equation [3]. The essential features of the SdH effect depend on the velocity \( \nu_k \), which is a function of the density of states. Since the broadening of the energy levels is determined by the quantum lifetime \( \tau_q \), the SdH oscillations conform to the LK formalism in much the same way as the dHvA effect [8]. QI effects, on the other hand, are a manifestation of the mean free displacement \( \Lambda_k = \int_{\infty}^{\nu_k} \nu_k(t) \exp[(t - t_0)/\tau] dt [3] \), which is a summation over all possible paths throughout the MB network. Since Eq. (2) describes the semiclassical magnetotransport, \( \Lambda_k \) is determined by the transport scattering time \( \tau_q \). In Ref. [4] it was shown that QI introduces oscillatory contributions

\[ \bar{P}_j = 2\rho^n q^m \cos \phi_j \exp(-\pi/\omega_j/\tau_q) \] 

(3)

to the flux of carriers between two points. Adopting the notation developed by Falicov and Stachowiak [16], \( P = p^2 \) and \( Q = q^2 \) are the MB and Bragg reflection probabilities, respectively, and \( n \) and \( m \) are the respective number of nodes at which MB and Bragg reflection occur.

It follows from Eq. (3) that there are two contributions to the temperature dependence of the oscillations. Since the phase \( \phi_j = \hbar A_j/eB \) can be a function of \( \epsilon_k \) as well as

\[ B \]

upon integration over \( \epsilon_k \), the Fermi-Dirac distribution smears the \( \epsilon_k \)-dependent phase contributions of \( \Lambda_k \), to result in the conventional thermal damping factor \( X_j/\sinh X_j \) [15], where \( X_j = 2\pi^2 \hbar m^* T / eB (r \text{ being the harmonic index}) \). The mass enhancement due to the electron-phonon (e-ph) interaction should therefore be the same for the QI oscillations as it is for the LQ oscillations. In the quantum mechanical picture, it is well established that the (e-ph) interaction does not contribute to \( \tau_q \). Instead, the density of electronic states at the Fermi energy increases, resulting in an increase of the effective mass \( m^*_f \) relative to the band mass \( m_b \) by a factor \((\lambda + 1)\), where \( \lambda \) parametrizes the strength of the (e-ph) interaction [17]. Comparisons of the measured effective masses in LaB$_6$ with those from the calculated band structure indeed suggest a strong (e-ph) coupling [10], with \( \lambda \approx 0.53 \). Considering only the above effect of the Fermi-Dirac distribution on the QI oscillations, the solid line in Fig. 3 illustrates the temperature dependence that should be expected for the \( \alpha_{1,2} \pm \epsilon \) and \( \alpha_{1,2} + \gamma \) QI frequencies for the effective masses given in Table I [18]. Evidently, the thermal smearing effects of the Fermi-Dirac distribution are not sufficient to account for the observed temperature dependence of any of the QI frequencies, let alone that of the zero mass BZ frequency.

The second contribution to the temperature dependence originates directly from \( \tau_q \). Unlike \( \tau_q \), \( \tau_t \) includes the effects of phonon scattering. This difference originates from the fact that \( \tau_q \) represents only the quantum lifetime of electrons on closed orbits within the Landau levels and does not translate directly to the actual motion of carriers throughout the metal. Previous investigations of QI effects have been made at temperatures far below the Debye temperature, where the number of phonons is still very low [1,3,4,6,9]. While LaB$_6$ is a relatively hard
material, the resistivity in the inset of Fig. 3 indicates a notable phonon contribution to the scattering at temperatures above ~20 K [13], becoming particularly strong by 70 K. To a first approximation, the phonon-modified transport scattering rate can be estimated by applying the Drude formula \( \rho_{B=0} = m^* e^2 n \tau \), to the measured resistivity (Fig. 3 inset) in the absence of a magnetic field. For this we can assume a FS-averaged mass of \( m^* \approx 0.65m_e \), while the carrier density \( n \) corresponds to exactly one electron per unit cell. The period \( 1/\omega' = m_j' eB \) is the sum of the times taken for the carriers to complete each branch of the QI orbit. This defines a scattering effective mass \( m_j' \) which is equal to the sum of the masses of the two branches and is therefore different from the thermal effective mass \( m^*_T \). Upon incorporating the additional temperature dependence of \( \tau \), into the amplitude reduction shown in Fig. 3, the theoretical temperature dependences (shown by dotted and dashed lines) now reproduce the experimental temperature variation more closely. In this model, the temperature dependence of the induced voltage now has the form \( U \approx R_T \exp[-\pi/\omega' \tau] / \rho \). Since LaB₆ has only a very small magnetoresistance when the field is oriented along the \langle100\rangle axis [20], we have used the zero field values of \( 1/\rho \). It should be noted that the values of \( \tau \) estimated from \( \rho \) in this work were inserted directly into the above expression for \( U \) without any adjustment. In contrast, an interpretation of the “rapid oscillation” effect in LD (TMTSF)₂ClO₄ by Uji et al. [6] in terms of QI had yielded notable discrepancies between the values of \( \tau \) obtained from the temperature dependences of the QI and \( \rho \) [19]. While there are some inconsistencies with the application of the QI model to (TMTSF)₂ClO₄ (for example, this does not explain why oscillations of the same frequency appear in the magnetization [6]), LaB₆, on the other hand, has a simple 3D metallic ground state for which the FS is well understood [11–13]. One feature of our experimental results that cannot be explained by the model is the apparent loss of amplitude (of up to 40%) of the BZ frequency below 30 K. One obvious possibility is that the BZ frequency differs by only (1–2)% from the third harmonic of the \( \alpha_3 \) frequency, which is the more dominant at low temperatures and can lead to spurious amplitudes in the FT. In summary, investigations of the magnetization of LaB₆ in pulsed magnetic fields of up to 60 T reveal the presence of QI effects within the induced eddy currents. The temperature dependence of one of the frequencies, which corresponds to an area equal to that of the BZ and has a thermal effective mass of zero, requires the temperature dependence of \( \tau \) to be considered within the Boltzmann transport equation. Finally, we note that oscillations at the BZ frequency have been observed in pure Sn [21], and were attributed to Pippard’s “zone oscillation” effect [22]. The Fermi surface of Sn does, however, allow the possibility of QI, including an enclosed area equal to that of the BZ, as is the case in LaB₆. Given that the BZ frequency in Sn has been reported only in the magnetoresistance and is also observed to have an “anomalously low effective mass,” QI appears to be the more likely explanation.

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[14] This technique has recently been applied to investigate eddy-currents “resonances” in a-BEDT-TTF₂Cl₂Cl₆Hg(SCN)₄ [N. Harrison et al., Phys. Rev. Lett. 77, 1576 (1996)]. In that case, due to its high resistivity, we would not expect to see large oscillatory eddy currents. They appear due only to the near vanishing of the in-plane magnetoresistance due to the possible occurrence of the quantum Hall effect. Subsequent experiments in static fields have lent support to this explanation [N. Harrison et al., Phys. Rev. B 55, R16005 (1997)].