Fermi surface of the heavy-fermion superconductor $CeCoIn_5$: The de Haas–van Alphen effect in the normal state

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Measurements of the de Haas–van Alphen effect in the normal state of the heavy-fermion superconductor $CeCoIn_5$ have been carried out using a torque cantilever at temperatures ranging from 20 to 500 mK and in fields up to 18 T. Angular-dependent measurements of the extremal Fermi surface areas reveal a more extreme two-dimensional sheet than is found in either $CeRhIn_5$ or $CeIrIn_5$. The effective masses of the measured frequencies range from 9 to $20m^*/m_0$.

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I. INTRODUCTION

The compounds $CeMIn_5$ (M=Co, Ir, Rh) are a fascinating family of heavy-fermion superconductors.[1,2] These materials crystallize in the tetragonal $HoCoGa_5$ structure and are built of alternating stacks of $CeIn_3$ and MIn_2. The compounds $CeCoIn_5$ and $CeIrIn_5$ have superconducting transition temperatures of 2.3 K and 0.4 K, respectively, whereas $CeRhIn_5$ orders antiferromagnetically at 3.8 K at ambient pressure, but applied pressures of order 16 kbar can induce an apparently first-order transition from the magnetically ordered state to a superconducting one with $T_c = 2.1$ K. Below 1.4 K the transition from the normal state to the superconducting state as a function of magnetic field in $CeCoIn_5$ has been found to be first order at ambient pressure.[3] The particular attraction of these materials, then, is that not only do they represent a substantial increase in the number of known heavy-fermion superconductors, but they also appear to be quasi-two-dimensional (quasi-2D) variants of $CeIn_3$, an ambient-pressure antiferromagnet in which superconductivity can be induced at 25 kbar and 200 mK (Ref. 4) and have properties of unconventional superconductivity. Movshovich *et al.*[5] have shown a power-law temperature dependence in the specific heat and thermal conductivity suggesting strongly that the superconductivity in $CeCoIn_5$ is unconventional. If one can demonstrate that the reduced dimensionality is responsible for the factor of 10 increase in superconducting T_c, the impact of these compounds on the physics of superconductivity will far exceed that of just another family of heavy-fermion superconductors.

As a first step in determining the dimensionality and nature of the electronic structure in $CeCoIn_5$ we report the results of de Haas–van Alphen (dHvA) measurements that show the quasi-2D nature of the Fermi surface (FS) as well as the large effective masses of electrons on this FS. We also compare our results to previously reported dHvA studies of $CeRhIn_5$ (Ref. 6) and $CeIrIn_5$ (Ref. 7).

II. MEASUREMENTS

The measurements reported here were performed at the National High Magnetic Field Laboratory, Tallahassee, FL, using a rotating torque cantilever magnetometer designed for operation at low temperatures between 20 and 500 mK in applied fields ranging from 5 to 18 T. Complete field rotations in the [100] and [001] planes of the tetragonal structure were made, and temperature-dependent measurements of the dHvA amplitudes were studied.

The sample was grown from an In flux[8] and etched in a 25% HCl in H_2O solution down to a small plate that was mounted on the cantilever with GE varnish. The sample was mounted in multiple orientations with respect to the cantilever to remove any possibility of systematic instrumental error which might affect frequency and mass determinations.

In the dHvA measurements the oscillatory part of the magnetization of the sample is measured as a function of field. The resulting signal is periodic in $1/B$. This oscillatory magnetization $\tilde{M}$ is given by the Lifshitz-Kosevitch (LK) equation (see Ref. 9 for the mathematical details)

$$\tilde{M} = -2.602\times 10^{-6}\left(\frac{2\pi}{HA''}\right)^{1/2}\frac{\Gamma F T \exp(-\alpha p x/H)}{p^{3/2}\sinh(-\alpha p T/H)} \times \sin\left[\left(\frac{2\pi p F}{H}\right) - \frac{1}{2} \pm \frac{\pi}{4}\right], \quad (1)$$

where $\alpha = 1.47(m/m_0)\times 105$ G/K, A'' is the second derivative of the area of the FS cross section that is perpendicular to the applied field, Γ is the spin reduction factor, p is the harmonic number, and x is the Dingle temperature. The frequencies of the dHvA oscillations are proportional to extremal areas of the FS. Applying this formula to extract the FS properties of a heavy-fermion material presents no new complications.[10]

The measured signal from the torque cantilever is a voltage proportional to the gap between the flexible cantilever plate to which the sample is attached and a fixed (reference) plate. The total gap separation is measured as a capacitance using a precision capacitance bridge that can detect changes to better than 1 part in 10^6. The measured oscillations in the torque arise from anisotropy in the Fermi surface, such that

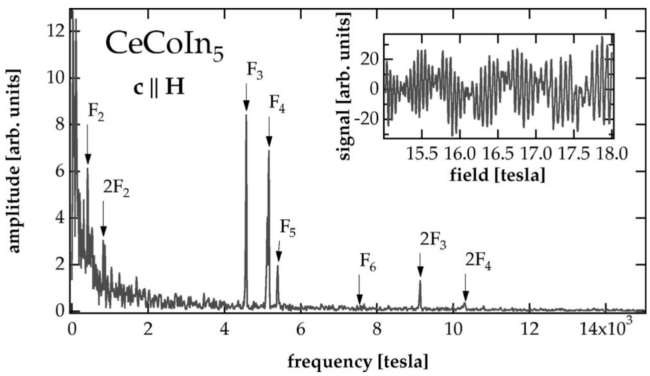

FIG. 1. The Fourier spectrum of the dHvA oscillations shown in the inset for the applied field along [001]. Six fundamental frequencies and associated harmonics are observed.

$$\tilde{\tau} = \frac{-1}{F}\frac{dF}{d\Theta}\tilde{M}HV, \tag{2}$$

where F is the dHvA frequency, Θ is the angle of the applied field, $\tilde{M}$ is the LK expression above, and V is the volume of the sample. It should be noted that for field directions near high symmetry axes where extremal FS areas go through maxima or minima such that $dF/d\Theta$ becomes small, the signals measured with a torque cantilever also become small.

III. RESULTS

For the field directed along the [001] axis oscillations are clearly seen at the lowest temperatures (20 mK) as shown in Fig. 1 along with a fast Fourier transform (FFT) of the data. The frequencies of these oscillations are listed in Table I. As the field is rotated away from the [001] the signals become stronger due to the larger values of $dF/d\Theta$ away from the axis. The determination of the dHvA frequencies for angles between [001] and [100] and between [001] and [110] was possible with the results displayed in Fig. 2. The masses for the field applied along the [111] where $dF/d\Theta$ is large were measured and had values from nearly $9m^*/m_0$ to $20m^*/m_0$. The effective masses for carriers on three orbits for the field applied along the [111] were determined, the results of which are summarized in Table II. Mass determinations for the

TABLE I. Measured dHvA frequencies for CeCoIn$_5$ with B along [001]. Both F_1 and F_6 are difficult to see in this FFT. The amplitude of F_1 grows with increasing angle. F_6 is also more evident at the higher angles, but it is observable in this data set if the high-field data are analyzed apart from the low-field part of the sweep.

Symbol	F (T)
F_6	7535
F_5	5401
F_4	5161
F_3	4566
F_2	411
F_1	267

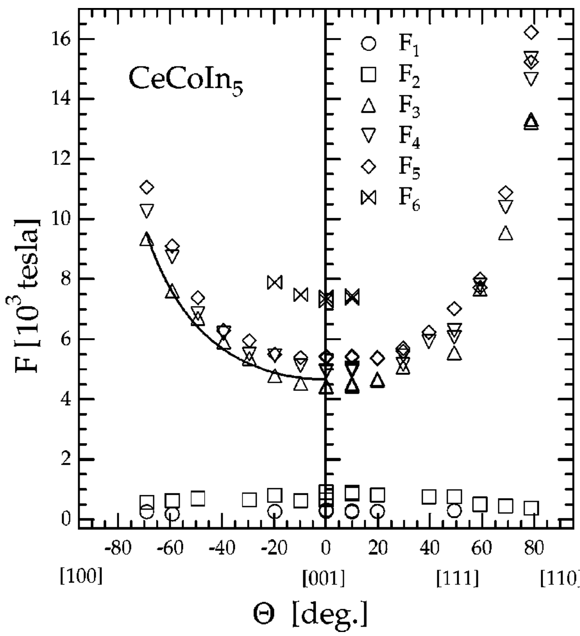

FIG. 2. The angular dependence of the dHvA frequencies for CeCoIn$_5$ is shown here for rotations around [001]. The solid line shows a fit to the expected $1/\cos\Theta$ dependence for a 2D FS. The low frequencies are due to small 3D ellipsoidal pockets.

[100] and [001] principles axes were not possible in these measurements due to a near zero slope in the frequency versus angle plots that causes very small signals and a rapidly diminishing signal with increasing temperature. This temperature behavior is the signature for high effective masses as the high masses in Table II illustrate.

IV. DISCUSSION

The dHvA measurements on CeIrIn$_5$ (Ref. 7) and CeRhIn$_5$ (Ref. 6) find multiple branches for rotations in the [001]-[100] and [001]-[110] planes of the tetragonal structure. Most of these branches are associated with large quasi-2D undulating cylinders that show the expected $1/\cos(\theta)$ dependence with θ being the angle at which the field is applied away from the [001] axis. Band structure calculations, in both Refs. 7 and 6, show, in addition, that several small pieces of FS should exist in both CeRhIn$_5$ and CeIrIn$_5$.

We find a very similar situation in CeCoIn$_5$ in that the F_3, F_4, and F_5 branches in Fig. 2 are closely spaced in frequency, corresponding to extremal areas on an open 2D undulating cylinder extending along the [001] direction. However, fewer frequencies are observed for CeCoIn$_5$ than was

TABLE II. Measured masses for dHvA frequencies for CeCoIn$_5$ with B along [111].

Symbol	F (T)	m^*/m_0
F_4	6064	20.3 $\pm$ 0.7
F_3	5550	11.2 $\pm$ 0.2
F_2	760	8.7 $\pm$ 2.2

the case for $CeRhIn_5$ (Ref. 6) or $CeIrIn_5$ (Ref. 7). Some of the frequencies observed in these two cases are attributed to holes in the cylinders and the band structure calculations bear out this assignment. Because the mass enhancements expected in all of these materials are comparable, based on heat capacity data,[11] the reduced number of observed frequencies seen here cannot be attributed to particularly heavy carriers in $CeCoIn_5$. The cylindrical surface in $CeCoIn_5$ appears to be closed with no holes and much more 2D like than in either of the other two cases. The fact that we observe three closely spaced frequencies for the field applied along [001] indicates that there are small undulations on this cylinder giving rise to the three extremal areas. Based on comparisons of the observed closely spaced frequencies near 6000 T, the magnitude of this undulation in $CeCoIn_5$ is approximately 50% less than that observed in $CeRhIn_5$ and $CeIrIn_5$. In addition, the number of low frequencies in $CeCoIn_5$ is much smaller than in either the Rh or Ir analogs, so there are a smaller number of electrons exhibiting 3D behavior.

These results indicate that many of the transport properties and cooperative phenomena that are seen in $CeCoIn_5$ should be much more 2D in character than those found in either $CeRhIn_5$ or $CeIrIn_5$. The fact that the T_c in $CeCoIn_5$ is 5 times higher than that observed in $CeIrIn_5$ would suggest that the increasingly two-dimensional electronic structure has a direct correlation with enhanced T_c. Studies of the Fermi surface of $CeRhIn_5$ at pressures adequate to produce superconductivity would be valuable in confirming this supposition because the T_c of $CeRhIn_5$ under pressure is comparable to that of $CeCoIn_5$.

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