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High magnetic field investigation of the Fermi surface of the pnictinide compound $SmSb_2$

C H Mielke†, N Harrison†, A H Lacerda†, S A Bud'ko‡§ and P C Canfield‡

† Los Alamos National Laboratory, Los Alamos, NM 87545, USA

‡ AMES Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA

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Abstract. The Fermi surface of the pnictinide compound $SmSb_2$ has been studied by means of the Shubnikov–de Haas and de Haas–van Alphen quantum oscillatory effects in pulsed magnetic fields to 60 T. Spectral analysis of the magnetoresistance and magnetization shows several closed-pocket regions of the Fermi surface. Closed pockets of 65, 190, 700, and 760 T are determined to account for the Fermi surface. The respective effective masses were found to be of the order of the free electron mass.

The rare earth diantimonide family, RSb_2 (where R = La, Ce, Pr, Nd, Sm) [1], exhibits a variety of interesting magnetic properties, including superconductivity, antiferromagnetism, and metamagnetic transitions [2, 3]. In $LaSb_2$ a superconducting transition [2] occurs at $T = 400$ mK, while the diantimonide compounds containing Pr, Nd, and Sm, all undergo antiferromagnetic (AF) ordering at 5.5, 7.0, and 12.6 K respectively.

In this report we present details of the Fermi surface of the R = Sm member of this family. These high-quality single crystals are anisotropic layered systems with typical residual resistivity ratios (RRR) of ≈500. The large RRR and high quality of the single crystals make them good candidates for the observation of quantum oscillations. Little is presently known about the Fermi surfaces of the diantimonide family of compounds. Clear Shubnikov–de Haas (SdH) and de Haas–van Alphen (dHvA) oscillations are observed at high magnetic fields in $SmSb_2$. The range of measured dHvA and SdH frequencies are from 65 to 835 T, which is much smaller than expected from a conventional metal with a Brillouin zone of order 20 000 T. From the temperature dependence of the quantum oscillation amplitude we have determined that the quasiparticle effective masses are of the order of the free electron mass.

Single crystals of $SmSb_2$ were mounted with the c-axis parallel to the applied field ($c \| \boldsymbol{H}$). The electrical contacts were formed with 25.4 μm gold wires held in place with conductive silver paste on sputtered gold pads. The contact arrangement was in the standard four-wire resistivity configuration with the current flowing within the a–b plane of the sample. The transport measurements were performed using an rf lock-in detector at a frequency of 511 kHz. The sample was held in place with epoxy to prevent movement during the magnetic field pulse.

The magnetization measurements employed the compensated-coil detection technique [4]. In this case the sample was placed on the end of the magnetization coil and

§ Present address CBPF/CNPq, DME, Rio de Janeiro, RJ, Brazil 22290-180.

held in place with vacuum grease. Both the transport and magnetization measurements were performed in a plastic ^{3}He refrigerator with the samples in contact with liquid ^{3}He. The base temperature of the ^{3}He refrigerator was approximately 400 mK. Capacitor driven 50 and 60 T pulsed magnets at the National High Magnetic Field Laboratory, Los Alamos facility, with rise times of 6.5 ms, were used in this investigation.

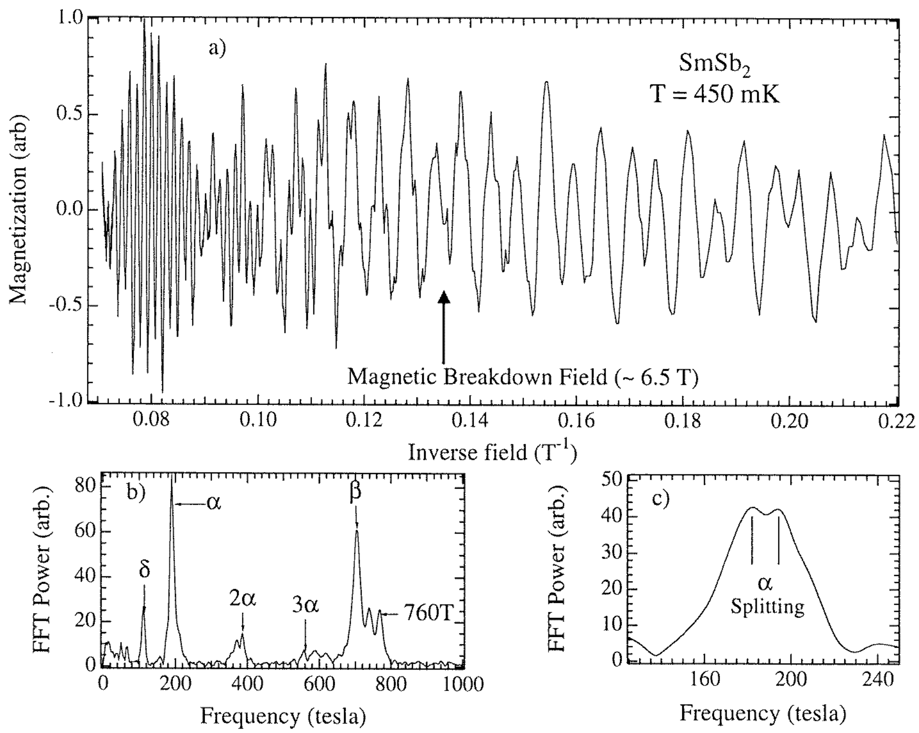

Figure 1. (a) Clear de Haas–van Alphen oscillations are shown for fields between 4.5–15 T. A breakdown orbit is seen emerging at approximately 6.5 T. (b) Spectral analysis of the dHvA oscillations of the above trace show many closed pockets and harmonics of the α orbit. (c) Splitting of the α frequency is due to the neck and belly orbits of the modulated 2D Fermi surface. The splitting is resolved by analysing the dHvA data between 4 and 41 T.

Pulsed field magnetization measurements (see figure 1) show the dHvA oscillations beginning at fields as low as 4 T (dHvA oscillations have been observed at fields as low as 1.5 T in SQUID results in [3]). Spectral analysis of the magnetization data reveals frequencies of 115, 190, 700, and 760 T, which we have labelled δ, α, β, and γ respectively. Higher harmonics of the 190 T fundamental are also observed, as is evident in figure 1(b). Although the γ orbit is equal in frequency to the 4α harmonic it is a separate orbit; this determination is presented later. Splitting of the peaks is observed in the harmonics and in the fundamental by application of more intense fields. A splitting of 13 ± 2 T is shown in the power spectrum of figure 1(c) for the fundamental orbit. The higher harmonics show splitting corresponding to $p \times 13$ T, where p is the harmonic index. The peak splitting is an indication of the degree of warping of a 2D Fermi surface where the frequencies correspond to maxima and minima (neck and belly) orbits of the modulated Fermi tube. The 700 T (β) orbit may be due to magnetic breakdown phenomena since the β frequency appears at higher fields and the amplitude of the β orbit grows more rapidly than the α orbit as the field intensity is increased. dHvA results from 4.5 to 15 T are shown in figure 1(a) which clearly indicate a higher frequency emerging at approximately 6.5 T. If the energy gap between adjacent closed orbits is small enough for the carriers to hop across, a new breakdown orbit can be formed. The probability of breakdown [5] is

$$P = \exp \frac{\pi E_g^2}{4\hbar\omega_c \sin 2\Theta\epsilon_F} \equiv \exp \frac{-B_0}{B} \qquad (1)$$

where $\omega_c = eB/m^\star$, 2Θ is the Bragg reflection angle, $m^\star$ is the effective mass, E_g is the energy gap between the adjacent Fermi surfaces, and B_0 is the breakdown field. At fields above 20 T the α frequency becomes strongly attenuated and the β frequency dominates the power spectrum. The low frequencies present in the magnetization data (figure 1(b)) suggest that the Fermi surface contains several small pockets. Figure 1(a) indicates that the breakdown field is $\approx 6.5 \pm 1$ T, while $m^\star$ is determined by fitting the temperature dependence of the quantum oscillations to a functional form originating from the Lifsitz–Kosevich [6] equation:

$$R_T(T) \propto \lambda\left(\frac{m^\star}{m_0}\right)\frac{T}{B}\bigg/\sinh\left(\lambda\left(\frac{m^\star}{m_0}\right)\frac{T}{B}\right) \qquad (2)$$

where R_T is the amplitude of the quantum oscillations as a function of temperature and $\lambda = 2\pi^2 m_0 c k_B e\hbar = 14.69T/\mathrm{K}$ is a constant. Magnetoresistance measurements at finite angles provide information on the dimensionality of the Fermi surface. Figure 2 shows angular dependence measurements which are in good agreement with a $1/\cos(\theta)$ fit, where θ is the axis normal to the field direction, shown in the inset to figure 2. A $1/\cos(\theta)$ dependence is expected for a 2D Fermi surface. These results are consistent with earlier magnetic anisotropy [3] studies which also found a 2D nature of the Fermi surface. Equation (2) provides an accurate determination of $m^\star$ in the limit that the 2D Fermi surfaces are warped and the spacing between the Landau levels is small compared to the degree of warping. In this limit several Landau tubes permeate the warped Fermi surface. Equation (2) was originally derived [6] for the case of a metal with a three-dimensional Fermi surface. It is appropriate, however, in certain cases of anisotropic materials with a large ratio of warping to Landau level spacing. Using equation (2) the effective masses are listed in table 1.

Table 1. The effective masses in $SmSb_2$ in units of m_e.

	Frequencies (T)						
Method	65	120(δ)	190(α)	380(2α)	700(β)	760(γ)	835
dHvA	—	—	0.707	1.39	1.25	1.18	—
SdH	1.00	0.98	0.630	—	1.08	1.23	1.09

The condition for magnetic breakdown is that $\hbar\omega_c \gtrsim E_g^2/\epsilon_F$. By using the α frequency and the corresponding $m_\alpha^\star \approx 0.65 m_e$ an approximation for ϵ_F is made. Assuming a quadratic potential $\epsilon_F = \hbar eF/2m^\star c$, where F is the quantum oscillation frequency in inverse field space. The effective Fermi energy is $\approx 15 \pm 1$ meV where this quantity represents the kinetic energy associated with α orbit quasiparticles. The energy gap (E_g) between adjacent Fermi surfaces can also be estimated by using the breakdown condition, resulting in $E_g \approx 3.3 \pm 0.2$ meV.

The zero-field temperature sweep (figure 3(c)) shows a sharp transition at 12.6 K, similar to data in Bud'ko *et al* [3]. A clear antiferromagnetic transition [3] was detected

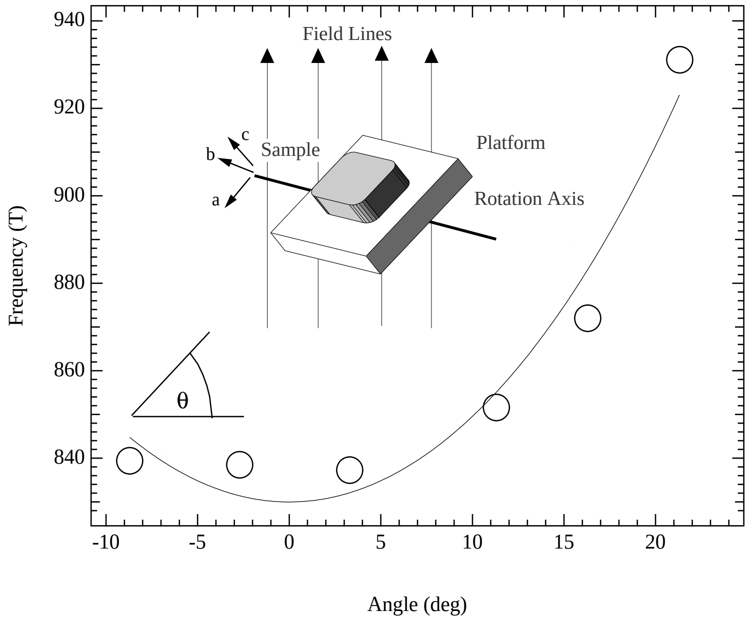

Figure 2. The angular dependence of the frequency of the quantum oscillations is fit to a $1/\cos(\theta)$ function. This angular dependence is consistant with that of a 2D Fermi surface. The inset shows the orrientation with respect to the applied magnetic field.

by use of a SQUID magnetometer. The sharp decrease in zero-field resistivity is due to suppression of spin disorder scattering that occurs at temperatures above the AF transition (T_N). Magnetotransport experiments (see figure 3(a)) clearly show Shubnikov–de Haas oscillations and a strong negative slope [7] in the magnetoresistance at temperatures below T_N and fields above 17 T.

The spectral analysis of the SdH oscillations differ from the dHvA results. It is clear that the β frequency is not as strong as the γ (760 T) peak in the magnetotransport results. Also, the transport spectrum indicates a peak at 835 T that is absent in the dHvA results. The existence of magnetic breakdown and the presence of a spectral feature occurring only in the magnetotransport indicates that Stark quantum interference (SQI) is occurring between adjacent regions of the Fermi surface. SQI is a phenomena that occurs in transport only [8, 9, 10]. At high magnetic fields the γ orbit is very intense in both dHvA and SdH experiments. The γ frequency is coincidental with the fourth harmonic of the α frequency. In the Lifsitz–Kosevich formalism the pth harmonic amplitude is suppressed by an exponential damping factor and $m^\star_{p\alpha}$ is increased by a factor of p, such as in our results for α and 2α. Since $m^\star_\gamma$ ($\approx 1.2m_e$) is not close to $m^\star_{4\alpha}$ ($\approx 2.4m_e$) it is reasonable to assume it is a seperate orbit. A very small pocket at $\approx$65 T is very strong in the high-field transport results and also appears in the magnetization at fields above 20 T. The effective mass of the quasiparticles occupying the 65 T orbit was determined by the SdH effect to be $1.00m_e \pm 0.02$. The high intensity of this spectral feature overpowers the δ frequency and prevents us from making a reliable estimate of $m^\star_\delta$.

In this report we have presented magnetotransport and magnetization results at very low temperatures and very high magnetic fields in $SmSb_2$. These results demonstrate the basic energy structure of one of the members of the diantimonide family at very high magnetic

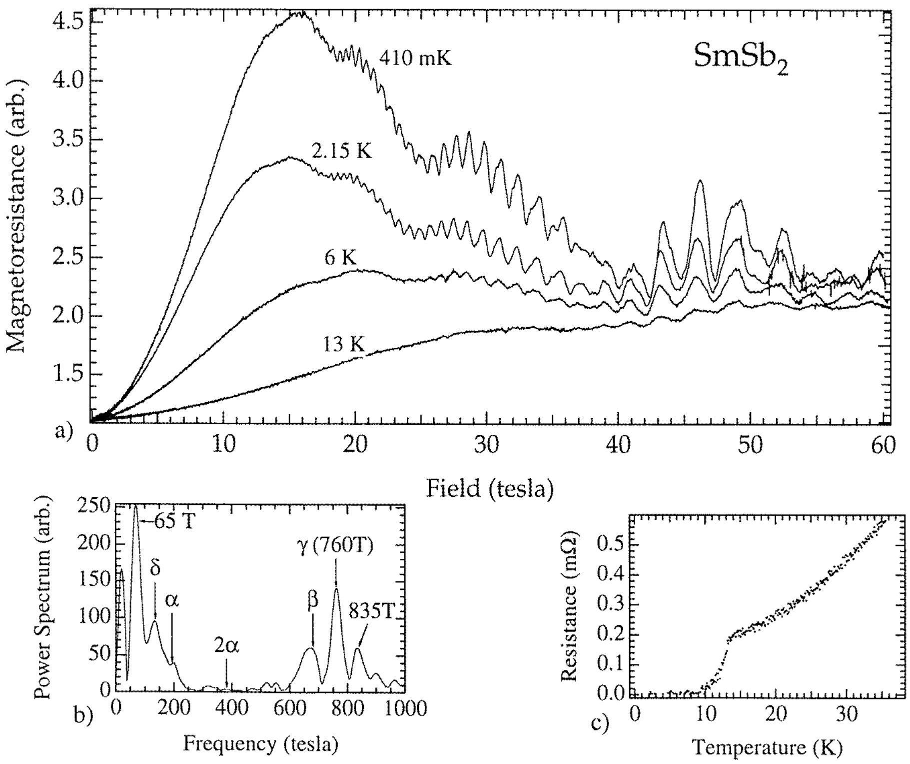

Figure 3. (a) Magnetoresistance of SmSb$_2$ at various temperatures to 60 T. The strong negative slope of the magnetoresistance is due to suppression of the antiferromagnetic ground state. (b) The spectral analysis of the SdH quantum oscillations between 15 and 60 T. (c) The temperature dependence of the resistance showing T_N at ≈12.6 K.

field. Our results indicate that the Fermi surface of SmSb$_2$ consists of several closed pockets. It is also shown that magnetic breakdown and quantum interference effects occur at very high magnetic fields in the titled compound. Without the complete bandstructure calculations we cannot precisely determine the origin of the γ orbit, however our results indicate that it is a separate closed pocket and not the fourth harmonic of the α orbit. The high-field results have not only provided us with indications of the effective carrier mass but also give us insight into the interaction of the antiferromagnetic ground state with magnetotransport at very high magnetic fields. Based on the rare earth constituent and approximate size of the Brillouin zone in SmSb$_2$ [11], frequencies higher than an order of magnitude would be expected for this compound. The α orbit is approximately 1% of the FBZ while the β orbit is ≈3.5% of the FBZ. Further investigation is needed to determine the nature of this phenomena.

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