

Fermi surface and heavy quasi-particles of URu₂Si₂

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Abstract

We present Shubnikov–de Haas measurements performed on two samples of URu₂Si₂ (I||c and I||a) in magnetic fields up to 24 T and at temperatures down to 60 mK. Four different energy bands could be determined between the [0 0 1]–[1 0 0] and the [1 0 0]–[1 1 0] directions of the tetragonal structure. Their corresponding cyclotron masses range between 5.8*m_e* and 13.0*m_e*. The measured Fermi surface is compared to available band structure calculations. Surprisingly, for magnetic fields oriented in the tetragonal plane, a nonlinear splitting of the 1.2 kT frequency could be discerned in the field range between 17 and 21 T. © 1998 Elsevier Science B.V. All rights reserved.

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The heavy fermion compound URu₂Si₂ is extensively studied as it exhibits two successive phase transitions into an antiferromagnetic (AF) state at $T_N = 17.5$ K [1] and into a superconducting state at $T_c = 1.5$ K [2]. Magnetization measurements in pulsed fields [3, 4] have revealed the presence of a three-step magnetization process at 35.8, 37.3 and 39.4 T. A model of a frustrated magnetic constellation [4] with the AF state as the zero field ground state has been proposed to account for these three high field transitions. Also magnetoresistance and Hall effect measurements [3] performed in pulsed fields present huge anomalies at the field values of the three-step magnetic transitions, possibly indicating significant changes in the quasi-particle excitation spectrum. Some pre-cursor effects of these transitions can already be seen in the field range between 20 and 24 T. Recently, it has been demonstrated that quantum oscillations in the magnetoresistance [5] can be observed for URu₂Si₂.

In this study, we present measurements of the Shubnikov–de Haas (SdH) effect extended up to 24 T. The aim of this study was to study the topology of the Fermi

surface and to search for pre-cursor effects of the high field transitions in the field range 20 and 24 T.

Experiments were performed on two rectangular shaped single crystals of URu₂Si₂ which were cut by means of spark-erosion from a Czochralski grown single crystalline batch. The samples had their principle axis along a [0 1 0] (sample #1) and a [0 0 1] direction (sample #2). Standard four point resistivity measurements were performed on both of the samples at a base temperature of 60 mK and in magnetic fields up to 24 T. We observed pronounced SdH oscillations on both of the URu₂Si₂ samples (see insert Fig. 1). Without further treatment, already three different frequencies can be identified. We applied the standard theoretical description of SdH conductivity oscillations [6] assuming strongly renormalized Fermi-liquid behaviour of the quasi-particles well below the characteristic temperature (~ 10 K for URu₂Si₂). The data was Fourier transformed in the total and restricted field ranges of $\Delta B = 3$ T width. From the Fourier spectra obtained (see Fig. 1) aspects of the topology of the Fermi surface and the cyclotron masses of the corresponding orbits were determined. Four pronounced frequencies can be observed at 0.07, 0.15, 0.26 and 1.2 kT at $\theta = 10^\circ$ away from the [1 0 0]-axis in the {0 1 0}-plane which are in agreement with the measurements by Julian et al. [5]. The largest orbit f_1 , which covers

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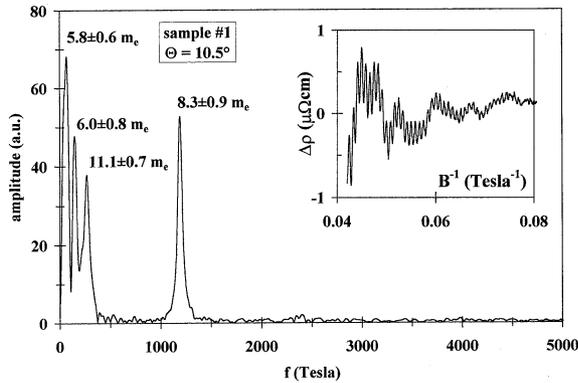


Fig. 1. Calculated Fourier spectrum of Shubnikov–de Haas oscillations measured on URu₂Si₂ (sample #1) at 90 mK and at $\Theta = 10.5^\circ$ away from the [1 0 0] axis. Inset: measured magnetoresistance oscillations on sample #1 at $\Theta = 10.5^\circ$.

a Fermi-surface area of 4.7% of the Brillouin zone, exhibits a cyclotron mass of $5.8 \pm 0.6 m_e$. The largest mass of $m_3^* = 11.1 \pm 0.7 m_e$ is observed for the frequency $f_3 = 0.28$ kT. The cyclotron masses determined for all the four frequencies range between these two values (see Fig. 1). The angular variation of the cyclotron frequencies as determined from the Fourier transformed data is reported in Fig. 2. The only noteworthy angular variation can be observed for the frequency f_4 . Otherwise the orbits of the Fermi surface seem to be essentially spherical. The two frequencies f_2 and f_3 seem to join or cross at an angle of about $\Theta \approx 60^\circ$ in the [1 0 0]–[0 0 1] plane. However, we do not have enough data points to clarify this behaviour. We assume the cyclotron frequency at about 2.4 kT to be the second harmonic of the f_4 frequency.

Band structure calculations [7] show two electron sheets around the Γ -point and two hole sheets around the Z-point in reciprocal space. Compared to our experimental results only the smallest electron sheet around the Γ -point can be identified with the f_2 frequency. However, the band structure calculations were not performed for an antiferromagnetic ground state and therefore cannot completely account for the experimental situation.

Finally, we would like discuss the field dependence of the f_4 cyclotron frequency and its corresponding mass for fields oriented in the tetragonal plane. Surprisingly, at a magnetic field of 17 T the cyclotron frequency at 1.2 kT splits into two branches and they join again at about 21 T (see Fig. 3). For fields oriented between the [1 0 0] and the [0 0 1] directions (sample #1) no such splitting could be observed. The corresponding cyclotron mass also shows such a significant suppression of its value in the 17–21 T field range. This kind of nonlinear field dependence of the cyclotron frequency and mass cannot be explained by a magnetic breakdown or an internal magnetization effect.

A more detailed analysis of our data will be published elsewhere [8].

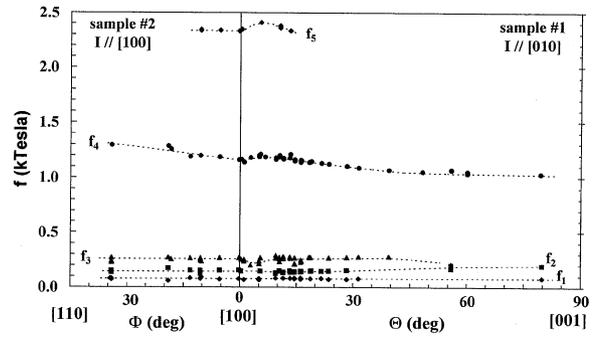


Fig. 2. Angular variation of the cyclotron frequencies for the rotation of the magnetic field in the {0 1 0} and the {0 0 1} plane. Four different frequencies could be discerned in the calculated Fourier spectra. In the high field range (20 to 24 T) a second harmonic of the 1.2 kT frequency can be identified.

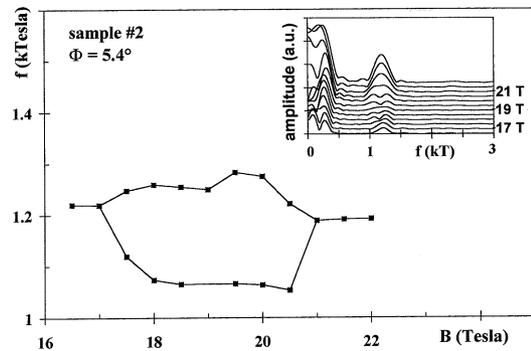


Fig. 3. The f_4 frequency at $\Phi = 5.4^\circ$ away from the [1 0 0] direction in the tetragonal plane (sample #2) exhibits a nonlinear frequency splitting in the field range of 17 to 21 T. The insert shows the calculated Fourier spectra for field intervals of $\Delta B = 3$ T around the average field.

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