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### Authors

Haanappel, EG  
Hedderich, R  
Joss, W  
et al.

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# De Haas–van Alphen effect in CeB<sub>6</sub> in fields up to 52 T

## Reduction of the cyclotron mass and new frequencies

E.G. Haanappel<sup>a</sup>, R. Hedderich<sup>a</sup>, W. Joss<sup>a</sup>, S. Askenazy<sup>b</sup> and Z. Fisk<sup>c</sup>

<sup>a</sup>Hochfeld–Magneilabor, Max Planck Institut für Festkörperforschung, BP 166, 38042 Grenoble Cedex 9, France

<sup>b</sup>Service des Champs Magnétiques Intenses, INSA-CNRS, Avenue de Rangueil, 31077 Toulouse, France

<sup>c</sup>Los Alamos National Laboratory, Los Alamos, NM 87545, USA

The de Haas–van Alphen effect is used to study CeB<sub>6</sub> in pulsed fields up to 52 T. Two cyclotron orbits are observed; a previously unreported orbit may be due to magnetic breakdown. The cyclotron masses corresponding to these orbits decrease with increasing field.

### 1. Introduction

CeB<sub>6</sub> is a well studied Kondo lattice with a number of interesting properties. The linear coefficient  $\gamma$  of the low temperature specific heat is very large:  $\gamma \approx 250 \text{ mJ}/(\text{mol K}^2)$ , indicating a large density of states at the Fermi energy. For comparison, the reference compound LaB<sub>6</sub>, which differs from CeB<sub>6</sub> by the absence of the 4f-electron, has a  $\gamma$  which is two orders of magnitude lower:  $\gamma \approx 2.5 \text{ mJ}/(\text{mol K}^2)$ .

The first to perform a de Haas–van Alphen (dHvA) study of CeB<sub>6</sub> were Van Deursen et al. [1, 2]. These measurements were done in pulsed fields up to 40 T. It was found that the Fermi surface of CeB<sub>6</sub> was very similar to the Fermi surface of LaB<sub>6</sub> (Arko et al. [3]), indicating that the additional f-electron is localized rather than itinerant. This conclusion is confirmed by the band structure calculations of Norman and Min [4].

The electron cyclotron mass  $m^*$  can be deduced from the temperature dependence of the amplitude of the dHvA oscillations. Van Deursen found a value of the cyclotron mass of  $(6 \pm 2) m_e$  at a field of 30 T. This value is much larger than the cyclotron mass of LaB<sub>6</sub> ( $m^* = 0.61 m_e$  for LaB<sub>6</sub> [3]) but still an order of magnitude too small to explain the large value of  $\gamma$ .

This discrepancy was resolved by the observation of Joss et al. [5] that the cyclotron mass strongly depends on the magnetic field. Joss reported a value of  $m^* = 20 m_e$  at a field of 10 T, decreasing to  $m^* = 10 m_e$  at 20 T. From measurements of the specific heat of CeB<sub>6</sub> in relatively low magnetic fields (Marcenat [6] and Bredl [7]) and in fields up to 22 T by Müller et al. [8] a similar decrease is deduced.

In this paper we report measurements of the dHvA effect in CeB<sub>6</sub> in pulsed fields up to 52 T. The main features of the dHvA spectrum are the same as in refs. [1, 2, 4], but also a new orbit is observed. The cyclotron mass decreases further to a value of about  $3 m_e$  at  $B = 47 \text{ T}$ . The dHvA signal seems to vanish at temperatures above 2.3 K; the origin of this phenomenon is not fully understood.

### 2. Experimental procedure

Since the magnet has an inner diameter of only 10 mm, experimental space is very limited. A liquid <sup>4</sup>He cryostat with a tail section of 6 mm inner diameter fits into the magnet. By pumping on the <sup>4</sup>He bath a lowest sample temperature of 1.9 K can be maintained. The temperature is measured with a Lake Shore DT470 diode,

which is mounted as close as possible to the sample. A silicon diode is not suited for use in a magnetic field, but for pulsed field applications this is no problem.

The dHvA oscillations are detected by a pick-up system consisting of two coils, which are identical within 0.5%. Each coil has 200 turns of 50  $\mu\text{m}$  copper wire. The rectangular CeB<sub>6</sub> sample (typical dimensions  $0.6 \times 0.6 \times 3 \text{ mm}^3$ ) is mounted in one of the coils with the field along the [100] direction; the other coil remains empty. The sample orientation cannot be changed. The signals of both coils are subtracted in an electronic bridge circuit. Fine compensation is done with potentiometers. The difference signal is amplified by a gated low-noise amplifier.

The magnetic field is measured by integrating the signal induced in a field pick-up coil (100 turns,  $\phi = 5 \text{ mm}$ ) wound around the sample holder.

The dHvA signal and the field signal are both converted to a numerical value by a transient recorder, which samples the signals at a maximum frequency of 200 kHz and with a resolution of 16 bit. After the measurement the numeric data is transferred to the computer via the IEEE-bus.

### 3. Results and discussion

Clear dHvA oscillations are observed at nine temperatures in the range 1.9–2.3 K and in the field range 30–52 T. As a result of the large cyclotron masses involved the signal-to-noise ratio is deteriorating rapidly with increasing temperature or decreasing field. A typical dHvA signal is shown in fig. 1(a) with the corresponding Fourier transform in fig. 1(b). As the measuring system is not very sensitive to low frequencies, we will concentrate on the high frequency part of the spectrum. The dHvA spectrum is dominated by a frequency of 8670 T. This frequency corresponds to the X-point centered belly orbit, which was already studied by Van Deursen et al. [2] and by Joss et al. [5]. Following their notation we will refer to this orbit as the  $a_3$  orbit. Also the second harmonic corresponding to the  $a_3$  orbit is

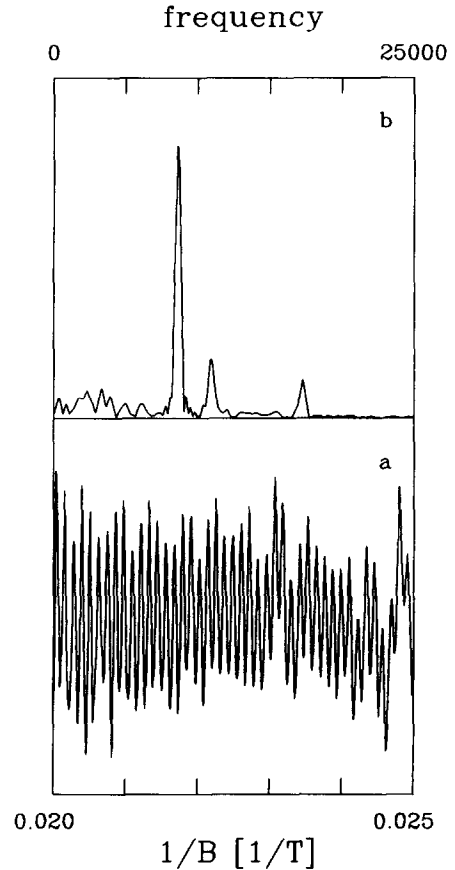


Fig. 1. (a) dHvA oscillations of CeB<sub>6</sub> between  $B = 40 \text{ T}$  and  $B = 50 \text{ T}$ . The sample temperature is 1.99 K. (b) Fourier transform of the signal shown in (a).

observed at  $F = 17\,300 \text{ T}$ . A third peak is observed at  $F = 11\,000 \text{ T}$ . This peak corresponds to an orbit with very high cyclotron mass and is only observed at the highest field values, which accounts for the fact that it has not been reported before. A similar orbit is observed in LaB<sub>6</sub> [3] and is ascribed to magnetic breakdown. If the orbit we observe is also due to magnetic breakdown, then it will not even exist at lower fields.

The cyclotron mass is determined in the usual way by fitting the observed temperature dependence of the dHvA amplitude to the Lifshitz–Kosevich formula. As an example the temperature dependence of the dHvA amplitude of the  $a_3$  orbit is shown in fig. 2. For all three fre-

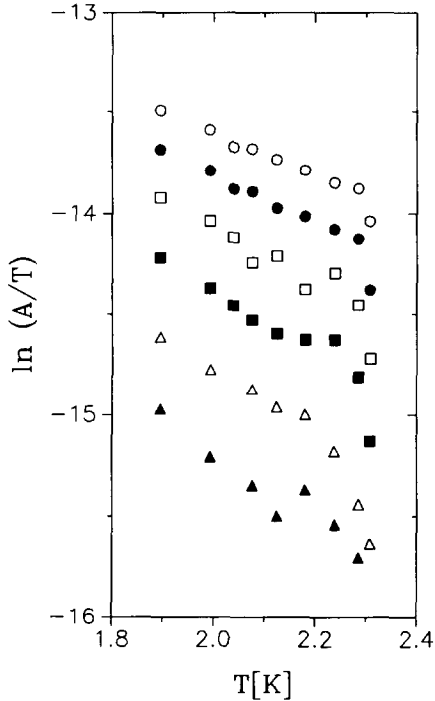


Fig. 2. Temperature dependence of the amplitude of the dHvA frequency of 8670 T. The different symbols correspond to different mean magnetic fields: (○)  $B = 46.9$  T; (●)  $B = 43.4$  T; (□)  $B = 40.4$  T; (■)  $B = 37.8$  T; (△)  $B = 35.5$  T; and (▲)  $B = 33.5$  T.

quencies the cyclotron masses are given in table 1. For the  $a_3$  orbit the mass decreases from  $m^* = (4.34 \pm 0.13)m_e$  at  $B = 37.8$  T to  $m^* = (3.06 \pm 0.13)m_e$  at  $B = 46.9$  T. The second harmonic has a mass twice as large, as should be the case.

A striking feature of the temperature dependence of the dHvA amplitudes in fig. 2 is the

Table 1

Cyclotron masses corresponding to the different orbits observed. Each orbit is specified by its dHvA frequency.  $B_{\text{mean}}$  is the mean value of the field interval in which the dHvA amplitude is calculated.

$B_{\text{mean}}$ (T)	$F = 8670$ T	$F = 17\,300$ T	$F = 11\,000$ T
46.9	$(3.06 \pm 0.13) m_e$	$(7.0 \pm 2.1) m_e$	$(5.0 \pm 1.1) m_e$
43.4	$(3.26 \pm 0.13) m_e$	$(7.3 \pm 2.2) m_e$	$(6.5 \pm 2.2) m_e$
40.4	$(3.93 \pm 0.37) m_e$		
37.8	$(4.34 \pm 0.13) m_e$		

abruptly vanishing of the signal at temperatures above 2.3 K. A possible reason for this could be a rise in sample temperature during the field pulse due to eddy current heating. However, this vanishing is not observed in measurements on Au or Ag single crystals, where the oscillations can be followed up to 4.2 K. Since the Joule heating in a sample due to eddy currents is proportional to the conductivity of the sample, and since the conductivity of the Ag and Au samples is higher than that of the CeB<sub>6</sub> sample, the temperature change in the CeB<sub>6</sub> sample is expected to be less than that in a Au or Ag sample. On the other hand, it is not clear what mechanism might cause a sudden change of the dHvA amplitude. We speculate that the sample undergoes a transition to a phase with enhanced electronic scattering, leading to an increase in the Dingle temperature. CeB<sub>6</sub> is known to have a number of different phases with complex magnetic ordering but the phase diagram is only studied up to a field of 15 T [9]. A magnetization study is planned to explore the phase diagram at higher fields.

#### 4. Conclusion

In conclusion, we have performed a dHvA study of CeB<sub>6</sub> in pulsed magnetic fields up to 52 T. A number of orbits is observed. The most pronounced frequency in the spectrum corresponds to the  $a_3$  orbit; the corresponding cyclotron mass is measured between 37.8 T and 46.9 T. A second orbit is new and may be due to magnetic breakdown. We have also observed the vanishing of the dHvA signal for temperatures above 2.3 K. The reason for this is not clear.

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