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Rapid note

Magnetoacoustic quantum oscillations in the heavy fermion superconductor UBe_{13}

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In UBe_{13} magnetoacoustic quantum oscillations (MAQO) are observed for the attenuation- and the sound velocity-changes in the superconducting and normal state. The observed extremal areas and the effective masses are small.

The investigation of the heavy fermion superconducting state using ultrasonic methods by our group has given pronounced strain-order parameter coupling effects for longitudinal waves in UPt_3 [1, 2], URu_2Si_2 [2] and $CeCu_2Si_2$ [3]. Shear waves for the same compounds have exhibited Lorentz force effects in magnetic fields, especially for URu_2Si_2 with its large critical field B_{c2} [2].

An analogous investigation in UBe_{13} has produced quite unexpected results: the attenuation and velocity change for the shear c_{44}-mode exhibits magnetoacoustic quantum oscillations in the normal and superconducting region as shown in Fig. 1a, b.

The superconducting transition temperature T_c and the critical fields were determined by susceptibility measurements. The values of $T_c = 0.85$ K and $B_{c2} = 9.5$ T at 45 mK agree with literature values [4]. Figure 1a gives results for relative attenuation and velocity at 45 mK with magnetic field B parallel to the propagation axis [100] up to 11 T. One can clearly distinguish several oscillations which start at $B = 2\,\mathrm{T} < B_{c2}$. In Fig. 1b analogous results are shown for the same geometry at $T = 3\,\mathrm{K} > T_c$. The results of Fig. 1a, b demonstrate already qualitatively that the oscillation frequencies are practically the same for the normal and superconducting phase and that the effective masses for the observed orbits are very small. A preliminary analysis for the 305 T frequency gives $m^*/m_e \cong 0.2$ with a Dingle temperature $T_D \cong 3$ *K*.

The UBe_{13} single crystal was prepared in a way described elsewhere [4]. We took a lot of care to select and polish the material to obtain a sample which is free of inclusions, especially of aluminium. Inclusions of this material are easily visible. ac-susceptibility measurements with our single crystal exhibited no superconducting transition around the temperature T_c of Al. Microprobe analysis and X-ray fluorescence investigations show that our sample is free from Al inclusions.

In Fig. 2 we show the Fourier transform of the results of Fig. 1a indicating four clearly resolved frequencies F (from $\cos(2\pi F/B)$) at 33, 59, 305 and 384 T. Both the

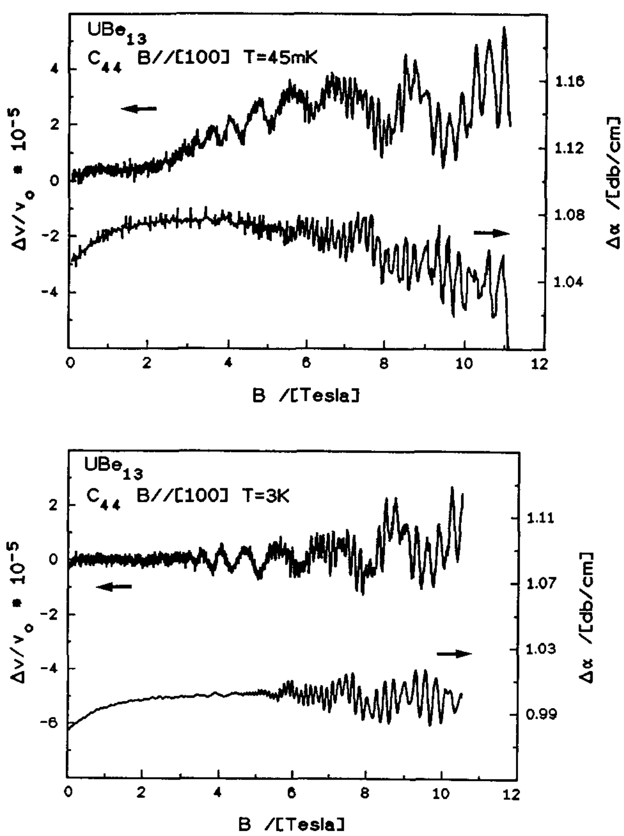

Fig. 1a, b. Ultrasonic attenuation change $\Delta\alpha$ and relative velocity $\Delta v/v_0$ for the c_{44}-mode at 30 MHz as a function of magnetic field in propagation direction. **a** $T = 45$ mK; **b** $T = 3$ K

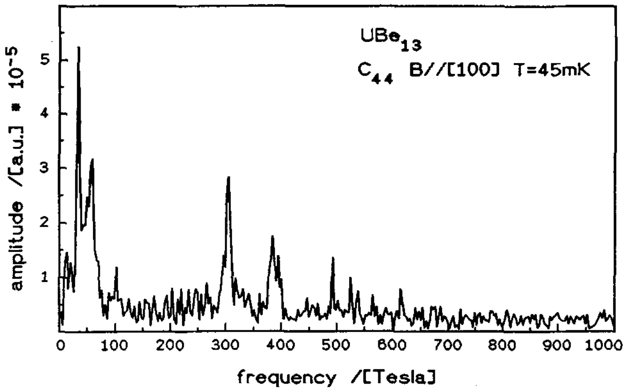

Fig. 2. Fourier transform of the data of Fig. 1a for the sound velocity data

attenuation and relative velocity change give the same Fourierspectrum. These frequencies give Fermi surface areas which correspond to rather small pieces (for 305 T $=0.08(2\pi/a)^2$). MAQO can probe only small Fermi surface orbits [5]. In UPt_3 frequencies up to 5950 T have been measured using conventional dHvA techniques for $B > B_{c2}$ [6]. We have also investigated the angular dependence of these oscillations for B varying from the [100]- to the [010]-direction. We find for example a splitting of the 305 T frequency and a slight shift. Al gives strong acoustic oscillations with a fequency of F $\approx$ 400 T [7] compared to 305 T in UBe_{13}. The angular dependence of these frequencies are quite different in these materials.

The significance of this experiment can be summarised as follows:

- For the first time dHvA type quantum oscillations have been observed in the superconducting phase of a heavy fermion compound. In the superconducting layer compound $NbSe_2$ dHvA-oscillations have been found in the normal and superconducting region [8]. The reasons that one can observe it in UBe_{13} are the rather large critical field B_{c2} so that the oscillations can develop already in the superconducting state, the large Ginzburg-Landau parameter κ and the use of acoustic waves which circumvent the problem of penetration depths.
- The important question now is: which electrons participate in MAQO? Are they from Fermi-surface pieces which remain normal or are they normal electrons in the vortices developing as B approaches B_{c2}? The characteristic lengths for this problem are the following: cyclotron radius $r_c = v_F/\omega_c = 1020$ Å for $B = 6$ T and the 305 T orbit, coherence length [4] $\xi = 96$ Å for low temperatures and the mean free path l from the quoted Dingle temperature is $l = 2070$ Å. These figures point to Fermi surface regions remaining normal for $T < T_c$ and small masses. We do not yet consider the exotic possibility of observing orbits of nodal lines or induced nodal lines in the superconducting phase.
- The fact that we observe Fermi surface pieces with small effective masses (in the normal and superconducting phase) indicates that not all electrons in UBe_{13} hybridise to form the heavy electron state. This is detrimental to common belief and it has been proposed before from experiments [9]. Small masses have also been observed in $CeRu_2Si_2$ another heavy fermion compound, above the metamagnetic transition [10].

These experiments are to be continued also with other elastic modes and with other field directions in order to compare the results with existing band structure calculations [11]. A further investigation of the deformation potential coupling effects in the normal and superconducting phases will also be persued in a similar way as has been done for LaAg [12].

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