ULTRASONIC ATTENUATION AND ELASTICITY IN URu_2Si_2*

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We present ultrasonic attenuation and elastic constant results on the heavy-fermion state of URu_2Si_2 both as a function of temperature and magnetic fields up to 50 T. We find distinct anomalies as a function of field and temperature for the longitudinal modes c_{11} and c_{33}. We construct a B–T phase diagram including $T_N(B)$, the so-called metamagnetic transition and the spin-flop transition into the paramagnetic phase.

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1. Introduction

Most heavy-fermion compounds, in addition to strong antiferromagnetic fluctuations, order magnetically at low temperatures. In URu_2Si_2 the phase transition at $T_N = 17.4$ K has been attributed to such an antiferromagnetic order. In addition, the system becomes superconducting below $T_c = 1.2$ K. The great mystery in URu_2Si_2 is the measured moment of 0.03 μ_B in the ordered phase, which is too small to account for the large specific heat anomaly at T_N. Many different experimental facts have pointed to a so far unidentified type of phase transition, which we label therefore a pseudomagnetic transition. For a review on the properties and physics of this pseudomagnetic transition see Ref. [1].

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2. Experiments

Acoustic experiments in URu_2Si_2 concentrated in the past on an investigation of the superconducting transition at T_c [2] and the overall temperature dependence of the elastic constants [2–4]. It was found that the longitudinal elastic constants show anisotropic behaviour in the normal and superconducting state. The temperature dependence could be well described with the so-called Grüneisen parameter coupling, especially for the longitudinal c_{11} mode. This coupling arises from the volume dependence of the narrow quasi-particle band of the heavy-fermion systems. For anisotropic systems it is useful to introduce the uniaxial Grüeisen parameters Ω_a and Ω_c, which are related to the uniaxial pressure dependences of the characteristic temperature.

The elastic anomalies around the pseudomagnetic transition at 17.4 K are anomalous and quite different in comparison to typical uniaxial antiferromagnets [5] and have been attributed to a spin-nematic strain coupling, *i.e.* a strain coupling to itinerant quadrupoles of the quasiparticles. Fig. 1(a) exhibits $\Delta c_{ii}/c_{ii}(0)$ for the longitudinal modes c_{11}, c_{33} and the transverse modes c_{44}, c_{66}. The anomalies are rather weak and no precursor effect is observed for $T > T_N$. This behaviour has to be contrasted with results for large moment uniaxial antiferromagnets like UPd_2Al_3 [5] or MnF_2 [6] where pronounced minima in the elastic modes are found. In Fig. 1(b) we show ultrasonic attenuation results at frequencies ω of 400–600 MHz. Again the attenuation anomalies are quite different from those observed in ordinary antiferromagnets, *e.g.* MnF_2 and $RbMnF_3$ [7]. While the height of the maximum follows roughly a ω^2 dependence there is no clear singularity at T_N but instead a broad maximum. Further on, $\alpha(T)$ drops rapidly below T_N different from a power-law dependence but reminiscent of the behaviour found in a BCS superconductor. Accordingly, the ultrasonic attenuation can be described with a mean-field like expression using a gap value comparable to those observed in specific heat or the resistivity measurements. This result indicates that the elastic waves couple in the first place to a (spin)-density wave forming on a part of the Fermi surface below T_N. Accordingly, the elastic constant changes, shown in Fig. 1(a), may reflect changes in the deformation potential coupling constant upon cooling through T_N.

In Fig. 2(a) we show elastic constant and attenuation data for the longitudinal c_{11} mode as a function of magnetic field. The attenuation data of the c_{11} mode in Fig. 2(a) help to pinpoint the anomalies already seen in the sound velocity measurements published before [9]. The $\alpha(B)$ data appear as pronounced spikes for the transitions at 34.2 T, 36.1 T and 38.7 T (at 4.2 K). The spin-flop transition at 38.7 T exhibits only a smaller and broader attenuation anomaly, similar to those observed before in uniaxial an-

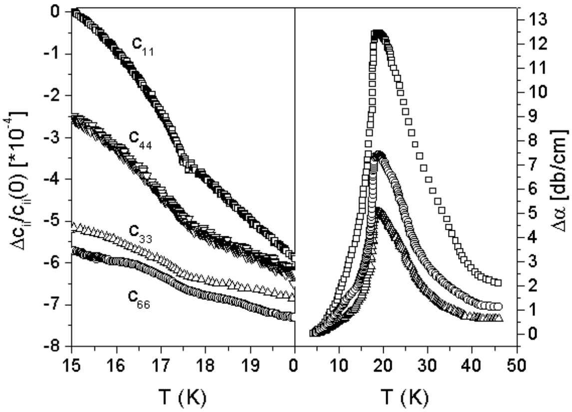

Fig. 1. (a) Relative elastic constant changes for the modes c_{11}, c_{33}, c_{44} and c_{66} in the vicinity of T_N. (b) Attenuation near T_N for sound waves of 400 MHz (diamonds), 500 MHz (circles) and 600 MHz (squares).

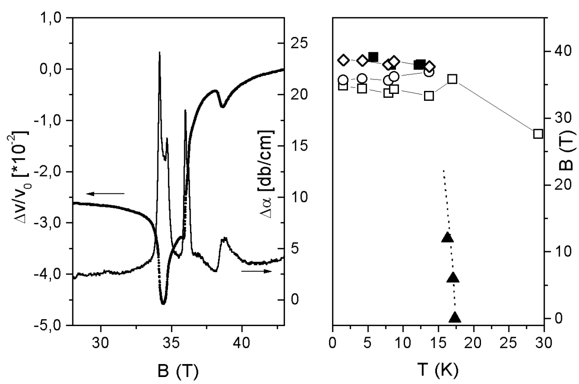

Fig. 2. (a) Ultrasonic attenuation at 4.2 K for the c_{11} mode at 46.6 MHz. Included is also the relative velocity change at the same temperature. (b) B–T phase diagram constructed from elastic anomalies. Pulse-field experiments: filled squares c_{33}(B) mode; open diamonds, open circles, open squares $c_{11}(B)$; filled triangles from $c_{11}(T)$ in constant field.

tiferromagnets [10]. Especially at the metamagnetic transition at 34.2 T the ultrasonic attenuation anomaly is strongly enhanced and the elastic constant exhibits a pronounced minimum. This behaviour is similar to the metamagnetic transitions in other heavy-fermion systems like $CeRu_2Si_2$ or UPt_3 [11]. At the moment there is no explanation for the attenuation peak at 36.1 T, which is also clearly seen in the magnetic susceptibility [8].

Finally we can construct a B–T phase diagram as shown in Fig. 2(b) from the data of Figs. 1(a), (b), 2(a), and the data of Ref. [9]. The open symbols are determined from the c_{11} anomalies where the open squares indicate the metamagnetic transition. The open diamonds and the filled squares mark the phase boundary between the antiferromagnetic and the paramagnetic state. Apparently $T_{\mathrm{N}}(B)$ does not connect to the metamagnetic transition, which can be followed at least up to 30 K in the c_{11} mode.

3. Summary

In summary, the high-field data of URu_2Si_2 can be explained for increasing field with a change from itinerant to a more localized picture of an uniaxial magnet. The metamagnetic transition at 34.2 T is pronounced for the c_{11} mode with a large Ω_a and absent for c_{33} with a small Ω_c in agreement with the temperature-dependent measurements. For higher fields, where the heavy-fermion state changes to a localized spin state both modes give pronounced effects at the spin flop state. On the other hand the zero-field data for the elastic constant and the attenuation in the vicinity of T_{N} are so far unexplained although they show a behaviour typical for a coupling between the strain and a spin density wave. Whether this coupling is related to the hidden order parameter [12] is not clear yet.

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