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Elastic anomalies of YbIrGe in magnetic fields

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Abstract. The Yb-based heavy-fermion compound YbIrGe, which has the orthorhombic structure, shows the crystal electric field effect at high temperatures and antiferromagnetic orderings at T_N = 2.4 K and T_m = 1.4 K. We previously found anomalous elastic softening in zero magnetic field originating from an indirect quadrupole interaction between the ground doublet and the excited doublets, and determined the crystal electric field level scheme: the ground doublet and an excited doublet at 138 K. To investigate the antiferromagnetic orderings at T_N and T_m, we performed ultrasonic measurements under magnetic fields along the *a*-axis on YbIrGe single crystals. Temperature dependence of elastic modulus C_{11} exhibits elastic hardening below both T_N and T_m at 0 T. As increasing the magnetic field along the *a*-axis, both T_N and T_m decrease monotonically, suggesting that both transitions are antiferromagnetic ordering. T_N closes around 2 T, and T_m disappears above 1 T. We clarified the magnetic field-temperature phase diagram along the *a*-axis.

1. Introduction

The Yb-based intermetallic compounds have been intriguingly investigated for their physical properties originating from the competition between the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction and the Kondo interaction. In the Yb-based Yb*MX* (*M*: transition metal; *X* = Al, Ga, Ge, Sb) system, some compounds such as YbPtAl, YbNiGa, and YbRhSb are heavy-fermion antiferromagnets which have both the heavy-fermion state and magnetic phase transitions [1-3].

YbIrGe with the orthorhombic TiNiSi-type structure (space group *Pnma*) is also considered as a heavy-fermion antiferromagnet with transitions at T_N = 2.4 K and T_m = 1.4 K [4-6]. At high temperatures, the electrical resistivity exhibits a metallic behaviour. The magnetic susceptibility obeys the Curie-Weiss law above 100 K with the effective magnetic moment of the free Yb^{3+} ion. There exists the crystal electric field (CEF) effect on 4*f*-electrons at high temperatures, because a Schottky anomaly centered around 80 K is observed in the magnetic specific heat. We previously measured the *T* dependences of elastic moduli in zero magnetic field on single-crystalline YbIrGe samples using an

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ultrasonic technique [7,8]. We found characteristic softening of the zero-field elastic moduli arising from a quadrupole interaction. From theoretical analyses of the transverse elastic moduli by using the so-called strain susceptibility [9], we determined the CEF level scheme: the ground doublet Γ_5, the first excited doublet Γ_5 at 138 K, and the second excited doublet Γ_5 at 270 K, where Γ_i is the irreducible representation [8]. Although all doublets have no quadrupole degeneracy, we found the anomalous elastic softening. This softening is caused by the indirect quadrupole interaction between the ground doublet and the excited doublets. The magnetic susceptibility and the Schottky specific heat are well reproduced by the CEF effect between 10 and 300 K.

At low temperatures, the specific heat enhances below 10 K, and the electrical resistivity also increases below 20 K accompanied by a minimum around 20 K. The estimated electronic specific heat coefficient below 1 K is 280 mJ/mol K^2, and the released magnetic entropy equals to $0.65R\ln 2$ at T_N, where R is the gas constant. From these results, the heavy-fermion state due to the dense Kondo effect is suggested at low temperatures [6].

As for the successive phase transitions at T_N and T_m: a cusp-type anomaly is observed at T_N only along the crystallographic *a*-axis in the magnetic susceptibility, suggesting antiferromagnetic ordering with magnetic moments in parallel with the *a*-axis. Below T_m, a canted spin structure toward the *b*-axis and antiparallel along the *c*-axis is proposed since the magnetic susceptibility along the *b*- and *c*-axes turns into increase and decrease at T_m, respectively [6]. In our ultrasonic measurements, elastic hardening due to a magnetostrictive effect is observed below both T_N and T_m in all elastic modes, suggesting a rather strong coupling between the strain and the magnetic order parameters [8]. In this paper, to investigate the antiferromagnetic transitions at T_N and T_m, we performed ultrasonic measurements on YbIrGe in magnetic fields along the *a*-axis.

2. Experimental

Single crystals of YbIrGe were grown by the Bridgman method [4,6]. We used two samples. The dimensions of the samples are 1.10(1.31), 2.68(1.60), and 1.58(2.45) mm along the *a*-, *b*-, and *c*-axes, respectively. We measured temperature T and magnetic field H dependence of the elastic modulus C_{11} using the phase comparison-type pulse echo method [10]. The modulus C_{11} is the longitudinal mode propagating along the *a*-axis. Magnetic fields were applied up to 4 T along the *a*-axis by a superconducting magnet. The temperature range was from 0.5 to 4 K. The frequency of ultrasound was 31 MHz.

3. Results and discussion

Figure 1 shows the T dependences of the longitudinal elastic modulus C_{11} in H along the *a*-axis. At 0 T, the modulus C_{11} decreases below 3 K, and then exhibits abrupt elastic softening at T_N. These will be caused by spin fluctuations of the phase transition at T_N and by the change of specific heat at T_N through the strain dependence of T_N from the Ehrenfest relation, respectively. With further decreasing T, elastic hardening is observed below both T_N and T_m owing to the magnetostriction. Under magnetic fields, both T_N and T_m decrease monotonically with increasing H. T_N and T_m are not detected at 4 T. Curious elastic softening from above 3 K appears at 4 T. This softening occurs in the non-ordered state. We will discuss the mechanism of the softening later.

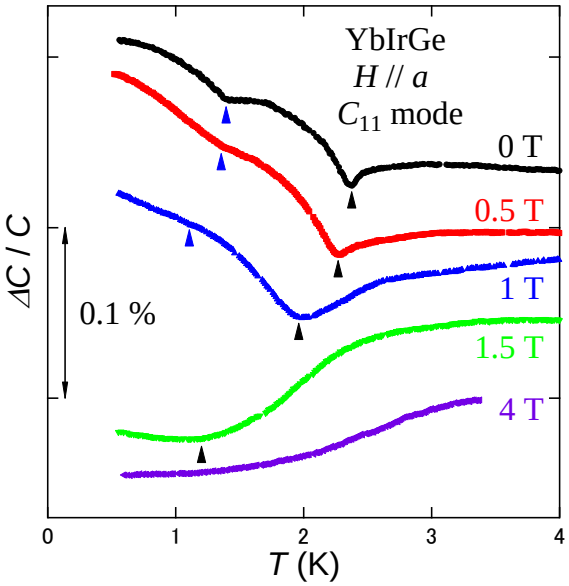


Figure 1. T dependences of the elastic modulus C_{11} in H along the a-axis. Solid arrows indicate the phase transitions.

The H dependences of the modulus C_{11} are shown in Figure 2. The C_{11} at 0.56 K exhibits elastic softening with increasing H, and then shows a broad minimum with two kinks at 1.7 T and 2 T, which are indicated by triangles in Figure 2. The positions of the two kinks are plotted as solid squares at 0.56 K in Figure 3. In the H dependence of C_{11} at 4.2 K, which is in the non-ordered state, the curious elastic softening is also observed.

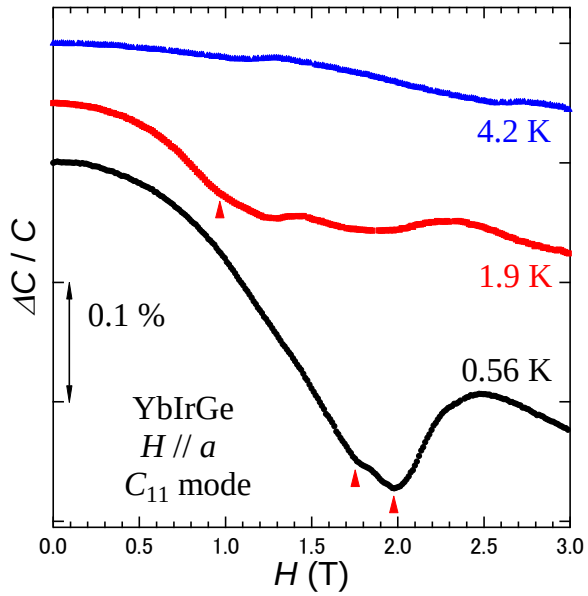


Figure 2. H dependences of the elastic modulus C_{11} in H along the a-axis. Solid arrows indicate the phase transition.

We have determined the phase boundaries of T_N and T_m from the T and H dependences of the elastic modulus C_{11}, as shown in Figure 3. T_N closes around 2 T, and T_m becomes unclear above 1 T. The antiferromagnetic ordering in parallel with the *a*-axis at T_N and a canted spin structure toward the *b*-axis and antiparallel along the *c*-axis at T_m are proposed by Katoh *et al*. with the magnetic susceptibility measurements. Katoh *et al*. also proposed the *H-T* phase diagram using their experimental data of the specific heat, resistivity and *dM/dH* where *M* is the magnetization [6]. They found two peaks at 1.5 T and 1.9 T in *dM/dH* at 0.55 K, and an anomaly at 1.6 T in the resistivity at 0.6 K. As mentioned above, we observed two kinks at 1.7 T and 2 T in the elastic modulus C_{11} at 0.56 K. We believe that the *H-T* phase diagram shown in Figure 3 is almost identical with the diagram proposed by Katoh *et al*. within the experimental accuracy regardless of how to line out the guides for the eye. Here, it is noteworthy that the possibility of an intermediate phase between 1.7 T and 2 T around 0.56 K cannot be excluded because not only the magnetic experiment (*dM/dH*) but also thermodynamic experiment (C_{11}) observed two anomalies near 0.56 K. In our ultrasonic measurements, both T_N and T_m decrease monotonically with increasing *H*. These results confirm that both phase transitions are due to the antiferromagnetic interaction.

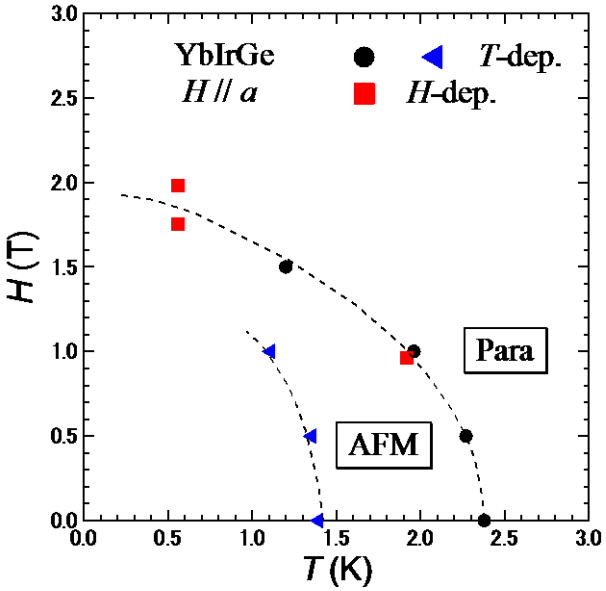


Figure 3. The *H-T* phase diagram in *H* along the *a*-axis. The broken curves are guides for the eye.

Let us consider the unusual elastic softening of the *T* and *H* dependences of C_{11} in the non-ordered state in higher magnetic fields. The Kondo effect (T_K = 2.4 K) would be weak at 4 T [6]. To check whether the softening is explained by the strain susceptibility, we firstly calculated the *T* and *H* dependences of the transverse elastic moduli under magnetic fields using the parameters previously reported in ref. 8. We assumed that the effective Hamiltonian contains the CEF effect, the strain-quadrupole interaction, the quadrupole-quadrupole interaction, and the Zeeman interaction. Figure 4 shows the *T* dependences of the calculated strain susceptibilities in *H* = 4 T along the *a*-axis, for instance. We obtained elastic softening of the *T* dependence at 4 T and the *H* dependence at 4.2 K in the transverse moduli C_{55} and C_{66}, arising from an indirect quadrupole interaction among the ground doublet split by *H*. Then, we calculated the response of J_x^2 to obtain *T* and *H* dependences of the longitudinal modulus C_{11}. However, the unusual elastic softening in the C_{11} mode was not reproduced. Since the longitudinal modes include the bulk modulus, the e_{xx} strain can couple with the higher order multipoles such as the CEF Hamiltonian [11]. The softening in the non-ordered state in C_{11} may be caused by the indirect multipole interaction among the doublet split by *H*.

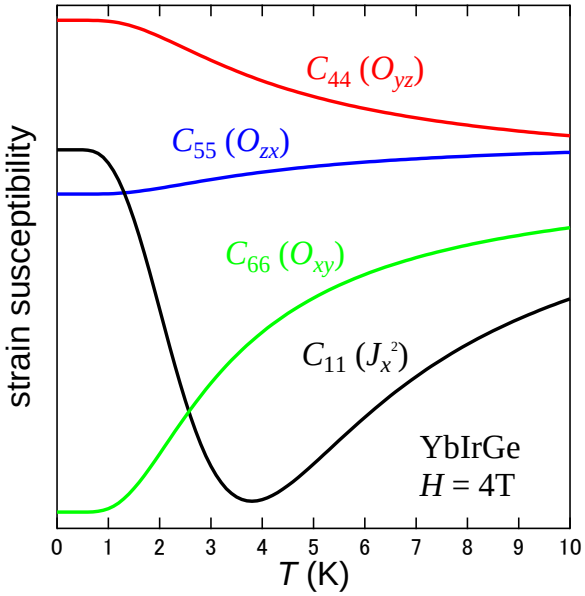


Figure 4. T dependences of the calculated strain susceptibilities in H = 4 T along the a-axis.

4. Conclusion

We carried out ultrasonic experiments on the heavy-fermion antiferromagnet YbIrGe under magnetic fields. In zero field, elastic hardening is observed below both T_N and T_m in the T dependence of elastic modulus C_{11}. The monotonic decrease of both T_N and T_m with increasing H along the a-axis suggests that both transitions are antiferromagnetic ordering. We clarified the H-T phase diagram along the a-axis, of which T_N closes around 2 T and T_m disappears above 1 T. In the non-ordered state, unusual elastic softening is observed in the T dependence at 4 T and in the H dependence at 4.2 K of C_{11}. These would be caused by the indirect multipole interaction among the doublets split by H.

Acknowledgments

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