Pressure Dependence of the Magnetic and Quadrupolar Ordering in YbRu₂Ge₂

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Abstract We have investigated the pressure dependence of the magnetic field-temperature phase-diagram of the tetragonal compound YbRu₂Ge₂ by electrical resistivity measurements in the pressure range up to 10 GPa and for magnetic fields up to 14 T.

Keywords High pressure · Quadrupolar order · YbRu₂Ge₂

1 Introduction

The ground state of intermetallic compounds based on Ce or Yb can be tuned from a magnetic to a non-magnetic state, e.g., by applying external pressure. While in Ce compounds external pressure suppresses magnetism, in Yb compounds magnetism is generally enhanced. Of special interest is the crossover from the non-magnetic to the magnetic state. Here, quite often unusual physical properties like heavy-fermion behavior or unconventional superconductivity are observed.

YbRu₂Ge₂ is special among the intermetallic YbT₂X₂ (*T*—transition metal, *X*—Si, Ge) compounds. Magnetic and thermodynamic properties indicate that the *f* hole of Yb³⁺ is almost completely localized [1]. At ambient pressure anomalies in specific heat (*C*), electrical resistivity (*ρ*), and magnetic susceptibility (*χ*)

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Fig. 1 (Color online) Panel (a): $\rho(T)$ data obtained in a piston-cylinder pressure cell for different pressures; panel (b): p - T phase diagram of YbRu_2Ge_2 . Open symbols correspond to data obtained in a piston-cylinder cell, solid symbols to data from a Bridgman-type cell

at $T_0 = 10.2$ K, $T_1 = 6.5$ K, and $T_2 = 5.7$ K evidence complex ordering phenomena [1]. The entropy around T_0 obtained from integrating the specific heat data is very close to $R \ln 4$, which corresponds to a quasiquartet crystal-field ground-state. This is rather unique among the YbT_2X_2 compounds. The anomaly at T_0 is discussed to be associated to a quadrupolar ordering, while the anomaly at T_1 is related to an antiferromagnetic ordering and the anomaly at T_2 likely to a change of the magnetic structure [1, 2].

2 Experimental Details

Single crystals of YbRu_2Ge_2 were grown from a Sn or In flux. X-ray-powder diffraction confirmed the ThCr_2Si_2 ($I4/mmm$) structure type. $\rho(T, H)$ measurements in the temperature range $1.8 \text{ K} \leq T \leq 300 \text{ K}$ and in magnetic fields up to 14 T were carried out utilizing a standard four-probe technique. A piston-cylinder cell ($p \leq 3 \text{ GPa}$) and a Bridgman-type cell ($p \leq 10 \text{ GPa}$) using silicone fluid and steatite as pressure transmitting medium, respectively, were employed. In both cases lead served as pressure gauge.

3 Experimental Results

Figure 1 shows $\rho(T)$ measured with current $I \parallel a$ for selected pressures. At all pressures $\rho(T)$ linearly decreases from room temperature down to 80 K and shows a minimum before it starts to increase on further decreasing temperature. This increase possibly indicates some weak Kondo-type interactions. On increasing pressure this increase becomes weaker. The transitions at T_0 , T_1 , and T_2 are clearly visible as a kink in the resistivity data. Below T_0 a strong decrease of $\rho(T)$ is visible at all pressures. In the whole pressure range investigated T_0 is nearly independent of the applied

Fig. 2 (Color online) Resistivity of YbRu_2Ge_2 at $p = 1.23$ GPa. The electrical current is always flowing along the crystallographic a direction. Panel (a): $\rho(T)$ for different magnetic fields $H \parallel a$; panel (b): corresponding data for $H \parallel c$. $\rho(H)$ for different temperatures for $H \parallel a$, panel (c), and for $H \parallel c$, panel (d), respectively

pressure. The antiferromagnetic transition temperature, T_1 , is initially pressure independent ($p \leq 1$ GPa), but starts to decrease with further increasing pressure from 6.5 K at ambient pressure to 3.5 K at $p = 9$ GPa. Above 7 GPa T_1 shows a trend to saturation. T_2 reflects the pressure dependence of the T_1 just shifted to lower temperatures. This behavior gives an additional hint that the anomaly at T_2 is directly coupled to the magnetic ordering at T_1 and can be ascribed to a change of the magnetic structure. Quadrupolar ordering in a tetragonal Yb system requires the energy splitting of the first excited crystal-field doublet to be by accident very small. One then expects the quadrupolar order to be very sensitive to pressure, while magnetic order, being incipient of a (well localized) Kramers ion, should be robust. Surprisingly our pressure results evidence just the opposite. This is in contrast to the effect of substituting Si for Ge, which corresponds to positive chemical pressure, but leads to a very fast suppression of T_0 [3]. This anomalous behavior deserves further investigations.

We now turn to the response of YbRu_2Ge_2 to an external magnetic field. The results of $\rho(T, H)$ measurements at $p = 1.23$ GPa are depicted in Fig. 2. Panels a and b show $\rho(T)$ for different fields. The effect of magnetic field on ρ depends strongly on its direction. Field parallel to the crystallographic a -axis leads to a much stronger reduction of the magnitude of ρ ($T \leq 20$ K) than for field applied parallel c . For $H \parallel c$ the kink corresponding to T_0 shifts to lower temperatures on increasing magnetic field. Simultaneously, the feature becomes more and more rounded. Above $H = 70$ kOe no clear feature is visible in the data anymore. To determine T_0 , T_1 , and T_2 we used the derivative $(\partial\rho(T)/\partial T)_H$, which is in good correspondence to the specific-heat data at atmospheric pressure [1]. The kinks at T_1 and T_2 stay clearly visible up to the highest field of our experiment ($H = 140$ kOe). For $H \parallel a$ the kink

Fig. 3 (Color online) H – T phase diagram of YbRu_2Ge_2 at $p = 1.23$ GPa. Open symbols correspond to data obtained with magnetic field $H \parallel a$, solid symbols to $H \parallel c$

indicating the transition at T_0 shifts also to lower temperatures on increasing field and remains easily detectable up to 140 kOe. $T_1(H)$ and $T_2(H)$ show a much stronger H -dependence than for $H \parallel c$ with a tendency to saturation. The magnetoresistance is displayed in panels c and d of Fig. 2. At low temperatures below T_2 (or T_1) $\rho(H)$ initially increases before it starts to decrease on further increasing field for both field orientations. For $T > T_1$ $\rho(H)$ decreases in the whole field range. Arrows in the figure indicate the kink in $\rho(H)$ at $H(T_1)$ and $H(T_2)$, respectively. The H – T phase diagram shown in Fig. 3 summarizes the results from the resistivity experiments at 1.23 GPa. $T_0(H)$ shows for both field orientations initially only a weak field dependence. Above $H = 70$ kOe for $H \parallel a$ T_0 shifts strongly to lower temperatures, from 10.8 K at ambient pressure to 8.8 K at 140 kOe, while for $H \parallel c$ T_0 cannot be detected unambiguously above 70 kOe. In contrast to the reported behavior at atmospheric pressure $T_0(H)$ decreases for both field orientations [1]. The field dependence of T_0 for $H \parallel c$ is in reasonable agreement with the $p = 0$ data. For $H \parallel a$, $T_0(H)$ shifts significantly to lower temperatures on increasing field. This behavior, which is distinct from the observations at atmospheric pressure, where $T_0(H)$ increases for $H \parallel a$, might point to a change of the character of the transition at T_0 under pressure. However, in this case it would be surprising that T_0 is nearly pressure independent up to 9 GPa. The transitions at T_1 and T_2 exhibit roughly the same H -dependence. However, both transitions show a strong anisotropy with respect to the direction of the magnetic field. Increasing magnetic field suppresses T_1 , as well as T_2 to lower temperatures. While they can be observed up to 140 kOe for $H \parallel c$, already a field of 70 kOe moves both transitions out of our measurement window for $H \parallel a$.

4 Summary

Our pressure studies showed that ordering at T_0 is robust against pressure, T_0 nearly stays constant up to $p = 9$ GPa, while the magnetic transitions at T_1 and T_2 shift to lower temperatures on increasing pressure. The H – T phase diagram at low pressures exhibits a strong anisotropy for $H \parallel a$ and $H \parallel c$.

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