RESEARCH ARTICLE | OCTOBER 18 2018

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Special Collection: 21st International Conference on Magnetism

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AIP Advances 8, 101337 (2018)
https://doi.org/10.1063/1.5042811

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Elastic properties of $SmPt_2Cd_{20}$ probed by ultrasound measurements

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(Received 5 June 2018; accepted 9 October 2018; published online 18 October 2018)

Ultrasound measurements have been carried out to investigate the elastic and low-temperature 4f-electronic properties of the Sm-based 1-2-20 system $SmPt_2Cd_{20}$. It was found that $SmPt_2Cd_{20}$ shows a pronounced elastic softening toward the magnetic transition temperature T_c = 0.64 K in the temperature dependence of the transverse elastic constant $C_E = (C_{11} - C_{12})/2$. The clear elastic softening behavior is suppressed gradually with increasing a magnetic field. The obtained results can be explained reasonably by a deformation potential approximation in which a coupling between conduction electrons and elastic strains caused by sound waves leads to a temperature dependence of elastic constants. This suggests possibly that the 4f electrons would become itinerant in the ground state in $SmPt_2Cd_{20}$. The nature of the low-temperature elastic and electronic states involving the ground state multiplets of Sm ions are discussed. https://doi.org/10.1063/1.5042811

I. INTRODUCTION

A series of RTr_2X_{20} (R = rare-earth element, Tr = transition metal element, X = Al, Zn, Cd) of intermetallic compound crystallizes in the cubic $CeCr_2Al_{20}$ -type structure with a space group Fd$\bar{3}$m (No. 227). In this structure, the rare-earth atoms occupy the 8a site with cubic T_d symmetry located at the center of an X16 cage (CN 16 Frank-Kasper polyhedron), forming a diamond structure sublattice.[1] Among the series, Sm-based systems $SmTr_2X_{20}$ exhibit often unusual magnetic-field-insensitive heavy fermion (HF) behavior, being markedly different from those of Ce-based HF ones. In fact, it was found recently that $SmTr_2X_{20}$ exhibits anomalous field-insensitive phase transition and HF state in the ordered state.[2,3] Since $SmTr_2Al_{20}$ shows a weak temperature dependence of the magnetic susceptibility and the field-insensitive nature of physical properties, the valence fluctuation of Sm ions is expected to play a crucial role in these systems. The present research aims to gain more insight into the behavior of magnetic-field insensitive HF systems. $SmPt_2Cd_{20}$ undergoes a magnetic phase transition at 0.64 K to a ferromagnet (FM) state.[2] The effective magnetic moment μ_{eff} and paramagnetic Curie temperature Θ were determined to be 0.46 μ_B/Sm and 0.53K, respectively. The positive value of Θ suggests that ferromagnetic interaction is predominant in this system. The temperature dependence of the electrical resistivity shows a shoulder-like structure around 10 K, possibly indicating the reduction of crystalline electric field (CEF) excitation of 4f electrons. Furthermore, the magnetic resistivity, determined by subtraction of the non-magnetic reference $LaPt_2Cd_{20}$ shows a gradual increase below around 200 K, followed by a sharp decrease below around 50 K with decreasing temperature. It should be noted that the specific heat divided by temperature increases with decreasing temperature even below T_c and attains 4.5 J/mol K^2 at 0.26 K, suggesting formation of the HF state and possibly strong magnetic quantum fluctuations. In cubic symmetry, the CEF splits the sixfold

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degenerate $^6H_{5/2}$ multiplet of the Sm^{3+} $4f^5$ state into a Γ_7 doublet and a Γ_8 quartet. The estimated magnetic entropy from the specific heat suggests the Γ_7 doublet to be the ground state and the Γ_8 quartet the excited state at around 30 K above. Although much effort has been devoted to experimental and theoretical studies of the Sm-based HF systems so far, the mechanism to form the magnetic-field-insensitive HF state is poorly understood. We have carried out the ultrasound investigations of $SmPt_2Cd_{20}$ in a wide temperature range and at applied external magnetic field. In this short communication, we report the low-temperature property of $SmPt_2Cd_{20}$ proved by ultrasound measurements.

II. EXPERIMENTAL DETAILS

Single crystals of $SmPt_2Cd_{20}$ were prepared by Cd self-flux method. Typical size of obtained single crystals is approximately 1 × 1×2 mm^3, but only with the crystallographic ⟨110⟩ axis. In consequence, the $C_E = (C_{11} - C_{12})/2$ was possible in this study. For sample quality evaluation, we have performed elemental analysis using an x-ray fluorescence spectrometer JSX-1000S (JEOL). No impurity elements have been detected. The details have been described elsewhere.[2] For ultrasound measurements, single crystalline $LiNbO_3$ transducers were employed to generate and detect ultrasound in a frequency range between 10 and 50 MHz. A phase comparison and phase sensitive method was used in our experiments. We performed the ultrasound measurements on $SmPt_2Cd_{20}$ in the extremely low temperature ranges covering the magnetic transition temperature $T_c = 0.64$ K, using a ^{4}He refrigerator down to 1.4 K and a ^{3}He-^{4}He dilution refrigerator down to 80 mK. Superconducting magnets equipped with the refrigerators were employed for the ultrasonic measurements in applied magnetic fields.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 1 shows the relative change of the transverse elastic constant $\Delta C(T)/C_0$ as a function of temperature in $SmPt_2Cd_{20}$. One observes a slight elastic softening effect below around 2 K. The softening is gradually suppressed with increasing a magnetic field. Here let us attempt to describe the softening effect in terms of CEF effect. The CEF level scheme for $SmPt_2Cd_{20}$ was proposed from the magnetic entropy result as Γ_7 (0 K) - Γ_8 (30 K).[2] In this case, a characteristic minimum structure is expected in $\Delta C(T)/C_0$ at around 15 K. In fact, it is difficult to obtain the good-fitted results taking only CEF effect into account. Thus, it is likely that the CEF effect is not primary origin to cause the observed elastic softening in the $\Delta C(T)/C_0$. This point directs attention to something else to explain the softening effect. If a system has a large density of states of quasiparticles in the

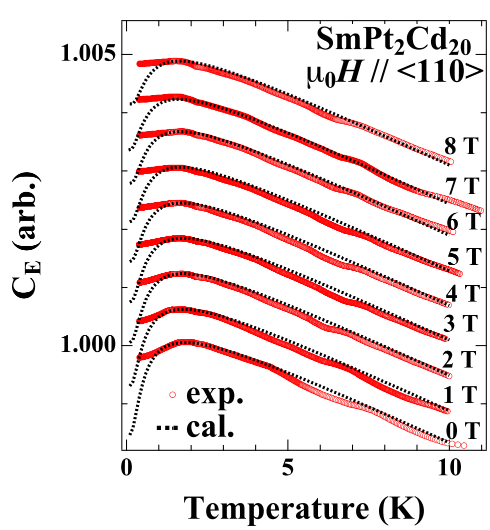

FIG. 1. Temperature dependence of the elastic constant of $SmPt_2Cd_{20}$ under selected fields along the ⟨110⟩ axis. For clarity each curve is shifted by an arbitrary offset on the vertical scale.

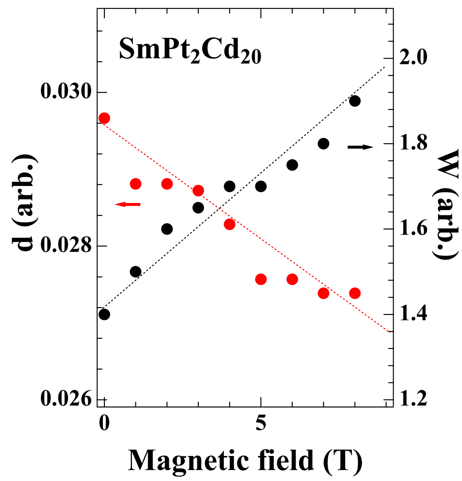

FIG. 2. Magnetic field dependence of the coupling constant d and the total band width W under magnetic field along the $\langle 110\rangle$axis.

vicinity of Fermi level formed by the hybridization, a coupling constant d between the quasiparticles and their relevant elastic strain induced by sound waves becomes significantly strong.[4–6] This often causes elastic anomalies at low temperatures, so-called deformation-potential approximation which is described by,

$$C_\Gamma(T) = C_\Gamma^{(0)}(T) - \frac{4d^2}{W}\tanh\left(\frac{\beta W}{4}\right) \tag{1}$$

where, ${C_\Gamma}^{(0)}$, d and W denote the background elastic constant, the coupling constant and a total band width, respectively. β denotes $1/k_B T$. Dotted lines in Fig. 1 show the calculated results by using the above formula. The results are in a good agreement between theory and experiment above T_c. This is consistent with the simple model that the coupling between the strongly mass-enhanced mobile electrons and the lattice through the deformation-potential leads to the elastic anomaly. Figure 2 shows the field dependence of the d and W. The d increases while the W decreases gradually by applying the magnetic field. Thus, it is likely that itinerant to localized view on $4f$-electron of Sm ions would be tuned by external magnetic field in this field range. That is to say, our observations suggest that the magnetic fluctuation i.e., Kondo screening is suppressed, and reduction of itinerant $4f$ state would occur under magnetic field in $SmPt_2Cd_{20}$.

IV. CONCLUDING REMARKS

As a summary, we have investigated the elastic properties of the Sm-based 1-2-20 system $SmPt_2Cd_{20}$. A distinct elastic softening toward the transition temperature was observed in the $\Delta C(T)/C_0$. This softening would be possibly ascribed to the coupling between the quasiparticles with a highly enhanced effective mass and the relevant elastic strain, suggesting the formation of a coherent many-body, heavy fermion state at low temperatures.

ACKNOWLEDGMENTS

The measurements have been performed in the Cryogenic Division of the Center for Instrumental Analysis, Iwate University. This work was supported by JSPS KAKENHI Grant Number JP15H05883 (J-Physics).

[1] M. S. Torikachvili *et al.*, PNAS **104**, 9963 (2007).
[2] A. Yamada *et al.*, Phys Rev. B **96**, 085102 (2017).
[3] H. Doto *et al.*, J. Alloys Compounds **693**, 332 (2017).
[4] B. Lüthi *et al.*, J. Magn. Magn. Mater. **52**, 70 (1985).
[5] P. Thalmeier *et al.*, J. Magn. Magn. Mater. **76-77**, 299 (1988).
[6] S. Nakamura *et al.*, J. Phys. Soc. Jpn. **60**, 2305 (1991).