Journal of Physics: Conference Series **592** (2015) 012026 doi:10.1088/1742-6596/592/1/012026

Shubnikov-de Haas Oscillation in the cubic Γ_3-based heavy fermion superconductor PrV_2Al_{20}

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Abstract. PrV_2Al_{20} is the cubic Γ_3 doublet system that exhibits strong hybridization effects and heavy fermion superconductivity. We measured the magnetoresistance using a high quality single crystal of PrV_2Al_{20} under the DC high magnetic field up to 35 T below $\sim$ 0.4 K. We have succeeded in detecting the Shubnikov-de Haas (SdH) oscillation with a frequency of 250 T. Our analysis of this SdH oscillation yields the cyclotron effective mass ($m_c^*/m_0 \sim 5$) and the mean-free path ($l = 170$ Å).

1. Introduction

Strong hybridization in $4f$ electron systems leads to various exotic phases such as heavy Fermi liquids, superconductivity nearby quantum critical, and non-Fermi-liquid states [1, 2, 3]. Recently, a lot of attention has been paid to novel phenomena arising from the strong hybridization between multipole moments and conduction electrons. In particular, it is useful to study the non-magnetic systems that only carry the multipole moments and that carry no magnetic moments. Thus, the cubic Pr-based compounds that have a Γ_3 doublet crystalline-electric-field (CEF) ground doublet are ideal because they only carry quadrupole and octapole moments. While most of the cubic Γ_3 doublet systems have been found to show strongly-localized behaviors, recent studies on $PrTr_2Al_{20}$ (Tr = Ti, V) have revealed strong hybridization effects of the Γ_3 ground doublet that are well separated from the excited CEF state by 60 K (Ti) and 40 K (V) [4].

One of the most significant evidence is the observation of the heavy fermion superconductivity in $PrTr_2Al_{20}$ [5, 6, 7]. For example, $PrTi_2Al_{20}$ exhibits superconductivity at 0.2 K with the effective mass of $\sim$ 16 m_0 in the ferroquadrupolar state at ambient pressure. In addition, the application of the pressure up to 8 GPa enhances both superconducting transition temperature and effective mass up to $\sim$ 1 K and $\sim$ 110 m_0, respectively. Very recently, heavy fermion superconductivity exhibiting $\sim$ 140 m_0 was observed in PrV_2Al_{20} below T_c = 0.05 K in the multipole ordering phase with T_Q = 0.6 - 0.7 K.

In PrV_2Al_{20}, evidence of the strong hybridzation between quadrupole moments and conduction electrons was also observed in the paramagnetic region [4]. The magnetic

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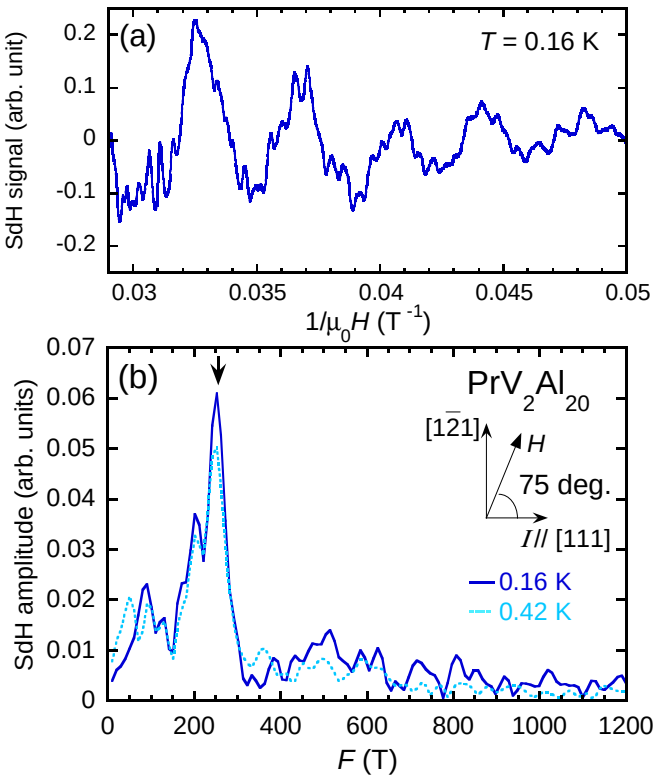


Figure 1. (Color online) (a) Shubnikov-de Haas (SdH) signal observed at 0.16 K above 20 T. (b) SdH amplitude obtained by the fast Fourier transform at 0.16 K (solid line) and 0.42 K (dotted line).

susceptibility and resistivity exhibit a distinct and strong $T^{1/2}$ dependence below ~ 20 K in spite of the non-magnetic Γ_3 ground doublet. This temperature dependence is consistent with the theoretical prediction of the quadrupole Kondo effect, indicating the overscreening of quadrupole moments by conduction electrons [8].

To find further additional evidence for the heavy quasiparticles in PrV_2Al_{20}, we measured the magnetoresistance at ambient pressure. In this paper, we show the results of the Shubnikov-de Haas oscillation observed in the high-magnetic field region above ~ 15 T.

2. Experimental

Single crystals of PrV_2Al_{20} were grown by the Al-self-flux method [4]. The magnetoresistance was measured by the standard AC four-probe methods. The current direction was parallel to the [111] direction and the magnetic field direction was inclined at 75 degrees angle from [111] to [1$\bar{2}$1] direction as shown in the inset of Fig. 1 (b). Using the resistive magnet in National High Magnetic Field Laboratory, the DC magnetic field up to 35 T was applied for the sample installed in the dilution refrigerator.

3. Results and Discussion

Figure 1 (a) shows the SdH signal above $\mu_0 H = 20$ T ($1/\mu_0 H = 0.05$ T^{-1}) at 0.16 K obtained after subtracting the background magnetoresistance estimated by the polynominal fitting. A clear oscillation with the wavelength of $\Delta(1/\mu_0 H) \sim 0.004$ T^{-1} was observed. Figure 1 (b)

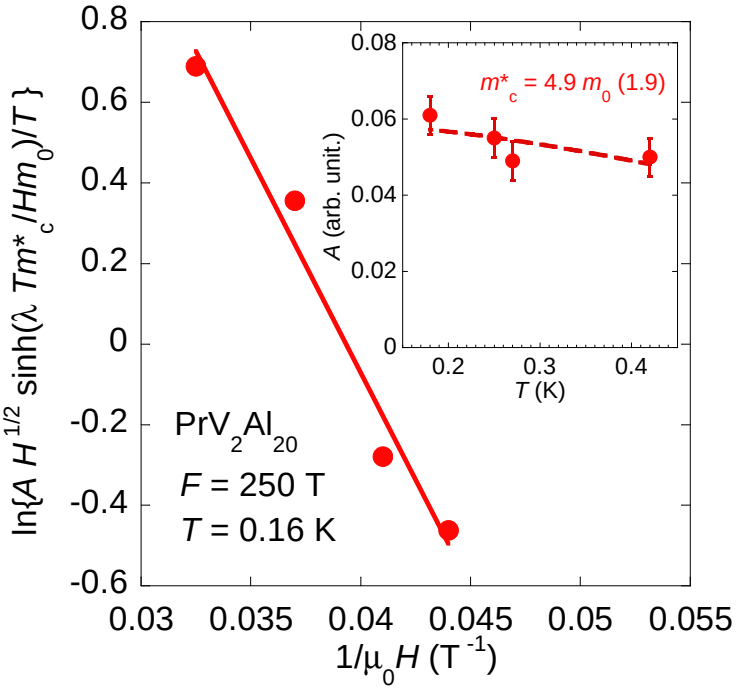


Figure 2. (Color online) Dingle plot for the SdH amplitudes A for $F = 250$ T at 0.16 K and its linear fitting (solid line). Inset shows the temperature dependence of A and the fitting by the Lifshitz-Kosevich relation as shown in the text (broken line).

indicates the SdH amplitude obtained by the fast Fourier transform (FFT) for the SdH oscillation at 0.16 K and 0.42 K. In this FFT analysis at each temperature, we adopt the field region from 17 T to 35 T. The arrow indicates the peak at $F = 250$ T. In addition, we also observed another peak at $F = 2000$ T (not shown), which will be discussed elsewhere.

Figure 2 shows the analysis for the temperature and field dependence of the peak amplitude $A(T, H)$ at $F = 250$ T. From this temperature dependence, cyclotron effective mass can be estimated by the Lifshitz-Kosevich relation described as below,

$$A \propto \frac{T}{\sinh(\lambda T m_c^*/H m_0),} \tag{1}$$

where m_c^*, m_0 and λ are cyclotron effective mass, electron rest mass and the constant value of 14.69 (T/K), respectively. The fitting by this equation provides slightly-enhanced effective mass of $m_c^*/m_0 = 4.9 \pm 1.9$, which is much larger than that of $m_c^*/m_0 < 1$, estimated for $PrTi_2Al_{20}$ from the de Haas-van Alphen effect measurements [9]. The larger effective mass suggests the stronger hybridization. This result is consistent with the fact that the effective mass in PrV_2Al_{20} ($\sim 140\ m_0$), associated with the superconductivity, is much more enhanced than that in $PrTi_2Al_{20}$ ($\sim 16\ m_0$) [5, 7].

Based on m_c^* and field dependence of the amplitudes, the Dingle temperature T_D can be calculated by using the equation,

$$\ln\left(\frac{A\sqrt{H}\sinh(\lambda T m_c^*/H m_0)}{T}\right) = -\frac{\lambda T_D m_c^*}{H m_0} + \text{Const.} \tag{2}$$

Figure 2 shows the so-called Dingle plot, the $1/H$ dependence of $\ln(AH^{1/2}\sinh(\lambda T m_c^*/Hm_0)/T)$. Here, the field dependence of amplitudes $A(H)$ is obtained from the quantum oscillation at 0.16 K as shown in Fig. 1 (a). $T_{\rm D}$ and the mean-free path l estimated from the Dingle plot are 1.7 $\pm$ 0.7 K and 170 Å, respectively.

4. Conclusion

We measured the magnetoresistance using the single crystal of PrV_2Al_{20} under the DC field up to 35 T below $\sim$ 0.4 K. Above 15 T, a clear SdH oscillation with the frequency of $F = 250$ T was detected. The analysis of this oscillation yielded the moderately-heavy cyclotron effective mass $\sim 5\ m_0$, the Dingle temperature ~ 1.7 K and the mean-free path 170 Å.

Acknowledgments

This work was partially supported by Grants-in-Aid (No. 25707030 and 25887015) from the Japanese Society for the Promotion of Science. Y.S. is partially supported by the Institute of Complex Adaptive Matter (ICAM). The NHMFL is supported by NSF through NSF-DMR-0084173 and the State of Florida. L.B. is supported by DOE-BES through award DE-SC0002613. This work was supported in part by NSF Grant No. PHYS-1066293 and the hospitality of the Aspen Center for Physics.

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