Shubnikov-de Haas Oscillation in the cubic $\Gamma_3$-based heavy fermion superconductor $\text{PrV}_2\text{Al}_{20}$

Yasuyuki Shimura$^1$, Masaki Tsujimoto$^1$, Akito Sakai$^{1,2}$
Bin Zeng$^3$, Luis Balicas$^3$, Satoru Nakatsuji$^1$

$^1$Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan
$^2$I. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany
$^3$National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, USA

E-mail: simu@issp.u-tokyo.ac.jp

Abstract. $\text{PrV}_2\text{Al}_{20}$ is the cubic $\Gamma_3$ doublet system that exhibits strong hybridization effects and heavy fermion superconductivity. We measured the magnetoresistance using a high quality single crystal of $\text{PrV}_2\text{Al}_{20}$ under the DC high magnetic field up to 35 T below $0.4 \text{ K}$. We have succeeded in detecting the Shubnikov-de Haas (SdH) oscillation with a frequency of $250 \text{ T}$. Our analysis of this SdH oscillation yields the cyclotron effective mass ($m_c / m_0 \approx 5$) and the mean-free path ($l = 170 \text{ Å}$).

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 $\Gamma_3$ doublet crystalline-electric-field (CEF) ground doublet are ideal because they only carry quadrupole and octapole moments. While most of the cubic $\Gamma_3$ doublet systems have been found to show strongly-localized behaviors, recent studies on $\text{PrTr}_2\text{Al}_{20}$ ($\text{Tr} = \text{Ti, V}$) have revealed strong hybridization effects of the $\Gamma_3$ ground doublet that are well separated from the excited CEF state by $60 \text{ K (Ti)}$ and $40 \text{ K (V)}$ [4].

One of the most significant evidence is the observation of the heavy fermion superconductivity in $\text{PrTr}_2\text{Al}_{20}$ [5, 6, 7]. For example, $\text{PrTi}_2\text{Al}_{20}$ exhibits superconductivity at $0.2 \text{ K}$ 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 $\sim 1 \text{ K}$ and $\sim 110 m_0$, respectively. Very recently, heavy fermion superconductivity exhibiting $\sim 140 m_0$ was observed in $\text{PrV}_2\text{Al}_{20}$ below $T_c = 0.05 \text{ K}$ in the multipole ordering phase with $T_Q = 0.6 - 0.7 \text{ K}$.

In $\text{PrV}_2\text{Al}_{20}$, evidence of the strong hybridization between quadrupole moments and conduction electrons was also observed in the paramagnetic region [4]. The magnetic
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 $\sim 20$ K in spite of the non-magnetic $\Gamma_3$ 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$_2$Al$_{20}$, 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 $\sim 15$ T.

2. Experimental

Single crystals of PrV$_2$Al$_{20}$ 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 [121] 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 $\mu_0H = 20$ T ($1/\mu_0H = 0.05$ T$^{-1}$) at 0.16 K obtained after subtracting the background magnetoresistance estimated by the polynomial fitting. A clear oscillation with the wavelength of $\Delta(1/\mu_0H) \sim 0.004$ T$^{-1}$ was observed. Figure 1 (b)
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,

\[
A \propto \frac{T}{\sinh(\lambda T \frac{m^*}{m_0})},
\]

where $m^*$, $m_0$ and $\lambda$ 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 $m^*/m_0 = 4.9 \pm 1.9$, which is much larger than that of $m^*/m_0 < 1$, estimated for PrTi$_2$Al$_{20}$ 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$_2$Al$_{20}$ ($\sim 140 m_0$), associated with the superconductivity, is much more enhanced than that in PrTi$_2$Al$_{20}$ ($\sim 16 m_0$) [5, 7].

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

\[
\ln \left( \frac{A \sqrt{H \sinh(\lambda T m^*/H m_0)}}{T} \right) = -\frac{\lambda T_D m^*}{H m_0} + \text{Const.}
\]
Figure 2 shows the so-called Dingle plot, the $1/H$ dependence of $\ln(AH^{1/2}\sinh(\lambda Tm^*/Hm_0)/T)$. Here, the field dependence of amplitudes $A(H)$ is obtained from the quantum oscillation at 0.16 K as shown in Fig. 1 (a). $T_D$ and the mean-free path $l$ estimated from the Dingle plot are 1.7 ± 0.7 K and 170 Å, respectively.

4. Conclusion

We measured the magnetoresistance using the single crystal of PrV$_2$Al$_{20}$ under the DC field up to 35 T below ~ 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 ~ 5 $m_0$, the Dingle temperature ~ 1.7 K and the mean-free path 170 Å.

Acknowledgments

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