Abstract. Electrical resistivity and specific heat measurements were performed at high magnetic fields up to 45 T in Ce_{0.6}La_{0.4}In_{3}, which is the La-substituted material to heavy fermion antiferromagnet CeIn_{3}. In Ce_{0.6}La_{0.4}In_{3}, the H-T phase diagram was drawn and the critical magnetic field was estimated to be approximately at 39 T. The critical field of Ce_{0.6}La_{0.4}In_{3} is about 20 T lower than that at 60 T of CeIn_{3}. Lower critical field facilitates observing Fermi surfaces when crossing phase boundary between antiferromagnetic and paramagnetic phases. Thus, the phase diagram obtained from our results should be a guide when we compare the Fermi surface topology in antiferromagnetic phase to that in paramagnetic phase.

1. Introduction

The Heavy fermion (HF) system is a cradle of exotic properties such as non-Fermi liquid behavior or unconventional superconductivity, appearing near the quantum critical point (QCP). The QCP emerges when the long range magnetic (RKKY) interaction, stabilizing magnetic ordering, balances the intrasite (Kondo) interaction as depicted in Doniach diagram. As seen in Doniach diagram, it is tunable that which interaction dominates if one dopes, or applies pressure or high magnetic field to a HF system.

CeIn_{3}, crystallizing into AuCu_{3}-type cubic structure, is a prototype HF system showing antiferromagnetic ordering at 10 K. Applying pressure to CeIn_{3} suppresses Néel ordering and the superconductivity emerges when Néel temperature (T_{N}) reaches near absolute zero in temperature. If applied high magnetic field that is another external tuning parameter, the Néel order is also suppressed to absolute zero temperature near 60 T. We need to sweep the magnetic field if we observe the de Haas-van Alphen (dHvA) effect, thus such high critical magnetic field as 60 T in CeIn_{3} prevents us to observe the change of topology of Fermi surface when crossing antiferromagnetic (AF)-field induced paramagnetic (PM) phase boundary or QCP. When Cerium ion is replaced by Lanthanum ion in Ce-HF system, the replacement does not introduce severe disorder to the system, but subtracts the 4f electrons to weaken the magnetic interaction leading to lowering critical magnetic field. Therefore, the La substitution effect to CeIn_{3} makes it easier to perform physical property measurements including measurements of Fermi surface property. In this paper, we report the field dependence of specific heat and electrical resistivity for observing Néel temperature shift and for mapping H-T phase diagram in 40 % La doped CeIn_{3}.
2. Experimental Techniques

Single crystals of Ce$_{0.6}$La$_{0.4}$In$_3$ were grown by the flux-method. For the growth, 99.9% Ce and La, and 99.9999%In were used. The sample was checked to be single phase by X-ray powder diffraction measurement and single crystal by back-Laue method. The electrical resistivity and specific heat at high magnetic fields were measured by the standard four-probe and the relaxation methods, respectively, at DC field facilities in National High Magnetic Field Laboratory (NHMFL), USA.

3. Experimental Results and Conclusion

We show temperature dependence of electrical resistivity at various magnetic fields in Fig.1. Shoulders, which are indicated by black arrows and attributed to Néel order, are seen at 0 and 11.5 T. Shallow upturns, indicated by thin gray arrows, are observed at 27.5 and 30 T. After development of higher periodicity by magnetic ordering, scattering of electron is reduced and electrical resistivity becomes smaller than that before magnetic ordering. Since no anomaly is observed above 40 T, it is expected that critical magnetic field ($H_c$) could exist between 30 and 40 T.

![Figure 1. Temperature and magnetic field dependence of electrical resistivity in Ce$_{0.6}$La$_{0.4}$In$_3$. Black arrows indicate shoulders attributed to Néel order. Gray arrows indicate upturns possibly corresponding to Néel order.](image)

In Fig. 2, we shows temperature dependence of specific heat at various magnetic fields. Black arrows indicate sudden rises of specific heat, which are attributed to Néel ordering. With increasing magnetic field, the anomaly is broadened and the peak height of anomaly is shortened. We see the anomalies below 30 T but an anomaly is not seen above 40 T. Thus, it is also expected there could exists $H_c$ between 30 and 40 T.

Figure 3 shows magnetic phase diagram. Red and blue open circles with error bars show Néel temperatures determined by electrical resistivity and specific heat measurements, respectively. Dotted line shows fitting curve for eight data points shown in Fig.3. The fitting function is $T_N = T_{N,0} \times [1 - (H/H_c)^2]$ where $T_{N,0}$ is the Néel temperature at zero field and $H_c$ is the critical magnetic field.[3] The estimated $T_{N,0}$ and $H_c$ from the fitting are 5.2±0.2 K and 38.7±1.4 T, respectively. The critical field estimated by fitting is in a range from 30 to 40 T that is roughly expected from electrical resistivity and specific heat measurements at various magnetic fields.
shown in Figs. 1 and 2. In Fig. 1, the origin of upturns at 27.5 and 30 T is not clear yet. However those anomalies may correspond to Néel ordering, because the upturns begin at the estimated Néel temperatures shown in Fig. 3.

Figure 2. Magnetic field dependence of specific heat in Ce_{0.6}La_{0.4}In_3. Black arrows indicate upturns caused by Néel ordering.

Figure 3. Magnetic field dependence of T_N determined from electrical resistivity and specific heat measurements in Ce_{0.6}La_{0.4}In_3. Red open circles and blue open circles show Néel temperatures determined by electrical resistivity and specific heat measurements, respectively.

In conclusion, we measured temperature dependence of electrical resistivity and specific heat at various magnetic fields to draw magnetic phase diagram and to estimate the critical magnetic field (H_c). The magnetic phase diagram was drawn and the H_c is estimated to be 38.7±1.4 T. The lowered H_c comparing to the H_c ≈ 60 T in CeIn_3 facilitates observing de Haas-van Alphen effect.
Acknowledgments

T. E. thanks to CASIO science promotion foundation, Suzuki Foundation, Shizuoka Research Institute for their grants. High magnetic field work was performed under auspices US department of Energy.

References
[1] Lawrence J M and Shapiro S M 1980 Phys. Rev. B 22 4379
[2] Mathur N D, Grosche F M, Julian S R, Walker I R, Freye D M, Haselwimme R K W, Lonzarich G G 1998 Nature 394 39
[3] Ebihara T, Harrison N, Jaime M, Uji S and Lashley J C 2004 Phys. Rev. Lett. 93 246401
[4] Brandt N B and Moscharkov V V 1984 Advances in Physics 33 373
[5] Iwamoto Y, Ebihara T, Harrison N, Jaime M, Silhanek A, Tezuka K, Morishita K, Terashima T, Iyo A 2007 J. Mag. Mag. Mat. 310 300