Spin fluctuation and giant magnetoresistance in CeSi

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Abstract. We measured temperature-dependent resistivity of a CeSi single crystal under several magnetic fields in order to study the effect of the magnetic field on the spin fluctuation in the commensurately modulated antiferromagnetic state of CeSi. Resistivity under each magnetic field exhibits a clear $T^2$ dependence at low temperatures. The coefficient $A$ of $T^2$ term decreases monotonously with increasing magnetic field. The residual resistivity at 0 T is steeply reduced around 1 T, and almost constant above 1 T. Temperature dependence of the magnetoresistivity near $T_N$ is compared with that of the isothermal change in the magnetic entropy.

1. Introduction
CeSi crystallizes in the orthorhombic FeB type structure [1] and it exhibits an antiferromagnetic order below $T_N = 6$ K [2,3]. The antiferromagnetic ordering is a commensurate sinusoidal or square wave magnetic structure characterized by the wave vector $q = (0, 1/2, 1/16)$ [4,5], showing a metamagnetic transition at $B_c = 0.6$ T [2,3]. A large anisotropy has been observed by our group in the magnetization, magnetic susceptibility and resistivity measurements [6]. A large negative magnetoresistivity (MR) attained to $-\Delta\rho/\rho(0) \sim 0.7$ was observed for the field direction parallel to the $b$ axis. It shows the $M^4$ dependence at 4.2 K, where $M$ is the magnetization of CeSi for $B//b$ [7]. A peculiar field dependence of the anomalous Hall resistivity has been found at 4.2 K, changing the sign at 5 T [8]. Temperature dependence of the Hall coefficient fits to the susceptibility data above 30 K for the $b$-axis with a proper scale factor and offset [8], suggesting the strong exchange interaction between the 4f spins and the conduction electrons. Kondo effect is very weak in CeSi [3]. The valence-band electronic structures have been investigated using ultraviolet photoemission spectroscopy, which shows that the 4f electrons hybridize with the valence electrons though Kondo resonance peak was not detected [9]. They found from temperature dependence of high-resolution resonant photoemission spectra of CeSi that the heavy fermion behaviour is strongly suppressed by the antiferromagnetic ordering due to the RKKY interaction [10]. Recently, magnetocaloric effect (MCE: the isothermal change in magnetic entropy) was studied in the CeSi polycrystals by Snyman et al. [11]. They calculated the anisotropic exchange parameters from the analysis of the MCE data. More recently, the MCE data calculated from the magnetization measurements were reported by Wang et al. [12].

In this paper, we present temperature-dependent resistivity of the CeSi single crystal under several magnetic fields in order to study the effect of the magnetic field on the spin fluctuation in the commensurately modulated antiferromagnetic state of CeSi. We note that temperature dependence of the MR around $T_N$ is similar to that of the MCE, which suggests that the RKKY interaction is dominant in this compound.
2. Experimental

The CeSi single crystals were prepared by the Czochralski pulling method in a tri-arc furnace. The resistance measurements were performed by a standard dc 4-terminal method in a conventional superconducting magnet system up to 8 T. The magnetocaloric effect was obtained from the data of the specific heat measurements performed previously by our group [8].

![Figure 1](image)

**Figure 1.** (a): Temperature-dependent resistivity of CeSi single crystal under magnetic fields along the $b$-axis. (b): Temperature-dependent magnetoresistivity obtained by subtracting the zero-field data. (c): Temperature-dependent magnetoresistivity divided to $B^2$ for $B = 5$ T and 8 T. Two data are almost the same values above 25 K. (d): The detail of temperature-dependent resistivity at low temperatures as a function of $T^2$.

3. Results and discussions

Temperature-dependent resistivity of the CeSi single crystal under the magnetic fields $B = 0, 1, 3, 5$ and 8 T along the $b$-axis was measured below 50 K down to 1.5 K, as shown in Fig. 1 (a). The current parallel to the magnetic field was applied so as to avoid mixing the orbital MR. The data at zero magnetic field shows a small hump at 6 K, corresponding to the antiferromagnetic ordering temperature $T_N$, which suggests the change in density of states with the magnetic ordering. By subtracting the zero-field data from the data under each magnetic field, resistivity due to the phonon scattering and the nonmagnetic impurity scattering are cancelled, and subsequently temperature dependence of the MR is extracted as shown in Fig. 1 (b). A large negative MR appears in the temperature below 50 K. Broad peaks observed around 10 K are attributed to the effect of the magnetic field that suppresses the fluctuation of the paramagnetic spins. A small peak at 6 K is caused by the antiferromagnetic transition observed as the small hump in the zero-field data. Fig. 1 (c) shows the MR divided by $B^2$ for 5 T and 8 T. Both curves are in good accordance at high temperatures above 25 K, where the magnetization $M$ is proportional to the applied field. This suggests that the MR is proportional to $M^2$ in the temperature range. Below 25 K, both curves are not the same trace because
$M$ deviates from the proportional relation to $B$ in the Brillouin function at low temperatures under high magnetic fields. The $M^2$ dependence of the MR is commonly recognized in the compounds showing a large negative MR such as the GMR [13] and the CMR [14] compounds. At 4.2 K, we previously reported a large negative magnetoresistance proportional to $M^4$ [7]. So, the MR dependence of $M^2$ changes to that of $M^4$ between 4.2 K and 20 K at most.

The data at low temperatures below 3 K obey clear $T^2$ dependence as shown in Fig. 1 (d). By fitting the simple equation,

$$\rho = \rho_0 + AT^2$$

(1)
we obtained both the coefficient of the $T^2$ term $A$ and the residual resistivity $\rho_0$ as a function of the magnetic field as shown in Fig. 2. The value of $\rho_0$ at 0 T is almost 3 times larger than the values above 1 T. This change is attributed to the metamagnetic transition from the commensurately modulated antiferromagnet to the field-induced paramagnet in CeSi. This suggests that the change in density of states associated with the antiferromagnetic ordering is reset by the magnetic field. Above 1 T, the value of $\rho_0$ is almost constant. $A$ shows a monotous decrease with increasing magnetic field, which may be attributed to the suppression of the spin fluctuation by applying magnetic field in the field-induced paramagnetic state. Field dependence of $A$ can be qualitatively explained by the self-consistent renormalization theory of spin fluctuations [15].

![Figure 2. Magnetic field dependence of the parameters A and $\rho_0$. Solid curves are drawn by a spline interpolation.](image)

We previously measured the iso-field specific heat of the CeSi single crystal for $B$//b-axis, where the lattice contribution was subtracted by using the specific heat of LaSi [8]. From the data, we calculated temperature dependence of the magnetic entropy $S_{mag}$ as shown in Fig. 3(a). The value of the magnetic entropy under zero magnetic field at $T_N$ is almost corresponding to $R \ln 2$, where $R$ is the
gas constant. This suggests a doublet ground state of 4f localized electron in CeSi as previously pointed out [6]. By subtracting the zero-field data from the data under each magnetic field, temperature dependence of the MCE $\Delta S_{\text{mag}}$ is extracted as shown in Fig. 3 (b). A small positive peak below $T_N$ for 1 T and large negative peaks around $T_N$ appear, which is well in agreement with the MCE data of the CeSi polycrystal by Snyman et al. [11], although the absolute value of $\Delta S_{\text{mag}}$ is almost twice larger than their data. The absolute value of the MCE for 5 T is -2.40 J/K/mol at 7 K, which is in good agreement with the MCE data of -13.7 J/K/kg for 5 T evaluated from the isothermal magnetization measurements of CeSi by Wang et al. [12]. These suggest that the MCE is anisotropic.

The temperature dependence of the MCE data are well corresponding to that of the MR in Fig. 1 (b). Campoy et al. have showed that MR is a probe to the MCE in ferromagnetic rare-earth aluminum compounds [16]. In the antiferromagnetic case, the scaling between the MR and the MCE may not be so simple because the metamagnetic or spin-flop transition generally occurs in the antiferromagnets. Theoretical studies are required.

![Figure 3](image)

**Figure 3.** (a): Temperature-dependence of the magnetic entropy of the CeSi single crystal under magnetic fields along the $b$-axis. (b): Temperature-dependent MCE obtained by subtracting the zero-field data.

### 4. Conclusion

We measured temperature-dependent resistivity of a CeSi single crystal under several magnetic fields in order to study the effect of the magnetic field on the spin fluctuation in the commensurately modulated antiferromagnetic state of CeSi. Resistivity under each magnetic field exhibits a clear $T^2$
dependence at low temperatures. The coefficient $A$ of $T^2$ term decreases monotonously with increasing magnetic field. This is qualitatively explained by the self-consistent renormalization theory of spin fluctuations. The residual resistivity at 0 T is steeply reduced around 1 T, and almost constant above 1 T. This suggests that the change in density of states associated with the antiferromagnetic ordering is reset by the magnetic field. Temperature dependence of the magnetoresistivity near $T_N$ is compared with that of the isothermal change in the magnetic entropy, suggesting the strong exchange interaction between the $4f$ spins and the conduction electrons.

5. References

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