The hyperfine interaction at $^{140}$Ce nucleus in CeRu$_2$Ge$_2$ has been investigated, using the $^{140}$Ce Time-Differential Perturbed Angular Correlation (TDPAC) method. $^{140}$Cs ions, which are fission products from $^{235}$U, have been implanted into a single crystal of CeRu$_2$Ge$_2$ at room temperature. $^{140}$Cs decays to $^{140}$Ce + intermediate state through $^{140}$Ba with the life-time of 12.752 days and $^{140}$La with a life-time of 1.6781 days. TDPAC spectrum at 4.2 K clearly shows the existence of the magnetic perturbation, which is absent at room temperature. Larmor frequency observed at 4.2 K is 1.32(1) Grad/s corresponding to the hyperfine magnetic field of 24.2(2) T at $^{140}$Ce nucleus. Magnetization measurements of CeRu$_2$Ge$_2$ performed by using the SQUID magnetometer revealed the magnetic moment of 1.848 $\mu_B$ which indicates that the hyperfine coupling constant of Ce is 13.1(3) T/$\mu$.

Table 1 Magnetic properties of CeT$_2$Ge$_2$ (FM: ferromagnetism, AF: antiferromagnetism, PP: Pauli paramagnetism, P: paramagnetism).

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>Mn</th>
<th>Fe</th>
<th>Co</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = 3d$</td>
<td>FM</td>
<td>PP</td>
<td>P</td>
<td>P</td>
<td>AF</td>
</tr>
<tr>
<td>$T = 4d$</td>
<td>Ru</td>
<td>Rh</td>
<td>Pd</td>
<td>Ag</td>
<td></td>
</tr>
<tr>
<td>$T = 5d$</td>
<td>Ir</td>
<td>Pt</td>
<td>Au</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Introduction

It is known that the Ce compounds show interesting physical properties like a heavy fermion system and valence fluctuations. These characteristic features originate from the nature of $f$ electrons in these compounds.

The specific heat coefficient values $\gamma$ of Ce compounds are larger by $10^2$ to $10^3$ times than that found in an ordinary ferromagnetism system. It implies, that the large effective mass is formed in the low temperature range. These compounds are called heavy fermion systems. The magnetic nature of a heavy electron compound is governed by the competition of the Kondo effect and RKKY interaction. The Kondo effect is derived from the discovery of the phenomenon that electrical resistance has a minimum. The RKKY interaction arises from interaction between conduction electrons and the local magnetic moment. The interaction between a conduction electron and localized $f$ electron causes the Kondo effect and RKKY interaction. The Kondo effect is the phenomenon that tries to cancel the magnetic moment. On the other hand, the RKKY interaction exhibits ferromagnetism and other magnetic long range order. Accordingly, depending on which interaction is dominant the magnetic order-disorder transition appears.

The CeT$_2$Ge$_2$ ($T =$ transition metal) compound has ThCr$_2$Si$_2$ crystal structure. CeT$_2$X$_2$ shows various physical properties, namely ferromagnetism, antiferromagnetism, Pauli paramagnetism, paramagnetism, depending on $T$ (Table 1).

Transition metals, except for Mn, do not have a magnetic moment. Magnetism is decided by RKKY interaction between Ce atoms. This system is investigated extensively. In the case of CeT$_2$Ge$_2$ in which the transition metal of the same line of the periodic table formed the structure and causes the $f - d$ hybridization. Among the CeT$_2$Ge$_2$ compounds, CeRu$_2$Ge$_2$ is ferromagnetic. The cause of this ferromagnetism in CeRu$_2$Ge$_2$ is an important problem for understanding the heavy fermion systems.

The experimental data of Besnus et al. are shown below for CeRu$_2$Ge$_2$. The crystal structure of CeRu$_2$Ge$_2$ is a ThCr$_2$Si$_2$ structure (space group I4/mmm) (Fig. 1), where lattice constants are $a = 0.42694$ nm and $c = 1.00395$ nm. From the neutron experiment it is known that, CeRu$_2$Ge$_2$ is a ferromagnetic material with the magnetic moment facing towards $c$ axis. Ordered moment is 1.90(15) $\mu_B$. When a magnetic field is applied along $c$ axis the spontaneous magnetization is deduced to be $M_f = 1.96(2) \mu_B$/mol. Simultaneously the magnetization along the $a$ axis is $M_a = 0.26(2) \mu_B$/mol. In a polycrystal sample the anisotropy of the specific heat occurs at 7.51 K and 7.92 K and the weak shoulder is seen in 8 K neighborhood. These behaviors are the same as the result of Thompson et al. However, only one peak at 7.9 K is seen in a single crystal specimen. The 7.9 K peak originates from ferromagnetic transition and the weak shoulder at 8 K is related to the antiferromagnetic transition [Thompson et al.].

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2 Graduate Student, Osaka University.
The phase transition is a typical second order phase transition according to the specific heat measurement. The maximum specific heat is $34.1 \, \text{mJ/mol K}$ at $7.91 \, \text{K}$. At low temperature range the electron specific heat coefficient $\gamma$ is $20 \, \text{mJ/mol K}^2$ and the ferromagnetic magnon excitation of the energy gap is $11 \, \text{K}$.

The method that uses radioisotope beam obtained by online isotope separation of radioisotope is carried out prosperously in recent years at Isotope Separator On-Line DEvice (ISOLDE) of the European organization for nuclear research (CERN). A probe atom is ionized, accelerated with high voltage, and infused into a specimen. Therefore, the method is able to control easily the depth of infusion by changing the accelerating voltage. In addition, it is possible to make such a sample that the probe atom cannot be dissolved by usual heat treatment. We made a sample by irradiating CeRu$_2$Ge$_2$ with the $^{140}$Cs ion beam that is available at Isotope Separator On-Line (ISOL), $^{140}$Cs that was infused $\beta$ collapsed in a process of $^{140}$Cs $\rightarrow$ $^{140}$Ba $\rightarrow$ $^{140}$La and we measured the perturbed angular correlation by using the $\gamma$ ray-cascades of $329$–$487\, \text{keV} \quad$ of $^{140}\text{Ce} \quad$ after $\beta$ decay of $^{140}\text{La}$.

The nuclear spectroscopy experiment of the nuclide that parted distant from the $\beta$ stable line that is formed by the nuclear fission of $^{235}\text{U}$ has been carried out, by using ISOL gas-jet-type (He + N$_2$) online isotope separation equipment in Kyoto University Research Reactor Institute (KURRI). The RI beam that is obtained by ISOL has come to be used in other fields in addition to the field of nuclear experiment in recent years. ISOLDE is applied to the research in the field of solid-state physics is prosperously. The probe nucleus that has a particular mass number is injected to the depth that can be controlled easily by changing the injection energy by ISOL. Therefore, the future development is expected in the research of material surface especially. KURRI has carried out researches investigating the physical properties of solids using the RI beam obtained by ISOL for several years. The studies are performed by using the Time-Differential Perturbed Angular Correlation (TDPAC). The $\gamma$–$\gamma$ cascade of $^{111}\text{Cd}$ following the electron capture of $^{111}\text{In}$ is used as the radiation source of TDPAC. However, this time we used the $329$–$487\, \text{keV} \quad$ gamma cascades of $^{140}\text{Ce} \quad$ following the $\beta$ decay of $^{140}\text{Cs}$. There is the report with regard to $^{140}\text{CeN}_2$ that measured with NaI (TI) scintillators for TDPAC of the gamma cascade of $^{140}\text{Cs}$ by RI ion infusion method. However, the time resolution of a NaI scintillator is not sufficient for $^{140}\text{Ce}$ whose life-time of the intermediate state is too short. Later, the BaF$_2$ scintillator that has a faster time characteristics was developed. The decay time of scintillation is shorter than $1 \, \text{ns}$ with this scintillator, which produced enough precision to measure the precession of TDPAC with the $^{140}\text{Ce}$ as the probe.

The $\gamma$ ray perturbed angular correlation is known as a method that provides empirical information regarding nucleus such as NMR or Mössbauer spectroscopy. It is impossible to measure the state of a nucleus by NMR that does not have a magnetic moment with nuclear spin $0$ in ground state. The experiment in the range that is not accessible for measurements by NMR and Mössbauer spectroscopy is possible in TDPAC, therefore, Mössbauer spectroscopy, NMR and PAC are complementary. We cannot measure the nuclear state of $^{140}\text{Ce}$ by NMR, because the spin of the ground state is $0$. $^{140}\text{Ce}$ is one of the general probe nuclei of TDPAC for solid state research. In this research, we performed the $^{140}\text{Ce}$ TDPAC measurement for CeRu$_2$Ge$_2$, to investigate the magnetic nature of Ce in CeRu$_2$Ge$_2$. TDPAC is well known as a powerful technique to investigate the local structure of a solid through the hyperfine interaction of probe nucleus. Electric and magnetic field of a lattice interact with the corresponding moment of the probe nucleus. When we investigate the hyperfine interaction of the nucleus, the environment of the probe atom in an atomic scale can be studied. TDPAC measures the time dependence of a gamma rays radiation pattern. We can also consider that TDPAC measures the rotation or precession of angular correlation. The origin of precession is a hyperfine interaction. For a detailed discussion of the theory of TDPAC, see, e.g. Frauenfelder and Steffen.

In this paper, we investigated the magnetic properties of CeRu$_2$Ge$_2$ by $^{140}\text{Ce}$ TDPAC measurement, and by means of SQUID magnetometer. By using $^{140}\text{Ce}$ TDPAC we investigated the hyperfine interaction of $^{140}\text{Ce}$ nucleus in CeRu$_2$Ge$_2$. The $^{140}\text{Cs}$ ion, that is the nuclear fission product from $^{235}\text{U}$ was implanted to the single crystal of CeRu$_2$Ge$_2$ at room temperature.

2. Experiment

The specimen used in the experiment was a single crystal. It is produced from an ingot of the polycrystal by the Czochralski method that used the tri-arc furnace. Each element that we used to produce the polycrystal, Ce, Ru, Ge, has the purity of 99.9% or better. Ce, Ge are in ingot and Ru is in powder forms. Ce used was washed by the ultrasonic 2 waves in trichloro ethylene, cut by the carbon cutter and the oxidized layer was removed in alcohol before measurements. The necessary quantity of Ru powder was melted with an arc furnace into a button shape. Melting was repeated 7 to10 or more times in the arc furnace. The mass defect during this process was $0.05 \, \text{to} \, 0.8\%$. This is probably due to the nature of the surface to tend to burst when cooling. We raise the obtained ingot of the polycrystal with $0.2 \, \text{mm/min}$ speed by the tri-arc furnace, and produced the single crystal specimen. We did not do any annealing in the present work. In order to identify the single crystal, we made the Laue photograph in the axis
alignment. Sample was cut and the cleavage surface always a c-face. The size of the specimen was 7.2 mm in the width of ellipse, 3.4 mm in the length, and 1.1 mm in the thickness.\footnote{2}

The susceptibility and magnetization were measured by using SQUID magnetometer (MPMS-XL5, Quantum Design). Magnetization was measured in a magnetic field range of 0.0 to 1.0 T. We made the measurement of the field dependence of magnetization at every 0.02 T, for 0 to 0.2 T and every 0.05 T, for 0.2 to 1.0 T at 4.2 K at which the CeRu$_2$Ge$_2$ is in the ferromagnetic state. The magnetic field of 0.78 T was applied in the measurement of susceptibility, for the temperature range of 0 to 100 K. We did measurement of temperature dependence at every 1 K for 2 to 20 K, every 2 K for 20 to 30 K, every 10 K for 30 to 100 K, to obtain the detailed information at about 8 K neighborhood when the transition to ferromagnetism occurs. Also, to make the same condition for the perturbed angular correlation measurement, the external magnetic field 0.78 T was applied along c axis.

The weight of the sample was 0.0133 g and was in a fragment form. The susceptibility is obtained by:

$$\chi = \frac{MX}{mH} \quad (1)$$

$$(M: \text{measurement magnetization}, X: \text{molecular weight}, m: \text{the mass of the specimen}, H: \text{external magnetic field}) and magnetization was calculated by$$

$$\mu(\mu_B/\text{Ce-atom}) = \frac{XM}{mN_0\mu_B} \quad (2)$$

($N_0$: Avogadro constant, $\mu_B$: Bohr magneton)

We did the ion implantation of $^{140}$Cs by ISOL in KUR-RI to do the specimen activation. As for the detailed description with regard to the injection of the $^{140}$Cs ion by ISOL, refer to Ref. 6). Ionized nuclear fission product of $^{235}$U is accelerated. The thermal neutron flux of KUR is about $3 \times 10^{12}$ neutrons cm$^{-2}$ s$^{-1}$. Neutron intensity can be adjusted continuously by changing the distance between the reactor core and $^{235}$U. The target chamber consists of 3 cylinders made of aluminum. Inside, 93%-enriched $^{235}$U have been electrodopesitised with thickness of 0.7 mg cm$^{-2}$. This target chamber is inserted from the T-1 experimental tube installed in KUR reactor. Neutron irradiation in the reactor core induces the nuclear fissions of $^{235}$U. The nuclear fission products of about $1.3 \times 10^{11}$ fission s$^{-1}$ is generated. Fission product obtained is transported by the He mixed with N$_2$ jet. Also, we have mixed the aerosol that is generated from PbI$_2$ heated to 653 K into the transfer jet. Fission product adheres to this and is carried to the schemer through capillary with the inside diameter of 1.5 mm. A part of gas and the aerosol that the nuclear fission product adhered to enter into an ion source of the surface ionization type. The high voltage of about 30 kV is applied to the ion source. Fission product that was drawn from an ion source is accelerated. The ion that was accelerated becomes a parallel beam by the einzel lens. It enters into an analyzer magnet through quadrupole lenses system. After bending by 45 degree in the analyzer magnet, the required ion beam mass is separated, and focused. Hence, it is possible to choose a fission product of a particular mass number by putting the slit at the focus. After passing the slit, the fission product is accelerated with the voltage of about 110 kV furthermore. Probe nucleus is thus implanted into a sample. After all, fission product is accelerated with the total of voltage about 140 kV (sum of 30 kV and 110 kV; 30 kV is applied to the ion source and 110 kV is applied to fission product passed through the slit). The beams flux of $^{140}$Cs of probe ions was about $10^6$ ions/s. The diameter of the strong beam is 5 mm by 5 mm, at the beam center. The ion implantation was performed in vacuum of $10^{-8}$ Pa at room temperature. The radioactivity of the sample was 120 µSv/h, at a distance of about 3 cm, measured by an ionization chamber ICS-313. $^{140}$Cs is implanted in a very shallow region near the surface. Before the implantation, the impurities on the surface of the sample were removed, but no heat treatment before or after implantation was performed. The ion radius of Ce, Ru, Ge is 0.182, 0.134, 0.137 nm, respectively. The ion radius of Ce is still the largest in CeRu$_2$Ge$_2$ and Cs is larger than the radius of Ce. Also, the distances between the atoms of Ce–Ce, Ce–Ru, Ce–Ge are 0.42974, 0.32964, 0.32694 nm, respectively.\footnote{3} Therefore the atom radius of Ce, Ru, Ge are 0.21347, 0.11602, 0.11347 nm, respectively. $^{140}$Cs ion is considered to replace the Ce atom. However, how many % of $^{140}$Cs occupies the substitutional positions by ion implantation is not clear.

The decay scheme of $^{140}$Cs that was implanted to the sample by ISOL is shown in Fig. 2. As can been seen from this figure, the life-time of $^{140}$Ba (12.8 days) is, fairly long. Therefore, the radioactive equilibrium of $^{140}$Ba$^{140}$La is obtained. $^{140}$Cs decays to $^{140}$Ce $I = 4+$ intermediate state through $^{140}$Ba with life-time of 12,752 days and $^{140}$La with a lifetime 1.6781 days. The hyperfine interaction at an intermediate state was measured, by detecting angular correlations of 328.8 keV and 487.0 keV cascade following the $\beta$-decay of $^{140}$La. The parameters of the hyperfine interaction in the intermediate state of $^{140}$Ce are shown in Table 2. Here I is the nuclear spin, $\tau_N$ is the life-time of intermediate state, $\mu$ is the magnetic dipole moment, and $Q$ is the quadrupole moment.

![Fig. 2 Simplified decay scheme of the relevant A = 140 mass chain.](Image)

<table>
<thead>
<tr>
<th>$I$</th>
<th>$\tau_N$</th>
<th>$\mu$</th>
<th>$Q$</th>
<th>$A_{22}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4+$</td>
<td>3.45</td>
<td>$+4.35$</td>
<td>0.35</td>
<td>$-0.14$</td>
</tr>
</tbody>
</table>
Since the anisotropy of angular correlation is small and the life-time of the intermediate state is short, the $^{140}\text{Ce}$ perturbed angular correlation measurement is difficult. The value of $Q$ is fairly small in $^{140}\text{Ce}$, so we can analyze only a hyperfine magnetic field component.

We did TDPAC measurements in Osaka university radioisotope center Toyonaka annex. We used photomultiplier tubes (XP2020Q, Phillips) with scintillators of BaF$_2$ (the cylinder form of diameter 1.5 inch, height 1 inch, OKEN) to detect $\gamma$ rays. The time resolution in the conventional NaI scintillation counter is about 512 keV $\gamma$ rays of $^{22}\text{Na}$. The lifetime of the intermediate state of $^{140}\text{Ce}$ is short, 3.4 ns. Therefore, the time resolution of NaI was not sufficient. BaF$_2$ scintillator shows a fluorescence of 220 nm whose decay time is about 875 ps that is very short. Even the TDPAC that used the short lifetime probe of an intermediate state like $^{140}\text{Ce}$ could be measured with good accuracy. Also, $^{60}\text{Co}$ is sometimes used to measure the time resolution of the experimental setup, because the two cascade $\gamma$ rays of 1.17 and 1.33 MeV are emitted after $\beta$ decay of $^{60}\text{Co}$. The time resolution of the measurement system used was about 588 ps.

We performed the measurements of TDPAC at 4.2 K and at room temperature. CeRu$_2$Ge$_2$ is ferromagnetic with magnetic moments aligned along the $c$ axis. The ferromagnetic transition temperature is 7.9 K. An external magnetic field was applied to the sample along the $c$ axis to order the magnetic moments of the specimen. We inserted the sample sealed with polyethylene in a glass liquid He dewar. The external magnetic field of 0.784(9) T was applied to the sample upwards, perpendicular to the detector plane (Fig. 3). The top and bottom of the sample was fixed with 2 small size permanent magnets (NEOMAX) with the height of 5 mm, and the diameter of 6 mm. Since room temperature is higher than $T_c$, the CeRu$_2$Ge$_2$ is paramagnetic, and we did the room temperature measurement without applying an external magnetic field.

The detectors were arranged as can be seen in Fig. 3. We arranged 3 detectors, so that the angle with respect of each other is 135°, 90°, and 135°. In this configuration, the time spectra in $+135^\circ$ and $-135^\circ$ angles were measured. The $\theta = +135^\circ$ of the time spectra (1, 2), (3, 1) and the $\theta = -135^\circ$ of the time spectra (2, 1), (1, 3) are measured simultaneously. Here, $(x, y)$ means that $\gamma_1$ (328.762 keV) is detected by $D_x$ (see Fig. 3), and $\gamma_2$ (487.021 keV) is detected by $D_y$. Four time spectra are obtained simultaneously. We define the channel that corresponds to time 0 with each spectrum. By substituting four time spectra to the following eq. (3), we obtain one PAC spectrum.

The measurement was performed by a conventional fast-slow method. We subtract backgrounds from 4 time spectra, and take out the part of a perturbation as follows:

$$R(t) = \frac{4}{3} \sqrt{C_{12}C_{31}} - \sqrt{C_{21}C_{13}} \cong A_{22}G_{22}(t)$$

$$C_{12}, C_{31},$$ are time spectra of $+135^\circ$, $C_{21}, C_{13}$ are time spectra of $-135^\circ$, respectively. If the magnetic field at the nucleus is not perpendicular to detector plane, or, if electric field gradient (EFG) is added to the magnetic field, $R(t)$ cannot analytically be expressed.

We consider the easiest case that a nucleus is sensing only a uniform static magnetic field. The magnetic field is either the external magnetic field or hyperfine magnetic field or a combination of both. The magnetic field is perpendicular to detector plane. The time spectrum $R(t)$ is simplified to the form:

$$R(t) \approx -A_{22} \sin(2\omega_Lt).$$

The $A_{22}$ is an angular correlation coefficient. It is $-0.105$ for the 328.8 keV–487.0 keV cascade. Larmor frequency $\omega_L$ is proportional to hyperfine magnetic field $H_{hf}$:

$$\omega_L = -2\pi g_\mu_NT_{hf}/h.$$  

If we know the $g$ factor of the level of an intermediate state, we can obtain $H_{hf}$. Various measured values of the $g$ factors of 2083 keV level of $^{140}\text{Ce}$ are reported. In the present work, we used the value of $g = 1.11(4)^{(1)}$ derived by Rijswijk et al.

3. Results and Discussion

We performed magnetization measurement by using the SQUID magnetometer to obtain information with regard to the magnetism of CeRu$_2$Ge$_2$. The temperature dependence of reciprocal susceptibility and magnetic susceptibility are shown in Figs. 4(a), (b), together with the magnetization in the applied magnetic field along $c$ axis in Fig. 4(c).

Figure 4(b) shows the temperature dependence of the susceptibility. Susceptibility $\chi$ is expressed by the Curie-Weiss law:

$$\chi = \frac{C}{T - \Theta}$$

$$C = \frac{N\mu_{eff}^2}{3k_B}$$

Here, $C$ is the Curie’s constant, $\Theta$ is the Weiss temperature, $\mu_{eff}$ is effective magnetic moment, $N$ is the number of atoms included in unit volume. However, susceptibility $\chi$, at the time of $H \to 0$, becomes

$$\chi = \frac{C}{T - \Theta} + \alpha_2.$$
\( \alpha_i \) is a non temperature dependent term. This term is called temperature independent paramagnetism. When we fit the experimental data to the eq. (7), the fixed numerical term becomes negative. Therefore it is conceivable that the influence of diamagnetism is larger than constant paramagnetism. By curve fitting, Weiss temperature is obtained to be 9.27 K.

From Fig. 4(a), the \( \chi^{-1} \) follows the Curie-Weiss rule well in the high temperature range above about 20 K. Equation (6) was transformed, and became

\[
\frac{\mu_{\text{eff}}}{\mu_B} = \sqrt{\frac{3k_B C}{N\mu_B^2}}. \tag{8}
\]

\( k_B = 1.38 \times 10^{-16} \text{ [erg K}^{-1}] \), \( N = 6.02 \times 10^{23} \text{ [mol}^{-1}] \), \( C = 1.41 \text{ [erg K mol}^{-1} \text{ G}^{-2}] \) were substituted to this equation. The value of \( C \) was obtained from the reciprocal of the inclination, which was obtained from fitting high temperature range of Fig. 4(a) by straight line. The result is calculated with the cgs system of units \( \mu_{\text{eff}} = 3.36 \mu_B \). Then, the \( \mu_{\text{eff}} \) of a free Ce\(^{3+} \) ion is as follows:

\[
\mu_{\text{eff}} = g \sqrt{J(J+1)} \mu_B \tag{9}
\]

The \( g \) factor is expressed by using total spin \( S \), total orbital angular momentum \( L \), the total angular momentum \( J \), as

\[
g = 1 + \frac{J(J+1) + S(S + 1) - L(L + 1)}{2J(J + 1)}. \tag{10}
\]

In the case of free Ce\(^{3+} \) ion, \( S = 1/2, L = 3, J = 5/2 \). Substituting these values to eq. (10), \( g = 0.857 \), and \( \mu_{\text{eff}} = 2.54 \mu_B \) from the eq. (9) are obtained. The experimental value of the present work is larger by about 0.82 \( \mu_B \). The following is conceivable for this increase. Temperature range where the Curie law is applied in this case is too narrow (20 to 100 K), thus it was not able to disregard the existence of paramagnetic term which does not contribute to temperature such as Pauli paramagnetism or orbital paramagnetism. The influence of the deficit of Ce could also be considered. However, the evidence is not sufficient for explaining the experiment.

The susceptibility for 0 to 300 K of the similar sample was measured by SQUID magnetometer (MPMSR2, Quantum Design) in the Onuki laboratory where the sample was prepared. As a result of fitting the susceptibility at the high temperature range, the \( \mu_{\text{eff}} = 2.829 \mu_B \) and Weiss temperature is 40.3 K, in accordance with Curie-Weiss rule. This value of \( \mu_{\text{eff}} \) is about 10% larger than the calculated value of Ce\(^{3+} \). There is a strong anisotropy, by changing axis direction from \( a \) to \( c \), and the \( c \) axis direction is an easy axis from the measurement result of susceptibility. Also, there was not the hysteresis at the transition point. Susceptibility goes up sharply at about 8 K.

From Fig. 4(c), the magnetic moment at 4.2 K is saturated with about 0.2 T. Therefore it has already been saturated in external magnetic field 0.78 T that was applied in TDPAC measurement. As a result, the saturation magnetic moment is 1.848 \( \mu_B/\text{Ce atom} \). This value is very near to 1.96 \( \mu_B \) obtained by neutron scattering result by Besnus et al.\(^4 \) and 1.81 \( \mu_B \) of the magnetization measurement in the Onuki et al.\(^2 \) From these results, it is clear that, CeRu\(_2\)Ge\(_2\) shows ferromagnetism at 4.2 K. It is understood that the saturation magnetic moment depends on the ferromagnetic transition. From the magnetization measurements the magnetization towards the \( c \) axis direction is saturated by a small magnetic field of 0.1 T and the saturation magnetic moment of \( c \) axis direction is about 1.81 \( \mu_B \), and that of \( a \) axis is about 0.57 \( \mu_B \).\(^2 \) The ferromagnetic transition temperature is to be about 8.0 K. This is in accord with the earlier paper.\(^5 \) However, Thompson et al.\(^5 \) reports according the specific heat measurement that two magnetic transitions exists in this compounds (see Introduction). But antiferromagnetic transition was not found in our measurement result of the susceptibility.

The \(^{140}\text{Ce} \) TDPAC spectra at 4.2 K and 298 K of the CeRu\(_2\)Ge\(_2\) single crystals are shown in Figs. 5(a), (b). Also, the spectra transformed by Fourier transformation with the method of MEM, are shown in Figs. 5(c), (d). The solid line in Fig. 5(a) shows the results from fit with eq. (4).

CeRu\(_2\)Ge\(_2\) is paramagnetic at 298 K. Therefore the clear Larmor frequency was not observed in the spectrum. On the other hand, the evident Larmor frequency component of \(-1.32(1) \text{ Grad/s} \) is observed at 4.2 K (Fig. 5(c)). We calculated the hyperfine magnetic field at \(^{140}\text{Ce} \) from eq. (5). As a result, the hyperfine field obtained is +24.9(2) T. However, this value is the vector sum of an external magnetic field and hyperfine magnetic field. The value of the real hyperfine magnetic field is 24.2(2) T. Thus the hyperfine magnetic field of the Ce nuclear site in a Ce compound was obtained for the first time. The result obtained shows a good fit with single magnetic field. This fact implies that the implanted Cs ion occupies a Ce site in this compound. Because, if Cs occupies an interstitial, Ru and Ge sites, these should be other hyper-
140 Ce ($\leftarrow$ 140 La) Time-Differential Perturbed Angular Correlation Study of CeRu$_2$Ge$_2$

Fig. 5 140 Ce TDPAC spectra of CeRu$_2$Ge$_2$ measured at (a) 4.2 K with an applied external magnetic field of 0.784(9) T, (b) room temperature. Fourier transformed spectra of R(\(t\)) for CeRu$_2$Ge$_2$ measured at (c) 4.2 K with an applied external magnetic field of 0.784(9) T, (d) room temperature.

The fine magnetic field. Hyperfine coupling constant is given by

\[
A \equiv \frac{H_i(T)}{M\mu_B} = \frac{24.2 \pm 0.2}{1.848 \pm 0.025} \cong 13.1(3) T / \mu_B. \tag{11}
\]

The value of the magnetic field obtained is small as compared with the measured value of 41(2) T, reported with the experiment of NMR/ON of 141 CeFe. Also, Ishikawa also measured TDPAC measurement of 140 CeFe and obtained the hyperfine magnetic field of 18.0(7) T. There are also few reports regarding the magnetic field at Ce nucleus in CeRu$_2$Ge$_2$.

4. Summary

CeRu$_2$Ge$_2$ is known as one of the few ferromagnetic compounds among CeT$_2$Ge$_2$ (T = transition metal series). In order to obtain information concerning the magnetism of CeRu$_2$Ge$_2$, we did magnetization measurements and 140 Ce TDPAC. As a result the saturation magnetic moment of 1.848 $\mu_B$, and Weiss temperature 9.27 K are obtained. Also, an effective magnetic moment of 3.36 $\mu_B$ is obtained. This value is slightly larger than the effective magnetic moment of free Ce$^{3+}$ ion. We did the measurement of the single crystal of CeRu$_2$Ge$_2$ at 4.2 K and RT by using the time differential perturbed angular correlation method of 140 Ce nuclei. The ferromagnetic transition temperature of CeRu$_2$Ge$_2$ is 7.9 K. This compound is paramagnetic at RT, therefore any perturbation in TDPAC spectrum has not been observed at room temperature. On the other hand, this compound is ferromagnetic at 4.2 K. The Larmor frequency of 1.32(1) Grad/s is observed at 4.2 K by applying the external magnetic field along c axis. The magnitude of the hyperfine magnetic field at 140 Ce nucleus was 24.2(2) T at 4.2 K.

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