Nuclear magnetic moment of the ^{143}Ce ground state

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(Received 25 April 2001; published 30 November 2001)

The nuclear magnetic moment of the ^{143}Ce ground state ($T_{1/2}=33.0$ h, $I^{\pi}=3/2^{-}$) has been measured with the technique of nuclear magnetic resonance on oriented nuclei (NMR-ON) at low temperature. A sample (^{143}Ce*Fe*) was prepared by implanting into an Fe foil nuclei of mass number 143, which were separated from fission products with an on-line isotope separator. The NMR-ON spectra were obtained by detecting specific β and γ rays, and the resonance frequency was thereby determined to be 84.3(1) MHz. Using the reported value of the hyperfine magnetic field at other Ce nuclei in Fe, the nuclear magnetic moment of the ^{143}Ce ground state was determined to be $|\mu|=0.43(1)$ μ_N. This value is discussed based on a systematics of the magnetic moments of other $N=85$ nuclei.

DOI: 10.1103/PhysRevC.65.017301 PACS number(s): 21.10.Ky, 27.60.+j

Many experimental methods have been developed to measure nuclear magnetic dipole moments with great precision, the quantities of which provide important information on nuclear structure. The method of nuclear magnetic resonance on oriented nuclei (NMR-ON) is such a useful technique. Because of its highly sensitive detection of the magnetic hyperfine-splitting frequency, this method has been well employed to determine the magnetic moments of many nuclei with high precision. However, only a few NMR-ON experiments have been performed for nuclei in the rare-earth region owing to difficulties in source preparation. Moreover, the $4f$-electron contribution to the effective magnetic field generally makes it difficult to obtain resonance spectra for ferromagnetic hosts. The first successful NMR-ON experiment for rare-earth nuclei was performed on the ground state of ^{141}Ce by Rijswijk *et al.* using a ^{141}Ce*Fe* sample [1]. (Here and hereafter, ^{141}Ce*Fe*, for example, stands for ^{141}Ce doped in an Fe matrix.) In this case, they considered that the $4f$-electron contribution might be quenched by the crystal field interaction. After a long interval, the magnetic moments of ^{137m,g}Ce and ^{139}Ce were measured by Muto *et al.* using the NMR-ON technique [2]. For a further investigation of the nuclear structures in this region, NMR-ON experiments should be continued.

The ground state of ^{143}Ce is one of targets to which the NMR-ON technique is applicable. Although the value of its magnetic moment has already been reported by Haag *et al.* [3], i.e., $1.0(3)\mu_N$, the attached error is rather large. They studied odd nuclei of Ce from ^{137}Ce to ^{143}Ce using the low-temperature nuclear orientation (NO) method. This technique usually requires knowledge of the nuclear decay parameters, the sample temperature and, in some cases, the fraction of nuclei substituted into regular lattice sites. On the other hand, the NMR-ON technique can directly determine the magnetic hyperfine-splitting frequencies. Therefore, the magnetic moments obtained from NMR-ON experiments are more reliable than those from NO experiments. Moreover, their value for the magnetic moment of the ^{143}Ce ground state was obtained assuming its spin to be 7/2. However, several nuclear spectroscopic experiments, carried out afterwards, with the atomic-beam resonance method, using the ^{142}Ce$(d,p)^{143}$Ce and ^{142}Ce$(n,\gamma)^{143}$Ce reactions, have established the spin value of the ^{143}Ce ground state to be 3/2 [4–6]. In the present experiment, by applying the NMR-ON method to this nuclear state, we could successfully obtain the value of its magnetic moment with better precision. We discuss our value of the moment by comparing it with those of other $N=85$ nuclei.

We applied a radioactive ion-implantation technique to the source preparation using a gas-jet type on-line isotope separator installed at Research Reactor Institute of Kyoto University (KUR-ISOL) [7]. Radioactive nuclides were produced by the thermal fission of a neutron-irradiated 50-mg ^{235}U target under a flux of 3×10^{12} *neutrons* cm^{-2}s^{-1}. After being transported through a capillary (1.5-mm inner diameter) and a two-stage skimmer chamber, the fission products were ionized by a surface ionization ion source. In the present experiments, the ion source was adjusted to effectively ionize the Ba and Cs atoms as their metal ions. The ionized fission products were accelerated to 30 keV and then mass separated. Subsequently, the mass-separated $A=143$ nuclei were reaccelerated up to 110 keV with a recently installed electrostatic postaccelerating equipment and implanted into a polycrystalline iron foil of 99.997% purity. The implantation depth was estimated to be about 20 nm. A schematic diagram of the postaccelerator is shown in Fig. 1. The implanted $A=143$ nuclei changed to ^{143}Ce through β^- decay in several hours and a ^{143}Ce*Fe* sample was thereby prepared. The radioactivity of ^{143}Ce was about 60 kBq.

The prepared sample was transported to Niigata University. A part of strong radioactivity was punched out (4 mm in diameter) from the foil and was soft soldered to the bottom of a copper cold finger together with a ^{60}Co*Co* single crys-

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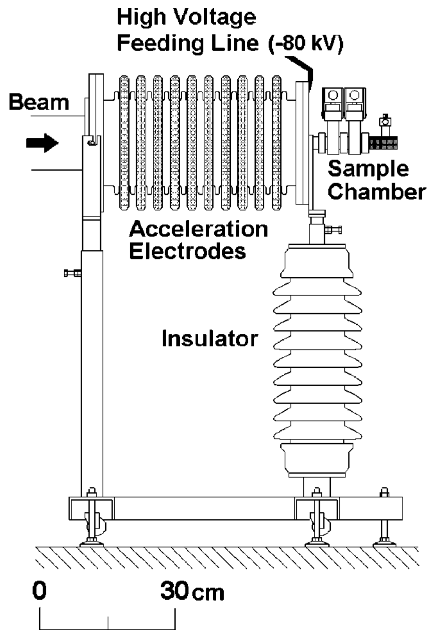

FIG. 1. Side view of the postaccelerator installed at KUR-ISOL. Its full length is about 70 cm and a high voltage of -80 kV was applied at the end flange. The sample was mounted in the small chamber shown.

tal, serving as a thermometer. The sample was then cooled down to about 7 mK in a few hours using a ^{3}He-^{4}He dilution refrigerator [8,9]. To polarize ^{143}Ce nuclei through the strong hyperfine magnetic interaction in the ferromagnetic host, an external magnetic field (B_0) of 0.2 T was applied with superconducting split coils. A radio-frequency (r.f.) field was then applied to this sample to destroy the nuclear orientation, and the resonance frequency was determined by observing the largest change in the anisotropy of β and γ rays. The γ rays were measured with four Ge detectors placed outside of a ^{3}He-^{4}He dilution refrigerator. The β rays were measured with two Si detectors with a surface area of 50 mm^2 and a thickness of 0.7 mm at 0° and 180° with respect to B_0. The Si detectors were mounted on a 0.7 K heat shield in the refrigerator.

The β ($Q_\beta = 1461.6$ keV) and 293-keV γ transitions following the ^{143}Ce decays were used to detect the resonance in ^{143}Ce*Fe* (see Fig. 2). The resonance spectra were taken by

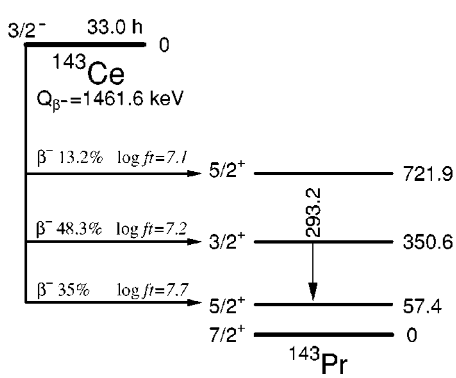

FIG. 2. Relevant part of the decay scheme of ^{143}Ce.

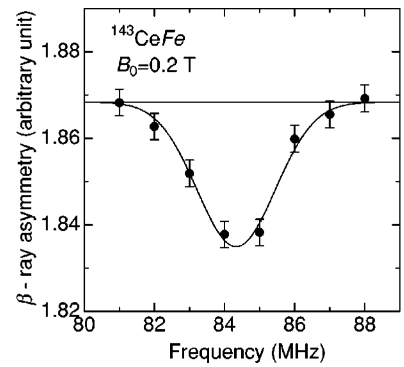

FIG. 3. β-NMR-ON spectrum for ^{143}Ce*Fe* at $B_0 = 0.2$ T with ± 1 MHz FM. The β-rays asymmetry $N(0°)/N(180°)$ was measured with respect to B_0.

increasing the r.f. field in steps of 1 MHz, the modulation of which was ± 1 MHz.

Figures 3 and 4 show the resonance spectra obtained with β- and γ-NMR-ON, respectively. The data-accumulation period for each point was 900 s with no time interval between them, and life-time ($T_{1/2} = 33.0$ h) corrections were made for the observed yields. Generally, the spin-lattice relaxation time (T_1) is inversely proportional to the square of the resonance frequency (ν): $T_1 \propto 1/\nu^2$. From the values of $T_1 = 7.8(33)$ min and $\nu = 54.25$ MHz for ^{137m}Ce*Fe* [2], the relaxation time of ^{143}Ce*Fe* was evaluated to be 3.2 min. The solid lines in the resonance spectra represent the results of least-squares fits to the data of an expression consisting of a Gaussian distribution, which was modified for the effect of the relaxation time. In the fitting procedure, we neglected electric quadrupole interactions.

The resonance frequencies determined from the β-NMR-ON and the NMR-ON of the 293-keV γ transition are 84.3(1) MHz and 84.5(4) MHz, respectively, and the weighted average $\overline{\nu}$ is 84.3(1) MHz. For a pure magnetic interaction, the resonance frequency is given by

$$\nu = \left| \frac{\mu}{Ih} [B_{\rm HF} + (1+K)B_0] \right|,$$

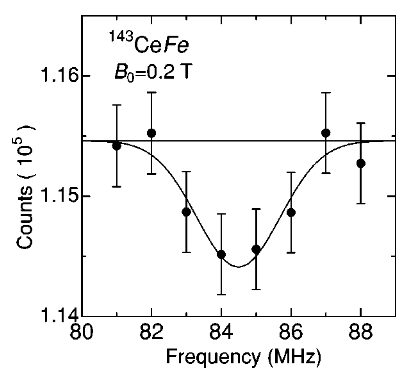

FIG. 4. NMR-ON spectrum of the 293-keV γ transition for ^{143}Ce*Fe* at $B_0 = 0.2$ T with ± 1 MHz FM. This spectrum was obtained with a high-purity Ge detector (60% efficiency) placed at $\theta = 180°$ with respect to B_0.

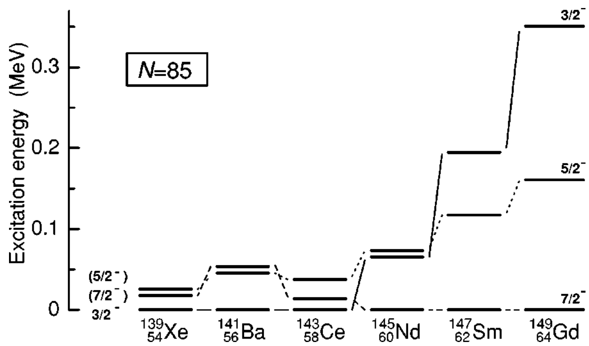

FIG. 5. Low-lying levels of $N=85$ isotones. The spin and parity values were taken from Ref. [18].

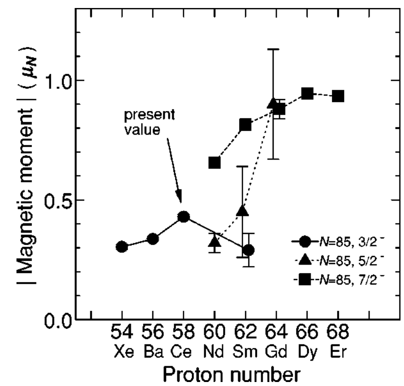

FIG. 6. Systematics of the magnetic moments of $N=85$ nuclei.

where I is the nuclear spin, B_0 the external magnetic field, $B_{\rm HF}$ the hyperfine field, and K the Knight shift factor. The values of $I=3/2$, $B_0=0.2$ T, and $B_{\rm HF}=-38.8(10)$ T were used to evaluate the magnetic moment of the ^{143}Ce ground state. For the $B_{\rm HF}$ value, two values are reported: $-38.8(10)$ T for ^{137}CeFe [2] and $-41(2)$ T for ^{141}CeFe [10]. We adopted the former value because of its higher precision. As mentioned above, the relaxation time of ^{143}CeFe is about 3 min, which is long enough for K to be safely neglected. The finally determined magnetic moment of ^{143}Ce is

$$|\mu(^{143}\mathrm{Ce},3/2^-)|=0.43(1)\ \ \mu_N.$$

The sign of the magnetic moment of ^{143}Ce was not determined, although the β-ray asymmetry $[N(0°)/N(180°)]$ was measured in the present experiment. As can be seen from Fig. 2, the strong β^- transitions of ^{143}Ce can be classified as a non-unique first forbidden decay. When the β-ray angular distribution is evaluated, the ξ approximation can be applied to most of the non-unique first forbidden transitions [11]. For the β decay of ^{143}Ce, it was suggested that the two strong β transitions, $3/2^-\rightarrow 5/2^+$ and $3/2^-\rightarrow 3/2^+$, fit into the ξ approximation [12–14]. However, even when the ξ approximation is used, a requisite β-angular distribution coefficient A_1 for the $3/2^-\rightarrow 3/2^+$ transition, cannot be estimated reliably because it is difficult to obtain accurate nuclear matrix elements for this transition [15]. Although the sign was not determined from the present experiment, it is expected to be negative from the facts that the signs of the magnetic moments of most $N=85$ nuclei in the neighborhood of ^{143}Ce are negative and that the Schmidt value for ^{143}Ce is negative, -1.91.

Nuclei of mass $A\cong 150$ show various complicated features. For example, the nuclear deformation changes drastically with only a small change in the mass number. The properties of these nuclei arise from an interplay between single-particle excitations and collective motions. The $N=85$ nuclei have three valence neutrons above the $N=82$ major shell, which cause various phenomena. In the low-lying levels of $N=85$ nuclei, triplet states of $3/2^-,5/2^-$, and $7/2^-$, which are basically due to the $(f_{7/2})^3$ configuration, are typically observed and we can easily see a significant change in the nuclear structure along with a change in the sequence of these levels. As can be seen in Fig. 5, the $7/2^-$ level is the ground state and the $3/2^-$ one is the highest state in $^{149}_{64}$Gd$_{85}$. These three low-lying states of ^{149}Gd represent approximately a property of the closed proton shell ($Z=64$) structure. The $3/2^-$ state is systematically lowered as the mass number decreases, and then becomes the ground state in ^{143}Ce, ^{141}Ba, and ^{139}Xe. This effect is known as the $I=j-2$ anomaly [16]. Moreover, a change is also seen in the deformation parameters for these nuclei. The values of the quadrupole deformation parameter (β_2) of the ground states were calculated by Möller *et al.*: $\beta_2(^{139}\mathrm{Xe})=0.100$, $\beta_2(^{141}\mathrm{Ba})=0.116$, $\beta_2(^{143}$Ce and $^{145}\mathrm{Nd})=0.134$, $\beta_2(^{147}\mathrm{Sm})=0.143$, and $\beta_2(^{149}\mathrm{Gd})=0.134$ [17]. These two examples indicate that the nuclear structure changes at ^{143}Ce. Therefore, ^{143}Ce should contain important information for studies of the $N=85$ nuclei. In order to examine the present result on ^{143}Ce, we first compare our value with those of $N=85$ nuclei in the neighborhood of ^{143}Ce. Figure 6 shows the systematics of the experimental magnetic moments of $N=85$ nuclei with $54\leqslant Z\leqslant 68$ [18], including the present work. Our value is consistent with the $3/2^-$ systematics, although the magnetic moment of the $3/2^-$ state of ^{145}Nd has not been measured. Moreover, the systematics of the ground-state magnetic moments also reflects the aforementioned large change between ^{143}Ce and ^{145}Nd.

We attempted to investigate the magnetic moments using two nuclear models: the rotation-vibration coupling model (RVCM) [19] and the interacting boson fermion model (IBFM) [20]. However, the experimental magnetic moments of the $j-2$ anomaly nuclei (^{139}Xe, ^{141}Ba, and ^{143}Ce) were not reproduced. Therefore, the present experimental result cannot be examined using these theoretical models. Dias and Krmpotić have discussed the structure of the low-lying levels of $N=85$ nuclei within the framework of the three-particle cluster-phonon coupling model; the magnetic moments of the triplet levels $3/2^-,5/2^-$, and $7/2^-$ were calculated to be $-0.698\ \mu_N$, $-0.506\ \mu_N$, and $-0.794\ \mu_N$, respectively [21]. Although the calculated value for the $7/2^-$ level seems to be consistent with the experimental values shown in Fig. 6, that for the $3/2^-$ level is considerably larger than the present value. In order to reproduce the values of the magnetic moments of $N=85$ nuclei with these theoretical calculations, higher order effects, as Dias and Krmpotić suggested [21], might have to be included in each model.

To summarize, we used the ion-implantation technique with KUR-ISOL and the NMR-ON method with a ^{3}He-^{4}He dilution refrigerator in order to determine the magnetic moment of the ^{143}Ce ground state with high precision. The magnetic moment of the ^{143}Ce ground state $(3/2^-)$ thereby determined is $|\mu|=0.43(1)\ \mu_N$. The present value is reasonably consistent with the systematics of the magnetic moments of $N=85$ nuclei. On the other hand, this value was not reproduced in calculations based on the RVCM and the IBFM and was also inconsistent with the value calculated using the three-particle cluster-phonon coupling model. Therefore, the determined magnetic moment would stimulate theoretical calculations. We hope that further theoretical studies on the magnetic moment of $N=85$ nuclei, including the present result, will be conducted in order to understand the properties of $N=85$ nuclei more profoundly.

One of the authors (A.T.) would like to thank Professor Nobuaki Yoshida of Kansai University for his IBFM calculation and Professor Shigeru Yamada of Research Reactor Institute, Kyoto University for his useful suggestions concerning the RVCM calculation. This research was supported in part by a Grant-in-Aid for the Scientific Research (Grant No. 10044080) of the Ministry of Education, Culture, Science, Sports and Technology, Japan.

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