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Quenching of neutron E2 effective charge in neutron-rich nuclei and the ground-state spin-parity of ^{17}C

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Abstract. The electric quadrupole moment of ^{17}B and the g-factor of ^{17}C were measured by using the fragmentation-induced nuclear polarization technique combined with the β-NMR method. The experimental quadrupole moment of ^{17}B is found strikingly close to that of the neutron closed-shell isotope ^{13}B, indicating a strong quenching of the neutron $E2$ core-polarization charge. From the result obtained for the ^{17}C g-factor, we can conclude that the ground-state spin-parity of ^{17}C is $3/2^+$.

PACS. 21.10.Ky Electromagnetic moments – 24.70.+s Polarization phenomena in reactions – 25.70.Mn Projectile and target fragmentation

1 Introduction

The nuclear moment is one of the basic observables which sensitively probes the nuclear structures and interactions. We have been conducting the measurement of magnetic moments and electric quadrupole moments in neutron-rich nuclei by means of the spin-polarized radioactive isotope beams from the projectile fragmentation combined with the β-ray detected nuclear magnetic resonance (β-NMR) method [1–6]. The present status for the nuclear moments in a nuclear chart up to $Z = 9$ is shown in fig. 1. From the previous measurement of electric quadrupole moment Q for B isotopes ($A \leq 15$) [5], it has been suggested that the neutron $E2$ effective charge e_{n} is substantially smaller in ^{14}B and ^{15}B than those usually employed in sd-shell nuclei near the β-decay stability. In order to clarify whether this phenomenon also occurs when neutron richness increases, the Q-moment measurement for the more neutron-rich isotope ^{17}B ($I^\pi = 3/2^-, T_{1/2} = 5.08$ ms) was performed.

The ground-state spin-parity of ^{17}C($T_{1/2} = 193$ ms) has attracted attention and has been studied using several theoretical and experimental approaches [7–13]. According to shell model calculations, $I^\pi = 1/2^+, 3/2^+$ or $5/2^+$ are candidates for the ground state, but to choose one among them from theory is very difficult since the calculated energies for these three low-lying states are very close to each other as evident in fig. 2. Experimentally, from the β-decay branching ratio, the $I^\pi = 5/2^+$ spin-parity assignment is excluded [7]. Of the remaining two candidates, $I^\pi = 1/2^+$ and $3/2^+$, the latter has been proposed in recent experiments based on the β-delayed neutron spectroscopy [8,9] and on one-neutron removal reactions [10–13].

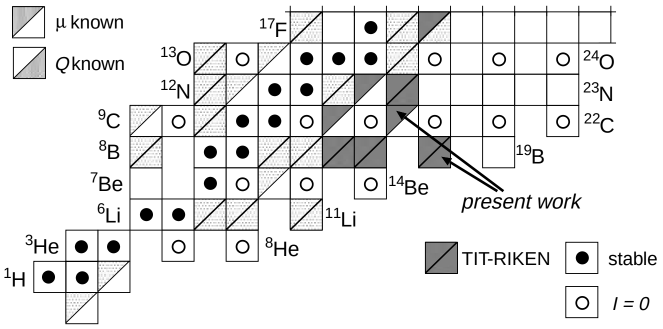

Fig. 1. Recent status of the nuclear moment measurements for nuclei up to $Z = 9$.

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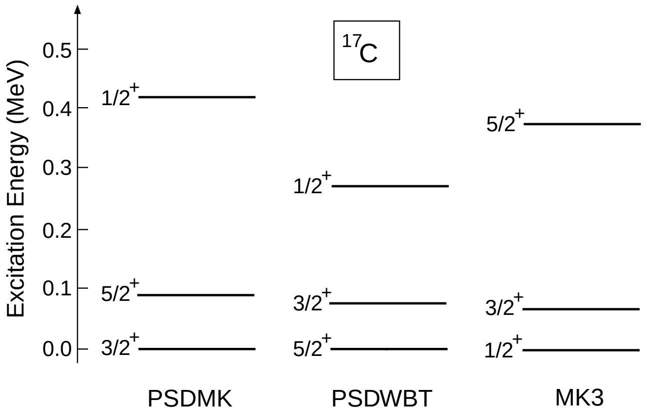

Fig. 2. Energy level diagram for the low-lying states of ^{17}C, calculated by shell models with *p-sd* model space. Those with PSDMK and PSDWBT interactions are obtained by using the OXBASH code, while that with the MK3 interaction is taken from ref. [7].

Under such a circumstance, the measurement of the g-factor would play a decisive role because it is extremely sensitive to whether the spin-parity is $1/2^+$ or $3/2^+$. In fact, the Schmidt value for $I^\pi = 1/2^+$ is 5 times larger than that for $I^\pi = 3/2^+$. In the present work, the g-factor of the ^{17}C ground state was measured to pin down the spin-parity.

2 Experiment

The experiments were carried out with the RIKEN Projectile Fragment Separator RIPS [14]. A ^{17}B (^{17}C) beam was produced from the fragmentation of ^{22}Ne projectiles on a ^{93}Nb target at an energy of 110 A MeV. In order to obtain the spin-polarized fragments, the emission angle θ_{L} and the outgoing momentum p_{F} of the fragments were selected by using an entrance slit of the RIPS combined with a beam swinger installed upstream and a slit at the momentum dispersive plane after the first dipole magnet, respectively. The produced spin-polarized ^{17}B (^{17}C) fragments were transported to the final focus of the RIPS, and then were implanted in a stopper to which a static magnetic field $\mathbf{B}_0$ was applied.

The nuclear magnetic substates of the fragments are split into $2I+1$ Zeeman levels by an energy $g\mu_{\mathrm{N}}B_0$ between the adjacent substates. When the axially symmetric electric field gradient q exists in a host material, the energy levels are shifted due to the electric quadrupole interaction. Thus, the energy E_m of the magnetic substate m is given by the first-order perturbation theory as

$$E_m = -g\mu_{\mathrm{N}}B_0 m + \frac{eqQ(3\cos^2\beta - 1)(3m^2 - I(I+1))}{8I(2I-1)}, \tag{1}$$

where β denotes the angle of the principal axis of the electric field gradient q with respect to the direction of the holding magnetic field $\mathbf{B}_0$. After the implantation of the fragments, the β-rays emitted from the fragments in the stopper were detected with plastic scintillator telescopes located above and below the stopper. The angular distribution of β-rays from the polarized fragments is expressed as

$$W(\theta) = 1 + \frac{v}{c}A_\beta P\cos\theta, \tag{2}$$

where θ is the angle between the emitted β-ray relative to the axis of the fragment polarization P, A_β the β-ray asymmetry factor, and $\frac{v}{c}$ the velocity of a β-particle measured in unit of speed of light. An oscillating magnetic field $\mathbf{B}_1$ with frequency ν is applied perpendicular to the static magnetic field with an RF coil around the stopper. If the applied frequency ν matches with the transition frequency $\nu_{m,m+1}$,

$$\nu_{m,m+1} = \frac{E_m - E_{m+1}}{h} = \frac{g\mu_{\mathrm{N}}B_0}{h} - \frac{3eqQ(3\cos^2\beta - 1)(2m+1)}{8I(2I-1)h}, \tag{3}$$

between the magnetic substates m and $m+1$, a spin-flip due to the nuclear magnetic resonance takes place, and the spin-flip is observed through detecting a change in the β-ray up/down asymmetry as $(1 + 2\xi A_\beta P) \to (1 - 2\xi A_\beta P)$, where ξ denotes the attenuation factor for the β-asymmetry due to a finite solid angle of the β-ray detection ($\xi \approx 0.75$ in the present setup).

2.1 The measurement of the quadrupole moment for ^{17}B

The production of spin-polarized ^{17}B beam has been previously studied [4]. The polarized fragments were implanted in a Mg single-crystal stopper whose c-axis was oriented perpendicular ($\beta = 90°$) or parallel ($\beta = 0°$) to the direction of the B_0 field. As described above, the quadrupole interaction between the Q moment of ^{17}B($I = 3/2$) and the cylindrically symmetric electric field gradient q at the ^{17}B site, splits the transition frequency $\nu_{m,m+1}$ into three components; ν_{L}, $\nu_{\mathrm{L}} \pm \nu_Q/2$ for $\beta = 0°$, where $\nu_Q = |eqQ/h|$ and $\nu_{\mathrm{L}} = |g\mu_{\mathrm{N}}B_0/h|$ (Larmor frequency). An oscillating field having these three frequency components was applied, each frequency being swept in the same direction and at the same rate.

Figure 3 shows the NMR spectrum obtained with a broad-bin frequency sweep $\Delta\nu_Q = 28.4$ kHz and at an angle of the c-axis $\beta = 90°$. The up/down ratio observed in the frequency region $\nu_Q = 120.8$–149.2 kHz shows a clear departure from the RF-off value (thin horizontal line) by 3.3 times the standard deviation, indicating that the resonance frequency of ν_Q is included in this region. Then more precise measurement was performed with a narrower-bin width $\Delta\nu_Q = 7.1$ kHz and at an angle of $\beta = 0°$. As a consequence, the value for ν_Q is obtained as $\nu_Q \equiv |\frac{eqQ}{h}(^{17}\mathrm{B\ in\ Mg})| = 138.1 \pm 4.7$ kHz in the present analysis. Taking the present value for ν_Q and the literature value for q [15], the quadrupole moment for ^{17}B is tentatively deduced as $|Q(^{17}\mathrm{B})| = 38.8 \pm 1.5$ mb.

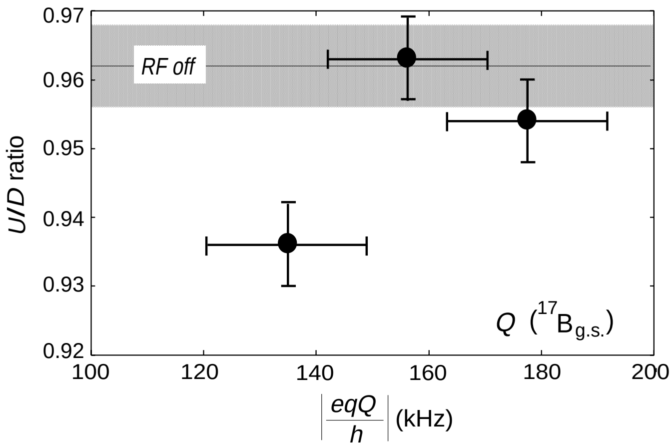

Fig. 3. β-NMR spectrum obtained in the quadrupole moment measurement for ^{17}B. The ^{17}B atoms were implanted in a Mg single crystal with the q principal axis (c-axis) aligned perpendicular to the holding magnetic field $\mathbf{B}_0$. The up/down ratio of β-ray intensities is plotted as a function of $\nu_Q = |eqQ/h|$. For each experimental point the statistical error and the width of the frequency sweep are indicated by the vertical and horizontal bars, respectively. The ratio measured without an oscillating radio frequency field $\mathbf{B}_1$ is marked by "RF-off".

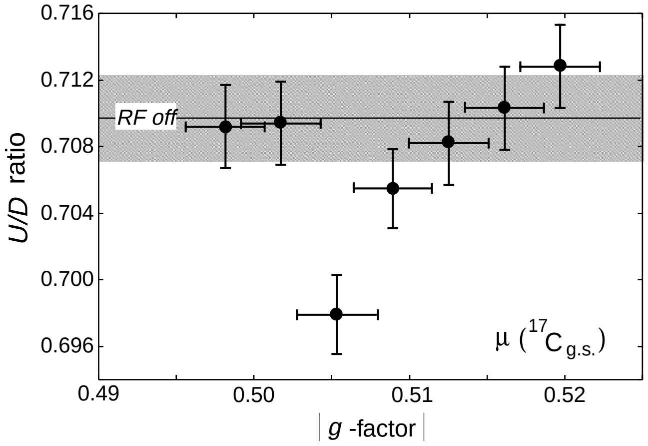

Fig. 4. β-NMR spectrum obtained in the measurement of the g-factor of ^{17}C, with bin widths ($\Delta\nu/\nu$) of 0.01.

2.2 The measurement of the g-factor for ^{17}C

As was already mentioned, the predicted g values for ^{17}C differ largely for the different assumptions on its spin value. The resonance search, therefore, should cover a wide frequency region, but such an experiment is difficult to perform in a single run: Several separate runs, each covering one of the divided frequency regions, need to be performed. Furthermore, the degree of polarization P obtained for fragments in the projectile fragmentation reaction shows steep variations with emisson angle θ_L and momentum p_F, and therefore is practically impossible to predict. Without knowing the size of ^{17}C polarization, the resonance search runs are forced to be pursued under an unknown sensitivity to detect NMR, since the sensitivity in the β-NMR depends critically on P. In order to overcome this difficulty, we introduced a method to determine the polarization P of ^{17}C before running the β-NMR experiments, by means of an adiabatic field rotation of a holding field [6]. With this method the settings for θ_L and p_F were successfully sought to optimize the polarization before knowing the g-factor, as $\theta_L = 3.8 \pm 1.5°$ and $p_F = 7.21$–7.66 GeV/c, and a β-ray asymmetry of $A_\beta P = -1.2 \pm 0.4\%$. After thus confirming the β-NMR sensitivity, the measurement of the g-factor was performed by using the adiabatic fast passage (AFP) method of NMR. The polarized ^{17}C fragments were implanted in a Pt stopper cooled at around 75 K. Then the frequency ν of the RF field was swept from $\nu - \frac{\Delta\nu}{2}$ to $\nu + \frac{\Delta\nu}{2}$. We started the measurement with a rather wide-bin width, and in the succeeding runs $\Delta\nu$ was gradually narrowed for more precise measurements. Finally, the g-factor of the ground state for ^{17}C, $|g(^{17}C)| = 0.5054 \pm 0.0025$, was preliminary obtained from the β-NMR spectrum shown in fig. 4.

3 Discussion

3.1 The quadrupole moment of ^{17}B

The obtained Q for ^{17}B, $|Q(^{17}B)| = 38.8 \pm 1.5$ mb, is noticeably close to that for ^{13}B, $|Q(^{13}B)| = 36.9 \pm 1.0$ mb [16]. A similar observation has been remarked in the previous work [5] for Q of ^{15}B, $|Q(^{15}B)| = 38.0 \pm 1.1$ mb. The neutron p-shell is closed in the $N = 8$ isotope ^{13}B, and by attaching two or four neutrons to it, one would expect the Q moment to increase due to increased polarizability of the neutron group. In this context, the noted similarities of $Q(^{15}B)$ and $Q(^{17}B)$ to $Q(^{13}B)$ may have relevance to the behavior of the neutron effective charge. In fig. 5, the experimental Q moments for the odd-mass B isotopes are compared with shell model calculations in the $0\hbar\omega$ model space with the effective interactions PSDMK

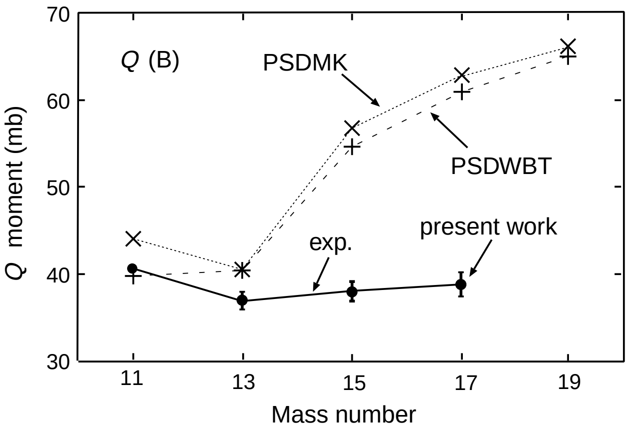

Fig. 5. Comparison between the experimental (exp.) and theoretical Q moments for odd-mass B isotopes. The calculated Q moments, using the effective interactions PSDMK and PSDWBT with $e_p = 1.3$ and $e_n = 0.5$, increase with the mass number in the neutron-rich region, while the experimental values are almost stable against the mass number and are considerably smaller than the shell model calculations for $A = 15$ and $A = 17$.

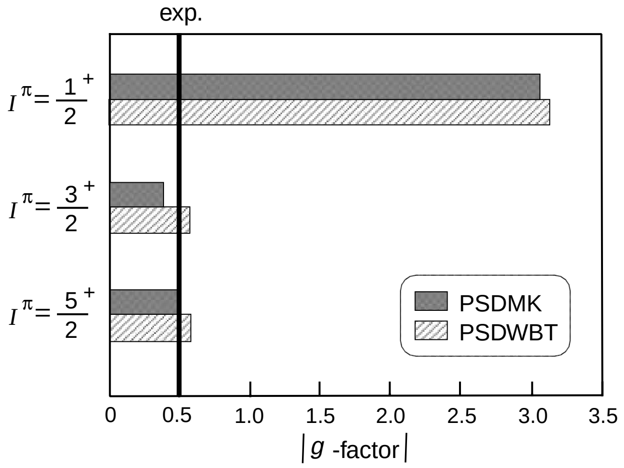

Fig. 6. Comparison of the experimental g-factor (exp.) for the ^{17}C ground state with theoretical predictions (PSDMK and PSDWBT). The calculated g-factor for a spin-parity $I^\pi = 1/2^+$ state is substantially larger than the experimental value.

and PSDWBT [17–19] using the OXBASH code [19]. The experimental Q moments stay almost constant against the mass number, while the calculated Q moments with effective charges $e_\mathrm{p} = 1.3$ and $e_\mathrm{n} = 0.5$ [20], the values normally employed in the sd-shell region, increase rapidly with mass number A for $A > 13$, reflecting the increasing contribution of neutrons in the sd orbit.

The Q moment of the ^{A}B isotope may be expressed as $eQ(^A\mathrm{B}) = e_\mathrm{p}Q_\mathrm{p}(^A\mathrm{B}) + e_\mathrm{n}Q_\mathrm{n}(^A\mathrm{B})$, where Q_p and Q_n are the mass quadrupole moments of proton and neutron groups, respectively, and e_p and e_n the effective charges for proton and neutron. If we replace $e_\mathrm{p}Q_\mathrm{p}(^A\mathrm{B})$ with $Q(^{13}\mathrm{B})$ and insert experimental values for $Q(^A\mathrm{B})$ and shell model values for $Q_\mathrm{n}(^A\mathrm{B})$, we obtain $e_\mathrm{n} = 0.02$ for ^{15}B and $e_\mathrm{n} = 0.03$ for ^{17}B. It is interesting to note that plotting the e_n values deduced for nuclei, including $Q(^{14}\mathrm{B})$ and $Q(^{18}\mathrm{N})$ from our preceding experiments and Q and $B(E2)$ data for light sd-shell, reveals a tendency that the neutron effective charge becomes gradually quenched as the degree of neutron excess develops.

3.2 The g-factor of ^{17}C

The experimental g-factor for the ground state of ^{17}C is much smaller than the Schmidt value for a $I^\pi = 1/2^+$ state, *i.e.*, $g_s(\mathrm{neutron}) = -3.83$. One might either take an effective g-factor $g_s^\mathrm{eff}(\mathrm{neutron}) = -3.48$ empirically determined from observed magnetic moments and $M1$ transitions of the sd-shell nuclei [21], but it again shows much larger in absolute value than the experimental $g(^{17}\mathrm{C})$. This suggests that the ground-state spin-parity is different from $1/2^+$. In fact, more elaborate theoretical g-factors for the $1/2^+$ state from shell model calculations using the PSDMK and PSDWBT interactions with the free $M1$ operator, shown in fig. 6, greatly exceed the experimental g-factor. Note that this argument does not depend on the choice of the $M1$ operator. For instance, the calculated g-factor employed with the effective $M1$ operator from the work of Arima, Shimizu, Bentz and Hyuga [22] for protons and that from Brown and Wildenthal [21] for neutrons, is only 10% smaller than that with the free $M1$ operator. We can thus clearly exclude the possibility of $1/2^+$ for the ground-state spin-parity from the present g-factor. Therefore the only remaining possibility for the ground-state spin-parity is restricted to $3/2^+$. Indeed, the experimental g-factor lies between the predictions for the $3/2^+$ state as shown in fig. 6.

4 Summary

The Q moment of ^{17}B and the g-factor of ^{17}C have been measured by using the β-NMR method with spin-polarized fragment beams. The obtained Q moment of ^{17}B, $|Q(^{17}\mathrm{B})| = 38.8 \pm 1.5$ mb, is considerably smaller than the shell model calculations with neutron effective charge $e_\mathrm{n} = 0.5$ which is commonly used in the sd-shell region. This quenching feature of the $E2$ core-polarization effect has been also indicated in the previous results for $Q(^{14}\mathrm{B})$, $Q(^{15}\mathrm{B})$ [5], and $Q(^{18}\mathrm{N})$ [6]. These observations may suggest the tendency that the core-polarization effect induced by the excess neutrons gets diminished with increasing degree of neutron richness. The g-factor of ^{17}C is an excellent tool for the assignment of its ground-state spin-parity. From the measured g-factor, $|g(^{17}\mathrm{C})| = 0.5054 \pm 0.0025$, the ground-state spin-parity of ^{17}C was assigned to be $I^\pi = 3/2^+$, and the possibility of $I^\pi = 1/2^+$ was clearly excluded.

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