Study of electromagnetic moments in unstable nuclei with radioactive nuclear beams

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Abstract. The measurements of nuclear moments have been conducted at RIKEN for the study of nuclei far from the β stability. Recent results for the magnetic moments of ³⁰Al and ³²Al obtained by means of β-NMR spectroscopy with spin-polarized radioactive beams from the projectile fragmentation reaction are presented. Remarks are also made on the developments and prospects for future moment studies at the RI beam Factory.

1. Introduction

A number of novel, ingenious techniques in nuclear spectroscopy, especially those invented for use with radioactive nuclear beams (RNB), have opened routes for the study of exotic nuclei, and raised challenges to traditional framework of nuclear physics that stemmed essentially from studies of nuclei near the valley of β-stability [1]. For example, at extremely large N/Z ratios the nucleus shows tendency to depart from the domain governed by shell closures at the traditional magic numbers, and to undergo a fundamental restructuring. In such a situation the nuclear moments, as well as energy levels and B(E2)'s, serve as decisive observables.

The experimental determination of nuclear moments for exotic nuclei obviously requires that the objective nuclei should be produced at certainly high rate and that their spins should be polarized. We thus came to take advantage of the projectile fragmentation reaction which was found to be useful not only for producing RNB themselves but also for polarizing them [2]. At the beginning, this projectile-fragmentation based polarized RNB technique was considered to be better applied to lighter nuclei because of some technical reason. In fact, our nuclear moment measurements started from mass A ∼ 10 region and stayed below A ∼ 20 until recently [3]. The present report includes the result from our nuclear-moment study carried out in a A ≥ 30 region. Certainly, with more valence nucleons in the sd- and (in some case) f-orbits, nuclear structure should be much enriched as compared to lighter nuclei. We found that our polarization method based on the fragmentation reaction worked fine in this region and the nuclear spin

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preservation was well realized to facilitate the $\beta$-ray detected nuclear magnetic resonance ($\beta$-NMR) experiments.

In this report we first discuss the nuclear moment measurements by means of the $\beta$-NMR spectroscopy applied to the fragmentation-based polarized RNB. Specifically, the recent results obtained for the ground-state magnetic moments of $^{30}$Al and $^{32}$Al [4] are presented. We then discuss the development of an atomic beam resonance apparatus which should enable systematic studies of exotic nuclei through nuclear moments at the forthcoming radioactive nuclear beam facility at RIKEN.

2. Nuclear moment measurements with $\beta$-NMR on projectile fragments
The occurrence of strong deformation at the traditional magic number $N = 20$ in neutron-rich Na isotopes was first suggested from the mass and magnetic moment measurements [5, 6]. Experimental studies since then on the first excited-state energies [7, 8, 9, 10, 11], $B(E2)$ values [12], electric quadrupole moments [13] and magnetic moments [14] have presented evidences that this type of anomaly takes place in $^{30}$Ne, $^{31,32}$Na and $^{31,32,34}$Mg. Theoretical works [15, 16] to explain this phenomenon have been developed, in which the deformation is considered to set in when the extent of intrusion of the $f$-orbit from the upper shell into the $sd$-shell reaches some critical level (such a region of nuclei where this happens is called the “island of inversion”). The extent of intrusion is considered to vary gradually as the neutron to proton number ratio $N/Z$ increases, based on the notion that the shell gap for neutron at $N = 20$ varies with varying number of particles in the proton orbits [17, 18, 19]. It is noted here that nuclei $^{30}$Na and $^{31}$Mg are considered to locate somewhat close to the critical level, and the occurrence of the anomaly was conclusively identified only after the measurements of their ground-state moments.

2.1. Experiment
We have measured the ground-state magnetic moments ($\mu$) of the neutron-rich isotopes $^{30}$Al and $^{32}$Al. $^{32}$Al is a nucleus just after the $^{30}$Na and $^{31}$Mg nuclei within a chain of $N = 19$ isotones. Figure 1 shows the arrangement of the projectile-fragment separator RIPS at RIKEN, used for the production of spin-polarized radioactive beams. $^{30}$Al and $^{32}$Al nuclei were produced in the fragmentation of $^{40}$Ar projectiles on a $^{93}$Nb target at an energy of $E/A = 95$ MeV/u. The spin polarization was produced by the fragmentation reaction itself: By selecting the emission angles that are different from zero, spins of the fragment nuclei is observed to be polarized in the

![Figure 1. Schematic layout of the fragment separator RIPS for the production of spin-polarized radioactive beams for the $\beta$-NMR experiments at RIKEN.](image-url)
direction perpendicular to the reaction plane, with the sign and magnitude depending on the momentum [2]. The mechanism of polarization is explained in terms of the angular momentum transfer in the nucleon removal process [2]. The selection of the emission angles was implemented by a beam swinger located upstream of the target, thus introducing the primary beam to the target in an inclined direction from the axis of acceptance by RIPS. The range of angles selected for the fragment momentum corresponding to the projectile velocity.

The 30Al or 32Al nuclei thus produced and spin-polarized were isotope-separated and momentum-selected, and then delivered to a β-NMR apparatus installed at the final focus of RIPS. Experimental setup for the β-NMR experiment is shown schematically in Fig. 2. The fragment nuclei were implanted in a single crystal α-Al2O3 stopper to which a static magnetic field $B_0$ was applied. A pair of coils were wound close to the stopper in order to apply an rf field $B_1$ to the stopper. The stopper was cooled at a temperature below 100 K, in order to assure the spin preservation times in the stopper to be sufficiently long compared to the nuclear lifetimes. β Rays emitted from the stopped activities were detected by counter telescopes placed above and below the stopper. The adiabatic fast passage method of NMR was applied to determine the nuclear $g$-factor, $g = \mu/I\mu_N$ where $\mu$, $\mu_N$, and $I$ denote the magnetic moment, nuclear magneton and spin, respectively. In the static field $B_0$ the energy splitting between the magnetic substates $|m\\rangle$ and $|m + 1\\rangle$ is given by $\hbar\nu_0 = g\mu_N B_0$, where $\hbar$ denotes Planck’s constant. Actually, since an electric field gradient acting in the hexagonal crystal of the Al2O3 stopper should produce a quadrupole splitting in $\nu_0$, the $c$-axis of the crystal was oriented at an angle $\theta_{\text{magic}}$ to the $B_0$ field, where $\theta_{\text{magic}}$ is defined by $3\cos^2 \theta_{\text{magic}} - 1 = 0$. More detailed accounts of the experimental procedures and analyses including the quadrupole splitting and other corrections to $\nu_0$ are presented in Ref. [4] and in the forthcoming publication. When the frequency $\nu$ of the rf field $B_1$ is swept across the Larmor frequency $\nu_0$, the spin of the fragment is reversed and consequently the up/down ratio of the β-ray counts at the counter telescopes changes.

In Figs. 3 and 4 the β-NMR spectra obtained for 30Al or 32Al are presented. For each isotope, several runs of frequency scan were carried out with narrower and narrower frequency windows. In the 30Al experiment, a wide-window run presented in the upper half of Fig. 3 showed a considerable decrease of the up/down ratio for a frequency region 3.77-3.97 MHz. Based on this result the finer scan presented in the lower part of Fig. 3 was performed, which lead to the result for the resonance, $\nu_0 = 3.829$ MHz. With $I = 3$ and $B_0 = 500.59$ mT, the magnetic moment $|\mu_{\text{exp}}| = 3.010 \pm 0.007 \mu_N$ was obtained for the 30Al ($I^\pi = 3^+$) ground state. In Fig. 4, a similar procedure lead to the result for the magnetic moment $|\mu_{\text{exp}}| = 1.959 \pm 0.009 \mu_N$ for the 32Al ($I^\pi = 1^+$) ground state. The β-NMR spectra in Figs. 3 and 4 also indicate that the sizes of polarization thus obtained were as large as $|P| = 0.5 - 1 \%$, in spite of the large numbers of
nucleons that were removed from the projectile $^{40}\text{Ar}$.

2.2. Discussion

In a normal-order filling model, the $I^\pi = 3^+$ ground state of $^{30}\text{Al}$, with 13 protons and 19 neutrons, is represented by a wave function $|\pi d_{5/2}^{-1} \nu d_{3/2}^{3/2} J=3\rangle$. The magnetic moment [20] of $^{30}\text{Al}$, however, should be smaller than the expectation value$^5$ $\mu = 4.59 \mu_N$ for this wave function, because the mixing of configurations with proton and neutron $d_{3/2} \rightarrow d_{3/2}$ excitations would produce negative contributions through the off-diagonal matrix elements. Shell-model calculations in the $sd$ space with the USD interaction [21] was carried out using the OXBASH code [22]. The result, $\mu_{\text{USD}}(^{30}\text{Al}) = 3.19 \mu_N$, is in good agreement with the experimental $\mu$.

Remaining in the $sd$ space, the normal-filling configuration for $^{32}\text{Al}$ is given by $|\pi d_{5/2}^{-1} \nu d_{3/2}^{-1} \rangle$. That is, if the $N = 20$ magic number persists also in $^{32}\text{Al}$, just turning a particle in the $\nu d_{3/2}$ orbit of $^{30}\text{Al}$ into a hole would make this nucleus. The USD calculations describe the ground state of $^{32}\text{Al}$ to be rather purely (to $\approx 80\%$ abundance) of the $|\pi d_{5/2}^{-1} \nu d_{3/2}^{-1} \rangle$ configuration. The resulting theoretical magnetic moment is $\mu_{\text{USD}}(^{32}\text{Al}) = 2.06 \mu_N$. [To the contrary, one might also assume that two neutrons in the $d_{3/2}$ orbit are promoted to the $f$-orbit across the $N = 20$ shell gap. In order to get insight into such a situation, a calculation was performed using the WBMB interaction [23], with two neutrons restricted to the $f$-orbit and the other 14 valence nucleons restricted to some truncated $sd$ space. The resulting $\mu$ was 25\% smaller than the $\mu_{\text{USD}}$ value above. Of course, more quantitative discussion including mixing between the normal and intruder configurations should be made on this.] The experimental magnetic moment $|\mu_{\text{exp}}| = 1.959 \pm 0.009 \mu_N$ is found to be close to $\mu_{\text{USD}}$.

Thus, the present data for $^{30}\text{Al}$ and $^{32}\text{Al}$ are well accounted for by calculations within the $sd$ space with the USD interaction, and we find no evidence for the occurrence of intruder state in the ground states of these isotopes. At this point a further remark may be made on the level scheme of $^{32}\text{Al}$. As stated earlier, in an $sd$ space model both of the two nuclei $^{30}\text{Al}$ and $^{32}\text{Al}$ are represented by a hole in the proton $d_{5/2}$ orbit and a particle or hole in the neutron $d_{3/2}$ orbit,

$^5$ Theoretical magnetic moments are evaluated in this report employing the effective $g$-factors of Ref. [20].
and moreover, the two are connected to each other by the particle-hole replacement. In such a case there is a relation \([24]\) between the level spacings in the two nuclei, as expressed by

\[
\Delta E(j_p^{-1} j_n^{-1}; JM) = - \sum_{J'} (2J' + 1) \left\{ \begin{array}{c} J_p \\ j_n \\ J' \end{array} \right\} \Delta E(j_p^{-1} j_n^{-1}; J'M),
\]

where \(\Delta E(\alpha; JM)\) is the energy difference between states \(J\) of the configuration \(\alpha\). The relation is considered to be quite general, applying to broad classes of two-body interactions. Since the energy spectrum of \(^{30}\)Al is known, one may deduce from Eq. (1) the energy spectrum for \(^{32}\)Al. Inserting the level energies \(E(^{30}\)Al; \(2^+\)) = 243.9 keV, \(E(^{30}\)Al; \(1^+\)) = 687.5 keV and \(E(^{30}\)Al; \(4^+\)) = 1245.6 keV (where the \(3^+\) state is the ground state) in \(^{30}\)Al [25], one obtains for \(^{32}\)Al [by setting the resulting lowest level energy \(E(^{32}\)Al; \(1^+\)) to be zero in this isotope], \(E(^{32}\)Al; \(2^+\)) = 746 keV, \(E(^{32}\)Al; \(4^+\)) = 1060 keV and \(E(^{32}\)Al; \(3^+\)) = 1404 keV. The former two level energies are found in quite good agreement with the empirical levels \(E_{\text{exp}}(^{32}\)Al; \(2^+) = 734\) keV and \(E_{\text{exp}}(^{32}\)Al; \(4^+) = 956\) keV [26], whereas the latter is not known experimentally. The ground-state spin of \(J = 1\) was reproduced correctly. It is interesting to note that, under the assumption that both of \(^{30}\)Al and \(^{32}\)Al are described within the \(sd\) shell model space, Eq. (1) with the empirical \(^{30}\)Al spectrum predicts correctly the ordering between the \(J^\pi = 2^+\) and \(4^+\) states in \(^{32}\)Al, which the WBMB calculations fails to reproduce [26].

3. Future plan

Thus far, we have studied magnetic moments of unstable nuclei using the \(\beta\)-NMR method, by taking advantage of spin polarization that is created in the RNB production process itself. Measurements are under way also for the electric quadrupole moments \((Q)\), which are considered even more sensitive to collectivity playing an essential role in the nuclear restructuring. For future, with increased production yields and expanded regions of accessible nuclei, it will become quite feasible to make systematic measurements of \(\mu\) and \(Q\), \(e.g.\) for a series of nuclei of same \(N\) but with varying \(Z\) (isotones) or those of same \(Z\) but with varying \(N\) (isotopes) in the nuclear chart. If, for example, \(N\) in the former case or \(Z\) in the latter is the magic number \(\pm 1\), the wave function of the ground state \(\psi_{\text{A}}^{J=j}\) of odd-\(A\) nuclei would contain an admixture from the low-lying quadrupole vibration so that \(\psi_{\text{A}}^{J=j} = \sqrt{1 - \alpha^2} |0^+ \otimes j^{J=j} + \alpha |2^+ \otimes j^{J=j}\). The magnetic moment \(\mu_{\text{A}}^{J=j}\) in this case is expressed as

\[
\mu_{\text{A}}^{J=j} = (1 - \alpha^2) \mu(j) + \alpha^2 \left[ \frac{3}{2(j+1)} \mu(2^+) + \left(1 - \frac{3}{j(j+1)}\right) \mu(j) \right]
\]

in terms of the moments \(\mu(j)\) and \(\mu(2^+)\) of the single particle state \(j\) and collective excitation \(2^+\), respectively. The mixing amplitude \(\alpha\) may then be deduced from the measured value of

![Figure 5. Schematic drawing of the present setup for RIABR experiment.](image-url)
such studies would disclose the evolution of nuclear structure, and in some case a phase transition with e.g. the deformation as an order parameter and the single particle energies or the number of valence particles as control parameters.

In pursuing such a systematic study extending wide in the nuclear chart, the present \(\beta\)-NMR + fragment polarization” scheme for \(\mu, Q\) measurements should serve as a very useful tool at least for a certain range of nuclei, but one might also need another method to complement it for other cases. We are developing a new method applying the atomic beam resonance technique to radioactive isotopes (RIABR) [27]. Figure 5 shows the present setup, designed for use at the forthcoming radioactive beam facility, the RI Beam Factory at RIKEN. In this method, the projectile fragments separated in a fragment separator are stopped in a rare gas in a stopping chamber. The stopped ions are transported by an electric field to the vicinity of an exit orifice, where a gas flow also assists them to spout out into a neutralizer section. The atoms thus neutralized are collimated to form a beam to be sent to a sextupole magnet. The atoms are spin-selected in the sextupole, then subjected to the rf transition between the hyperfine-coupled states in an rf cavity under a weak dipole field, and finally spin-selected again in a quadrupole magnet. Thus, the occurrence of the rf transition is detected through the appearance of atoms at the detector downstream of the quadrupole magnet. An advantage of the RIABR method is that, because it does not rely on the reaction-induced polarization nor the \(\beta\)-decay asymmetry, it is applicable in principle to any nuclei except those of rare-gas and alkaline-earth elements, irrespective of nuclear lifetimes, decay modes, and spin relaxation times in matter. The drawback would be its tendency towards low efficiency. We have been focusing our major efforts on this aspect in off-line experiments, and tests are going to be carried out using accelerator beams.

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