Electric quadrupole moment of the neutron-rich ^{33}Al

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Abstract. The nuclear electric quadrupole moment (Q moment) of the neutron-rich nucleus ^{33}Al ($I = 5/2$, $T_{1/2} = 41$ ms) has been measured by the β -ray detected nuclear quadrupole resonance (β -NQR) method for the first time. The ^{33}Al nucleus is considered to be on the border of the *island of inversion* within which a significant intrusion of the pf orbits occurs across the $N = 20$ shell gap and the intrusion causes an anomalous enhancement of the Q moment. Polarized ^{33}Al nuclei were produced from ^{36}S (77.5 MeV/ u) beams through the fragmentation process and separated by LISE fragment separator at GANIL. The ^{33}Al nuclei were implanted into a Al_2O_3 single-crystal plate and the β -NQR spectrum was successfully obtained.

PACS. 21.10.Ky Electromagnetic moments – 76.60.Gv Quadrupole resonance – 21.60.Cs Shell model – 25.70.Mn Projectile and target fragmentation

1 Introduction

The nuclear shell structure evolution which progresses toward the neutron drip line is an intriguing problem for both theorists and experimentalists. Nuclei which are located near the stability line have the closed shell structure at the magic numbers (2, 8, 20, 28, etc.) and it has been considered to be a universal truth for all nuclei. However, surprising experimental discoveries in γ -decay studies of ^{32}Mg , *e.g.* low location of the first 2^+ level [1,2] and sizably enhanced $B(E2)$ strength [3], were considered to reflect an anomalous deformation of the ground state in spite of the neutron closed shell structure of $N = 20$. Theoretical analysis [4] also suggested that the shell gap between the sd -shell and the fp -shell reduced for neutron-rich nuclei in a limited region ($Z = 10$ –12, $N = 20$ –22), and the $2p$ - $2h$ excitation played an important role to describe their nuclear structures. The limited region is known as the *island of inversion*. Moreover, anomalous

ground-state properties around the original *island of inversion* were revealed from recent studies of the electromagnetic moments of Na [5,6] and Mg [7,8] isotopes. Because the neutron-rich Al isotopes are considered to be on the border of the *island of inversion*, the nuclear structure of these Al isotopes is interesting to reveal the shell structure evolution. The $\mu(^{30,32}\text{Al})$ [9] and $Q(^{31,32}\text{Al})$ [10, 11] were reported by RIKEN and Tokyo Tech groups and $\mu(^{31-34}\text{Al})$ [12,13] by Leuven group. The $\mu(^{33,34}\text{Al})$ seem to deviate from the conventional sd -shell model prediction. From the Monte Carlo shell model calculation (SDPF-M), the probability of the fp -shell intruder configuration is predicted to be 64% in the ground state of ^{33}Al [14]. The Q moment is more sensitive to the *intrusion* phenomena than the μ moment because the $2p$ - $2h$ excitation causes the anomalous deformation. In the present work, the Q moment of ^{33}Al ($I = 5/2$, $T_{1/2} = 41$ ms) has been measured by the β -ray detected nuclear quadrupole resonance (β -NQR) in a high magnetic field for the first time. In this report, we will describe the details of the measurement.

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2 Experiments

The experiment was performed at GANIL. ^{33}Al nuclei were produced through the projectile fragmentation process in heavy-ion collisions of ^{36}S (77.5 MeV/u) and Be nuclei. The thickness of the production target was 1212 μm . The produced ^{33}Al were separated by two dipole magnets and a wedge-shaped energy degrader of Be (1068 μm thick) installed in the high-resolution fragment separator LISE. The purity of ^{33}Al was typically 75%. To induce nuclear spin polarization, ^{33}Al fragments with higher momenta than the peak momentum and deflection angle of $2^\circ \pm 1^\circ$ relative to the primary beam were selected. After these selections, the 1.3 kcps polarized ^{33}Al nuclei were transported to our NMR setup installed at the end of the beam line at the primary beam current of 2.1 e μA . The ^{33}Al nuclei were implanted into a cubic Si single crystal and a non-cubic $\alpha\text{-Al}_2\text{O}_3$ single crystal (corundum) for the $\beta\text{-NMR}$ and $\beta\text{-NQR}$ measurements, respectively. The crystal was set at the center of the NMR setup. The static magnetic field B_0 of 0.5000 tesla was applied parallel to the polarization to maintain the polarization and to induce the Larmor precession. To induce NMR of ^{33}Al , a strong radio frequency (rf) was applied perpendicular to the B_0 . Asymmetric β -ray emission from the polarized ^{33}Al was detected by two sets of the plastic-scintillation-counter telescopes which consisted of three thin plastic scintillation counters. These detectors were placed above (up) and below (down) the crystal. The up/down ratio of the β -ray counts R_0 were proportional to the polarization P as

$$R_0 = \zeta(1 + AP)/(1 - AP) \simeq \zeta(1 + 2AP), \quad (1)$$

where ζ is the geometrical asymmetry including the β -ray detection efficiencies and A is the asymmetry parameter of the β -ray angular distribution. By means of the adiabatic fast passage (AFP) method of the NMR technique, the polarization was flipped when the strong rf-field with the resonance frequency was applied. In the case of the NMR of ^{33}Al in Si, the resonance frequency was corresponding to the Larmor frequency $\nu_L = g\mu_N B_0/h$. Taking the ratio of the up/down ratio R obtained by applying the resonance frequency to the R_0 , the large asymmetry change was observed around the resonance frequency as

$$\text{asymmetry change} \equiv R/R_0 - 1 \simeq -4AP. \quad (2)$$

In the case of the $\beta\text{-NQR}$ measurement, the electric field gradient q of the implantation site of ^{33}Al in the non-cubic $\alpha\text{-Al}_2\text{O}_3$ induced the quadrupole interaction with the Q moment of ^{33}Al , and the Larmor frequency ν_L split into five frequencies as shown in fig. 1. These five frequencies were corresponding to the two-level transition between neighboring magnetic sublevels m and $m+1$ and were given as

$$f_{m,m+1} \simeq \nu_L - \nu_Q(3\cos^2\theta - 1)(2m+1)/4, \quad (3)$$

Fig. 1. Sequential AFP-NQR method. The upper part shows the schematic resonance frequencies under the electric quadrupole interaction, and they correspond to two-level transitions between m and $m+1$. The lower part shows a sequence of AFP-r.f.s to invert the polarization.

where ν_Q was the quadrupole frequency $\nu_Q \equiv \frac{3}{2I(2I-1)} \frac{eqQ}{h}$ and θ was the angle between B_0 and the direction of q which was parallel to the crystalline c -axis of Al_2O_3 . In the present measurement, the c -axis was set perpendicular to B_0 ($\theta = 90^\circ$). In eq. (3), the first-order perturbation of the quadrupole interaction was taken into account for simplicity, and the distances between the neighboring resonances were equivalent to $|\nu_Q|/2$ ($\theta = 90^\circ$). We actually applied these frequencies calculated within the second-order perturbation of the quadrupole interaction in order to correct the small deviation from the $|\nu_Q|/2$ caused by the comparatively large ν_Q especially for $\theta = 90^\circ$. To obtain a maximum asymmetry change, a sequential AFP-NQR method was employed. In the case of $q \neq 0$, the population of the neighboring two sub-levels m and $m+1$ was interchanged by an rf-field with the corresponding frequency $f_{m,m+1}$ with the AFP method. To flip the polarization completely, a set of five frequencies which were determined as a function of the ν_Q was applied sequentially, *e.g.*, we applied fifteen rf-fields in the following order as $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 1 \rightarrow 2 \rightarrow 1$, as shown in the lower part of fig. 1. The resonant asymmetry change was detected around the $\nu_Q = \frac{3}{2I(2I-1)} \frac{eqQ}{h}$ in a similar way to the $\beta\text{-NMR}$ measurement.

3 Results

The obtained $\beta\text{-NMR}$ spectrum of ^{33}Al in Si at room temperature (R.T.) at $B_0 = 0.5000$ T was shown in fig. 2. The strength of the rf-field was about 8 gauss and it satisfied the AFP condition. As is shown in fig. 2, the Larmor frequency obtained from the Gaussian fit was found to be consistent with that reported in ref. [12]. The degree of polarization of ^{33}Al multiplied by the asymmetry parameter (AP) was determined as $|AP| = 1.8(2)\%$ from the amplitude of the NMR spectrum of ^{33}Al in Si. The $\beta\text{-NQR}$ spectrum of ^{33}Al in Al_2O_3 at R.T. was successfully obtained as shown in fig. 3. The maximum asymmetry change was observed between the scan width of ν_Q from 317 kHz to 366 kHz represented by dashed lines in fig. 3. The magnitude of the maximum asymmetry

Fig. 2. Obtained NMR spectrum (points) of ^{33}Al in Si at room temperature together with the best-fit Gaussian curve.

Fig. 3. Obtained NQR spectrum (points) of ^{33}Al in Al_2O_3 ($\theta = 90^\circ$) at room temperature together with the asymmetry change obtained by β -NMR on ^{33}Al in Si (band).

change was consistent with the polarization determined from the β -NMR of ^{33}Al in Si. As a reference to extract $Q(^{33}\text{Al})$, we utilized the electric quadrupole coupling constant eqQ of ^{27}Al in Al_2O_3 and Q moment of ^{27}Al , which

were well determined as $eqQ/h(^{27}\text{Al}) = 2389(2) \text{ kHz}$ [15] and $|Q(^{27}\text{Al})| = 146.6(10) \text{ emb}$ [16], respectively. The quadrupole moment of ^{33}Al is extracted from the following equation:

$$|Q(^{33}\text{Al})| = \left| \frac{eqQ/h(^{33}\text{Al})}{eqQ/h(^{27}\text{Al})} \right| \times |Q(^{27}\text{Al})|. \quad (4)$$

From fig. 3 and eq. (4), we obtained the preliminary Q moment of ^{33}Al as $|Q(^{33}\text{Al})| \sim 130 \text{ emb}$. The theoretical predictions of $Q(^{33}\text{Al})$ are 118 emb and 166 emb with the conventional shell model and SDPF-M [14], respectively. From the present result, the contribution of the intruder configuration seems to be not so large as the SDPF-M prediction. To describe the details of the nuclear structure of ^{33}Al and to conclude whether the ^{33}Al isotope is located inside or outside of the *island of inversion* clearly, further analyses on the other NQR spectra obtained with narrower scan width compared to that as shown in fig. 3 are in progress.

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