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Abstract

The highly neutron-rich nucleus ^{34}Mg has been studied via the Coulomb excitation using a radioactive ^{34}Mg beam at 44.9 MeV/nucleon with a Pb target. The $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \rightarrow 2^+_1)$ value for the previously proposed 2^+_1 state

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in ^{34}Mg was determined for the first time to be 631(126) e^2fm^4. This value corresponds to the quadrupole deformation parameter β_2 of 0.58(6), implying an anomalously large deformation of ^{34}Mg.

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Experimental evidence for deformed nuclei in the so-called 'island of inversion' [1] centered at $Z \sim 11$ and $N \sim 21$ was first obtained by the mass measurement [2], which revealed that the neutron-rich ^{31,32}Na isotopes are more tightly bound than predicted theoretically. Later mass measurements extended to neighboring isotopes [3–5] have indicated that the anomaly generally appears for the neutron-rich isotopes of Ne, Na, and Mg. For the neutron-rich fluorine isotopes, a strong tendency towards deformation has also been suggested by the extra push of stability up to ^{31}F with N=22, where six more neutrons are bound as compared with the case of the most neutron-rich oxygen ^{24}O [6]. The study on these nuclei has been further directed to the measurements on excited state properties, such as the excitation energies $E(2_1^+)$ of the 2_1^+ states and the $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \to 2_1^+)$ strengths. For example, the most convincing evidence for the anomalous deformation has been obtained in the N=20 nucleus ^{32}Mg from the low $E(2_1^+)$ of 886 keV [7] and the large B(E2) of 454(78) e^{2}fm^4 [8] as well as the enhancement of the binding energy [3]. Recently, the deformation was suggested also for ^{31}Na with N=20 from its low-lying E2 properties [9]. Currently, a great interest is focused on investigation of more neutron-rich nuclei beyond N=20 to elucidate how the anomaly evolves across the region of the island.

In the present letter, we report the first measurement of $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \to 2_1^+)$ for the very neutron-rich nucleus ^{34}Mg with N=22, which was performed with the intermediate-energy Coulomb excitation technique by detecting de-excitation γ-rays in coincidence with scattered ^{34}Mg. A very large value of the measured B(E2), together with the low $E(2_1^+)$ as found in Ref. [10], indicates that deformation of ^{34}Mg is even larger than the classical case of ^{32}Mg.

Theoretically, the anomalous quadrupole deformation has been treated in terms of the shell model [1,11–14] or by mean-field approaches [14–17]. In the shell model studies [1,11–14], the effect of $2p2h$ excitations as well as that of the narrowed shell gap across N=20 has been noted to promote the occurrence of the island of inversion. For example, the Monte Carlo shell model calculation (MCSM) [13], which accommodates these features, provides a quantitative and systematic prediction for the E2 properties and the level schemes over the nuclei around the island. In the calculation, the largest quadrupole collectivity is predicted for ^{34}Mg.

Recently, various reactions have become available for γ-ray spectroscopy with radioactive beams, including Coulomb excitation [8,18,19], inelastic proton scattering [20], one-neutron knockout [21], and projectile fragmentation [10,22]. Among these reactions, the Coulomb excitation provides a unique means to determine both the level energy and transition probability simultaneously. Moreover, the intermediate-energy Coulomb excitation affords other attractive features such as large cross section, feasibility of using a thick target, and kinematical focusing of the ejectiles. With all these advantages combined, this method can be now applied to very neutron-rich nuclei even with a beam intensity of a few counts per second.

The experiment was performed at the RIPS facility [23] in RIKEN. A secondary ^{34}Mg beam was produced by fragmentation of a 95 MeV/nucleon ^{40}Ar primary beam impinging on a 463 mg/cm^2-thick ^{9}Be target. A typical intensity of the primary beam was 60 pnA. An aluminum wedge with a mean thickness of 444 mg/cm^2 was used to allow a clear isotopic separation of the reaction fragments. By operating RIPS at the maximum values of the momentum acceptance and solid angle, we obtained the ^{34}Mg beam with a typical intensity of 4 counts per second. Particle identification of the incident beam was carried out event-by-event using the time-of-flight (TOF)-ΔE method. The TOF was determined by two 0.3 mm-thick plastic scintillators placed 5.3 m apart along the beam line. The ΔE information was measured by a 0.35 mm-thick silicon detector placed at the first achromatic focal plane (F2) of RIPS. The horizontal and vertical positions of the fragments at F2 were measured by a parallel-plate avalanche counter (PPAC) in order to check that RIPS was tuned to be optimal for the ^{34}Mg isotope. A 693 mg/cm^2-thick Pb target was placed at the final focal plane (F3) to excite the projectiles. The averaged energy of ^{34}Mg in the target was calculated to be 44.9 MeV/nucleon. The position and incident angle of the beam at F3 were monitored by two sets of PPAC placed upstream of the target. The beam spot size and angular spread at the target were found to be 22 mm and 1.1° (FWHM) in the horizontal direction and 11 mm and 2.8° (FWHM) in the vertical direction, respectively.

Scattered particles were detected and identified by a counter telescope located 44 cm downstream of the target. The telescope comprised 4 layers of ion-implanted silicon detectors. Their thicknesses were 0.5, 1.0, 1.0, and 0.5 mm, respectively. The counter telescope with an active diameter of 92 mm covered the scattering angle up to 6.0 degrees. Isotopic identification of the scattered particles was achieved by the ΔE-E method, and was useful to reject events originated from the breakup reaction of ^{34}Mg in the secondary target. In the present study, we obtained the effective angle-integrated cross section, which is defined as the differential cross section for the 2_1^+ population integrated over the detection angle with the weight of particle detection efficiency. The effective cross section was found to be about 85% of the total cross section using a Monte Carlo simulation, which was based on the theoretical angular distribution calculated with the ECIS79 code [24]. Here, the spot size and angular spread of the incident beam, the multiple scattering in the secondary target, and the detector geometry were taken into account. This simulation was also used in extracting the transition probability from the measured cross section as described later.

De-excitation γ rays were measured by a granular array of 66 NaI(Tl) scintillators described in Ref. [10]. The energy and efficiency calibrations of each NaI(Tl) detector were made by using standard ^{22}Na, ^{60}Co, ^{88}Y, and ^{137}Cs sources. The energy resolution was typically 9.1% (FWHM) for the 662-keV γ ray as measured with the ^{137}Cs source. The absolute efficiency and the line shape of the γ-ray energy spectrum were simulated by means of the GEANT code [25]. The total photo-peak efficiency was calculated to be 23.9% for a 656-keV γ ray emitted from a ^{34}Mg nucleus in flight. The simulated spectral shape of the γ ray was used as a fitting function in estimating a photo-peak yield from the experimental energy spectrum.

The energy spectra of γ rays measured in coincidence with scattered ^{34}Mg are shown in Fig. 1. The top (bottom) panel shows the spectrum obtained in the laboratory (projectile) frame. As a result of Doppler-shift correction, a single dominant peak stands out at 656(7) keV in the projectile-frame spectrum, demonstrating that the γ line originates from the moving ^{34}Mg nuclei. No other peaks are significant in the spectrum. Since the intermediate-energy Coulomb excitation selectively excites the 2_1^+ state of an even-even nucleus, we conclude that the γ transition corresponds to the de-excitation of the first excited 2_1^+ state of ^{34}Mg located at 656(7) keV. In the previous study on ^{34}Mg [10], the authors observed two γ-ray peaks at 660(10) keV and 1460(20) keV, which are tentatively attributed to the $2_1^+ \rightarrow 0_{\rm g.s.}^+$ and $4_1^+ \rightarrow 2_1^+$ transitions, respectively. The present observation of the 656-keV γ rays confirms the assignment for the former transition.

The effective angle-integrated cross section was obtained to be 286(52) mb from the measured γ-ray yield. An experimental deformation parameter β_2 of 0.57(6) was deduced through the ECIS calculation by searching the β_2 value which best reproduced the measured cross section. The quoted error is dominated by the statistical one, while it also includes systematic uncertainties arising from the efficiency simulation. In the ECIS calculation, the standard rotational model was assumed. The nuclear deformation parameter $\beta_2^{\rm N}$ was taken to be equal to the Coulomb one $\beta_2^{\rm C}$, which is directly related to B(E2) as $\beta_2^{\rm C} = 4\pi\sqrt{B({\rm E2}; 0_{\rm g.s.}^+ \rightarrow 2_1^+)}/3ZeR^2$. We used an optical potential parameter set determined from the ^{40}Ar + ^{208}Pb elastic scattering data [26]. Possible uncertainty arising from the choice of the optical potential was examined by using a different parameter set determined by the ^{17}O + ^{208}Pb elastic scattering [27]. The extracted deformation parameter β_2=0.57(5) was in good agreement with the result from the ^{40}Ar + ^{208}Pb potential.

To evaluate the ambiguity due to the nuclear excitation contribution, we performed an additional measurement of the inelastic scattering with a 339 mg/cm^2-thick C target. Since the Coulomb interaction becomes negligibly small for the C target, the data provided useful information on the nuclear deformation parameter $\beta_2^{\rm N}$, which accounts for the nuclear contribution to the 2_1^+ excitation. From the measured cross section of 40(12) mb, we extracted the experimental $\beta_2^{\rm N}$ values to be 0.41(7) and 0.56(9), respectively, with the ^{40}Ar + ^{208}Pb and ^{17}O + ^{208}Pb potentials. By setting these values for $\beta_2^{\rm N}$, the best-fit $\beta_2^{\rm C}$ values of 0.60 and 0.57 were, respectively, extracted from the Pb data. The $\beta_2^{\rm C}$ values thus deduced are very close to those obtained by assuming that $\beta_2 = \beta_2^{\rm N} = \beta_2^{\rm C}$.

By taking an average of the four values deduced above, we determined $\beta_2^{\rm C}$ for the 2_1^+ state of ^{34}Mg to be 0.58(6). The error includes both experimental uncertainties and theoretical ambiguities regarding to the choice of optical potentials and the nuclear contribution. We then obtain $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \rightarrow 2^+_1) = 631(126)\ \mathrm{e^2fm^4}$, which is the largest among the E2 strengths observed for the nuclei in the vicinity of the island of inversion.

To check the consistency of the present measurement with the previous works on ^{32}Mg [8,28,29], we also studied the Coulomb excitation of ^{32}Mg to its 2^+_1 state using a secondary ^{32}Mg beam at 44.0 MeV/nucleon with a 573 mg/cm^2-thick Pb target. From the experimental cross section of 217(23) mb, we obtained the $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \rightarrow 2^+_1)$ value to be 449(53) e^{2}fm^4. Since the nature of high-lying levels of ^{32}Mg is not known well, no correction was made for the possible decay cascades feeding the 2^+_1 state. The ambiguity due to the nuclear contribution was estimated to be less than 3% using the previous data of the ^{32}Mg + ^{12}C scattering [8]. The previously reported values of B(E2) for ^{32}Mg are 454(78) e^{2}fm^4 (with 5% reduction for the feeding correction) [8], 333(70) e^{2}fm^4 and 440(55) e^{2}fm^4 (with and without the feeding correction, respectively) [28], and 622(90) e^{2}fm^4 (with 8% reduction for the feeding correction) [29]. The absolute value of the 2^+_1 population obtained presently is in good agreement with the two former measurements [8,28] and significantly smaller than the value reported in Ref. [29].

In Fig. 2, the deformation parameters β_2 extracted from the measured B(E2) values are compared among the N=22 isotones [30–32]; ^{40}Ar : 0.25(2), ^{38}S : 0.25(2), ^{36}Si : 0.26(4), and ^{34}Mg : 0.58(6). A sudden increase of quadrupole deformation is apparent at ^{34}Mg. The experimental data are also compared with the results of the $0\hbar\omega$ shell model calculation in Refs. [12,33]. The calculation assumes the N=20 shell closure and predicts moderate deformation due to the presence of the two valence neutrons. The data for ^{40}Ar, ^{38}S, and ^{36}Si are consistent with the $0\hbar\omega$ calculations, while the drastic increase of β_2 observed at ^{34}Mg is far beyond the theoretical prediction, showing an anomalous deformation of ^{34}Mg.

Figure 3 shows the plot of the B(E2) values for the neutron-rich Mg isotopes [8,28,30]. Enhanced E2 collectivity is evident in ^{32}Mg and ^{34}Mg, showing characteristic features of the nuclei in the island of inversion. The systematic behaviour of B(E2) may afford a stringent test of the shell model picture on the abrupt appearance of the island. For this sake, the experimental data are compared with two types of shell model calculations, i.e., the MCSM [13] and $0\hbar\omega$ calculations [12]. The MCSM calculation treats the effects of a narrowed shell gap at N=20 and enhanced $2p2h$ excitations, while the $0\hbar\omega$ calculation does not include any such effects. It is evident that the former calculation reproduces the experimental results very well, while the latter fails to account for the enhanced strengths of ^{32}Mg and ^{34}Mg. The MCSM calculation predicts B(E2) of 570 e^2fm^4 ($\beta_2 \approx 0.55$) and $E(2_1^+)$ of 620 keV for ^{34}Mg, which are in good agreement with the present results. In addition, the MCSM calculation predicts a strong prolate deformation of ^{34}Mg.

The shape of the deformed ^{34}Mg has also been treated by the mean-field approach using the method of angular-momentum projection [17]. The authors considered four possible configurations for the $0^+_{g.s.} \rightarrow 2^+_1$ transition by taking either the prolate or oblate minimum for the $0^+_{g.s.}$ and 2^+_1 states. The very collective B(E2) value of 549 e^2fm^4 was obtained if both the $0^+_{g.s.}$ and 2^+_1 states are in the prolate shape, while the other combinations yielded smaller results by one order of magnitude. Here again, the present result of 631(126) e^2fm^4 supports a large prolate deformation of ^{34}Mg.

In summary, we have extended the intermediate-energy Coulomb excitation study to the highly neutron-rich nucleus ^{34}Mg with a beam intensity of only 4 counts per second. The B(E2) value for the $0^+_{g.s.} \rightarrow 2^+_1$ transition was measured for the first time to be 631(126) e^2fm^4. The very large B(E2) value, corresponding to the quadrupole deformation parameter of $\beta_2 \approx 0.58$, strongly indicates that ^{34}Mg is a well deformed nucleus. The present result supports a large prolate deformation of ^{34}Mg as predicted in Refs. [13,17].

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FIGURES

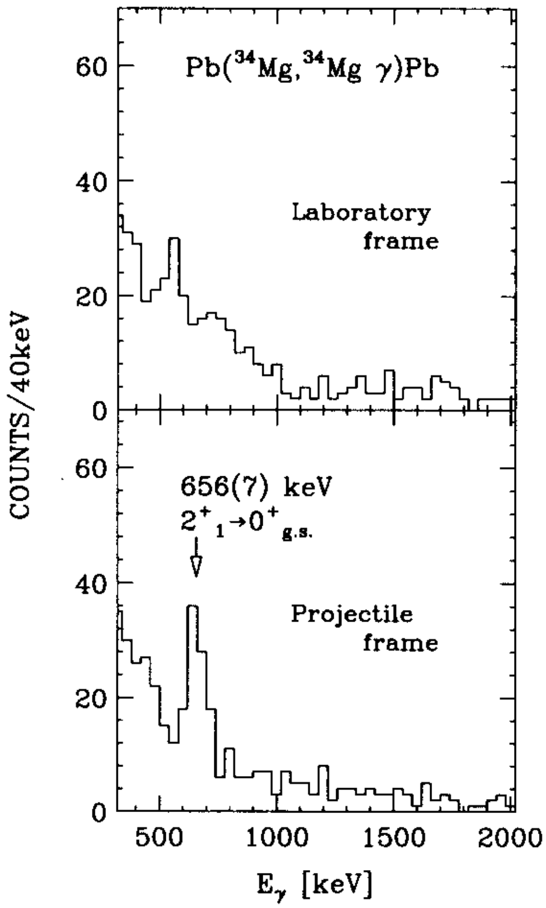

FIG. 1. Energy spectra of γ rays measured in the inelastic scattering of ^{34}Mg at 44.9 MeV/nucleon with the Pb target. Top (bottom) panel shows the spectrum obtained in the laboratory (projectile) frame.

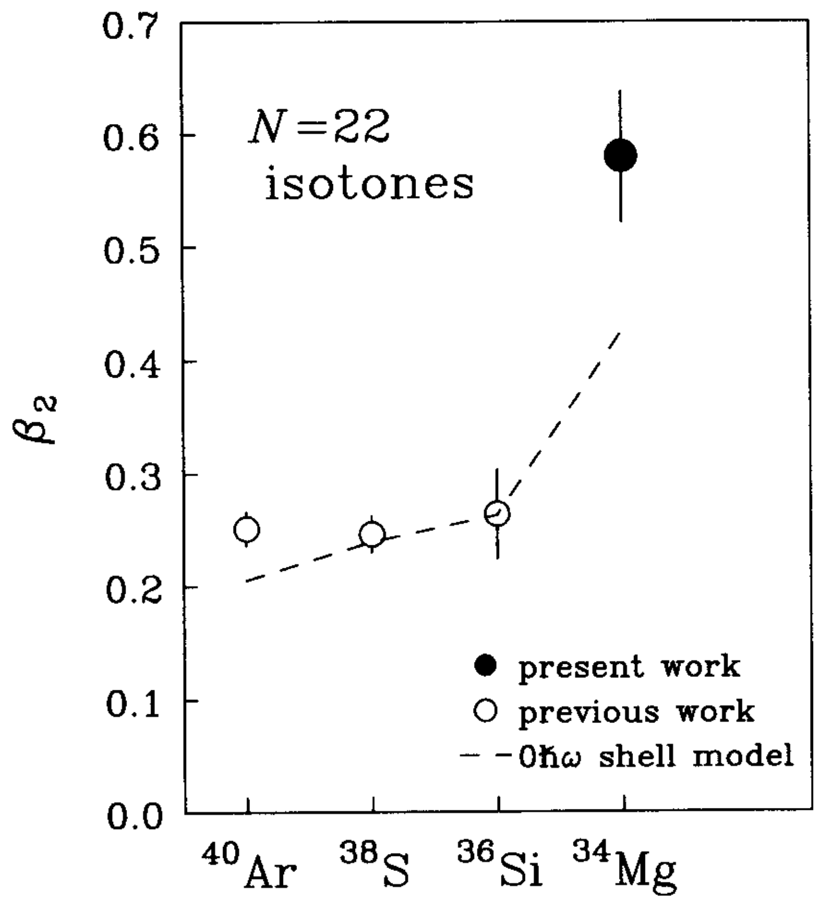

FIG. 2. The quadrupole deformation parameters β_2 extracted from the $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \rightarrow 2^+_1)$ values in the N=22 isotones. The experimental data (circles) are compared with the $0\hbar\omega$ shell model calculation in Refs. [12,33] (dashed line). The data for ^{34}Mg is the result of the present work.

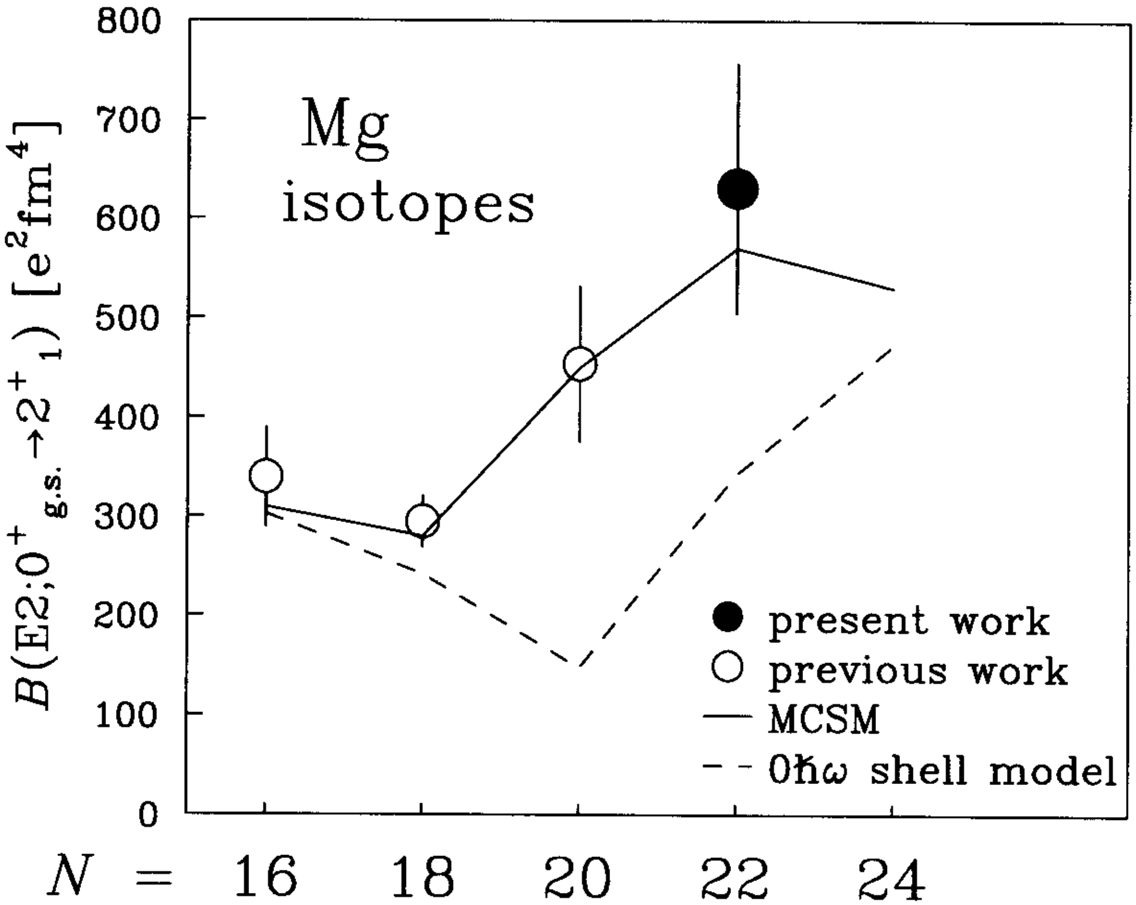

FIG. 3. Measured $B(\mathrm{E2}; 0^+_{\mathrm{g.s.}} \rightarrow 2^+_1)$ values for ^{28}Mg [30], ^{30}Mg [28], and ^{32}Mg [8] as well as the present result on ^{34}Mg are compared with two shell model calculations. Predictions by the Monte Carlo shell model (MCSM) [13] and the $0\hbar\omega$ shell model calculation in Ref. [12] are indicated by the solid and dashed lines, respectively.