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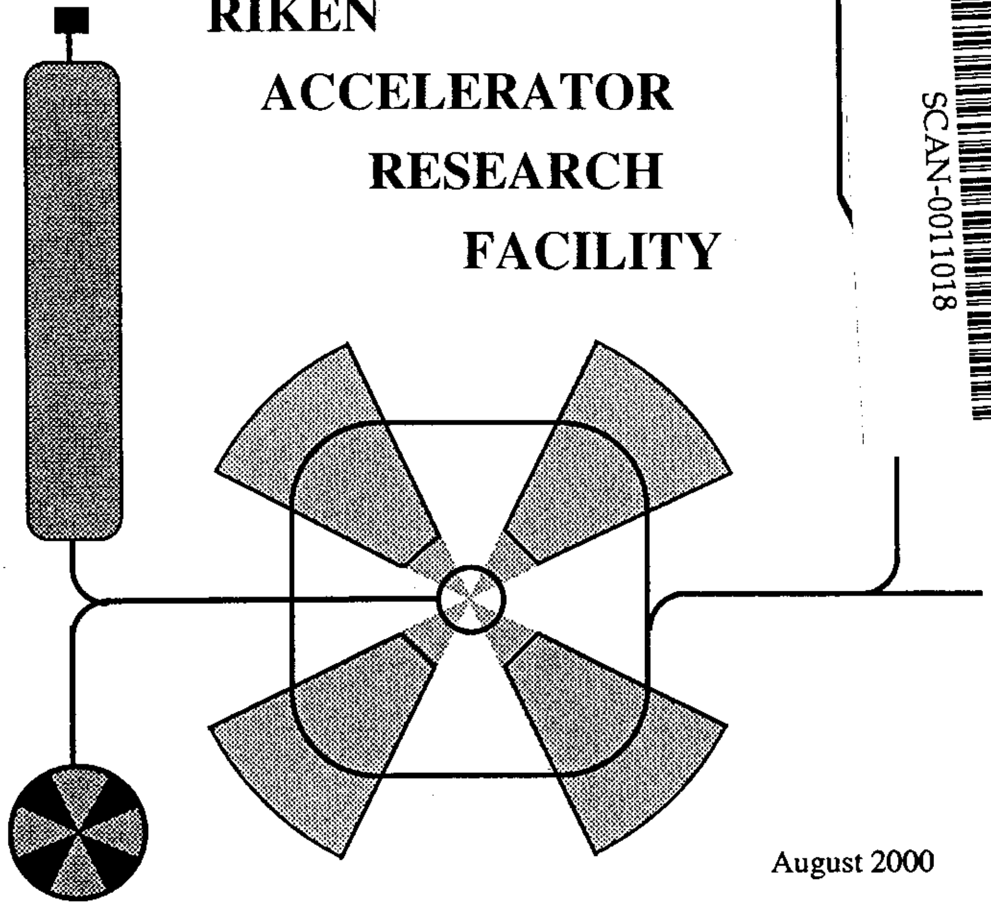

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Large deformation of the neutron-rich isotope ^{34}Mg from in-beam γ-ray spectroscopy using RI beam fragmentation

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Abstract

Locations of the low-lying states of the very neutron-rich isotope ^{34}Mg have been studied for the first time. In-beam γ-ray spectroscopy was performed using a two-step fragmentation reaction. Two γ-lines observed at 660(10) keV and 1460(20) keV are attributed to the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ and $4_1^+ \rightarrow 2_1^+$ transitions in ^{34}Mg, respectively. The very low 2_1^+ energy and large $E(4_1^+)/E(2_1^+)$ ratio of about 3.2 conform with the properties of a well deformed isotopes.

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Nuclear shell closures and the resultant magicity are the most fundamental features of nuclear structure, and have been well-established for the isotopes on and near the stability line. One of the manifestations of the magicity has been derived from the global systematics of nuclear deformation; the isotopes around the shell closures tend to be spherical, whereas the isotopes far from the shell closures to be deformed [1]. However, it has recently been revealed that this feature vanishes at some of the regular magic numbers when the isotopes are located far-off the stability line. The most remarkable case can be seen for the isotopes located around $Z \sim 11$ and $N \sim 20$ region, i.e., the so-called 'island of inversion' region [2, 3], for which large deformation was suggested by the extra enhancement of the binding energies [2, 4–8]. The sudden gain of particle stability in fluorine isotopes, as indicated by the particle stability of ^{31}F vs. particle instability of ^{26,28}O, may also be related to this anomaly [9].

More direct information on deformation can be obtained from the properties of the low-lying excited states. Indeed, spectroscopic studies on the first 2^+ state performed for the $N = 20$ isotope ^{32}Mg yielded strong evidences for enhanced quadrupole deformation; $E(2^+_1)$ was found to be a very low energy of 885.5(7) keV [10, 11], and an enhanced B(E2) of 454(78) e^{2}fm^4 was obtained in the $0^+_{\mathrm{g.s.}} \rightarrow 2^+_1$ Coulomb excitation [12]. So far, such spectroscopy on low-lying excited states is only limited to the case of ^{32}Mg among the isotopes in the 'island of inversion'. Theoretically, the possible deformation in this region have attracted much interest and several works are reported using either shell models [3, 13–16] or mean field approaches [15, 17, 18]. While most of the papers favor deformation, their results are fairly dispersed as for the extent of the E2 collectivity and isotopic dependence of deformation. In order to clarify the basic mechanism for the occurrence of the anomalous deformation, it should certainly be desirable to extend experimental studies beyond ^{32}Mg. In the present work, we have attempted in-beam γ-ray spectroscopy on ^{34}Mg to find whether and how deformation evolves in the isotope of $N = 22$.

The powerful method for in-beam γ-ray spectroscopy with radioactive isotope (RI) beams has been the intermediate-energy Coulomb excitation, which has been extensively employed to determine $E(2_1^+)$ and $B(\mathrm{E2};\ 0_{\mathrm{g.s.}}^+ \rightarrow 2_1^+)$ for a large variety of neutron-rich even-even isotopes [12, 19]. In the present work we have used an alternative method [20–22], which incorporates the projectile-fragmentation reaction to populate excited isotopes. As compared to the Coulomb excitation method, the fragmentation method affords a better access to higher excited states, and hence opens a possibility to determine the $E(4_1^+)/E(2_1^+)$ ratio. On the other hand, the method may suffer from S/N ratios since all γ-rays emitted in a variety of reaction channels are to be detected simultaneously. This is particularly disturbing when one tries to study isotopes very far from the original projectile which are produced only very weakly. Heavy loading on the detectors due to the γ-rays from the other reaction channels hampers to obtain a reasonable counting rate of the isotopes of rare production. To remove this difficulty, we have introduced a modified scheme of the fragmentation method. Namely, the isotopes of ^{34}Mg were produced in two steps; an RI beam of ^{36}Si was first produced from the ^{40}Ar projectile, and ^{34}Mg isotopes were produced in the subsequent projectile fragmentation of ^{36}Si. In this two-step fragmentation scheme ^{34}Mg isotopes are apart from the secondary projectile only by two nucleons so that they share a fairly large fraction of the total γ-ray flux. This situation has facilitated use of a highest possible intensity of ^{40}Ar beam and a thick target for the secondary projectile fragmentation, providing an improved overall efficiency of the γ-ray detection.

The experiment was carried out at RIKEN Accelerator Research Facility, using the RIKEN projectile-fragment separator RIPS [23]. A primary ^{40}Ar beam of 95 MeV/nucleon with a typical intensity of 60 pnA bombarded a production target ^{9}Be with a 462.5 mg/cm^2 thickness. Various products of the projectile fragmentation reaction were collected and analyzed through RIPS to produce an RI beam of ^{36}Si. The isotopes in the beam were identified event by event using the time-of-flight (TOF) measured between two plastic scintillators placed along the beam line. The typical intensity of the ^{36}Si beam was around 2×10^4 particles per second.

The RI beam of ^{36}Si was transported to a secondary target of 385 mg/cm^2 ^{9}Be placed at the final achromatic focus of RIPS. The beam energy was 38 MeV/nucleon at the center of the target. Reaction products from the ^{36}Si + ^{9}Be fragmentation were detected at forward angles by a parallel plate avalanche counter (PPAC) and four sets of counter telescopes arranged in a 2×2 matrix. The distances from the target to the PPAC and to the telescopes were 48 cm and 56 cm, respectively. Each telescope consisted of three layers of ion-implanted silicon detectors with an effective area of 50×50 mm^2 and with a thickness of 350 μm, 500 μm, and 500 μm, respectively, followed by a 1 mm thick Si(Li) detector with the same area. The first three detectors measured the fragments of interest, while the last detectors were used to identify light particles that punched through the three ion-implanted detectors. Particle identification was performed by the ΔE-E method using the first three detectors, combined with the TOF information between the secondary target and the PPAC. A typical mass resolution for $A \sim 30$ isotopes was about 0.3 (r.m.s.) in mass number unit, which is sufficient to identify reaction products in a wide range of $Z = 8$–14 and $A = 14$–36.

Sixty-six NaI(Tl) scintillators were placed around the target to detect the γ-rays emitted from excited fragments. Each scintillator crystal is of rectangular shape with a size of $6 \times 6 \times 12$ cm^3, coupled to a 5.1 cm ϕ photo-multiplier tube. The high granularity of the setup allows us to measure the angle of the γ-ray emission with about 20° accuracy. The angular information was used to correct for the large Doppler shift with $v/c \approx 0.27$. The total full-energy peak efficiency was 18% for a 1 MeV γ-ray. A 5 cm thick lead shield was mounted around the NaI(Tl) scintillators for background reduction.

Gamma-ray energy spectra were obtained for various isotopes identified with the detectors behind the target. We first studied the spectra for even-even isotopes other than ^{34}Mg, whose γ-lines are known and can be used to test the total performance of the present method. Figure 1 shows the case of ^{32}Mg, where the spectra obtained with and without Doppler correction are compared. To reduce background contributions, only events with γ-ray detection multiplicity $M = 1$ were selected. In the Doppler-corrected spectrum of Fig. 1(b), one can clearly see two prominent peaks around 885 keV and 1430 keV, while they are vague in the spectrum of Fig. 1(a). Thus the peaks are associated with the γ-rays emitted from the moving nuclei of ^{32}Mg. The strongest peak at 885 keV corresponds to the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ transition. To identify another peak around 1430 keV, γ-γ coincidence was applied. In an energy spectrum gated on the second peak (1330 keV–1530 keV), which is shown in Fig. 1(c), the first peak is clearly seen, confirming the coincidence relation between the two lines. These results are in good harmony with the earlier experimental results obtained in the spectroscopy with the ^{36}S + ^{9}Be fragmentation reaction [20, 21].

The systematic study of the even-even isotopes also provided useful information as for the general feature of the γ-ray spectrum obtained in the fragmentation reaction. For most cases two known γ-lines were observed. The stronger peak always corresponds to the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ transition, and the other to the $4_1^+ \rightarrow 2_1^+$ transition. This suggests that the excited states along the Yrast line are favorably populated in the products of the fragmentation reaction. This trend, which was also observed in the ^{36}Si + ^{9}Be fragmentation [21], is helpful for the assignment of γ-transitions.

The γ-ray spectrum for the very neutron-rich isotope ^{34}Mg was observed for the first time in the present work, as shown in Fig. 2(a). The spectrum for ^{33}Mg, which is also shown for the sake of comparison, exhibits γ-lines around 490 keV, 900 keV, and 1250 keV as observed in the measurement of β-delayed γ decays of ^{33}Na [24]. The spectrum for ^{34}Mg is weakly contaminated by the γ-rays from ^{33}Mg due to the limited mass resolution for reaction products. Beside these contaminants the spectrum clearly exhibits two significant γ-lines at 660(10) keV and 1460(20) keV, which are assigned to γ-transitions in ^{34}Mg. According to the systematics for the fragmentation reaction the strongest line at 660 keV can be assigned to the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ transition, hence yielding $E(2_1^+) = 660$ keV for ^{34}Mg. In Fig. 3, this $E(2_1^+)$ value is compared with those of the other even-even magnesium isotopes. The energy of 660 keV is the lowest among those isotopes, being even lower than that of ^{32}Mg, which is supposed to be largely deformed. According to the empirical formula [11],

$$E(2_1^+) = 1224(\langle\beta^2\rangle A^{7/3})^{-1}(\mathrm{MeV}),$$

the obtained energy corresponds to a large deformation with $\sqrt{\langle\beta^2\rangle} \approx 0.7$.

There are several theoretical calculations available to be compared with the experimental

$E(2_1^+)$ values [14, 16, 18]. Results of three recent theoretical works shown in Fig. 3 appear to reproduce the global trend of $E(2_1^+)$ behavior. In particular, the quantum Monte Carlo shell model calculation made by Utsuno et al. [16], reproduces the data of $E(2_1^+)$ surprisingly well all through the magnesium isotopes with $N = 16$–20. Their prediction of $E(2_1^+) = 620$ keV is also in good agreement with the present result for ^{34}Mg. The result of $E(2_1^+)$ for ^{34}Mg calculated by Caurier et al. [14] considerably deviates from that of Utsuno et al. [16]. A major difference between the two calculations lies in the treatment of the $2p$-$2h$ excitations across the gap between the $(sd)_\nu$ and $(fp)_\nu$ shells. The present result in favor of the latter supports the importance of such excitations [3, 16].

As for the second strongest line in the ^{34}Mg spectrum, the assignment of the transition is less certain. However, it is most likely that the line corresponds to the $4_1^+ \rightarrow 2_1^+$ transition by again referring to the systematic rules for the fragmentation reaction. In that case the value of $E(4_1^+)$ is deduced to be 2120 keV, and hence $E(4_1^+)/E(2_1^+)$ to be about 3.2. This ratio is very close to the value of 10/3, which is valid for the rotational band of the well-deformed isotopes. The deduced ratio is also in good harmony with the result of the quantum Monte Carlo shell model calculation, i.e. about 3.0 [16].

In summary, the spectroscopic study of the very neutron-rich isotope ^{34}Mg was performed to extend experimental information on the isotopes in the 'island of inversion'. A novel method of in-beam γ-ray spectroscopy was applied by employing the two-step projectile fragmentation. By assigning the two strongest γ-lines to the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ and $4_1^+ \rightarrow 2_1^+$ transitions, the values of $E(2_1^+)$ and $E(4_1^+)$ were deduced to be 660 keV and 2120 keV, respectively. This $E(2_1^+)$ value is the lowest among the even-even isotopes nearby, being even lower than that of the deformed isotope ^{32}Mg. The deduced $E(4_1^+)/E(2_1^+)$ ratio close to the limit of rotational nuclei also indicates a very large deformation of ^{34}Mg. These results are in good agreement with the recent calculation of the quantum Monte Carlo shell model, which involves features of narrowing of the shell gap at $N = 20$ and enhanced $2p$-$2h$ excitation across the gap.

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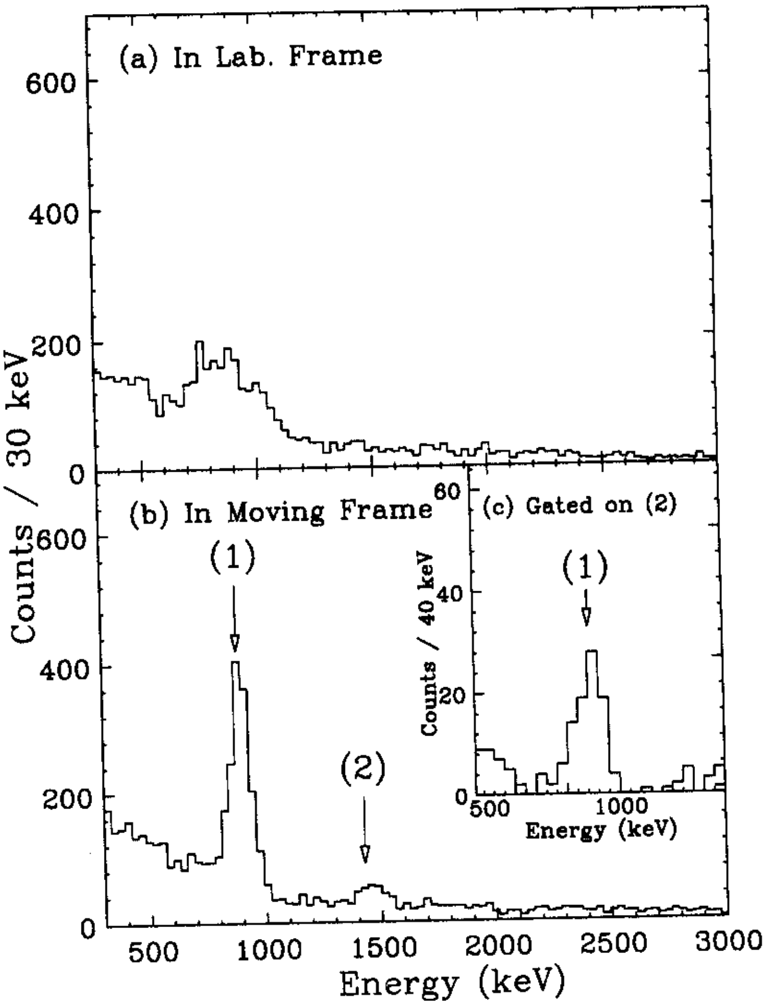

FIG. 1: Energy spectra of γ-rays detected in coincidence with ^{32}Mg fragments; (a)γ-ray energy spectrum in the laboratory frame, (b)Doppler-corrected energy spectrum with $v/c = 0.27$. Two peaks at 885 keV (1) and 1430 keV (2) can be clearly seen. (c)Doppler-corrected energy spectrum gated on the energy of the peak (2) (1330 keV – 1530 keV), which clarifies a cascade relation between the γ-rays of (1) and (2).

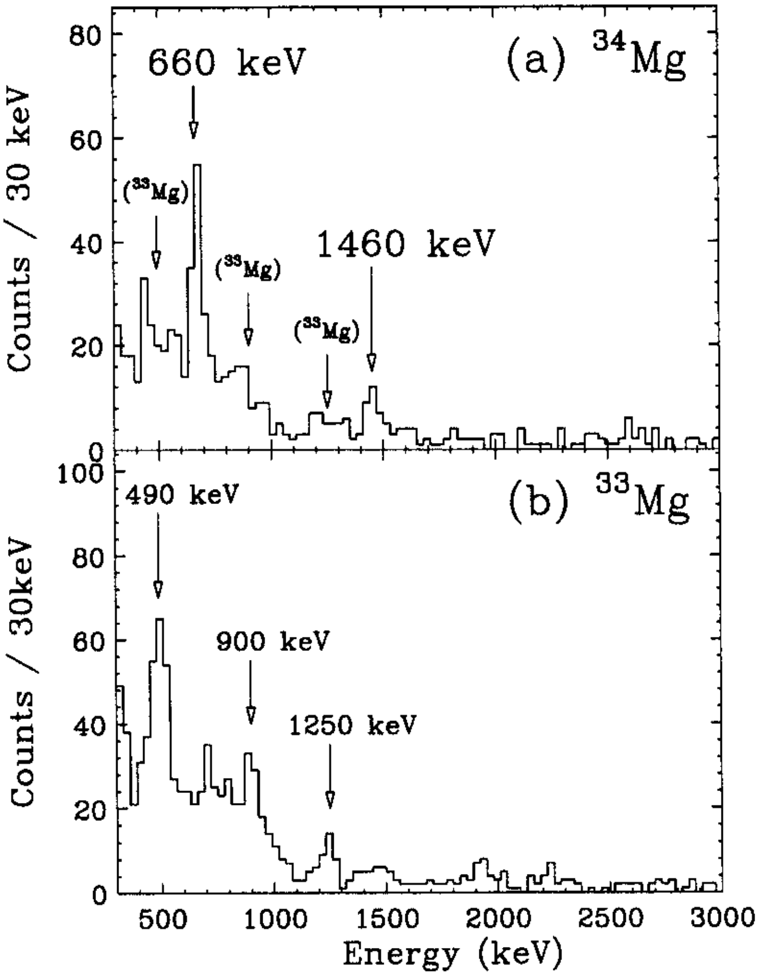

FIG. 2: Doppler-corrected γ-ray spectra associated with ^{34}Mg (a) and ^{33}Mg (b). In the spectrum of ^{34}Mg (a), two sharp peaks can be seen at energies of 660 keV and 1460 keV. Three peaks associated with ^{33}Mg are seen in (a) due to the limited mass resolution of reaction products.

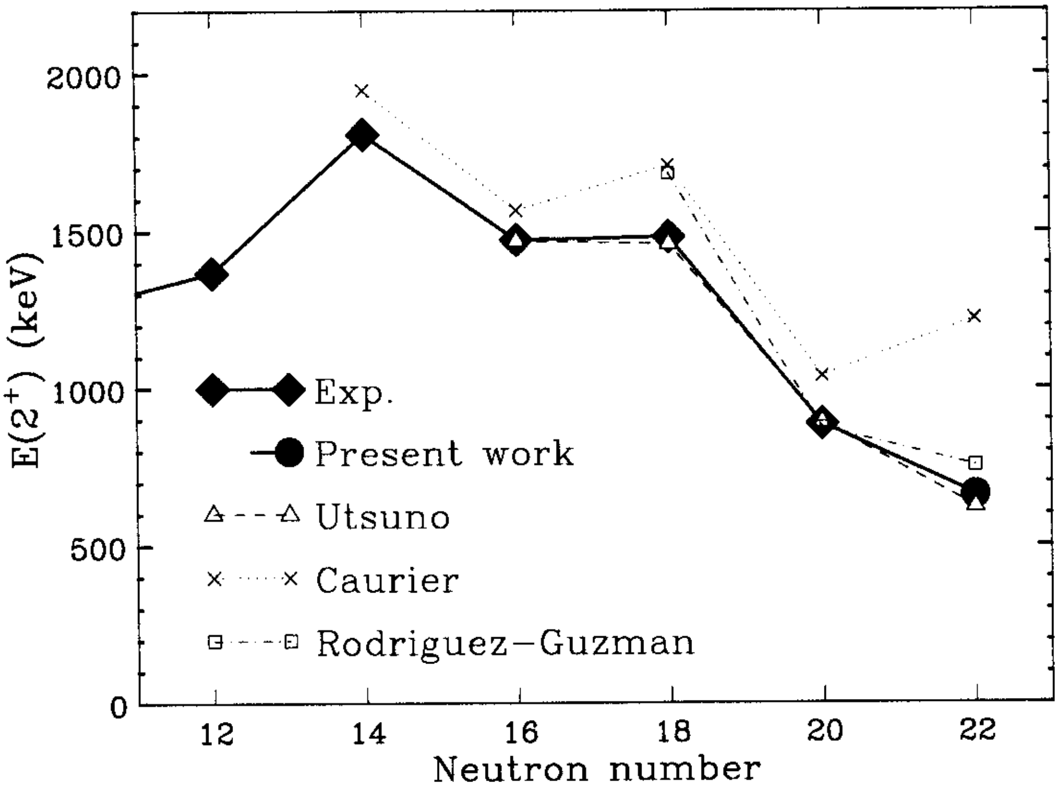

FIG. 3: Plot of energies of the first excited states $E(2_1^+)$ of even-even magnesium isotopes as a function of neutron numbers. Experimental values are plotted with filled diamonds, together with the result of the present work represented by a filled circle, where experimental errors are within the size of the symbols. Predictions of two shell model calculations, by Utsuno et al. [16] and by Caurier et al. [14], and a mean-field calculation by Rodríguez-Guzmán et al. [18], are also plotted with triangles, crosses, and squares, respectively.