Spectroscopy on very neutron-rich nuclei at N=20∼28

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Abstract

Recent studies on nuclear structure by using radioactive isotope beams available at the RIKEN projectile-fragment separator (RIPS) are introduced. Special emphasis is given to experiments selected from two recent programs that highlight studies at N=20∼28; on the large deformation of ^{34}Mg via the in-beam gamma spectroscopy, and on the particle stability of very neutron-rich nuclei, ^{34}Ne, ^{37}Na and ^{43}Si.

1 Introduction

Nuclear shape of isotopes far from the stability is one of the major subjects in the unstable nuclear physics. Intensively investigated is the so-called island-of-inversion region around $Z\approx 11$ and $N\approx 20$, where the nuclei have the tendency toward prolate deformation in spite of the effect of spherical stability due to the magicity of the neutron number of 20 [1]. The large deformation has been experimentally suggested, for example, by the extra enhancement of the binding energies [2, 3, 4], a very low energy of the first 2^+ state [5] and a large B(E2) value [6] for ^{32}Mg. Theoretically, the possible deformation in this region has attracted much interest and several recent works are reported using shell models and mean field approaches. One of the shell models [7] predicts the deformation center at N=22 for the Mg isotopes.

Moving towards a more neutron-rich region with $Z\sim 12$, i.e., beyond the island-of-inversion, it is of great interest to investigate a possible transition from the intruder configuration to the normal one and the role of the N=28 magicity for the stability of very neutron-rich nuclei. Stimulated by a recent mass measurement [2] and the experimental findings for ^{44}S[8, 9], possible deformation at $N\sim 28$ has been theoretically discussed.

In this report, we introduce recent highlights of experimental results at RIKEN–RIPS [10] for very neutron-rich nuclei at N=20∼28. Among them, two studies are selected here; degrees of deformation of ^{34}Mg [11, 12], and the particle bound and unbound characters of ^{33,34}Ne, ^{36,37}Na and ^{39}Mg related to the character of the extra enhancement of binding energies due to deformation [13].

2 In-beam gamma spectroscopy

The in-beam gamma spectroscopy via several reactions has been developed for fast RI beams, and extensively applied to obtain nuclear properties through observation of low-lying and bound-excited states. To find whether and how deformation evolves in the isotopes with N=22, two experimental works for ^{34}Mg are shown; energy values of low lying excited states by the RI beam fragmentation [11] and a B(E2) value by the Coulomb excitation [12].

The RI beam fragmentation method is a modified scheme of the fragmentation method originally proposed by Azaiez *et al.* [14], which incorporates the projectile fragmentation reaction to populate excited nuclei. As compared to the Coulomb excitation method [6], 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, in general, in-beam gamma spectroscopy techniques with heavy loading of γ detectors suffer from strong γ-ray yields from other fragmentation products, which tend to overwhelm the limit of counting rate acceptable for γ-ray detection. To remove this difficulty, we have introduced a modified scheme of the fragmentation method. Namely, the ^{34}Mg isotope was produced in two steps: An RI beam of ^{36}Si was first produced from the ^{40}Ar primary beam, and the ^{34}Mg isotope was produced in the subsequent projectile fragmentation of ^{36}Si. In this scheme, ^{34}Mg is apart from the secondary projectile only by two nucleons so that the production cross section of ^{34}Mg with the ^{36}Si beam is expected several orders of magnitude larger than with the ^{40}Ar beam.

The γ-ray energy spectrum observed for ^{34}Mg clearly exhibited two significant γ-lines at 660(10) keV and 1460(20) keV. According to the systematics of the γ-ray intensities [11], the strongest line at 660 keV can be assigned to the $2^+_1 \rightarrow 0^+_{\rm g.s.}$ transition, resulting in $E(2^+_1)$=660 keV. As for the next strongest line, the assignment is less certain. However, it is plausible that the line corresponds to the $4^+_1 \rightarrow 2^+_1$ transition. With this assignment, the value of $E(4^+_1)$ is 2120 keV. The $E(2^+_1)$ value of ^{34}Mg can be compared with those of other Mg isotopes. Among the isotopes, the energy of 660 keV is the lowest. The small $E(2^+_1)$ value of ^{34}Mg, which is even smaller than that of ^{32}Mg, suggests a very large deformation for ^{34}Mg. The resulting value of the $E(4^+_1)/E(2^+_1)$ ratio is about 3.2, close to the limit for rotation nuclei, 10/3.

The B(E2) value of ^{34}Mg has been obtained by the intermediate-energy Coulomb excitation [12]. The energy spectrum of γ rays was measured in coincidence with scattered ^{34}Mg, and a single dominant peak standing out at 656(7) keV was found. Since the intermediate energy Coulomb excitation selectively excites the 2_1^+ state of an even-even nucleus, we concluded that the γ transition corresponds to the de-excitation of the first excited state of ^{34}Mg located at 656(7) keV. The present observation of the 656 keV γ rays confirmed the previous assignment in the RI beam fragmentation experiment for ^{34}Mg [11]. The measured cross section gave us a value of deformation parameter through a coupled channel calculation. We determined $\beta_2^{\rm C}$ for the 2_1^+ state of ^{34}Mg to be 0.58(6). We then obtained B(E2) = 631(126) e^2fm^4, which is the largest among the E2 strengths observed for the nuclei in the vicinity of the island of inversion.

All the above results are compared with the predictions from the recent theoretical works. The quantum Monte Carlo shell model (MCSM) calculation [7] reproduces the experimental results very well, and the value of $E(2_1^+)$ = 620 keV is predicted for ^{34}Mg. The predicted value of the $E(4_1^+)/E(2_1^+)$ ratio is 3.0, also in good agreement with the experimental results. Concerning the B(E2) value, the large value cannot be reproduced by the $0\hbar\omega$ calculation [15], while the MCSM calculation predicts B(E2) of 570 e^2fm^4 ($\beta_2\sim$ 0.55), which is in good agreement with the experimental result. A mean-field approach discusses the shape of ^{34}Mg [16]. The very collective B(E2) value of 549 e^2fm^4 is obtained if both the $0^+_{\rm g.s.}$ and 2_1^+ states have a prolate shape. The present results support a large prolate deformation of ^{34}Mg.

For very neutron-rich nuclei with low beam intensities, a new technique is being developed to determine first excited states for even-even isotopes. This technique is based on the proton inelastic scattering with a liquid hydrogen target to enhance luminosities, and recently applied for ^{30}Ne [17].

3 Particle stability at N=20$\sim$28

The neutron-rich stable isotope ^{48}Ca has been a major tool to produce extremely neutron-rich nuclei up to $N\sim$28 by the projectile fragmentation reaction. In the most recent work using the RIPS [18], where the ^{38}Mg and ^{41}Al isotopes were discovered, the beam intensity was about 4 pnA. A high intensity beam of 140 pnA at its maximum has been recently realized via a new acceleration scheme at RIKEN, where the newly developed linear accelerator complex of the RFQ+RILAC+CSM was used as an injector to the RIKEN

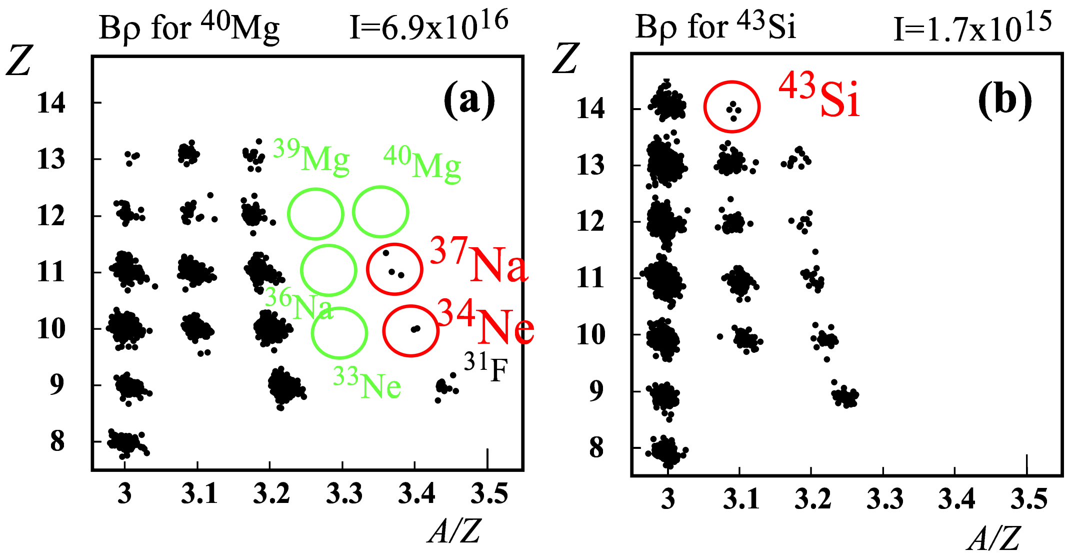

Figure 1: Two dimensional A/Z versus Z plot, which was obtained in the reaction of the ^{48}Ca beam at 64A MeV on a 336 mg/cm^2 tantalum target [13]. (a) was obtained at the ^{40}Mg $B\rho$ setting and (b) at the ^{43}Si setting. The integrated beam intensities for the two settings are 6.9×10^{16} and 1.7×10^{15} particles, respectively. The new isotopes, ^{34}Ne, ^{37}Na and ^{43}Si, are cleary separated and visible. No events associated with ^{33}Ne, ^{36}Na and ^{39,40}Mg, were obtained. the expected yields for

Ring Cyclotron. By using this intense ^{48}Ca beam, an experiment searching for new isotopes has been recently performed [13].

The 64A MeV ^{48}Ca beam reacted with a ^{181}Ta target. The reaction fragments were collected and analyzed with the RIPS spectrometer. Two different settings of the magnetic rigidity ($B\rho$) were employed to search for new isotopes; one optimized for ^{40}Mg and the other for ^{43}Si. The particle identification was performed event-by-event by a standard method on the basis of TOF-ΔE-E-$B\rho$ measurements. Further details of the experimental setup are found in Ref. [13].

Fig. 1 (a) shows a two-dimensional plot of A/Z versus Z, obtained from the data accumulated with the ^{40}Mg $B\rho$ setting, while Fig. 1 (b) is for the ^{43}Si setting. We observed for the first time three new isotopes, ^{34}Ne, ^{37}Na and ^{43}Si. The ^{33}Ne, ^{36}Na and ^{39,40}Mg isotopes have not been observed in this experiment. According to the systematic behaviors of the production cross sections for the observed isotopes [13], the expected cross sections for the ^{33}Ne, ^{36}Na and ^{39}Mg isotopes are obtained to be about 10, 3, and 1 pb, respectively. The 1 pb cross section corresponds to about 30 events for ^{39}Mg at the ^{40}Mg $B\rho$ setting. Thus, the absence of events of ^{33}Ne, ^{36}Na and ^{39}Mg clearly deviates from the expectation and provides a proof for the particle unbound character of ^{33}Ne, ^{36}Na and ^{39}Mg. The expected cross section for ^{40}Mg is an order of 0.01 pb. One event observation of ^{40}Mg at the ^{40}Mg $B\rho$ setting corresponds to about 0.03 pb, which gives the detection limit of the experiment. Therefore, the question whether ^{40}Mg is particle bound or not is left for a future attempt with a higher luminosity.

In this work, the heaviest isotopes of Ne, Na and Si have been extended to ^{34}Ne, ^{37}Na and ^{43}Si, and particle instability of ^{33}Ne, ^{36}Na and ^{39}Mg has been found. These findings are rather in good agreement with the recent mass formula [19]. Concerning the stability of ^{43}Si, two mass formulas, FRDM [19] and ETFSI [20], disagree each other. The FRDM predicts instability with S_n=−1.68 MeV, while the ETFSI does stability. A main difference between the two formulas lies in the degree of deformation. The ETFSI predicts a large deformation than the FRDM for the silicon isotopes at $N\sim 28$. Recent shell model [21, 22] and mean field calculations [23] have also indicated a possible deformation of a nearby nucleus ^{42}Si. Thus, the particle stability found for ^{43}Si may be attributed to a deformation effect.

4 Summary

The exotic properties of very neutron-rich nuclei at N=20∼28 have been observed on the basis of the high luminosity obtained at RIPS as well as the newly developed spectroscopic technique. The energies of low excited states and B(E2) value for ^{34}Mg were observed and obtained via the in-beam gamma spectroscopy with the RI beam fragmentation and the intermediate energy Coulomb excitation method, suggesting that ^{34}Mg has a larger deformation than ^{32}Mg. The particle stability of ^{34}Ne, ^{37}Na and ^{43}Si and the particle instability of ^{33}Ne, ^{36}Na and ^{39}Mg were shown by the experiment using a high-intensity ^{48}Ca beam. On the basis of the high-intensity beam, further experiments towards the $N\sim 28$ region, for example, in-beam gamma spectroscopy on ^{42}Si, will proceed in near future.

This work described here represents the efforts of many people, whom I have tried to adequately reference. In particular, most of the experiments presented here have been performed in collaboration with Univ. of Tokyo, Rikkyo University and RIKEN.

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