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**In-beam gamma-ray spectroscopy with RIB on very
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In-beam gamma-ray spectroscopy with RIB on very neutron-rich nuclei

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The advent of radioactive isotope beams (RIB) has stimulated spectroscopic studies on extremely neutron-rich nuclei where exotic phenomena such as considerable modification of shell structure may occur. To pursue such spectroscopy a new type of in-beam gamma-ray methods using radioactive beam have been developed. The present paper presents a brief review of these methods and recent results of in-beam gamma-ray studies on ^{12}Be and ^{34}Mg , which revealed anomalous features of low-lying states to be associated with shell quenching at $N=8$ and 20 .

1. INTRODUCTION

Traditionally, in-beam gamma-ray spectroscopy has been performed by primarily using low-energy heavy-ion fusion reactions. Such reactions are powerful for producing residual nuclei with large units of angular momentum so that the spectroscopy on high spin states has been extensively promoted. At the advent of radioactive isotope beam (RIB) a new type of in-beam gamma-ray spectroscopy has emerged. In most of the RIB facilities the method of projectile fragmentation (PF) is employed to provide intermediate energy beams of unstable isotopes. A good feature of the PF beams is the wide accessibility of nuclei very far from the stability line. In particular, it is useful to populate a broad range of neutron-rich nuclei even extending to the drip line. This feature, which can be hardly achieved with classical heavy-ion reactions, offers a unique opportunity to study those exotic nuclei in which the numbers of protons and neutrons are drastically unbalanced. Such extremely neutron-rich nuclei would generate a situation where the Fermi energies differ considerably between the two species of nucleons, hence stimulating major modification of the shell structure and various properties of nuclei.

To extend spectroscopic studies to these nuclei, new spectroscopic methods incorporating RIB have to be cultivated. A major difficulty in facilitating RIB arises from its weak intensity. Even a beam of a few particles per second often has to be exploited. A class of methods relevant to "in-beam gamma-ray spec-

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troscopy with RIB" has now developed to make the RIB experiments most useful. These methods commonly use intermediate-energy reactions to populate the states of interest. They benefit considerably from the high energy of the beams for achieving a good efficiency of the experiment.

In this paper I first present a short review of these new methods for gamma-ray spectroscopy and discuss their prospects and limits for the study of neutron-rich nuclei. In the second part I describe some of the latest results of such in-beam gamma-ray studies performed at RIKEN. The isotopes of ^{12}Be and ^{34}Mg were observed to study the phenomena related to shell quenching, which can occur in very neutron-rich nuclei located around $N = 8$ and 20 . The level schemes and transition probabilities were determined for low-lying excited states. Anomalous features were revealed in enhanced E2 collectivity and appearance of low-lying 1^- with unhindered E1 strength.

2. IN-BEAM GAMMA-RAY SPECTROSCOPY WITH RIB

The in-beam gamma-ray spectroscopy with RIB is to be performed in secondary reactions induced by intermediate-energy radioactive beams of projectile fragments. The reactions occur in inverse kinematics: Radioactive nuclei bombard a target to be excited to the states of interest. Outgoing projectile-like nuclei fly towards a narrow cone of forward angles, emitting de-exciting gamma rays in flight. By observing these gamma rays in coincidence with the outgoing nuclei the spectroscopy with fair energy resolution can be conducted. Segmentation of the gamma detector is to be involved for Doppler shift correction crucial for the gamma rays from rapidly moving nuclei.

Any practical methods incorporating RIB are requested to accomplish an extremely high efficiency of event collection in order to cope with the weak intensity inherent to the radioactive beams. In achieving such high efficiency intermediate-energy reactions are effective since they allow the use of thick secondary targets and make use of the kinematical focusing of the ejectiles. To enhance the overall efficiency further one should choose those reactions that exhibit favorable cross sections at intermediate energies. With all these factors combined the in-beam gamma-ray method has now reached a fairly high level of efficiency. One can make a sound spectroscopic experiment even with weak beam intensities of a few incident particles per second.

The first experiment of in-beam gamma ray spectroscopy with RIB was performed on ^{32}Mg using Coulomb excitation at about 50 MeV/u [1]. The first 2^+ state of ^{32}Mg was Coulomb excited and the subsequent gamma transition was observed. The deduced E2 strength indicated an enhanced collectivity, supporting a large deformation of the $N = 20$ nucleus.

This work depicts a typical case of the experimental setup and procedures, which are to be involved in the in-beam gamma-ray measurement with RIB. A

radioactive beam of ^{32}Mg with an intensity of about 300 particles per second was used to bombard a $\sim 350\text{mg/cm}^2$ foil of ^{208}Pb . Coulomb scattered particles were detected and identified with a compact array of silicon detectors spanning a small forward solid angle. A gamma-ray detector array consisting of 55 NaI (TI) detectors provided an overall photo-peak efficiency of 5-15% for the gamma rays of interest. The segmentation of the array facilitated Doppler-shift corrections, which are essential to treat the gamma rays from the moving ^{32}Mg . The cross section for the excitation of the 2^+ state was as large as about 90 mb. With these favorable conditions combined, a spectrum as shown in Fig. 1 can be obtained in a running time of less than a few days.

A unique feature of this work is attributed to the use of Coulomb excitation at intermediate energy far above the Coulomb barrier. This is in contrast to the traditional method, where the Coulomb excitation is performed below the Coulomb barrier, and yields an enormous increase of the efficiency. On the other hand the high-energy Coulomb excitation may suffer from the possible contamination of the competing nuclear process. To assess this competition, cross sections of Coulomb and nuclear excitations are compared in Fig. 2 for E1 and E2 transitions. The cross sections are shown as a function of atomic number (Z) of the projectile for a ^{208}Pb target and the excitation energy and incident energy are fixed at 5 MeV and 70 MeV/u, respectively. The Coulomb excitation dominates over the nuclear excitation almost over the entire domain of Z except for a limited region of light nuclei, where the nuclear contribution may become more im-

Figure 1. Doppler-corrected energy spectrum of gamma rays from the $^{32}\text{Mg} + ^{208}\text{Pb}$ inelastic scattering at 49.2 MeV/u.

Figure 2. Relative cross sections of Coulomb and nuclear excitations vs. the atomic number of projectile calculated for E1 (left) and E2 (right) transitions (see text).

portant for the case of E2 excitation. Thus the intermediate-energy Coulomb excitation offers an indispensable means for efficient and sound spectroscopy of unstable nuclei.

Besides the Coulomb excitation, a couple of other intermediate-energy reactions, i.e., proton inelastic scattering and fragmentation reactions, have recently been employed for in-beam gamma-ray spectroscopy [2,3]. As a general feature of intermediate-energy reactions the amount of angular momentum deposited in the residual nuclei is rather small, resulting in gamma-ray cascades with low multiplicities. Thus only a limited number of low-lying states are populated. Among those, the first 2^+ state is always populated most strongly in even-even residual nuclei while other states such as the first 4^+ or second 2^+ can be excited occasionally. Observation of these states is particularly useful to investigate E2 collectivity (or non-collectivity). For this purpose the most important observables are the energy of the first 2^+ state, $E(2^+)$, and the transition probability, $B(E2; 0^+ \rightarrow 2^+)$. The determination of $E(4^+)$ supplements to determine the band structure of collective states. It is worth noting that 1^- states appear at low energies in some of the neutron-rich nuclei when the magicity vanishes. This phenomenon is not trivial and is particularly so when the accompanying E1 transition is rather unhindered. To study such anomaly the most relevant observables are $E(1^-)$ and $B(E1; 0^+ \rightarrow 1^-)$.

The three reactions employed bear their own characteristics with respect to cross sections, selectivity for populating states, reach to rare isotopes, and so on.

	$E(2^+)$	$E(4^+)$	$B(E2)$ ($2^+ \rightarrow 0^+$)	$E(1^-)$	$B(E1)$ ($1^- \rightarrow 0^+$)	Remarks
Int-E Coulomb	○		⊙	⊙	⊙	$B(E\lambda)$ (EM)
(p, p')	○		○			β_2 (DWBA)
FR	○	○				yrast levels!?
2nd-step FR	○	○				far from stability

Figure 3. Spectroscopic applicability of four different methods, which use Coulomb excitation (Int-E Coulomb), proton inelastic scattering (p,p'), fragmentation reaction (FR), and two-step fragmentation reaction (2nd-step FR).

Thus one can choose among the reactions to best exploit their advantages complementarily. In Fig. 3 spectroscopic merits of these reactions are compared in terms of the low-lying E2 and E1 excitations in even-even nuclei. The applicability is rated for different variables to be observed: A circle indicates an adequate applicability while a double circle denotes a superb case. As for the study of E2 excitation, any of the three reactions can be useful to determine $E(2^+)$. In measuring $B(E2; 2^+ \rightarrow 0^+)$ the Coulomb excitation is most powerful because of the large cross section and it is transparent due to the Coulomb nature of the relevant interaction. The proton inelastic scattering is also useful while some theoretical assumptions may need to be incorporated. It is worth noting that proton inelastic scattering and Coulomb excitation complement each other by exhibiting different sensitivities to protons or neutrons. The former is more effective than the latter in exciting neutrons while the opposite is the case for proton excitation. Thus a combined use of the two reactions may allow to separate the proton and neutron contributions [4]. Another useful feature of the proton scattering is its applicability to light nuclei for which the validity of Coulomb excitation method becomes uncertain.

While these two reactions are effective for the study of 2^+ states they tend to fail to populate the 4^+ state. In this respect fragmentation reactions offer a good opportunity by populating a more variety of low-lying states including high spin states. The fragmentation method, however, may involve uncertainty in determining the spin and parity of the observed states. A systematic study is in progress to verify a plausible empirical rule that transitions along yrast states are most favorably populated. For the study of the E1 mode Coulomb excitation is

superb since the cross section is sizable with little contamination from nuclear contribution.

Among the three reactions considered Coulomb excitation has been most extensively used, facilitating systematic studies of quadrupole deformation over a broad domain of neutron rich nuclei [5]. Gamma-ray spectroscopy with proton inelastic scattering has been attempted quite recently [2]. This method benefits from the use of a proton target. This implies the largest number of atoms for a given target thickness, enhancing the reaction yield accordingly. The fragmentation method is also new [3], and is being developed intensively. A new approach was recently made by facilitating fragmentation reactions in two steps [6]. In this modified scheme the first fragmentation is used to produce a beam of unstable nuclei, which in turn will be used to induce the second fragmentation to produce the final nucleus of interest. By choosing the first fragment to be closer to the final nucleus one can improve the experimental efficiency considerably. This scheme is specially useful to study nuclei very far from the stability line as demonstrated by the study on ^{34}Mg [6].

3. SHELL QUENCHING IN NEUTRON RICH NUCLEI

In this section the results of recent in-beam gamma-ray spectroscopy experiments performed at RIKEN are reported. The basic subject addressed is the phenomena of anomalous shell quenching which may occur in extremely neutron-rich nuclei. The possibility that the shell structure will suffer a major change when the numbers of proton and neutrons are drastically unbalanced has been discussed since the early 70's [7]. This problem has recently attracted much attention as experimental information accumulates on relevant neutron-rich nuclei. Such a change of shell structure may imply a significant reduction of the shell gap at ordinary magic numbers or give rise to appearance of new magic numbers.

This paper deals with properties of low-lying states of ^{12}Be and ^{34}Mg . These isotopes are typical neutron-rich nuclei with $N = 8$ and 20 , where the effects of shell quenching are most likely to be manifested. Specifically, three topics are involved; 1) E2 collectivity of ^{12}Be studied in proton inelastic scattering [2], 2) the low-lying 1^- state of ^{12}Be and its E1 strength as studied in Coulomb excitation [8], and 3) the quadrupole deformation of ^{34}Mg studied with the two-step fragmentation method [6]. These experiments involve the three different in-beam methods discussed in Sect. 2.

3.1. E2 collectivity of ^{12}Be studied in proton inelastic scattering

Indications of shell quenching around $N = 8$ have been accumulated through many years. The basic nature of the anomaly may be represented by the diagram of Talmi and Unna [9], which compares the relative energy of the $2s_{1/2}$ state

with respect to the $1p_{1/2}$ state in $N = 7$ isotones. As the isotone moves from ^{15}O to ^{11}Be the $2s_{1/2}$ state gradually lowers and even falls below the $1p_{1/2}$ state at ^{11}Be . Recent experiments have shown that the reversal of the two states persists in ^{10}Li [10]. It was also indicated that the trend towards degenerate two states with decreasing atomic number may also be relevant in $N = 9$ isotones [11].

The near degeneracy of the $2s_{1/2}$ and $1p_{1/2}$ states will considerably affect the low-energy properties of $N = 8$ nuclei, since the energy gap is small at $N = 8$, however, it is more significant at $N = 10$. In such a case the outermost neutrons can easily be excited, leaving the nucleus to be softer. In the case of ^{12}Be the first 2^+ state is located at an excitation energy of 2.10 MeV, which is even lower than that of ^{10}Be (3.37 MeV). This lowered energy is in contrast to the usual cases for nuclei located at a well established magic number, and may be considered to be a signature of shell quenching. The possible shell quenching may also result in enhancement of quadrupole deformation of the $N = 8$ nucleus.

In this section we discuss the quadrupole deformation of ^{12}Be as obtained from the excitation probability to the first 2^+ state in proton inelastic scattering [2]. The adjacent nucleus ^{10}Be was also studied for comparison. Proton scattering was used instead of heavy-ion scattering since the latter involves mixed contributions from nuclear and Coulomb interactions for these light nuclei and is hence subject to theoretical uncertainties in the deduced transition probability. As mentioned before proton scattering is more sensitive to neutrons relatively to Coulomb excitation. This feature was effective for the present study since the enhanced deformation if any should be mostly attributed to valence neutrons.

The experiment was performed using the RIKEN Projectile Fragment Separator (RIPS). Secondary beams of ^{12}Be and ^{10}Be obtained through RIPS were separately used to bombard a 90.2 mg/cm^2 thick $(\text{CH}_2)_n$ target with energies of 53.8 and 59.2 MeV/u, respectively. Inelastically scattered Be nuclei were recorded at a plastic scintillator hodoscope placed 5 m downstream from the target, which was segmented to locate the hit position of the scattered particles. Particle identification was performed by combining ΔE , E and TOF signals provided from the hodoscope. Gamma rays were detected with an array of 55 NaI(Tl) scintillators surrounding the target from 67 to 148 degrees with respect to the beam axis. Each of the scintillators had a rectangular-prism shape with a size of $6 \times 6 \times 12 \text{ cm}^3$, yielding a photopeak efficiency of about 7% at 2.10 MeV.

Figure 4 shows the Doppler corrected gamma-ray spectrum obtained in coincidence with scattered particles of ^{12}Be . A single dominant peak stands out at around 2.1 MeV, representing the good selectivity for the 2^+ state. The cross section obtained (27(4) mb) can be used to extract the deformation parameter β_2 by incorporating a coupled-channel calculation with the code ECIS79 [12]. The deformation parameter can then be related to the deformation length δ , which presents a measure of deformation to be compared with theoretical results. After accounting for the ambiguities due to optical parameters we finally obtain a deformation length of $\delta = 2.00(23) \text{ fm}$ for ^{12}Be , while we obtain $\delta = 1.80(25) \text{ fm}$ for

Figure 4. Doppler-corrected gamma-ray spectra of ^{12}Be (left) and ^{10}Be (right) observed in proton inelastic scatterings.

^{10}Be . The δ value of ^{12}Be is not at all suppressed but it is even larger than that of ^{10}Be in conflict with the expectation for nuclei at shell closure.

A comparison was made with shell-model calculations using p - sd model space and the PSDMK effective interaction [13]. In order to depict the effect of shell quenching at $N = 8$ we have tested two values of 0.0 MeV and -3.41 MeV chosen for the change of the $2s_{1/2}$ neutron energy, where the former corresponds to the normal shell gap while the latter represents a quenched shell gap as taken in Ref. [14]. For the case of ^{10}Be the choice between the two values did not affect the result of the δ value significantly. For the case of ^{12}Be , however, the choice of 0.0 MeV underestimated the δ value by a factor of about 2 while the choice of the lowered $2s_{1/2}$ state provided an excellent agreement with the experimental result. Thus the enhanced deformation observed for ^{12}Be may be attributed to the neutron shell quenching at $N = 8$.

3.2. Low-lying 1^- state of ^{12}Be and its E1 strength

In most nuclei low-energy E1 transitions are considerably hindered because of the effects of the Giant Dipole Resonance (GDR), which exhausts a large portion of the E1 strength. The near degeneracy of the two single particle states with opposite parities may give rise to a unique possibility that a low-energy E1 transition occurs with a significant strength because of a promoted decoupling from GDR. The loose binding of the valence neutrons may enhance the phenomena. In the case of a $N = 7$ nucleus of ^{11}Be an E1 transition occurs between the ground and first excited states, which may correspond to the $2s_{1/2}$ and $1p_{1/2}$ neutron states, respectively. The E1 strength is as large as 0.36 W.u., which represents one of the strongest low-energy E1 transitions. In the case of ^{12}Be the degeneracy may cause the appearance of a low-lying 1^- state, which is strongly connected with the ground state. Indeed such a 1^- state has been identified in our Coulomb excitation experiment [8].

Figure 5. Doppler-corrected gamma-ray spectra observed for ^{12}Be inelastic scatterings on ^{208}Pb (left) and ^{12}C (right).

The experiment was performed using the same setup as described in Sec. 3.1. To facilitate the Coulomb excitation a 350.8mg/cm^2 thick ^{208}Pb target was bombarded with a beam of ^{12}Be at an energy of 53.3 MeV/u . Figure 5 shows the Doppler corrected gamma-ray spectrum obtained in coincidence with ^{12}Be isotopes scattered on the lead target. Besides the line of the $2^+ \rightarrow 0^+$ transition a strong peak is observed at 2.68 MeV . A carbon target was bombarded for comparison. In sharp contrast the second peak was hardly seen in the carbon spectrum. This clearly indicates that the 2.68 MeV gamma rays seen in the lead spectrum is dominantly due to Coulomb excitation by the high Z target. By incorporating the deduced cross section (4.9 mb) the excitation mode was uniquely identified to be an E1 transition leading to a 1^- state located at $2.68(3)\text{ MeV}$, the second lowest excited state of ^{12}Be . The $B(\text{E1}; 0^+ \rightarrow 1^-)$ value was deduced to be $0.051(13)\text{ e}^2\text{fm}^2$, which is strongest among low-energy E1 transitions ever observed for even-even nuclei.

3.3. Quadrupole deformation of ^{34}Mg studied with the fragmentation method

It has been known for some time that neutron-rich isotopes in the neighborhood of ^{32}Mg tend to show enhanced binding as revealed by mass measurements [15]. This phenomenon may be associated with the manifestation of a deformed nucleus, which is unusual for ordinary nuclei with the magic number $N = 20$. In the experiments which followed a lowered excitation energy ($E(2^+) = 0.89\text{ MeV}$) [16] and an enhanced E2 strength ($B(\text{E2}; 0^+ \rightarrow 2^+) = 454(78)\text{ e}^2\text{fm}^4$) [1] were found for the 2^+ state of ^{32}Mg , providing further evidences for occurrence of anomalous deformation.

Early theoretical studies [17] indicated that such an anomaly may occur due to a possible reduction of the shell gap and promoted contributions from 2-particle and 2-hole excitations across the two major shells of the *sd* and *pf* orbitals. It was also noted that the phenomenon should occur in a specific region as called the island of inversion, which ranges from $N = 20$ to 22 and $Z = 10$ to 12 . Recently, more quantitative predictions for these nuclei have become available from extensive calculations using the quantum Monte Carlo shell model [18]. The results reinforce the above arguments for the presence of deformation.

Experimental studies for these nuclei were rather limited to ^{32}Mg until recently. The present work [6] is a new attempt to extend the spectroscopy across the island. It is aimed at locating low-lying yrast states of ^{34}Mg , which may provide a measure of deformability of the heaviest nucleus in the island of inversion.

The two-step fragmentation method was employed for the first time. The first fragmentation reaction with a primary beam of ^{40}Ar was used to produce a secondary beam of ^{36}Si through RIPS, while the ^{36}Si ions hit a target of ^9Be at the end of RIPS to be further fragmented to make ^{34}Mg nuclei. The resultant fragments were detected and identified with a parallel plate avalanche counter as well as four sets of counter telescopes consisting of three layers of ion-implanted silicon detectors at forward angles. Gamma rays from fragments in flight were detected with the array of the NaI(Tl) scintillators surrounding the secondary target of ^9Be . ^{34}Mg has only two nucleons less than ^{36}Si so that the intensities of gamma rays from ^{34}Mg are relatively strong compared to gamma rays from the other secondary fragmentation products. This feature has helped to improve the experimental efficiency considerably.

Figure 6 shows the Doppler corrected gamma-ray spectrum obtained in coincidence with ^{34}Mg fragments. The spectrum involves some contamination peaks due to the adjacent nucleus ^{33}Mg , which were identified from a spectrum separately obtained for ^{33}Mg . Besides these peaks, two significant peaks are found at 660(10) and 1460(20) keV to be attributed to ^{34}Mg . According to an empirical rule that the fragmentation reaction tends favorably to populate yrast states the strongest line at 660 keV may be assigned to be the $2^+ \rightarrow 0^+$ transition. This leads to a value of $E(2^+) = 660(10)$ keV, which has turned out to be in good agreement with the theoretical result of $E(2^+) = 620$ keV obtained from quantum Monte Carlo shell model calculation [18]. Assuming the same empirical rule, the second strongest line at 1460 keV may be assigned to be the $4^+ \rightarrow 2^+$ transition, corresponding to an $E(4^+)$ value around 2120 keV.

The deduced $E(2^+)$ value of ^{34}Mg can be compared with those of other Mg isotopes. Among the lighter isotopes, ^{32}Mg has a distinguishably low energy of 885 keV. This is lower than any of the others by a factor of about two, providing a strong indication of deformed ^{32}Mg . It is remarkable that the energy for ^{34}Mg is even lower than that of the ^{32}Mg , suggesting a still larger deformation of ^{34}Mg . By incorporating the tentatively deduced $E(4^+)$ value one obtains the ratio of

Figure 6. Doppler-corrected gamma-ray spectra for ^{32}Mg (left) and ^{34}Mg (right) observed in fragmentation of ^{36}Si .

$E(4^+)/E(2^+) = 3.2$, which is very close to that for the rotational band of deformed nuclei. These results are all suggestive that ^{34}Mg is indeed a very well deformed nucleus. Recently the $B(E2; 0^+ \rightarrow 2^+)$ value was measured with Coulomb excitation [19]. The preliminary result indicates a $B(E2)$ value fairly larger than that of ^{32}Mg , further supporting a large deformation of ^{34}Mg .

4. SUMMARY

We have developed several methods for in-beam gamma-ray spectroscopy using radioactive isotope beams which include intermediate-energy reactions of Coulomb excitation, proton inelastic scattering and fragmentation reactions. They have been used successfully to study low-lying excited states of very neutron-rich nuclei. Among others the studies on ^{12}Be and ^{34}Mg revealed anomalous properties which may be attributed to the change of shell structure: For ^{12}Be an enhanced quadrupole collectivity was found for the $0^+ \rightarrow 2^+$ excitation, and a low-lying 1^- state which is accompanied by a very strong E1 transition was located at 2.68 MeV. For ^{34}Mg the 2^+ and possibly 4^+ states were located at lowered energies, indicating the most deformed nucleus among Mg isotopes.

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