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Spectroscopy of nuclei around N = 20 with direct reactions

T. Motobayashi[a]

Department of Physics, Rikkyo University, 3 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan

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Abstract. Due to the recent development of radioactive beam production, various direct reaction studies in reversed kinematics have been made to investigate the behavior of the $N = 20$ shell closure in the neutron-rich region. Coulomb excitation, proton inelastic scattering, and fragmentation of unstable nuclei have been studied with γ-ray detection.

PACS. 23.20.Lv Gamma transitions and level energies – 25.40.Ep Inelastic proton scattering – 25.60.-t Reactions induced by unstable nuclei – 25.70.De Coulomb excitation

1 Introduction

Sudden disappearance of the $N = 20$ shell closure in very neutron-rich nuclei was suggested by mass measurements [1] in 1975 and the low excitation energy (885 keV) of the first-excited state in ^{32}Mg observed in 1979 [2]. Recently, intermediate-energy radio-isotope (RI) beams have become available, and several direct reaction studies have been performed for spectroscopy of nuclei around $N = 20$.

To produce the RI beams for these studies, the projectile-fragmentation scheme is used, and hence the energy resolution of the separated RI beam is poor (a few %) and the intensity is low. The latter condition requires a thick target for secondary reactions. Therefore the energy-loss measurement, where the energy of the reaction product is measured in resolving nuclear levels in the final state, is limited in use. In an alternative method, de-excitation γ-rays from excited levels are measured in coincidence with the outgoing particles to select the reaction channel. In this scheme, the final state resolution is independent of the beam energy spread, though the Doppler shift of measured γ-rays from fast ejectiles should be corrected for. This method has been employed to study the structure of unstable nuclei at several laboratories, such as RIKEN, MSU, GANIL, and GSI, where fast RI beams are available.

2 Coulomb excitation at intermediate energies

Coulomb excitation with intermediate-energy RI beams is a powerful tool to study low-lying states of exotic nuclei. The traditional energy region for Coulomb excitation studies is a few MeV/nucleon where the Coulomb barrier suppresses nuclear excitation. On the other hand, the intermediate-energy region, a few tens to a few hundreds MeV/nucleon, is far above the Coulomb barrier. However, the Coulomb excitation method can be still used for $E1$ and $E2$ transitions, because the nuclear-excitation amplitude is negligible or well under control for certain combinations of the projectile and the target [3].

One of the first experiments with intermediate-energy RI beams was performed at RIKEN in 1994 for the neutron-rich $N = 20$ nucleus ^{32}Mg [4]. Radioactive ^{32}Mg beams with an average energy of 49.2 MeV/nucleon bombarded a ^{208}Pb target with 350 mg/cm^2 thickness, and γ-rays from the 2^+ state in ^{32}Mg were detected. The extracted large $B(E2)$ value of $454 \pm 78\ e^2\mathrm{fm}^4$ supports the idea of disappearance of the $N = 20$ shell closure in ^{32}Mg. As shown in fig. 1(b), the experimental result agrees with a shell model prediction [5] which exhibits a large amplitude of pf-shell neutrons in ^{32}Mg. The disappearance of the $N = 20$ shell closure for ^{32}Mg is also demonstrated in fig. 1(a) by the comparison with the results calculated by the $N_\mathrm{p}N_\mathrm{n}$ scheme [6] in the condition that the last twelve neutrons are regarded as valence particles.

This experiment was followed by extensive Coulomb excitation studies with intermediate-energy RI beams at MSU and GANIL for neighboring nuclei with $19 \leq N \leq 21$, including the region called "island of inversion" with large deformation. A topical review for the Coulomb excitation with fast exotic beams was given recently by Glasmacher [7].

Recently, we extended the Coulomb excitation study to the more neutron-rich nucleus ^{34}Mg with only 4 particle/s intensity of the beam [8]. The experimental method was essentially the same as that for the ^{32}Mg experiment. As discussed later, ^{34}Mg is a candidate of a well-deformed nucleus, and hence determination of $B(E2)$ for the 2^+-0^+ transition is of crucial importance.

[a] e-mail: motobaya@rikkyo.ne.jp

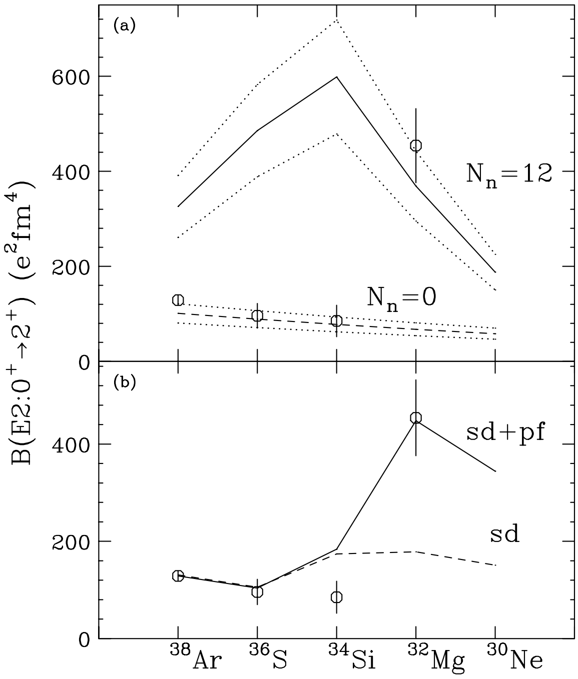

Fig. 1. Plots of $B(E2 : 0^+ \rightarrow 2^+)$ values for several $N = 20$ nuclei. The solid lines represent predictions of the N_pN_n scheme [6] (a) and the shell model of ref. [5] (b).

Figure 2 shows spectra of γ-rays measured in coincidence with outgoing particles identified as ^{34}Mg. The spectrum in the moving frame (bottom) was obtained by correcting for the Doppler shift arising from the high velocity ($\beta \approx 0.3$) of the γ emitter. This correction was made by the γ-ray emission angle measured by an array of NaI(Tl) scintillators called DALI, which consisted of 66 crystals with the dimension of $6 \times 6 \times 12$ cm^3. As shown in the figure, a clear peak is observed at around 656 keV which corresponds to the 660 keV peak observed in the fragmentation study discussed later, and is attributed to the 2^+-0^+ transition in ^{34}Mg. From the yield of the peak, one can extract the Coulomb excitation cross-section and hence the electromagnetic transition probability $B(E2)$.

Preliminary analysis suggests a large $B(E2)$ value around 600 e^2fm^4. This corresponds to the quadrupole deformation $\beta_2 \approx 0.6$, which is even larger than ≈ 0.5 for ^{32}Mg [4]. This supports the picture of a well-developed prolate deformation and a large pf-shell contribution in this nucleus. The predictions of the mean-field calculation assuming prolate shapes for both the 0^+ and 2^+ states by Rodríguez-Guzmán, Egido and Robledo [9] agree with the present experimental result. The Monte Carlo shell model by Utsuno *et al.* [10] predicts a large prolate deformation of $\beta_2 \approx 0.55$, which is consistent with the experimental value.

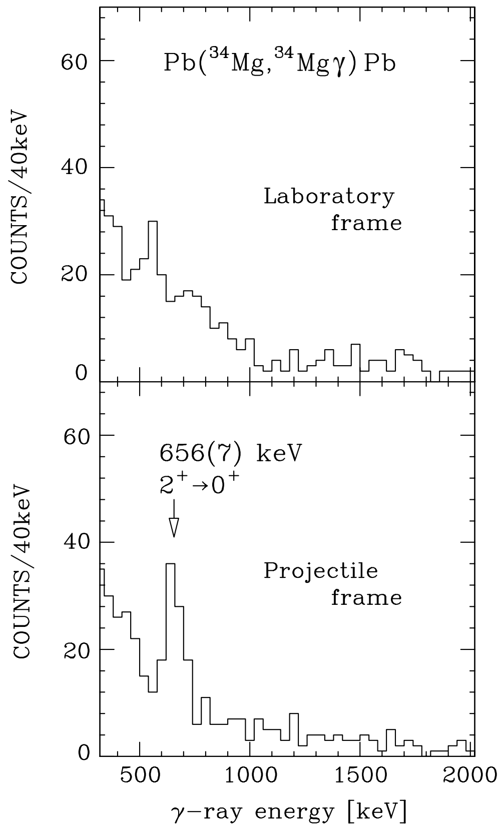

Fig. 2. Spectra of γ-rays measured in coincidence with outgoing ^{34}Mg particles from the inelastic ^{34}Mg + Pb scattering at the ^{34}Mg energy of 44.9 MeV/nucleon. The top and bottom panels, respectively, show the spectra obtained in the laboratory and projectile frames.

3 Proton inelastic scattering

Proton inelastic scattering in reversed kinematics has been studied mostly with the energy-loss method where the recoil protons are measured. Extracted deformation parameters are sensitive to the deformation of neutron distribution about three times more than to that for proton due to the strong p-n effective interaction compared with the p-p interaction in the energy range of several tens MeV/nucleon. Since the electromagnetic transition probability is determined by the proton distribution, comparison between the deformation parameters obtained from a (p, p') and an electromagnetic probe may provide a piece of information on the difference in proton and neutron deformation.

Figure 3 shows an example of such comparison. Quadrupole deformation parameters β_2 are plotted for even sulfur isotopes. The data are compiled by Blumenfeld *et al.* [11]. Up to $N = 20$ ($A = 36$), deformation parameters from (p, p') (open circles) agree with those obtained from lifetime measurements or Coulomb excitation experiments (crosses). However, for ^{38}S and ^{40}S, larger deformation is observed for (p, p') scattering, suggesting larger deformation for the neutron distribution. This can be interpreted as an effect of valence neutrons in the pf-shell

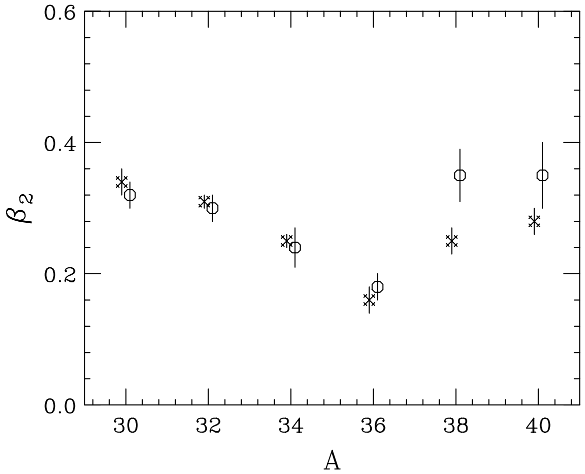

Fig. 3. Quadrupole deformation parameter β_2 for sulfur isotopes. The crosses and open circles are obtained from electromagnetic probes and inelastic proton scatterings, respectively. The data are taken from ref. [11].

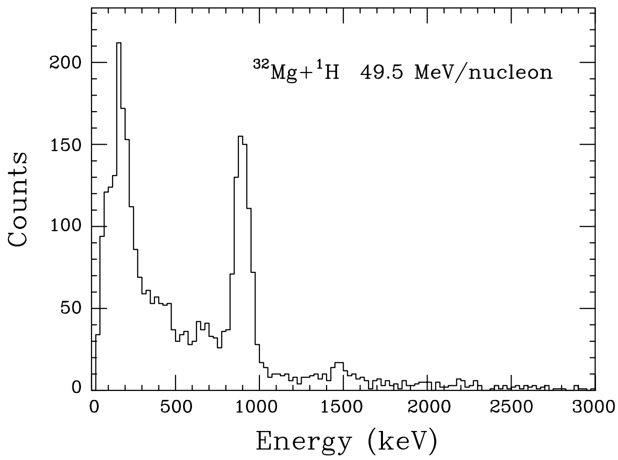

Fig. 4. Doppler-corrected spectrum of γ-rays associated with the $^{32}\mathrm{Mg} + {}^{1}\mathrm{H}$ inelastic scattering at $E(^{32}\mathrm{Mg})$ = 49.5 MeV/nucleon.

orbitals. The $N = 20$ shell closure persists for sulfur isotopes with $N \leq 20$.

Recently, an experiment of the particle-γ coincidence type was made for the $^{32}\mathrm{Mg} + \mathrm{p}$ inelastic scattering at RIKEN [12]. Our preliminary result yields a $\beta_2^{(\mathrm{pp}')}$ value close to the value obtained in the previous Coulomb excitation experiment for ^{32}Mg [4], suggesting the proton and neutron deformations are almost the same in ^{32}Mg. A Doppler-corrected γ-spectrum is shown in fig. 4. Besides the peak at 895 keV for the 2^+-0^+ transition, a small peak is seen at about 1.5 MeV. This energy coincides with that of the peak (1430 keV) observed in the fragmentation experiments at GANIL [13] and RIKEN [14], which corresponds to a transition to the 2^+ state from a higher state the spin of which is not established. For example, from the systematics of spin population in the fragmentation reaction, Azaiez proposes the spin of 4^+ [15], whereas the $^{32}\mathrm{Mg} + {}^{28}\mathrm{Si}$ measurement favors 3^- [16]. However, the relative yield of the two peaks in fig. 4 depends much on the width of the gate for identifying ^{32}Mg by a ΔE-E silicon telescope: The second peak gets smaller as the gate width gets narrower, whereas the counts for the first peak (2^+-0^+) do not change much. This implies that the second peak (at least a part of it) is associated with a Mg isotope other than ^{32}Mg. This puzzle may be related to the question concerning possible feeding of the 2^+ state from higher states in the Coulomb excitation experiments [17, 18]. Since the spin of the second-excited state is important to understand the nuclear structure of ^{32}Mg, and also the amount of the feeding influences the final $B(E2)$ value, further investigation is required.

Another advantage of the $(\mathrm{p}, \mathrm{p}')$ reaction experiments with the particle-γ method is its high experimental efficiency. Very low-intensity beams of the order of 0.1 particle/s are enough to determine the location of the first-excited state of a very neutron-rich nucleus. Recently, we made a $(\mathrm{p}, \mathrm{p}')$ experiment to study ^{30}Ne, another neutron-rich $N = 20$ nucleus the first 2^+ state of which is not known. Several predictions have been given, and the location of the 2^+ state might provide a useful information to understand the behavior of very neutron-rich $N = 20$ nuclei. A liquid-hydrogen target [19] with the thickness of 180 mg/cm^2 was used instead of usual $(\mathrm{CH}_2)_n$ target to much improve the signal-to-noise ratio. Using a 60 MeV/nucleon ^{30}Ne beam with the intensity of 0.3 particle/s, a γ-ray peak was observed [20]. This demonstrates the usefulness of the method.

4 Spectroscopy with "two-step fragmentation"

Measurements of γ-rays associated with projectile fragments are also useful for spectroscopy of exotic nuclei [13]. In contrast to Coulomb excitation, where only the first-excited states are populated with large cross-sections for even-even isotopes, the fragmentation method has the advantage of the possibility to feed higher states. We applied the method to observe γ-rays from the very neutron-rich nucleus ^{34}Mg in the two-step fragmentation scheme [14]: First, a radioactive ^{36}Si beam was produced from a ^{40}Ar beam. Then, the secondary beam bombarded a beryllium target, and ^{34}Mg fragments and their de-excitation γ-rays were detected in coincidence. If the primary ^{40}Ar is used as the incident particle, the fraction of the γ-rays from ^{34}Mg in the total γ yield is quite small due to the small production cross-section. This leads to the use of high beam-target luminosity and hence to a heavy load from γ-ray detection. In the two-step scheme, on the other hand, the fragmentation is induced by a nuclide close to ^{34}Mg (^{36}Si in this case). Its large production cross-section allows the use of much more intense primary beams.

As shown in fig. 5, the Doppler-corrected γ-ray spectrum exhibits two distinct peaks at 660 keV and 1460 keV. From the systematics of spin population observed for known nuclei, the first peak is assigned to be the 2^+-0^+

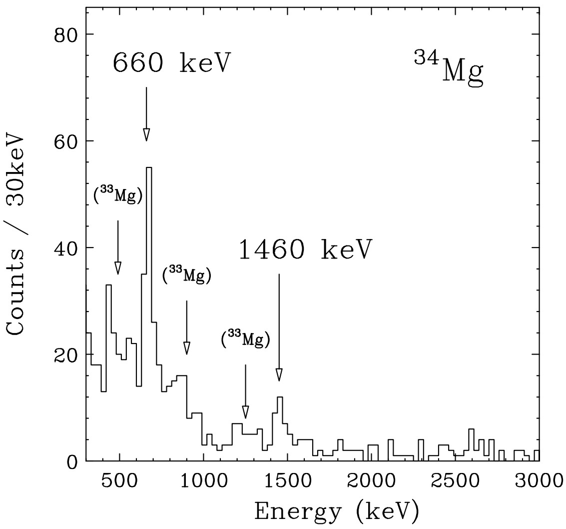

Fig. 5. Doppler-corrected spectrum of γ-rays associated with ^{34}Mg fragments produced by the ^{36}Si + ^{9}Be interaction at $E(^{36}\mathrm{Si})$ = 38 MeV/nucleon. Besides the two distinct peaks at 660 keV and 1460 keV, a few small peaks associated with ^{33}Mg are seen due to the limited mass resolution for the reaction products.

transition in ^{34}Mg. The excitation energy 660 keV is even lower than that for ^{32}Mg, suggesting larger deformation of ^{34}Mg. Based on the assignment of the second peak to the 4^+-2^+ transition [14], the ratio of the energies $E(4^+)/E(2^+)$ is calculated to be 3.2, which is very close to the value 3.3 expected for a rigid rotor. Therefore, ^{34}Mg might be a nucleus with well-developed quadrupole deformation. Furthermore, these energies are close to the prediction by the Monte Carlo shell model [10], the ingredients of which are large prolate deformation and large amount of 2p-2h configuration mixing across the $N = 20$ shell gap.

5 Summary

Direct reactions with intermediate-energy RI beams are very powerful in studying properties of exotic nuclei. In resolving the nuclear level of interest, measurements of de-excitation γ-rays in coincidence with nuclei in the final state of the reaction match the conditions of experiments with secondary beams, the intensity of which is usually weak and the energy spread of which is large.

Using intermediate-energy beams of unstable nuclei, much effort has been made to study the structure of nuclei around the neutron magic number $N = 20$ since the experiment of ^{32}Mg excitation was performed in 1994 [4]. The Coulomb excitation, proton inelastic scattering, and fragmentation reaction have been studied so far.

Electromagnetic transition probabilities (or the reduced transition matrix elements $B(E2, 0^+ \to 2^+)$) can be extracted from Coulomb excitation measurements. The method is extremely useful when the lifetime is too short to be measured directly and/or the excited state of interest is hard to be populated by a β-decay or other reactions. Thus 2^+-0^+ transitions in exotic even-even nuclei around $N = 20$ may be able to be studied only by the Coulomb excitation method. By extensive studies at RIKEN, MSU and GANIL, the behavior of the "island of inversion" becomes clearer, and the vanishing of the shell gap between the *sd*- and *pf*-shells in the neutron-rich region is now discussed in detail. The most recent measurement suggests a quite large deformation of $\beta_2 \approx 0.6$ for the very neutron-rich nucleus ^{34}Mg.

The proton inelastic scattering has also been studied to extract the matter deformation. In the region of several tens MeV/nucleon, the $(\mathrm{p}, \mathrm{p}')$ cross-section is sensitive mainly to the neutron distribution. Therefore comparison with the electromagnetic deformation obtained from the Coulomb excitation yield or lifetime is useful to separate the deformation of proton and neutron distribution. Such comparison was made for sulfur isotopes, and larger neutrons deformation is observed for $N > 20$. A comparison can be made also for the nucleus ^{32}Mg using our Coulomb excitation and recent $(\mathrm{p}, \mathrm{p}')$ results.

The fragmentation reaction can populate higher states compared with the Coulomb excitation, providing us with a unique tool for spectroscopy. By the "two-step fragmentation" scheme, we could observe two γ transitions in ^{34}Mg. Their energies imply a well-developed deformation, since the energy ratio $E(4^+)/E(2^+)$ is quite close to the value for a rigid rotor.

An advantage common to these reactions, which enables the experimental studies with weak RI beams, is their large cross-sections. Typical values are a few tens or even a few hundreds mb. This is partly due to their good kinematical matching even at intermediate energies. These reactions do not involve any mass transfer, and hence the kinematical matching is not harmed at high energies. The neutron knockout reaction [21] is another reaction with a good kinematical matching. On the other hand, the nucleon stripping reactions involve mass transfer, and therefore their application might be limited to low incident energies below $\approx$ 50 MeV/nucleon depending on the angular momentum of the final state. Since they are useful in studying the nature of single-particle orbitals, the behavior of transfer reactions should be studied carefully.

There are several projects for the next-generation RI beam facilities. More intense beams will be available, and hence more exotic nuclei may be supplied. The direct reaction in reversed kinematics would hopefully be a good tool to explore exotic areas of nuclear chart.

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