Eur. Phys. J. A **13**, 55–58 (2002)

THE EUROPEAN PHYSICAL JOURNAL A

Inelastic scattering on ^{12}Be and disappearance of the N = 8 magic number

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Received: 1 May 2001 / Revised version: 26 June 2001

Abstract. Experimental studies on in-beam γ-ray spectroscopy using a ^{12}Be radioactive beam are presented. Inelastic scattering of the neutron-rich ^{12}Be nucleus on ^{208}Pb, ^{12}C, and $(CH_2)_n$ targets has been studied by measuring de-excitation γ-rays in coincidence with scattered particles. The level schemes and transition probabilities are determined for low-lying excited states in ^{12}Be. The present paper presents a brief review of the spectroscopic results, which may be associated with the $N = 8$ shell quenching near the drip line.

PACS. 21.10.Re Collective levels – 23.20.-g Electromagnetic transitions – 25.60.-t Reactions induced by unstable nuclei – 27.20.+n $6 \le A \le 19$

1 Introduction

The availability of radioactive isotope beams (RIBs) has opened broad access to unstable nuclei, offering various opportunities for spectroscopic studies. The first experiment of in-beam γ-ray spectroscopy with RIBs was performed at RIKEN in the intermediate-energy Coulomb excitation of ^{32}Mg at about 50 AMeV [1]. The 2_1^+ state of ^{32}Mg was excited in the Coulomb field of a lead target and the subsequent γ transition was observed. This experimental technique had attractive aspects in terms of both efficiency and resolution. The use of a thick target and a high-efficiency array of γ-ray detectors offset weak beam intensities of around 300 s^{-1}. The kinematical focusing of the ejectiles was also an advantage for high-efficiency measurements. In addition, a good energy resolution was achieved by measuring de-excitation γ-rays instead of measuring particle energies. Together with extensive studies at MSU [2], the experimental technique becomes a typical method of spectroscopy of unstable nuclei. Besides the Coulomb excitation, various kinds of in-beam γ-ray spectroscopy with RIBs have recently been performed in intermediate-energy reactions, such as inelastic proton scattering [3], one-neutron knockout reactions [4], and fragmentation reactions of both primary [5] and secondary [6] beams.

In this paper, we report recent experimental studies performed at RIKEN using a radioactive ^{12}Be beam. The neutron-rich nucleus ^{12}Be attracts great interest because of the possible shell quenching in the $N = 8$ isotones [7,8]. So far, several studies have been focused on the ground-state properties of ^{12}Be. Recently, a knockout reaction of ^{12}Be measured at MSU showed a strong indication that intruder $2s_{1/2}$ and $1d_{5/2}$ configurations would play an important role in its ground state [4]. A large breaking of the p-shell closure in ^{12}Be was also suggested by the theoretical study based on shell model about the quenching of the Gamow-Teller transitions [8].

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One of the most interesting problems to be investigated is how the configuration mixing in the ground state affects the excitation properties. Low-lying excited states in ^{12}Be are intriguing subjects, since properties of low-lying states in even-even nuclei, such as level schemes and transition probabilities, are sensitive to modification of nuclear shell structure. We thus performed two studies on low-lying excited states in ^{12}Be by using the in-beam γ-ray spectroscopic technique. At first, we searched for the low-lying 1^- state by intermediate-energy Coulomb excitation [9]. Information on the shell gap can be obtained from the excitation energy of the 1^- state. Secondly, we studied quadrupole deformation of ^{12}Be by proton inelastic scattering exciting the 2_1^+ state [3].

2 Experiment

The experiment has been performed at the RIPS facility [10] at RIKEN. The ^{12}Be beam at 54.6 *A*MeV was produced by fragmentation of a 100 *A*MeV ^{18}O beam incident on a 1.11 g/cm^2 Be target. The ^{12}Be beam was separated by RIPS with a high purity of around 96%. The secondary-beam intensity was typically a few tens of thousands counts per second with a momentum spread of ±1%. The secondary ^{12}Be beam bombarded a secondary target placed at the focal plane of RIPS. We used three different targets to excite the projectiles; 351 mg/cm^2 thick ^{208}Pb, 89.8 mg/cm^2 thick ^{12}C, and 90.2 mg/cm^2 thick $(CH_2)_n$. Coulomb and nuclear excitations were studied by the ^{208}Pb and ^{12}C targets in order to populate and identify the 1^- state in ^{12}Be. The $(CH_2)_n$ and ^{12}C targets were used to study the inelastic proton scattering exciting the 2_1^+ state in ^{12}Be.

Inelastically scattered particles were detected by a plastic-scintillator hodoscope placed 5 m downstream of the secondary target. Particle identification was performed by combining ΔE, E, and TOF signals from the hodoscope. De-excitation γ-rays were detected in coincidence with the scattered particles. An array of 55 NaI(Tl) detectors surrounding the target was used for the γ-ray detection. The high granularity of the setup was useful to correct for large Doppler-shifts of γ-rays emitted from moving nuclei. Angle-integrated inelastic cross-sections were obtained from the observed γ-ray yields after taking into account detection efficiencies of both scattered particles and γ-rays.

3 Low-lying 1^- state in ^{12}Be and its E1 strength

In most nuclei, almost all the strength in $E1$ excitation is exhausted by a giant dipole resonance and low-energy $E1$ strength is strongly hindered.

However a strong low-energy $E1$ strength is found in some of light nuclei, in particular where two single-particle states with opposite parities appear close to each other. The transition between the $1/2^+$ ground state and the first excited $1/2^-$ state at 0.32 MeV in ^{11}Be is a famous example of this anomaly, representing one of the strongest low-lying $E1$ transitions [11]. In the case of ^{12}Be, it is expected that the smaller gap between p-shell and sd-shell may cause an appearance of a low-lying 1^- state. We thus performed the experiment to find the 1^- state in ^{12}Be using intermediate-energy Coulomb excitation technique. Such a study will give a further understanding of the shell quenching in the neutron-rich $N = 8$ region.

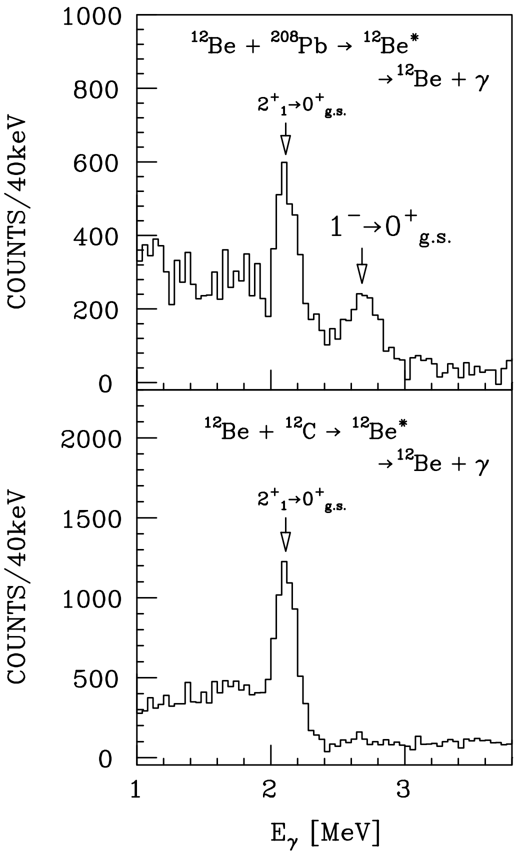

Fig. 1. Doppler-corrected γ-ray spectra of ^{12}Be observed in inelastic scattering on ^{208}Pb (top) and ^{12}C (bottom).

Figure 1 shows Doppler-corrected γ-ray energy spectra measured in coincidence with scattered ^{12}Be on ^{208}Pb (top) and ^{12}C (bottom) targets. Besides the γ-ray peaks of the $2_1^+ \to 0_{\text{g.s.}}^+$ transition, another peak is clearly observed at 2.68 MeV with the ^{208}Pb target. On the other hand, no significant transition is observed with the ^{12}C target. This yield dependence on the target indicates the dominance of the Coulomb contribution to the 2.68 MeV γ-rays observed with the ^{208}Pb target. By referring to the observed target dependence, the excitation of the 2.68 MeV state was identified to be an $E1$ excitation, leading to an assignment of $J^\pi = 1^-$ for the excited state. From the excitation cross-section (46.5(11.5) mb) obtained with the ^{208}Pb target, the $B(E1; 0_{\text{g.s.}}^+ \to 1^+)$ value was deduced to be $0.051(13) e^2\,\text{fm}^2$, which is the first

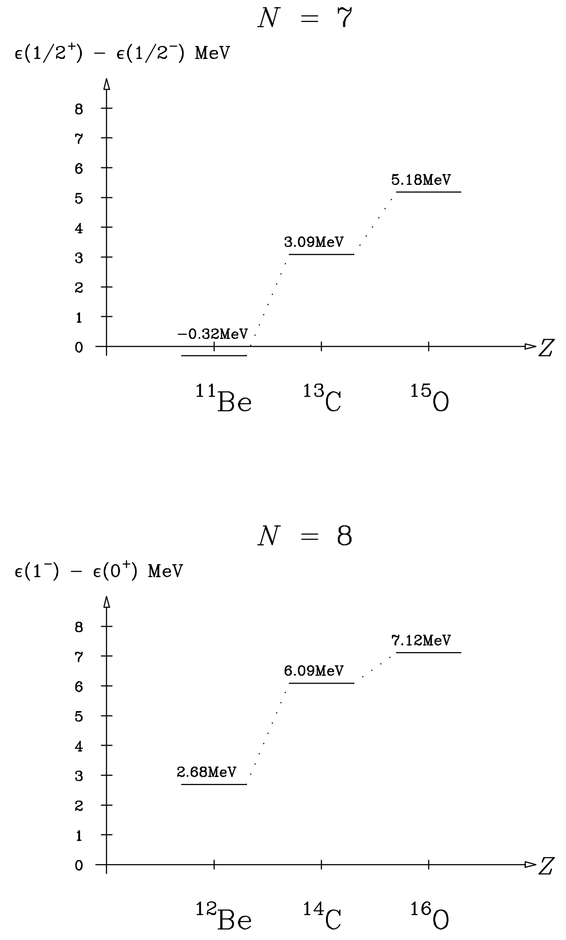

Fig. 2. Energy levels in the Be, C, and O isotopes plotted as a function of the atomic number Z. Top panel shows energy differences between the $1/2^+$ and $1/2^-$ states for the $N = 7$ nuclei, while bottom panel shows excitation energies of the lowest 1^- states for the $N = 8$ nuclei.

example of strong low-energy $E1$ transition observed in even-even nuclei. The present result on the $B(E1)$ value agrees well with the recent theoretical value of $B(E1) = 0.063e^2\,\mathrm{fm}^2$ studied by the large-scale shell model calculations [12].

We discuss the modification of the shell gap near the drip line based on level schemes in neighboring nuclei. At first, we plot, in fig. 2 (top), the energy difference between $2s_{1/2}$ and $1p_{1/2}$ states, $\epsilon(1/2^+) - \epsilon(1/2^-)$, as a function of proton number Z for $N = 7$ nuclei. As pointed out by Talmi and Unna, the energy gap decreases as proton number decreases [13]. The two $2s_{1/2}$ and $1p_{1/2}$ states are nearly degenerate at ^{11}Be. We make a similar plot for $N = 8$ nuclei including the present result. In fig. 2 (bottom), the excitation energies of the lowest 1^- states, $\epsilon(1^-) - \epsilon(0^+)$, are plotted as a function of Z. The energy gap similarly decreases in ^{12}Be. In a naive shell model picture, the 1^- state in ^{12}Be may correspond to the excitation of the $1p_{1/2}$ state to the $2s_{1/2}$ state. Thus, we can conclude that the $N = 8$ shell gap is also narrowing in ^{12}Be to a large extent.

4 Quadrupole collectivity of ^{12}Be studied by proton inelastic scattering

In this section, we discuss the quadrupole deformation of ^{12}Be in terms of the 2^+_1 excitation by proton inelastic scattering. The small shell gap as inferred from the low excitation energy of the 1^- state may enhance quadrupole deformation of ^{12}Be. We also performed the same measurement on ^{10}Be for comparison. The ^{10}Be nucleus may exhibit a large quadrupole deformation, since it has a large $E2$ strength corresponding to 8.1 W.u. [14]. The behavior of the $0^+_{\mathrm{g.s.}}$–2^+_1 level spacing among the Be isotopes: 3.04 MeV for ^{8}Be, 3.37 MeV for ^{10}Be, and 2.10 MeV for ^{12}Be, suggests possible enhancement of quadrupole deformation in the $N = 8$ nucleus ^{12}Be. This is a similar situation to the case of ^{32}Mg, where the small $0^+_{\mathrm{g.s.}}$–2^+_1 level spacing [15] and the large $B(E2)$ value [1] indicate quadrupole collectivity enhanced by the broken shell closure at $N = 20$.

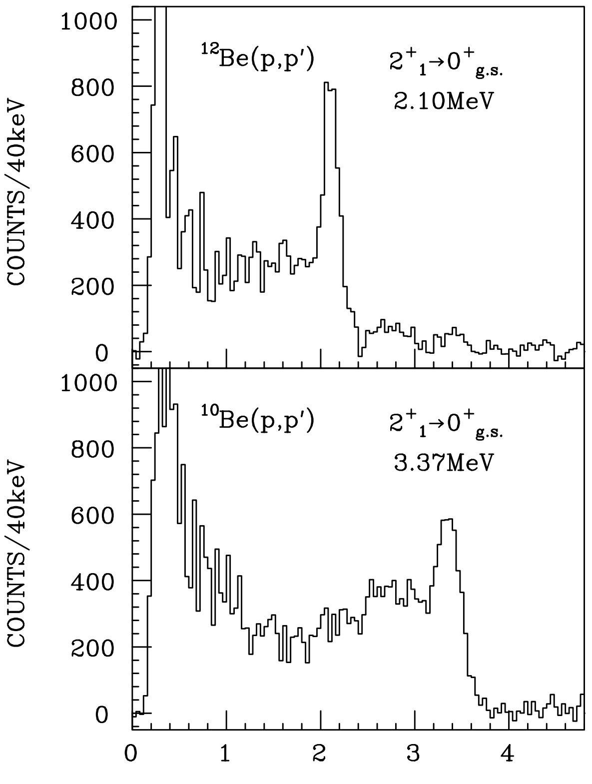

Fig. 3. Doppler-corrected γ-ray spectra of ^{12}Be (top) and ^{10}Be (bottom) observed in proton inelastic scattering.

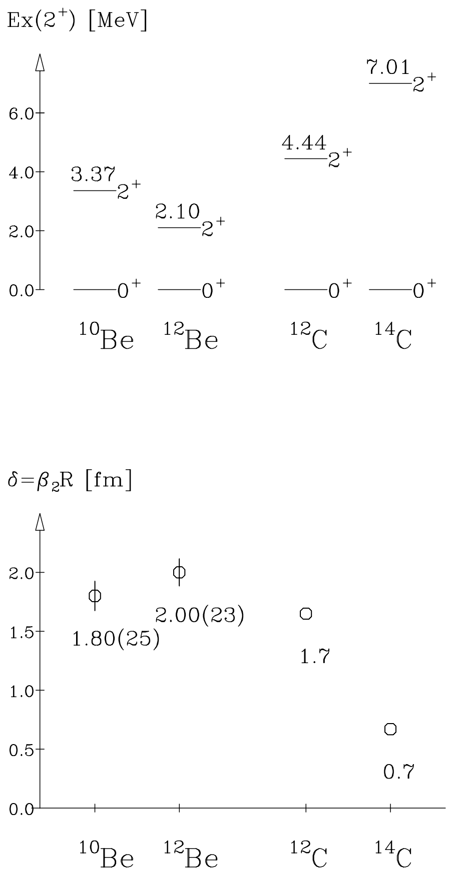

Fig. 4. Comparison of the excitation energies of the 2_1^+ states (top) and deformation lengths (bottom) in the Be and C isotopes.

Figure 3 shows energy spectra of γ-rays measured in coincidence with inelastically scattered ^{12}Be (top) and ^{10}Be (bottom) isotopes. The contribution from ^{12}C in the $(CH_2)_n$ target was subtracted to deduce the result for the proton scattering. In the figure, the photo-peaks from the 2_1^+ states are clearly seen at 2.10 MeV and 3.37 MeV, respectively, for ^{12}Be and ^{10}Be. The deformation parameters can be extracted from the observed cross-sections, 27.0(4.0) mb for ^{12}Be and 17.6(3.2) mb for ^{10}Be, by performing a coupled-channel calculation with the ECIS79 code [16]. For ^{12}Be, we obtained a large deformation length $\delta = 2.00(23)$ fm, corresponding to $\beta_2 \sim 0.7$. For ^{10}Be, we obtained $\delta = 1.80(25)$ fm, which is consistent with previous results of 1.84–1.90 fm deduced from several works on inelastic proton scattering at $E_{\mathrm{p}} = 12.0$–16.0 MeV [17]. Fairly large deformation parameters are obtained for both ^{12}Be and ^{10}Be, showing that quadrupole deformation is promoted in ^{12}Be as well as in ^{10}Be.

In fig. 4, we compare the excitation energies of the 2_1^+ states and deformation lengths obtained in the Be and C isotopes. The deformation lengths for the C isotopes are taken from refs. [18,19], where the inelastic deutron scattering was studied. For the C isotopes, the energy of the 2_1^+ state of ^{14}C is highest among the other isotopes and the deformation length is strongly suppressed at ^{14}C with $N = 8$. On the other hand, the energy of the 2_1^+ state in ^{12}Be is lower than that of ^{10}Be and the deformation length is not suppressed at ^{12}Be. This contrast indicates that there is little evidence of the $N = 8$ magicity in ^{12}Be.

5 Summary

In summary, we have studied in-beam γ-ray spectroscopy using a radioactive ^{12}Be beam. By utilizing inelastic scattering at intermediate energies, we have made a fair progress for understanding of low-lying excitation properties in ^{12}Be. A low-lying 1^- state accompanied with a strong $E1$ transition was observed by the intermediate-energy Coulomb excitation. From the inelastic proton scattering measurement, large quadrupole collectivity was found for the $0_{\mathrm{g.s.}}^+ \to 2_1^+$ transition. Both the present results provide a strong indication for the shell quenching in ^{12}Be, showing that the regular magic number, $N = 8$, disappears far off stability.

This paper was prepared on the basis of recent experiments at RIKEN. The present work is supported in part by the Ministry of Education, Science, Sports and Culture by Grant-In-Aid for Scientific Research under the program number (B) 08454069.

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