In-beam spectroscopy of exotic nuclei probed by α-induced direct reactions

Susumu Shimoura
Center for Nuclear Study (CNS), University of Tokyo, Wako branch at RIKEN, Saitama 351-0198, Japan
E-mail: shimoura@cns.s.u-tokyo.ac.jp

Abstract. The α inelastic scatterings and the (α,t) reaction on exotic nuclei at 50–60 A MeV are discussed. A new multipole decomposition analysis taking into account the angular correlation of decaying process originated from the alignments of the residual nucleus is applied for a study of cluster states in 12Be. The proton transfer reaction on the 12Be nucleus populates a possible proton single-particle state bound by a deformed core in the 13B nucleus of which ground state is spherical.

1. Introduction
Nuclear properties of nuclei apart from the stability line attract much attention, since exotic natures, such as a neutron halo, soft collective excitations, and disappearance of ordinary magic numbers, have been observed and provided rich information on nuclear structures as a function of the proton and the neutron numbers. One of the powerful experimental tools for investigating exotic nuclei is the measurements of the decays of the excited states populated by the direct reactions of the RI beams at intermediate energies. In this report, recent experimental results on α induced direct reactions by the inverse kinematics combined with invariant-mass/γ-ray spectroscopy.

2. Experimental consideration
One of the most important techniques in experiments using intermediate-energy unstable nuclear beams is inverse kinematics, where the beam or beam-like nuclei are to be investigated (physical targets) through interactions with the target nuclei (physical probes). In order to measure α induced direct reaction with the inverse kinematics, we developed a liquid helium target system[1]. The beam-like nucleus is produced by interacting with target nucleus through a direct reaction and subsequently decays by emitting particle(s) and/or photon(s). Experimentally, instead of detecting the recoils of the targets, all the emitted particles and/or photons are detected to determine their excited energies by reconstructing the invariant masses or decay energies.

Because of the kinematic focusing in intermediate-energy reactions, velocities of all the emitted particles are almost same as the beam velocity, which enables us to detect the decay particles with a large acceptance by using detectors placed at a forward direction. The extracted momentum vectors are used to reconstruct the decay energy, which is defined as the difference...
between the invariant mass and the threshold energy. The excitation energy is deduced by adding the separation energy for the decay channel to the decay energy.

When the decays are accompanied by emissions of γ-ray(s), it is required to correct Doppler shifts from fast-moving emitters. Since the magnitudes of the shifts amount to ±30 % for β = 0.3, a segmented array of γ-ray detectors should be used to measure the emission angle of the γ-ray as well as its energy. It is noted that the Doppler-shift correction of the γ-ray is the same as the deduction of the decay energy from the invariant mass of the γ and the emitting particle.

By using tracking information of secondary beams and position information of particle and γ detectors, we can deduce angular distributions of the direct reaction and angular correlations of the decaying process which relate to the alignment of the excited states.

An example of experimental setup for α induced reaction with inverse kinematics is shown in Fig. 1, where a secondary beam was tracked by a set of PPAC and γ rays and outgoing particles were detected by a combination of the NaI(Tl) and the segmented Ge arrays and hodoscope made by plastic scintillators, respectively. It is noted that this kind of setup allows us to measure different types of reactions, such as inelastic scattering, transfer and knockout reactions, simultaneously by reconstructing the excited states of the residual nuclei.

![Figure 1. Typical setup for measurements of α-induced reactions with inverse kinematics.](image)

### 3. Alpha inelastic scatterings

Alpha inelastic scatterings at intermediate energies are useful for exciting the isoscalar states. For stable nuclei the (α,α′) reactions have been extensively studied at 60 A MeV to extract isoscalar E0, E1, and E2 strengths in excited states[2]. It is interesting to extend such studies for unstable nuclei having exotic nature in the ground states. Firstly, I report recent measurements of the α inelastic scatterings to the low-lying 2⁺ and 1− states in the neutron-rich nucleus ¹²Be at 60 A MeV. It is noted that several experimental evidences of the breaking of the N = 8 shell closure in the ¹²Be have been reported[3, 4, 5].

Figures 2 and 3 respectively show the angular distributions of the differential cross section of the α inelastic scatterings and the angular distribution of the γ decays for the 2⁺ (closed symbols) and 1− (open symbols) states in the exit channel. The lines denote the predictions of DWBA calculations with a folding model, where the transition potentials are calculated by folding the collective transition densities[6, 7]. As shown in the figures the DWBA calculations predict
Figure 2. Angular distributions of $\alpha$ inelastic scatterings $^4\text{He}(^{12}\text{Be},^{12}\text{Be}^*)$ at 60 MeV to the $2^+_1$ (closed symbols) and the $1^-_1$ (open symbols) states in the $^{12}\text{Be}$ nucleus. Solid lines denote the predictions of DWBA calculations.

Figure 3. Angular distributions of $\gamma$ rays from the $2^+_1$ (closed symbols) and the $1^-_1$ (open symbols) states in the $^{12}\text{Be}$ nucleus populated by $\alpha$ inelastic scatterings. Solid and dashed lines denote the predictions for the $2^+_1$ and the $1^-_1$ states, respectively, by using statistical tensors calculated by DWBA.

Experimental data very well not only for the angular distribution but also for the alignments of the excited states.

The same distorting and transition potentials were used for a new type of multipole decomposition analysis (MDA) for the $^4\text{He}(^{12}\text{Be},^{12}\text{Be}^*\rightarrow^{6}\text{He}^++^{6}\text{He})$ reaction, where the angular distributions of the decaying $^{6}\text{He}$ particles depending on the transferred angular momenta were included simultaneously[8]. Figure 4 shows an excitation energy spectrum deduced by the invariant mass of the final $^{6}\text{He}^++^{6}\text{He}$ system, which consists of several multipoles ($\ell=0, 2$, and 4).

The present MDA was performed by using DWBA angular distribution of each multipole and the decay amplitudes obtained by the statistical tensors calculated by DWBA where amplitudes of different multipoles interfere each other. As shown in Fig. 5, the MDA reproduces both the angular distribution and the angular correlations well and provides the excitation energy spectrum for each multipole (Fig. 6). It is noted that the angular correlations exhibit clearly the characteristics of the multipole: almost isotropic for 10.8 MeV region indicates the dominance of $\ell=0$ and the other two show large contributions from $\ell=2$.

Each spectrum was fitted by a sum of several peaks and a background, which suggests existence of resonances with $\ell=0$ and 2. Assuming that the peak positions correspond to the resonance, an yrast diagram is constructed (Fig. 7) together with the previously reported states[9, 10]. The parallel three lines in the figure correspond to the moment of inertia of the $^{6}\text{He}^++^{6}\text{He}$ system where the two $^{6}\text{He}$ touch each other at their surfaces. The present results may be members of molecular bands which may be connected to the results of ref. [10] and qualitatively consistent with recent theoretical predictions of molecular bands[11, 12].
Figure 4. Excitation energy spectrum of the $^4$He($^{12}$Be,$^{12}$Be$^*$) at 60 $\text{A MeV}$ deduced by the decay energy of the $^{12}$Be$^*$ → $^6$He+$^6$He process.

Figure 5. Angular distributions of the $^4$He($^{12}$Be,$^{12}$Be$^*$) reaction and angular correlations of the $^{12}$Be$^*$ → $^6$He+$^6$He process for $E_x$=10.8, 11.4 and 12.4 MeV. Lines denotes the components of the MDA and their sums (thick).

Figure 6. Excitation energy spectra for $\ell$=0, 2, and 4. Lines denote the results of fit assuming the sum of several peaks and backgrounds.

Figure 7. Yrast diagram of the $^{12}$Be nucleus. Closed circles denote the present results and the other symbols are the previously reported results.

4. Proton transfer reaction ($\alpha$,t)
In order to investigate the shell evolution in the nuclei far from the stability line, excited states with a single-particle nature are interested. The single-particle states are populated by nucleon
transfer reactions such as (d,p) and (d,n) reactions, which are effective below 10 $A$ MeV region, because of the matching condition in the momentum. In secondary-beam experiments with the inverse kinematics this fact requires a use of relatively thinner target or results a small cross section at higher incident energies. However, in the nucleon transfer of $\alpha$ particle the matching condition becomes better for higher incident energies, because of the larger separation energy and the larger Fermi momentum than the deuteron[13]. Based on this consideration, we performed ($\alpha$,t) reaction of the $^{12}$Be, which produced excited states in $^{13}$B.

Experimental conditions was almost the same as that of the previous $\alpha$ inelastic scattering, except for six segmented Ge detectors[14, 15] were used in order to resolve the known excited states.

Figure 4 shows the $\gamma$-ray spectrum taken by the Ge detectors after the correction of the Doppler shifts. There are several peaks corresponding to the transitions of the known excited states to the ground states (3.48, 3.53, 3.68, 3.71, 4.13 and 4.83 MeV). The yields of $\gamma$-rays are deduced by fitting the spectrum with a sum of the response functions of the corresponding energies. The 4.83-MeV state having the largest yield, this state could have a proton single-particle nature, comparing to the reported yields to this state in other reactions[16, 17, 18, 19].

In order to determine the transferred angular momentum ($\ell$) to the 4.83-MeV state, the angular distribution of the transfer reaction is examined (Fig. 4). As shown in the figure, a forward peaking angular distribution is deduced, which suggests $\ell=0$ corresponding to $J^\pi=1/2^+$. The $\ell=0$ transfer is supported by the comparison of the DWBA predictions assuming $\ell=0$, 1, and 2. The present result indicates that the 4.83-MeV state is a proton intruder state.

Although the ground state of the $^{13}$B nucleus is known to be spherical, the excited state may be deformed because of a large deformation of the $^{12}$Be nucleus. If the proton is bound by the deformed $^{12}$Be core, the proton intruder orbit of [220]1/2 come down to the p-shell region. The present 1/2$^+$ state may be this deformed intruder state, which may be a kind of shape coexistence in the $^{13}$B nucleus.
5. Summary

Alpha induced reactions (inelastic scatterings and nucleon transfers) combined with invariant-mass $\gamma$ spectroscopy become new tools for the spectroscopy of excited states in exotic nuclei. Although the qualities (emittance, intensity, etc.) of the secondary beams worse, coincident measurements make it possible to perform detailed spectroscopy of the excited states by the combination of the analyses of the angular distributions of the primary process and the decay process. New information on changes in the nuclear structure as a function of proton and neutron numbers such as shell evolution and change of nuclear shapes will be investigated extensively by such detailed measurements and analysis.

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