Total reaction cross sections and neutron-removal cross sections of neutron-rich light nuclei measured by the COMBAS fragment-separator

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Abstract. Preliminary results of measurements of the total reaction cross sections $\sigma_R$ and neutron removal cross section $\sigma_{n_{2n}}$ for weakly bound $^6$He, $^8$Li, $^9$Be and $^{10}$Be nuclei at energy range (20-35) A MeV with $^{28}$Si target is presented. The secondary beams of light nuclei were produced by bombardment of the $^{22}$Ne (35 A MeV) primary beam on Be target and separated by COMBAS fragment-separator. In dispersive focal plane a horizontal slit defined the momentum acceptance as 1% and a wedge degrader of 200 µm Al was installed. The Bρ of the second section of the fragment-separator was adjusted for measurements in energy range (20-35) A MeV. Two-neutron removal cross sections for $^6$He and $^{10}$Be and one –neutron removal cross sections $^8$Li and $^9$Be were measured.

1. Introduction

Radioactive nuclear beam (RNB), or also called radioactive ion beam (RIB) technology was intensively developed since the middle of 80s (see for review Ref.[1]). It has become possible to determine the nuclear size for unstable nuclei, mainly based on the interaction and reaction cross sections for intermediate energies (<100 A MeV). Measurements of reaction cross section ($\sigma_R$) started at GANIL [2]. There are two major methods to measure $\sigma_R$ at intermediate energies: associated $\gamma$ -ray detection method [3]; and the transmission method using Bρ–ΔE–TOF identification or ΔE–E identification [4]. Our experiment has taken place using the COMBAS fragment-separator with experimental set-up similar to one used in [5]. The experiment was aimed an attempt to measure the neutron-removal cross section of several light exotic isotopes. The secondary beams of the stable and short-lived light nuclei $^6$He, $^7$Li, $^9$Be and $^{12}$Be were produced by bombardment of the $^{22}$Ne (35/A MeV) primary beam on the Be (89 mg/cm$^2$) target and separated by COMBAS fragment-separator [6]. The secondary products were detected by a telescope consisting of four Si detectors ($\Delta E$) with 300, 300, 300 and 500 µm thicknesses, respectively, and $E$-detector CsI(Tl) with 15mm thickness. In the present paper, preliminary results of measurements of total cross section and the n-removal cross sections $\sigma_{n_{n_{2n}}}$ for weakly bound $^6$He, $^8$Li, $^9$Be and $^{10}$Be nuclei at energy range (20–35)/A MeV are presented and compared with all other available previous experimental data.

2. The experimental procedure

Our $\sigma_R$ measurements require magnetic separation analysis and particle identification (PID) to obtain a narrow monoenergetic projectile beam which is stopped in one or more Si or CsI detectors. A target
(89 mg/cm²) target of ⁹Be placed at the entrance focus of the COMBAS separator was irradiated separately with ²²Ne (35 AMeV) beam accelerated at the U-400M cyclotron of FLNR, JINR. The secondary beams were then transmitted through the COMBAS magnetic analyzing system [7]. In dispersive focal plane a horizontal slit defined the momentum acceptance as 1% and a wedge degrader of 200 μm Al was installed. Figure 1 (not to scale) shows our detector system. The first Si detector ΔE₁ (300 μm) was set into a cylinder chamber to obtain ΔE information. Behind ΔE₁, there is a rectangular parallelepiped box containing ΔE₀ and two detectors with 16 horizontal X strips and 16 vertical Y strips in near side of (300 μm) ΔE₂ and (300 μm) ΔE₃, respectively. These detectors are designed for both measuring spectra of the secondary beams and determining their space distribution. And the silicon (500 μm) ΔE₄ detector was also installed inside the box to obtain ΔE information. In order to measure remain energy of particles, a thick CsI(Tl) detector is used and placed at the end of the telescope.

Figure 1. Detectors system (not to scale) used in this experiment.

3. Data analysis and results
Each detector was calibrated to take into account the known energy losses of both the projectiles of interest. All analyzed events were required to pass tight energy gates, appropriate to the projectile of interest, for both position sensitive detectors and the ΔE counter. We obtained total kinetic energy spectra are shown for ⁶He, ⁸Li, ⁹Be and ¹⁰Be in figure 2. The off-scale peaks are produced by nonreacting projectiles. For the two-neutron-halo nuclei as ⁶He, 2n removal is one of the strongest reaction channels [8]. Both the magnitude and energy dependence of ⁶He (a) demonstrate a prominent two-neutron-removal peak above the continuum caused by core reactions. On average, ⁶He breaks up two neutrons then carry off two-sixth of the remaining kinetic energy.
Figure 2. Total kinetic energy spectra for $^6$He (a), $^8$Li (b), $^9$Be (c) and $^{10}$Be (d) projectiles in Si telescope and CsI(Tl) detector, with structure due to 2n-removal from $^6$He, $^{10}$Be and 1n removal from $^8$Li and $^9$Be indicated.

A similar effect for $^{10}$Be (d) is attributed to the weak binding of two last neutrons. As for $^9$Be, due to its Borromean structure, the breakup of which may occurred directly to two alpha particles and a neutron, or via one of two unstable intermediate nuclei: $^5$Be and $^3$He. We determined $^9$Be nucleus and one neutron removal from the breakup of $^9$Be (c) in this experiment. That fact is very intrigue because $^1$Be is unbound nucleus and we are going to clarify this effect in further data analyze. In figure 2 (b) the similar peak in energy spectra for $^8$Li was identified as corresponding to $^7$Li. This also indicates that $^7$Li is the core of $^8$Li nucleus.

We determined $\sigma_R$ by transmission method. This procedure is described clearly in Ref[9]. Yields in the n-removal peaks for $^6$He, $^8$Li, $^9$Be and $^{10}$Be were obtained by fitting and background subtraction. We report measurements of $\sigma_R$ and $\sigma_{2n}$ for $^6$He and $^{10}$Be, and $\sigma_{1n}$ for $^8$Li and $^9$Be in the table 1 with comparisons of data from [8,10].

Table 1. Measured cross sections on Si for total, 2n and 1n removal from $^6$He, $^{10}$Be, $^8$Li and $^9$Be

| Type | Energy (MeV/nucleon) | $\sigma_{2n}$ (b) [this work] | $\sigma_{1n}$ (b) [this work] | $\sigma_R$ (b) [8] | $\sigma_R$ (b) [8] |
|------|----------------------|-------------------------------|-------------------------------|------------------|------------------|
| $^6$He, $\sigma_{2n}$ | 23.7 | 0.68 | 0.47±0.04 [8] | 1.59±0.06 [8] | 1.53±0.15 |
| $^8$Li, $\sigma_{1n}$ | 29.4 | 0.15 | 1.58±0.05 [8] | 1.65±0.15 |
| $^9$Be, $\sigma_{1n}$ | 33.4 | 0.49 | 0.085±0.006 [10] | 1.63±0.05 [10] | 1.63±0.16 |
| $^{10}$Be, $\sigma_{2n}$ | 32.6 | 0.23 | 0.046±0.004 [10] | 1.57±0.05 [8] | 1.73±0.16 |

4. Conclusion

The particle identification for secondary beam was performed by employing the $\Delta E$–$E$ method for a various isotopes ranging from He to Be. The $\Delta E$ and $E$ were measured by the Si and CsI(Tl) detector telescope, respectively. Preliminary results on the neutron-removal cross sections of some neutron-rich light isotopes ($^6$He, $^8$Li and $^{9,10}$Be) were obtained. Data analysis is still in progress. The obtained data was compared to previous results [8,10]. We found good agreement with the previous experiment results of other laboratory. The next experiment on total reaction cross section, n-removal cross section and elastic scattering measurements of other light neutron-rich nuclei are planned by using this technique and COMBAS fragment separator. Both 2n and 4n removal from $^1$He were observed. Subtraction analysis of the data indicates that $^4$He is a good core within $^6$He and $^8$He, as is $^8$Be within $^{10}$Be and $^{9}$Be.
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