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

B Erdemchimeg\textsuperscript{1,2}, A G Artukh\textsuperscript{1}, S Davaa\textsuperscript{2}, B M Hue\textsuperscript{1,3}, T Isataev\textsuperscript{1}, S A Klygin\textsuperscript{1}, G A Kononenko\textsuperscript{1}, G Khuukhenkhuu\textsuperscript{1}, S M Lukyanov\textsuperscript{1}, T I Mikhailova\textsuperscript{1}, V A Maslov\textsuperscript{1}, K Mendibaev\textsuperscript{1,4}, Yu M Sereda\textsuperscript{1}, Yu E Penionzhkevich\textsuperscript{1} and A N Vorontzov\textsuperscript{1}

1Joint Institute for Nuclear Research, 141980, Dubna, Russia
2National University of Mongolia, NRC, Ulaanbaatar, Mongolia
3Institute of Physics, Hanoi, Vietnam
4Eurasian Gumilev University, Astana, Kazakhstan
E-mail: erdem@jinr.ru

Abstract. Preliminary results of measurements of the total reaction cross sections \(\sigma_R\) for nuclei \(^4\text{He}, ^6\text{He}, ^8\text{He}, ^6\text{Li}, ^6\text{Li}, ^9\text{Li}, ^{11}\text{Li}, ^7\text{Be}, ^8\text{Be}, ^{10}\text{Be}, ^{11}\text{Be}, ^{12}\text{Be}, ^9\text{B}, ^{10}\text{B}, ^{11}\text{B}, ^{12}\text{B}\) nuclei at energy range (10-50) A MeV with \(^{28}\text{Si}\) target is presented. The secondary beams of light nuclei were produced by bombardment of the \(^{15}\text{N}\) (50 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 600 \(\mu\text{m}\) Al was installed. The \(B_0\) of the second section of the fragment-separator was adjusted for measurements in energy range (10-45) A MeV. The strong absorption model reproduces the A-dependence of \(\sigma_R\), but not the detailed structure. We are comparing our experimental data with predictions of microscopic (dashed line) and strong absorption model, Glauber multiple scattering theory and preliminary results are obtained.

1. Introduction

Nowadays one of the major goals of nuclear science is to learn about the behavior of isotopes with exotic neutron to proton number ratios. The production of radioactive ion beams of light nuclides from the 1980s onwards has contributed towards a substantial increase of information on the properties of nuclei far away from the beta stability line, mainly on new aspects of their nuclear structure such as skins, haloes shells and others, in such a way that heavy-ion reaction cross-section measurements can be considered today as an essential tool to investigate the nuclear structure of exotic nuclei. Measurements of the total reaction cross-section, \(\sigma_R\), defined as the total, \(\sigma_t\), minus the elastic, \(\sigma_{el}\), cross-sections for two colliding nuclei (\(\sigma_R = \sigma_T - \sigma_{el}\)) are important for the evaluation of the nuclear matter radius, thus providing information about the size of nuclei.

We report \(\sigma_R\) measurements \(^4\text{He}, ^6\text{He}, ^8\text{He}, ^6\text{Li}, ^6\text{Li}, ^9\text{Li}, ^{11}\text{Li}, ^7\text{Be}, ^8\text{Be}, ^{10}\text{Be}, ^{11}\text{Be}, ^{12}\text{Be}, ^9\text{B}, ^{10}\text{B}, ^{11}\text{B}\) and \(^{12}\text{B}\) nuclei at energy range (10-50) A MeV with \(^{28}\text{Si}\) target is. Most of these nuclei are proton-rich; some are on the proton drip line, and therefore may be proton-halo candidates. The measurements were made by aiming these projectiles at a stack of thin Si elements which served as both targets and detectors. We interpret our data using phenomenological strong absorption models, as well as more elaborate models such as the optical limit of Glauber multiple-scattering theory.
2. The experimental details

In our experiment, a primary $^{15}$N beam was accelerated to around 50 A MeV by the U-400M cyclotron of the Flerov Laboratory of Nuclear Reactions, JINR, and sent to a $^9$Be target of 89 mg/cm$^2$ thickness. A secondary beam cocktail consisting of particles He, Li, Be and B isotopes was produced and transported by the COMBAS fragment separator system [1] to the detector system (see figure 1). The secondary beams were partially purified by 600 µm Al wedge. The energy dispersion was limited to less than 1% FWHM by analyzing slits. COMBAS separator a magneto-optic configuration is realized on the rigid focusing principle. Three parameters are important for particle separation and trajectory analysis by COMBAS setup: magnetic rigidity (Bρ), energy loss difference in the degrader ($\Delta E/\Delta x$) and time of flight (TOF).

![Figure 1](image1.png)

**Figure 1.** Experimental schematic view of detection set-up. The first Si $\Delta E_1$ double-sided strip detector (100 µm thickness, was used to obtain $\Delta E$ information and space $x$–$y$ distribution of incoming secondary beam.

![Figure 2](image2.png)

**Figure 2.** The scatter plot illustrates our secondary beam composition, by energy loss measurement $\Delta E$) versus the remain energy deposited in one of the CsI-detector, as the total energy in the telescope.

Behind this detector, there was a $\Delta E_2$ detector (620 µm thickness, 50 x 50 mm$^2$) and two other detectors with 16 horizontal X strips and 16 vertical Y strips in rear side of $\Delta E_3$ (300 µm thickness, 55 x 55 mm$^2$) and $\Delta E_4$ (300 µm thickness, 55 x 55 mm$^2$), respectively. These detectors were designed for both precise measurement of spectra of the secondary beams and control of divergence by the $x$–$y$
coordinate distribution. The silicon $\Delta E_i$ (500 µm thickness, 50 x 50 mm$^2$) detector was acquiring additional $\Delta E$ information and performing identification of fragments (see figure 2). In order to measure the remaining energy of particles (Er) a CsI(Tl) detector with 15-mm thickness was used and mounted at the end of the telescope.

3. Total reaction cross section measurement

Transmission method [2] is based on one simply counting of the number of beam particles incident on the target $N_{\text{inc}}$, and the corresponding number of outgoing particles, which have not undergone a reaction in the target $N_{\text{el}}$. The difference between these two numbers $N_{\text{inc}}$ and $N_{\text{el}}$ represents the number of reactions $N_{\text{reac}}$, which occurred in the target for $N_{\text{inc}}$ incident particles:

$$\sigma_R = \frac{N_{\text{inc}} - N_{\text{el}}}{N_{\text{inc}}} \cdot \frac{A}{dN_A}$$  \hspace{1cm} (1)

where $A$ is mass number, $d$ is target thickness, $N_A$ is Avogadro’s number.

Figure 3. We compared our measured data with the A dependence lines of the Kox formula (when the reduced strong absorption radius $r_0=1,1$ blue line) [3].
The Kox formula gives excellent results for stable nuclei when the reduced strong absorption radius $r_0$ is fixed at 1.1 fm, and therefore any significant departure from its predictions may disclose a halo structure. The smooth $A$ dependence of the predictions reproduces the data on average, but is unable to explain the scatter of the reaction cross sections observed in the experiment. (see figure 3) This observation suggests that a more sophisticated theory is needed to explain these data. We are comparing our experimental data with Glauber multiple scattering calculation [4] and preliminary results are obtained. (see figure 4)

Figure 4. Experimental reaction cross sections points for $^6$Li, $^7$Be, $^{10}$Be compared with calculation preliminary results of optical limit of the Glauber model (continues lines).

4. Conclusions
1. We have measured total reaction cross sections ($\sigma_r$) for Li and Be, He, B in Si with energies of (10-50) A MeV on $^{28}$Si targets. The success of the method shows that Si telescope measurements of $\sigma_r$ for other solid targets are also feasible.
2. The measured total reaction cross-sections $\sigma_r$ are compared the calculations by reduced strong absorption and optical limited of the Glauber models.

References
1. Artukh A G et al. 1999 Nucl. Instrum. Methods. A 426 605
2. Warner R E et al. 1996 Phys. Rev. C 54 1700
3. Kox S, et al. 1987 Phys. Rev. C. 35 1678
4. Bertulani C A and Gade A 2006 Comput.Phys.Commun. 175 372