The study of nuclear reactions involving neutron-rich weakly bound nuclei makes it possible to obtain information on the structure of the investigated nuclei (clusters, neutron halo nuclei) and to manifest in their reactions [1]. The total reaction cross section, σ_react, is one of the important parameters that are available for direct measurement. The measurement of the energy dependence of the reactions +He with +Si and +Li with +Si by direct measurement method allowed a clear view of σ_react above the theoretical predictions in the region of 10–20 MeV [2,3]. The results of the measurements provide a good set of data for testing of the microscopic models of nuclear reactions [4,5]. Results of the measurements were successfully described with the time-dependent Schrödinger equation for the external weakly-bound nuclei [6].

Radioactive beams of light, neutron-rich nuclei with high $N/Z$ ratio from 0.5 – 3.0 for $^{111}$Li and 1.0 – 2.67 for $^{133}$I isotopes offer a unique opportunity to investigate the properties of weakly bound neutron in neutral and neutron skin. Secondary beams from fragment separators consists of a cocktail of different radioactive nuclei produced in projectile fragmentation reactions with momentum characteristics close to the primary beam. Direct measurement of the σ_react is achieved by event-by-event registration of the nuclear reactions in the 4n gamma-ray spectrometer surrounding the target. The method of the registration process is based on two parameters: the efficiency of registration for a given reaction channel and the yield of the secondary beam. Modification of the method is represented by active target instead of using E stop-detector. The experimental technique includes the detection of neutrons and prompt gamma rays accompanying the nuclear reactions by gamma-ray spectrometer surrounding the target event tagging [9].

Construction of the spectrometer

For total reaction cross section measurement a spectrometer designed for the event-by-event measurement of the total reaction cross section for exotic nuclei with a radioactive beams. It consists of a multi-detector telescope for beam-particle identification and a 4n gamma-ray spectrometer for the detection of prompt photons accompanying the nuclear reactions (fig. 1). The assembly part of the spectrometer is designed for measurement of beam characteristics. Active collimators provide information about beam transmission, define irradiated area of the target and provide time-of-flight (TOF) measurement of the secondary beam projectiles. Together with planar surface barrier detector B1, they provide identification of the secondary beam projectiles (fig 2a). Gamma-ray spectrometer is located outside vacuum volume. It consists of gamma-ray detectors for registration of gamma-rays accompanying the nuclear reactions. Registration of signal over threshold is a tag of a nuclear reaction event in the target (fig. 2b). Crucial aspect of the measurement of its efficiency is close to unity for all gammas. For measurement of gamma-ray energies, Spectrometer response was investigated as a secondary beam modulating the number of detector modules registering signal over threshold for multiplicities M ≥ 8 and energies E ≥ 10 MeV (fig. 3). The experimentally measured values in the total reaction cross section measurements is deposition in the detected gamma ray-spectrometer, and the result of the number of registered signals, N. It depends on the open reaction channels and the multiplicity of emitted gamma quanta and neutrons. The probability of triggering $n$-detectors per reaction event is $p_n = 1 - e^{-p}$, Monte Carlo simulations showed that the value $p_n$ is a function of gamma-ray energy and multiplicity $M$. Simulated probability distributions of spectrometer response were used to evaluate the total reaction cross section from observed signal. The detection efficiency, $η$, for a given nuclear reaction is derived from the analysis of measured distribution of n-values. The registration efficiency $η$ for given reaction channel is defined as a sum of particular efficiencies $p_n$. That triggering of $n$-detectors was caused by a gamma beams with $M ≥ 5$ values with corresponding registration efficiencies $η(M, n) = η(0) + η(1) + ... + η(n)$. Simulations of the registration efficiency for $M ≥ 5$ were confirmed by measurement with +He spectroscopic source. Beta decay is followed by emission of two angular correlated gamma quanta with energies 1325.2 keV and 1732.2 keV. External high-voltage CeBr$_2$ detector was placed into the vacuum pipe, where it served as a start detector. Threshold was set to register 1325.2 keV gamma quantum, which provided start of the acquisition. The second 1713.2 keV gamma was registered by the Be7+ spectrometer. Registration efficiency $η$ for E = 1713.2 keV and M = 1 was measured. Registration efficiency $η$ for multiplicities $M = i$ were obtained by connecting i-subsequent events into one event. Detailed description of the procedure can be found in [11]. Result showed good agreement with Geant4 simulations (fig. 5).

Experimental Results

The results of the measurements with exotic nuclei

In the most recent experiments, energy dependence of the total reaction cross section, $\sigma_{\text{react}}$, for nuclei +He and +Li on $^{10}$Si, $^{28}$Si, and $^{181}$Ta targets was measured in the energy range 6 – 36 MeV [13]. Results are in good agreement with the previous measurements [8]. Method of evaluation of the $\sigma_{\text{react}}$ energy dependence is based on the event-by-event detection of detection efficiency based on measured distributions of the spectrometer response simulations and the registered event. The principle is in the measurement of secondary beam entering and exiting the target with T target nuclei per unit area. The intensity $I_{\gamma}$, corresponding to inelastic nuclear reaction channels, is determined from the number of tagged events T. They are detected by the gamma-ray spectrometer with efficiency $\eta$.

The total reaction cross section, $\sigma_{\text{react}}$, is described as $\sigma_{\text{react}} = \frac{I_{\gamma} \times N_{\text{tagged}}}{T} \times \text{efficiency} \times \text{multiplicity}$

Detailed procedure of $\sigma_{\text{react}}$ evaluation, taking into account measurement of background events, is described in [13]. Energy dependence of the total reaction cross section for the projectile +Li with +Si, +Cs, and +Ta targets is shown on fig. 6 and for the projectiles +He with the same targets on the fig. 7a and b respectively. Theoretical model calculations, whose real part is described by a double-folding procedure [4]. However, it succeeded to describe only the high-energy regions of measured $\sigma_{\text{react}}$ energies. The low energy region between 10 – 20 MeV, where the rise above theoretical predictions is measured, was described by the time-dependent Schrödinger equation. Results are published only for reaction Ly+Si [14].

The nucleus is a famous name of energy-resource analytic the total and differential reaction cross section of $\sigma_{\text{react}}$, $\sigma_{\text{diff}}$.

$\sigma_{\text{react}}$ = $\frac{I_{\gamma}}{T} \frac{N_{\text{tagged}}}{N_{\text{incident}}} \times \text{efficiency} \times \text{multiplicity}$

References


[2] Yu. E. Penionzhkevich et al., Energy dependence of the total cross section for the reactions +He with +Si and +Li with +Si by direct measurement method allowed a clear view of σ_react above the theoretical predictions in the region of 10–20 MeV [2,3]. The results of the measurements provide a good set of data for testing of the microscopic models of nuclear reactions [4,5]. Results of the measurements were successfully described with the time-dependent Schrödinger equation for the external weakly-bound nuclei [6].


[5] Yu. E. Penionzhkevich et al., Energy dependence of the total cross section for the reactions +He with +Si and +Li with +Si by direct measurement method allowed a clear view of σ_react above the theoretical predictions in the region of 10–20 MeV [2,3]. The results of the measurements provide a good set of data for testing of the microscopic models of nuclear reactions [4,5]. Results of the measurements were successfully described with the time-dependent Schrödinger equation for the external weakly-bound nuclei [6].


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[16] Yu. E. Penionzhkevich et al., Energy dependence of the total cross section for the reactions +He with +Si and +Li with +Si by direct measurement method allowed a clear view of σ_react above the theoretical predictions in the region of 10–20 MeV [2,3]. The results of the measurements provide a good set of data for testing of the microscopic models of nuclear reactions [4,5]. Results of the measurements were successfully described with the time-dependent Schrödinger equation for the external weakly-bound nuclei [6].