A SETUP FOR MEASUREMENT OF THE TOTAL REACTION CROSS SECTION

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Study of weakly bound neutrons in exotic nuclei

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, etc.) and its manifestation in reactions [1]. The total reaction cross section, σ_R, is one of the important parameters that are available for direct measurement. The measurements of energy dependence of the reactions ^{4,6}He + $^{nat.}$Si and ^{7}Li + $^{nat.}$Si by direct method showed a local rise of σ_R above the theoretical predictions in the region of 10–20 MeV/u [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 neutrons [6].

Radioactive beams of light, neutron-rich nuclei with high N/Z ratio from 0,5 – 3,0 for $^{3-8}$He isotopes and 1,0 – 2,67 for $^{6-11}$Li isotopes offer a unique opportunity to investigate the phenomena related to the structure of weakly bound neutrons in neutron halo 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_R is achieved by event-by-event registration of the nuclear reactions in the 4π gamma-ray spectrometer surrounding the target. The method of the direct measurement is based on transmission method [7] with active collimators [8]. 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].

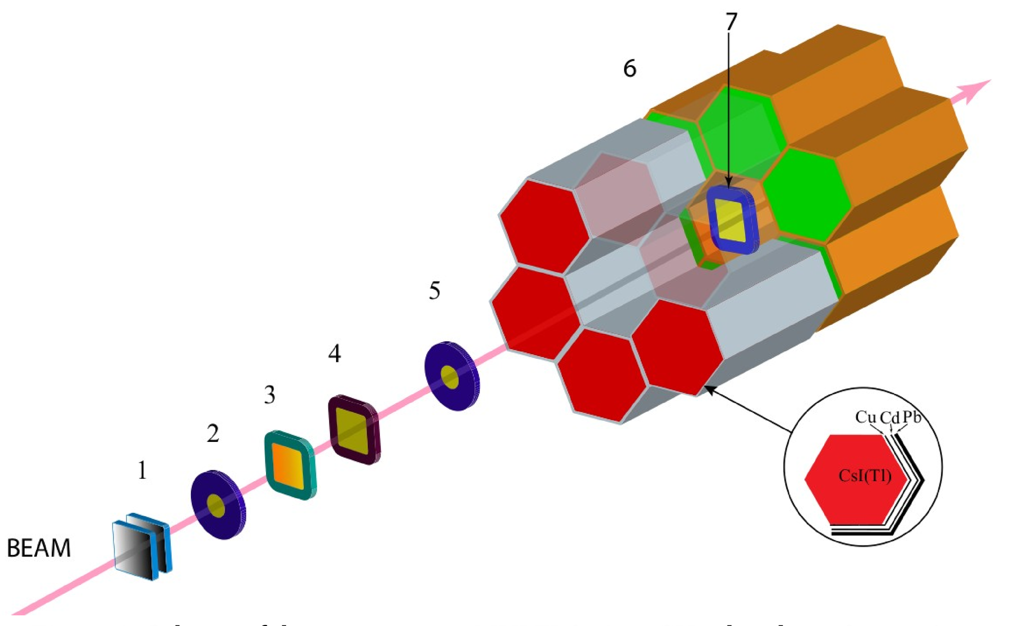

Figure 1: Scheme of the spectrometer MULTI-2: 1 — CH_2 absorbers, 2 — active collimator AC1, 3 — silicon dE_0 detector, 4 — removable pixel detector 16x:16y, 5 — active collimator AC2, 6 — gamma-ray spectrometer consisting of 12x CsI(Tl) detectors, 7 — target

Construction of the spectrometer

The 4π spectrometer for total reaction cross section measurements is a portable 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 4π gamma-ray spectrometer for the detection of prompt photons and neutrons accompanying the nuclear reactions (fig. 1). The in-beam 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 silicon planar surface barrier detector dE_0, 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 and neutrons accompanying the nuclear reactions. Registration of signal over threshold is a tag of nuclear reaction event in the target (fig. 2b). Crucial aspect of the measurement is shielding the spectrometer from background radiation, namely gamma rays and neutrons, emerging from nuclear reactions outside the target (Cd and Pb plates) and X-rays (Cu plates), created in the process of beam interaction with detectors and construction materials (fig. 1). Additional shielding is provided by a dome made of 50 mm thick low-background lead bricks built around the spectrometer. Previous version of the gamma-ray spectrometer, MULTI, consisted of 6 CsI(Tl) detectors in the form of hexagonal prisms, covering a large solid angle [10]. Actual setup, MULTI-2, consists of 12 CsI(Tl) detectors [11]. Modification of the spectrometer was aimed to improve the registration efficiency and to lower its dependency on the gamma-ray multiplicity M_γ. Upgrade possibilities of this spectrometer, aimed to eliminate the dependency on M_γ, were investigated by the Monte Carlo simulations [12]. Introduction of new, high-resolution scintillation detectors based on $CeBr_3$ crystals (res. 4,2% at 661 keV) open the possibility to upgrade current setup to the MULTI-purpose spectrometer, suitable for measurement in different fields of nuclear physics (beta-delayed neutron emission, nuclear resonances and other).

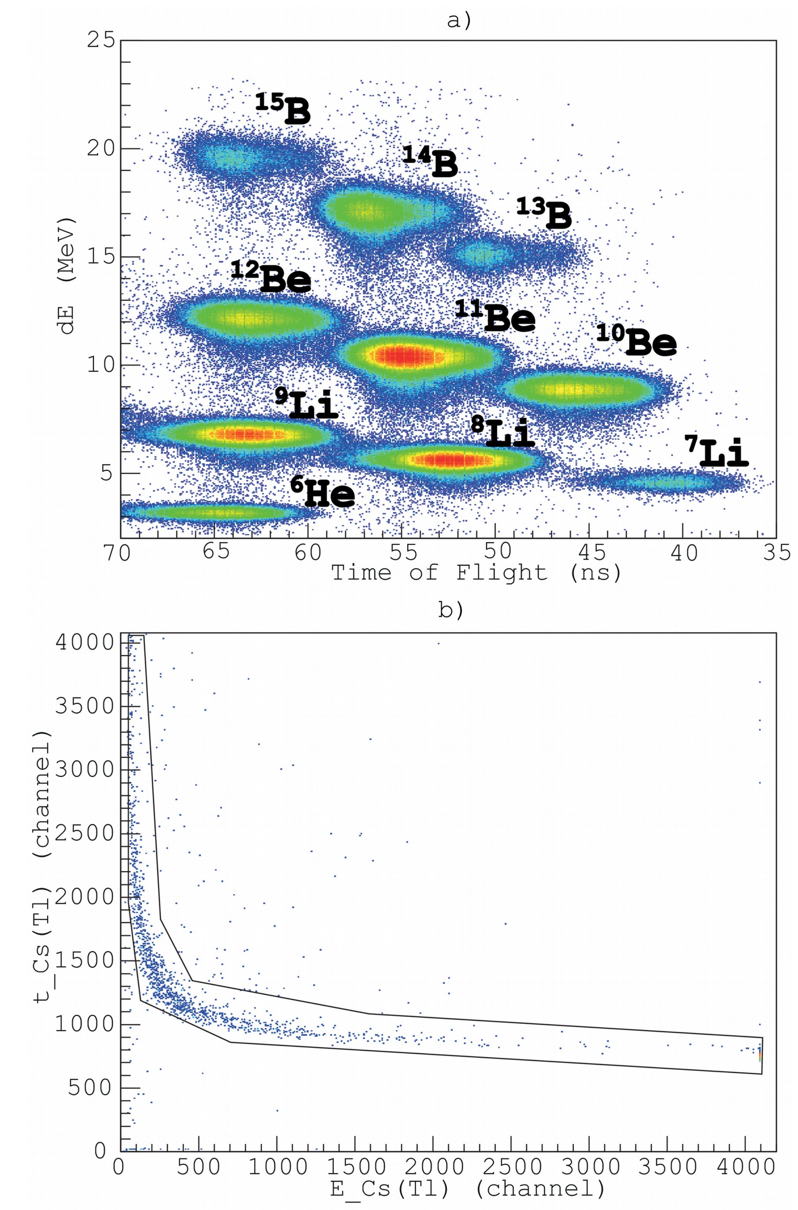

Figure 2: a) Secondary beam dE:TOF identification matrix from the reaction $^{15}N+^{9}Be$, b) selection of events registered in one of 12 CsI(Tl) gamma-ray detectors

Investigation of the gamma-ray spectrometer properties with Monte Carlo method

Every reaction channel has its own specific multiplicity of emitted gamma rays, M_γ. It represents the number of gamma quanta emitted in every single physical event of the nuclear reaction. The registration efficiency of the gamma spectrometer is dependent on the M_γ value. The dependency, together with response function of the spectrometer, was subject to Monte Carlo simulations in Geant4. Registration efficiency is a probability of registering a signal over 170 keV threshold in any of the 12 detector modules. It represents the tag of a nuclear reaction event. Results of the simulations showed the influence of multiplicity M_γ on the registration efficiency η (fig. 3). The minimum value, η ~ 70%, is achieved for M_γ = 1. For $M_\gamma \geq 5$, the efficiency is close to unity for all gamma-ray energies. Spectrometer response was investigated as the number of detector modules registering signal over threshold for multiplicities $M_\gamma \leq 8$ and energies $E_\gamma \leq 10$ MeV (fig. 4). The experimentally measured value in the total reaction cross section measurements is energy deposition in the detectors of gamma-ray spectrometer and the number of triggered detectors, 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. Monte Carlo simulations showed that the value p_n is a function of gamma-ray energy E_γ and multiplicity M_γ. Simulated probability distributions of spectrometer response were used to evaluate the total reaction cross section from measured data. The value of the detection efficiency, η, for a given nuclear reaction is obtained from analysis of the measured distribution of n-values. The registration efficiency η(n) for given event with n-triggered detectors is defined as a sum of particular probabilities $p_{n,i}$,that triggering of n-detectors was caused by a gamma rays with $M_\gamma \leq i$ values with corresponding registration efficiencies $\eta(M_{\gamma,i})$.

$$\eta(n)=\sum_i p_{n,i}\,\eta(M_{\gamma,i})$$

Simulations of the registration efficiency for $M_\gamma \geq 5$ were confirmed by measurement with ^{60}Co spectroscopic source. Beta decay is followed by emission of two angular correlated gamma quanta with energies 1332,5 keV and 1173,2 keV. External high-volume $CeBr_3$ detector was placed into the vacuum pipe, where it served as a start detector. Threshold was set to register 1332,5 keV gamma quantum, which provided start of the acquisition. The second 1173,2 keV gamma was emitted quasi-isotropically into the volume of the gamma-ray spectrometer. Registration efficiency η for E_γ = 1173,2 keV and M_γ = 1 was measured directly. Registration efficiency η for multiplicities M_γ = 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).

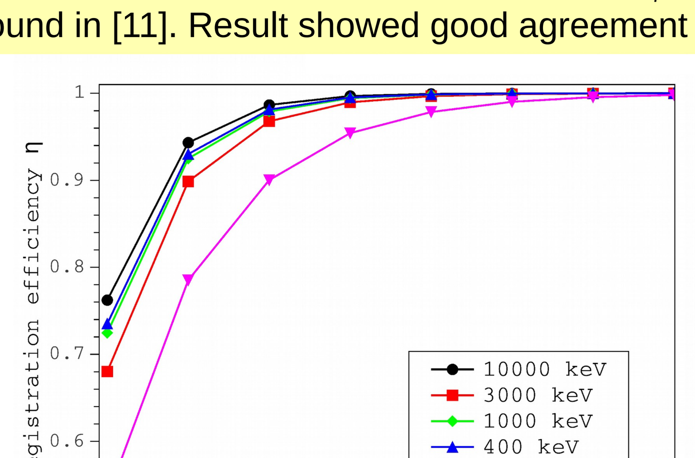

Figure 3: Monte Carlo simulations of the gamma-ray spectrometer registration efficiency as a function of multiplicity M_γ.

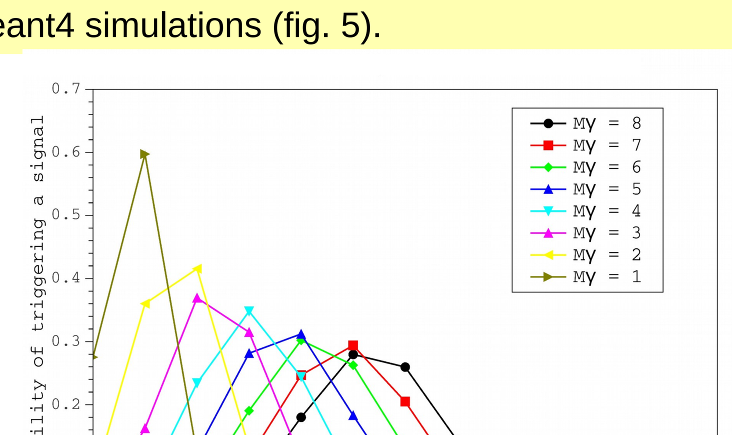

Figure 4: Spectrometer response simulation – probability distributions for triggering n-detectors with $M_\gamma \geq 8$.

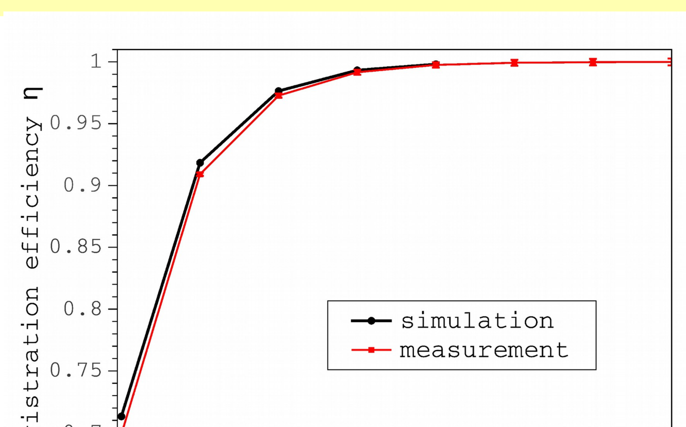

Figure 5: Comparison of the registration efficiency for E_γ = 1173,2 keV, obtained by Monte Carlo simulation and measurement with ^{60}Co source.

Results of the measurements with exotic nuclei

In the most recent experiments, energy dependence of the total reaction cross section, σ_R, for nuclei ^{6,8}He and ^{9}Li on ^{28}Si, ^{59}Co, and ^{181}Ta targets was measured in the energy region 6 – 36 A MeV [13]. Results are in good agreement with the previous measurements [6]. Method of evaluation of the σ_R energy dependence is based on the event-by-event evaluation of detection efficiency based on measured distributions of the spectrometer response simulations and the measured distribution of triggered detectors in each nuclear reaction event. The principle is in the measurement of secondary beam intensity, I_0, hitting the target with N target nuclei per unit area. The intensity I_R, 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 η.

$$\mathbf{I_R = T / \eta}$$

The total reaction cross section, σ_R, is described as

$$\mathbf{\sigma_R = I_R / N(I_0 + I_R)}$$

Detailed procedure of σ_R evaluation, taking into account measurement of background events, is described in [13]. Energy dependency of the total reaction cross section for the projectile ^{7}Li with ^{28}Si, ^{59}Co, and ^{181}Ta targets is shown on fig. 6 and for the projectiles ^{6,8}He with the same targets on the fig. 7a and 7b respectively. Previous results were subject to theoretical analysis with optical model calculations, whose real part is obtained by a double-folding procedure [4]. However, it succeeded to describe only the high-energy regions of measured σ_R energy dependencies. The low energy region between 10 – 20 A MeV, where the rise above theoretical predictions is measured, was described by the time-dependent Schrödinger equation. Results are published yet only for reaction ^{11}Li + ^{28}Si [6]. The actual set of data is currently undergoing theoretical analysis and the results will be published soon.

Acknowledgements

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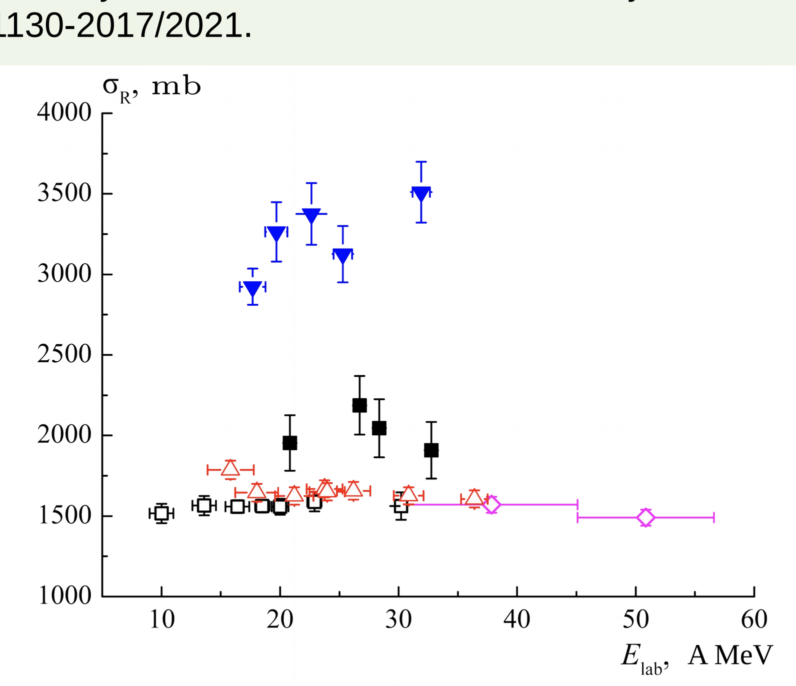

Figure 6: Total cross sections of the reactions of ^{9}Li nuclei on ^{28}Si (empty triangles), ^{59}Co (solid squares), and ^{181}Ta (solid triangles) targets obtained in our recent work [13], compared to the total cross section of the ^{7}Li + ^{28}Si reaction obtained in our previous work [2] (empty squares) and work of R. E. Warner [14] (diamonds).

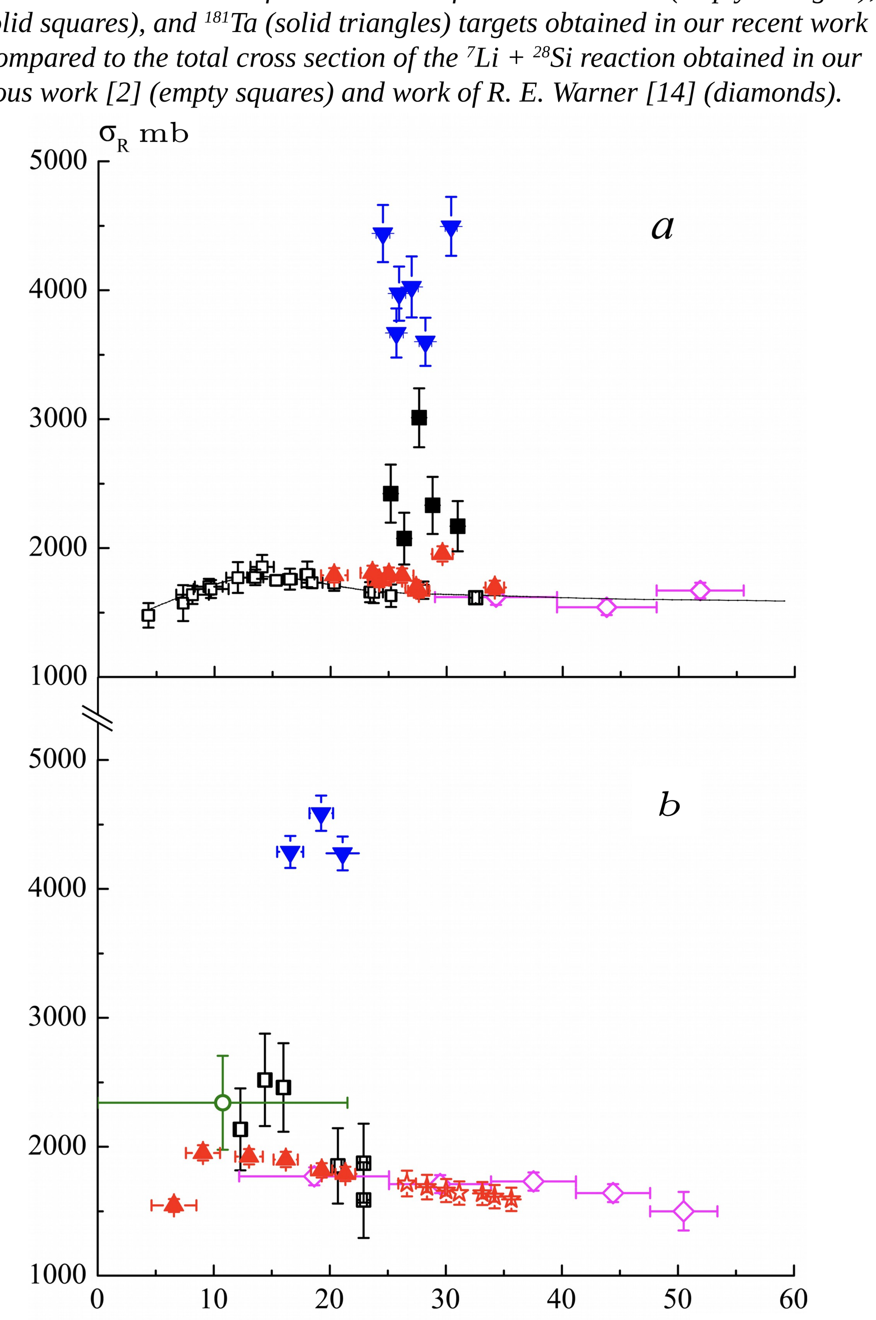

Figure 7: a) Total cross sections of reactions ^{6}He + ^{28}Si (upright triangles), ^{6}He + ^{59}Co (solid squares), and ^{6}He + ^{181}Ta (inverted triangles) obtained in our recent work [13], compared to the results of the ^{6}He + ^{28}Si reaction obtained in our previous work [2] (empty squares) and [14] (diamonds); b) total cross sections of the reactions ^{8}He + ^{28}Si (upright triangles) and ^{8}He + ^{181}Ta (inverted triangles) from our recent work [13], compared to the results of ^{8}He + ^{28}Si reaction obtained in our previous work [15] (empty squares) and works [14] (diamonds), [7] (circle), and [9] (stars).

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