Peculiarities of interaction of weakly bound lithium nuclei (A=6–11) at low energies: Elastic scattering and Total reaction cross sections

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Abstract. The paper presents new experimental data on the total cross sections of ^{8,9}Li + ^{28}Si reactions at low energies as well as the analysis of previously obtained data for ^{6,7}Li. Based on a large collection of data (authors' and literature data) we carried out a comparative analysis of the two main experimental interaction cross sections (angular distributions of the differential cross sections and total reaction cross sections) for the weakly-bound lithium ($^{6-9}$Li, ^{11}Li) nuclei in the framework of Kox parameterization and macroscopic optical model. We identified specific features of these interactions and predicted the experimental trend in the total reaction cross sections for Li-isotopes at energies close to the Coulomb barrier.

An experimental technique for measuring TCS of Li- isotopes

Total reaction cross sections (TCS, σ_R) for the beam of incident particles I_0 and the attenuated beam (the beam of particles passing through the target without interaction) are connected by the relation:

$$I = I_0 \cdot \exp(-N\sigma_R)$$

where N is the specific number of target nuclei. When N is small ($N\sigma_R$ 10^{-3}), it is possible to use the expansion transforming the exponential expression (1) into a linear form (2):

$$N\sigma_R = (I_0 - I) \cdot I_0^{-1}$$

The linear expression (2) connects the product of quantities σ_R and N with the beams of the particles I and I_0, the beam incident on the target and the beam passed through the target nuclei N without interaction, respectively. The expression (2) shows that for the direct measurement of the total cross section σ_R it is sufficient to measure two quantities simultaneously, namely, the difference $(I_0 - I)$ and the corresponding flow rate I_0. This method, called the "transmission method", is the most common method used to measure TCS.

In this paper, to measure the excitation functions σ_R(E) in the interactions of secondary ions with ^{8,9}Li nuclei targets, we applied the new improved technique – the combined use of 4π-geometry γ-spectrometer and transmission methods [1].

The target (*dE*-detector) was placed in the central zone of γ-spectrometer, whereas the other telescope detectors, in particular, dE_0 and dE_1identifiers, detectors-identifiers of reaction products dE_3 and detector of the full beam stop *E* were located in the n-γ protection zone, beyond the sensitive area of the γ-spectrometer. The experimental procedure using 4π-scintillation γ-spectrometer is described in detail in [1].

The experiment was conducted at the U-400 accelerator of G.N. Flerov Laboratory of Nuclear Reactions, JINR (Dubna). The beam of secondary ^{8,9}Li nuclei of intensity $I_0 \sim 10^3\ s^{-1}$ in the energy range E = (12.6 – 23.8) MeV/nucleon was obtained as a product of fragmentation of the primary beam ^{11}B (E = 32 MeV/nucleon) on the generating ^{9}Be target. The secondary ^{8,9}Li beam was formed using the elements of the magnetic system of AKKULINA fragment separator, equipped with the eight-meter TOF transport line for particle identification.

In the first and last parts of the channel separator, thin plastic scintillation detectors for identification of beam particles by the energy release *dE* and the time of flight TOF were mounted. Multipole focusing elements provided further transportation of ^{8,9}Li beam to the low-background separator cabin.

In the low-background cabin, scintillation 4π-geometry CsI (Tl) γ-spectrometer in the additional Pb-shielding was mounted. In the center of the γ-spectrometer (see Figure 1), the studied target, in particular, *dE* Si-detector, was placed. All other *dE* and *E* semiconductor telescope detectors were placed along the beam axis before and after the studied target zone, beyond the sensitive zone of γ-spectrometer.

Semiconductor dE_0 and dE_1 detectors and active dE_{AK} collimator were placed before the target to identify ^{8,9}Li nuclei and their separation from other particles of the secondary beam products. Information was recorded for each event of particle passage through the dE_1 detector. Variation of thicknesses of dE_0 and dE_1 detectors enabled us to change and measure the energy of ^{8,9}Li particles incident on the target for each event of particle passage.

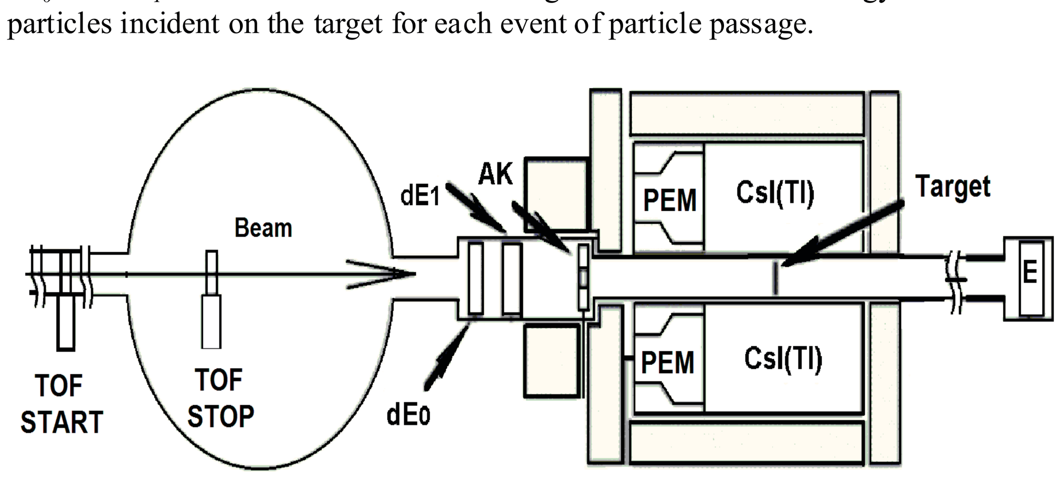

Figure 1. The scheme of the experiment for measurement of reaction cross sections using 4π-scintillation γ-spectrometer.

The secondary beam of ^{8,9}Li nuclei successively passed through:

- the group of plastic scintillator TOF - *dE* detectors of ACCULINA separator;
- the group of semiconductor dE_0 and dE_1 detectors for additional identification of the beam particles and reduction of their energy;
- the detector of the active collimator;
- the target located in the center of 4π-geometry CsI (Tl) γ-spectrometer in the n-γ protection zone;
- the detector *E* located along the beam axis after the target. The *E* detector was placed beyond γ-spectrometer and recorded the beam particles having passed the target.

Fig. 2 shows the two-dimensional spectra: (left) energy losses in dE_0 and *TOF,* and (right) energy losses in dE_0 and dE_1 detectors. Compact grouping of points in the two-dimensional spectra demonstrates a fairly good separation of ^{6}He and ^{8,9}Li isotopes.

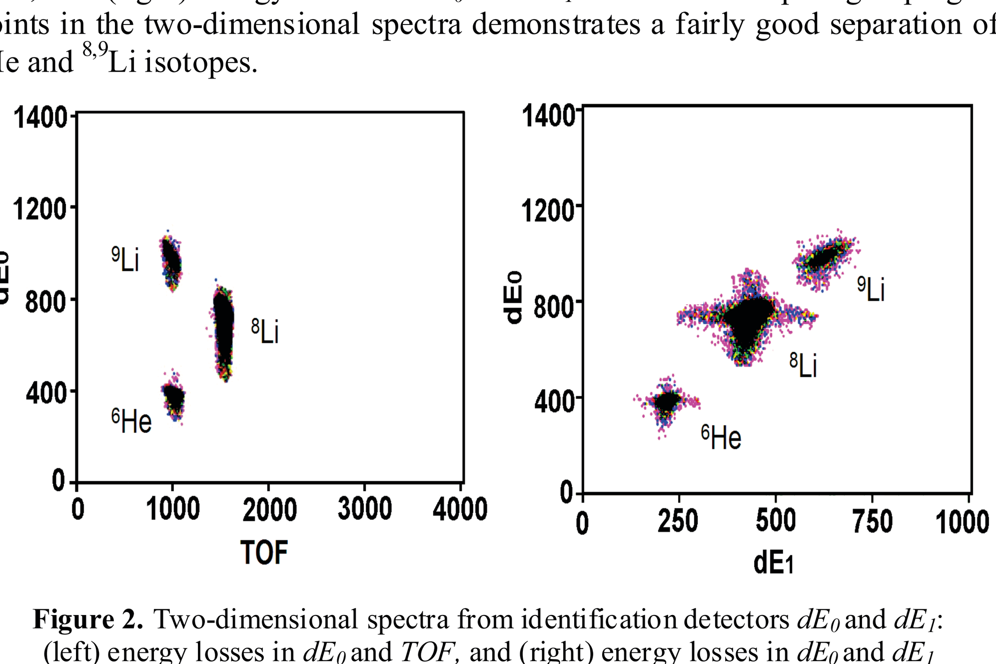

Figure 2. Two-dimensional spectra from identification detectors dE_0 and dE_1: (left) energy losses in dE_0 and *TOF,* and (right) energy losses in dE_0 and dE_1 detectors. The spectra demonstrate a fairly good separation of ^{6}He and ^{8,9}Li isotopes formed as products of the nuclear reaction ^{11}B + ^{9}Be.

4π-geometry γ-spectrometer registered γ-quanta in coincidence with the start dE_1 detector. For each event, the system recorded information about γ-rays energy and the time of their registration.

The number of «reaction events» $\Delta R = (I_0 - I)$ was determined by recording radiation in, at least, one of the γ-spectrometer detectors in coincidence with the start dE_1 detector. Thus, according to (2) the value of the total cross section of the reaction was calculated from the measured I_0 and ΔR values.

We took into account methodological errors made in the previous works. The attempts of joint application of a γ-spectrometer with 4π-geometry and transmission techniques had significant drawbacks and enabled scientists to obtain only estimates and only for "energy integrated reaction cross sections".

One of the disadvantages was that the main source of gamma and neutron background (total energy absorption E-detector of the telescope) was placed within the sensitive area of the γ-spectrometer, so that the spectrometer registered γ-radiation from reactions both in the test target and in the material of E-detector, where the number of nuclei was several orders of magnitude greater than that in the target. In our experiment, all major background γ-sources were minimized, removed from the sensitive area of the γ-spectrometer, and the ensemble of events was selected by the set of equipment, where the most important role was played by γ-spectrometer, so that the E-detector was not a background γ-source. The other events, pretending to be nuclear reactions, were chosen by the method of transmission, in which the γ-spectrometer played a secondary role. Therefore, the physical setup gave a possibility of two separate exposures "$\theta >> 0^0$" and "$\theta \sim 0^0$" with the corresponding intensities of ^{8,9}Li beam, γ-spectrometer functions and other characteristics.

A special attention was paid to the errors of σ_R measurements. They are shown in the figures and do not exceed (5 – 8) %. The main contribution to these errors was made by statistical errors and errors in the thickness of the target.

We have carried out a series of experiments on TCS measurements. Total cross sections for incident particles ^{6}He and ^{8,9}Li were measured simultaneously and under the same conditions. It should be noted that the experimental TCS values for the reaction ^{6}He + ^{28}Si, measured earlier using the conventional transmission method of the multilayer telescope, and the values measured using a modified transmission method coincide in the energy range of (10 – 40) MeV/nucleon. Therefore, we can conclude that the new experimental data presented in this paper are valid within the experimental errors.

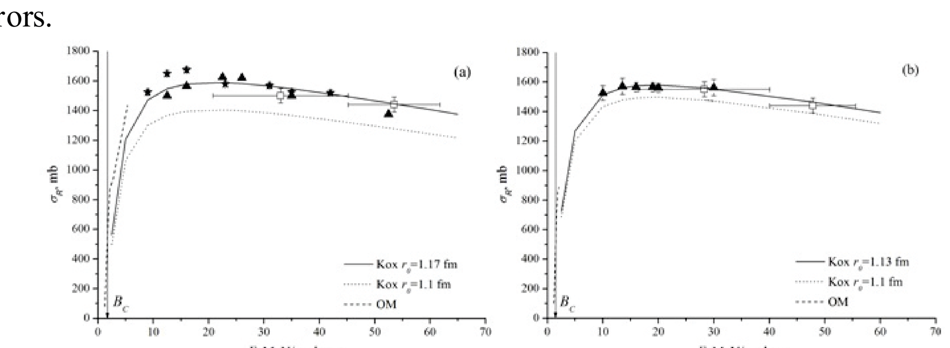

Figure 3. Experimental TCS data for (a) ^{6}Li + ^{28}Si and (b) ^{7}Li + ^{28}Si reactions. Experimental data: closed triangle – [2], open square – [3], stars – [4, 5]. Solid and dot curves are the results of calculations using the semi-empirical Kox formulas, dashed curves are OM calculations.

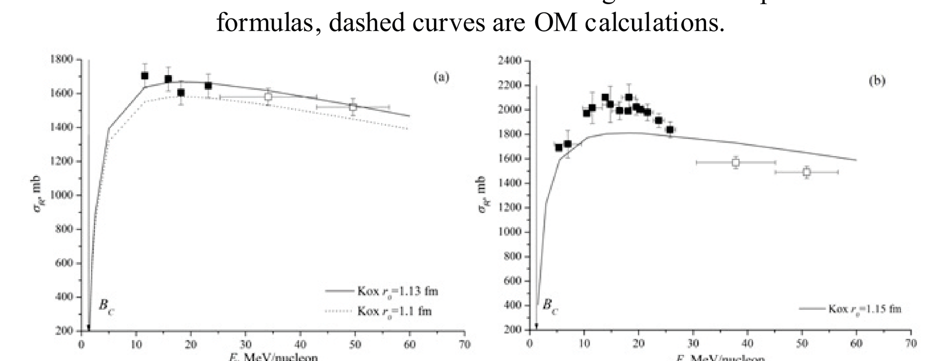

Figure 4. Experimental TCS data for (a) ^{8}Li + ^{28}Si and (b) ^{9}Li + ^{28}Si reactions. Experimental data: closed square – this work, open square – [3]. The curves are the results of calculations using the semi-empirical Kox formulas.

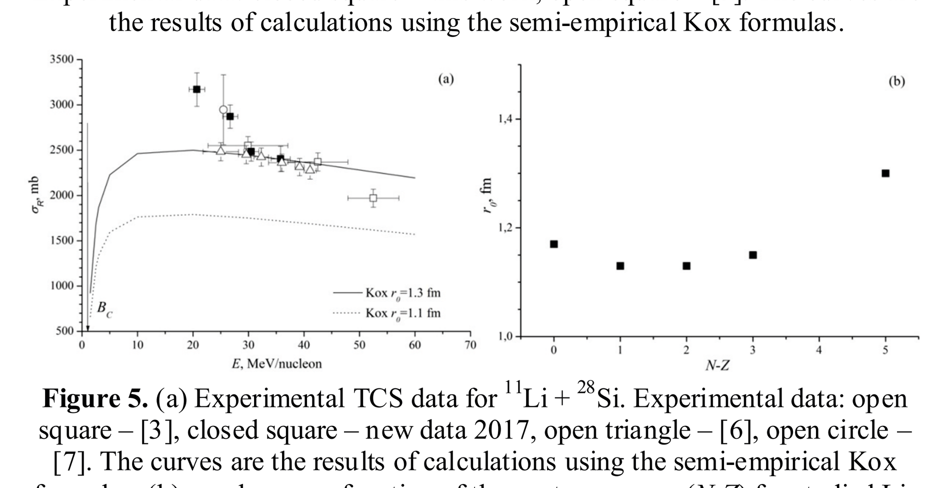

Figure 5. (a) Experimental TCS data for ^{11}Li + ^{28}Si. Experimental data: open square – [3], closed square – new data 2017, open triangle – [6], open circle – [7]. The curves are the results of calculations using the semi-empirical Kox formulas; (b) r_0 values as a function of the neutron excess (*N-Z*) for studied Li-isotopes.

Table 1. r_0 and a values for interactions of $^{6-9}$Li and ^{11}Li ions with ^{28}Si.

	^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{11}Li
r_0 (fm)	1.17	1.13	1.13	1.15	1.3
a (fm)	1.85	1.85	1.85	1.85	1.85

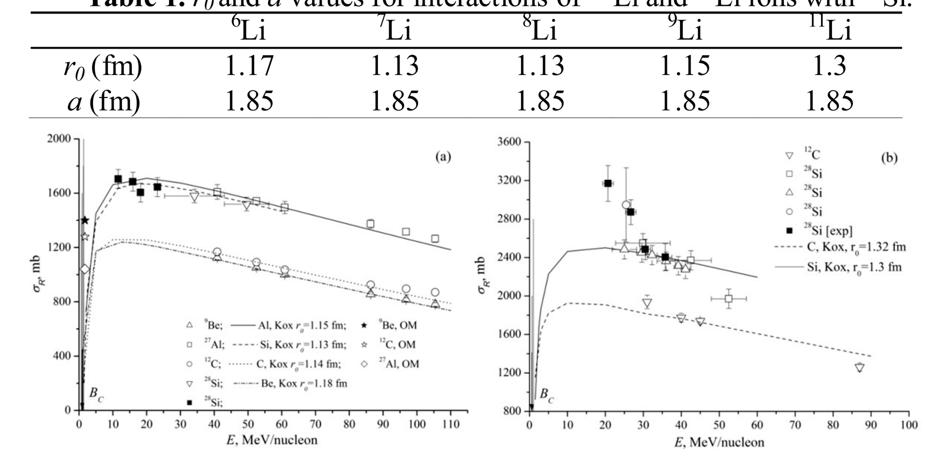

Figure 6. (a) Experimental TCS data for ^{8}Li interactions with ^{9}Be, ^{12}C, ^{27}Al and ^{28}Si nuclei. Experimental data: closed square – this work, open triangle – [8], open square – [8], open circle – [8], open triangle – [3]. The curves are the results of calculations using the semi-empirical Kox formulas. Stars and a diamond are the OM calculations.
(b) Experimental TCS data for ^{11}Li interactions with ^{12}C, ^{28}Si. Experimental data: open square – [3], open circle – [9]. The curves are the results of calculations using the semi-empirical Kox formulas.

Table 2. r_0 and a values for interactions of ^{8}Li and ^{11}Li nuclei with ^{9}Be, ^{12}C, ^{27}Al, ^{28}Si.

	^{8}Li + ^{9}Be	^{8}Li + ^{12}C	^{8}Li + ^{27}Al	^{8}Li + ^{28}Si	^{11}Li + ^{12}C	^{11}Li + ^{28}Si
r_0 (fm)	1.18	1.14	1.15	1.13	1.32	1.3
a (fm)	1.85	1.85	1.85	1.85	1.85	1.85

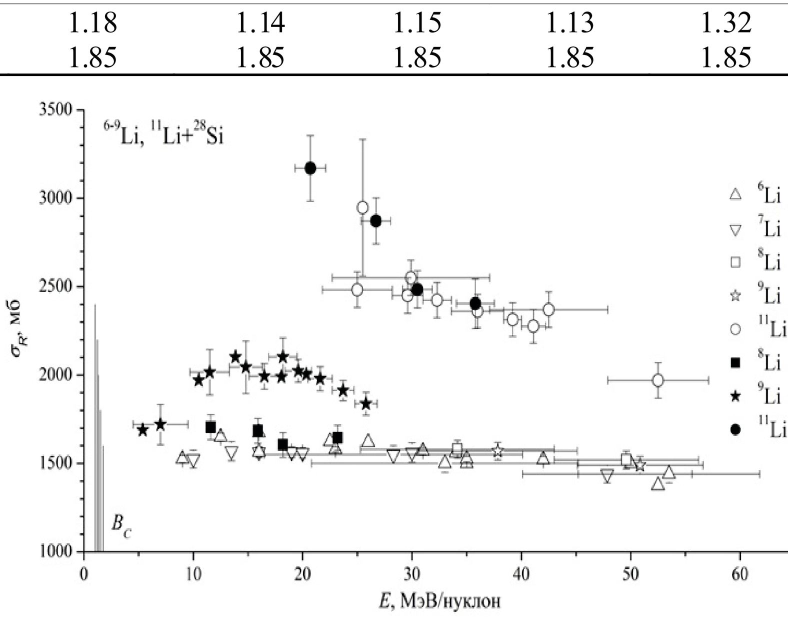

Figure 7. Energy dependence of all available experimental TCS data in the literature for interactions of $^{6-9}$Li and ^{11}Li with ^{28}Si nuclei. Symbols are experimental data. Vertical lines are B_c of the corresponding reactions.

We carried out a theoretical calculation of the $\sigma_R(E)$ values for the (^{11}Li + ^{28}Si) reaction within the semi-microscopic folding-model using the density- and energy-dependent effective nucleon-nucleon interaction CDM3Y-Paris.

$$U(r) = (N_r + iN_w) V_{CDM3Y}(r)$$

The results of the calculations are shown in Figure 8 by a solid line. Also the results of calculations by the modernized Kox formula with the parameters r_0= 1.6, b = -0.25 are shown in Figure 8.

$$\sigma_R(E) = \pi \cdot R_{int}^2 \cdot \left(1 - \frac{B_c}{E_{cm}}\right) - (r_0 - b)^2 \cdot \left(\frac{E_{cm}}{B_c}\right)$$

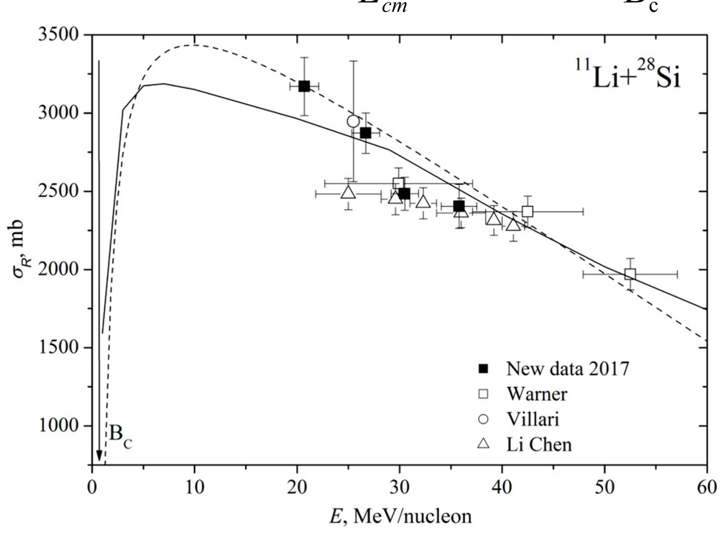

Figure 8. Energy dependence of TRC for (^{11}Li + ^{28}Si). Experimental data: closed square - new data, open square – [3], open circle – [7], open triangle – [6]. Solid line – calculations within the framework of a semi-microscopic folding-model ($N_r = N_w = 1$). Dotted line – calculation using Kox formula with r_0= 1.6, b = -0.25

^{11}Li+*d*: B_C=5.59 MeV, (^{9}Li+2*n*)=0.369 MeV, $E_{binding}$ = 2.22 MeV (for *d*)

^{11}Li+^{9}Be: B_C=6.20 MeV, (^{8}Be+*n*)=1.66 MeV, $E_{binding}$ = 58 MeV (for ^{9}Be)

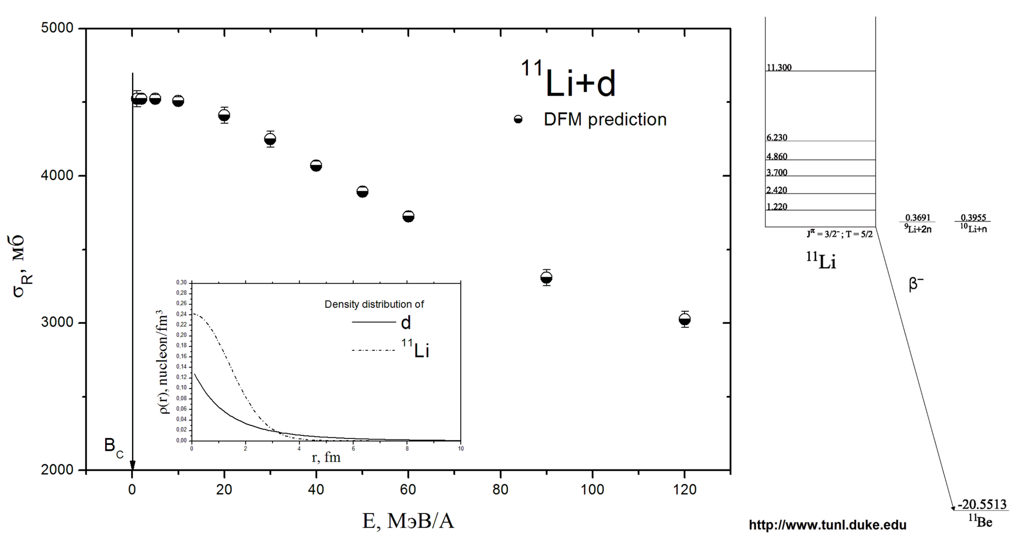

Figure 9. Predictive analysis of total reaction cross sections for (^{11}Li+d) in the framework of double folding model

Conclusion

We have presented the new data on σ_R measurements for ^{8,9,11}Li + ^{28}Si interactions at energies (5 – 40) MeV/nucleon.

In the ^{9}Li + ^{28}Si reaction we first discovered a «bump» in the energy dependence of the TCS, manifested as a local increase in the cross section in the energy range (10 – 30) MeV/nucleon, which requires further theoretical analysis and experimental research.

It should be noted that to analyze some important features of interactions of lithium isotopes at low energies it is necessary to have the experimental TCS data at energies from B_c to 40 MeV/nucleon, which are not available now.

We carried out predictive calculations of the total reaction cross section values for the (^{11}Li + ^{28}Si) reaction at energies from the Coulomb barrier to 300 MeV/nucleon within the framework of a semi-microscopic folding model and a new Kox parametrization. This is necessary for describing the trend in behavior of the total reaction cross section excitation functions at near-barrier energies. Namely, for the description of the recently experimentally discovered quite large values of the total reaction cross sections. In the energy range (20–55) MeV/nucleon, both models describe the existing and new experimental data on the total reaction cross sections quite satisfactorily.

Large TCS values (in relative terms) detected in the $\sigma_R(E)$ dependence and its rapid increase in the narrow energy range at low energies can lead to the release of a large amount of energy, which is interesting in terms of search for new sources in nuclear technologies.

These new data (the existence of an abnormal increase in the TCS) in a narrow energy range of (10 – 30) MeV/nucleon in reactions (^{6}He, ^{9}Li) + ^{28}Si at near-barrier energies will enable us to explain some important problems of nucleosynthesis (nuclear astrophysics).

One of the most important results explaining the prevalence of light elements in the universe is a bump in cross sections of nuclear reactions with light weakly bound nuclei at sub-barrier energies. This effect is especially strongly manifested for light cluster nuclei of ^{6,9,11}Li [10-12] and nuclei with neutron halo ^{6,8}He, ^{11}Li [13].

A similar effect is well known for *dp*-reactions where in the deep sub-barrier region a significant increase in the cross-section is observed. It is the so-called Oppenheimer-Phillips resonance [14] caused by polarization of a weakly bound deuteron. This phenomenon was used in the fusion reaction accompanied by an enormous energy release. In the case of ^{6}He and ^{11}Li reaction, this effect is more pronounced as ^{6}He and ^{11}Li have lower binding energy than the deuteron, larger Coulomb repulsion forces causing polarization of these nuclei, and large positive values of Q-reactions.

These results are extremely important for understanding the mechanism of formation of light elements in the universe. In the process of nucleosynthesis, large cross section of interaction of cluster weakly bound nuclei (^{6}He, ^{9}Li, ^{7}Be and others) can change the chains of γ-decay leading to formation of various elements [15, 16]. In this case, the following channels are the most probable for the synthesis of stable nuclei: ^{1}H(^{6}He,nγ)^{6}Li, ^{12}C(^{6}He, 2nγ)^{16}O, ^{1}H(^{9}Li, nγ)^{9}Be, ^{3}He(^{9}Li, 2nγ)^{10}B and others.

Such peculiarities of interactions manifested in the appearance of a bump in the cross-section of cluster transfer reactions as well as in total fusion reactions near the Coulomb barrier are typical of various weakly bound nuclei.

A new idea for the experiment. Measure σ_R(E) for reactions (^{11}Li+d) or (^{11}Li+^{9}Be) at low lithium energies (E_{lab}(^{11}Li) from B_c~6 MeV to 30 MeV/nucleon).

[1] Sobolev Yu G, Ivanov M P, Penionzhkevich Yu E 2012 *Instr. and Exp. Technique* **55** 618
Sobolev Yu G *et al* 2017 *Physics of Elementary Particles and Atomic Nuclei* **48** 4 (accepted for publishing)
[2] Kuznetsov I V *et al* 2002 *Phys. Atomic Nuclei* **65** 1569
[3] Warner R E *et al* 1996 *Phys. Rev.* C **54** 1700
[4] Kuterbekov K A *et al* 2014 *Phys. Atomic Nuclei* **77** 581
[5] Lukyanov K V, Zemlyanaya E V, Lukyanov V K, Kukhtina I N, Penionzhkevich Yu E and Sobolev Yu.G 2008 *Bull. Rus. Acad. Sci. Phys.* **72** 356
[6] Li Chen *et al.* 2007 *High Energy Physics and Nuclear Physics* **31** 1102.
[7]Villari A.C.C. et al. 1991 *Phys.Lett.B* **268** 345
[8]Fan G W *et al* 2014 *Phys. Rev.* C **90** 044321
[9] Moriguchi T *et al* 2013 *Phys. Rev.* C **88** 024610
[10] Dasgupta M *et al* 2004 *Phys.Rev.* C **70** 024606
[11] PenionzhkevichYu E *et al* 2009 *J.Phys.(London)* G **36** 025104
[12] Loveland W *et al* 2006 *Phys.Rev.* C **74** 064609
[13] Lemasson A *et al* 2009 *Phys.Rev.Lett.* **103** 232701
[14] Oppenheimer J R, Phillips M 1935 *Phys.Rev.* **48** 500
[15] Bartlett A *et al* 2006 *Phys. Rev.* C **74** 015802
[16] Zagrebaev V I 2007 *Phys. Rev.* C **75** 035809