DESCRIPTION OF ENHANCEMENT OF TOTAL CROSS SECTIONS OF REACTIONS WITH ^{6}HE AND ^{9}LI NUCLEI

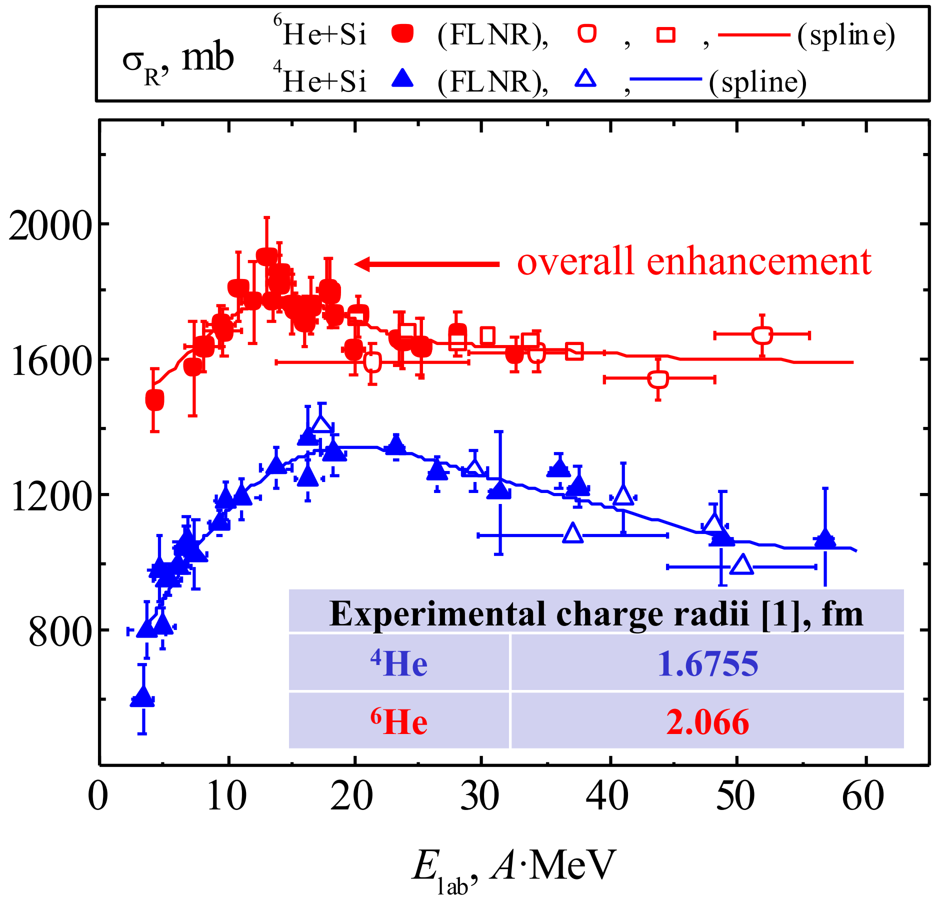
Yu. E. Penionzhkevich, Yu. G. Sobolev, V. V. Samarin, M. A. Naumenko

FLEROV LABORATORY of NUCLEAR REACTIONS
Joint Institute for Nuclear Research, Dubna, Russia

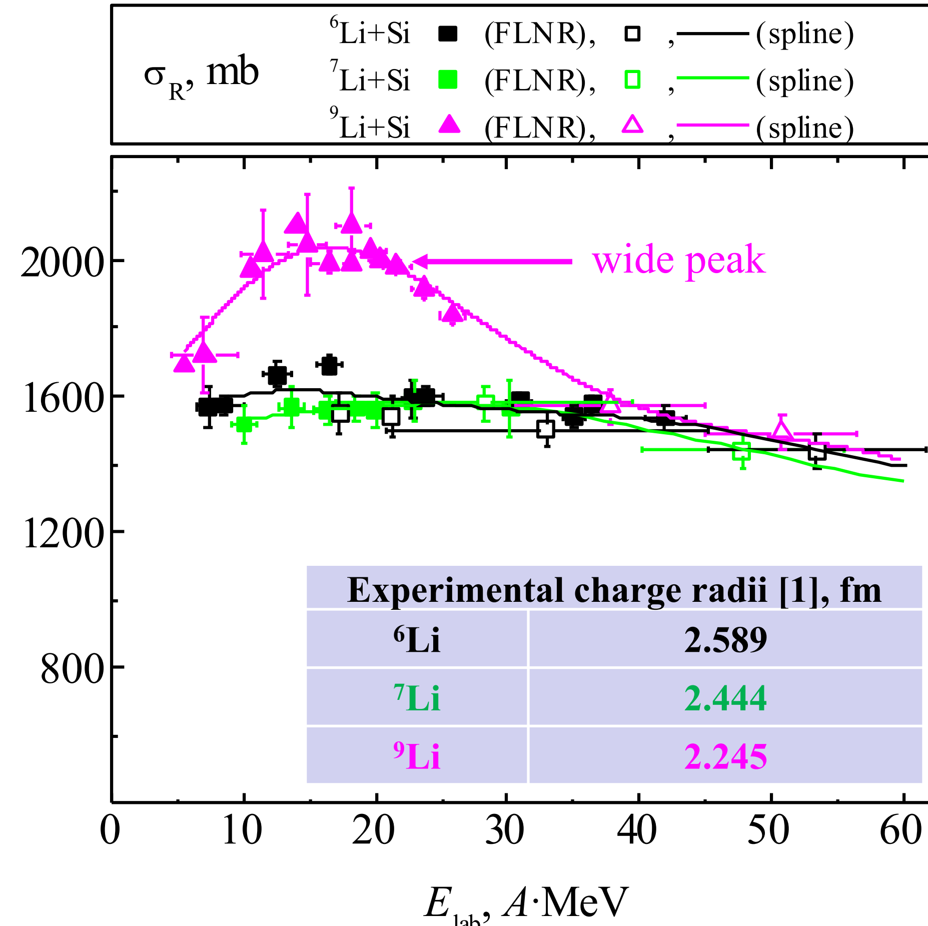
Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

ENSAR2 – NUSPRASEN Workshop on Nuclear Reactions (Theory and Experiment),
22-24 January 2018.

Peculiarities of total reaction cross sections for $^{6}He + ^{28}Si$ and $^{9}Li + ^{28}Si$ compared with $^{4}He + ^{28}Si$ and $^{6,7}Li + ^{28}Si$



Experimental charge radii [1], fm	
^{4}He	1.6755
^{6}He	2.066

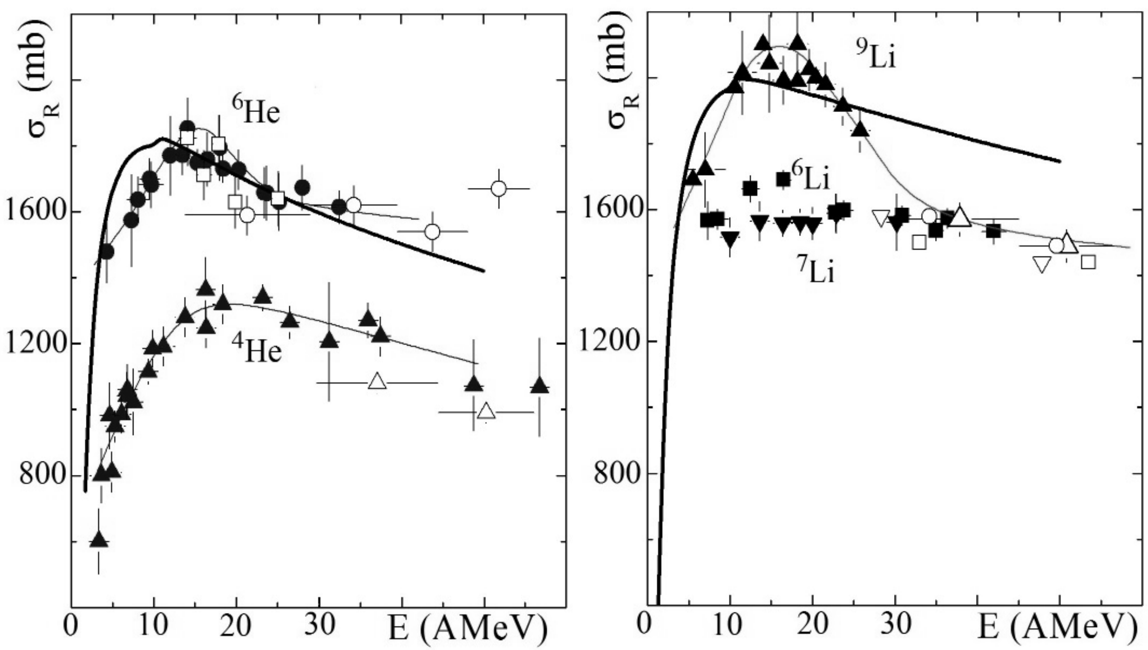


Experimental charge radii [1], fm	
^{6}Li	2.589
^{7}Li	2.444
^{9}Li	2.245

$^{6}He + ^{28}Si$: enhancement in whole energy range: geometric effect;
$^{9}Li + ^{28}Si$: wide peak in energy range 10 – 30 *A*·MeV: structural & dynamical effect.

[1] NRV web knowledge base on low-energy nuclear physics. URL: http://nrv.jinr.ru/

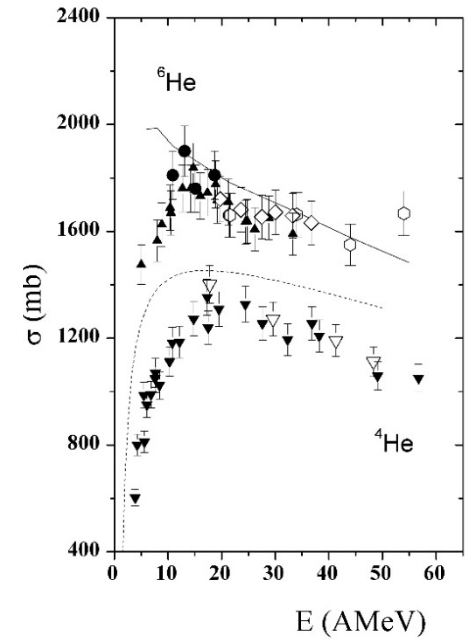
Previous attempts of theoretical description



Thin lines are interpolation curves, thick lines are calculations based on microscopic optical potential [1].

[1] K.V. Lukyanov et al., Bull. Rus. Acad. Sci. Phys. **72**, 356 (2008).

Picture from Yu.G. Sobolev *et al.*, PEPAN **48**, in press, (2017).

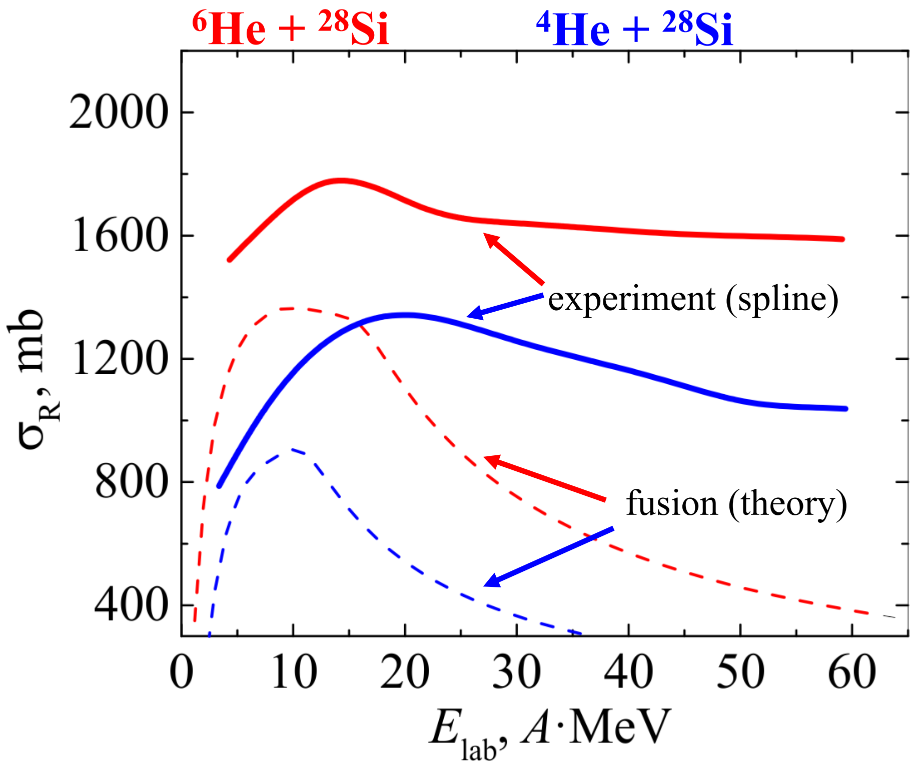


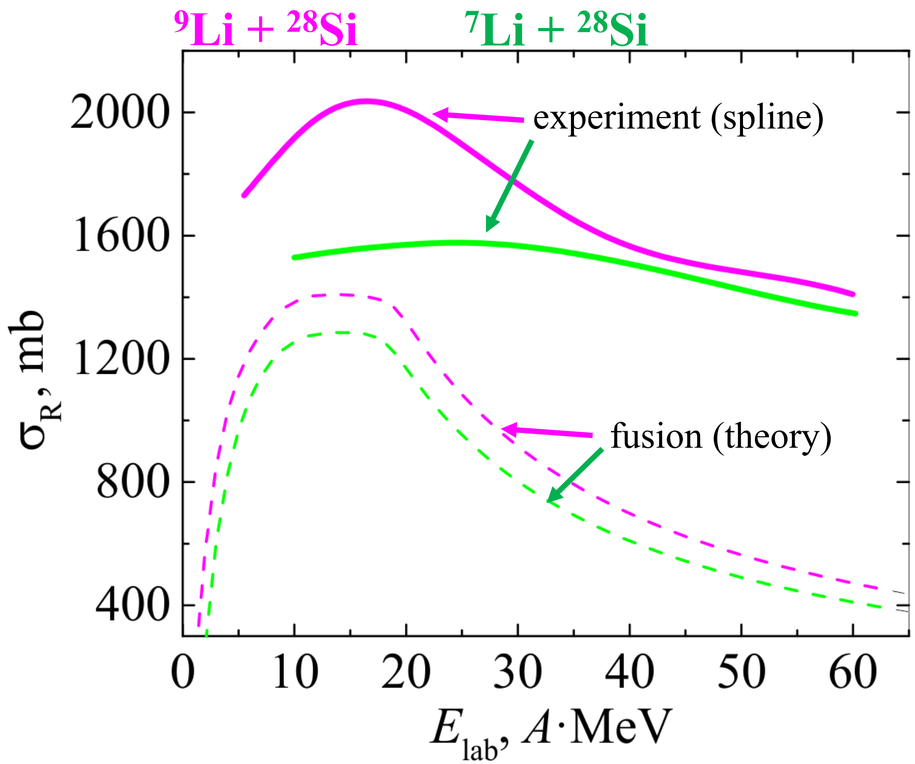
Dotted curve is an empirical model (Phys. Rev C 35, 1678 (1987)), solid curve is semimicroscopic optical model (Phys. Part. Nucl. 30, 870 (1999)).

Picture from G.D. Kabdrakhimova *et al.*, Phys. At. Nucl. **80**, 32 (2017).

These models provided only partial agreement with experimental data

Estimation of contribution of complete fusion channel to total cross sections within one-dimensional barrier penetration model [1]



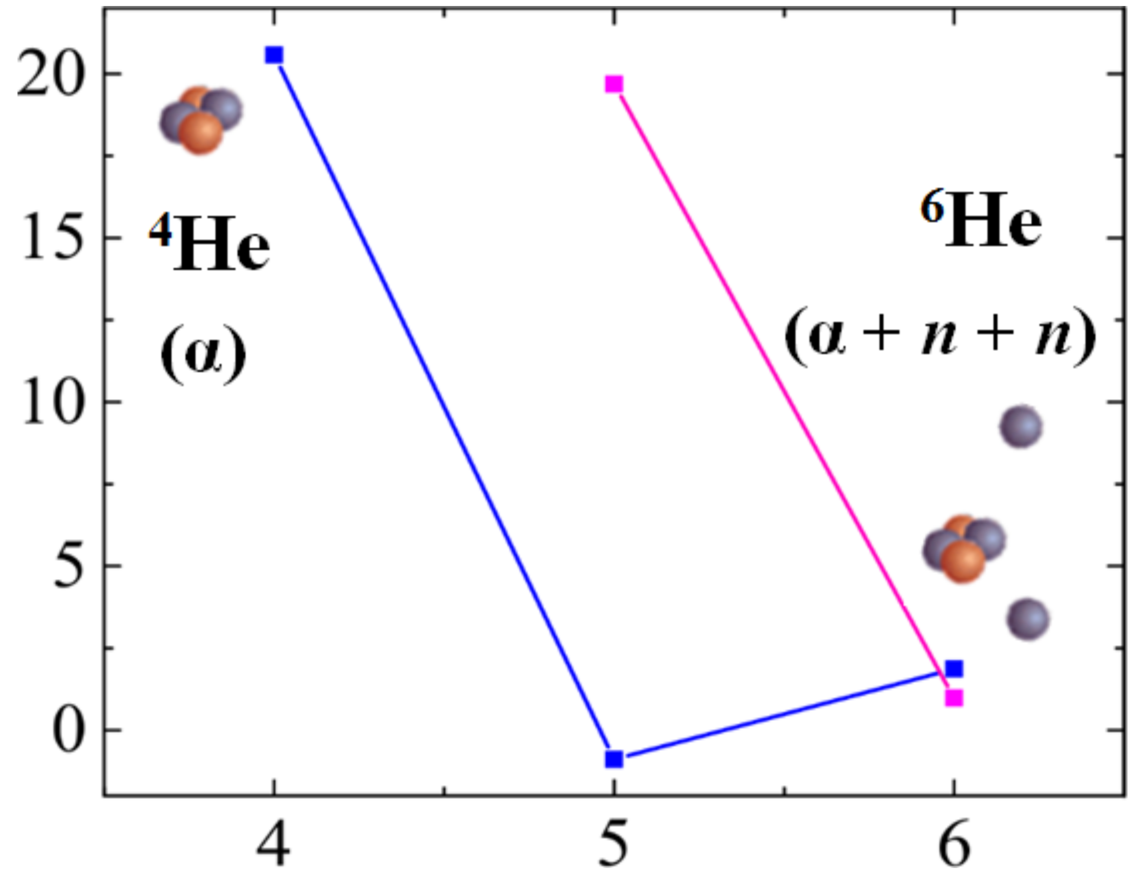


Complete/incomplete fusion is one of the main channels contributing to total reaction cross sections. Other possible channels are breakup, nucleon transfer, etc.

[1] NRV web knowledge base on low-energy nuclear physics. URL: http://nrv.jinr.ru/

Structure of nuclei $^{4,6}He$

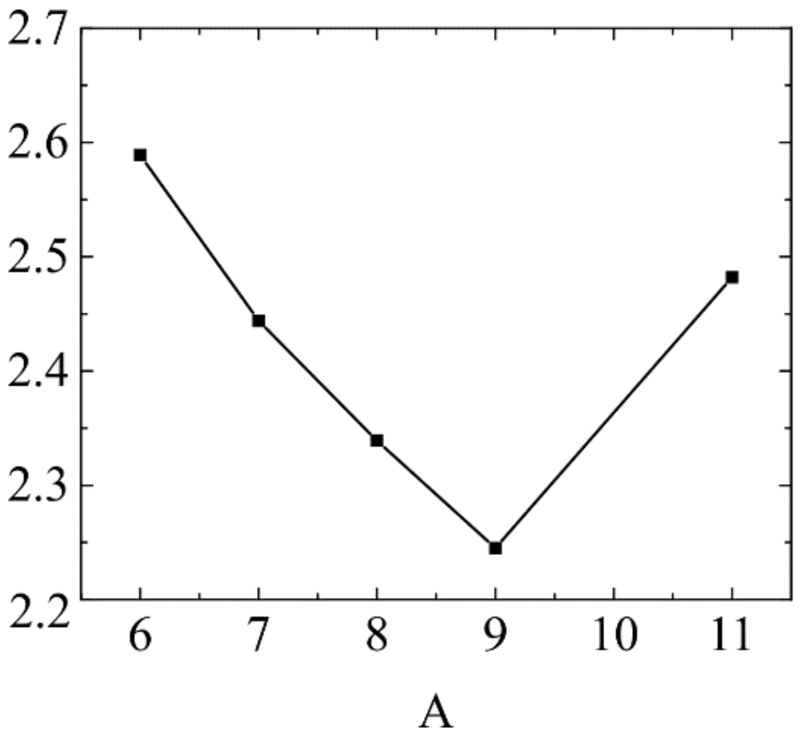
Neutron separation energy: 1n & 2n



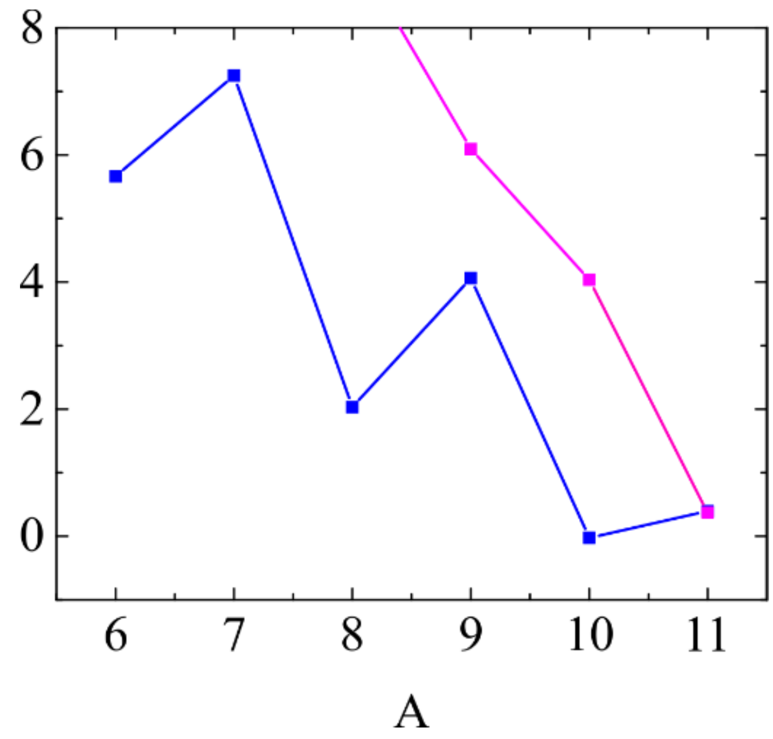
^{6}He **can be represented as ($\alpha + n + n$) based on experimental data on neutron separation energies, charge radii, etc.**

Structure of nuclei ^{6,7,9}Li

Charge radii



Neutron separation energies: 1n & 2n



^{6}Li ($\alpha + d$)
^{7}Li ($\alpha + t$)
^{9}Li (^{7}Li + n + n):

^{9}Li can be represented as (^{7}Li + n + n) based on experimental data on neutron separation energies, charge radii, etc.

Time-dependent Schrödinger equation approach

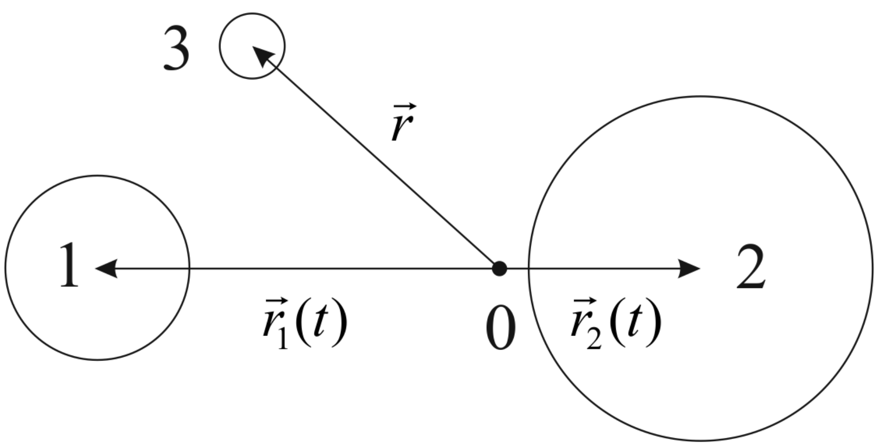
- Classical motion of centers of nuclei

$$m_1 \ddot{\vec{r}}_1 = -\nabla_{\vec{r}_1} V_{12}\left(\left|\vec{r}_1 - \vec{r}_2\right|\right),\; m_2 \ddot{\vec{r}}_2 = -\nabla_{\vec{r}_2} V_{12}\left(\left|\vec{r}_2 - \vec{r}_1\right|\right).$$

- Transfer (rearrangement) of neutrons during collision is described by time-dependent Schrödinger equation with spin-orbit interaction [1-4]

$$i\hbar \frac{\partial}{\partial t}\Psi(\vec{r},t) = \left\{-\frac{\hbar^2}{2m}\Delta + V_1(\vec{r},t) + V_2(\vec{r},t) + \hat{V}_{LS}^{(1)}(\vec{r},t) + \hat{V}_{LS}^{(2)}(\vec{r},t)\right\}\Psi(\vec{r},t).$$

- The initial wave function is determined from shell model. Parameters of shell model were chosen based on experimental data on charge radii and neutron (proton) separation energies.



1,2 are two heavy classical particles; 3 is light quantum particle (neutron of projectile or target).

References

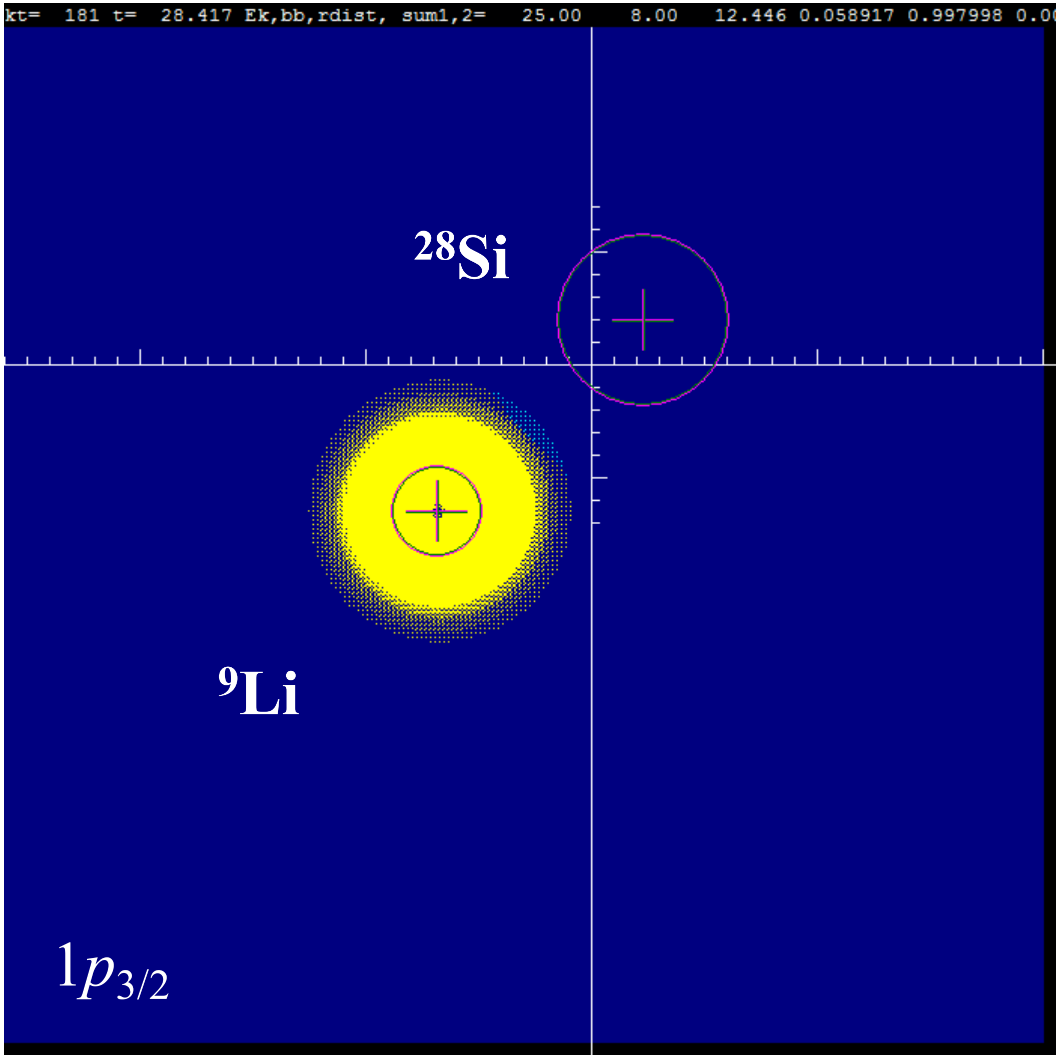
[1] V. V. Samarin, EPJ Web Conf. 66, 03075 (2014); 86, 00040 (2015).

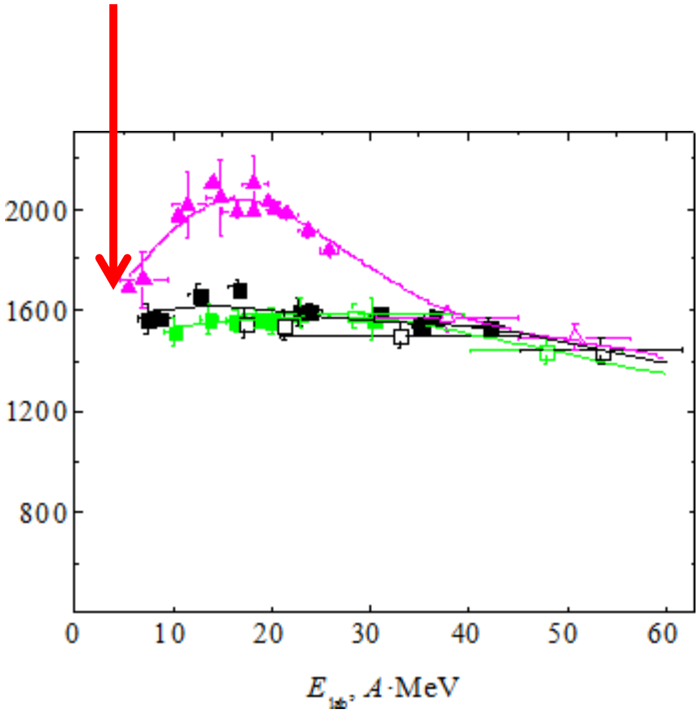
[2] V. V. Samarin. Phys. At. Nucl. 78,128 (2015).

[3] M. A. Naumenko, V. V. Samarin, Yu. E. Penionzhkevich, N. K. Skobelev. Bull. Russ. Acad. Sci. Phys. 80, 264 (2016).

[4] M. A. Naumenko, V. V. Samarin, Yu. E. Penionzhkevich, N. K. Skobelev. Bull. Russ. Acad. Sci. Phys. 81, 710 (2017).

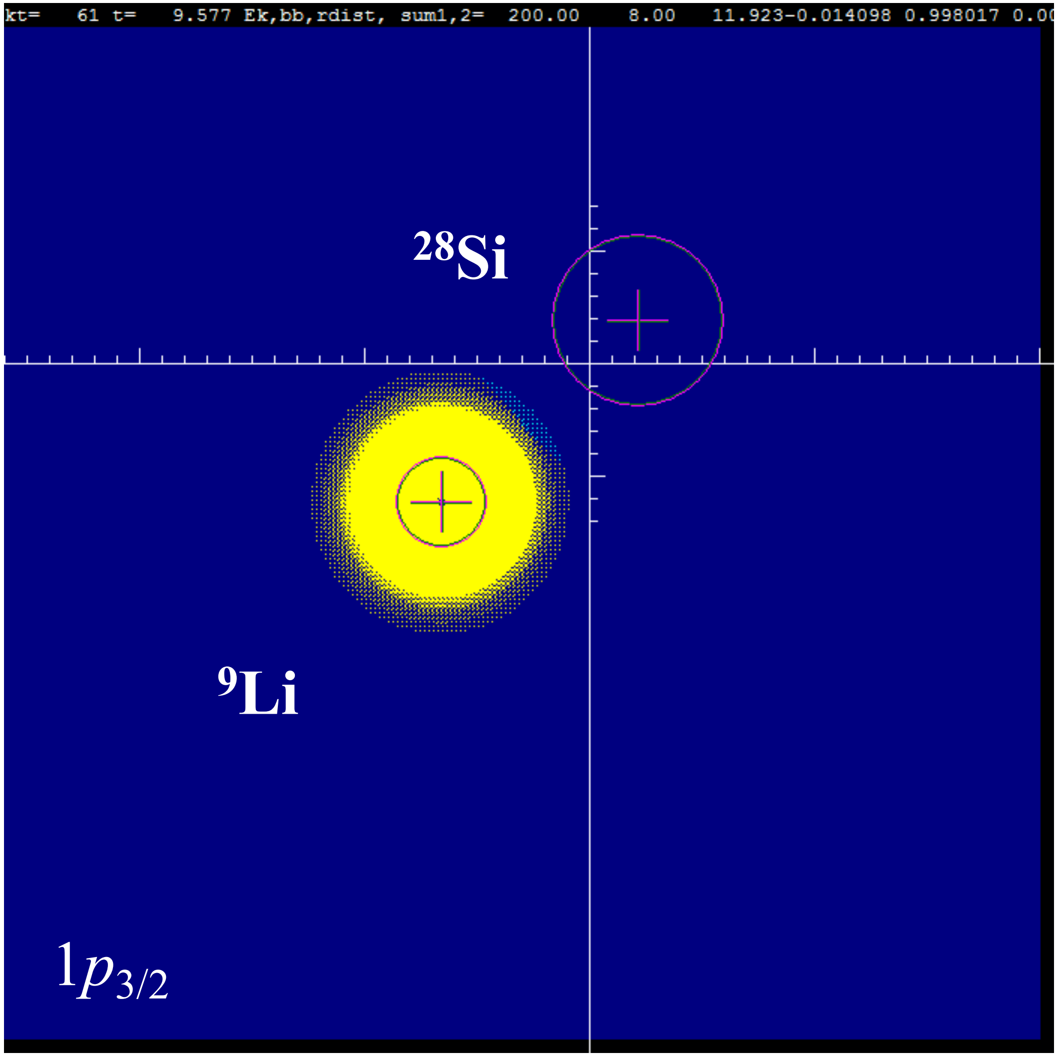
Evolution of probability density of one external neutron of ^{9}Li nucleus in collision $^{9}Li + {}^{28}Si$ at 3.7 A·MeV

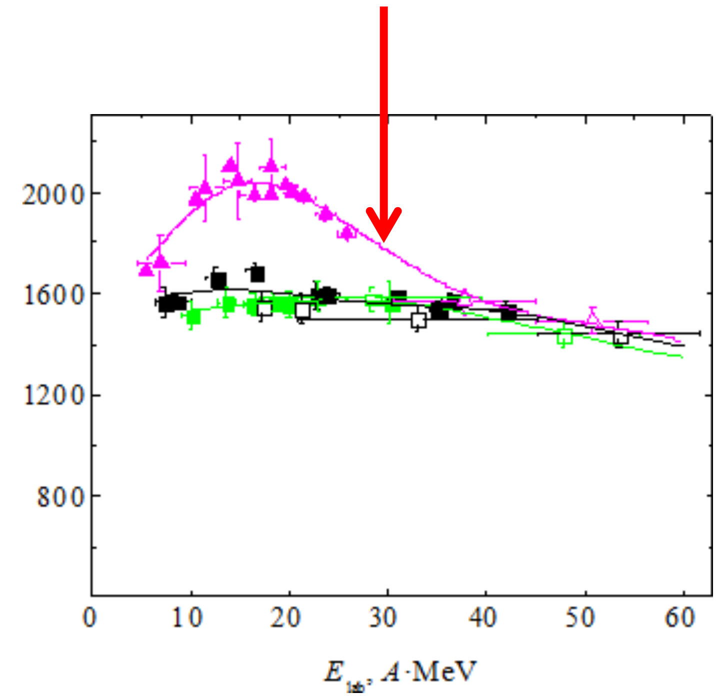




Evolution is similar to adiabatic process

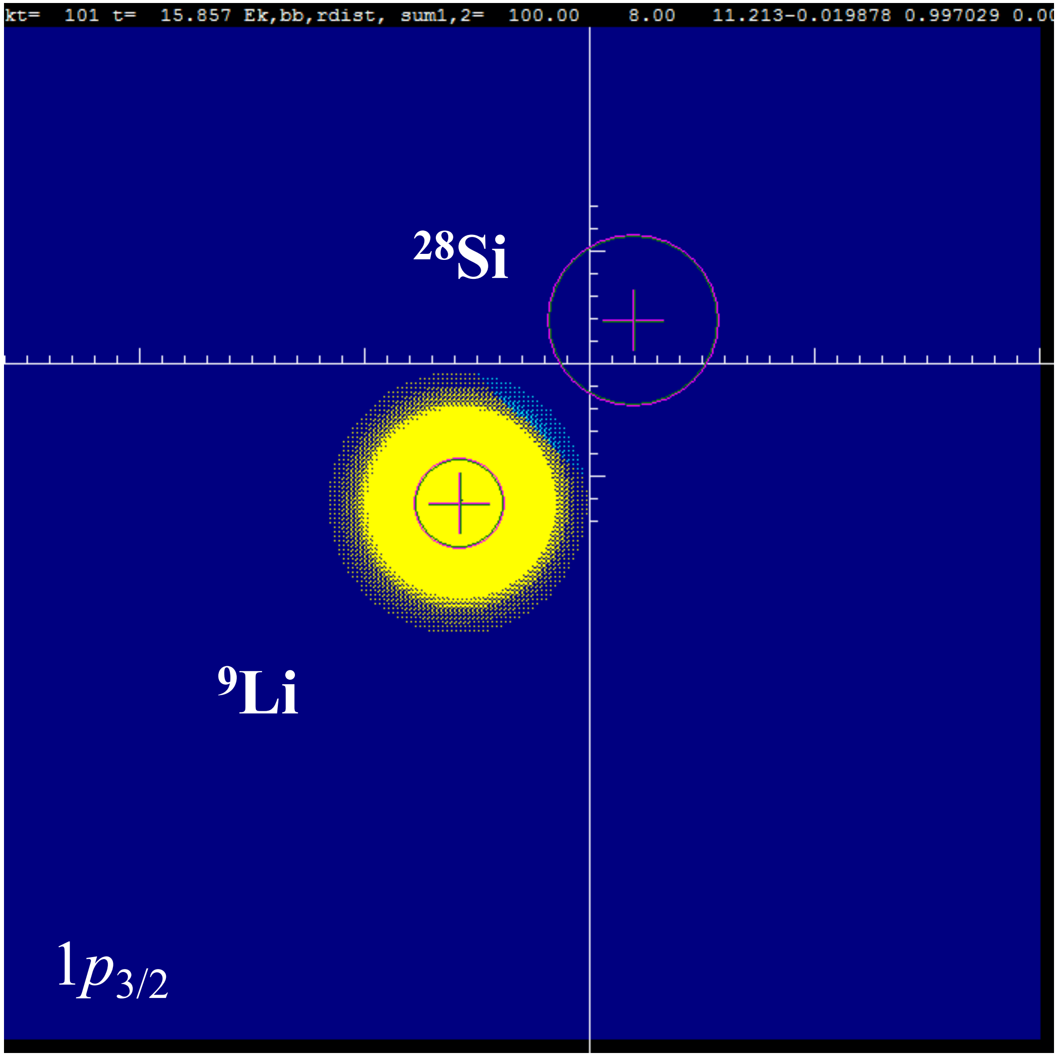
Evolution of probability density of one external neutron of ^{9}Li nucleus in collision $^{9}Li + ^{28}Si$ at 30 A·MeV

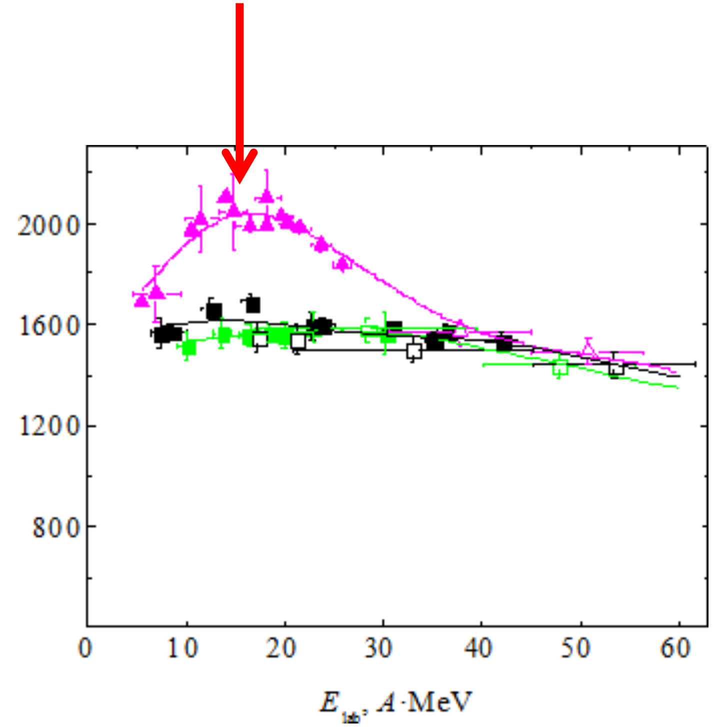




Evolution is similar to diabatic process

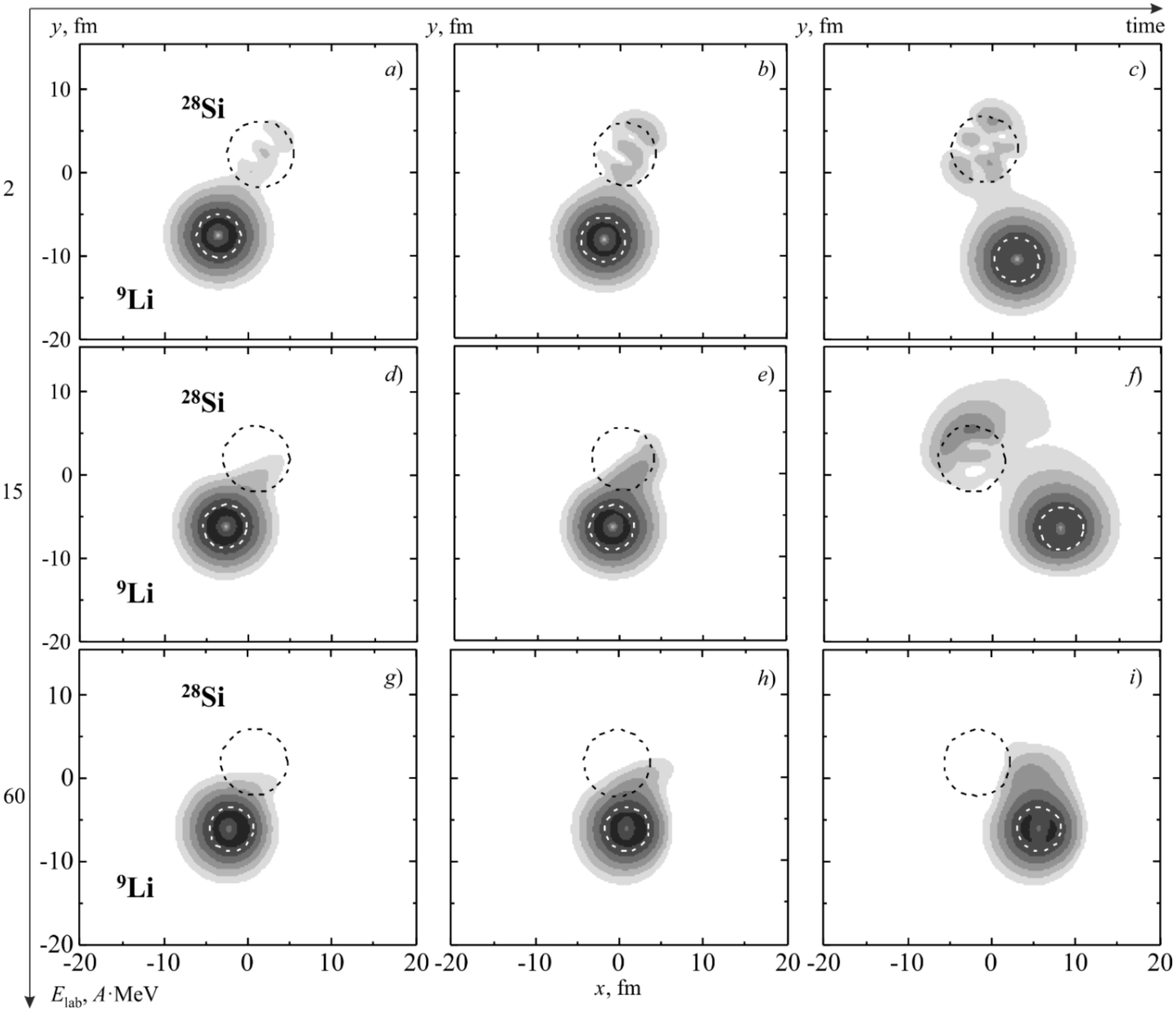
Evolution of probability density of one external neutron of ^{9}Li nucleus in collision ^{9}Li + ^{28}Si at 15 A·MeV





Transition from adiabatic to diabatic process

Evolution of probability density of one external neutron of ^{9}Li nucleus in collision ^{9}Li + ^{28}Si: summary



$$\delta\rho_1(r_1,t) = \rho_1(r_1,t) - \rho_1^{(0)}(r_1,t)$$

Adiabatic motion:
two-center "molecular" states; small value of $\delta\rho_1(r_1,t)$ between surfaces of nuclei

---

Intermediate case:
appreciable value of $\delta\rho_1(r_1,t)$ between surfaces of nuclei

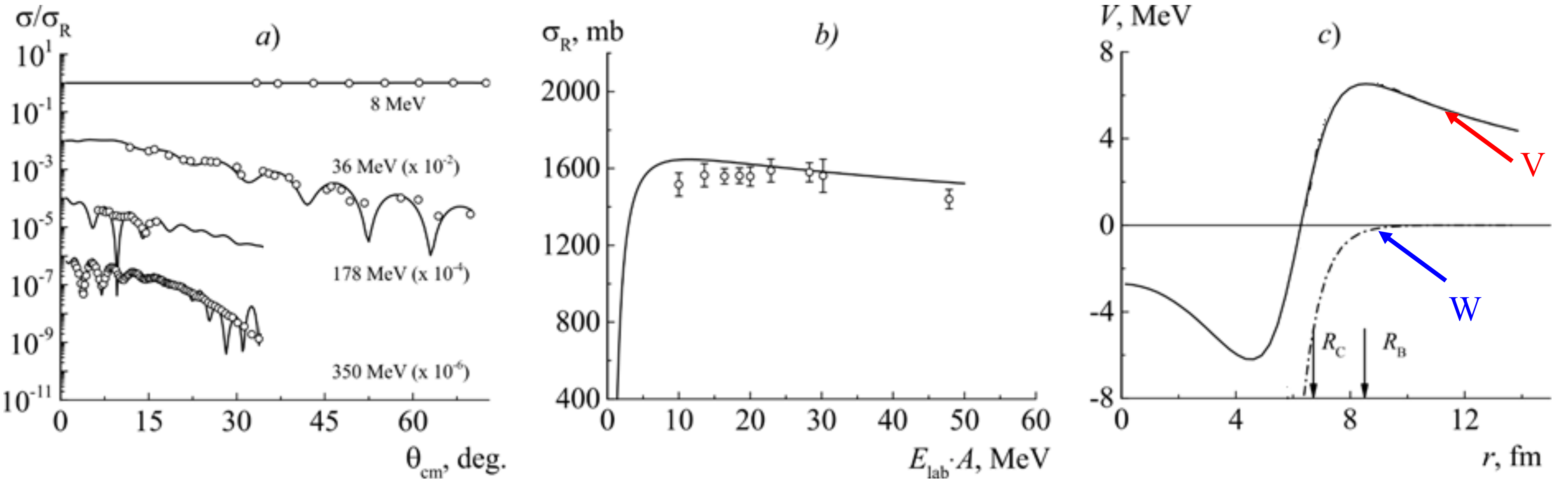
---

Diabatic motion:
small value of $\delta\rho_1(r_1,t)$ between surfaces of nuclei

---

Rearrangement of external weakly bound neutrons of ^{6}He & ^{9}Li depending on energy suggests introduction of **energy-dependent corrections to nuclear part of nucleus-nucleus potential in optical model.**

Choice of parameters of optical potential for reaction $^{7}Li + ^{28}Si$



Energy-independent parameters of optical potential in Woods-Saxon form for the $^{6,7}Li + ^{28}Si$ reactions were chosen based on analysis of experimental data on angular distributions of elastic scattering for a number of energies in wide range: $^{6}Li + ^{28}Si$ (E_{lab}=7.5 ÷ 318 MeV) & $^{7}Li + ^{28}Si$ (E_{lab}= 8 ÷ 350 MeV).

Energy-independent parameters of optical potential in the Woods-Saxon form for $^{9}Li + ^{28}Si$ reaction were obtained by extrapolating the parameters for $^{6,7}Li + ^{28}Si$.

Good agreement with experimental data on elastic scattering;
acceptable agreement with experimental data total cross section;
parameters for $^{9}Li + ^{28}Si$ were chosen close to the parameters for $^{6,7}Li + ^{28}Si$.

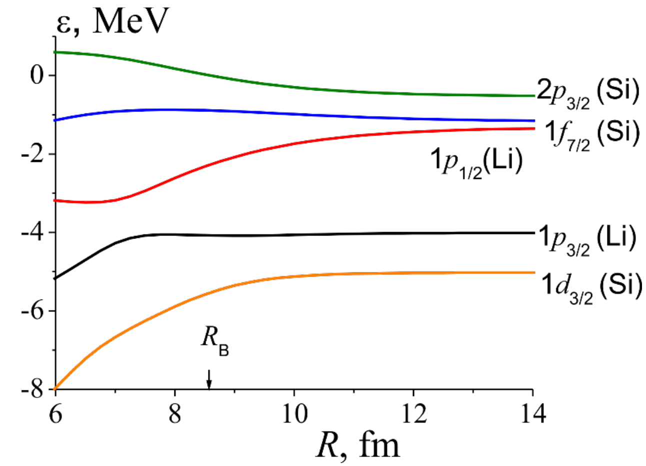
Energy-dependent corrections to nuclear part of nucleus-nucleus potential

$$\mathrm{Re}\{V_{\mathrm{N}}(r)\} \equiv V(R, E_{\mathrm{lab}}) = \bar{V}(R) + \eta_1(E_{\mathrm{lab}})\left[\varepsilon_\nu(R) - \varepsilon_\nu(\infty)\right] + \eta_2(E_{\mathrm{lab}})\delta V_{\mathrm{d}}(R, E_{\mathrm{lab}})$$

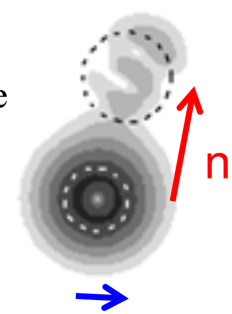
$$\eta_1(E_{\mathrm{lab}}) + \eta_2(E_{\mathrm{lab}}) = 1$$

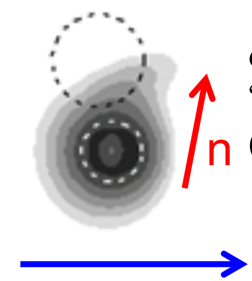
Adiabatic correction

Diabatic correction



"molecular" (two-center) state





deformed neutron "cloud" (one-center state)

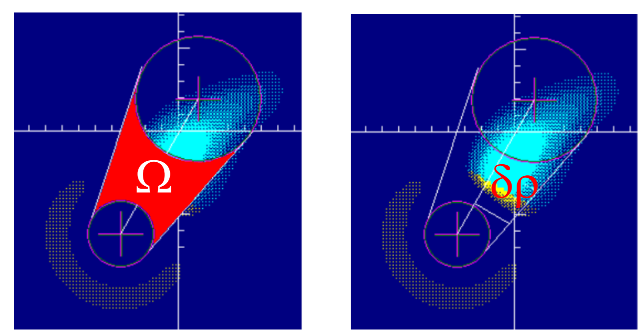
$$\eta_1(E) \to 1, \quad \text{if } \frac{v_1}{\langle v \rangle} << 1$$

$$\eta_2(E) \to 1, \quad \text{if } \frac{v_1}{\langle v \rangle} >> 1$$

$\varepsilon_\nu(R)$ is energy of two-center ("molecular") state with number ν [1], R is distance between centers of nuclei.

$$\delta V_{\mathrm{d}}\left(R(t), E_{\mathrm{lab}}\right) = \int_\Omega d^3 r \delta\rho_1(r,t) U_{\mathrm{T}}\left(\left|\vec{r} - \vec{r}_2(t)\right|\right)$$

$$\left|\varepsilon_{1p(\mathrm{Li})}(R) - \varepsilon_{1p(\mathrm{Li})}(\infty)\right| << 1 \text{ MeV}$$ **adiabatic correction may be neglected**



v_1 is velocity of projectile nucleus relative to target nucleus

$\langle v \rangle$ is average velocity of external neutrons in projectile nucleus

(method of calculation) [1] V.V. Samarin, Phys. At. Nucl. 78, 128 (2015).

Energy-dependent diabatic correction to nuclear part of nucleus-nucleus potential

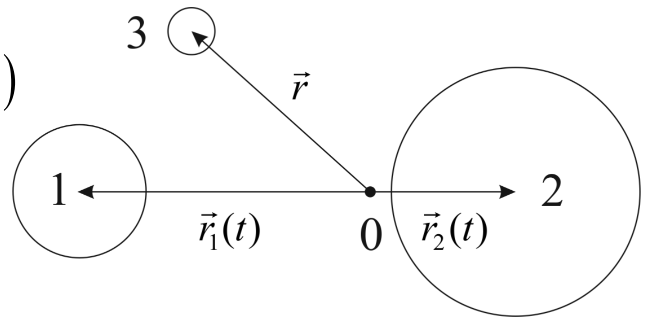
$$\mathrm{Re}\{V_{\mathrm{N}}(r)\} \equiv V(R,E_{\mathrm{lab}}) = \bar{V}(R) + \eta_2(E_{\mathrm{lab}})\delta V_{\mathrm{d}}(R,E_{\mathrm{lab}})$$

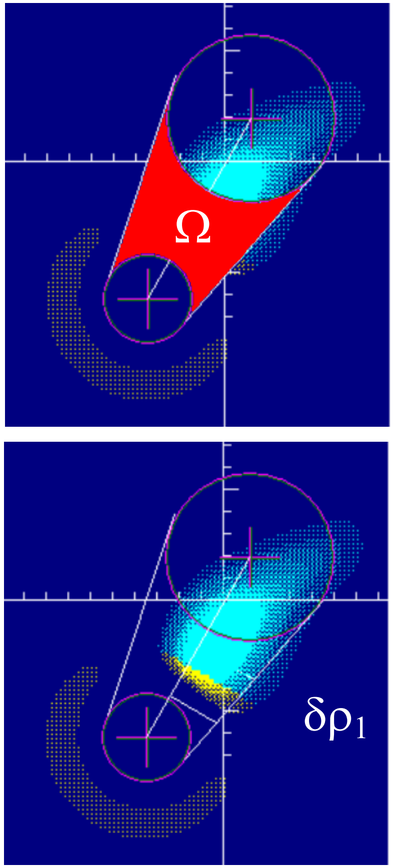
Diabatic correction

Similar to single folding

$$\delta V_{\mathrm{d}}\left(R(t),E_{\mathrm{lab}}\right) = N\int_{\Omega} d^3 r\,\delta\rho_1(r,t)U_{\mathrm{T}}\left(\left|\vec{r}-\vec{r}_2(t)\right|\right)$$

$$\delta\rho_1(r,t) = \rho_1(r,t) - \rho_1^{(0)}(r,t)$$





Ω is integration region;

$\rho_1(r,t)$ is the probability density of external neutrons of projectile taking into account their interaction with the target;

$\rho_1^{(0)}(r,t)$ is the probability density of external neutrons of projectile without taking into account their interaction with the target;

$U_{\mathrm{T}}(r)$ is mean field of the target nucleus for neutrons;

$N = 2$ is number of independent neutrons for ^{6}He ($\alpha + n + n$) & ^{9}Li (^{7}Li $+ n + n$).

This way one can take into account the effect of neutron rearrangement

Weight of diabatic correction to nuclear part of nucleus-nucleus potential

$$\mathrm{Re}\{V_{\mathrm{N}}(r)\} \equiv V(R, E_{\mathrm{lab}}) = \bar{V}(R) + \boxed{\eta_2(E_{\mathrm{lab}})\delta V_{\mathrm{d}}(R, E_{\mathrm{lab}})}$$

Diabatic correction

Weight of diabatic correction:

$$\eta_2(E_{\mathrm{lab}}) = \frac{1}{1 + \exp\left[\frac{1}{\alpha}\left(\langle \varepsilon_{\mathrm{kin}} \rangle - \left(\frac{E_{\mathrm{lab}}}{A}\right)\right)\right]}$$

$$\eta_2(E_{\mathrm{lab}}) \to 0, \quad \text{if} \quad \frac{\mathrm{v}_1}{\langle \mathrm{v} \rangle} << 1$$

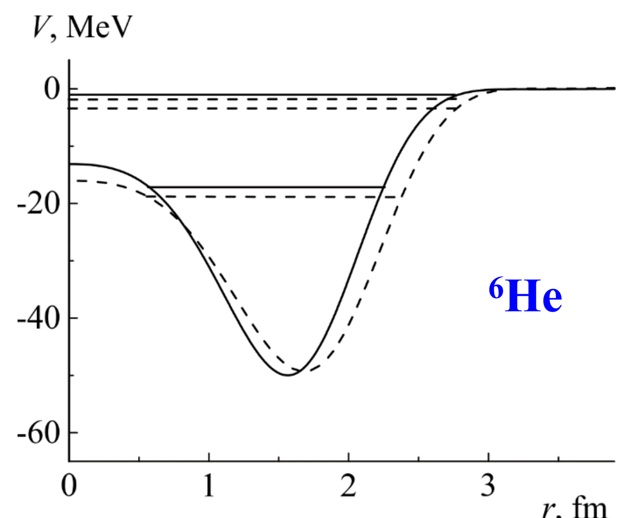
$$\eta_2(E_{\mathrm{lab}}) \to 1, \quad \text{if} \quad \frac{\mathrm{v}_1}{\langle \mathrm{v} \rangle} >> 1$$

average velocity of external neutron in projectile nucleus, determined from shell model:

$\langle \varepsilon_{\mathrm{kin}} \rangle \approx 10$ MeV,

$\alpha \sim 2$ MeV,

R is distance between centers of nuclei.



Weight of correction is determined by the ratio of velocity of projectile nucleus relative to target nucleus to average velocity of external neutrons in projectile nucleus

Energy-dependent potential of optical model

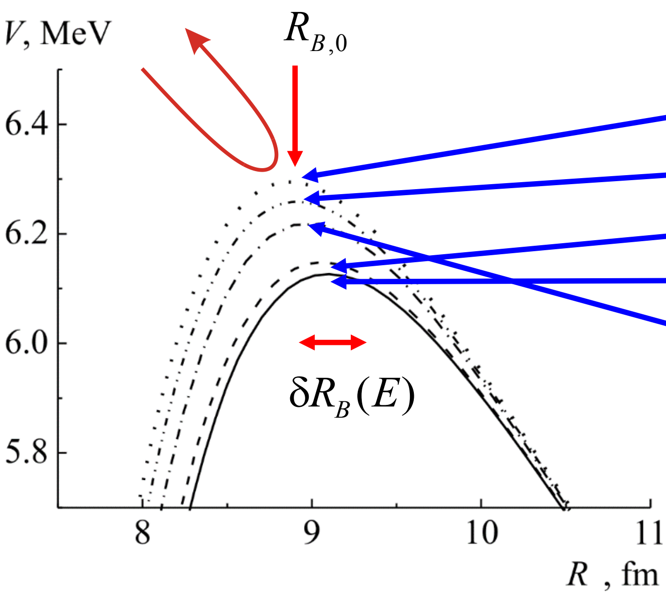
$$\mathrm{Re}\{V_{\mathrm{N}}(r)\} \equiv V(R, E_{\mathrm{lab}}) = \bar{V}(R) + \eta_2(E_{\mathrm{lab}})\delta V_{\mathrm{d}}(R, E_{\mathrm{lab}})$$

Change in the radius of the imaginary part was chosen to be proportional to the change in the position of the barrier of the real part (for example, as in [1]):

$$\mathrm{Im}\{V_{\mathrm{N}}(r)\} \equiv W(r) = \begin{cases} -W_1, r < R_b \\ W_1 \exp\left(-\frac{r - R_b}{b}\right), r \geq R_b \end{cases}$$

$$R_B(E) = R_{B,0} + \delta R_B(E), \quad R_b(E) = R_a + k\delta R_B(E),$$

where R_a and k are parameters.

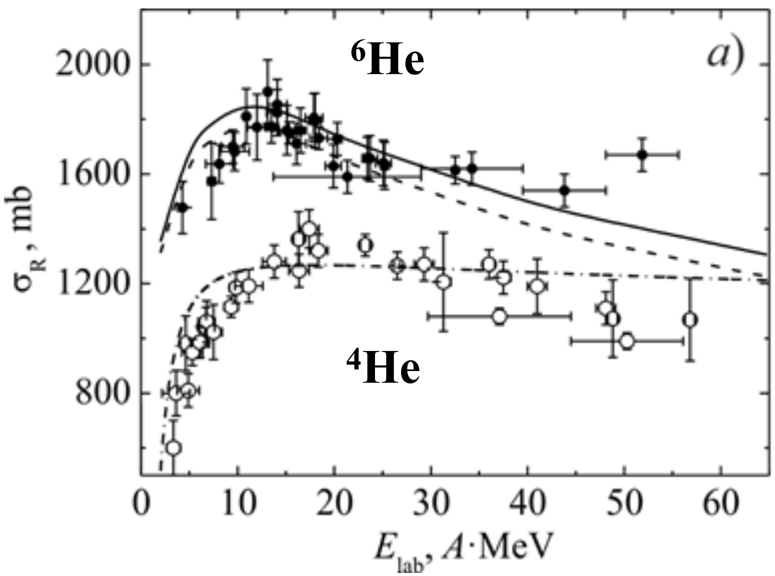


Change in the height and position of the barrier with increase of energy for $^{9}Li + ^{28}Si$, associated with the rearrangement of neutrons

With increasing energy, the barrier first decreases and shifts to the right, and then returns to the original energy-independent one

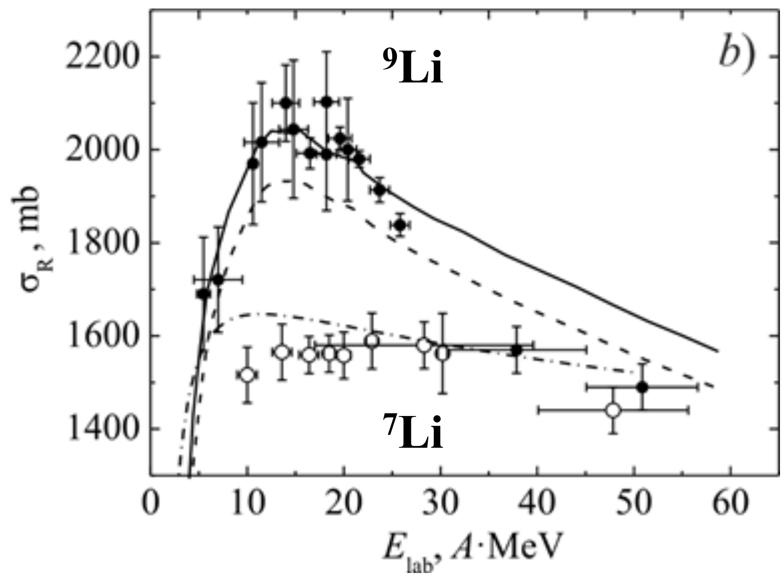
[1] Dymarz R., Molina J.L., Shitikova K.V., Z. Phys. A. 299, 245 (1981).

Results of calculation of total reaction cross sections



^{6}He vs. ^{4}He: geometric effect prevails

^{6}He + ^{28}Si: α= 1.8, W_1= 10 MeV, b = 1 fm, k = 2, R_a = 5.0 fm (solid line) and 4.8 fm (dashed line).



^{9}Li vs. ^{6,7}Li : dynamic effect prevails

^{9}Li + ^{28}Si: α= 1.8, W_1= 10 MeV, b = 1 fm, k = 2, R_a = 5.8 fm (solid line) and 5.6 fm (dashed line).

Good agreement with experimental data

Conclusion

- Physical mechanism is proposed that qualitatively explains the observed features of the total cross sections for the reactions $^{4,6}He + {}^{28}Si$ and $^{6,7,9}Li + {}^{28}Si$.

- Based on the solution of the time-dependent Schrödinger equation, an energy-dependent correction to the optical potential was calculated, which for the first time made it possible to obtain good agreement between the calculations and the experimental data on the total cross sections for these reactions.


Thank You