INVESTIGATION OF THE NUCLEAR REACTIONS RELEVANT FOR THERMONUCLEAR FUSION

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Exothermal nuclear reactions of interaction of particles with ^{6}Li and ^{7}Li nuclei are considered. It is shown that resonant mechanism of interaction is mainly connected with the dominant cluster structure of these nuclei. The main channels of light nuclei interaction are shown, their peculiarities are discussed, and reactions energies are given.

Introduction

^{6}Li and ^{7}Li nuclei are widely used in nuclear and thermonuclear power engineering. So, interaction of ^{6}Li and ^{7}Li nuclei with neutrons serves for recovery of tritium nuclei necessary for thermonuclear fusion (process of tritium-breading in lithium blanket):

$$n + {}^6Li \rightarrow t + \alpha + 4.78 \text{ MeV} \tag{1}$$

There exists a problem of absence of stable isotopes with mass number A=8 when one tries to explain nucleosynthesis in the Big Bang and that is why the Gamow mechanism of one-nucleon radiation capture (N,γ) does not “work”. Indeed, average lifetime of the main isotope ^{8}Be is short, of the order of 10^{-16}sec. However, in ^{7}Li(n,γ)^{8}Li process the nucleus ^{8}Li forms which lives about 1 sec. Further, there exist several possible channels leading to formation of stable nuclei with A=9. Particularly such a process is ^{8}Li(n,γ)^{9}Li with stable ^{9}Be nucleus formation as the result of β-decay.

^{6}Li and ^{7}Li nuclei have peculiar “cluster” structure. Because of the low binding energy of ^{6}Li in αd-channel ($\varepsilon_{\alpha d}$ = 1.475 MeV) and ^{7}Li in αt-channel ($\varepsilon_{\alpha t}$ =2.467 MeV) in the ground states wave functions of these nuclei there αd- and αt- components absolutely dominate respectively. The weight of these both components exceeds 90 %. Cluster structure of the lithium isotopes leads to the resonant nature of interaction of light particles with them. Indeed in the framework of cluster folding model the interaction potential of projectiles can be expressed via a sum of interactions with separate fragments of ^{6}Li and ^{7}Li nuclei, averaged by the ground states wave functions of these nuclei. At low energies αα, αt, αd, etc. interactions have resonant nature. These resonances in the subsystems appear in interactions of particles with the nuclei.

In figures 1 and 2 there are represented energy dependence of the elastic αt- и αd-scattering phases [1].

It is shown that *s*-phase of αt-scattering monotonically decreases as energy increasing; *d*-phase does not near change with an energy increase up to $E_{c.m.}$~10 MeV, and then monotonically decreases, this phase is split by the spin-orbital interaction; *p*-phase monotonically decreases with an energy increase and also is weakly split by the spin-orbital interaction.

Resonances appear in the places where phases pass through π/2, (3π/2). At zero energy the phases are normalized according to the generalized Levinson theorem:

$$\delta_\ell(0) - \delta_\ell(\infty) = (n + m)\pi, \tag{2}$$

here n – number of allowed bound states, m – number of forbidden bound states.

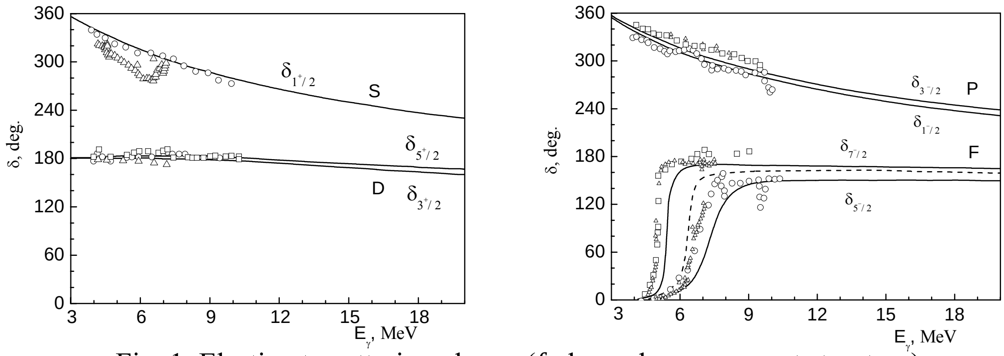


Fig. 1. Elastic αt-scattering phases (*f*-phases have resonant structure)

Energy behavior of *f*-phase denoted by dashed line in figure 1 shows that in α + t -system there appears a resonance.

In figure 2 there are represented energy dependences of the αd-scattering phases. Apparently the *d*-phases have resonant structure corresponding to the low levels $3^+, 2^+$ and 1^+ with isospin T=0 in the nucleus ^{6}Li what defines the nature of the energy dependence of cross sections of processes ^{6}Liγ→αd.

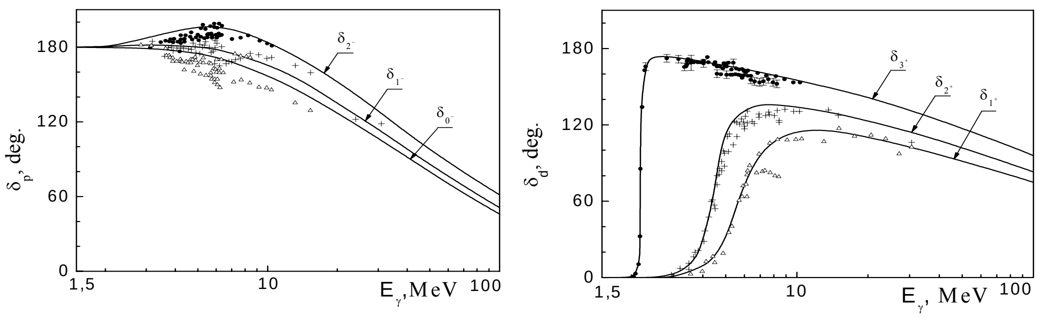


Fig. 2. Elastic αd-scattering phases (*d*-phases have resonant structure)

In αα-scattering there are observed 3 resonances for L=0, 2, 4 (Fig. 3) [2].

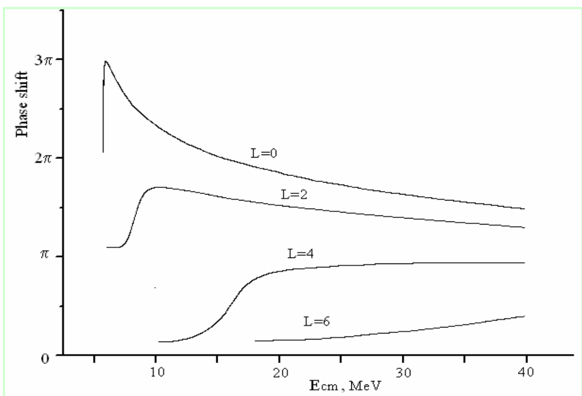


Fig. 3. αα-scattering phases (resonances for L=0,2,4)

Reactions mechanisms

Peculiar structure of lithium isotopes leads to the fact that there appear different mechanisms in an interaction of the nuclei with particles. Let us consider very important for the d^{6}Li-plasma capability estimation the reaction of tritium-breading from ^{6}Li:

$$d + {}^6\text{Li} \rightarrow p + t + \alpha, \quad Q = 2.56 \text{ MeV}. \tag{3}$$

Here three main mechanisms of the reaction are possible.

1. The mechanism of neutron pickup by incident deuteron (Fig. 4.a).

a - neutron pickup b - neutron stripping

Fig. 4. $d\,^6$Li reaction mechanisms

In the energy spectrum there must be observed strong (resonance) correlation. α-particle and proton energies are equal $\approx 1{,}5$ MeV.

2. The mechanism of neutron stripping with ^{7}Li nucleus excited states' formation with quantum numbers $J^\pi, T = 7/2^-, 1/2$ at the energy equal to 4.63 MeV (Fig. 4.b).

In this case there must be observed a pronounced correlation between α and t, and proton is slow (E_p □ $0{,}4$ МэВ).

3. The reaction of compound nucleus formation

$$d + {}^6\text{Li} \rightarrow {}^8\text{Be}^* \rightarrow \alpha + t + p. \tag{4}$$

The absence of energy correlations between separate products must be typical.

Thus in this example the indication to that or other mechanism of the process is a presence or an absence of energy correlations between separate products of the reaction.

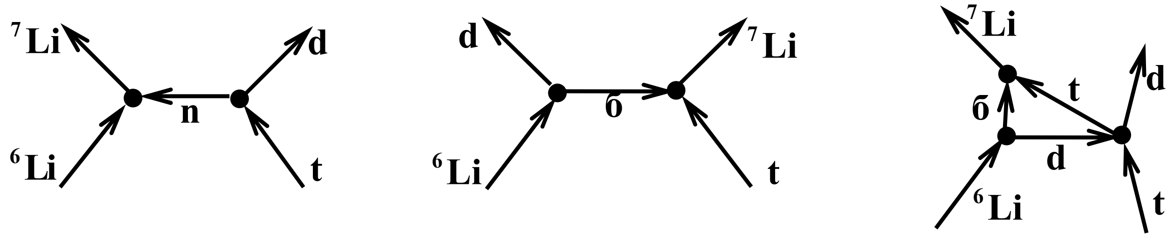
Manifestation of the reaction mechanisms in angular distributions

Especially obviously the characteristic mechanisms can appear in angular distributions of the products of two-particle reactions.

Let us consider the reaction ^{6}Li(t,d)^{7}Li. In figure 5 there are represented main mechanisms arising from angular distributions of the reaction (t,d) on ^{6}Li nucleus. It is well known that the polar mechanism of a neutron stripping (Fig. 5.a) gives main contribution to a deuteron yield on small angles, the triangular diagram of a deuteron knock-out (Fig. 5.c) gives main contribution to a deuteron yield on small and average angles, and the mechanism of a heavy particle stripping (Fig. 5.b) gives main contribution to the observable in the experiment cross section increase on large angles close to π (backward scattering).

It is worth to notice that diagrams calculation methods were developed by the soviet physicists I.S. Shapiro, L.D. Blokhintsev and others. Using light nuclei structure peculiarities and choosing the process kinematics one can separate different mechanisms of reaction.

It is obvious that if there appears one-particle (shell) aspect of nuclear wave function in reactions of one-nucleon stripping or pickup, then there appears other, cluster aspect in processes of “knock-out” or “heavy” stripping which connect with an exchange of the whole groups of nucleons.



a – polar mechanism of a neutron stripping; b – heavy stripping; c – triangular diagram of a deuteron knock-out

Fig. 5 – Main mechanisms in (t,d) reactions on $^{6}\mathrm{Li}$ nucleus

If we consider formation of ^{7}Li nucleus in the excited states in the reaction (t,d) on ^{6}Li nucleus then 2 close levels of ^{7}Li with $J^{\pi},T = 5/2^{-}, 1/2$ are of especial interest. One of them has a pronounced αt-cluster structure at energy $E_1 = 6.76$ MeV. The evidence of that is a large value of the spectroscopic factor (or reduced width) for triton yield for this level $S_t \approx 1$ [3]. At the same time nucleon width of this level is quite small. For the higher level $E_2 = 7.47$ MeV there is observed a reverse picture: the level is characterized by large value of neutron spectroscopic factor S_n and very small value for triton factor S_t. That is why if one fixes in an experiment the level of ^{7}Li at $E_2 = 7.47$ MeV, then the polar mechanism will dominate for it, and for the level $E_1 = 6.76$ MeV the mechanisms of heavy stripping and cluster knock-out will dominate.

It is also necessary to point out to great number of channels in an interaction of particles with lithium nuclei. So there are possible seven exothermal processes in the reaction d + ^{6}Li, and number of secondary reactions with energy release exceeds 80 [4]!

Discussion of the reactions interested

These reactions have a pronounced resonant nature [5, 6]. Detailed calculation of the reactions are shown in work [7]. Here we display the tables from [7] to make the discussion of the results comfortable.

In tables 1 and 2 there are represented experimental characteristics for the reactions considered and values of theoretically calculated total cross sections of scattering in resonances in lab. system, the order of the cross sections reaches millibarns (mb). For photonuclear processes the cross sections of the order of mikrobarns (μb) are typical, i.e. cross sections magnitudes are quite large.

^{11}B and ^{10}B nuclei have a peculiar structure. For them as for other strongly clusterized light nuclei as ^{6}Li, ^{7}Li, ^{8}Be, the cluster decay channels (α-particle) open firstly, and nucleon channels lie higher by energy [8, 9]. Since nuclear particles yield under action of strong (nuclear) interaction, then the partial decay widths for them are quite larger than the radiation ones. However for α-particles widths there are some peculiarities. So, spectroscopic factors for α-particle yield with formation of the ground states of daughter nuclei are strong suppressed for levels of “anomalous” parity , i.e. parity which opposite to the parity of the ground state of the nucleus.

Table 1 – experimental characteristics [8] and resonant γ-quanta formation cross sections in the reaction $^7Li(\alpha,\gamma)^{11}B$.

№	E_{res}, MeV $E_\alpha^{l.s.}$ ($E_\alpha^{c.m.}$)	$J_i^\pi;T \to J_f^\pi;T$, $E_i \to E_f$	Dominant transitions multipolarity	E_γ MeV	ω_γ eV	Γ_{total} eV	$\sigma_{reaction}$ μb
1	0.401 (0.255)	$5/2^- \to 3/2^-$ 8.920 → g.s.	E2, M1	8.920	$8.8\cdot10^{-3}$	4.37	$5.2\cdot10^3$
2	0.819 (0.518)	$7/2^+ \to 5/2^-$ 9.185 → 4.445	E1, M2	4.740	$3.1\cdot10^{-1}$	3	$1.3\cdot10^5$
3	0.819 (0.518)	$7/2^+ \to 3/2^-$ 9.185 → g.s.	M2, E3	9.185	$3.1\cdot10^{-3}$	3	$1.3\cdot10^3$
4	0.958 (0.607)	$5/2^+ \to 3/2^-$ 9.275 → g.s.	E1, M2	9.275	$2.9\cdot10^{-1}$	$4\cdot10^3$	$7.7\cdot10^1$
5	0.958 (0.607)	$5/2^+ \to 5/2^-$ 9.275 → 4.445	E1, M2	4.835	1.2	$4\cdot10^3$	$3.21\cdot10^2$

Table 2 – experimental characteristics [9] and resonant γ-quanta formation cross sections in the reaction $^6Li(\alpha,\gamma)^{10}B$.

№	E_{res}, MeV $E_\alpha^{l.s.}$ ($E_\alpha^{c.m.}$)	$J_i^\pi;T \to J_f^\pi;T$, $E_i \to E_f$	Dominant transitions multipolarity	E_γ MeV	ω_γ eV	Γ_{total} eV	$\sigma_{reaction}$ μb
1	1.085 (0.651)	$2^-; 0 \to 3^+; 0$ 5.1103 → g.s.	E1	5.1103	$5.9\cdot10^{-2}$	$1.63\cdot10^3$	$3.6\cdot10^1$
2	1.173 (0.704)	$2^+; 1 \to 3^+; 0$ 5.1639 → g.s.	M1	5.1639	$1.8\cdot10^{-2}$	2.868	$5.78\cdot10^3$
3	2.433 (1.459)	$2^+; 0 \to 3^+; 0$ 5.9195 → g.s.	M1	5.9195	$1.9\cdot10^{-1}$	$1\cdot10^4$	8.42
4	2.609 (1.565)	$4^+; 0 \to 3^+; 0$ 6.0250 → g.s.	M1	6.0250	$3.4\cdot10^{-1}$	$8\cdot10^1$	$1.758\cdot10^3$
5	4.022 (2.413)	$1^-; 0+1 \to 3^+; 0$ 6.873 → g.s.	M2	6.873	$4.8\cdot10^{-1}$	$2\cdot10^5$	$6.45\cdot10^{-1}$

In case of ^{11}B nuclei the "anomalous" levels are the levels of positive parity because the ground state of the nucleus has quantum numbers $3/2^-$. That is why for separate levels of positive parity lying not very high over threshold (and widths for particles yield depend on transition energy) the partial widths Γ_α turn out to be small and comparable by magnitude with radiation widths Γ_γ. This leads to anomalous large cross sections for definite energy γ-quanta yield. For example, for the reaction $^7Li(\alpha,\gamma)^{11}B$ such cases of cross sections increase are observed for 3 near-threshold resonant states with quantum numbers $J^\pi = 5/2^-$ at energy E=8.920 MeV, $J^\pi = 7/2^+$ at energy E=9.185 MeV and $J^\pi = 5/2^+$ at energy E=9.275 MeV [9, 10, 11].

Reactions analysis on the base of Breit-Wigner formula for a single resonance shows that the necessary conditions for large value of the cross sections for high energy γ-quanta yield in such processes must be large threshold for inverse reactions of photodisintegration and at the same time for compound nucleus levels the total widths Γ must be small and comparable with radiation ones – only one channel for α -particle yield must be open for it. For the reaction $^7Li(\alpha,\gamma)^{11}B$ the inverse reaction of photodisintegration has quite high threshold value Q = 8.665 MeV. Small α -widths are the result as of small energy of yielding α -particles at resonant levels decay so of prohibition for their yield because of definite shell structure of the states. Calculations carried out show that cross sections for γ -quanta yield with energies E_γ = 8.920, 9.185 and 9.275 MeV with formation of the ground state of the nucleus ^{11}B and energies 4.740 and 4.835 MeV with formation of the excited state of the nucleus at energy 4.445 MeV turn out to be large and reach order of millibarns. For the reaction $^6Li(\alpha,\gamma)^{10}B$ the cross sections for γ-quanta yield with energies E_γ = 5.1639, 5.9195, 6.025, 5.1103 and 6.873 MeV with formation of the ground state of the nucleus ^{10}B also reach order of millibarns (table 2).

There were used modern data for ^{11}B и ^{10}B nuclei [8, 9] in the calculations differing from used in work [11].

As it is clear from the table 1 for the low level with E=8.920 MeV by quantum selection rules the dominant transitions are E2- and M1-multipolarities. From table 1 it is clear that the transitions resonances strengths ω_γ connected with the magnitude of radiation width when electric dipole transitions are impossible (first and third cases in table 1) turn out to be twice smaller than in other three cases when E1-decays are allowed. The peculiarity of γ-transition from the level with E=8.920 MeV to the ground state of ^{11}B ($5/2^- \rightarrow 3/2^-$) is a small partial α -width Γ_α. In this case the total width of the level which is equal to a sum $\Gamma_\gamma + \Gamma_\alpha = \Gamma_{total}$=4.37 eV practically coincides with the radiation one Γ_γ. In the framework of the shell model $\Gamma_\alpha \approx$0.006 eV. Smallness of the partial width for the mentioned transition is connected with a smallness of proportional to it spectroscopic factor for this transition. As the calculations in the many particle shell model show [3] for this level of the nucleus ^{11}B the main components of the wave function have Young schemes characterizing permutable symmetry of the nuclear wave function in the form $[4421]$. The wave function of the ground state of the nucleus ^7Li has Young scheme in the form $[43]$. By quantum selection rules α -particles yield (having Young scheme $[4]$) from states with Young scheme $[4421]$ of the nucleus ^{11}B to the ground state of the nucleus ^7Li turns out to be forbidden and the transition is possible only because of the wave function components having small weight, and this leads to the smallness of the spectroscopic factor and ultima analysi of the partial α -particle width. Cross section for γ -quanta yield with energy E=8.920 MeV turns out to be quite large and equal to σ =8.1mb in c.m. system. More intensive is a transition from the level E=9.185 MeV to the level E=4.445 MeV ($7/2^+ \rightarrow 5/2^-$). In this case by quantum selection rules for angular momentum the dipole transition to the ground state is not possible. Smallness of the total width of the level which is equal approximately 3 eV leads to large value of cross section of the process equal $\sigma = 2.05 \cdot 10^2$ mb in c.m. system for photon yield with energy E_γ=4.445 MeV. Because of smallness of the total width of the level (the same 3 eV) in spite of small value of radiation width for the transition to the ground state of the nucleus ^{11}B – radiation width Γ_γ to the ground state is about 90 times smaller in comparison with the corresponding width to the level 4.445 MeV, considered above, the cross section for γ -quanta yield with energy E_γ =9.185 MeV is also not small – σ =2.05 mb.

The next considered level with quantum numbers $5/2^+$ with energy 9.275 MeV at γ -decay to the ground and excited states with energy 4.445 MeV leads to appearance of resonant photons with energy E_γ =9.275 MeV and E_γ =4.835 MeV respectively.

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ТЕРМОЯДРОЛЫҚ СИНТЕЗ ҮШІН МАҢЫЗДЫ ЯДРОЛЫҚ РЕАКЦИЯЛАРДЫ ЗЕРТТЕУ

Р.С. Қабатаева

^{6}Li және ^{7}Li изотоптарының бөлшектермен әрекеттесу ядролық экзотермалық реакциялары қарастырылды. Әрекеттесудің резонанстық механизмі көбінде осы ядролардың доминанттық кластерлік құрылымымен байланысты екендігі көрсетілді. Жеңіл бөлшектердің әрекеттесу негізгі каналдары келтірілген, олардың ерекшеліктері талқыланды, реакциялар энергиялары келтірілген.

ИССЛЕДОВАНИЕ ЯДЕРНЫХ РЕАКЦИЙ АКТУАЛЬНЫХ ДЛЯ ТЕРМОЯДЕРНОГО СИНТЕЗА

Р.С. Кабатаева

Рассмотрены экзотермические ядерные реакции взаимодействия частиц с изотопами ^{6}Li и ^{7}Li. Показано, что резонансный механизм взаимодействия во многом связан с доминирующей кластерной структурой этих ядер. Приведены основные каналы взаимодействия легких частиц, обсуждаются их особенности, даны энергии реакций.