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# RADIATIVE TRITIUM CAPTURE ON $^3$He AT LOW AND ASTROPHYSICAL ENERGIES

**Abstract.** The radiative tritium capture on $^3$He at low and astrophysical energies was considered in the framework of the modified potential cluster model. It is shown that on the basis of potentials coincided with scattering phase shifts and the energy of bound state it is possible to correctly represent available experimental data. The two-cluster potential model described in this paper, used intercluster forces with forbidden states, in many cases, allow one correctly to describe some nuclear characteristics for different light and lightest nuclei, and, evidently do not yet exhaust completely their potential. The more especially as reported here methods and results are applicable to certain problems of nuclear astrophysics, concerned to light atomic nuclei and ultralow energies of interacting particles. In other words, these results have direct relationship to thermonuclear processes flowing in the Sun, stars, some other objects of our Universe and Universe in whole, at different stages of its forming and developing. It is possible to use one channel cluster model, which, in more cases, is a good approach to the real existent situation. Such model allows relatively easy to carry out any calculations of nuclear characteristics in scattering processes and bound states, even in that systems, where solving methods of many-body problem either very cumbersome in numerical implementation or do not lead to the concrete quantitative results at all.

**Key words:** Nuclear astrophysics; primordial nucleosynthesis; light atomic nuclei; radiative capture; thermonuclear processes; potential cluster model.

## 1. Introduction

The structure of atomic nucleus is very multiform and occasionally discover, as seems, alternative properties. For example, properties of nucleon independent motion, collective demonstration of degree of freedom, association of nucleons into almost independent groups – clusters with characteristics close to properties of correspondent free nuclei can realize in nucleus. Earlier available ideas about permanently existent clusters in nuclei change to the conception that in the process of almost independent motion of nucleons in nucleus such virtual sub-systems as clusters are formed and destroyed. Therefore, it is possible to say only about probability of existence one or another cluster channel in the atomic nucleus [1,2].

However, if this probability is relatively large, it is possible to use one channel cluster model, which, in more cases, is a good approach to the real existent situation. Such model allows relatively easy to carry out any calculations of nuclear characteristics in scattering processes and bound states, even in that systems, where solving methods of many-body problem either very cumbersome in numerical implementation or do not lead to the concrete quantitative results at all.

Certainly, two-body presentation is a certain idealization for really existent situation in nucleus, i.e. suppose that the bound state has the big degree of clusterization for particles of the initial channel. Therefore, the success of this potential model for description of the system of $A$ nucleons in the bound state is determined by the fact how much is the real clusterization of this nucleus in the channel of $A_1 + A_2$

nucleons. At the same time, some nuclear characteristics of individual, even not cluster, nuclei can be predominantly determined by one cluster channel, i.e. to have certain cluster structure at the small contribution of other possible cluster configurations. In this case, the used single-channel cluster model allows one to identify dominating cluster channel, mark and describe that properties of the nuclear system, which is possible to consider as a certain test of single-channel cluster configurations in such nuclei.

Different options of three-body models have intensively developed and purchased big extension in the end of the past century, which were used, for example, for $^6$Li in the three-cluster np$^4$He channel that allow one correctly to describe many properties of this nucleus [3]. The large success was achieved in the microscopic models like resonating group method (RGM) [4], based on the nucleon-nucleon interactions with the evident extraction of cluster channels.

However, the described above two-cluster potential models described above, used intercluster forces with forbidden states, in many cases, allow one correctly to describe some nuclear characteristics for different light and lightest nuclei, and, evidently do not yet exhaust completely their potential. The more especially as reported here methods and results are applicable to certain problems of nuclear astrophysics, concerned to light atomic nuclei and ultralow energies of interacting particles. In other words, these results have direct relationship to thermonuclear processes flowing in the Sun, stars, some other objects of our Universe and Universe in whole, at different stages of its forming and developing.

## 2. Interaction potentials and scattering phase shifts

The orbital states in the $^3$He$^3$H system for $^6$Li are pure by Young diagrams [5]. Therefore, potentials obtained on the basis of the scattering phase shifts are possible to use directly for considering characteristics of bound states of these nuclei. Results will depend on the clusterization degree of nuclei in the considered cluster channels. Because, the probability of clusterization lithium nuclei is relatively high, then the calculation results should generally reproduce experimental data.

The Gaussian form is used for potentials

$$V(r) = V_0 \exp(-\alpha r^2) + V_c(r) \tag{1}$$

with the point-like Coulomb term. Interaction parameters for pure cluster states in $^6$Li nucleus, obtained in [6,7], are given in Table 1. In the $^3$He$^3$H system at $S = 0$ for $D$ and $F$ phase shifts the same potentials are used that for the $S$ and $P$ waves correspondingly.

Table 1 - Potential parameters in the $^3$He$^3$H system [1,2]. $R_c = 0$ fm for the $^3$He$^3$H system

| | $S = 1$ | | $S = 0$ | |
|---|---|---|---|---|
| $L_J$ | $V_0$, (MeV) | $\alpha$ (fm$^{-2}$) | $V_0$, (MeV) | $\alpha$ (fm$^{-2}$) |
| $S$ | –90 | 0.18 | –85.0 | 0.18 |
| $P_0$ | –52.5 | 0.2 | – | – |
| $P_1$ | –65.0 | 0.2 | –74.0 | 0.2 |
| $P_2$ | –80.0 | 0.2 | – | – |
| $D_1$ | –72.0 | 0.18 | – | – |
| $D_2$ | –85.0 | 0.18 | – | – |
| $D_3$ | –90.0 | 0.18 | – | – |

Due to the absence of the experimental results, the potentials for the $^3$He$^3$He system are constructed exclusively on results of the calculation of phase shifts, obtained in the RGM [8,9]. Parameters of such interactions coincide with potentials of the $^3$He$^3$He system at $S = 0$. There fore, $^3$He$^3$He it is a system of identical particles, here even $L$ correspond to zero spin, and odd to unit spin.

The quality of the phase shift description is shown in figure 1 with experimental data from woks [10–13] for $^4$He$^2$H, [14–16] for $^4$He$^3$H and [17,18] for $^3$He$^3$H systems. The calculation results of the $^3$He$^3$He elastic scattering phase shifts obtained in the RGM [19] are shown by crosses in figure 1.

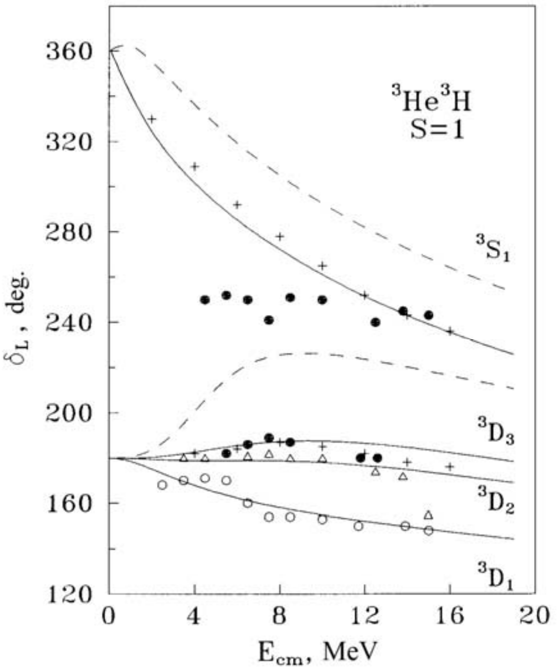

Figure 1a - Phase shifts of the $^3$He$^3$H scattering. Curves are calculations for potentials with parameters from table 1. Points, triangles and circles are experimental data from [17,18]. Crosses are RGM calculations from [19]

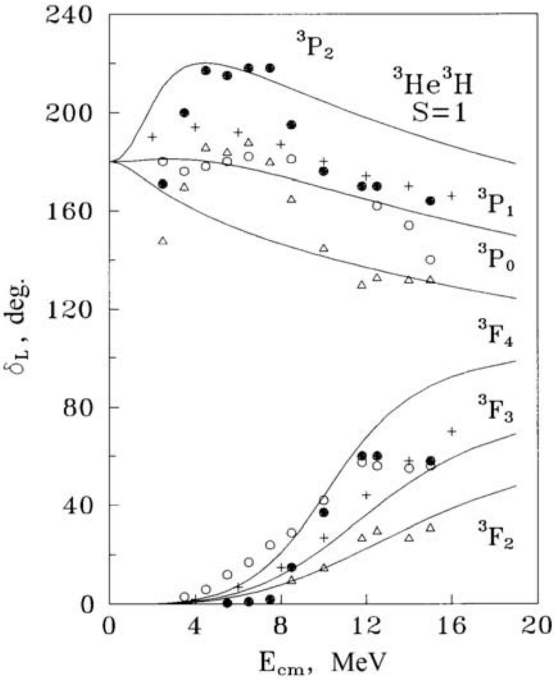

Figure 1b - Phase shifts of the $^3$He$^3$H scattering. Curves are calculations for potentials with parameters from table 1. Points, triangles and circles are experimental data from [17,18]. Crosses are RGM calculations from [19]

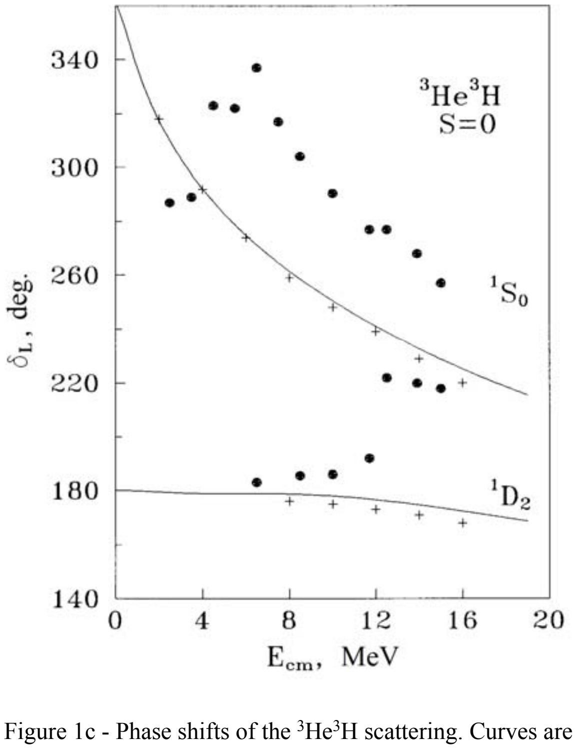

Figure 1c - Phase shifts of the $^3$He$^3$H scattering. Curves are calculations for potentials with parameters from table 1. Points are experimental data from [17,18]. Crosses are RGM calculations from [19]

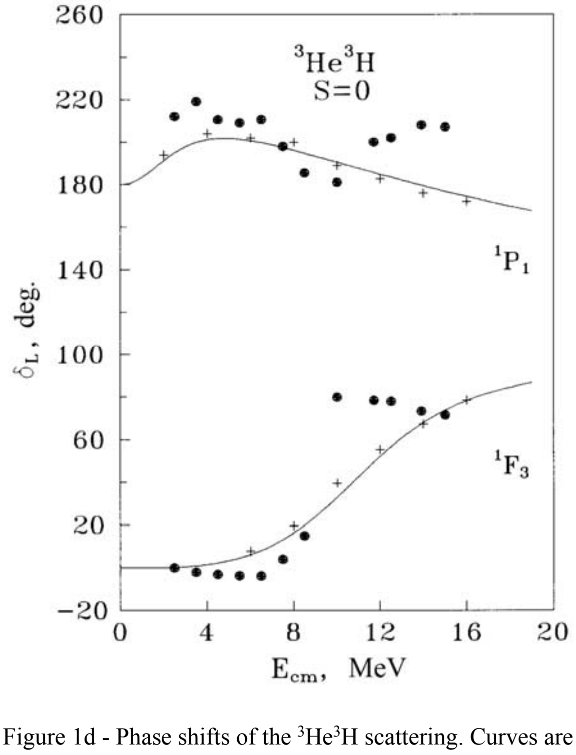

Figure 1d - Phase shifts of the $^3$He$^3$H scattering. Curves are calculations for potentials with parameters from table 1. Points are experimental data from [17,18]. Crosses are RGM calculations from [19]

### 3. Total capture cross sections

Using the known equations for matrix elements of different operators, given in [20], one can obtain the final expression [7] for the total capture cross section

$$\sigma_c(NJ,J_f)=\frac{8\pi Ke^2}{\hbar^2 q^3}\frac{\mu}{(2S_1+1)(2S_2+1)}\frac{J+1}{J[(2J+1)!!]^2}A_J^2(NJ,K)\cdot$$

$$\cdot\sum_{L_i,J_i}P_J^2(NJ,J_f,J_i)I_J^2(J_f,J_i), \qquad (2)$$

where matrix elements of $EJ$ transitions have the form

$$P_J^2(EJ,J_f,J_i)=\delta_{S_iS_f}[(2J+1)(2L_i+1)(2J_i+1)(2J_f+1)](L_i0J0\,|\,L_f0)^2\begin{Bmatrix}L_i & S & J_i\\ J_f & J & L_f\end{Bmatrix}^2 \qquad (3)$$

$$A_J(EJ,K)=K^J\mu^J\left(\frac{Z_1}{m_1^J}+(-1)^J\frac{Z_2}{m_2^J}\right),\ I_J(J_f,J_i)=\left\langle\chi_f\left|r^J\right|\chi_i\right\rangle.$$

In the case of $E1$ capture in the $^3$He$^3$H cluster channel to the ground state (GS) of $^6$Li the $P_J$ value is presented in the form

$$P_J^2=2J_i+1, \qquad (4)$$

if the capture is to the GS from the scattering states with $L = 2$ and $J_i = 1,2,3$ for the initial states with $J_i = 0,1,2$ and $L = 1$. In the $^3$He$^3$H cluster model it is possible also to consider $E1$ transition to the $3^+$ resonance state. In this case the $P_J$ value is listed in Table 2. Parameters of the $^3$He$^3$H potentials taken into account spin-orbital splitting are given in Table 1.

Table 2 - Coefficients $P_J$ in the $^3$He$^3$H cluster channel of $^6$Li nucleus

| $^3$He$^3$H ($3^+$) | |
|---|---|
| $L_J$ | $P_J(E1)$ |
| $^3P_2$ | 42/5 |
| $^3F_2$ | 1/35 |
| $^3F_3$ | 1 |
| $^3F_4$ | 81/7 |

Calculation results for the total capture cross section with the $S$ potential, correctly describing binding energy of the nucleus (see sec. 3), are shown in figure 4a by the solid line [7]. Experimental data are from [21,22]. It is seen that using this potential and $P$ interaction, correctly representing energy behavior of scattering phase shifts, allows one to describe experimental results well. Note that there are other measurements of cross sections [23], noticeably differ from reproduced in the figure.

In the case of $M1$ transitions to the GS, the process when the change of the spin state from singlet to triplet takes place was considered. Only the spin term $W_{Jm}(S)$ with coefficient $-\sqrt{3/2}$ remains in the transition operator. $P_J$ is found from (3) for $E2$ transitions to the GS from the $D$ wave with $J_i = 1, 2, 3$. Results of these calculations are shown in figure 2a by the dotted and dashed curves [7].

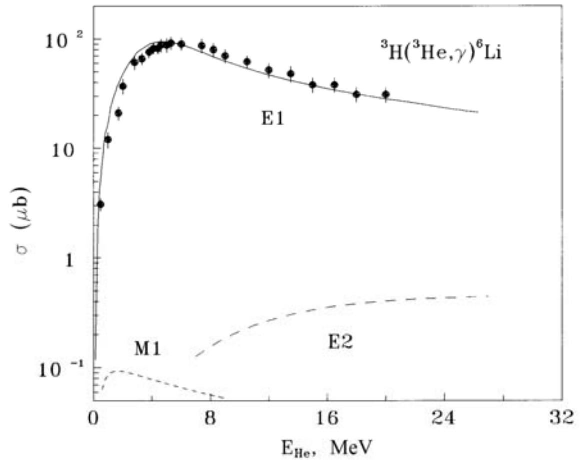

Figure 2a - The total cross section of the radiative tritium capture on $^3$He with the formation of $^6$Li in the GS. Solid curve is the calculated *E*1 cross sections for scattering potentials from Table 1. Dotted curve is the cross section of the *M*1 process, dashed curve is the *E*2 cross section. Points are experimental data from [21,22]

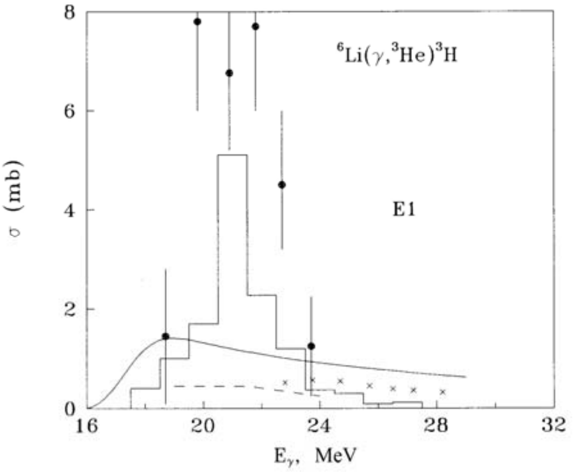

Figure 2b - The total cross section of the photodisintegration process of $^6$Li. Solid curve is the cross section obtained on the basis of detailed balancing principle from the calculated capture cross sections [7]. Points, histogram, dashed curve and crosses are experimental data from [24–27]

Differences in total experimental cross sections for the $^6$Li(γ,$^3$He)$^3$H photodisintegration is more than in the case of radiative capture. The measurements results obtained in [24–27] are shown in Fig. 3b. The solid figure shows the results obtained on the basis of detailed balancing principle from the calculating capture cross sections [7].

The astrophysical *S*-factor for the $^3$H($^3$He,γ)$^6$Li capture at low energies is shown in Fig. 3a. The value equals 0.06 keV·b was obtained by the linear extrapolation of the *S*-factor at zero energy in the *E*1 process.

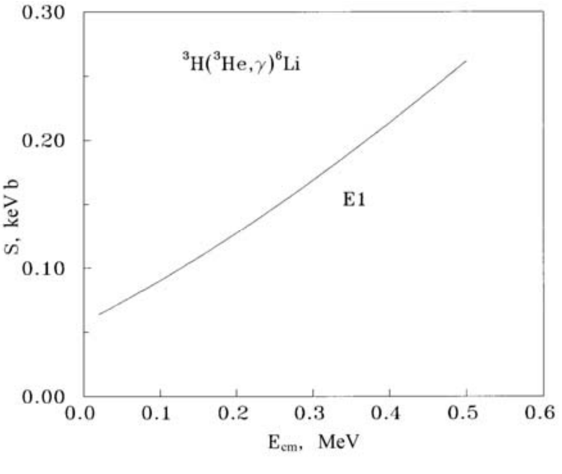

Figure 3a - Astrophysical *S*-factor for the *E*1 process at the $^3$H($^3$He,γ)$^6$Li capture [7].

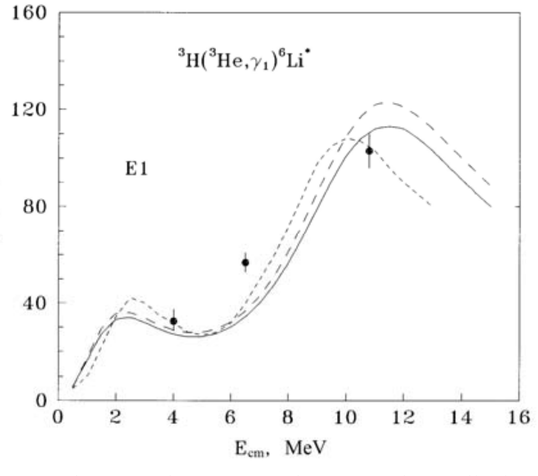

Figure 3b - Total cross sections for the radiative capture process in the $^3$He$^3$H channel with the formation of the $^6$Li nucleus in the excited $3^+$ state. Points are experimental data from [28]

The calculation results of capture cross sections to the $3^+$ level for potentials from Table 1 [7] together with data and computations (dotted curve), obtained in [28], are shown in Fig. 3b. The potentials of the $D_3$ bound state with the depth 105 MeV (solid curve) and 107.5 MeV (dashed curve) are used here, which were discussed in sec. 3.

## 4. Conclusion

The radiative tritium capture on $^3$He at low and astrophysical energies was considered in the framework of the modified potential cluster model. It is shown that on the basis of potentials coincided with scattering phase shifts and the energy of bound state it is possible to correctly represent available experimental data.

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## ТӨМЕНГІ ЖӘНЕ АСТРОФИЗИКАЛЫҚ ЭНЕРГИЯЛАРДАҒЫ РАДИАЦИЯЛЫҚ $^3$He$^3$H ҚАРМАУ

**Аннотация.** Модификацияланған потенциалды кластерлік модель аясында төменгі және астрофизикалық энергиялардағы радиациялық $^3$He$^3$H қармау қарастырылған. Шашырату кезеңдері және байланысқан энергия күйімен үйлестірілген потенциалдар негізінде алынған эксперименттік мәліметтерді дұрыс жіберуге болатындығы көрсетілген. Мақалада сипатталып отырған, тиым салынған кластерлераралық күшті пайдаланатын, екікластерлі потенциалдық моделдер, көп жағдайда, әр түрлі жеңіл және өте жеңіл ядролардың кейбір ядролық сипаттамаларын дұрыс көрсете білуге мүмкіндік береді және өзінің мүмкіндіктерін әлі толық тауыса қоймаған секілді. Мұнда көрсетіліп отырған әдістер мен нәтижелерді, жеңіл атомдық ядролар мен бөлшектер өзарабайланысының өте төмен энергияларына қатысы бар ядролық астрофизиканың кейбір мәселелерін шешуде қолдануға болады. Басқаша айтқанда, бұл нәтижелердің Күнде, жұлдыздарда, Ғаламның басқа да кейбір нысандарында, бүкіл Ғаламның түрлі қалыптасу кезеңдері мен дамуына қатысты өтетін термоядролық үдерістерге тікелей қатысы бар. Бір арналы кластерлік модельді пайдалануға болады, ол көптеген жағдайларда нақты жағдайға жақсы жақындайды. Мұндай модель шашырау процестері мен байланысты жағдайлардағы, тіпті көптеген денелердің есебін шешу әдістері немесе сандық орындаудағы өте ауқымды немесе нақты сандық нәтижелерге әкелмейтін жүйелерде де Ядролық сипаттамалардың кез келген есебін салыстырмалы түрде оңай орындауға мүмкіндік береді. Атом ядросының құрылымы алуан түрлі және кейде бір бірін жоққа шығаратын құрылымдар табылады. Мысалы, ядрода нуклондардың тәуелсіз қозғалысы, еркіндік дәрежелерінің бірлестігінің көрінісі, ұқсас бос ядролардың құрылымдарының кластерлеріне - ұқсас нуклондардың дербес топтарға бөлінуі мүмкін. Бұған дейінгі ядродағы тұрақты кластерлер ұғымы тәуелсіз нуклондар қозғалысы кезінде ядрода виртуалды жүйе бөлігі – кластерлер пайда болады және бүлінеді деген ұғымға ауысты. Сондықтан, атомдық ядродағы әйтеуір бір кластерлік каналдың бар екендіні туралы ғана айтуға болады. Әрине, екіге бөлінген түсінік ядрода болып жатқан жағдайдың анық мінсіз күйі болып табылады, себебі, бастапқы каналдың бөлшектері үшін кластерлендірудің үлкен дәрежесіне ие деп болжам жасалуда. Сондықтан мұндай потенциалды үлгінің жетістігі байланған күйдегі $A$ нуклондардың жүйесін сипаттауда нуклондардың $A_1$ + $A_2$ каналындағы осы ядроның шынайы кластерлендірілуі қаншалықты үлген екендігімен анықталады. Сонымен қатар, кейбір кластерлік емес дербес ядролардың сипаттамалары бір анықталған кластерлік каналмен айрықша шарттасуы мүмкін, яғни басқа да мүмкін кластерлік конфигурацияны қосқанда анық кластерлік құрылымға ие болу. Бұл жағдайда пайдаланылып отырған бір каналды кластерлік модель басымдық көрсететін кластерлік каналды теңдестіруге, шарттасқан ядролық жүйенің құрылымын ерекшелеуге және сипаттауға мүмкіндік береді. Сондықтан, бір каналды модельде алынған нәтижелерді осындай ядролардағы кластерлі конфигурацияның бір каналдылығының тесті ретінде қарастыруға болады.

**Түйін сөздер:** ядролық астрофизика; бастапқы нюклеосинтез; жеңіл атомдық ядролар; радиациялық қармау; жылуядролық үдерістер; потенциалды кластерлік модель.

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## РАДИАЦИОННЫЙ $^3$He$^3$H ЗАХВАТ ПРИ НИЗКИХ И АСТРОФИЗИЧЕСКИХ ЭНЕРГИЯХ

**Аннотация.** В рамках модифицированной потенциальной кластерной модели рассмотрен радиационный $^3$He$^3$H захват при низких и астрофизических энергиях. Показано, что на основе потенциалов, которые согласованы с фазами рассеяния и энергией связанного состояния удается правильно передать имеющиеся экспериментальные данные. Двухкластерные потенциальные модели, описанные в данной статье, использующие межкластерные силы с запрещенными состояниями, во многих случаях, позволяют правильно описывать некоторые ядерные характеристики для самых различных легких и легчайших ядер и, по-видимому, не исчерпали еще полностью свои возможности. Тем более, что изложенные здесь методы и результаты применимы к некоторым задачам ядерной астрофизики, имеющим отношение к легким атомным ядрам и сверхнизким энергиям взаимодействия частиц. Иначе говоря, эти результаты имеют непосредственное отношение к термоядерным процессам, протекающим на Солнце, звездах, некоторых других объектах нашей Вселенной и Вселенной в целом на различных этапах ее формирования и развития. Можно использовать одноканальную кластерную модель, которая во многих случаях оказывается хорошим приближением к реально существующей ситуации. Подобная модель позволяет сравнительно легко выполнять любые расчеты ядерных характеристик в процессах рассеяния и связанных состояниях, даже в тех системах, где методы решения задачи многих тел или очень громоздки в численном исполнении или вообще не приводят к конкретным количественным результатам. Структура атомного ядра очень многообразна и порой обнаруживает, казалось бы, взаимоисключающие свойства. Например, в ядре могут реализоваться свойства независимого движения нуклонов, коллективные проявления степеней свободы, ассоциирование нуклонов в почти независимые группы – кластеры с характеристиками, близкими к свойствам соответствующих свободных ядер. Ранее существовавшие представления о стабильно существующих в ядре кластерах заменились на понимание, что в процессе почти независимого движения нуклонов в ядре формируются и разрушаются виртуальные подсистемы – кластеры. Поэтому можно говорить лишь о вероятности существования в атомном ядре того или иного кластерного канала. Конечно, двухчастичное представление является определенной идеализацией реально существующей в ядре ситуации, т.к. предполагает, что связанное состояние имеет большую степень кластеризации для частиц начального канала. Поэтому успех данной потенциальной модели при описании системы из $A$ нуклонов в связанном состоянии определяется тем, насколько велика реальная кластеризация этого ядра в канале $A_1 + A_2$ нуклонов. В то же время, некоторые ядерные характеристики отдельных, даже не кластерных ядер могут быть преимущественно обусловлены одним определенным кластерным каналом, т.е. иметь определенную кластерную структуру при малом вкладе других возможных кластерных конфигураций. В этом случае используемая одноканальная кластерная модель позволяет идентифицировать доминирующий кластерный канал, выделить и описать те свойства ядерной системы, которые им обусловлены. Поэтому результаты, получаемые в одноканальной модели, можно рассматривать как некоторый тест одноканальности кластерных конфигураций в таких ядрах.

**Ключевые слова:** ядерная астрофизика; первичный нюклеосинтез; легкие атомные ядра; радиационный захват; термоядерные процессы; потенциальная кластерная модель.

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