ISSN 2518-1726 (Online),
ISSN 1991-346X (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ
әл-Фараби атындағы Қазақ ұлттық университетінің

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
Казахский национальный университет
имени аль-Фараби

NEWS

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN
al-Farabi Kazakh National University

SERIES
PHYSICO-MATHEMATICAL

4 (338)

JULY – AUGUST 2021

PUBLISHED SINCE JANUARY 1963

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

NAS RK is pleased to announce that News of NAS RK. Series physico-mathematical journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of chemistry and technologies in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of chemical sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Физикалық-математикалық сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын усынады. ҚР ҰҒА Хабарлары. Химия және технология сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді химиялық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия физико-математическая» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по химическим наукам для нашего сообщества.

Бас редактор:

МҰТАНОВ Ғалымқайыр Мұтанұлы, техника ғылымдарының докторы, профессор, ҚР ҰҒА академигі, ҚР БҒМ ҒК «Ақпараттық және есептеу технологиялары институты» бас директорының м.а. (Алматы, Қазақстан) H=5

Редакция алқасы:

ҚАЛИМОЛДАЕВ Мақсат Нұрәділұлы (бас редактордың орынбасары), физика-математика ғылымдарының докторы, профессор, ҚР ҰҒА академигі, ҚР БҒМ ҒК «Ақпараттық және есептеу технологиялары институты» бас директорының кеңесшісі, зертхана меңгерушісі (Алматы, Қазақстан) H=7

БАЙГУНЧЕКОВ Жұмаділ Жаңабайұлы (бас редактордың орынбасары), техника ғылымдарының докторы, профессор, ҚР ҰҒА академигі, Кибернетика және ақпараттық технологиялар институты, Сатпаев университетінің Қолданбалы механика және инженерлік графика кафедрасы, (Алматы, Қазақстан) H=3

ВОЙЧИК Вальдемар, техника ғылымдарының докторы (физика), Люблин технологиялық университетінің профессоры (Люблин, Польша) H=23

БОШКАЕВ Қуантай Авғазыұлы, Ph.D. Теориялық және ядролық физика кафедрасының доценті, әл-Фараби атындағы Қазақ ұлттық университеті (Алматы, Қазақстан) H-10

QUEVEDO Hemando, профессор, Ядролық ғылымдар институты (Мехико, Мексика) H=28

ЖҮСІПОВ Марат Абжанұлы, физика-математика ғылымдарының докторы, теориялық және ядролық физика кафедрасының профессоры, әл-Фараби атындағы Қазақ ұлттық университеті (Алматы, Қазақстан) H=7

КОВАЛЕВ Александр Михайлович, физика-математика ғылымдарының докторы, Украина ҰҒА академигі, Қолданбалы математика және механика институты (Донецк, Украина) H=5

МИХАЛЕВИЧ Александр Александрович, техника ғылымдарының докторы, профессор, Беларусь ҰҒА академигі (Минск, Беларусь) H=2

РАМАЗАНОВ Тілекқабыл Сәбитұлы, физика-математика ғылымдарының докторы, профессор, ҚР ҰҒА академигі, әл-Фараби атындағы Қазақ ұлттық университетінің ғылыми-инновациялық қызмет жөніндегі проректоры, (Алматы, Қазақстан) H=26

ТАКИБАЕВ Нұрғали Жабағаұлы, физика-математика ғылымдарының докторы, профессор, ҚР ҰҒА академигі, әл-Фараби атындағы Қазақ ұлттық университеті (Алматы, Қазақстан) H=5

ТИГИНЯНУ Ион Михайлович, физика-математика ғылымдарының докторы, академик, Молдова ғылым Академиясының президенті, Молдова техникалық университеті (Кишинев, Молдова) H=42

ХАРИН Станислав Николаевич, физика-математика ғылымдарының докторы, профессор, ҚР ҰҒА академигі, Қазақстан-Британ техникалық университеті (Алматы, Қазақстан) H=10

ДАВЛЕТОВ Асқар Ербуланович, физика-математика ғылымдарының докторы, профессор, әл-Фараби атындағы Қазақ ұлттық университеті (Алматы, Қазақстан) H=12

КАЛАНДРА Пьетро, Ph.D (физика), Наноқұрылымды материалдарды зерттеу институтының профессоры (Рим, Италия) H=26

«ҚР ҰҒА Хабарлары.
Физика-математикалық сериясы».
ISSN 2518-1726 (Online),
ISSN 1991-346X (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.). Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 14.02.2018 ж. берілген **No 16906-Ж** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *математика, информатика, механика, физика, ғарыштық зерттеулер, астрономия, ионосфера.*
Мерзімділігі: жылына 6 рет.
Тиражы: 300 дана.
Редакцияның мекен-жайы: *050010, Алматы қ., Шевченко көш., 28, 219 бөл., тел.: 272-13-19*
http://www.physico-mathematical.kz/index.php/en/

© Қазақстан Республикасының Ұлттық ғылым академиясы, 2021

Типографияның мекен-жайы: «Аруна» ЖК, Алматы қ., Мұратбаев көш., 75.

Главный редактор:

МУТАНОВ Галимкаир Мутанович, доктор технических наук, профессор, академик НАН РК, и.о. генерального директора «Института информационных и вычислительных технологий» КН МОН РК (Алматы, Казахстан) Н=5

Редакционная коллегия:

КАЛИМОЛДАЕВ Максат Нурадилович, (заместитель главного редактора), доктор физико-математических наук, профессор, академик НАН РК, советник генерального директора «Института информационных и вычислительных технологий» КН МОН РК, заведующий лабораторией (Алматы, Казахстан) Н=7

БАЙГУНЧЕКОВ Жумадил Жанабаевич, (заместитель главного редактора), доктор технических наук, профессор, академик НАН РК, Институт кибернетики и информационных технологий, кафедра прикладной механики и инженерной графики, университет Сатпаева (Алматы, Казахстан) Н=3

ВОЙЧИК Вальдемар, доктор технических наук (физ.-мат.), профессор Люблинского технологического университета (Люблин, Польша) Н=23

БОШКАЕВ Куантай Авгазыевич, доктор Ph.D, преподаватель, доцент кафедры теоретической и ядерной физики, Казахский национальный университет им. аль-Фараби (Алматы, Казахстан) Н=10

QUEVEDO Hemando, профессор, Национальный автономный университет Мексики (UNAM), Институт ядерных наук (Мехико, Мексика) Н=28

ЖУСУПОВ Марат Абжанович, доктор физико-математических наук, профессор кафедры теоретической и ядерной физики, Казахский национальный университет им. аль-Фараби (Алматы, Казахстан) Н=7

КОВАЛЕВ Александр Михайлович, доктор физико-математических наук, академик НАН Украины, Институт прикладной математики и механики (Донецк, Украина) Н=5

МИХАЛЕВИЧ Александр Александрович, доктор технических наук, профессор, академик НАН Беларуси (Минск, Беларусь) Н=2

РАМАЗАНОВ Тлеккабул Сабитович, доктор физико-математических наук, профессор, академик НАН РК, проректор по научно-инновационной деятельности, Казахский национальный университет им. аль-Фараби (Алматы, Казахстан) Н=26

ТАКИБАЕВ Нургали Жабагаевич, доктор физико-математических наук, профессор, академик НАН РК, Казахский национальный университет им. аль-Фараби (Алматы, Казахстан) Н=5

ТИГИНЯНУ Ион Михайлович, доктор физико-математических наук, академик, президент Академии наук Молдовы, Технический университет Молдовы (Кишинев, Молдова) Н=42

ХАРИН Станислав Николаевич, доктор физико-математических наук, профессор, академик НАН РК, Казахстанско-Британский технический университет (Алматы, Казахстан) Н=10

ДАВЛЕТОВ Аскар Ербуланович, доктор физико-математических наук, профессор, Казахский национальный университет им. аль-Фараби (Алматы, Казахстан) Н=12

КАЛАНДРА Пьетро, доктор философии (Ph.D, физика), профессор Института по изучению наноструктурированных материалов (Рим, Италия) Н=26

«Известия НАН РК.
Серия физика-математическая».
ISSN 2518-1726 (Online),
ISSN 1991-346X (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **No 16906-Ж** выданное 14.02.2018 г.
Тематическая направленность: *математика, информатика, механика, физика, космические исследования, астрономия, ионосфера.*
Периодичность: 6 раз в год.
Тираж: 300 экземпляров.
Адрес редакции: *050010, г. Алматы, ул. Шевченко, 28, оф. 219, тел.: 272-13-19*
http://www.physico-mathematical.kz/index.php/en/

© Национальная академия наук Республики Казахстан, 2021

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75.

Editor in chief:

MUTANOV Galimkair Mutanovich, doctor of technical Sciences, Professor, Academician of NAS RK, acting director of the Institute of Information and Computing Technologies of SC MES RK (Almaty, Kazakhstan) H=5

Editorial board:

KALIMOLDAYEV Maksat Nuradilovich (Deputy Editor-in-Chief), doctor in Physics and Mathematics, Professor, Academician of NAS RK, Advisor to the General Director of the Institute of Information and Computing Technologies of SC MES RK, Head of the Laboratory (Almaty, Kazakhstan) H=7

BAYGUNCHEKOV Zhumadil Zhanabayevich, (Deputy Editor-in-Chief), doctor of Technical Sciences, Professor, Academician of NAS RK, Institute of Cybernetics and Information Technologies, Department of Applied Mechanics and Engineering Graphics, Satbayev University (Almaty, Kazakhstan) H=3

WOICIK Waldemar, Doctor of Phys.-Math. Sciences, Professor, Lublin University of Technology (Lublin, Poland) H=23

BOSHKAYEV Kuantai Avgazievich, PhD, Lecturer, Associate Professor of the Department of Theoretical and Nuclear Physics, Al-Farabi Kazakh National University (Almaty, Kazakhstan) H=10

QUEVEDO Hemando, Professor, National Autonomous University of Mexico (UNAM), Institute of Nuclear Sciences (Mexico City, Mexico) H=28

ZHUSSUPOV Marat Abzhanovich, Doctor in Physics and Mathematics, Professor of the Department of Theoretical and Nuclear Physics, al-Farabi Kazakh National University (Almaty, Kazakhstan) H=7

KOVALEV Alexander Mikhailovich, Doctor in Physics and Mathematics, Academician of NAS of Ukraine, Director of the State Institution «Institute of Applied Mathematics and Mechanics» DPR (Donetsk, Ukraine) H=5

MIKHALEVICH Alexander Alexandrovich, Doctor of Technical Sciences, Professor, Academician of NAS of Belarus (Minsk, Belarus) H=2

RAMAZANOV Tlekkabul Sabitovich, Doctor in Physics and Mathematics, Professor, Academician of NAS RK, Vice-Rector for Scientific and Innovative Activity, al-Farabi Kazakh National University (Almaty, Kazakhstan) H=26

TAKIBAYEV Nurgali Zhabagaevich, Doctor in Physics and Mathematics, Professor, Academician of NAS RK, al-Farabi Kazakh National University (Almaty, Kazakhstan) H=5

TIGHINEANU Ion Mikhailovich, Doctor in Physics and Mathematics, Academician, Full Member of the Academy of Sciences of Moldova, President of the AS of Moldova, Technical University of Moldova (Chisinau, Moldova) H=42

KHARIN Stanislav Nikolayevich, Doctor in Physics and Mathematics, Professor, Academician of NAS RK, Kazakh-British Technical University (Almaty, Kazakhstan) H=10

DAVLETOV Askar Erbulanovich, Doctor in Physics and Mathematics, Professor, al-Farabi Kazakh National University (Almaty, Kazakhstan) H=12

CALANDRA Pietro, PhD in Physics, Professor at the Institute of Nanostructured Materials (Monterotondo Station Rome, Italy) H=26

News of the National Academy of Sciences of the Republic of Kazakhstan. Physical-mathematical series.
ISSN 2518-1726 (Online),
ISSN 1991-346X (Print)

Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty). The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. 16906-Ж,** issued 14.02.2018
Thematic scope: *mathematics, computer science, mechanics, physics, space research, astronomy, ionosphere.*
Periodicity: 6 times a year.
Circulation: 300 copies.
Editorial address: *28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19*
http://www.physico-mathematical.kz/index.php/en/

© National Academy of Sciences of the Republic of Kazakhstan, 2021

Address of printing house: ST «Aruna», 75, Muratbayev str, Almaty.

NEWS
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
PHYSICO-MATHEMATICAL SERIES
ISSN 1991-346X
Volume 4, Number 338 (2021), 31 – 40 **https://doi.org/10.32014/2021.2518-1726.63**

UDC 52-48, 524, 539.14, 539.17

Dzhazairov-Kakhramanov A.V.[1,2]*****, **Imambekov O.**[1,3], **Karipbayeva L.T.**[1,2], **Steblyakova A.A.**[2]

[1]V.G. Fesenkov Astrophysical Institute “NCSRT” NSA RK, Almaty, Kazakhstan;
[2]International Informatization Academy, Almaty, Kazakhstan;
[3]Al-Farabi Kazakh National University, Almaty, Kazakhstan.
E-mail: albert-j@yandex.ru

THE ROLE OF RESONANCES IN THE CAPTURE OF ^{8}Li(p,γ)^{9}Be ON THE REACTION RATE OF THE RELEVANT ASTROPHYSICAL SYNTHESIS OF ^{9}Be

Abstract: the total cross sections of the radiative proton capture on ^{8}Li at astrophysical energies are considered in the framework of the modified potential cluster model with forbidden states, with the classification of the orbital cluster states according to Young diagrams. The recalculation of the total cross sections for ^{9}Be(γ,p_0)^{8}Li photodisintegration is used as experimental data. Parameters for Gaussian partial potentials were obtained for description the ^{8}Li(p,γ)^{9}Be capture at astrophysical energies. It is evident that the processes of two-body radiative capture connected with them by the detailed balancing principle lead to the synthesis of ^{9}Be and require the corresponding estimation contextually in the astrophysical supplements. Meanwhile, it should be noted that the first three reactions have the Coulomb barrier in channels p^8Li, d^7Li and t^6Li lower than in ^{3}He^{6}He along with ^{4}He^{5}He channels, namely, in the ratio of 3:4. The cross section of ^{8}Li(p,γ)^{9}Be is hard to obtain directly due to low ^{8}Li beam intensity and the small cross section at astrophysical energies. In addition, the difficulty of studying the reaction of ^{8}Li(p,γ)^{9}Be also lies in the fact that the direct experimental measurement of cross sections is practically impossible due to the very short half-life of ^{8}Li – 838 ms. However, as in the case of the neutron capture on ^{8}Li, some indirect methods of extracting direct capture cross sections can be used with the help of the radiative capture model and spectroscopic factor. The data obtained from the ^{9}Be(γ,p_0)^{8}Li photodisintegration process according to the detailed balancing principle are used for the experimental data of the ^{8}Li(p,γ)^{9}Be capture. It is possible to reproduce the available data on cross sections at the energies up to 7.0 MeV. Astrophysical S-factors and reaction rates $\langle\sigma v\rangle$ are calculated at the temperature range of 0.01 to 10 T_9. It is shown that the reaction rate is significantly affected by the resonances in the p^8Li scattering channel, and, especially by the first $1/2^-$ resonance at 87 keV. The analytical parametrization is performed for the calculated reaction rate $\langle\sigma v\rangle$.

Key words: nuclear astrophysics; primordial nucleosynthesis; thermal and astrophysical energies; p^{8}Li cluster system; radiative capture; total cross section.

Introduction. The study of the formation mechanisms of ^{9}Be directly concerns the problem of the overlap of the $A = 8$ mass gap and the synthesis of heavier elements in the early Universe, as well as the r-process nucleosynthesis in supernovae (see, for example, [1,2]). In the present time, it is considered that ^{9}Be is formed as a result of a two-stage process: the radiative capture of alpha particles $\alpha(\alpha,\square)^8$Be, leading to the synthesis of the short-half-life isotope ^{8}Be ($t_{1/2} = 6.7\times10^{-17}$s), and radiative neutron capture ^{8}Be($n,\square$)^{9}Be [2,3]. In addition, there is the more difficult process of the direct three-particle capture $\alpha\alpha n \rightarrow \square\,^9$Be, (see, for example, [4–8]).

Simultaneously, in [8], different binary channels of disintegration of ^{9}Be, namely, ^{9}Be($\square,p$)^{8}Li, ^{9}Be($\square,d$)^{7}Li, ^{9}Be($\square,t$)^{6}Li and also ^{9}Be($\square,^3$He)^{6}He, were experimentally studied. It is evident that the processes of two-body radiative capture connected with them by the detailed balancing principle lead to the synthesis of ^{9}Be and require the corresponding estimation contextually in the astrophysical supplements. Meanwhile, it should be noted that the first three reactions have the Coulomb barrier in channels p^8Li, d^7Li and t^6Li lower than in ^{3}He^{6}He along with ^{4}He^{5}He channels, namely, in the ratio of 3:4.

The cross section of ^{8}Li(p,γ)^{9}Be is hard to obtain directly due to low ^{8}Li beam intensity and the small cross section at astrophysical energies. In addition, the difficulty of studying the reaction of ^{8}Li(p,γ)^{9}Be also lies in the fact that the direct experimental measurement of cross sections is practically impossible due to the very short half-life of ^{8}Li – 838 ms [9]. However, as in the case of the neutron capture on ^{8}Li [10], some indirect methods of extracting direct capture cross sections can be used with the help of the radiative capture model and spectroscopic factor [9,11].

The $p^8\text{Li}\to{}^9\text{Be}\gamma$ reaction presents significant astrophysical interest because it is included in the list of processes of primordial nucleosynthesis of the Universe [12]. However, its experimental investigation in the astrophysical range has so far been insufficient. Intrinsically, there is only one work [13] where the astrophysical range is considered. In [14], it is also added, where measurements were carried out at higher energies. However, these works were published in the 1960s and we do not currently possess more modern experimental studies of the total cross sections of the considered reaction [15]. This is in spite of the fact that studies of spectra ^{9}Be in the p^{8}Li channel are still continuing [16]. In addition, the available and considered further theoretical results differ so greatly that it is difficult to draw certain conclusions regarding the rate of this reaction. Furthermore, these calculations do not take into account the existence of resonances in the p^{8}Li system at low energies [16].

In the present study, we consider the reaction of the proton capture on ^{8}Li in the frame of the modified potential cluster model (MPCM) [17] and define how the criteria of this model allow us to correctly describe total cross sections and the astrophysical S-factor at astrophysical energies. The energy range of 10 keV to 7.0 MeV is considered but only taking into account the structure of resonances up to 2.0 MeV, as discussed previously [16]. The rate of the reaction is calculated at the temperature range of 0.01 to 10 T_9. The analysis of the influence of the location and magnitude of resonances to the value and shape of the reaction rate is presented.

Materials and methods. *Model and calculation methods.* Further we use well-known formulas for total cross sections and matrix elements of E1 transition operators [18] ($S_i = S_f = S$)

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

where matrix elements of EJ – transitions have a form

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

$$A_J(EJ,K)=K^J\mu^J\left(\frac{Z_1}{m_1^J}+(-1)^J\frac{Z_2}{m_2^J}\right),\qquad I_J(J_f,J_i)=\left\langle\chi_f\left|r^J\right|\chi_i\right\rangle \tag{2}$$

Here S_i, S_f, L_f, L_i, J_f, J_i – are total spins and moments of input (i) and output (f) channel particles, m_1, m_2, Z_1, Z_2 are masses and charges of input channel particles, I_J is the integral over wave functions of the initial χ_i and final χ_f states, as relative motion functions of clusters with intercluster distance r, μ – reduced mass.

For the spin part of the magnetic process $M1(S)$ at $J = 1$, the following expression is obtained in the model used ($S_i = S_f = S$, $L_i = L_f = L$)

$$P_1^2(M1,J_f,J_i)=\delta_{S_iS_f}\delta_{L_iL_f}[S(S+1)(2S+1)(2J_i+1)(2J_f+1)]\begin{Bmatrix}S\;L\;J_i\\ J_f\;1\;S\end{Bmatrix}^2,$$

$$A_1(M1,K)=\frac{\hbar K}{m_0c}\sqrt{3}\left[\mu_1\frac{m_2}{m}-\mu_2\frac{m_1}{m}\right],\qquad I_J(J_f,J_i)=\left\langle\chi_f\left|r^{J-1}\right|\chi_i\right\rangle. \tag{3}$$

Here, m is the mass of the nucleus, μ_1, μ_2 are magnetic moments of the clusters, and the remaining notation, are given as in the previous expression.

Constant $\hbar^2/m_0$ is equal to 41.4686 MeV fm^2, where m_0 is the atomic mass unit (amu). The Coulomb potential at zero Coulomb radius $R_{\text{coul}} = 0$ is written in the form $V_{coul} = 1.439975\cdot Z_1Z_2/r$, where r is the relative distance between particles of the initial channel in fm and Z are charges of particles in the elementary charge "e" units. Furthermore, the magnetic moment of proton $\mu_p = 2.792847\mu_0$ and ^{8}Li nucleus $\mu(^8\text{Li}) = 1.65356\mu_0$ [18], where μ_0 is the nuclear magneton.

Criteria of the potential construction. The potentials of resonance waves are constructed in order to correctly describe the location of resonance E_r and its width $\Gamma_{\text{c.m.}}$, therefore their parameters are obtained quite unambiguously. GS potentials will be constructed in such a form that allows one to correctly describe the channel binding energy, the charge radius of ^{9}Be and its asymptotic constant in the p^8Li channel. Since, all known values of the asymptotic normalization coefficient (ANC) and the spectroscopic factor S_f, according to which the asymptotic constant (AC) is obtained, have enough large error. The GS potentials also can have few options with different parameters of width. However, at the given values of AC and binding energy, its parameters are constructed absolutely unambiguously.

The spectroscopic factor S_f of the GS and A_{NC} ANC are connected by the next way [19]:

$$A_{NC}^2 = S_f \times C^2 , \tag{4}$$

where C is the dimensioned asymptotic constant in fm$^{-1/2}$, which connects with dimensionless AC C_w [20] by $C = \sqrt{2k_0}C_w$, and the dimensionless constant C_w defined from the relation [20]:

$$\chi_L(r) = \sqrt{2k_0}C_w W_{-\eta L+1/2}(2k_0 r), \tag{5}$$

where $\chi_L(r)$ is the numerical BS radial wavefunction, obtained as the solution of the Schrödinger equation normalized to unit size, $W_{-\eta L+1/2}(2k_0 r)$ is the Whittaker function of the bound state, determining the asymptotic behavior of the wavefunction and obtained as the solution of the same equation without nuclear potential, k_0 is a wavenumber related to the channel binding energy E where $k_0 = \sqrt{2\mu E/\hbar^2}$ in fm^{-1}, η is the Coulomb parameter $\eta = \mu Z_1 Z_2 e^2/(\hbar^2 k_0)$ = $3.44476 \cdot 10^{-2}\ \mu Z_1 Z_2 / k_0$, Z_1 and Z_2 are the particle charges, L is the orbital momentum of the bound state.

Note that the spectroscopic factor S_f is used by us only for the standard procedure of the obtaining possible C_w range from the obtained in the experiment A_{NC} value [19,20].

Potentials of the p^8Li interaction. As in our previous works [17] for other nuclear systems, we use the potential of the Gaussian form with the point-like Coulomb term with the given orbital momentum L in each partial wave as the p^8Li interaction:

$$V(r,L) = -V_L \exp(-\gamma_L r^2). \tag{6}$$

The $^4P_{3/2}$ level we consider as the ground state of ^{9}Be in the p^8Li and such potential should correctly describe the AC for this channel. In order to extract this constant C in form (4) or C_w (5) from the available experimental data, let us consider information regarding the spectroscopic factors S_f and asymptotic normalization coefficients A_{NC}. For example, in [21], except for their own results, the authors add data of previous works. If to separate from these similar results, that is, with closely spaced values of spectroscopic factors that can be presented in the form of Table 3

Table 3. Data on spectroscopic factors S_f for the GS of ^{9}Be in the p^8Li channel from works [9,11,21,22]. $\bar{S}_f$ is the average value on data interval.

Reaction from what S_f	S_f for the $p^8\text{Li}_{GS}$	Ref.
^{8}Li$(d,n)^9$Be	0.64(21)	[21]
^{12}C(^{9}Be,^{8}Li)^{14}N	0.73(15)	[11]
Average value	*0.69, that is,* $\sqrt{S_f}$ = 0.83	
Average value on data interval	$\bar{S}_f$ *= 0.66(22), 0.43–0.88* $\sqrt{\bar{S}_f}$ *= 0.81(14)*	
^{9}Be(^{8}Li,^{9}Be)^{8}Li	1.50(28)	[22]
Potential model	1.50(27)	[9]
Average value on all results	*1.09,* $\sqrt{S_f}$ *= 1.05*	
Data interval on all results	$\bar{S}_f$ *= 1.11(68), 0.43-1.78* $\sqrt{\bar{S}_f}$ *= 1.05(28)*	

Furthermore, the ANC $^4P_{3/2}$ GS in the p^8Li channel was given in [23], where $A_{\rm NC}$ = 10.75(12) fm$^{-1/2}$ was obtained. The constant for the $^6P_{3/2}$ state is much less – 0.25(10) fm$^{-1/2}$ [23]. Therefore, we consider here only one spin channel with S = 3/2. On the basis of expression (4) and average value on interval $\sqrt{S_f}$ = 0.66(22) from Table 2 according works [11,21] for the AC GS, the value C = 13.71(2.52) fm$^{-1/2}$ was obtained, and because $\sqrt{2k_0} = 1.307$, so dimensionless AC (5) is equal to $C_{\rm w}$ = 10.49(1.93). However, if to use the average value $\sqrt{S_f}$ on all works from Table 3, equals 1.05(28), then for constant C, we obtain a wider data interval 11.06(3.06) fm$^{-1/2}$ and $C_{\rm w}$ = 8.46(2.34). Consequently, the possible interval of $C_{\rm w}$ values on two data groups from Table 3 is approximately from 6 (from the latest data) to 12.5 (from the previous results).

Furthermore, two options of the GS potentials with FS, which allow us to obtain the dimensionless asymptotic constant $C_{\rm w}$ in the given above limits, were obtained. The parameters of these potentials V_L and γ_L, and also main characteristics of the nucleus, obtained with them (binding energy $E_{\rm b}$, asymptotic constant $C_{\rm w}$, mass radius $<R>_{\rm m}$ and charge radius $<R>_{\rm ch}$) are listed in Table 4.

Table 4. GS potential parameters and main characteristics of ^{9}Be

No.	V_L, MeV	γ_L, fm^{-2}	$E_{\rm b}$, MeV	$C_{\rm w}$	$<R>_{\rm m}$, fm	$<R>_{\rm ch}$, fm
1.	212.151135	0.17	-16.88820	10.2(1)	2.40	2.46
2.	286.178045	0.25	-16.88820	6.6(1)	2.36	2.38

For example, potential No. 1 has the FS and leads to the binding energy -16.88820 MeV. The definition of the calculation expressions used here for the radii is given, for example, in [17]. The above AC errors are defined by their averaging over the distance interval from 6–8 to 10–12 fm, which is the AC stabilization range. The phase shift of the elastic scattering of this potential for the GS $^4P_{3/2}$ smoothly decreases down to zero and at 5.0 MeV has the value of ~330°. Here, we consider that in the presence of two bound FS and AS, the phase shift according to generalized Levinson theorem starting from 360° [24]. Furthermore, another option of the GS potential that leads to a smaller AC given in Table 4.

Table 5. Options of potential parameters with FS for resonance states of nuclear and some characteristics obtained with them. In the two last columns, the experimental values listed above in Table 1 are shown.

No.	$^{2s+1}L_J$	V_J, MeV	γ_J, fm^{-2}	$E_{\rm r}$ (c.m.), keV	$\Gamma_{\rm c.m.,}$ keV	$E_{\rm r}$ (c.m.), keV	$\Gamma_{\rm c.m.,}$ keV
1.	$^4S_{3/2}$	-5	0.1	–	–	–	–
2.	$^4D_{3/2}$	269.242	0.2	1100	56	1100(30)	50(22)
3.	$^4P_{1/2}$	66.69121	0.075	87	~0.4	87(1)	0.39(1)
4.	$^4P_{5/2}$	34.0399	0.04	410	203	420(7)	210(20)

Potential No. 3 from Table 5 leads to the $^4P_{1/2}$ scattering phase shift, plotted in Fig. 1 by the black solid curve, which is shown at energies up to 5.0 MeV and has the resonance at 87 keV. Scattering potential No. 4 has the phase shift $^4P_{5/2}$ presented in Fig. 1 by the red dashed curve and at the considered energies has the resonance at 410 keV. Potential No. 2 leads to the $^4D_{3/2}$ phase shift shown in Fig. 1 by the green solid curve. All resonance potentials have the phase shift of 90.0°(1) at the resonance energy and the bound FS.

Results and discussion. *Total cross sections, S-factor and reaction rate of radiative ^{8}Li(p,γ)^{9}Be capture.* Let us discuss calculation results of the total cross sections for the proton capture on ^{8}Li and comparing them with experimental measurements from [13,14]. The summed cross section is shown in Fig. 2a by the blue solid curve; the black dashed curve shows the nonresonance capture from the S wave with potential No. 1 from Table 5 to the GS with potential No. 1 from Table 4. The green dotted curve shows cross section at the capture from the first and the second resonances for potential No. 3 and No. 4 from Table 5. The red dashed curve shows the capture from the third resonance with potential No.2 from Table 5. The parameters of the *S* scattering wave without FS were determined so as correctly reproduce total cross sections in the "plateau" range, which occurs at energies of 0.5 to 7 MeV. The potential No. 1 from Table 4 is used as the GS potential that reproduces AC from [23] to the best advantage.

It should be noted that there is no second resonance at 410 keV in the available data [13]. However, it exists in spectra [16,25,26], we are taking it into account. A new resonance at 410 keV not observed in experiment [13] is clearly observed in Fig. 2a. In this experiment, at this energy, the cross section minimum is observed that is difficult to explain from the viewpoint of new data on ^{9}Be spectra [16]. However, it is necessary to remember that these experimental data were obtained in sixties of the past century and were not confirmed later by more modern methods.

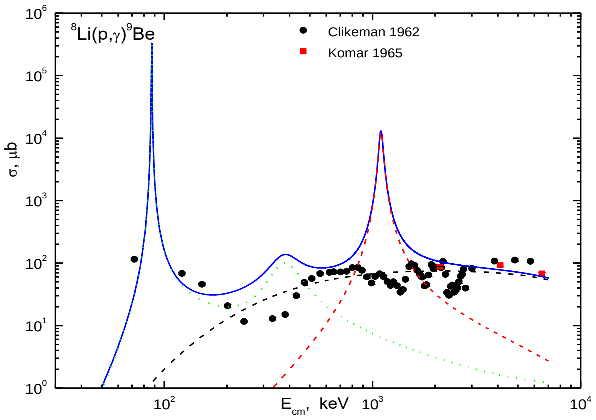

Fig. 2a Total cross sections of the radiative ^{8}Li(p,γ)^{9}Be capture to the GS of ^{9}Be. Black points are experimental data from [13] and red squares are from [14]. Curves are explained in the text.

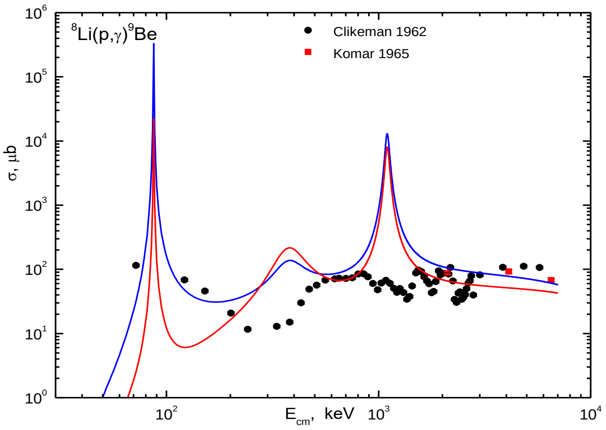

Fig. 2b Total cross sections of radiative ^{8}Li(p,γ)^{9}Be capture to the GS of ^{9}Be. Notations like in Fig. 2a.

Now take note of the resonance at 1.1 MeV from Table 2, which is leading to the $E1$ transition to the GS. The calculation results that take into account this transition are shown in Fig. 2a. The sharp rise of the total cross section is observed at the resonance energy and is shown by the red dashed curve. This resonance also is not observed in the available experimental data.

The comparison of cross sections for different GS potentials with FS is shown in Fig. 2b. The previous results for potential No. 1 from Table 4 are shown by the blue curve and the results for potential No. 2 from Table 4 are shown by the red curve. These results are slightly lower than previous ones almost in the whole energy range and overall show less agreement with the available data [13].

Now, let us discuss calculation results of the astrophysical *S*-factor of the radiative capture for potentials from Tables 4 and 5. They are represented in Fig. 3 – the blue curve similar to Fig. 2a, and the green dotted curve with the value of 2.85(1) keV·b at 10 keV corresponds to the same curve in Fig. 2a, and black dashed curve corresponds to the same curve in Fig. 2a and shown nonresonance scattering from the *S* wave with the value of 1.69(1) keV·b at 10 keV. The calculated *S*-factor at 10 keV for both options of calculations is equal to 4.5(1) keV·b.

The value of 0.15 keV·b with a smooth decrease at 2.0 MeV down to 0.1 keV·b was obtained for the astrophysical *S*-factor in [21]. The interval of possible *S*-factor values at zero energy (*S*(0)) is determined to be 0.075 to 0.23 keV·b. The value of 0.3 keV·b for the *S*(0) was obtained in [22] and furthermore up to 1.5 MeV the *S*-factor smoothly decrease approximately down to 0.25 keV·b. The interval of possible *S*(0) defined in this work near the range of 0.21 to 0.38 keV·b. In [9] the *S*(0) is of 0.85 keV·b was obtained and furthermore up to 1.5 MeV, the *S*-factor smoothly decreases approximately down to 0.75 keV·b. The interval of possible *S*(0) values defined near the range of 0.63 to 1.15 keV·b. However, in all of these works [9,21,22] none of the resonances have been taken into account and the *S*-factor has a smooth shape.

The general parametrization of the *S*-factor in the energy range up to 50 keV was obtained by the expression of the form:

$$S(E_{\mathrm{c.m.}}) = S_0 + S_1E + S_2E^2, \qquad (7)$$

where the energy is in keV and the corresponding parameters are $S_0 = 5.082$, $S_1 = –0.09391$ and $S_2 = 0.005359$. For these parameters, the χ^2 value is equal to 0.26 with 5% errors comparing the initial calculated data. The result of this parametrization is shown in Fig. 3 by the red curve.

Furthermore, in Fig. 4, the green and blue solid curves show the reaction rate of the proton capture on ^{8}Li, which corresponds to the same curves in Fig. 3 and is written in the form [27]:

$$N_A\langle\sigma v\rangle = 3.7313\cdot10^4\mu^{-1/2}T_9^{-3/2}\int_0^\infty \sigma(E)E\exp(-11.605E/T_9)dE\,, \tag{8}$$

where E is in MeV, the cross section $\sigma(E)$ is in μb, T_9 is the temperature in 10^9 K. Integration is carried out in the energy range of 10 keV–7 MeV. The black dashed curve shows the reaction rate that corresponds to the black dashed curve in Fig. 2a and takes into account only the E1 transition from the S scattering wave.

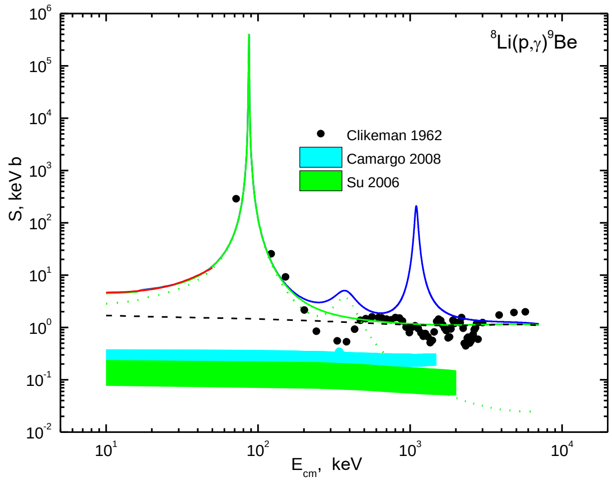

Fig. 3 Astrophysical S-factor of the radiative ^{8}Li(p,γ)^{9}Be capture to the GS of ^{9}Be. Black points are experimental data from [13]. Curves are explained in the text.

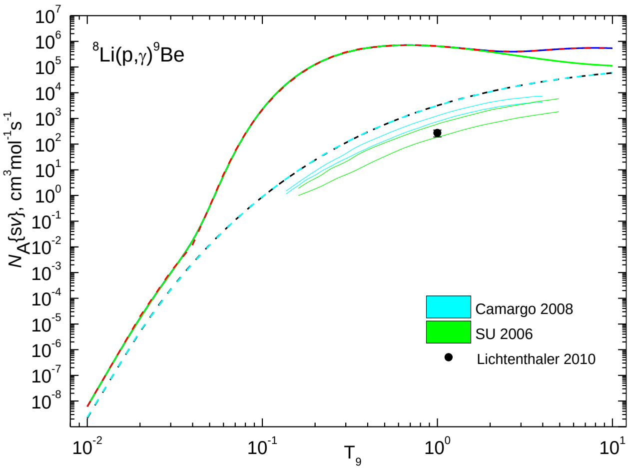

Fig. 4 Reaction rate of the proton capture on ^{8}Li. Curves are explained in the text. Point is the result from [28].

Here, the reaction rate for results of paper [22] is shown by the blue band. In addition, the green band is presenting in Fig. 4 the results for the $\langle\sigma v\rangle$ from [21]. Both of these calculations are lower than the result obtained here by some orders of magnitude. It is seen from Fig. 4 that consideration of the first resonance essentially changes the reaction rate as against results of publications [21,22], where only the nonresonance calculations were carried out. Accounting for the two next resonances in present calculations leads only to the small increasing of the $\langle\sigma v\rangle$ at highest temperatures.

The parametrization of the reaction rate was carried out using the expression of the form [27]:

$$\begin{aligned} N_A\langle\sigma v\rangle = {} & \frac{a_1}{T^{2/3}}\exp\left(-\frac{a_2}{T^{1/3}}\right)\left(1+a_3T^{1/3}+a_4T^{2/3}+a_5T+a_6T^{4/3}+a_7T^{5/3}+a_8T^{7/3}\right)+ \\ & +\frac{a_9}{T^{1/2}}\exp\left(-\frac{a_{10}}{T^{1/2}}\right)+\frac{a_{11}}{T}\exp\left(-\frac{a_{12}}{T}\right)+\frac{a_{13}}{T^{3/2}}\exp\left(-\frac{a_{14}}{T^{3/2}}\right)+\frac{a_{15}}{T^2}\exp\left(-\frac{a_{16}}{T^2}\right) \end{aligned} \tag{9}$$

with the parameters listed in Table 6. The results of these parametrization are shown above in Fig. 4 by the red dashed curve.

Table 6. Parameters of the analytical parametrization with $\chi^2 = 0.06$ at 5% errors of the calculated total reaction rate.

a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
-146.8134	7.52023	-1.57556E6	5.38408E6	-4.16671E6	109516	564105.0	-41092.96
a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}
-417.1643	2.34235	2.75351E6	0.94389	-2.82805E6	1.18361	1.26521E6	0.99103

Conclusion. It is possible to construct two-body potentials of the p^8Li interaction that allow to describe correctly the available data on characteristics of the bound state of ^{9}Be in the p^8Li channel in the frame of the MPCM. Suggested options of the GS potentials of ^{9}Be in the p^8Li channel allow one to obtain AC within limits of errors available for it and lead to the reasonable description of ^{9}Be radii. Such potentials generally allow one to reproduce the available experimental data for total cross sections of the radiative proton capture on ^{8}Li at low and ultralow energies. Obtained results for total cross sections and static characteristics of ^{9}Be strongly depend of GS potential parameters of this nucleus in the p^8Li channel.

New results for the astrophysical S-factor and reaction rate have been obtained. They turned to be essentially higher than similar results of previous works [21,22], where the first resonance $1/2^-$ (0.087) was not taken into account. The parametrization of the calculated S-factor in the energy range to 50 keV was carried out. Further account of two other resonances $5/2^-$ (0.410) and $3/2^+$ (1.100) leads only to small changes of the reaction rate at highest temperatures. Analytical parametrization of the calculated total reaction rate was carried out. As well as the nonresonance $E1$ reaction rate was parametrized. The obtained results for the reaction rate of the proton capture on ^{8}Li may lead to an essential re-estimation of the efficiencies of light nuclei in different thermonuclear processes in the Universe.

We consider the presented results as estimative, so as undoubtedly targeted measurements of the capture cross sections are needed in the range where our model predicts the resonance behavior of cross sections, supported by the modern data on ^{9}Be spectra near the proton threshold. Finally, let us note that further refinement of experimental characteristics of high-lying levels of ^{9}Be also is strongly desirable.

Acknowledgments. *This work was supported by the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP08855556) entitled “Study of additional thermonuclear reactions flowing in the process of the controlled thermonuclear fusion on lithium isotopes” through the Fesenkov Astrophysical Institute of the National Center for Space Research and Technology of the Ministry of Digital Development, Innovation and Aerospace Industry of the Republic of Kazakhstan (RK).*

Джазаиров-Кахраманов А.В.[1,2]*, Имамбеков О.[1,3], Карипбаева Л.Т.[1,2], Стеблякова А.А.[2]

[1] В.Г. Фесенков атындағы Астрофизика институты ЕЖШС, Алматы, Қазақстан;
[2]Халықаралық Ақпараттандыру Академиясы, Алматы, Қазақстан;
[3]Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан.
E-mail: albert-j@yandex.ru

^{8}Li(p,γ)^{9}Be ҚАРМАУЫ КЕЗІНДЕ СӘЙКЕС ^{9}Be АСТРОФИЗИКАЛЫҚ СИНТЕЗІ ҮШІН РЕАКЦИЯ ЖЫЛДАМДЫҒЫНА РЕЗОНАНСТАРДЫҢ МӘНІ

Аннотация: Юнга сызбасы бойынша орбиталық кластерлік күйді жіктеумен қатар, тыйым салынған күйдегі модификацияланған потенциалды кластерлі модель аясында, астрофизикалық энергияларда протондарды радиациялық қармауды толық кесу қарастырылған. Эксперименттік мәліметтерді алу үшін ^{9}Be(γ,p_0)^{8}Li фотоқирату реакциясын толық кесуді қайта есептеу қолданылады. Астрофизикалық энергияларда ^{8}Li(p,γ)^{9}Be радиациялық қармау үшін гаусс потенциалдарының көрсеткіштері анықталды. Сонымен қатар, [Shoda, Tanaka (1999)] ^{9}Be: ^{9}Be(γ,p)^{8}Li, ^{9}Be(γ,d)^{7}Li, ^{9}Be(γ,t)^{6}Li, сондай-ақ ^{9}Be(γ,^{3}He)^{6}He әртүрлі екілік тарату арналары эксперименталды зерттелді. Олардың егжей-тегжейлі тепе-теңдігімен байланысты екі бөлшекті радиациялық басып алу процестері ^{9}Be синтезіне алып келеді және астрофизикалық қосымшалар контекстінде тиісті бағалауды талап етеді. Бұл жағдайда, бірінші үш реакция p^8Li, d^7Li және t^6Li арналарында ^{3}He^{6}He-ге қарағанда төмен кулон кедергісінің болуына, яғни 3:4 қатынасында ^{4}He^{5}He арналарында, атап айтқанда 3:4 қатынасында назар аудару керек. ^{8}Li(p,γ)^{9}Be көлденең қимасы астрофизикалық қызығушылық тудыратын энергия кезіндегі екінші ^{8}Li шоғырдың және шағын қиманың төмен қарқындылығынан тікелей анықтау қиын. Сонымен қатар, ^{8}Li(p,γ)^{9}Be реакциясын зерттеу мәселесі ^{8}Li-838 мс ядросының жартылай ыдырауының өте аз кезеңінде қималарды тікелей эксперименталды өлшеу мүмкін емес болып табылады. Алайда, n^8Li-қармау жағдайында да радиациялық қармау моделін және спектроскопиялық факторды пайдалана отырып, тікелей қармау қимасын алу үшін кейбір жанама әдістер пайдаланылуы мүмкін. ^{9}Be механизмдердің пайда болуын зерттеу $A = 8$ массалы саңылауды еңсеру және ерте Әлемдегі ауыр элементтердің синтезіне, сонымен қатар supernovae r-процесс нюклеосинтез мәселесіне тікелей қатынасы бар. Қазіргі таңда ^{9}Be екі сатылы үрдіс нәтижесінде пайда болады деген ой қалыптасты: $\alpha(\alpha,\gamma)^8$Be альфа бөлшектердің радиациалық қармауы қысқа ғұмырлы изотоптың ^{8}Be ($t_{1/2} = 6.7\times10^{-17}$ s) синтезіне, одан кейін ^{8}Be(n,γ)^{9}Be нейтронының радиациалық қармауына әкеліп соғады. Бұл мақалада біз төменгі астрофизикалық энергиядағы $p^{8}\text{Li} \to {}^{9}\text{Be}\gamma$ реакциясын қарастырамыз, себебі жарияланғанына 20 жыл уақыт болғанына қарамастан «тәжірибелік зеттерулер жоспары» ретінде рөл атқаратын Terasawa et al. фундаменталды жұмысындағы ауыр элементтердің синтезіне алып келетін мәнді үрдістің тізбегіне қосылған. Leistenschneider et al. (2018) жаңа жұмысында келтірілген 2 МэВ-ке дейінгі резонанс құрылымын ескере отырып 10 кэВ-тен 7.0 МэВ-ге дейінгі энергияның аймағы қарастырылған. Бұл реакцияның жылдамдығы 0.01-ден 10 T_9 температура аймағына ғана есептелген. Резонанстар шамалары мен орындарының реакция жылдамдығының формасы мен шамасына әсерінің анализі ұсынылған.

Түйін сөздер: ядролық астрофизика; бастапқы нюклеосинтез; жылулық және астрофизикалық энергиялар; p^{8}Li кластерлі жүйесі; радиациялық қармау; толық кесу.

Джазаиров-Кахраманов А.В.[1,2]*, Имамбеков О.[1,3], Карипбаева Л.Т.[1,2], Стеблякова А.А.[2]

[1]Астрофизический институт В.Г. Фесенкова “НЦКИТ” АКК МИР РК, Алматы, Казахстан;
[2]Международная Академия Информатизации, Алматы, Казахстан;
[3]Казахский национальный университет им. аль-Фараби, Алматы, Казахстан.
E-mail: albert-j@yandex.ru

ЗНАЧЕНИЕ РЕЗОНАНСОВ НА СКОРОСТЬ РЕАКЦИИ ПРИ ^{8}Li(p,γ)^{9}Be ЗАХВАТЕ ДЛЯ СООТВЕТСТВУЮЩЕГО АСТРОФИЗИЧЕСКОГО СИНТЕЗА ^{9}Be

Аннотация: в рамках модифицированной потенциальной кластерной модели с запрещенными состояниями, с классификацией орбитальных кластерных состояний по схемам Юнга, рассмотрены полные сечения радиационного захвата протонов на ^{8}Li при астрофизических энергиях. Перерасчет полных сечений реакции фоторазвала ^{9}Be(γ,p_0)^{8}Li используется для получения экспериментальных данных. Были определены параметры гауссовых потенциалов для радиационного захвата ^{8}Li(p,γ)^{9}Be при астрофизических энергиях. В то же время в [Shoda, Tanaka (1999)] экспериментально исследованы различные бинарные каналы фоторасщепления ^{9}Be: ^{9}Be(γ,p)^{8}Li, ^{9}Be(γ,d)^{7}Li, ^{9}Be(γ,t)^{6}Li, а также ^{9}Be($\gamma,{}^{3}$He)^{6}He. Очевидно, что связанные с ними детальным равновесием процессы двухчастичного радиационного захвата приводят к синтезу ^{9}Be и требуют соответствующей оценки в контексте астрофизических приложений. При этом следует обратить внимание на то, что первые три реакции имеют кулоновский барьер в каналах p^{8}Li, d^{7}Li и t^{6}Li ниже, чем в ^{3}He^{6}He равно как и ^{4}He^{5}He каналах, а именно в соотношении 3:4. Поперечное сечение ^{8}Li(p,γ)^{9}Be трудно определить непосредственно из-за низкой интенсивности вторичного ^{8}Li пучка и малого сечения при энергиях, представляющих астрофизический интерес. Кроме того, проблема изучения реакции ^{8}Li(p,γ)^{9}Be заключается еще и в том, что прямое экспериментальное измерение сечений оказывается практически невозможным из-за очень малого период полураспада ядра ^{8}Li - 838 мс. Однако, как и в случае n^{8}Li-захвата, могут быть использованы некоторые косвенные методы для извлечения сечения прямого захвата с использованием модели радиационного захвата и спектроскопического фактора. Исследование механизмов образования ^{9}Be имеет прямое отношение к проблеме преодоления массовой щели с $A = 8$ и синтезу более тяжелых элементов в ранней Вселенной, а также в r-процесс нюклеосинтеза в суперновых. В настоящее время сложилось мнение, что ^{9}Be образуется в результате двухступенчатого процесса: радиационный захват альфа-частиц $\alpha(\alpha,\gamma)^{8}$Be приводит к синтезу короткоживущего изотопа ^{8}Be ($t_{1/2} = 6.7 \times 10^{-17}$ s), и далее радиационный захват нейтрона ^{8}Be(n,γ)^{9}Be. В данной статье мы рассматриваем реакцию $p^{8}\text{Li} \to {}^{9}\text{Be}\gamma$ при низких астрофизических энергиях в связи с тем, что она включена в цепочку значимых процессов, которые приводят к синтезу более тяжелых элементов в фундаментальной значимой работе Terasawa et al., которая с момента ее опубликования следующие почти 20 лет играет роль некоторого «плана практических исследований». Рассмотрена область энергий от 10 кэВ до 7.0 МэВ, но с учетом структуры резонансов только до 2 МэВ, которая была приведена в новой работе Leistenschneider et al. (2018). Скорость этой реакции рассчитана в области температур от 0.01 до 10 T_9. Представлен анализ влияния положения и величины резонансов на величину и форму скорости реакции.

Ключевые слова: ядерная астрофизика; первичный нюклеосинтез; тепловые и астрофизические энергии; кластерная система p^{8}Li; радиационный захват; полное сечение.

Information about authors:

Dzhazairov-Kakhramanov A.V. – Candidate of Physical and Mathematical Sciences, Fesenkov Astrophysical Institute. Academician of the European Academy of Natural Sciences (EANS), academician of the International Informatization Academy (IIA), awarded of the European Carl Friedrich Gauss medal, Professor of the Russian Academy of Natural Sciences. albert-j@yandex.ru, https://orcid.org/0000-0001-9207-7192;

Imambekov O. – Candidate of physical and mathematical sciences, assistant professor, vice professor in the chair of theoretical and nuclear physics. His experience of scientific and pedagogical work more than 30 years. Many diplomas, master's thesis were defended under his leadership. In this year, the PhD doctoral candidate is finishing his education and is representing his dissertation work. onlas@mail.ru, https://orcid.org/0000-0002-6238-2441;

Karipbayeva L.T. – Researcher, Fesenkov Astrophysical Institute, academician of the International Informatization Academy. larisa_karipbaeva@mail.ru, https://orcid.org/0000-0003-2730-922X;

Steblyakova A.A. – Researcher, Corresponding member of the International Informatization Academy, awarded of the National Order of Enbek Yzdigi. *a_steblyakova@mail.ru*.

REFERENCES

[1] Terasawa M. et al. (2001) New nuclear reaction flow during r-process nucleosynthesis in supernovae: critical role of light, neutron-rich nuclei, Astrophys. J., 562:470. DOI: 10.1086/323526.

[2] Casal J., Rodr´ıguez-Gallardo M., Arias J.M. (2014) Astrophysical reaction rate for ^{9}Be formation within a three-body approach, Phys. Rev. C, 90:044304. DOI: 10.1103/PhysRev C.90.044304.

[3] Robinson A.E. (2016) Reanalysis of radioisotope measurements of the ^{9}Be $(\gamma,n)^{8}$Be cross section, Phys. Rev. C., 94:024613. DOI: 10.1103/PhysRevC.94.024613.

[4] Casal J., Rodr´ıguez-Gallardo M., Arias J.M., Gómez-Camacho J. (2017) Three-body radiative capture reactions, EPJ Web of Conferences, 165:01010. DOI: 10.1051/epjconf/201716501010.

[5] Arnold C.W. et al. (2012) Cross-section measurement of ^{9}Be $(\gamma,n)^{8}$Be and implications for $\alpha+\alpha+n\rightarrow^{9}$Be in the *r* process, Phys. Rev. C, 85:044605. DOI: 10.1103/PhysRevC.85.044605.

[6] Ishikawal S., Kajino T., Shibagaki Sh., Baha Balantekin A., Michael Famiano A. (2017) Proc. 14th Int. Symp. on Nuclei in the Cosmos (NIC2016) JPS Conf. Proc. P.010406.

[7] Sasaqui T., Kajino T. et al (2005) Sensitivity of *r*-process nucleosynthesis to light-element nuclear reactions, Astrophys. J., 634:1173. DOI: 10.1086/497061.

[8] Shoda K., Tanaka T. (1999) Clusters in the photodisintegration of ^{9}Be, Phys. Rev. C, 59:239. DOI: 10.1103/Phys Rev C.59.239.

[9] Guimaraes V. et al (2008) Transfer reactions in the investigation of light–nuclei nucleosynthesis, Rev. Mexicana Fisica, 54:63–68.

[10] Dubovichenko S.B., Dzhazairov-Kakhramanov A.V. (2016) The reaction ^{8}Li$(n,\gamma)^{9}$Li at astrophysical energies and its role in primordial nucleosynthesis, Astrophys. J., 819:78(8p.). DOI:10.3847/0004-637X/819/1/78.

[11] Li ZH et al. (2013) New determination of the proton spectroscopic factor in ^{9}Be from the ^{13}C(^{9}Be,^{8}Li)^{14}N angular distribution, Phys. Rev. C, 87:017601. DOI: 10.1103/PhysRevC.87.017601.

[12] Kajino T., Boyd R.N. (1990) Production of the light elements in primordial nucleosynthesis, Astrophys. J., 359:267–276. DOI: 10.1086/169060.

[13] Clikeman F.M., Bureau A.J., Stewart M.G. (1962) Photoproton Reaction in Be^{9}, Phys. Rev., 126:1822. DOI: 10.1103/Phys Rev.126.1822.

[14] Komar A.P., Makhnovsky E.D. (1965) Photodisintegration of Be^{9}, Nucl. Phys., 65:662–672. DOI: 10.1016/0029-5582(65)90333-0.

[15] CENTRE FOR PHOTONUCLEAR EXPERIMENTS DATA. 2019; http://cdfe.sinp.msu.ru/exfor/index.php.

[16] Leistenschneider E. et al (2018) Spectroscopy of high-lying resonances in ^{9}Be by the measurement of (p,p), (p,d), and (p,α) reactions with a radioactive ^{8}Li beam, Phys. Rev. C, 98:064601. DOI: 10.1103/PhysRevC.98.064601.

[17] Dubovichenko S.B. (2019) Radiative neutron capture. Primordial nucleosynthesis of the Universe. First English edition. Walter de Gruyter GmbH, Berlin/Munich/Boston. DOI: 10.1515/9783110619607-202.

[18] Neugart R. et al. (2008) Precision Measurement of ^{11}Li Moments: Influence of Halo Neutrons on the ^{9}Li Core, Phys. Rev. Lett., 101:132502. DOI: 10.1103/PhysRevLett.101.132502.

[19] Mukhamedzhanov A. M et al (2003) Asymptotic normalization coefficients from proton transfer

reactions and astrophysical S factors for the CNO $^{13}C(p,\gamma)^{14}N$ radiative capture process, Nucl. Phys. A, 725:279–294. DOI:10.1016/S0375-9474(03)01618-X.

[20] Plattner G.R., Viollier R.D. (1981) Coupling constants of commonly used nuclear probes, Nucl. Phys. A., 365:8–12. DOI: 10.1016/0375-9474(81)90384-5.

[21] Su Jun et al (2006) Astrophysical Reaction Rates of the $^{8}Li(p,\gamma)^{9}Be_{g.s.}$ Direct Capture Reaction, Chin. Phys. Lett., 23:55. DOI: 10.1088/0256-307X/23/1/017.

[22] Camargo O. et al (2008) The $^{9}Be(^{8}Li,^{9}Be)^{8}Li$ elastic-transfer reaction, Phys. Rev. C, 78:034605. DOI: 10.1103/PhysRevC.78.034605.

[23] Nollett K.M., Wiringa R.B. (2011) Asymptotic normalization coefficients from *ab initio* calculations, Phys. Rev. C., 83:041001(R). DOI: 10.1103/PhysRevC.83.041001.

[24] Neudatchin V.G., Smirnov Yu.F. (1969) Nucleon associations in light nuclei. Nauka, Moscow. (in Russ.).

[25] Raimondi F. et al (2016) Deuteron-induced nucleon transfer reactions within an *ab initio* framework: First application to *p*-shell nuclei, Phys. Rev. C, 93:054606. DOI: 10.1103/PhysRevC.93.054606.

[26] Nortershauser W. et al (2009) Nuclear Charge Radii of $^{7,9,10}Be$ and the One-Neutron Halo Nucleus ^{11}Be, Phys. Rev. Lett., 102:062503. DOI: 10.1103/PhysRevLett.102.062503.

[27] Caughlan G.R., Fowler W.A. (1988) Thermonuclear reaction rates V, Atom. Data Nucl. Data Tab. 40:283. DOI: 10.1016/0092-640X(88)90009-5.

[28] Lichtenthäler R. et al (2010) The Research Program at RIBRAS (Radioactive Ion Beams in Brasil)-III, AIP, Int. Symp. Exotic Nucl., Eds. Yu.E. Penionzhkevich and S.M. Lukyanov, DOI: 10.1063/1.3431452.

МАЗМҰНЫ

ФИЗИКА

ИНФОРМАТИКА

МАТЕМАТИКА

СОДЕРЖАНИЕ

ФИЗИКА

ИНФОРМАТИКА

МАТЕМАТИКА

CONTENTS

PHYSICS

COMPUTER SCIENCE

MATHEMATICS

Publication Ethics and Publication Malpracticein the journals of the National Academy of Sciences of the Republic of Kazakhstan

For information on Ethics in publishing and Ethicalguidelines for journal publication see http://www.elsevier.com/publishingethics and http://www.elsevier.com/journal-authors/ethics.

Submission of an article to the National Academy of Sciences of the Republic of Kazakhstan implies that the described work has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis or as an electronic preprint, see http://www.elsevier.com/postingpolicy), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any otherlanguage, including electronically without the written consent of the copyright-holder. In particular, translations into English of papers already published in another language are not accepted.

No other forms of scientific misconduct are allowed, such as plagiarism, falsification, fraudulent data, incorrect interpretation of other works, incorrect citations, etc. The National Academy of Sciences of the Republic of Kazakhstan follows the Code of Conduct of the Committee on Publication Ethics (COPE), and follows the COPE Flowcharts for Resolving Cases of Suspected Misconduct (http://publicationethics.org/files/u2/New_Code.pdf). To verify originality, your article may be checked by the Cross Check originality detection service http://www.elsevier.com/editors/plagdetect.

The authors are obliged to participate in peer review process and be ready to provide corrections, clarifications, retractions and apologies when needed. All authors of a paper should have significantly contributed to the research.

The reviewers should provide objective judgments and should point out relevant published works which are not yet cited. Reviewed articles should be treated confidentially. The reviewers will be chosen in such a way that there is no conflict of interests with respect to the research, the authors and/or the research funders.

The editors have complete responsibility and authority to reject or accept a paper, and they will only accept a paper when reasonably certain. They will preserve anonymity of reviewers and promote publication of corrections, clarifications, retractions and apologies when needed. The acceptance of a paper automatically implies the copyright transfer to the National Academy of Sciences of the Republic of Kazakhstan.

The Editorial Board of the National Academy of Sciences of the Republic of Kazakhstan will monitor and safeguard publishing ethics.

Правила оформления статьи для публикации в журнале смотреть на сайтах:

www:nauka-nanrk.kz

http://physics-mathematics.kz/index.php/en/archive

ISSN2518-1726 (Online),
ISSN 1991-346X (Print)

Редакторы: *М.С. Ахметова, А. Ботанқызы, Д.С. Аленов, Р.Ж. Мрзабаева*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 15.08.2021.
Формат 60х881/8. Бумага офсетная. Печать –ризограф.
4,6 п.л. Тираж 300. Заказ 4.

Национальная академия наук РК
050010, Алматы, ул. Шевченко, 28, т. 272-13-19