ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

2022 • 4

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

REPORTS

OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN

PUBLISHED SINCE JANUARY 1944

ALMATY, NAS RK

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ 2022 • 4

«Қазақстан Республикасы Ұлттық ғылым академиясының баяндамалары»
ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)
Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» Республикалық қоғамдық бірлестігі (Алматы қ.). Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ93VPY00025418** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *өсімдік шаруашылығы, экология және медицина саласындағы биотехнология және физика ғылымдары.*
Мерзімділігі: жылына 4 рет. Тиражы: 300 дана.
Редакцияның мекен-жайы: 050010, Алматы қ., Шевченко көш., 28; 219 бөл.; тел.: 272-13-19
http://reports-science.kz/index.php/en/archive

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

ДОКЛАДЫ **2022 • 4**
НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН

Доклады Национальной академии наук Республики Казахстан»
ISSN 2518-1483 (Online), ISSN 2224-5227 (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 **№ KZ93VPY00025418,** выданное 29.07.2020 г.
Тематическая направленность: *биотехнология в области растениеводства, экологии, медицины и физические науки.*
Периодичность: 4 раз в год. Тираж: 300 экземпляров
Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28; ком. 219; тел. 272-13-19
http://reports-science.kz/index.php/en/archive

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

REPORTS **2022 • 4**

OF NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN

Reports of the National Academy of Sciences of the Republic of Kazakhstan.
ISSN 2518-1483 (Online), ISSN 2224-5227 (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. KZ93VPY00025418,** issued 29.07.2020.
Thematic scope: *biotechnology in the field of crop research, ecology and medicine and physical sciences.*
Periodicity: 4 times a year. Circulation: 300 copies.
Editorial address: 28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19
http://reports-science.kz/index.php/en/archive

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

REPORTS OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN
https://doi.org/10.32014/2022.2518-1483.175
Volume 4, 108-125

UDC 539.17.01; 539.17.02

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NEW RESULTS FOR $^2H(n,\gamma)^3H$ AND $^2H(p,\gamma)^3He$ REACTION RATES AT ASTROPHYSICAL ENERGIES

Abstract. The reactions $^2H(n,\gamma)^3H$, $^2H(p,\gamma)^3He$ are of significant interest both for nuclear astrophysics and in the field of controlled thermonuclear fusion. This is due to the fact that they can proceed intensively at sufficiently low temperatures, since the first one has a minimum Coulomb barrier, while the second one has no Coulomb barrier at all.

Therefore, in the presented work we have studied reaction rates of the neutron and proton capture reactions $^2H(n,\gamma)^3H$, $^2H(p,\gamma)^3He$, within the framework of the modified potential cluster model with allowed and forbidden states which follow from the classification orbital states of the clusters according to the Young tableaux. It is shown that on the basis of potentials that are consistent with the bound state energies and the asymptotic normalizing constant values one can obtain the total cross-sections and the astrophysical S-factors for the nuclear systems under consideration.

$^2H(n,\gamma)^3H$ reaction is considered at energies from 10 meV (0.01 eV) to 10 MeV and the $^2H(p,\gamma)^3He$ reaction – at energies from 1 keV to 10 MeV. The comparisons of the total cross-section (for the n^2H radiative capture) and the astrophysical S-factor (for the p^2H radiative capture) found by us with other experimental and calculation results are given in the work. On the basis of theoretical total cross sections, these reaction rates have been calculated in the temperature range from 0.01 T_9 to 10 T_9. The comparisons of the rates found by us with the rates obtained by other authors are presented in the work. The results for the rates are approximated by simple expressions, which simplify their use in applied thermonuclear and astrophysical researches.

Key words: Nuclear astrophysics, primordial nucleosynthesis, light atomic nuclei, low and astrophysical energies, radiative capture, thermonuclear processes, potential cluster model.

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АСТРОФИЗИКАЛЫҚ ЭНЕРГИЯЛАРДАҒЫ ^{2}H(n,γ)^{3}H ЖӘНЕ ^{2}H(p,γ) РЕАКЦИЯ ЖЫЛДАМДЫҒЫНЫҢ ЖАҢА НӘТИЖЕЛЕРІ

Аннотация. ^{2}H(p,γ)^{3}He, ^{2}H(n,γ)^{3}H реакциялары ядролық астрофизика үшін де, басқарылатын термоядролық синтез саласында да маңызды қызығушылық тудырады. Бұл олардың жеткілікті төмен температурада қарқынды жүруіне байланысты, өйткені біріншісінде минималды кулондық тосқауыл бар, ал екіншісінде кулондық кедергі мүлдем жоқ. Сондықтан, бұл жұмыста авторлар рұқсат етілген және тыйым салынған күйлері бар және Юнг схемасы бойынша кластерлердің орбиталық күйлерін жіктейтін модификацияланған потенциалды кластерлік модель аясында ^{2}H(n,γ)^{3}H, ^{2}H(p,γ)^{3}He нейтрондар мен протондардың қармау реакцияларының жылдамдығын зерттейді. Байланысты күйлердің энергиясымен және асимптотикалық нормалау тұрақтыларының мәндерімен сәйкес келетін потенциалдар негізінде қарастырылып отырған ядролық жүйелер үшін толық Қималар мен астрофизикалық S-факторларын алуға болатындығы көрсетілген.

^{2}H(n,γ)^{3}H реакциясы 10 МэВ (0.01 эВ) -ден 10 МэВ-ке дейінгі энергияларда, ал ^{2}H(p,γ)^{3}He реакциясы 1 кэВ-тен 10 МэВ-ке дейінгі энергияларда зерттелді. Жұмыста табылған толық қималарды (n^{2}H радиациялық қармау үшін) және астрофизикалық S-факторларды (p^{2}H радиациялық қармау үшін) басқа эксперименттік және есептік нәтижелермен салыстыру келтірілген. Теориялық толық қималар негізінде бұл реакциялардың жылдамдығы 0.01 T_9-дан 10 T_9-ға дейінгі температура аралығында есептелді. Бұл реакциялардың жылдамдығын басқа авторлар алған жылдамдықтармен салыстыра ұсынылған. Жылдамдықтар үшін есептелген нәтижелер қарапайым өрнектермен жуықталады, бұл оларды қолданбалы термоядролық және астрофизикалық зерттеулерде қолдануды жеңілдетеді.

Түйін сөздер: ядролық астрофизика, біріншілік нуклеосинтез, жеңіл атомдық ядролар, төмен және астрофизикалық энергиялар, радиацияны түсіру, термоядролық процестер, потенциалды кластерлік модель.

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НОВЫЕ РЕЗУЛЬТАТЫ ДЛЯ СКОРОСТЕЙ $^2H(n,\gamma)^3H$ И $^2H(p,\gamma)^3He$ РЕАКЦИЙ ПРИ АСТРОФИЗИЧЕСКИХ ЭНЕРГИЯХ

Аннотация. Реакции $^2H(p,\gamma)^3He$, $^2H(n,\gamma)^3H$ представляют существенный интерес как для ядерной астрофизики, так и в области управляемого термоядерного синтеза. Это обусловлено тем, что они могут интенсивно протекать при достаточно низких температурах, поскольку первая имеет минимальный кулоновский барьер, а вторая вовсе не имеет кулоновского барьера.

Поэтому в данной работе нами изучены скорости реакций захвата нейтронов и протонов $^2H(n,\gamma)^3H$, $^2H(p,\gamma)^3He$ в рамках модифицированной потенциальной кластерной модели с разрешенными и запрещенными состояниями и с классификацией орбитальных состояний кластеров по схеме Юнга. Показано, что на основе потенциалов, согласующихся с энергиями связанных состояний и значениями асимптотических нормировочных констант, можно получить полные сечения и астрофизические S-факторы для рассматриваемых ядерных систем.

Реакция $^2H(n,\gamma)^3H$ изучалась при энергиях от 10 мэВ (0.01 эВ) до 10 МэВ, а реакция $^2H(p,\gamma)^3He$ – при энергиях от 1 кэВ до 10 МэВ. В работе приведены сравнения найденных нами полных сечений (для радиационного захвата n^2H) и астрофизических S-факторов (для радиационного захвата p^2H) с другими экспериментальными и расчетными результатами. На основе теоретических полных сечений были рассчитаны скорости этих реакций в интервале температур от 0.01 T_9 до 10 T_9. В работе представлены сравнения найденных нами скоростей реакций, со скоростями, полученными другими авторами. Расчетные результаты для скоростей аппроксимируются простыми выражениями, что упрощает их использование в прикладных термоядерных и астрофизических исследованиях.

Ключевые слова: ядерная астрофизика, первичный нуклеосинтез, легкие атомные ядра, низкие и астрофизические энергии, радиационный захват, термоядерные процессы, потенциальная кластерная модель.

Introduction. Astrophysical aspects. The radiative capture reaction $n^2H\rightarrow{}^3H\gamma$ at astrophysical energies with formation of the long-lived unstable tritium nucleus plays a role in some models of the Big Bang. In such models it is assumed that primordial nucleosynthesis proceeded, for example, according to a chain of nuclear reactions of the form $^{1}H(n,\gamma)^{2}H(n,\gamma)^{3}H(^{2}H,n)^{4}He(^{3}H,\gamma)^{7}Li(n,\gamma)^{8}Li$, etc.

As is well known, the thermonuclear process of $p+^{2}H\rightarrow^{3}He+\gamma$ radiative capture is the first nuclear reaction of the proton-proton (pp) cycle, which takes place as a result of electromagnetic interactions and weakens the observed rate of heating of the Sun and the majority of stars of the Main Sequence of our Universe. In the pp cycle, the process of the proton radiative capture on ^{2}H is important for the transition from primordial fusion of protons $p+p\rightarrow^{2}H+e^{-}+\upsilon_{e}$, which proceeds due to weak interactions, to one of the final two ^{3}He nuclei in the pp chain of the capture reaction: $^{3}He+^{3}He\rightarrow^{4}He+2p$, proceeding due to strong interactions. A detailed study of the $p^{2}H$ radiative capture reaction continues without letup and at the beginning of the 2000's decade, thanks to the European project LUNA, new experimental data have been obtained for the astrophysical S-factor at energies from 2.5 keV.

Nuclear aspects. One extremely successful line of development of nuclear physics in the last 50-60 years has been the microscopic model known as the Resonating Group Method (RGM) and the associated with it models, for example, Generator Coordinate Method or algebraic version of RGM. However, the rather difficult RGM calculations are not the only way to explain the available experimental facts. The possibilities offered by a simple two-body potential cluster model (PCM) have not been studied fully up to now, particularly if it uses the concept of forbidden states (FSs). The potentials of this model for discrete spectrum are constructed in order to correctly reproduce the main characteristics of the bound states (BSs) of light nuclei in cluster channels. In the continuous spectrum they directly take into account the resonance behavior of the elastic scattering phase shifts of the interactive particles at low energies (Dubovichenko, 2019, 2015).

It is enough to use the simple PCM with FSs taking into account the described methods of construction of potentials and classification of the orbital states according to Young diagrams for consideration many problems of nuclear physics of low energy and nuclear astrophysics. Such a model can be called a modified PCM (MPCM). In many cases, such an approach, as has been shown previously, allows one to obtain adequate results in the description of many experimental studies for the total cross sections of the thermonuclear reactions at low and astrophysical energies (Dubovichenko, 2019, 2015).

In the present paper, we consider the reaction rate of the $n+2H\rightarrow3H\gamma$ capture in the low energy range on the basis of the same MPCM, which takes into account the supermultiplet symmetry of the wave function (WF) with classification of the orbital states according to Young diagrams. Such an approach makes it possible to analyze the structure of the intercluster interactions, and to determine the existence and positions of allowed and forbidden states in the intercluster potentials (Dubovichenko, 2019, 2015). We have already used this approach to describe more than 30 cluster systems (Dubovichenko, 2019, 2015).

We have already considered the process $^{2}H(p,\gamma)^{3}He$ at astrophysical energies in several works, beginning in 1995 (Dubovichenko, 1995) and extending up to 2009 (Dubovichenko et. al., 2009). These results were then presented in the monographs (Dubovichenko, 2019, 2015). But we never previously investigated the rate of this reaction, which we will now do here on the basis of the MPCM, used in all of our previous work, with classification of orbital states according to Young diagrams and leading to allowed states (ASs) and FSs (Dubovichenko, 2019, 2015).

Model and calculation methods. The nuclear part of the intercluster interaction potential, which depends on set of quantum numbers JLS, for carrying out calculations of photonuclear processes in the considered cluster systems. It has the form

$$V_{JLS\{f\}}(R) = V_0(JLS\{f\})\exp[-\alpha(JLS\{f\})r^2] +$$
$$+ V_1(JLS\{f\})\exp[-\beta(JLS\{f\})r^2], \qquad (1)$$

with Coulomb term of the potential of point-like form.

The dimensionless asymptotic constant C_w (AC) for any ground state (GS) potential was calculated using the asymptotics of the WF having a form of the exact Whittaker function

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

where $\chi_L(r)$ is the numerical WF of the BS, obtained from the solution for the radial Schrödinger equation and normalized to unity, the value $W_{-\eta L+1/2}$ is the Whittaker function of the BS, determining the asymptotic behavior of the WF, which is the solution of the same equation without the nuclear potential. k_0 is the wave number, caused by the channel binding energy E: $k_0 = \sqrt{2\mu \frac{m_0}{\hbar^2} E}$; η is the Coulomb parameter $\eta = \frac{\mu Z_1 Z_2 e^2}{\hbar^2 k}$, determined numerically $\eta = 3.44476 \cdot 10^{-2} \frac{\mu Z_1 Z_2}{k}$ and L is the orbital angular momentum of the BS. Here in this equation μ is the reduced mass, and the constant $\hbar^2/m_0$ is assumed to be 41.4686 fm^2, where m_0 is the atomic mass unit (amu). The magnetic moment of neutron equals $\mu_n = -1.91304272\mu_0$, of the proton $\mu_p = 2.792847\mu_0$, for ^2H nucleus $\mu(^2H) = 0.8574382338\ \mu_0$, where μ_0 is the nuclear magneton. Slightly transformed expressions (Dubovichenko, 2019, 2015) were used for total cross sections of the electromagnetic transitions.

Here we also use the relationship

$$A_{NC}^2 = S_f \times C^2, \qquad (3)$$

where A_{NC} is the asymptotic normalization coefficient (ANC), S_f is the spectroscopic factor of the GS, C is the asymptotic constant in $fm^{-1/2}$, which is related to the dimensionless AC C_w, used by us in the following way: $C = \sqrt{2k_0} C_W$.

The total radiative capture cross sections □(NJ,J_f) for the EJ and MJ transitions in the case of the PCM are given, for example, in (Dubovichenko, 2019, 2015) are written as:

$$\sigma_c(NJ,J_f) = \frac{8\pi K e^2}{\hbar^2 q^3} \frac{\mu}{(2S_1+1)(2S_2+1)} \frac{J+1}{J[(2J+1)!!]^2} \times A_J^2(NJ,K) \sum_{L_i,J_i} P_J^2(NJ,J_f,J_i) I_J^2(J_f,J_i) \qquad (4)$$

where σ_c – total radiative capture cross section; μ – reduced mass of initial channel particles; q – wave number in initial channel; S_1, S_2 – spins of particles in initial channel; K, J – wave number and momentum of γ -quantum in final channel; N – is the E or M transitions of the J multipole ordered from the initial J_i to the final J_f nucleus state.
The value P_J for electric orbital EJ(L) transitions has the form (Dubovichenko, 2019, 2015):

$$P_J^2(EJ,J_f,J_i) = \delta_{S_iS_f}[(2J+1)(2L_i+1)(2J_i+1)(2J_f+1)](L_i 0 J 0 | L_f 0)^2 \begin{Bmatrix} L_i & S & J_i \\ J_f & J & L_f \end{Bmatrix}^2 ,$$
$$A_J(EJ,K) = K^J \mu^J \left(\frac{Z_1}{m_1^J} + (-1)^J \frac{Z_2}{m_2^J}\right), \quad I_J(J_f,J_i) = \langle \chi_f | r^J | \chi_i \rangle . \qquad (5)$$

Here, S_i, S_f, L_f, L_i, J_f, and J_i – total spins, angular and total moments in initial (i) and final (f) channels; m_1, m_2, Z_1, Z_2 – masses and charges of the particles in initial channel; I_J –integral over WFs of initial χ_i and final χ_f states, as functions of clusters (composed of ^{2}H and n or p) relative motion with intercluster distance R.

For consideration of the M1(S) magnetic transition, caused by the spin part of magnetic operator, it is possible to obtain an expression (Dubovichenko, 2019, 2015):

$$P_1^2(M1,J_f,J_i) = \delta_{S_iS_f}\delta_{L_iL_f}\left[S(S+1)(2S+1)(2J_i+1)(2J_f+1)\right] \begin{Bmatrix} S & L & J_i \\ J_f & 1 & S \end{Bmatrix}^2 ,$$
$$A_1(M1,K) = i\frac{\hbar K}{m_0 c}\sqrt{3}\left[\mu_1 \frac{m_2}{m} - \mu_2 \frac{m_1}{m}\right], \quad I_J(J_f,J_i) = \langle \chi_f | r^{J-1} | \chi_i \rangle \quad J = 1. \qquad (6)$$

Here, m is the mass of the nucleus, and μ_1 and μ_2 are the magnetic moments of the clusters.

The construction methods used here for intercluster partial potentials at the given orbital moment L, are expanded in (Dubovichenko, 2019, 2015) and would not be topic of discussion further. The next values of particle masses are used in the given calculations: m_n = 1.008664916 amu, m_p = 1.00727646577 amu, m(^{2}H) = 2.014102 amu, and for 1 amu energy equivalent of 931.4941024 MeV is used.

Results and discations. Capture reaction $^2H(n,\gamma)^3H$. n^2H interaction potentials. To calculate radiative capture in cluster systems, the nuclear part of the intercluster potential of the n^2H interactions is represented in the form (1) with a Gaussian attractive part V_0 and a Gaussian repulsive part V_1 (Dubovichenko, 2019, 2015). Young-diagrams-mixed potentials of the p^2H interaction were obtained for the scattering processes whose parameters are shown in the first two rows of Table 1. Details of the classification of states according to Young diagrams for the n^2H system are given in (Dubovichenko, 2019, 2015). Pure scattering phase shifts with the {3} diagram were subsequently identified in the doublet channel, and on the basis of these phase shifts Young diagram pure potentials of the intercluster ^2S-interaction in the GS of the ^3He nucleus in the p^2H channel were constructed. These parameters are listed in the third row of Table 1 and in (Dubovichenko, 2019, 2015). Total cross sections of p^2H radiative capture and astrophysical S-factors were calculated at energies down to 10 keV (Dubovichenko, 2019, 2015). Parameters of the GS potential of ^3H in the n^2H system were adjusted somewhat to obtain a correct description of the binding energy of tritium, which is equal to – 6.257233 MeV. As a result, the parameters were obtained that are shown in the last row of Table 1 – such a potential reproduces the energy of the n^2H system exactly.

To check the behavior of the wave function of the BS at large distances, the AC C_w with the asymptotic limit of the WF in the form of the exact Whittaker function $\chi_L(R) = \sqrt{2k_0}C_w W_{-\eta L+1/2}(2k_0 R)$ (2) was calculated earlier, where χ is the numerical wave function of the bound state, obtained by solving the radial Schrödinger equation and normalized to unity, W is the Whittaker function of the bound state, defining the asymptotic behavior of the WF and being the solution of the same equation without the nuclear potential, i.e., the solution at large distances, k_0 is the wave number corresponding to the channel binding energy, □ is the Coulomb parameter, equal in the given case to zero, and L is the orbital angular momentum of the bound state. The asymptotic constants for such GS potentials of ^3He in the p^2H channel and of ^3H in the n^2H channel, obtained on the interval 10–30 fm, are listed in Table 1. The error of the constant is found by averaging it over the indicated interval of distances.

Table 1. Doublet interaction potentials of p^2H and n^2H systems (Dubovichenko et. al., 2020), mixed in Young diagrams {f} for scattering processes.

System	$^{(2S+1)}L\{f\}$	V_0, MeV	α	V_1, MeV	β	E_{BS}, MeV	E_{exp}, MeV	C_w
p^2H	^2S {3}+{21}	55.0	0.2	–	–	–	–	–
	^2P {3}+{21}	10.0	0.16	+0.6	0.1	–	–	–
	^2S {3}	41.55562462	0.2	–	–	-5.493423	-5.493423	2.095(5)
n^2H	^2S {3}+{21}	57.0	0.2	–	–	–	–	–
	^2S {3}	41.42616550	0.2	–	–	-6.257233	-6.257233	2.05(1)

Remark. Here E_{BS} is the energy of the bound state of the ^3He nucleus in the p^2H channel and of ^3H in the n^2H channel, E_{exp} is its experimental value, and C_w is the dimensionless asymptotic constant.

Neutron radiative capture on ^{2}H. In the present work we consider results for n^{2}H capture, when the negative sign of the magnetic moment is taken into account (Dubovichenko, 2019, 2015). Using the parameters of the p^{2}H nuclear potentials for the ^{2}S- and ^{2}P-scattering waves from Table 1 without the Coulomb term and the GS from the last row of Table 1, we calculated the total n^{2}H radiative capture cross sections in the energy range extending from 10 meV to 10 MeV. The results of this calculation for the sum of E1- and M1-transitions are shown in Fig. 1 by the double dash-dot curve. It turned out that at energies around 10 meV, the calculated cross sections are somewhat larger than the values measured in the experiments (Trail et. al., 1964). But at 25.3 meV they are somewhat less in comparison with the thermal cross sections from (Jurney et. al., 1982), for which the value 508(15) μb is given. In the most recent data for the thermal energy (Firestone et. al., 2016) the value 489(6) μb was obtained, which differs insignificantly from the previous results (these data are represented in Fig. 1 by an open triangle). The scattering phase shift of such a ^{2}S-wave p^{2}H scattering potential, determining the M1-transition, is plotted in Fig. 2 by the dashed curve. We emphasize that for the calculations of the M1-transition, we used the p^{2}H potential for ^{2}S scattering wave No. 1 from Table 1 without the Coulomb term, but the spread of the various experimental data over phase shifts of elastic p^{2}H-scattering, which are represented in Fig. 2 by points, reaches 20–30% (Schmelzbach et. al., 1972; Huttel et. al., 1983). As a result, even the p^{2}H scattering potential, whose phase shift is plotted in Fig. 2 by the dashed curve, is constructed on the basis of these data with large uncertainties.

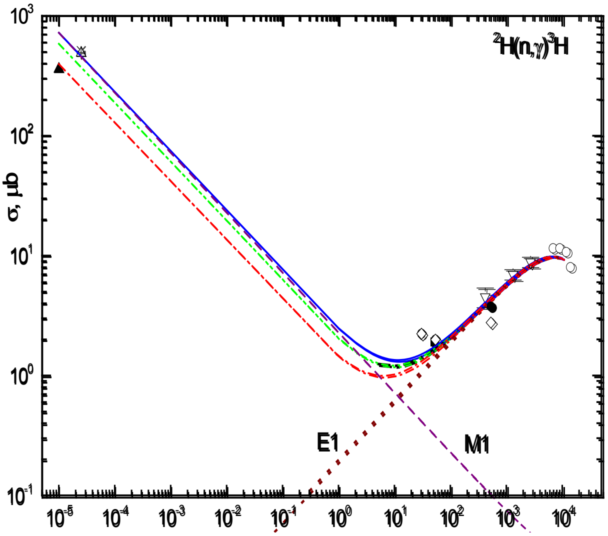

Figure 1. Total cross sections of n^{2}H radiative capture. Experimental results are from the indicated sources: (Nagai et. al., 2006) – points at energies 30, 55, and 530 keV, (Mitev et. al., 1986) – circles at energies in the range 7–14 MeV, (Trail et. al., 1964) – triangle at 10 meV, (Trail et. al., 1964) – asterisk at 25.3 meV, (Ohsaki et. al., 2008) – filled square at 50 keV, (Firestone et. al., 2016) – open triangle at 25.3 meV, (Nagai et. al., 1998) – open rhombuses, and data obtained from photo-breakup – inverted triangles from (Bosch et. al., 1964). Curves are explained in the text.

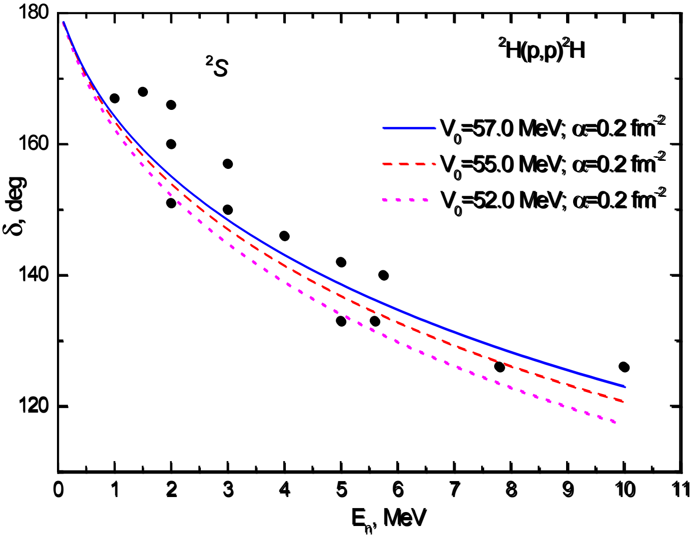

Figure 2. ^{2}S-phase shifts of p^{2}H elastic scattering (dashed curve and dotted curve) and n^{2}H-scattering (solid curve). The experimental data were taken from (Schmelzbach et. al., 1972; Huttel et. al., 1983). The potential parameters are given in Table1.

In connection with this, we considered changes which are needed for the p^{2}H potential in the ^{2}S scattering wave so that it can describe the available experimental data for n^{2}H-capture at 25.3 meV. As a result, we obtained results for the total cross section which are plotted in Fig. 1 by the solid curve with the dotted curve and the dashed curve representing the total cross sections for the E1 and M1 processes. For the depth of the ^{2}S-potential in p^{2}H-elastic scattering, we obtained the parameters shown in Table 1 in the second-to-the-last row. These results provide a good description of the available data at the thermal energy, but the ^{2}S-phase shift of the potential of p^{2}H elastic scattering is plotted in Fig. 2 by the solid curve – it lies entirely inside the band of experimental error. Such a small change in the parameters has a marked effect on the results of the calculation of total cross sections for the M1 process, but this small change in the parameters can be explained by the uncertainty of the available p^{2}H phase shifts and their absence for n^{2}H scattering. As a result, the implemented model was able to reproduce the available data in an energy range whose end points differ by more than nine orders of magnitude: from 10^{-5} to 10^4 keV.

In order to correctly describe the data at 10 meV shown in Fig. 1 by the filled triangle, it is necessary to decrease the depth of the ^{2}S-potential of p^{2}H-scattering to 52 MeV. The result of this calculation of the total cross section is plotted in Fig. 1 by the dash-dot curve. The scattering phase shift of the potential with such parameters is plotted in Fig. 2 by the dotted curve – it lies markedly lower than the phase shift analysis data (Schmelzbach et. al., 1972). However, for final conclusions about agreement of such a potential with the phase shifts, results of a phase shift analysis of specifically n^{2}H scattering are needed, which at the present time are lacking.

Since at energies from 10^{-5} to 0.1 keV the calculated cross section plotted in Fig. 1 by the solid curve is practically a straight line, it can be approximated by a simple function of the form

$$\alpha_{\text{ap}}(\mu\text{b}) = \frac{A}{\sqrt{E_n(\text{keV})}} . \qquad (7)$$

The value of the constant A = 2.286 μb·keV$^{1/2}$ was determined from one point in the cross sections at the minimum energy equal to 10^{-5} keV. The absolute value of the deviation from the calculated theoretical cross section of the approximation of this cross section by such a function in the range from 10^{-5} keV to 0.1 keV

$$M(E) = \left|[\sigma_{\text{ap}}(E) - \sigma_{\text{theor}}(E)] / \sigma_{\text{theor}}(E)\right| \qquad (8)$$

does not exceed 1%. It would seem possible to suppose that this form of the dependence of the total cross section on the energy will be preserved at lower energies. Therefore, we estimate the value of the cross section at 1 μeV (10^{-6} eV). We obtain 72.3 mb.

Next, for the total cross sections plotted in Fig. 1 by the solid curve, we have calculated the reaction rate of the n^2H capture reaction. To calculate it, we used the theoretical total cross sections at energies ranging from 10 meV to 10 MeV, and the obtained total reaction rate (see Fig. 3 – the solid curve) grows smoothly at all considered temperatures. The dotted curve, which is in complete agreement with our results at temperatures above 0.5 T_9, plots the capture rate from (Nagai et. al., 1998), which can be parameterized by the expression

$$N_{\text{A}} \langle \sigma v \rangle = 214 \cdot T_9^{0.075} + 742 \cdot T_9 . \qquad (9)$$

The dashed curve in Fig. 3 plots the rate of this reaction from (Fowler et. al., 1967), which is approximated by the form

$$N_{\text{A}} \langle \sigma v \rangle = 66.244 + 1250.157 \cdot T_9 . \qquad (10)$$

and coincides with the same form presented in (Nagai et. al., 1998).

The calculated reaction rate shown by the solid curve in Fig. 3 can be accurately approximated by the function

$$N_A \langle \sigma v \rangle = a_1 / T_9^{2/3} \exp(-a_2 / T_9^{1/3})(1.0 + a_3 T_9^{1/3} + $$
$$+ a_5 T_9 + a_6 T_9^{4/3} + a_7 T_9^{5/3} + a_8 T_9^{6/3}) . \qquad (11)$$

The parameters of this approximation are listed in Table 2.

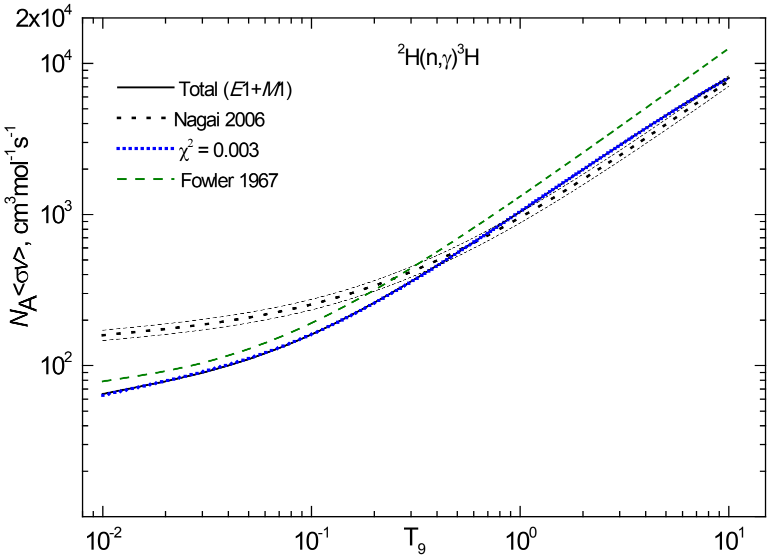

Figure 3. Total reaction rate of n^2H capture. The solid curve plots our results, the dotted curve plots the capture rate from (Nagai et. al., 1998), the thin dashed curves plot the error band from (Nagai et. al., 1998), the dashed curve plots results from (Fowler et. al., 1967), and the individual points plot the approximation of our calculated curve.

Table 2. Parameters of the parametrization given by eq. (11) of the reaction rate (Dubovichenko et. al., 2020).

i	1	2	3	4
a_i	$-0.6042998\cdot10^{-2}$	$0.2190303\cdot10^{0}$	$-0.1708195\cdot10^{4}$	$-0.2118940\cdot10^{5}$
i	5	6	7	8
a_i	$0.1110280\cdot10^{5}$	$-0.7034432\cdot10^{2}$	$-0.2525107\cdot10^{6}$	$0.4864969\cdot10^{5}$

Values of the reaction rate Eq. (11) calculated with these parameters are plotted in Fig. 3 by the tightly dotted curve, which merges with the solid curve with an average chi-square value $\chi^2 = 0.003$. One thousand of the calculation points shown in Fig. 3 were used in the approximation, and to calculate χ^2 the error of the calculated data was taken to be equal to 5%.

Capture reaction $^2H(p,\gamma)^3He$. The p^2H system in the continuous and discrete spectrum. We considered classification of orbital states of clusters according to Young diagrams for the n^2H and p^2H systems (see Sec. 3). We showed that the possible orbital Young diagrams {f} for the system of three nucleons in the 1 + 2 channel of the particle have the form $\{1\}\times\{2\} = \{3\} + \{21\}$ (Dubovichenko et. al., 2009). The first of these is compatible with orbital angular momentum L = 0 and is forbidden in the quartet spin channel (Dubovichenko, 2019, 2015). The second diagram is forbidden in any channel and is compatible with orbital angular momentum L = 1, which is determined on the basis of Elliott's rules. The state for the first Young diagram corresponds to the bound forbidden ground state of the ^3He nucleus in the p^2H channel and has angular momentum and isospin $J^\pi,T = 1/2^-,1/2$ (for the ^2H nucleus the characteristics are known: $J^\pi,T = 1^+,0$). This bound allowed state for the $^2S_{1/2}$ wave (the second Young diagram) corresponds to the GS of the ^{3}He nucleus and has channel binding energy E_0 = –5.493423 MeV.

In the calculations of the nuclear characteristics of the considered reaction, the cluster interaction potentials have the form (1) with a pointlike Coulomb term and a Gaussian attractive part V_0 and a Gaussian repulsive part V_1. The potential is constructed in such a way as to correctly describe the corresponding elastic scattering partial phase shift. Employing these ideas, we obtained potentials of the p^{2}H-interaction for scattering processes whose parameters are given in (Dubovichenko, 2019, 2015; Dubovichenko, 1995; Dubovichenko et. al., 2009) and Table 1. Since we have different Young diagrams in the scattering state and in the BS, we use different potentials for them.

Here it should be noted that starting from our paper (Dubovichenko et. al., 2009) and proceeding further in the papers and reviews (Dubovichenko et. al., 2020), and also in the books (Dubovichenko, 2019, 2015), the form of potential (1) is given with a typographical error. In all of these works, the potential parameters of the P wave for the p^{2}H system, shown in Table 1, are given, but the repulsive part of potential (1) was written in the form of the exponential $V_1\exp(-\beta r)$ and the units indicated for β are fm^{-1}. However, the values of the parameters for the P-wave were obtained and used in all the calculations specifically for the repulsive part as is written above in expression (1). In other words, the numerical values of the parameters for this potential are listed in the works enumerated above and in Table 1 correctly, but the form of the potential should have a Gaussian repulsive component as is written now in expression (1).

To track the behavior of the WFs of the BS at large distances, we calculated the AC C_w with the asymptotic limit of the WF in the form of the Whittaker function (3), whose value in the interval 5–20 fm turned out to be equal to C_w = 2.095(5). The normalized error is determined by averaging the constant over the indicated interval. This constant as determined by the experimental data is found to lie in the interval 1.76–2.35, which is in complete agreement with the obtained results.

Total cross sections and reaction rate of the proton capture on ^{2}H. Previously, in (Dubovichenko et. al., 2009) it was shown that it is possible to consider the astrophysical S-factor of p^{2}H radiative capture in the energy range from 1 keV to 10 MeV on the basis of the E1-transition from the ^{2}P scattering wave to the ^{2}S bound ground state with the potential parameters shown in Table 1. For the S(E1)-factor at 1 keV we obtained the value 0.135 eV·b, which is in overall agreement with the known data. If we take into account the M1 process, then at 1 keV we obtain the total S-factor as being equal to 0.212(5) eV·b. The experimental data of one of the last papers presented in the review (Xu et. al., 2013) give as the value of the total astrophysical factor S(0) = 0.216(10) eV· b. That paper gives the following values of the linear extrapolation parameters: $S(E_{c.m.}) = S_0 + E_{c.m}\cdot S_1$ and S_0 = 0.216(6) eVb and S_1 = 0.0059(4) eV· b· keV^{-1}. The most recent determination of this S(0)-factor gave the value $0.2156\begin{pmatrix}+0.082\\-0.077\end{pmatrix}$ eV·b (Iliadis et. al., 2016), which coincides within the limits of error with the above results of (Xu et. al., 2013). If we change the width of the GS potential indicated in Table 1 by less than 4%, and adopt new parameters

$$V_0 = 40.55868 \text{ MeV and } \alpha = 0.1925 \text{ fm}^{-2}, \tag{12}$$

which lead to the AC being equal to 2.12(1), and the same binding energy, then at 1 keV we obtain the total S-factor as being equal to 0.220(1) eV·b for S(E1) = 0.139(1) eV·b and S(M1) = 0.081(1) eV·b. The potential parameters of the S and P scattering waves listed in Table 1 were left unchanged.

Our new calculations of the energy dependence of the S(E1)-factor of p^{2}H radiative capture for the GS potential given by Eq. (12) and the P-wave potential from Table 1 at energies from 1 keV to 10 MeV are plotted in Fig. 4 by the dashed line. The pink dotted curve in Fig. 4 plots the results of a calculation of the M1 process for the new version of the GS potential with the same S scattering wave potential with the parameters from Table 1. The continuous curve in Fig. 4 plots results for the total S-factor.

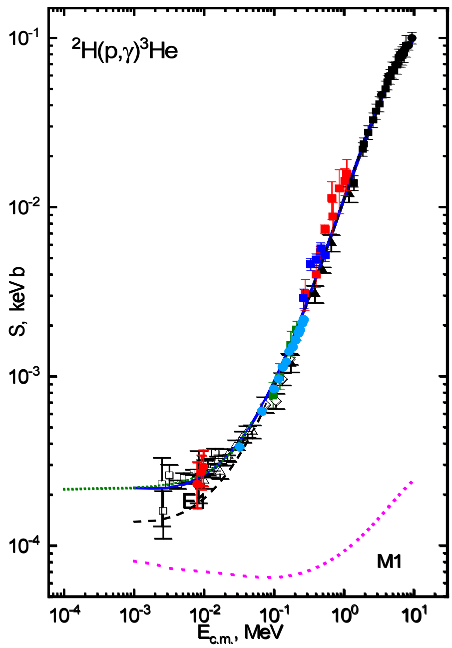

Figure 4. Astrophysical S-factor of the proton radiative capture on ^{2}H in the energy range of 1 keV to 10 MeV for the E1 and M1 transitions. The lines plot the calculations with the potentials indicated in the text. The triangles, open rhombuses, open triangles, open squares, squares, points and red points plot the measurements from corresponding works presented in the review (Xu et. al., 2013). Recent experiments are given by light blue points from (Mossa et. al., 2020), green squares plot the results from (Tišma et. al., 2019), red squares (target No. 3) and blue squares (target No. 4) are from (Turkat et. al., 2021).

The calculated total S-factor at energies down to 50 keV can be approximated by the form:

$$S(E_{c.m.}) = S_0 + E_{c.m.} S_1 + E^2_{c.m.} S_2 + E^3_{c.m.} S_3$$

with the parameters S_0 = 0.21508 eV·b, S_1 = 0.00452 eV·b·keV^{-1}, S_2 = 5.0455·10^{-5} eV·b·keV^{-2}, and S_3 = –1.3778·10^{-7} eV·b·keV^{-}, which lead to a χ^2 value equal to 0.11 for 5% errors in the calculated curve. The results of such a parameterization lead to the value S(0) = 0.216(1) eV□b at 0.1 keV and are plotted in Fig. 4 by the green closely spaced dotted curve. As can be seen, the version of the GS defined by the parameters assigned by Eq. (12) allows one to obtain a value of the S-factor at zero energy (more precisely at 0.1 keV) that coincides almost exactly with the results of (Xu et. al., 2013; Iliadis et. al., 2016).

The value $S_0 = 0.215$ eV□b can also be treated as the value of the S-factor at zero energy and is in good agreement with the results of (Iliadis et. al., 2016), which are equal to $0.2156 \begin{pmatrix} +0.082 \\ -0.077 \end{pmatrix}$ eV□b.

Moreover, our calculations of the proton radiative capture on ^2H for the E1 transition at the energy range down to 10 keV were carried out in 1990 and 1995, when only the experimental data above 150–200 keV was known. It was found that these results well describe the behavior of the S-factor from 10 keV to 200 keV, which was obtained in later measurements in 1997 (Xu et. al., 2013), at the energies down to 10 keV. Thus, using the MPCM with the classification of the orbital states according to Young tableaux allowed us not only to describe available experimental data, but also predicted the behavior of the astrophysical S-factor of the proton radiative capture on ^2H at the energy range from 10–20 to 150–200 keV.

Our next goal in this work was to calculate the reaction rate of p^2H capture. To calculate it, we used the theoretical total cross sections at energies range from 1 keV to 10 MeV, and the total rate so obtained and plotted in Fig. 5 by the continuous curve grows smoothly at all of the considered temperatures. The dotted curve, which agrees best of all with our results, plots the capture rate from the recent paper (Iliadis et. al., 2016), the dashed curve plots the results of (Xu et. al., 2013). This version of the reaction rate lies noticeably lower than our results and the results of (Iliadis et. al., 2016) at temperatures above (0.07–0.1) T_9.

The calculated reaction rate shown in Fig. 5 by the continuous curve can be approximated by the function

$$N_A \langle \sigma v \rangle = a_1 / T_9^{2/3} \exp(-a_2 / T_9^{1/3})(1.0 + a_3 T_9^{1/3} + a_4 T_9^{2/3} + a_5 T_9 + a_6 T_9^{4/3} + a_7 T_9^{5/3} + a_8 T_9^{6/3}) + a_9 / T_9^{a_{10}} \quad (13)$$

The parameters of this approximation are listed in Table 3. The result of calculation of reaction rate (13) with these parameter values is plotted in Fig. 5 by the closely spaced dotted curve, which merges with the continuous curve, with a mean χ^2 value equal to 0.001. The approximation was based on 1000 calculated points, shown in Fig. 5, and to calculate the χ^2 value, the error of the calculated data was taken to be equal to 5%.

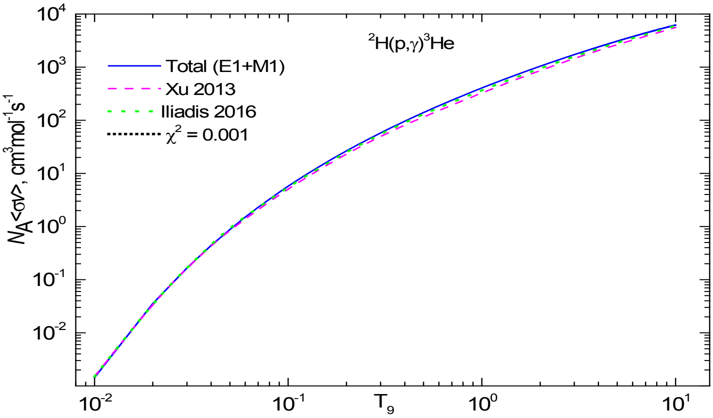

Figure 5. Total reaction rate of the proton capture on ^2H. The continuous curve plots our results, the dotted curve plots the capture rate from (Iliadis et. al., 2016), the dashed curve plots the result from (Xu et. al., 2013), and individual points plot our approximation.

Table 3. Parameters of the parametrization given by Eq. (13) of the reaction rate

i	1	2	3	4	5
a_i	$-0.6626269\cdot10^{-2}$	$0.1751989\cdot10^{1}$	$-0.4456296\cdot10^{4}$	$0.2126028\cdot10^{5}$	$0.4718858\cdot10^{5}$
i	6	7	8	9	10
a_i	$-0.2258075\cdot10^{6}$	$-0.2558771\cdot10^{6}$	$0.6352764\cdot10^{5}$	$-0.3199279\cdot10^{-1}$	$-0.5347412\cdot10^{0}$

Conclusions. $^2H(n,\gamma)^3H$ **reaction**. To summarize, our calculations of total cross sections of the neutron radiative capture on ^2H at energies from 10 meV to 10 MeV are in good agreement overall with the known experimental data. The implemented MPCM with forbidden states and classification of orbital states of the clusters according to Young diagrams, in addition to being able to describe the astrophysical S-factor of the proton capture on ^2H, proved capable of correctly reproducing the overall dependence of the total cross sections of n^2H capture over a very wide energy range. Small changes in the depth of the ^2S potential for this system are entirely admissible since the p^2H-phase shift analysis data contain large uncertainties, and n^2H-phase shift analysis data are in general lacking. Thus, here in comparison with our previous works (Dubovichenko, 2019, 2015) we summarize as follows:

1. Parameters of the S-wave scattering potential have been refined, allowing a better description of the available scattering phase shifts and affording a more accurate description of the values of the total cross section at thermal energies from the new experimental work (Firestone et. al., 2016);

2. The reaction rate has been calculated in the temperature interval $0.01T_9$–$10T_9$ and is in complete agreement with most of other results although at low temperatures of $0.01T_9$–$0.1T_9$ it differs from the results of (Nagai et. al., 1998) by a factor of 2–3;

3. The reaction rate has been approximated by a simple analytical form of Eq.

(11) which simplifies its use in a wide variety of other research efforts and applied problems.

$^{2}H(p,\gamma)^{3}He$ **reaction.** To summarize, comparative simple model concepts allowed us to obtain theoretical results, which are in good agreement with the available experimental data for the astrophysical S-factor of p^2H radiative capture. Here, we have done the following:

1. We have refined the parameters of the GS potential (Eq. (12)), which has made it possible to more accurately describe the magnitude of the S-factor at zero energy from the new experimental work of (Iliadis et. al., 2016).
2. We have parameterized the calculated S-factor at energies down to 50 keV, which allowed us to obtain the value of the S factor at 0 keV and at 0.1 keV.
3. We have calculated the reaction rate in the temperature interval (0.01–10) T_9 and compared it with other results.
4. We have approximated the reaction rate using a simple analytical form Eq. (13) which may be useful in applied studies.
5. We corrected a typographical error (made in some of our previous papers) in the form of the potential for the P wave of the p^2H interactions.

Acknowledgments. *This work was supported by the Grant of Ministry of Education and Science of the Republic of Kazakhstan under the program ИРН BR10965141 «Creation of National Virtual Observatory based on robotic telescopes, Big Data technologies and high-performance computing systems» through the V.G. 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.*

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www:nauka-nanrk.kz
ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)
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Директор отдела издания научных журналов НАН РК *А. Ботанқызы*
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Редакторы: *М.С. Ахметова, Д.С. Аленов*
Верстка на компьютере *Г.Д. Жадырановой*

Подписано в печать 12.12.2022.
Формат 60x88 1/8. Бумага офсетная. Печать - ризограф.
10,5 п.л. Тираж 300. Заказ 4.

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