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NEW RESULTS FOR RADIATIVE P-^{11}B CAPTURE AT LOW ENERGIES

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The results of new measurements of the yields of the ^{11}B(p,γ)^{12}C reaction of radiative capture to the ground and first excited states of ^{12}C are presented. By normalizing these results to the corresponding experimental literature data, differential cross sections have been extracted for the angle 0° and for incident proton energies from 482 to 1337 keV. Based on the obtained differential cross sections and using literature data on the angular distributions of the ^{11}B(p,γ)^{12}C reaction in this energy region, the total cross sections and astrophysical S factors of the ^{11}B(p,γ)^{12}C reaction for transitions to the ground and first excited states of ^{12}C have been determined with a statistical error of less than 10%. The experimental data obtained are well described within the framework of a modified potential cluster model with the classification of orbital states according to Young's diagrams and taking into account allowed and forbidden states. Based on the measured experimental cross sections and using the above theoretical model, the rate of this reaction was calculated in the temperature range from 0 to 100 million degrees of Kelvin. Within the limits of error, the results of this work are consistent with the data of earlier works.

Keywords: *nuclear astrophysics, radiative capture, thermonuclear processes, reaction ^{11}B(p,γ)^{12}C, astrophysical S-factor, nuclear reaction rates.*

INTRODUCTION

In nuclear astrophysics and in the field of controlled thermonuclear fusion, the reaction ^{11}B(p,γ)^{12}C is of significant interest [1]. It is one of the main reactions of ^{11}B burning and ^{12}C production in the Sun and stars. The rate of the ^{11}B(p,γ)^{12}C reaction (which took place in the interiors of first-generation stars) may be of great importance for the amount of ^{11}B observed today in the Earth's crust and in the interstellar medium. Material containing boron (80% - ^{11}B) can be used as neutron absorbers in advanced thermonuclear reactors.

To date, the only experimental work (for the energy range $E_{p,\,lab.}$ = 530–3100 keV, where lab. is a laboratory system) in which a full cycle of measurements has been carried out, and in which the differential and total cross sections of the ^{11}B(p,γ)^{12}C reaction are presented for captures to the ground and first excited states of ^{12}C remains the work [2] published in 1965 (in this work, however, errors are not given). Therefore, in this energy region (at $E_{p,\,lab.}$ = 482 – 1337 keV) we carried out new measurements of cross sections and the astrophysical S-factor of the ^{11}B(p,γ)^{12}Creaction of radiative capture to the ground and first excited states of ^{12}C with a statistical error of less than 10%.

RESEARCH METHODS

The experimental part of our work was performed on the electrostatic tandem accelerator UKP-2-1 of the Institute of Nuclear Physics in Almaty [3]. Protons were accelerated to energies $E_{p,\,lab.}$ = 340–1400 keV. Calibration of proton energies in the beam was made with an uncertainties of ±1 keV according to the ^{19}F(p,αγ)^{16}O and ^{27}Al(p,γ)^{28}Si reactions with many well-separated resonances in the region of $E_{p,\,lab.}$ = 340–1400 keV [4, 5].

In our experiments, the specially made reaction chamber [6] with indium vacuum seals, the water-cooled target holder and a quartz glass for obtaining a luminous image of the beam shape in front of the target was used. By an external handle, the quartz glass could be placed in the course of the beam in front of the target for alignment. The γ-ray registration system was realized by using high-pure Germanium (HpGe) γ-detector with a Ge-crystal of volume 111 cm^3. To reduce the room and cosmic ray background the γ-detector was surrounded by 60 mm - thick lead shield. The resolution of the γ-detector was typically 6.5 keV at E_γ<3000 keV.

Energy calibration of the spectrometer at low energies was carried out using the well-known lines of the γ-source ^{56}Co and background lines of 1461 keV (^{40}K) and 2614 keV (RdTh). For energies from 10 MeV to 18 MeV (the operating gamma quanta energy range of this experiment), calibration was carried out using a procedure for determining the position of the peaks (γ_0 and γ_1) from the ^{11}B(p, γ)^{12}C reaction, taking into account the energy of incident protons, target thickness, and reaction energy Q = 15957 keV [7] and the Doppler effect.

Copper plates (~2 mm thick, ~30 mm long, and ~15 mm wide) were used as target backing. The thicknesses of boron films (about 90% of ^{11}B and about 10% of ^{10}B) deposited on two target backings were 100±10 and 145±15 μg/cm^2, respectively. The first target was used for measurements at $E_{p,\,lab.}$ = 500–1100 keV, and the second at $E_{p,\,lab.}$ = 1150–1350 keV.

The detailed description of the reaction chamber and target manufacturing technology can be found in [6, 8, 9].

During the measurements, the γ-detector was at a distance of 11.4 cm from the region where the reaction was localized.

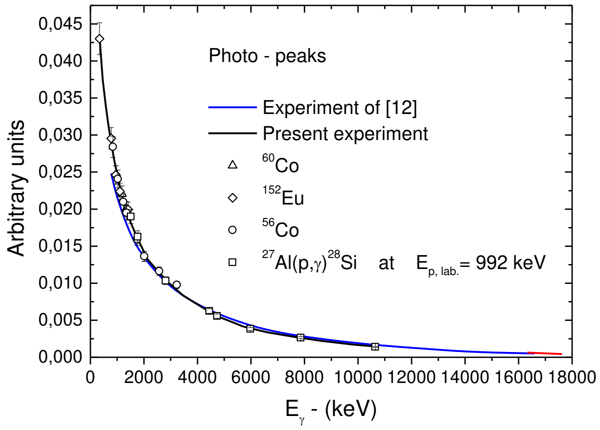
To determine the relative efficiency of the γ-detector in the region of γ-quanta energies from 100 to 3253.6 keV, we used a set of standard gamma sources ^{60}Co, ^{152}Eu and a ^{56}Co source ($T_{1/2}$ = 77 days), the relative intensities of γ lines of which are known with an error of no worse than 4.5% [10]. The relative efficiency of the γ-detector for the energy region from 3253.6 to 10763 keV was determined using the reaction of ^{27}Al(p,γ)^{28}Si at the resonance energy of protons $E_{p,\,lab.}$ = 992 keV. As a result of this reaction, γ lines are emitted in the energy range of 1.8–10.8 MeV, the relative intensities and angular distributions of which are known with an error of no more than 5% (for the main transitions) [11]. In this work, we used the transitions of the ^{27}Al(p,γ)^{28}Si reaction at $E_{p,\,lab.}$ = 992 keV with the following energies: 1522, 1779, 2839, 4497.6, 4743, 6020, 7931 and 10763 keV. For the energy range of gamma quanta from 10763 to 16500 keV, we used the efficiency curve of [12] (in which the geometry of the experiment is similar to ours and in which a gamma detector of the same type as ours was used) normalizing it to our curve for energies from 100 to 10763 keV. Further from 16500 to 17500 keV we made a simple linear extrapolation. Figure 1 shows the relative efficiency curves of the gamma detector used in the measurements and for the geometry of our experiment.

The yields of the ^{11}B(p,γ)^{12}C reaction for the transitions to the ground and first excited states were determined at $E_{p,\,lab.}$ = 500, 750, 800, 1000, 1100, 1150, 1250, 1300 and 1350 keV and at $\theta_{\gamma,\,lab.}$ = 0°.

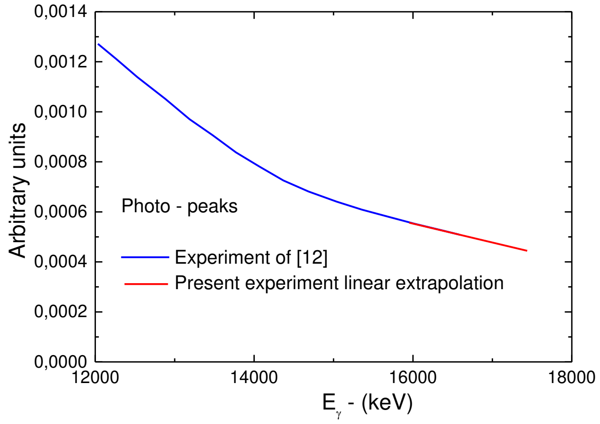
The value of the beam current was ranged from 3 to 8 µA. The energy spread of the beam was determined by the width of the front of ^{27}Al(*p, γ*)^{28}Si reaction yield curve near resonance at $E_{p,\,lab.}$ = 992 keV (resonance width <0.1 keV) and did not exceed 1.5 keV. The accumulated charges on the target were measured with an uncertainty of 3%. Dead-time effects were kept below 1.5% at all beam energies.

Figure 2 shows the γ-ray spectrum obtained at $E_{p,\,lab.}$ = 1350 keV and $\theta_{\gamma,lab.}$ = 0°. Figure 2 shows the photo peaks and single and double leakage peaks of the corresponding gamma transitions.

The number of counts in the spectral peak with the preliminarily subtracted background (with the form of a trapezium) divided by the integrator counter and relative efficiency values was taken as the yield of the ^{11}B(p,γ)^{12}C capture reaction. Statistical uncertainties in the determination of the yields (including uncertainties introduced by backgrounds subtracted) were less than 10%.



a) wide energy range



b) high energies

Figure 1. Relative efficiency curves of the HpGe detector. The black curve and open figures are ours, obtained experimentally, the blue curve is from [12], the red curve is linear extrapolation to the required energy region

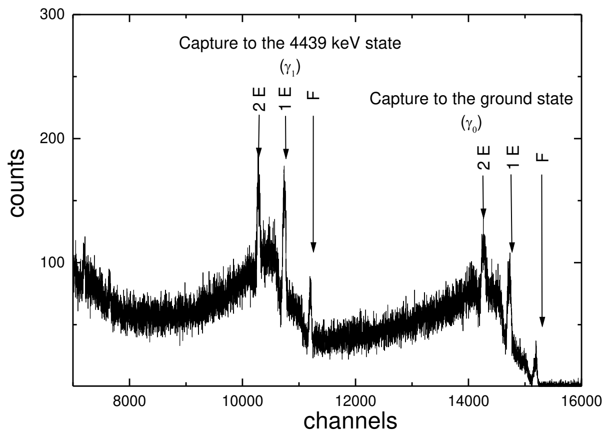


Figure 2. Fragment of the γ-spectrum of ^{11}B(p,γ)^{12}C reaction, obtained at $E_{p,\,lab.}$ = 1350 keV and $\theta_{\gamma,\,lab.}$ = 0°. Transitions to the ground and first excited states of ^{12}C are shown. 1 E – single leak peak, 2 E – double leak peak and F – full photo peak. The measurements were carried out with an HpGe detector with a volume of 111 cm^3, which was located at a distance of 11.4 cm from the reaction area

During each measurement, we plotted the number of registered γ-quanta of the transition to the ground and first exited states in ^{12}C (N_γ) on the current indication of the integrator counter (N_p). For each of the energies presented in the work, the dependence of N_γ on N_p represented a straight line within the current statistical uncertainty of determining N_γ, which indicated the stability of the target and the stability of the beam position on it during the whole exposure.

Since in the region of $E_{p,\ lab.}$ = 500–1350 keV the differential cross sections change quite slowly with energy, as can be seen, for example, from previous work [2], the effective laboratory energies were found using the expression $E_{p,\ eff.} = E_{p,\ lab.} - 0.5\Delta_{lab.}(E_{p,\ lab.})$, where $\Delta_{lab.}$ is the energy loss of protons in the target, determined using the LISE++ program [13].

Because the γ-detector energy resolution value and the proton beam energy spread value are significantly less than the energy losses of protons in the target, the upper parts of the $^{11}B(p,\gamma)^{12}C$ reaction γ-lines repeat the courses of the $^{11}B(p,\gamma)^{12}C$ reaction yield curves in the corresponding energy region, and the width of this γ-linesare largely due to the target thickness.This circumstance allowed us to determine the target thickness by analyzing the $^{11}B(p,\gamma)^{12}C$ reactionγ-lines shapes.Moreover, this analysis was one of the methods for monitoring the stability of targets during the experiment.

RESULTS

The differential cross sections for the $^{11}B(p,\gamma)^{12}C$ reaction of radiative capture to the ground and first excited states of ^{12}C for $\theta_\gamma = 0°$ were determined by normalizing the corresponding yields we measured to the differential cross sections of [2]. The results of normalization are presented in Table 1. Using the data on angular distributions from [2] and the differential sections we obtained for the angle 0°, we determined the integral crosssections, which are shown in Figures 3 and 4. From Figures 3 and 4 we can see good agreement between our integral cross sections and the integral cross sections of work [2] both in the form of excitation functions and in the ratio of the intensities of transitions to the ground and first excited states of ^{12}C.

Further according to the formula:

$$S(MeVb) = \sigma(b)E(MeV)exp\left(\frac{4.735}{\sqrt{E(MeV)}}\right),$$

(all quantities in the center of mass system) astrophysical S-factors were calculated, which are presented in Table 2 for the transitions to the ground and first excited states of ^{12}C, respectively. Figure 15 shows the total S-factors for the transitions to the ground and first excited states of ^{12}C together with the data recommended in [14]. From Figures 5 it is clear that, within the limits of statistical errors, our data are in a satisfactory agreement with the result obtained in work [14].

Table 1. Experimental differential cross sections for the $^{11}B(p,\gamma)^{12}C$ reaction. Errors are only statistical

$E_{p.lab.,eff}$, (MeV)	Transition to the ground state of ^{12}C		Transition to the state of 4439 keV of ^{12}C	
	$\frac{d\sigma}{d\Omega}^{exp.}(E,0°)$, (μb/sr)	Error in (%)	$\frac{d\sigma}{d\Omega}^{exp.}(E,0°)$, (μb/sr)	Error in (%)
482	0.282±0.028	<10	1.25±0.02	1.9
736.5	0.856±0.057	6.7	2.83±0.05	1.8
787	0.956±0.042	4.4	2.38±0.03	1.4
989	1.38±0.08	5.6	1.36±0.05	3.6
1089.5	1.60±0.04	2.3	1.31±0.03	2.0
1135	1.81±0.04	2.1	1.31±0.03	2.2
1236.5	1.93±0.06	3	1.22±0.04	3.5
1286.5	1.99±0.05	2.3	1.35±0.03	2.3
1337	2.33±0.05	2	1.28±0.03	2.3

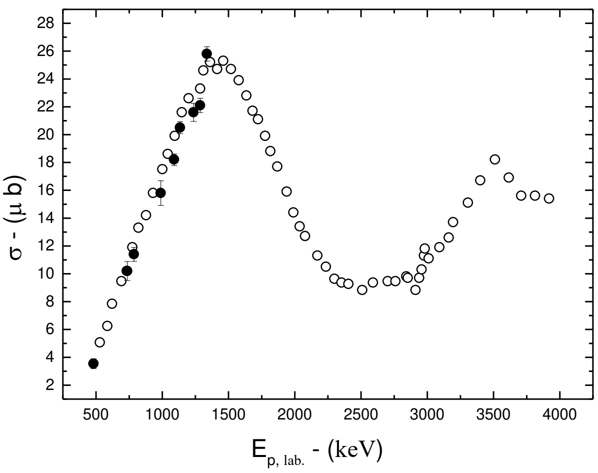


Figure 3. Experimental integral cross sections for the $^{11}B(p,\gamma)^{12}C$ capture reaction to the ground state of ^{12}C nucleus. Filled circles are our result. Open circles are the result of work [2].

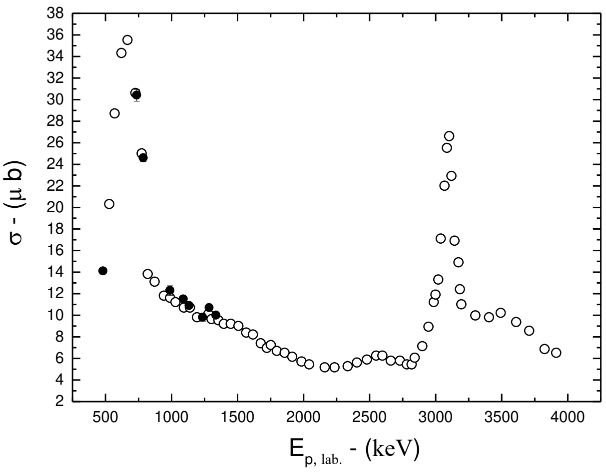


Figure 4. Experimental integral cross sections for the $^{11}B(p,\gamma)^{12}C$ capture reaction to the 4439 keV state of ^{12}C nucleus. Filled circles are our result. Open circles are the result of work [2]

Table 2. Experimental astrophysical S-factors for the $^{11}B(p,\gamma)^{12}C$ reaction. Errors are only statistical

$E_{p.c.m.,eff}$, (MeV)	Transition to the ground state of ^{12}C		Transition to the state of 4439 keV of ^{12}C	
	$S^{exp.}(E)$, (MeV b)	Error in (%)	$S^{exp.}(E)$, (MeV b)	Error in (%)
0.442	0.00194±0.00019	< 10	0.00773±0.00015	1.9
0.675	0.00219±0.00015	6.7	0.00653±0.00012	1.8
0.721	0.00217±0.00009	4.4	0.00468±0.00007	1.4
0.907	0.00207±0.00012	5.6	0.00161±0.00006	3.6
0.999	0.00208±0.00005	2.3	0.0013±0.00003	2.0
1.040	0.00222±0.00005	2.1	0.00118±0.00003	2.2
1.133	0.00209±0.00006	3	0.000949±0.000033	3.5
1.179	0.00204±0.00005	2.3	0.000978±0.000023	2.3
1.226	0.00228±0.00004	2	0.000883±0.00002	2.3

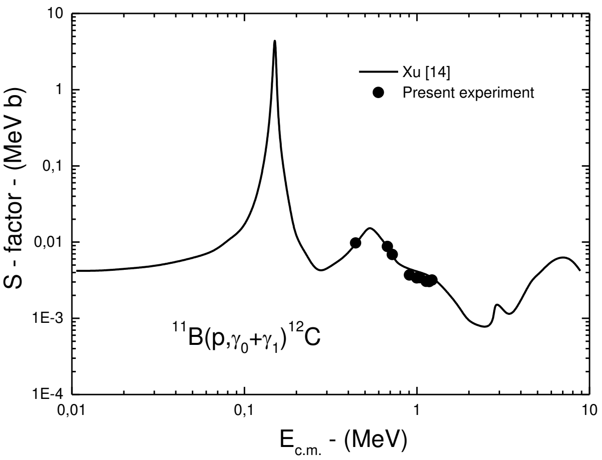


Figure 5. S-factors for the capture process $^{11}B(p,\gamma_0+\gamma_1)^{12}C$. The statistical errors are smaller than the sizes of the represented points

COMPARISON WITH CALCULATION

The integral cross sections for the $^{11}B(p,\gamma_0)^{12}C$ reaction obtained in this work were compared (see Figure 6) with calculations for this process at energies less than 1500 keV, performed in [15] within the framework of a modified potential cluster model with the classification of orbital states according to Young diagrams and taking into account allowed and forbidden states [16–19]. From Figure 6 we can see a good agreement between the calculated data of [15] and our experimental results and the experimental results of works [2, 20–22] obtained in the region from 80 keV to 1500 keV in a laboratory system. Also, calculations [15] correctly express the position of the first resonance. This means that it is quite possible to use the calculation results to extrapolate cross sections to the low-energy region and carry out various astrophysical calculations with them, in particular, to calculate the rate of the thermonuclear reaction of $^{11}B(p,\gamma_0)^{12}C$ occurring in stars in the CNO cycle.

Moreover, a comprehensive, experimental and theoretical (within the framework of a modified potential cluster model) study of the reaction $^{11}B(p,\gamma_0)^{12}C$ made it possible to determine important nuclear characteristics of the proton and ^{11}B system at low energies and for different orbital channels:

1) The process of proton capture in the reaction $^{11}B(p,\gamma_0)^{12}C$ is completely determined by the non-resonant E1-transition of $^3S_1 \rightarrow {}^3P_0$ and the resonant E2-transition of $^3P_2 \rightarrow {}^3P_0$.

2) All nuclear potentials have a Gaussian form of $V(r) = -V_0\exp(-\alpha r^2)$ (there is also Coulomb interaction);

3) For the potential of a resonant $^{3+5}P_2$-wave with a forbidden state and $J = 2^+ V_0 = 24.38058$ MeV, $\alpha = 0.025$ fm^{-2};

4) For the potentials of non-resonant $^3P_0$- and $^{3+5}P_1$-scattering waves with forbidden states $V_0 = 60.0$ MeV, $\alpha = 0.1$ fm^{-2};

5) For the potential of a resonant $^5S_2$ wave without a forbidden state with $J = 2^- V_0 = 10.9256$ MeV, $\alpha = 0.08$ fm^{-2};

6) For the $^3P_0$ potential of the ground state of ^{12}C nucleus with a forbidden state in the p + ^{11}B cluster channel $V_0 = 142.21387$ MeV, $\alpha = 0.1$ fm^{-2}.

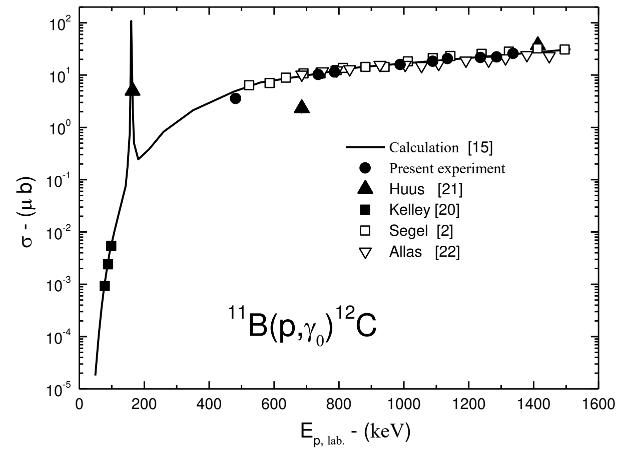


Figure 6. Integral cross sections for the radiative reaction of p + ^{11}B capture to the ground state of the ^{12}C nucleus in the energy region less than 1500 keV. Experimental errors are smaller than the sizes of the presented points

$^{11}B(P,\Gamma_0)^{12}C$ REACTION RATE

The measured cross sections for the radiative capture reaction, as well as the data from [15], were used for calculating the rate of $^{11}B(p,\gamma_0)^{12}C$reaction in the stars interior as a function of stellar temperature T_6, where $T_6 = T \cdot 10^6$ K. The Maxwellian-averaged reaction rates $N_A(\sigma v)$ as a function of temperature are defined by

$$N_A(\sigma v) = N_A\left(\frac{8}{\pi\mu}\right)^{1/2}\left(k_B T\right)^{-3/2}\int_0^\infty \sigma(E)\exp(-E/k_B T)E dE,$$

where N_A is the Avogadro's number, k_B is the Boltzmann constant, and $v = \sqrt{2E/\mu}$ is the relative velocity of the colliding particles. In Figure 7 we present the reaction rates of our calculation and its comparison with the data of [23]. It is seen that the result of our calculation is in good agreement with that recommended in [23] for a fairly wide temperature range (from 0 to 100 million degrees of Kelvin).

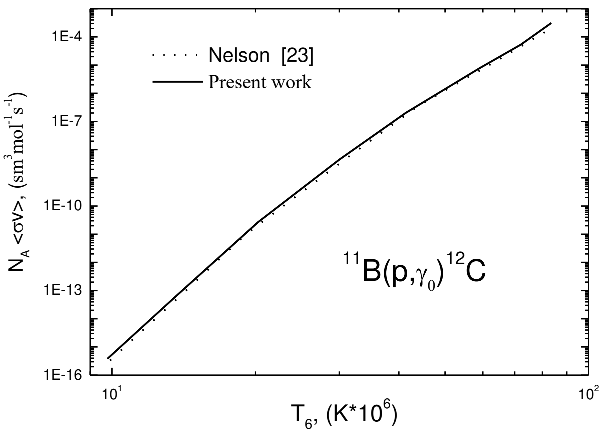


Figure 7. Rate for the radiative reaction of p + ^{11}B capture to the ground state of the ^{12}C nucleus.

DISCUSSION

In this work, with a statistical error of less than 10% at nine energies from 482 to 1337 keV in a laboratory system, new experimental data on differential (for angle 0^0) and integral cross sections, as well as on astrophysical S - factors of the reaction of $^{11}B(p,\gamma)^{12}C$ for transitions to the ground and first excited states of ^{12}C were obtained. The experimental results presented in this work are in good agreement with the literature data.

The work shows that the measured cross sections in the corresponding energy region are well described within the framework of a modified potential cluster model in which nuclear potentials are consistent with the spectrum of resonance levels and contain forbidden states in some partial waves, and the potential of the ground state is consistent (in general) with the main characteristics of the nucleus ^{12}C in the p + ^{11}B channel, including binding energy and charge radius.

The rate of the radiative capture reaction $^{11}B(p,\gamma_0)^{12}C$, which is consistent with previously performed calculations at temperatures up to $T_6 \simeq 100$ have been also calculated in this work.

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ТӨМЕНЭНЕРГИЯЛАРДАРАДИАЦИЯЛЫҚ P-^{11}B ТҮСІРУҮШІНЖАҢАНӘТИЖЕЛЕР

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$^{11}B(p,\gamma)^{12}C$ радиациялық қармау реакциясының негізгі және ^{12}C бірінші қоздырылған күйлеріне жаңа өлшемдердің нәтижелері берілген. Осы нәтижелерді сәйкес тәжірибелік әдебиет деректеріне қалыпқа келтіру арқылы 0° бұрышы және 482-ден 1337 кэВ дейінгі үдетілген протон энергиялары үшін дифференциалдық қималар алынды. Өлшенген ддифференциалдық қималар негізінде және осы энергетикалық аймақтағы $^{11}B(p,\gamma)^{12}C$ реакциясының бұрыштық таралулары туралы әдебиет деректерін пайдалана отырып, $^{11}B(p,\gamma)^{12}C$ радиациалық қармау реакциясының жалпы көлденең қималары мен астрофизикалық S факторлары ^{12}C негізгі және бірінші қозған күйі (барлық алынған мәндердің статистикалық қателері 10%-дан аз) үшін алынды. Алынған тәжірибелік деректер Янг схемалары бойынша орбиталық күйлердің жіктелуі мен және рұқсат етілген және тыйым салынған күйлерді ескере отырып, модификацияланған потенциалды кластерлік модель шеңберінде жақсы сипатталған. Өлшенген тәжірибелік көлденең қималар негізінде және жоғарыда келтірілген теориялық модельді пайдалана отырып, бұл реакция жылдамдығы 0-ден 100 миллион градус Кельвинге дейінгі температура диапазонында есептелді. Қателік шегінде бұл жұмыстың нәтижелері бұрынғы жұмыстардың деректерімен сәйкес келеді.

Түйін сөздер: *ядролық астрофизика, радиациялық қармау, термоядролық процестер, $^{11}B(p,\gamma)^{12}C$ реакциясы, астрофизикалық S-фактор, ядролық реакция жылдамдығы.*

НОВЫЕ РЕЗУЛЬТАТЫ ДЛЯ РАДИАЦИОННОГО P-^{11}B ЗАХВАТА ПРИ НИЗКИХ ЭНЕРГИЯХ

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Представлены результаты новых измерений выходов реакции ^{11}B(p,γ)^{12}C радиационного захвата на основное и первое возбужденные состояния ^{12}C. Нормированием этих результатов на соответствующие экспериментальные литературные данные извлечены дифференциальные сечения для угла 0° и при энергиях налетающих протонов от 482 до 1337 кэВ. На основе полученных дифференциальных сечений и с использованием литературных данных по угловым распределениям реакции ^{11}B(p,γ)^{12}C в этой области энергий со статистической погрешностью менее 10% определены полные сечения и астрофизические S-факторы реакции ^{11}B(p,γ)^{12}C для переходов на основное и первое возбужденные состояния ^{12}C. Полученные экспериментальные данные хорошо описываются в рамках модифицированной потенциальной кластерной модели с классификацией орбитальных состояний по схемам Юнга и с учетом разрешенных и запрещенных состояний. На основе измеренных экспериментальных сечений и с помощью вышеприведенной теоретической модели рассчитана скорость этой реакции в области температур от 0 до 100 млн градусов Кельвина. В пределах погрешностей результаты настоящей работы согласуются с данными более ранних работ.

Ключевые слова: *ядерная астрофизика, радиационный захват, термоядерные процессы, реакция ^{11}B(p,γ)^{12}C, астрофизический S-фактор, скорости ядерных реакций.*