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A new analysis of astrophysical S-factor from the experimental data

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ABSTRACT

Measurements of the ^{6}Li(p,γ)^{7}Be reaction γ-ray angular distributions have been done at beam energies of $E_{p,\ lab.}$ = 387, 690, 984 and 1283 keV for the γ-ray transitions to the ground and first excited (1/2-, 429 keV) states in ^{7}Be. cross section of the ^{6}Li (p, γ)^{7}Be reaction was calculated in the framework of the direct capture in the potential model using Fresco program. Spectroscopic factors of ^{7}Be and astrophysical S-factor ^{6}Li+p→^{7}Be+γ have been extracted from the experimental data available.

Keywords:^{6}Li(p,γ)^{7}Be reaction, astrophysical S-factor, Spectroscopic factors of ^{7}Be, γ-ray transitions, Fresco program

1.Introduction

The optical model parameters (OMPs) are widely employed to generate the distorted wave used to analyze the cross section of many reactions and these analyses have proved to be powerful tool to extract nuclear structure information [1]. Reactions at astrophysical energies are complicated by the fact that the matter-interaction energy in stars is very low, ranging between a few tenths of a keV unit and a few tens of keV units. With a few exceptions, it is impossible to measure nuclear-reaction cross sections directly at laboratory conditions at such energies which are necessary for astrophysical calculations. Usually, cross sections are measured at higher energies whereupon the results are extrapolated to the energy region of interest for nuclear astrophysics. As a rule, however, the measurements actually performed cover only the region of rather high energies from about 0.2 to 1 MeV.

An extrapolation of such experimental data to the astrophysical region is not always justified. As a result, only theoretical predictions can compensate in many cases for missing experimental information about the properties of astrophysical thermonuclear reactions. Under such conditions, resort to realistic models that are rather simple in practical applications, such as the potential cluster model (PCM), seems quite justified. Usually, the results of calculations performed on the basis of model concepts are contrasted against available low-energy experimental data and approaches leading to the best agreement with these data are selected by using the results of this comparison. After that, the calculations in the region of astrophysical energies are performed within the chosen conceptual framework. One can consider the results obtained in this way (for example, those concerning astrophysical S factors) as more realistic estimates of respective quantities than the extrapolation of experimental data, since the theoretical models used have quite a sound microscopic basis [2].

Radiative-capture reaction at energies of astrophysics interest is one of the most important processes for nucleosynthesis. The nucleon capture can occur either by a compound nucleus reaction or by direct process. The compound reaction cross sections are usually small, especially for light nuclei. The direct capture proceeds either via the formation of a single-particle resonance or non-resonant capture process. Unlike ^{7}Li and ^{6}Li to be formed at very low level in Big Bang

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nucleosynthesis, with abundance ratio Li/H = 10^{-14}. Whereas most elements are produced by stellar nucleosynthesis, Lithium is mainly destroyed in stellar interiors by thermonuclear reactions with protons. In fact, ^{6}Li is rapidly consumed at stellar temperature of 2×10^6 K. Low energy capture reaction ^{6}Li(p,γ)^{7}Be plays an important role in the consumption of ^{6}Li and formation of ^{7}Be [3]. S-factor of ^{6}Li(p,γ)^{7}Be reaction is dominated by captures to the ground state and first excited state of ^{7}Be. However, the number of studies devoted to measuring the total cross section for this reaction and to experimentally determining its astrophysical S factor in the region of low energies is comparatively small [4].The ^{6}Li(p,γ)^{7}Be reaction has been experimentally studied by Switkowski et al. [5] at low energies down to 200 keV. A theoretical extrapolation has been performed by Barker [6] within potential model, based on simultaneous fit of ^{6}Li(n,γ)^{7}Li and ^{6}Li(p,γ)^{7}Be cross sections. K. Arai et al. [7] used a four cluster microscopic model to investigate low-energy ^{6}Li+p and ^{6}Li+n reactions.

The S-factor of ^{6}Li(p,γ)^{7}Be reaction in [7] was in a good agreement with the available experimental data. Knowledge of the change rate of the S-factor with energy at very low energies is needed to perform a reliable extrapolation. Although this is frequently determined by the use of a direct capture-model calculation, there are cases when this does not work. Low-energy resonances or sub-threshold states can affect the extrapolation. The results of the measurement of the astrophysical S-factor slope for the^{6}Li(p,γ)^{7}Be reaction are reported, and a new mechanism is introduced to explain the observed slope[8]. Cecil et al. [9] measured the branching ratio of ^{6}Li(p,γ_0)^{7}Be and ^{6}Li(p,γ_1)^{7}Be with respect to ^{6}Li(p, α)^{3}He from 45 to 170 keV and deduced the S-factors for ^{6}Li(p,γ_0)^{7}Be and ^{6}Li(p,γ_1)^{7}Be as a function of energy. Their results gave a positive slope for the S factor. Switkowski et al. [5] measured the ^{6}Li(p,γ)^{7}Be cross section from 160 to 1150 keV. Their data points are all at energies above the present data set and show an S-factor that increases with increasing energy. Barker's analysis [6] of the data from [5] have a negative S-factor slope for ^{6}Li(p,γ_0)^{7}Beand ^{6}Li(p,γ_1)^{7}Beat energies below the range of the data. The present measurements were undertaken to examine this discrepancy in the previous measurements of Cecil et al.[5] and Switkowski et al. [6].The purpose of this work is to extract the spectroscopic factors of ^{7}Be from the ^{6}Li(p,γ)^{7}Be reaction and then use these values to extract astrophysical S-factor ^{6}Li+p→^{7}Be+γ.

2. Experimental data

2.1 ^{6}Li (p, p) ^{6}Li

Elastic scattering of protons on ^{6}Li nuclei at low energy region were measured using the extracted beam from UKP-2-1 accelerator in the Institute of Nuclear Physics (National Nuclear Center, Republic of Kazakhstan, Almaty, Kazakhstan) in the angular range 30-170°. The proton energy varied in the range 400 – 1150 keV. The beam intensity was 50 – 150 nA. Scattered particles were detected using surface-barrier silicon detectors. Full details of the experiment set up were discussed inprevious work [10].

2.2 ^{6}Li(p,γ)^{7}Be

Cross-sections of the ^{6}Li(p,γ)^{7}Be reaction were measured using a specially manufactured chamber with indium vacuum seals of fine adjustment and visual control of proton beam on the target during all measurements, with the possibility of precise placement of the target exactly into the chamber center and of its additional equipment by nitrogen trap and additional magneto-discharge pump. The new reaction chamber was connected to turbo-molecular, magneto-discharge pumps and nitrogen traps. The typical pressure in the reaction chamber was $1.5\cdot10^{-6}$ mm Hg, and the experimental error, stipulated by the formation of carbon deposit on the target during the measurement, was negligible. The measurements were made at beam energies of 387, 690, 984 and 1283 keV for the ^{6}Li(p,γ)^{7}Be reaction at the ground and first excited state (429 keV) of the ^{7}Be. Currents of the protons beam were in the range of 5-8μA. During the measurement of the integral current, the collected charge was from 0.05 to 0.25 Coulomb. Targets were placed in the chamber for the study of (p,γ) reactions.

In order to prevent the overload of the electronics caused by the powerful background line with the energy of Eγ =478keV, related with process ^{7}Li(p,pγ)^{7}Li and ^{7}Be ⟶ ^{7}Li*+β$^+$+ν ⟶ ^{7}Li+478 keV, between the detector and the reaction region, a lead plate of 1 cm-thickness was placed. Due to the lead plate, the intensity of the line with E_γ=478 keV decreases by a factor of about 5 and the intensity of lines from the ^{6}Li(p,γ)^{7}Be reaction (with E_γ=6000 keV) decreases only by several per cent. Fig.1 is an example of γ-spectrum obtained at $E_{\gamma,lab}$=984keV. In Fig. 1 there are well seen background lines, 1461 keV, and the annihilation line with E_γ=511 keV. Well-known energies of γ-transitions for these lines allowed to control the energy calibration. Peaks of the total absorption and peaks of unitary and double escapes for γ-transitions onto the ground and the

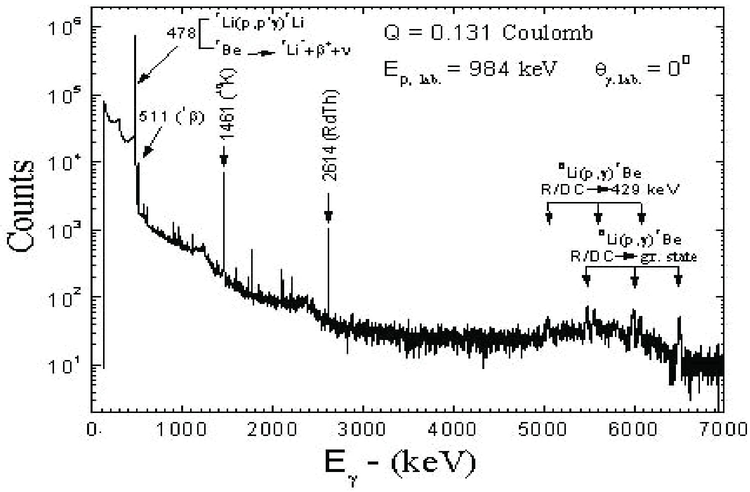

Fig. 1 An example of the γ-spectrum of the $^{6}Li(p,\gamma)^{7}Be$ reaction.

first excited state of the ^{7}Be shown in Fig. 1, with the use ofthe HpGe – detector (GEM20P) of the 111 cm^3 volume, placed in 6 cm from the reaction region.

3. Results and discussion

3.1 Phenomenological Elastic Scattering of protons on ^{6}Li

The analysis of protons datacarried out atwide energy range, had shown that for ^{6}Li nuclei, the most suitable parameters values are r_0=1.05 fm, r_c=1.3 fm, r_D=1.923 fm, a_s=0.20 fm and r_s=1.20 fm. The complete analysis have been mentioned at [11]. In the analogous approach with the use of measured elastic scattering, potential of protons scattering on ^{6}Li nuclei from the analysis of these data on the optical model. Parameters obtained for optical potentials of the interaction are presented in Table 1. The relation betweenV_0 and E_p is linear. The strength parameters can be represented by: $V_0 = 56.10 - 0.61E_p$, $W_D = - 0.66 + 0.46E_p$, respectively.

3.2 $^{6}Li(p,\gamma)^{7}Be$ reaction at the low energies

For each angle, the γ-detector was 6 cm from the beam spot on the target. The detector, just as the calibration sources, was placed to within 1 mm. The calibration source of ^{137}Cs (E_γ = 661.66 keV) was used to construct the dependence on γ-rays registration rate from the source detector distance. It was determined that at a distance of 6 cm, the deviation in ±1 mm results in a change of registration rate on 3.2%. The overall uncertainty of the absolute γ-detector photopeak efficiency determination introduced by statistical uncertainty of γ-ray counts determination, dead time in the measuring electronics. The accuracy of the γ-detector position was adopted to be precise at about 5.5% along the whole range of energies of registered γ-rays.The angular distributions of the $^{6}Li(p,\gamma)^{7}Be$ reaction were fitted at four fixed energies from the energy region of $E_{p,\ lab.}$= 387 - 1283 keV by Legendre polynomials [12]:

$$W(\theta_\gamma) = 1 + \Sigma_k a_k Q_k P_k(\cos\theta) \quad (k = 1,2,\ldots), \qquad (1)$$

where a_k are the expansion coefficients and Q_k are the attenuation coefficients, which take the solid angle subtended by the γ-detector into account as shown in Tables 2 and 3. In view of the limited number of angles, the fits were carried out by including only k = 1 and 2. Experiment within the point radioactive source approach by using the known dimensions of sensitive region of the γ-detector, the source-detector distances (D), and without taking lead plate located in front of the γ-detector into account. The lower limits of $Q_1$and Q_2 were calculated for the conditions of experiment within the point radioactive source approach by using the known dimensions of sensitive region of the γ-detector, the source-detector distances (D), and without taking lead plate located in front of the γ-detector into account. In this connection according to[8], $Q_i$can be written as:

$$Q_i = \frac{J_i}{J_0} \qquad (i = 1, 2), \qquad (2)$$

where;

$$J_k = \sum_{i=0}^{3} \int_{\theta_i}^{\theta_{i+1}} P_k(\cos\alpha) \cdot [1 - e^{-\mu(E_\gamma)\cdot l_{i+1}(\alpha)}] \cdot \sin\alpha \cdot d\alpha,$$

where k equals 0, 1, or 2 and $\mu(E_\gamma)$ is the absorption coefficient.

The values of $l_i(\alpha)$, and limits of integration of θ_i were determined by the experimental conditions. The value of J_0 represents a ratio of quantity of registered γ-rays, which passed through the γ-detector to the total quantity of γ-rays emitted by a point radioactive source beaming isotropic in the geometry of the present experiment. Coefficient of $\mu(E_\gamma)$ was found for energy of 661.66 keV by comparing the experimental dependence of γ-rays registration rate on the ^{137}Cs source-detector distance with the dependence counted by means of the expression for J_0. In addition, the correction of the geometrical dimensions of the γ-detector's sensitive region was carried out. The energy dependence of $\mu(E_\gamma)$ was then constructed by using these corrected dimensions and the curves of absolute detector efficiency for a photo-peak. The values of $J_0(D)$ for D = 10 - 300 mm and range of γ-rays energies from 661.66 to 8500 keV, which are of interest of present work, were further counted. After that, the values of $Q_1(D)$ and $Q_2(D)$ for the same range of D and γ-rays energies were calculated. It is found that $Q_1(D)$ and $Q_2(D)$ do not practically depend on γ-rays energy and tend to approach 1 with increasing D. Finally, the values of lower limits of $Q_1(E_\gamma)$ and $Q_2(E_\gamma)$ were calculated at D = 6 cm. It has been found that lower limits of $Q_1(E_\gamma)$ and $Q_2(E_\gamma)$ are constant (Q_1 = 0.97 and Q_2 = 0.91, respectively) in the range of energies E_γ = 661.66 - 8500 keV. The yields from the ground and first excited states transitions were used to calculate the branching ratio for these transitions. It was obtained that branching ratios were (65 ± 3)% and (35 ± 3)% for the ground state and first excited state transitions, respectively. Within the uncertainties of the individual spectral yields, these ratios were constant over the energy range of this experiment. These are consistent with the values from [8] of (63.4 ± 1.9)% and (36.6 ± 1.9)%, the values from [9]of 0.60 and 0.4, the values from [5] of (59 ± 3)% and (41 ± 3)%, and the values of 62% and 38% in [13]. The relative yield of the^6*Li(p,γ)*^{7}*Be* reaction for ground and first excited state is shown in Fig. 2.

Table 1. The phenomenological optical parameters for protons scattering on lithium nuclei

E_p MeV	V_0 MeV	r_0 fm	a_0 fm	W_D MeV	r_D fm	a_D fm	V_S MeV	r_s fm	a_S fm	J_R MeVfm^3	J_w MeVfm^3
0.746	59	1.05	0.85	0.300	1.923	0.575	9.30	1.077	0.66	490	20.47
0.975	57.2	1.050	0.67	0.355	1.923	0.650	9.30	1.020	0.200	475	22.19
1.136	54	1.05	0.52	0.355	1.923	0.57	9.30	1.020	0.200	454	22.19

Table 2. Coefficients of Legendry polynomial ($a_1(E)*Q_1$ and $a_2(E)*Q_2$) fitting for the ^{6}Li(p,γ)^{7}Be reaction γ-ray transition to the ground state in ^{7}Be, and differences (on percent) in integral cross sections determination realized by using data of Ref. [5] with γ-ray angular distributions taken from Ref. [14] and present work. The lower limits of Q_1 and Q_2 = 0.97 and 0.91 respectively.

$E_{p,\,lab.}$ (keV)	$a_1(E)*Q_1$ (absolute units)	$a_2(E)*Q_2$ (absolute units)	Difference $\sigma_{int}(E)$ in %
387	0.021±0.008	0.28±0.01	10
690	-0.017±0.023	0.21±0.03	15
984	0.012±0.021	0.122±0.026	17
1283	0.05±0.05	0.21±0.06	9

Table 3. Coefficients of Legendry polynomial ($a_1(E)*Q_1$ and $a_2(E)*Q_2$) fitting for the ^{6}Li(p,γ)^{7}Be reaction γ-ray transition to the 429 keV state in ^{7}Be, and differences (on percent) in integral cross sections determination realized by using data of Ref. [5]with γ-ray angular distributions taken from Ref. [14]and present work. The lower limits of Q_1 and Q_2 = 0.97 and 0.91 respectively.

$E_{p,\,lab.}$ (keV)	$a_1(E)*Q_1$ (absolute units)	$a_2(E)*Q_2$ (absolute units)	Difference $\sigma_{int}(E)$ in %
387	-0.034±0.04	0.36±0.03	-6
690	0.014±0.025	0.42±0.03	3
984	0.008±0.026	0.23±0.03	14
1283	-0.013±0.064	0.15±0.04	9

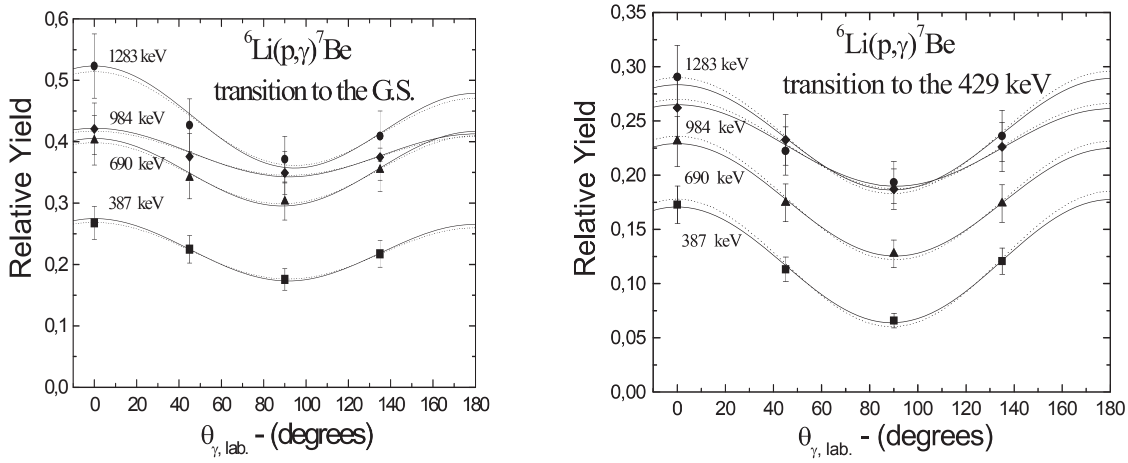

Fig. 2. The *^{6}Li(p,γ)^{7}Be* reaction γ-ray relative yield: left panel- for the *γ*-ray transition to the ground state in *^{7}Be,* right panel - for the *γ*-ray transition to the 429 keV state in *^{7}Be*. The curves are the results of polynomial fits with taking lower limits of $Q_1$and Q_2 (0.97 and 0.91 for $Q_1$and Q_2, respectively) into account (solid curves) and without taking $Q_1$and Q_2 into account (dotted curves).

Based on our calculations [10, 11]for ^{6}Li(p, p)^{6}Li, optical potential parameters at low energies had been enhanced. Spectroscopic factors have been extracted from measured experimental data of the radiative reaction ^{6}Li(p,γ)^{7}Be. The cross section calculations of the^{6}Li(p,γ)^{7}Be reaction were carried within the framework of the direct capture in the potential model using FRESCO Code. The calculation of the cross sections depended on OMPs and spectroscopic factors. The relation between spectroscopic factors and optical potential parameters used was verified here very clearly. As shown in Fig. 3, when we fixed the spectroscopic factors from [15], we obtained *the dotted line*. Another group of spectroscopic factors were extracted using our OMPs only and the result obtained by the analysis of the experimental data using these spectroscopic factors is shown as the *solid line* in Fig. 3.The spectroscopic factors of ^{7}Be at these low energies are energy dependent and their values changed from one energy to another especially at very low energies. For example, the spectroscopic factors for ground state extracted were $1P_{3/2}$= 0.207 and $1P_{1/2}$=0.18 and for excited state were $1P_{3/2}$= 0.306 and $1P_{1/2}$= 0.065 at E_p=387 keV. By increasing the energy, the values of spectroscopic factors also have been changed to analyze the experimental data as shown in Table 4. The extracted spectroscopic factors values depend on the choice of OMPs used. In order to calculate the astrophysical S factor, we employed the standard expression [17]:

$$S(NJ,J_f) = \sigma(NJ,J_f)E_{\rm cm}\exp\left(\frac{31.335Z_1Z_2\sqrt{\mu}}{\sqrt{E_{\rm cm}}}\right) \quad (3)$$

which was proposed as far back as the 1950s in [18] and σ is the total cross section for the radiative capture process (in barn units), $E_{c.m.}$is the c.m. energy of particles in the entrance channel (in keV units), μ is the reduced mass of the entrance-channel particles (in atomic mass units), Z values are the charges of the particles (in elementary charge units, e) and N stands for E (electric) or M (magnetic) transitions of multipolarity J to the final (J_f) state of the nucleus. The numerical coefficient 31.335 was obtained by the present authors in [10]. σ values were calculated using Fresco program. We have S(0)=37±5 eV.b as shown in Fig 4.

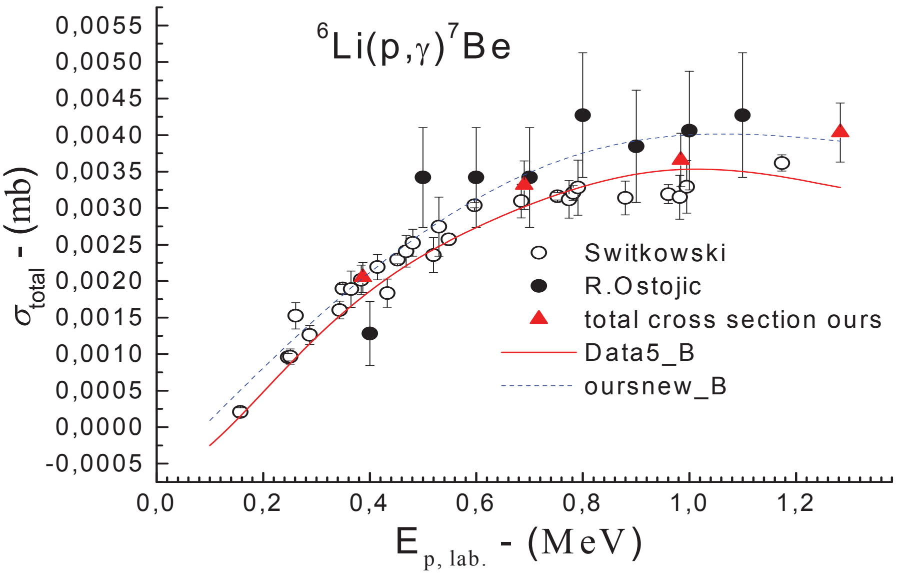

Fig. 3 Total cross section of the reaction ^{6}Li(p,γ)^{7}Be**.** The experimental points are from [5] (hollow circles), [14](solid circles) and our measurements are represented by triangles. Solid line is the calculated data depending on the OMPs from ^{6}Li(p,p)^{6}Li in ref. [10,11] where dotted line represents the calculations in the case of OMPs taken from [16].

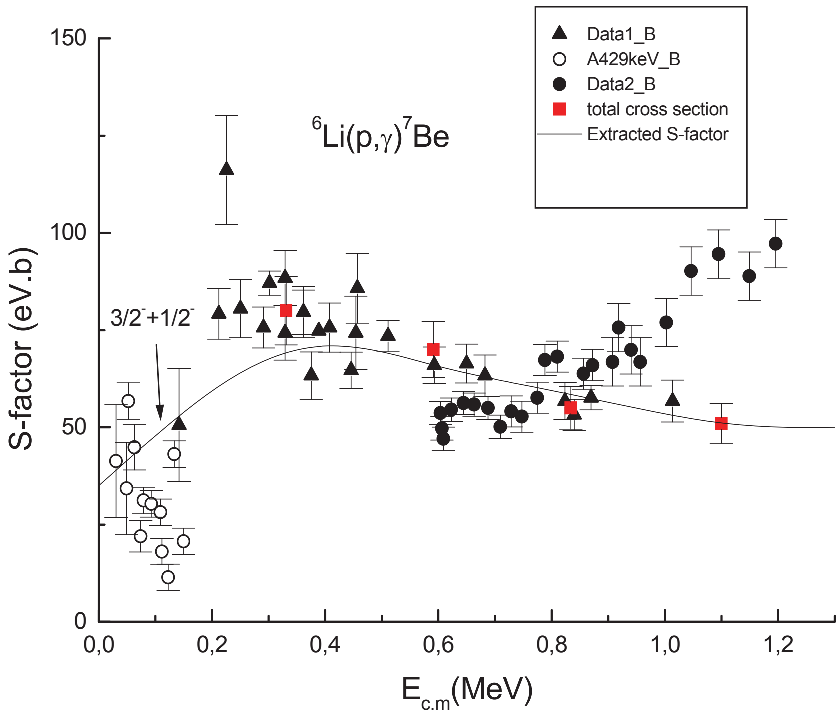

Fig. 4 Astrophysical S-factor calculated using our measurements and Fresco program, red points being our measurements. Other data correspond to experimental data from [5](they are presented in [7]).

Table 4 Spectroscopic factors extracted for ^{7}Be from the radiative reaction $^{6}Li(p,\gamma)^{7}Be$

E(p)	E_x, MeV	J_f,	Exp. values $C^2(S_{3/2})$	Exp. values $C^2(S_{1/2})$	Theory [15] $C^2S_{3/2}$	Theory [15] $C^2S_{1/2}$
387 keV	0.00	(3/2)-	0.207	0.18	0.431	0.289
	0.429	(1/2)-	0.306	0.065	0.854	0.039
690 keV	0.00	(3/2)-	0.357	0.208	0.431	0.289
	0.429	(1/2)-	0.729	0.056	0.854	0.039
984, 1283 keV	0.00	(3/2)-	0.431	0.209	0.431	0.289
	0.429	(1/2)-	0.910	0.045	0.854	0.039

4. Conclusion

Elastic scattering of $^{6}Li(p,p)^{6}Li$ has been studied. New sets of OMPs have been obtained for the proton elastic scattering from ^{6}Li. The recent measurements of the $^{6}Li(p,\gamma)^{7}Be$ reaction γ-ray angular distributions have been done at beam energies of $E_{p,\, lab.}$ = 387, 690, 984 and 1283 keV for the γ-ray transitions to the ground and first excited ($1/2^-$, 429 keV) states in ^{7}Be. The calculation of the cross section of the$^{6}Li\ (p,\gamma)^{7}Be$ reaction was carried within the framework of the direct capture in the potential model using FRESCO Code. Cross sections of $^{6}Li(p,\gamma)^{7}Be$ reaction were directly obtained from the calculations depending on OMPs from $^{6}Li(p,p)^{6}Li$. Spectroscopic factors have been extracted from our experimental data of the radiative reaction $^{6}Li(p,\gamma)^{7}Be$.

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