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Astrophysical S-Factor for $^{7}Li(P,\gamma)^{8}Be$ by Different Sets of Optical Parameters

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The available experimental data for $^{7}Li(p,p)^{7}Li$ elastic scattering have been investigated using both optical potential as well as single folding optical potential in which the real part of the potential is derived on the basis of single folding model. Approximated optical potential parameters have been obtained for the real part using DFPOT code. The real part was normalized and the imaginary part was optimized at all ranges of energies. The calculated normalization factor N_R was 0.8. The agreement between the experimental data and the theoretical calculations has been achieved at the different concerned energies using ECISS88 program. The calculation of astrophysical S-factor for $^{7}Li(p,\gamma)^{8}Be$ radiative capture reaction has been performed using a potential model. Different sets of optical potential parameters have been used during analysis. It has been found that different potential parameters play a crucial role and have a significant effect on the calculated S-factor. It has been shown that optical parameters have the greatest effect on astrophysical S-factor through the calculation presented in this study.

Introduction

Formation of ^{8}Be is a result of $^{7}Li(p,\gamma)^{8}Be$ reaction which a part of the pp-chain in the sun. ^{8}Be decays into two α-particles in 10^{-16} s as it is unstable nuclei [1]. Involving p-wave strength in cross sections calculations renewed the interest of studying $^{7}Li(p,\gamma)^{8}Be$ reaction which is very important in solar neutrino problem [2]. $^{7}Li(p,\gamma)^{8}Be$ reaction has been studied extensively by various investigations in the proton energy range of E_p= 200 keV to 1700 keV. Well-known proton resonances at E_p= 441 keV and 1030 keV have been confirmed by these experiments [3]. Two other resonances have recently been proposed by Cavallaro et al. [4] at E_p= 720 keV and 870 keV. The γ radiation resulting from the reaction corresponds to transitions to the ground state and first-excited state of ^{8}Be [3]. Resonances in the reaction $^{7}Li(p,\gamma)^{8}Be$ have been observed at proton energies 441 keV and 1030 KeV . Above the 441 keV resonance the cross section is larger than can be explained in terms of neighboring resonances and the weak 1030 keV resonance is superimposed on a steadily rising non-resonant background [5].

Optical potential parameters have an essential role in calculating astrophysical S-factor. The choice of optical potential parameters is very important especially at low energies. The effect of choosing optical potential parameters extends to extraction of astrophysical S-factor. The spectroscopic factor has been extracted from elastic scattering and nuclear reaction and there was a huge effect of the optical parameters on extracted values. Extraction of spectroscopic factor is the first step to obtain reliable values of astrophysical S-factor. Indirect techniques produced by A.M. Mukhamedzhanov [6] were a key to overcome the ambiguity arise from optical parameters. Asymptotic Normalization Coefficient (ANC) and Trojan Horse are two methods used to extract astrophysical S-factor independent on optical potential parameters. A potential model has been

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used to study astrophysical S-factor [7] and reliable fitting has been obtained.

The optical model parameters have a great importance and vast applications in the study of nuclear reactions. For analysis of nuclear reactions, the optical model parameters have been developed depending on the necessity of nuclear reactions study. Choosing a wrong set of parameters produces a discrepancy of astrophysical S-factor. Elastic scattering, radiative and transfer reactions need optical parameters for analysis of experimental data. Extraction of spectroscopic factor demands correct and reliable sets of optical parameters. During investigation, it is very important to choose the optical parameters to overcome the ambiguities of optical model parameters; one should choose radius and diffuseness for reacted nuclei.

It is impossible to measure differential cross sections at very low energies. The solution is to extract cross section (astrophysical S-factor in such a case). The optical potential parameters have an effective role in such study.

Two methods are used to obtain spectroscopic factors. Theory is the first choice where extraction of spectroscopic factor from experimental data is the second one .Extraction of spectroscopic factor from experimental data is the best choice when reliable sets of optical parameters are used. Choosing radius is very important through analysis. Standard parameters are one method to fit experimental data, radius is taken to be 1.25 fm and diffuseness is 0.65 fm. Systematic study have been done by the author and proved that the potential depth for light nuclei depends on the number of incident nuclei.

A systematic study of protons, deuteron, ^{3}He and α-particles has many benefits in nuclear physics. The analysis of nuclear reactions needs global optical potential parameters to reproduce differential cross section. A trail has been made to find another method to analyze the experimental data by produce a systematic study for charged particles with light nuclei (^{6,7}Li, ^{10,11}B, and ^{7}Be) for a wide range of energy. The attempt started in 2010 when the author studied the elastic scattering of protons with ^{6}Li. After few months, deuterons elastic scattering by ^{6}Li have been analyzed.

It has been noticed that with the same radius (r_0=1.05fm), the real potential depth was twice the value of it in case of protons with ^{6}Li. A further investigation has been conducted for ^{3}He elastic scattering by ^{6}Li when the author tried to analyze the reaction ^{6}Li(^{3}He, d)^{7}Be. In that situation, it was observed that the potential depth with the same radius (r_0) is systematic. Where the real potential depth for protons elastically scattered by ^{6}Li is about 40-50MeV and the value of potential depth for deuterons elastically scattered by 6Li was 80-90MeV.

In case of ^{3}He elastically scattered by ^{6}Li, the real potential depth derived was in the range 120-130 MeV. The values of optical parameters for α-particles scattering by light nuclei calculated were away from the expected values of systematic study. Global optical potential parameters for α-particles scattering by light nuclei is the best choice. Xin-Wu Su [8] has obtained optical parameters for α-particles scattering by light nuclei by simultaneously fitting the experimental data of reaction cross-sections and elastic scattering angular distributions. The values obtained in the last study by Xin-Wu Su agree well with our expectations for systematic study of protons, deuterons and ^{3}He. As the choice of radius (R) of the nucleus depends on the nucleus itself, the real potential depth of α-particles elastic scattering by light nuclei is about 175MeV which is four times the value of potential depth for protons elastic scattering by light nuclei ~45-50MeV.

The present study could solve the ambiguity of optical potential parameters .The standard parameters r_0=1.25fm and a=0.65fm are the best choice in addition to the potential depth from systematic study of protons, deuterons, ^{3}He and α-particles elastic scattering by light nuclei. The current study presents a good approximation for nuclear reaction study.

We have tried to apply such model on many reactions, for example, ^{6}Li(^{3}He, d)^{7}Be and has succeeded for a wide range of energies [9]. Also, for astrophysical applications , the present assumptions have been used to study ^{6}Li(p,γ)^{7}Be, ^{7}Li(p,γ)^{8}Be and ^{10}B(p,γ)^{11}C reactions [10]. The discussions have been concerned with real potential depth where imaginary (surface and volume) potential depths could be adjusted for each scale of energy. For very low energies surface part for imaginary potential works well where the volume increases with increasing energy. Spin-orbit is chosen to enhance the analysis of data.

The harmony of the optical potential parameters is very important and it is an art more than physics. The exact solution of optical potential parameters discrepancy is not found, but the errors can be reduced by choosing optical parameters suitable for the study under consideration where every range of A and energy needs especial sets of optical parameters.

Researchers spend a lot of time to calculate (extract) optical parameters where the solution is to find the best values of (r, and a) and guess the potential depth and this only for p, d, ^{3}He, and alpha elastically scattered by light nuclei. The choice of r is very important to overcome the difficulty of adjusting the optical potential parameters. Electron scattering is one and the best solutions to obtain reliable values of nuclei radii. The light nuclei contain few numbers of nucleons so their radii are very sensitive to any deviations from right values of radii. Nowadays, Nuclear Data Centers developed new programs of research for data collection and analysis. RILP and EXFOR are for such data where one can find experimental data and recommended global optical potential parameters for all reactions at any energy. The diffuseness also, needs some expectation before analysis. If there is no idea about its value, it could be put in a code as 0.65fm as starting parameter. So, the parameters are under-control by understanding their behavior before analysis [11].

For the nucleon transfer reaction, calculated angular distribution can vary significantly even through optical model (OM), parameters are used fit well the elastic scattering in the entrance and exit reaction channels. Different sets of optical potential parameters provide spectroscopic factors different by the factor 3.

It was the first time to extracted spectroscopic factor from experimental data by elastic scattering. Increasing the cross sections at backward angles, anomalous large angle backscattering (ALAS) phenomenon has been used to extract spectroscopic factor for ^{6}Li. A researcher will find some difficulties to choose the best set of parameters especially in the case of low energies and light nuclei as a target. The study will continue to solve problems and another puzzles will appear.

Procedure and Results

Wave function of input and output channels should be known for cross sections calculations within the framework of the direct capture. The optical potential parameters are necessary to generate wave functions of input and output channels in the two body approach. Spectroscopic factor of the 8Be – nucleus is the second factor should be used during calculations that may be obtained from extraction of experimental data or theory.

The present calculations of the cross section of the 7Li(p,γ)8Be reaction was carried within the framework of the direct capture in the potential model using FRESCO Code [12]. The choice of optical parameters used in the present calculation has been made depending on the assumption that the potential depth depends on the number of incident nucleons. Two steps have been achieved to obtain reliable calculations for astrophysical S-factor for 7Li(p,γ)8Be reaction. The choice of optical model parameters was the first step where finding (extracted or calculated) spectroscopic factor was the second step.

a- Optical Parameters

7Li(p,γ)8Be as a radiative reaction, needs just optical parameters for entrance channel (p+ 7Li). Phenomenological and single folding methods have been used to obtain different sets of optical parameters.

An analysis of the elastic scattering of protons on 7Li nuclei has been conducted in the framework of the optical model at the beam energies up to 50 MeV. For 7Li nuclei, the most suitable phenomenological parameters values are r0=1.15fm, rc=1.3fm, rD=1.95fm, as=0.60fm and rs=1.15fm. The optical parameters obtained for protons elastic scattering on 6Li are shown in Table (1). As expected, the relations between V0, WD and Ep are linear. The strength parameters in Table 1 can be represented by the following:

$$V_0 = 56.1 - 0.61E_p \, , W_D = -0.66 + 0.46E_p \, .$$

The calculations have been done using Ecis88 [13], and DEPOT [14] codes.

Table (1): Optical and single folding potential parameters for protons scattering on ^{7}Li nuclei

Optical Potential Parameters										
E_p (MeV)	V_0 (MeV)	a_0 (fm)	W_D (MeV)	a_D (fm)	V_s (MeV)	r_s (fm)	a_s (fm)	J_R (MeV· fm^3)	J_W (MeV· fm^3)	
Set 1	56.00	0.65	0.70	0.575	12.48	1.17	0.50	668.44	37.41	
Set 2	71.40	0.60	9.96	0.70	5.58	1.15	0.60	906.33	143.57	
Set 4	37.249	0.531	5.799	0.654	9.285	1.17	0.52	313.5	361.2	
Single Folding Parameters										N_R
Set 3	43.30	0.75	13.50	0.470	7.50	1.25	0.650	411.43	431.23	0.80

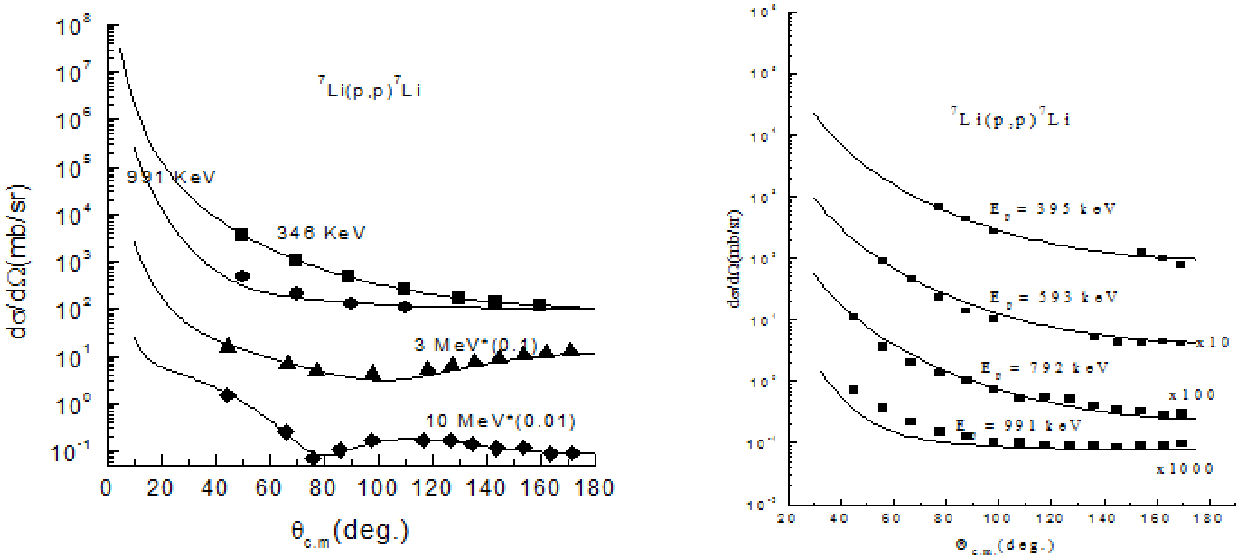

Figure (1) Angular distribution of protons scattered from ^{7}Li, where dots represent experimental data and lines represent the calculated values. Experimental data were taken from [15]

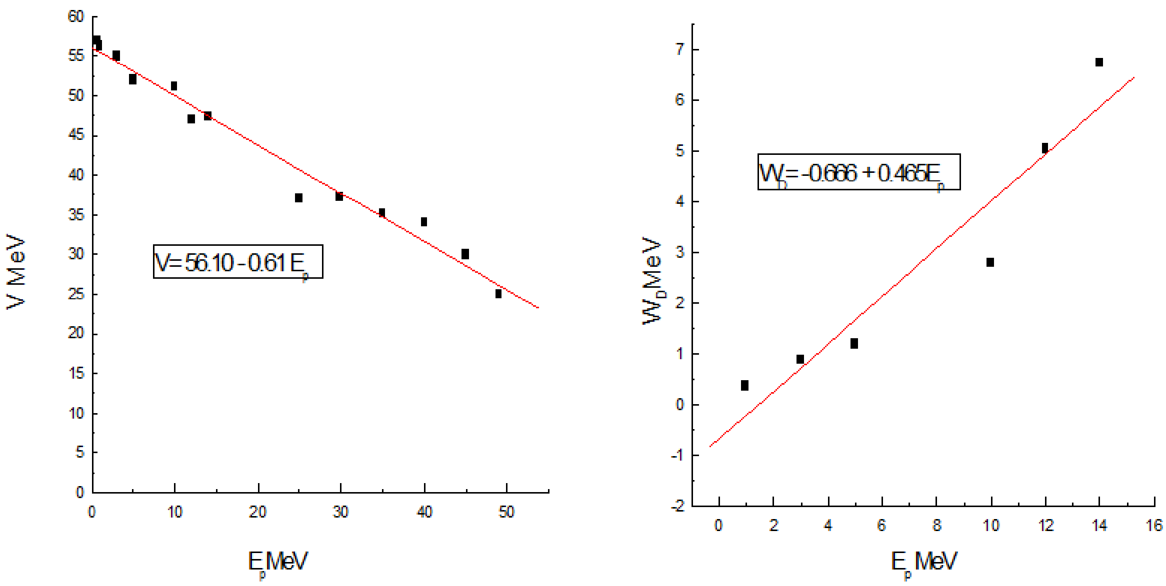

Figure (2): Linear relation between V_0, W_D and E_p for ^{7}Li

Single Folding Model

The real part of the optical potential parameters for the nucleon–nucleus elastic scattering is given by single folding model, in the following form:

$$U_F(R) = \int dr_1 \rho_1(r_1)\ V(r) , \qquad (1)$$

where r =R-r_1, $\rho_1(r_1)$is the density distribution of the target nucleus, V(r) is the effective NN-interaction. In the present calculation, the effective NN-interaction is taken in the form of M3Y-interaction [16]:

$$V(R) = 2999\ \frac{\exp(-4R)}{4R} - 2134\ \frac{\exp(-2.5R)}{2.5R} - 276\ (1 - \frac{0.005E}{A})\delta(R) \qquad (2)$$

For ^{7}Li nucleus the density is considered in the form [17]:

$$\rho(R) = \rho_0\left(1 + \alpha(\frac{R}{a})^2\right)\exp\left(-(\frac{R}{a})^2\right), \qquad (3)$$

where for harmonic oscillator a=1.77 fm and α=0.327fm. The analytical form of the real part of the optical potential is obtained by substituting Eqs. (2) and (3) into Eq. (1) and carrying out the required integrations over r_1.

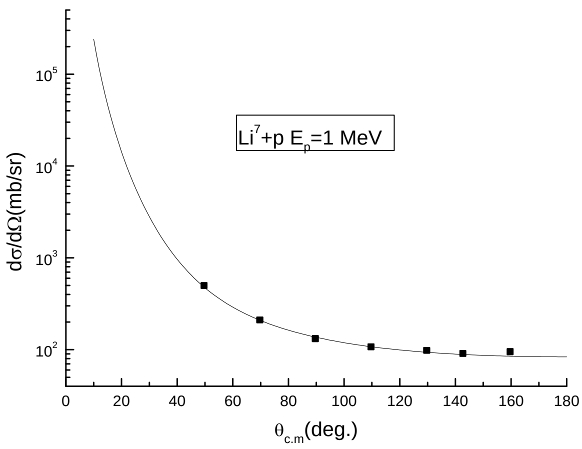

Figure (3): Measured diffrential cross sections of protons elastically scattering on 7Li at 1 MeV, where dots represent experimental data and lines represent the calculated values using single folding model Experimental data were taken from [15]

a- Spectroscopic factor

In general, extraction of spectroscopic factor is taken place from nuclear reaction (first minima). It was the first time to extract spectroscopic factor from elastic scattering depending on ALAS phenomenon. Extraction of spectroscopic factor is similarly ambiguous as the optical parameters since they depend on each other. First of all, optical parameters have been chosen, then, experimental data were reproduced. For researchers, it is a hard job to find a reliable sets of optical parameters used for extraction spectroscopic factor. In the author's point of view, a systematic study of the charged particles with light nuclei should be conducted as a starting point [18]. Potential depth has been expected before the study by knowing the number of incident particles in the nuclear reaction.

The choice of radius r_0 is the most important parameter to adjust optical parameters during analysis. Standard parameters are a good starting point for analysis as r_0 is taken 1.25fm and a0 0.65 fm. The available data on nuclear data center could be used to choose r_0, if not, one can obtain value of it from electron scattering. Few nucleons are found inside the nucleus for light nuclei, so the value of r_0 is very critical in the analysis. Global optical potential parameter is not the best choice for extraction spectroscopic factor, but it may be used in some cases. For low energies and light nuclei, it is very sensitive to any shift on radius value. The starting parameters are very important.

One of the most famous methods used to extract spectroscopic factor for (d,p) reaction has been discussed by N. Keeley [19]. The extraction of spectroscopic factor could be done for all reactions. Spectroscopic factors have been extracted from the relation using Distorted Wave Born Approximation (DWBA) method:

$$s_{l,j} = \frac{(\frac{d\sigma}{d\Omega})_{exp}}{(\frac{d\sigma}{d\Omega})_{DWBA}} \qquad (4)$$

Different reactions have been analyzed for ^{7}Be, ^{6}Li and ^{7}Li to extract spectroscopic factors [9, 13, 16]. ^{6}Li(^{3}He,d)^{7}Be reaction has been used to extract spectroscopic factor of ^{7}Be using Distorted Wave Born Approximation method. In the present study, Modified Distorted Wave Born Approximation (MDWBA) and Coupled Reaction Channel (CRC) methods have been used for ^{6}Li(^{3}He,d)^{7}Be reaction study. Reliable optical potential parameters have been obtained and used to extract spectroscopic factor for ^{7}Be [20]. Extraction of spectroscopic factors by DWBA and CRC methods has been done for the reaction ^{7}Li(d,t) ^{6}Li and a comparison between experimental and theoretical spectroscopic factors has been conducted [21]. Spectroscopic factors for ^{8}Be used are taken from a previous study [22], as ^{8}Be (g.s) =3.18, [7].

Experimental Data Analysis

Two parameters are used to reproduce differential cross sections of radiative reactions such as $^{7}Li(p,\gamma)^{8}Be$ reaction; optical potential parameters and spectroscopic factor. Depending on this fact, these two parameters are discussed. This section of the study discusses the effect of optical parameters on the calculated astrophysical S-factor. The optical parameters sets obtained at low energies at 0.346MeV (set 1) will be used to estimate astrophysical S-factor at wide range of energy up to 1.4MeV. The calculated Astrophysical S-factor obtained by such optical parameters is shown in Fig. (4). The effect of optical potential parameters is very obvious of such a case of analysis since no resonance is obtained at all during calculations. Other sets of parameters may be suitable for such radiative reaction. Further studies are planned to discover and enhance this point.

An input file for $^{7}Li(p,\gamma)^{8}Be$ reaction has been prepared by (set 2) and will be used in the analysis as shown in Fig. (4). We need to multiply the calculated value by factor 19 to obtain coincidence between calculated and experimental data as shown in Fig. (4).

Further analysis has been performed depending on parameters obtained by single folding model; set 3 of optical parameters has been used in our calculation as shown in Fig. (4). We had to divide calculated astrophysical S-factor by factor 10 to obtain converge between experimental and calculated data (see Fig. 4).

Set 4 has been used to calculate astrophysical S-factor which is multiplied by factor 4 to obtain agreement between experimental and calculated data (see Fig. 4). No resonances have been obtained using such set of parameters (sets 1, 3 and 4).

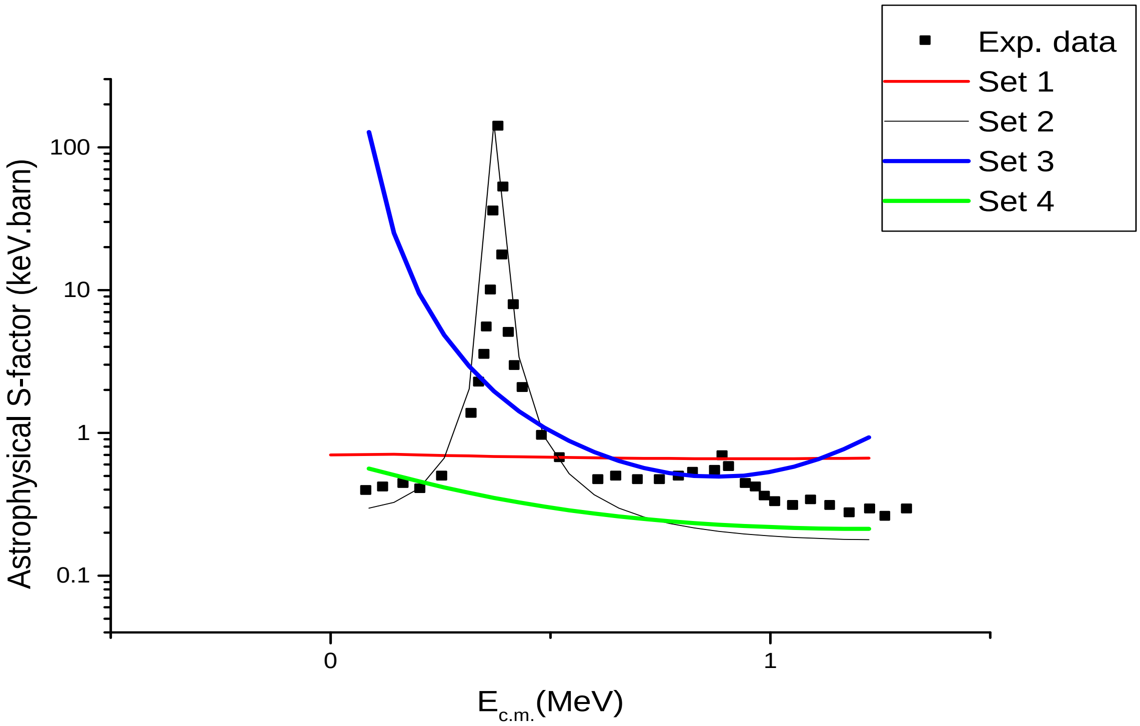

Fig. (4): Astrophysical S-factor for $^{7}Li(p,\gamma)^{8}Be$ reaction, experimental data is taken from [23] and calculated astrophysical S-factor by set 1, 2, 3 and 4

Conclusion

Different sets of optical potential parameters have been obtained for proton elastic scattering by ^{7}Li. A single folding has been used to calculate approximated set of parameters of p+^{7}Li. Astrophysical S-factor for ^{7}Li(p,γ)^{8}Be reaction has been calculated using different sets of parameters. Not all sets of parameters are suitable to study such radiative reaction. The choice of such parameters needs locality parameters to overcome the ambiguity of astrophysical S-factor. One set needs multiplication, others need division on a factor. A great effect on the calculated S-factor has been found due to the optical potential parameters and a minor effect results from spectroscopic factor. The optical parameters are responsible for the shape of analysis, but the position results from spectroscopic factor. There is a doubt on the obtained results in some previous studies, as the author tried to use the same optical potential parameters and there were completely different results.

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