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Discrepancy of Astrophysical S-Factor

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Optical potential parameters have been discussed as an art more than physics. The effects of optical model parameters (OMPs) on differential cross section calculations and hence extraction of spectroscopic factor has been discussed. Optical model parameters have been expected especially for charged particles with light nuclei. The ambiguity of the optical potential parameters has been solved. Global optical potential parameters have been explained as not the best choice for extraction spectroscopic factor and hence calculate astrophysical S-factor. The measurements of experimental data have been discussed as the most important parameter that produces discrepancy in the astrophysical S-factor. The models used to extract the spectroscopic factor are briefly presented, and examples are discussed. The importance of astrophysical S-factor has been explained under nuclear models. Few models have been chosen as just examples of discrepancy of astrophysical S-factor in spite of the presence of many models dealing with such point of view. The discussion has neglected some effects of extraction astrophysical S-factor as coulomb barrier and electron screening.

Keywords: Optical model parameters/ Spectroscopic factor/ Astrophysical S-factor

Introduction

The study of optical model parameters has wide importance and vast applications in the investigations of nuclear reactions. The optical model parameters have been developed through decades depending on the necessity for analysis of reactions under consideration. The importance of such study of optical model parameters comes from the discrepancy resulting from the of choice wrong set of parameters. The analysis of not only elastic scattering needs optical parameters but also radiative and transfer reactions needs optical parameters as well. Extraction of spectroscopic factors is done using optical potential parameters. Any deviation of optical parameters gives rise to extracted spectroscopic factors. So, it is very important to choose the parameters using in your investigation. A lot of attempts have been done in last decades to overcome the ambiguities of optical model parameters.

Our attempts to find set of parameters with physical meaning were the motivation to write this research. The harmonic of such parameters needs physical meaning. How to find out these parameters; How to overcome the ambiguities of the parameters already have been chosen. Reproducing differential cross section does not indicate for reality of optical potential parameters. Many sets of parameters could reproduce differential cross section and have no physical meaning.

The measurements of nuclear reactions in low energy ranges few keVs are impossible under normal circumstances. So, extrapolation of differential cross section (astrophysical S-factor) in such case is the available choice till now. The optical parameters also have an effect in such cases. The researcher will find some difficulties to choose the best set of parameters especially in case of low energies and light nuclei as a target. The

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study will continue to solve problems and another puzzles will appear.

Spectroscopic factor is very important parameter for nuclear reactions analysis. There are two methods to obtain spectroscopic factor. First, one can calculate it from theoretical models. Second, extraction spectroscopic factor from experimental data and this method from our point of view is the best choice if the set of optical potential parameters used in the analysis is close to reliable one. The radius is very important in this analysis so, you should choose radius from fitted data or put it through analysis as 1.25fm. For light nuclei, we have proved that the depth is systematic and could be expected for incident particles.

Our analysis was for p, d, ^{3}He and ^{4}He elastically scattered from ^{6}Li. The interaction of the complex particles with light nuclei has a specific effect called as an anomalous large-angle scattering (ALAS), which is impossible to explain in the framework of the standard optical model is often observed. The nature of this phenomenon can by different, but in certain cases for ^{6}Li and ^{7}Li targets, having the pronounced (α+*d*) and (α+*t*) cluster structure, increasing in angular distributions at large angle is observed. It is almost entirely connected with the transfer exchange mechanism, and superimposed on potential scattering. It should be mentioned that the spectroscopic factors obtained from analysis depend strongly on the shape of the bound state potential commonly used in the Woods-Saxon form [1].

The results of DWBA analysis of the transfer cross sections are typically highly sensitive to changing of the optical potential parameters. The calculated angular distribution of the nucleon transfer reaction can vary significantly even through the used OM parameters fit well the elastic scattering in the entrance and exit reaction channels. Moreover, different optical potential parameterizations can provide spectroscopic factors different up to factor 3. Consequently, it is very important to fix these values as long as possible. From theoretical analysis, the ^{6}Li≡α+d and ^{6}Li≡ d+α configurations are the same [2]. We have for first time extracted spectroscopic factor from experimental data of elastic scattering. Depending on increasing the cross sections at backward angles (ALAS), we have extracted spectroscopic factor for ^{6}Li as a target [1]. The extracted spectroscopic factor was in coincidence with that value obtained by theory. Extraction of spectroscopic factor has a special important for reproduce differential cross section for nuclear reaction. Spectroscopic factor from direct reactions has been extracted for long time ago. Our attempt here is to explain discrepancies result from different methods of extrapolation astrophysical S-factor; the study will concern on the light nuclei. The aim of this work is to discuss very important parameter (astrophysical S-factor) in astrophysics. The extracted values of astrophysical S-factor for the same values have a huge discrepancy for the same reaction. How to come over such discrepancy, we have produced the parameters have effects on extraction of astrophysical S-factor and examples for such discrepancy from literature and ours.

Factors have effects on extraction of astrophysical S-factor

1. *Optical potential parameters*

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. We tried to find another method to analyze 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 energies. Our attempt started in 2010 when we have studied elastic scattering of protons with ^{6}Li. After few months, we have analyzed deuterons elastic scattering by ^{6}Li. We noticed that, for ^{6}Li, with the same radius (r_0=1.05fm), the real potential depth were twice the value of it in case of protons with ^{6}Li. Further investigation has been done for ^{3}He elastic scattering by ^{6}Li when we tried to analyze the reaction ^{6}Li(^{3}He,d)^{7}Be. On that situation, we have discovered 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 40-50 MeV and the value of potential depth for deuterons elastically scattered by ^{6}Li was 80-90 MeV.

In case of ^{3}He elastically scattered by ^{6}Li, the real potential depth derived was in the range 120-130 MeV. The ambiguity of optical potential parameters is solved by our study. 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. Our studies present 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. Also, for astrophysical applications our assumptions have been used to study $^{6}Li(p,\gamma)^{7}Be$, $^{7}Li(p,\gamma)^{8}Be$ and $^{10}B(p,\gamma)^{11}C$ reactions. The discussions have been concerned with real potential depth where imaginary (surface and volume) could be adjusted for each scale of energy. For very low energies surface part for imaginary potential is working 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 has not been found but we can reduce the errors by choosing optical parameters suitable for the study under consideration where every range of atomic number and energy needs especial sets of optical parameters.

The researchers spend a lot of time to calculate (extract) optical parameters where the solution is to find 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 solution to obtain reliable values of nuclei radii. The light nuclei contain few numbers of nucleons so the radii of them 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 sources of 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 you have no idea about its value please, put it in your code equal 0.65fm as starting parameter. So, the parameters are under-control by understanding their behavior before analysis.

The choice of the optical parameters to reproduce differential cross section is sensitive especially at low energies for light nuclei. We have developed new method to expect optical parameters from number of incident particles. The main idea is that the potential depth depends on the number of incident nucleons. We calculated single folding for proton ^{6}Li interaction and obtained the potential depth 39 MeV. The potentials for $d+^{6}Li$ and $^{3}He+^{6}Li$ interaction will be twice and three times as large as for $p + ^{6}Li$ interaction. We obtained the potential depths for deuteron and ^{3}He as 76 and 127 MeV, respectively. These values are close to predicted ones. The calculated potential depth of ^{4}He by ^{6}Li using double-folding model was expected to be lower than 160 MeV as systematic variation because ^{4}He has no spin. Also, ^{4}He is compact nucleus so the depth of real potential obtained is lower than expected. The further analysis of the data will give us more information about the reaction contents. The obtained depth has an agreement with articles published in the same range of energy with light nuclei [3].

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* et al. have obtained global optical potential parameters for α-particles scattering by light nuclei using simultaneously fitting the experimental data of reaction cross-sections and elastic scattering angular distributions [4]. 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 ~45-50 MeV. ***The global optical potential parameters*** is one but not the best choice for studying nuclear reactions especially for light nuclei at low energies.

2. *Spectroscopic factor*

Spectroscopic information may be obtained from analysis of elastic scattering using more complicated calculations. A lot of attempts have been done to overcome the ambiguity of spectroscopic factor extraction. The choice of model used to extract spectroscopic factor is very important where optical model parameters also have the same importance. The choice of optical model parameters to be used in our extraction is a hard job for researchers; we have discussed this point in systematic study of charged particles with light nuclei [3]. The potential depth could be expected before study simply by knowing incident particle in the nuclear reaction. The radius r_0 is the most important parameter in the analysis of nuclear reaction for both elastic scattering and nuclear reactions. If you have not any values for r_0, you should put it equal to 1.25 fm as standard parameter. Electron scattering is available and acceptable technique to obtain r_0 from nuclear data centers. For light nuclei, the value of r_0 is very effective in your analysis where few nucleons are found inside the nucleus. Global optical potential parameter is one choice for data analysis in case of extraction of spectroscopic factor but this is choice not the best choice. The locality of optical parameters at low energies for light nuclei has been used. How to start your analysis is very important, all the time optical potential parameters should be chosen for exit and entrance channels for transfer reactions.

The extraction of spectroscopic factor from direct reactions has been done by many groups all over the world; N. Keeley has reviewed such attempts in lectures. N. Keeley has discussed the most famous methods used to extract spectroscopic factor for (d, p) reaction. Betty Tsang in 2005 through INFN Workshop on Reactions and Structure with Exotic Nuclei and under the address "Survey of the neutron spectroscopic factors from Li to Cr" has extracted spectroscopic factor from direct reactions. Wide range of energies and nuclei has been analyzed by the workshop. The analysis has been compared with shell model. The study produces a scheme for direct reaction rates for long time (from 1950 till now). The summary of such study also discussed published papers about spectroscopic factors which showed large fluctuations from analysis to analysis. The optical potential parameters also have an effect on the extracted spectroscopic factors so; they have used global optical potential parameters which we discussed before as a negative parameter in case of extracted spectroscopic factor.

For each reaction one can extract spectroscopic factor for each configuration, not only for neutron transfer in $^{12}C(d,p)^{13}C$ reaction. We have extracted spectroscopic factor from $^{6}Li(^{3}He,d)^{7}$ Be for proton transfer at energies 18, 33.3 and 34MeV. From direct reaction, we can extract spectroscopic factor from the relation using DWBA method:

$$s_{l,j} = \frac{(\frac{d\sigma}{d\Omega})_{exp}}{(\frac{d\sigma}{d\Omega})_{DWBA}} \quad (1)$$

Depending on the basic assumptions of DWBA; *the reaction is dominated by one-step direct transfer. Elastic Scattering is the main process in the entrance and exit channels.* We have analyzed different reactions and elastic scattering to extract spectroscopic factor for ^{7}Be, ^{6}Li and ^{7}Li. Distorted Wave Born Approximation method has been used to extract spectroscopic factor of ^{7}Be from $^{6}Li(^{3}He,d)^{7}Be$ reaction. In spite of efficiency of DWBA method to reproduce differential cross section, we have used MDWBA and CRC methods for $^{6}Li(^{3}He,d)^{7}Be$ reaction study. Our aim is to enhance optical potential parameters and use them to extract spectroscopic factor for ^{7}Be [2]. The $^{7}Li(d,t)^{6}Li$ reaction has been examined at different energies to reproduce differential cross section using different models. We have extracted spectroscopic factors by DWBA and CRC methods and the comparison between experimental and theoretical spectroscopic factors has been noticed [5].

3. *Experimental data ($^{6}Li(p,\gamma)^{7}Be$ reaction is taken as example)*

There are many examples where the discrepancy of astrophysical S-factor is obvious. Radiative capture of nucleons 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 [6]. The S-factor of the $^{6}Li(p,\gamma)^{7}Be$ reaction is dominated by captures to the ground state and first excited state of ^{7}Be. This reaction has been experimentally studied by Switkowski et al. [7] at low energies down to 200 keV. A theoretical extrapolation has been performed by Barker [8] within potential model, based on simultaneous fit of $^{6}Li(n,\gamma)^{7}Li$ and $^{6}Li(p,\gamma)^{7}Be$ cross sections. K. Arai et al. [9] used a four cluster microscopic model to investigate low-energy ^{6}Li+p and ^{6}Li+n reactions. Derived astrophysical S-factor for the $^{6}Li(p,\gamma)^{7}Be$ was in good agreement with the available experimental data.

Knowledge of the rate of change 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 is not sufficient. Low-energy resonances or sub-threshold states can affect the extrapolation.

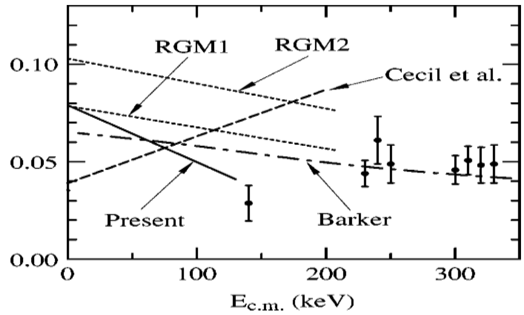

Fig. (1) Astrophysical S-factor for the radiative reaction of protons on ^{6}Li. The figure is taken from Prior et al. [10]. The line "Present" is the results of Prior et al

In [10] the results of a measurement of the slope of the astrophysical *S* factor for the ^{6}Li(p,γ)^{7}Be reaction are reported, and a new mechanism is introduced to explain the observed slope. The slope was determined from the relative yields at five incident proton energies. The slope of extracted astrophysical S-factor was found ***to be negative*** [10]. Cecil et al. [11] 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. Barker's analysis [8] of the data of Switkowski *et al.* does have a negative *S*-factor slope for ^{6}Li(p,γ_0)^{7}Be and ^{6}Li(p,γ_1)^{7}Be at energies below the range of the data. The present measurements were undertaken to examine this discrepancy in the previous measurements of Cecil et al. [11] and Prior et al. [10]. The measurements of angular distributions of gamma-quanta from the ^{6}Li(p,γ)^{7}Be for transitions were for the ground state and first excited state (429 keV) of the ^{7}Be at energies of incident protons of 387, 690, 984 and 1283 keV.

Another example for discrepancy that may appear from experimental data is NACRE II [12] the authors said" *In some cases, however, we omit from the analysis those data points which deviate very much from other measurements".* We have to ask about omitting experimental data, it is true or not. The choice of experimental data to be analyzed also is complicated process in spite of no choice is available for such argument.

4. Models used for analysis

Many examples could be used to discuss this argument about the model used for data analysis. C. Angulo et al. [13] have introduced such comparison between two models used for analyzing experimental data (see Fig. 2). The analysis has been done by the same parameters to perform R-matrix used by Schröder et al. [14] to understand the results and no agreement has been obtained, no parameter set has been found which reproduces Schröder et al. fit (dotted curve in Fig. 3).

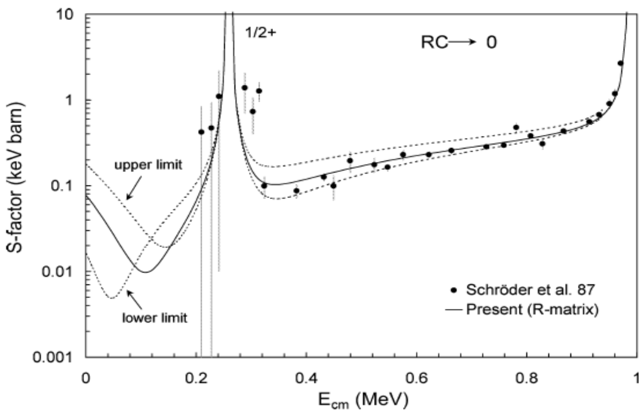

Fig. (2) The figure is taken from [12]

R-matrix fit leads to a S-factor at zero energy S(0) = 0.08keVb, where the error bar accounts for uncertainties on the sub-threshold-state and background parameters. This S(0) is about 20 times smaller than the value obtained by Schröder et al. [6].

C. Angulo et al. [15] have used different forms to calculate astrophysical S-factor in the same article and this is for example in page 3 one can calculate astrophysical S-factor from the relation 3 in the article. For the reaction ^{7}Li(p,α)^{4}He, astrophysical S-factor has been adopted to be:

$$S(0)=0.059+0.19E+0.35E^2 \quad (2)$$

Going further to introduce more examples as in case of A. Moghadasi et al. [16] have calculated astrophysical S-factor based on another method. The calculated astrophysical S-factor is reported in table 1 which give impression about the difference may appear on the results from models used.

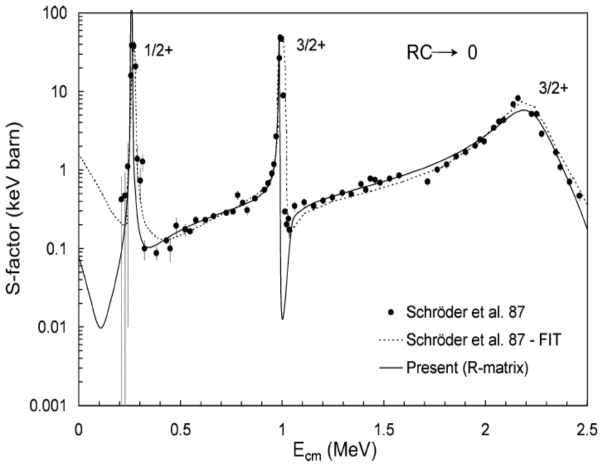

Fig. (3) The figure is taken from [12]

Table (1) Astrophysical S-factor calculated for $^{13}C(p,\gamma)^{14}N$ reaction for first resonance levels (taken from ref. [16])

Researcher	$S(0)$ (keV.b)
Bertulani and Guimarães	6.217
King et al.	5.25
Chakraborty et al.*	4.72 ± 0.86
Chakraborty et al.*	4.23 ± 0.82
Mukhamedzhanov et al.	5.16 ± 0.72
Genard et al.	3.94 ± 0.59
Li et al.	5.78 ± 0.48
This work	5.8 ± 0.7

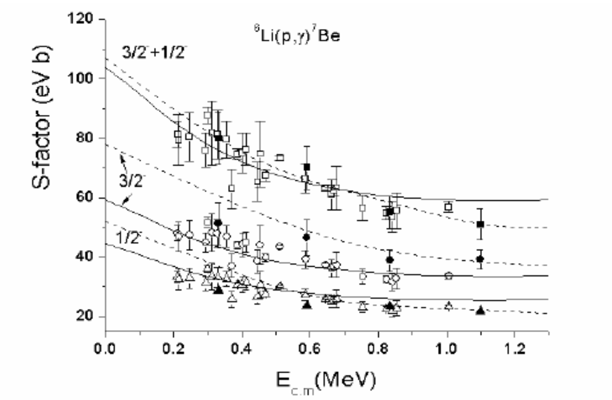

Fig. (4) the blank points are from [7], filled points are taken from [17]. The solid line is the result of R-matrix calculation, while dashed line belongs to the calculations using Fresco program [18], the figure is taken from [17]

The calculations obtained by Fresco is S(0)=114±5eVb which give obvious discrepancy between R-matrix and Fresco program calculations (potential model).

5. *Experimental data analysis*

An example of such discrepancy is given by $^{7}Li(p,\gamma)^{8}Be$ where the reaction has been analyzed such reaction using potential model.

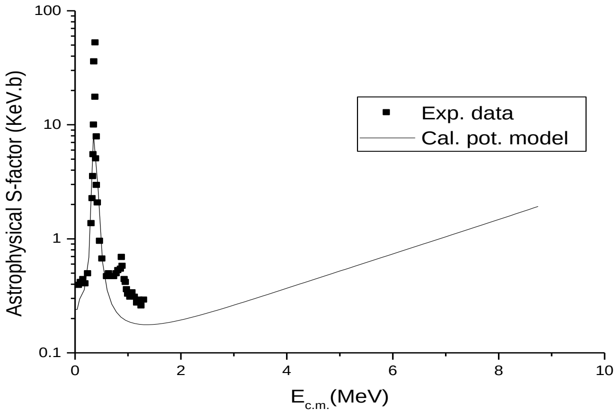

Fig. (5) Astrophysical S-factor for *$^{7}Li(p,\gamma)^{8}Be$ reaction*, experimental data is taken from [20]

The problem here is how to analyze experimental data with a certain model like potential model has been used in $^{7}Li(p,\gamma)^{8}Be$ reaction. We had to multiply the calculated data with potential model ***by the factor 25*** to obtain coincidence between experimental data and theory. The calculations have been done using Fresco code. The same reaction has been analyzed with [19] with potential model and they obtain results higher than ours by the factor 3. The potential parameters have been used in two calculations are completely different in spite of when we have used the same parameters we could not analyze experimental data.

J.M. Sampaio et al. [21] have calculated astrophysical S-factor, it was equal 0.27 keV. barn. The extracted astrophysical S-factor by us is shown in Fig. (5) is equal 0.24 keV. barn (after multiplied by the factor 25) which **25** times lower than value calculated by J.M. Sampaio et al.

A.M. Mukhamedzhanov et al. [22] have discussed indirect techniques to extract astrophysical S-factor (ANC, SF, and THM). These techniques are suitable to extract astrophysical S-factor. Such indirect techniques especially Asymptotic Normalization Coefficient and Trojan Horse are suitable to extract astrophysical S-factor since no dependence on optical parameters and spectroscopic factors. Cluster model and potential model are still need more adjustment to be accurate methods to extract astrophysical S-factor (S(0)).

Conclusion

There are many factors, which have effects on the astrophysical S-factor calculation. The most effective parameter is the experimental data measured at low energies where we have an objection on omitting experimental data on NACRE II. A lot of attempts have been done to overcome the discrepancy of astrophysical S-factor. We have showed just the problem result from different factors connected with the discrepancy of astrophysical S-factor where the solution needs further investigation, this is the next step.

As discussed in the article *the value of S(0) calculated by* C. Angulo *is about 20 times smaller than the value obtained by Schröder et al. which not the only case. Our impression about extraction of* astrophysical S-factor is diffused and has to study in different theoretical models. Further investigation should be done in near future for such study.

In my opinion, the experimental data is the most important parameter of all those parameters we have discussed above. The facilities used to study such lower energies are very important and have to develop to achieve the goal.

The second parameter is model used to analyze experimental data. LUNA and NACRE have produced models and methods to come over the discrepancy of astrophysical S-factor. Trojan horse nowadays is a fashionable technique to extract astrophysical S-factor. It is very important to study more and more techniques to adjust such parameter (astrophysical S-factor).

Spectroscopic factor and optical parameters have lower effects as they are limited to few models to extract astrophysical S-factor.

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