Calculation of Astrophysical S-factor for the ^{60}Ni(p,γ)^{61}Cu Reaction Below Coulomb Barrier

Animesh Kumer Chakraborty

Department of Physics, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh

Abstract: ***Astrophysical S-factor was calculated for the reaction*** ^{60}***Ni(p,γ)***^{61}***Cu, on the basis of experimental cross-section data, as a function of the incident proton energy ranges from 1.49 MeV to 3.96 MeV. Since the literature values of this reaction is rather scarcein low-energy region, the astrophysical S-factor was calculated which describes the possibility of the reaction to occur. The Coulomb-barrier potential, Sommerfeld parameter and the Gamow factor were also calculated in the centre-of-mass(C.M) system for the estimation of the probability of penetrating the Coulomb barrier through tunneling effect which leads to an insight of the mechanism of low-energy light-charged particle capture reactions those are very important for astrophysical aspects.***

Keywords: Astrophysical S-factor, (p,γ)-reaction, excitation function, reaction threshold, Coulomb barrier, Gamow factor, Sommerfeld parameter

1. Introduction

Nuclear reactions cross sections such as the radiative capture (p,γ), (α,γ), (n,γ)etc are of crucial interest in astrophysics, since they play an important role in basic processes such as steller burning,evolution of stars, nucleosynthesis [1]. It is well known that the experimental cross sections at energies far below the Coulomb barrier (i.e., steller energy region) are very scarce due to the fact that the probability of the tunneling effect decreases, hence cross sections drop for energies. As a result, precise determination of cross-sections in the threshold energy region becomes difficult (because the Coulomb barrier exponentially suppresses low-energy cross sections). Although it is true that measurements of nuclear reaction cross-sections for charged-particle induced reactions can be extended toward lower energies with improved experimental techniques, but in practice one can hardly reach the stellar energy region. This has lead to the implementation of indirect methods allowing the experimental difficulties inherent to the direct measurements of capture cross-section to be circumvented.

Generally, cross sections at low energy can be obtained by extrapolation from the values measured at higher energies, preferably with the help of some theoretical considerations. However, cross-sections for charged particle induced reactions that depends on energymakes this extrapolation difficult. Thus, for extrapolationat very low energies below the Coulomb barrier, instead of using the cross section, it is more convenient to use the much less energy dependent quantity, the astrophysical S-factor, S(E). In fact, the astrophysical S-factor of the reaction changes slowly with incident-particle energy (i.e., weakly depends on energy), thus this factor removes the coulomb dependence and only accounts the nuclear effects, hence evolved as more convenient in separating the energy dependence of Coulomb barrier penetration from the cross sections [2].For astrophysical applications, one needs to know the value of S-factor for many reactions at low energies. In respect of the formation of medium mass elements via nucleosynthesis in stellar process, the ^{60}Ni(p,γ)^{61}Cu reaction has a significant importance.

A number of authors have proposed different models and techniques in the last few decades for the calculations of astrophysical parameters for reactions those are important for understanding the overall mechanisms of stellar processes [1-10]. In fact, depending on temperature, density and other parameters, stellar burning may involve many reactions of different nuclei, from light to heavy, and from stable to neutron- and proton-rich ones.

The aim of this work is to calculate the astrophysical s-factor along with other related parameters for the reaction ^{60}Ni(p,γ)^{61}Cu using the experimental cross-sections measured recently at the Tandem Accelerator Facilities Division, INST, AERE, Dhaka, Bangladesh [11] and to compare the results with theoretical model calculations using TALYS 1.8 codes.

2. Theory

In some cases, the height of the Coulomb barrier becomes orders of magnitude higher than the energy of the interacting charged particles during the non-explosive nucleosynthesis. So, the quantum mechanical tunneling is the only way for the reactions to occur. The probability of penetrating the Coulomb barrier via tunneling effect is

$$P=\frac{\left|\Psi(\overrightarrow{R_n})\right|^2}{\left|\Psi(\overrightarrow{R_c})\right|^2} \qquad \text{(i)}$$

Where $\overrightarrow{R_c}$ is the so-called classical turning point and $\overrightarrow{R_n}$ is the nuclear radius. At low energies where E □ E_c (equivalently where $\left|R_c\right|$ □ $\left|R_n\right|$), this probability can be approximated with

$$P=\exp(-2\pi\eta) \qquad \text{(ii)}$$

Where η is the Sommerfeld parameter,

$$\eta=\frac{Z_xZ_ye^2}{\hbar v} \qquad \text{(iii)}$$

And the Gamow factor

$$2\pi\eta = 31.29105712 Z_x Z_y \left(\frac{\mu}{E}\right)^{\frac{1}{2}} \qquad \text{(iv)}$$

Where the centre-of-mass energy E is in keV and the reduced mass μin amu. Also, the Coulomb barrier potential E_c has the simplest form in MeV as

$$E_c = \frac{1.44 Z_x Z_y}{1.3(A_x^{1/3} + A_y^{1/3})} \qquad \text{(v)}$$

The suffices x and y represent the incident and target nuclei respectively.
If m_x and m_y are masses of projectile and target respectively, then

$$\mu = \frac{m_x m_y}{m_x + m_y} \qquad \text{(vi)}$$

And the lab-energy $E_l$is related to the centre-of-mass energy E as

$$E = \frac{E_l m_y}{m_x + m_y} \qquad \text{(vii)}$$

The charged particle cross section, $\sigma(E)$, drops rapidly for energies below the coulomb barrier because the probability of tunneling effect decreases exponentially

$$\sigma(E) \propto \exp(-2\pi\eta) \qquad \text{(viii)}$$

Therefore, in several cases the experiments can be performed at higher energies and then the results can be extrapolated to lower energy regions of astrophysical interest. However, the strong energy dependence of the cross section makes this extrapolation difficult. For extrapolation in the case of non-resonant reactions, instead of the cross section, the much less energy dependent quantity

$$S(E) = \frac{\sigma(E)E}{\exp(-2\pi\eta)} \qquad \text{(ix)}$$

Is used. This quantity is the so-called astrophysical S-factor[12].

3. Calculations

In this work, the experimental data were used as the input parameters for the calculations of s-factor and other related parameters. Cross sections for the ^{nat}Ni(p,x)^{61}Cu reactions were measured using the 3 MV tandem accelerator at AERE, Savar, Dhaka with the incident proton energy ranges from 1.49 to 3.6 MeV. Conventional stacked-foil technique was applied for the irradiation procedure [11]. ^{61}Cu ($T_{1/2}$ = 3.33h) can be produced via the ^{60}Ni(p,γ)^{61}Cu and ^{61}Ni(p,n)^{61}Cu reactions in ^{nat}Ni+p process within above mentioned energy range. The threshold energy for the reaction ^{61}Ni(p,n)^{61}Cu is 3.1 MeV whereas the threshold for the ^{60}Ni(p,γ)^{61}Cu reaction is zero. Moreover, in the natural nickel, the isotopic abundance of ^{61}Ni is 1.140%, for ^{60}Ni which is 26.223%. So, the contribution of the ^{61}Ni(p,n)^{61}Cu reaction for the production of ^{61}Cu is ignorable and the entire formation of ^{61}Cucan be considered to be through the ^{60}Ni(p,γ)^{61}Cu reaction i.e., only via (p,γ) process. Hence, the experimental cross-section values were extrapolated unambiguously to 100% enriched target. The energy of the projectile was measured in the laboratory system which was converted to centre-of-mass system. The Sommerfeld parameter and Gamow factor were calculated using equations (iii) and (iv) respectively. Probability of quantum mechanical tunneling is related to the Gamow factor and was calculatedwith s-wave approximation, i.e., only l=0 waves were taken into account. Coulomb barrier can be estimated easily using the equation (v). Finally, the S-factor was calculated.

4. Results and Conclusion

Values of all the parameters calculated in this work are presented in Table-1. The Coulomb barrier was found to be around 6 MeV. The variation of astrophysical s-factor and the corresponding values of the Coulomb barrier penetrability are shown in Fig.1 and Fig.2 respectively.The variation of Gammow factor is shown in Fig.3. The s-factor is found to be increasing almost exponentially with lowering energy and the quantum mechanical tunneling probability i.e., the Coulomb barrier penetrability shows an exponential increasing trend towards higher energy. The higher value of the S-factor up to 1.5 MeV confirms the possibility of the reaction to occur by the quantum mechanical tunneling of the Coulomb barrier and hence the radiative capture of proton by the ^{60}Ni nuclide is probable in the stellar energy region. In the EXFOR database no other data for the ^{60}Ni(p,γ)^{61}Cu reaction below 3 MeV is available, hence the calculated results could not be compared.

In this work, a simple method has been used for the calculation of S-factor for proton capture reactions in the stellar energy region. The method can be applied in general for the study of the radiative-capture reactions of charged particles below their respective thresholds those are most likely to take place in nucleosynthesis process in stellar energy region.

Table 1: Calculated values of different parameters

Proton Energy in C.M. (MeV)	Sommerfeld parameter, η	Gamow factor, 2πη	Coulomb barrier penetrability	S-factor (keV.barn)
3.90	2.25	14.11	7.46×10^{-7}	8.60
3.57	2.35	14.74	3.98×10^{-7}	12.37
3.36	2.42	15.18	2.55×10^{-7}	19.21
2.98	2.57	16.13	9.89×10^{-8}	26.58
2.77	2.66	16.72	5.48×10^{-8}	23.29
2.52	2.79	17.55	2.39×10^{-8}	28.25
2.33	2.90	18.24	1.20×10^{-8}	37.25
2.10	3.06	19.19	4.62×10^{-9}	69.97
1.84	3.27	20.53	1.21×10^{-9}	116.70
1.63	3.47	21.79	3.44×10^{-10}	164.46
1.47	3.66	23.00	1.02×10^{-10}	275.07

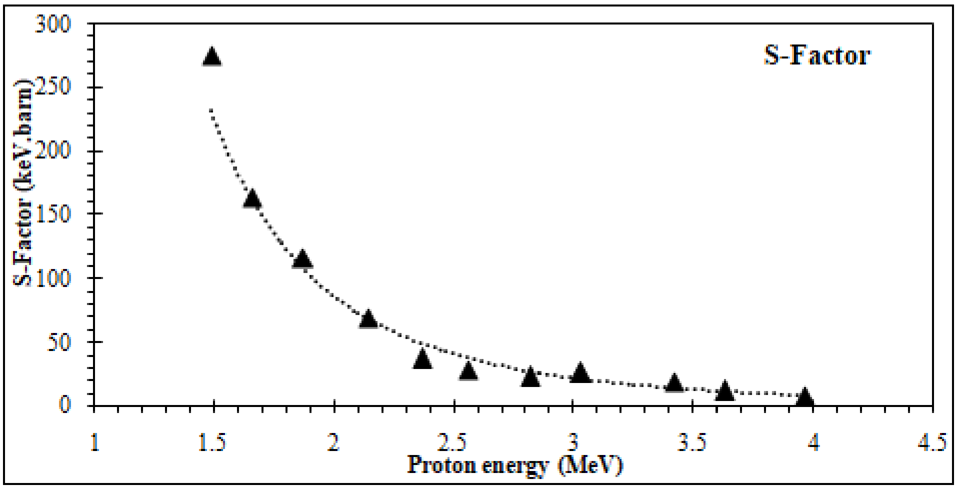

Figure 1: Astrophysical S-factor for the reaction $^{60}Ni(p,\gamma)^{61}Cu$

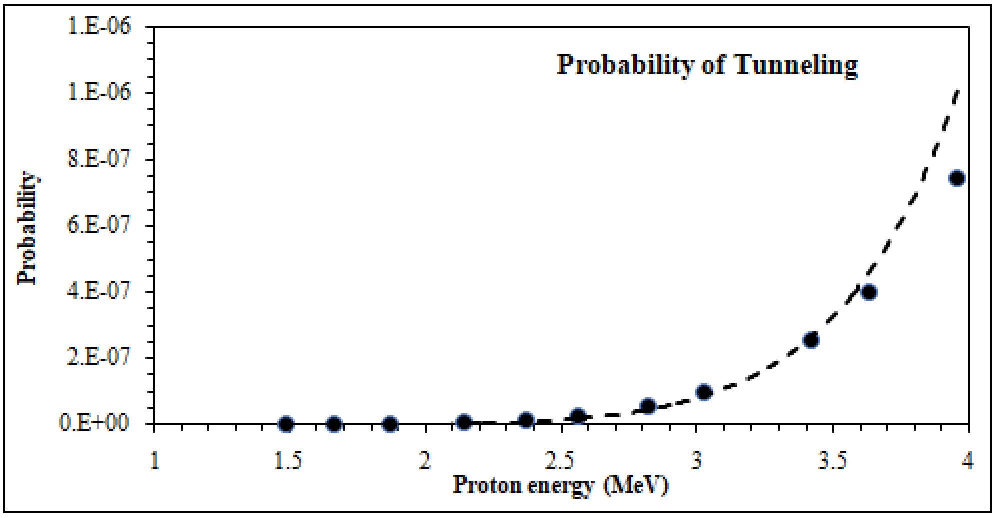

Figure 2: Variation of tunneling probability with incident proton energy

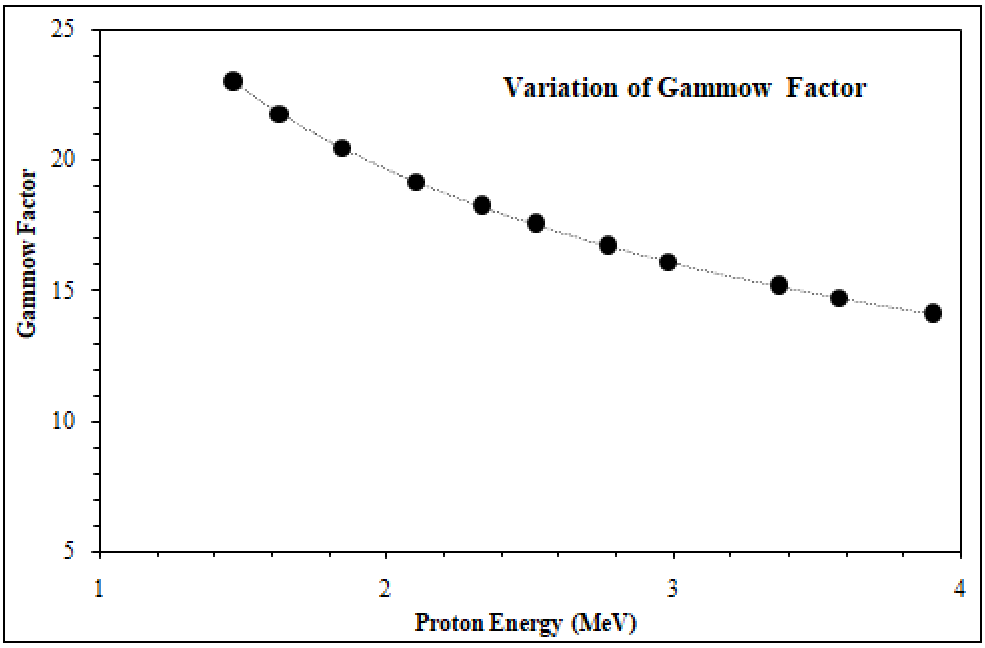

Figure 3: Variation of Gammow factor with incident proton energy

References

[1] M. S. Basunia, E. B. Norman, H. A. Shugart, A. R. Smith, M. J. Dolinski and B. J. Quiter, Measurement of Cross Sections for the ^{63}Cu(α,γ)^{67}Ga Reaction from 5.9 to 8.7 MeV, Phys. Rev. C **71**, 035801 (2005).

[2] R. Kunz, S. Barth, A. Denker, H. W. Drotleff, J. W. Hammer, H. Knee and A. Maye, Determination of the ^{9}Be(α,n)^{12}C Reaction Rate, Phys. Rev. C **53**, 2486 (1996).

[3] E. R. Claus and S. R. William, Cauldrons in the Cosmos, The University of Chicago (1998).

[4] H. I. Andic and O. Ozer, Calculation of Astrophysical S Factor at Low Energy Levels,AIP Con. Proc. 1815, 13001 (2017).

[5] K. H. Kim, Astrophysical S-factors of the ^{16}O(p,γ)^{17}F Reaction at Energies Applicable in Stellar Cores, J. Korean Phys. Soc., **43**(5), 691 (2003).

[6] S. B. Dubovichenko, A. V. Dzhazairov-Kakhramanoy and N. A. Burkova,Astrophysical S-factor for the ^{13}C(p,γ)^{14}N Radiative Capture Reaction, J. Nucl. Part. Phys. **2**(2), 6 (2012).

[7] E. Yildiz, A. Aydin, I. H. Sarpun and E. Tel, Calculations of Cross-Sections and Astrophysical S-factorsfor the (α,n) Reactions of Some Structural Fusion Materials, EPJ Web of Conference, **100**, 01010 (2015).

[8] D. G. Yakovlev, M. Beard, L. R. Gasques and M. Wiescher, A Simple Analytic Model for Astrophysical S-factors, Phys. Rev. C **82** 044609 (2010).

[9] H. Sadeghi, A. Moghadasi and M. Ghamary, The Astrophysical S-factor for the ^{2}H(α,γ)^{6}Li Nuclear Reaction at Low-Energies. J. Astrophys. Astr. **35**, 675 (2014).

[10] R. Ghasemi and H. Sadeghi, S-factor for Radiative Capture Reactions for Light Nuclei at Astrophysical Energies. Res. Phys. **9**, 151 (2018).

[11] M. S. Uddin, A. K. Chakraborty, S. Spellerberg, M. A. Shariff, S. Das, M. A. Rashid, I. Spahn and S. M. Qaim, Experimental Determination of Proton Induced Reaction Cross Sections on ^{nat}Ni Near Threshold Energy,Radiochim. Acta. **104**(5), 305 (2016).

[12] G. G. Kiss, Proton Induced Reactions and the Astrophysical P-Process, Ph. D. Thesis, University of Debrecen (2008).