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Impact of Neutron Sources of Stellar Reactions on Fluorine Abundances

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Abstract
There are many neutron sources in the universe that play an important role in the stellar slow neutron capture (*s*-process) nucleosynthesis. Fluorine-19 is a cosmically rare isotope that is generated in a series of reactions. The aim in this paper is to perform theoretical calculations to test the variance of neutron intensity generated within stellar conditions, especially in Asymptotic Giant Branch (AGB) stars, on the production of ^{19}F isotope. EMPIRE II program has been utilized with the aid of many MATLAB programs, and experimental comparisons have been made with NACRE II and Reaclib libraries. The results has shown that the high abundances of reactant nuclei responsible for ultimately generating ^{19}F are consumed by neutron poisoning reactions that highly affect the final generation of ^{19}F isotope. Also, the S_{eff} and $S(0)$ values for the reaction $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ have been approximately calculated in the present research.

Keywords: Nuclear Reactions, Stellar Physics, Thermonuclear Reactions, Nucleosynthesis, AGB stars.

تأثير مصدر النيوترون من التفاعلات النجمية على وفرة الفلورين

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الخلاصة:
هناك مصادر نيوترون عديدة في الكون والتي تلعب دورا مهما في عملية التخليق للعناصر اثناء عملية الاقتناص البطيء. الفلورين 19 هو من النظائر النادرة كونيا والذي يتولد خلال سلسلة من التفاعلات. في هذا البحث تم اجراء حسابات نظرية لتفحص تأثير تغاير مصادر النيوترون الموجودة في الظروف النجمية بالذات في نجوم AGB، على توليد نظير الفلورين 19. تم استخدام برنامج امباير بمساعدة وكتابة برامج عديدة بلغة ماتلاب، وتم اجراء مقارنات عملية مع مكتبات2 NACRE و Reaclib. بينت النتائج أن الوفرة العالية للنوى المتفاعلة المسؤولة في النهاية عن توليد نظير الفلورين 19 كما تم حساب المعامل الطيفي المؤثر S_{eff} و $S(0)$ للتفاعل $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ في هذا البحث وبصورة تقريبية.

1. Introduction

^{19}F isotope does not contribute to the main thermonuclear reactions inside active stars' cores, but its abundancy, with that of B, Be, and Li; form a group of universally-rare elements

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in the light mass number region. Only ^{7}Li isotope in this family is thought to be produced during the Big Bang [1]. However, among other processes, ^{19}F can be generated in massive stars during the branch of the slow neutron capture, or the *s*-process. The process of neutron production thus affects the total nucleosynthesis of this isotope.
Although rare, Fluorine has many isotopes, of which ^{19}F is the only stable and most abundant compared to the unstable ^{18}F, the second most abundant F-isotope. There is only a trace of ^{18}F isotope in the universe [2]. The low abundance of ^{19}F isotope is thought to be due to the limited sites where it is produced in the universe. Being the rarest amongst light elements in the universe, ^{19}F is possibly generated from three different mechanisms, namely [2]: (*i*)Type II Supernovae through the reaction $^{20}\mathrm{Ne}(\nu,\nu' p)^{19}\mathrm{F}$ (neutrino spallation), (*ii*) in Asymptotic Giant Branch (AGB) stars inside the He burning shell from the reaction $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ [3] (we shall call this reaction as $^{14}\mathrm{N}(2\alpha p,\alpha)^{19}\mathrm{F}$ for short), and (*iii*) within Wolf-Rayet (WR) stars with the same $^{14}\mathrm{N}(2\alpha p,\alpha)^{19}\mathrm{F}$ reaction. Such potential sources were theoretically predicted to fit with observed data [4].

Proton source in $^{14}\mathrm{N}(2\alpha p,\alpha)^{19}\mathrm{F}$ reaction comes from $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ reaction and this uses neutrons from $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ – see Figure (1). Therefore, there are quite a few parameters affecting the $^{14}\mathrm{N}(2\alpha p,\alpha)^{19}\mathrm{F}$ reaction. It is strongly believed that neutrons from $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ also contribute in the main component of the slow-neutron capture, or *s-process*, especially inside low-mass AGB stars $1.5M_{\Theta} \leq M \leq 3M_{\Theta}$ [5] - M_{Θ} is the solar mass. It is one of two key neutron sources feeding the *s-process* where the other reaction is $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ [6, 7]. Neutron sources, in return, are sensitive to many parameters, one of which is the optical model potential parameter.

The *s-process* consists of two components, *weak* and *main*. It was found that [8] some cosmic sites are preferable by the weak component, such as He-rich core regions of low-mass AGB reaching Red Giant (RG) stars with masses above ~ 7 to 8 M_{Θ}. These stars have good conditions such as enough temperature to ignite the Carbon-Nitrogen-Oxygen (CNO) cycle. When enough ^{14}N nuclei are formed from this cycle, the process of alpha capture can contribute to the production of ^{22}Ne element depending on the reaction $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$. Note that in this reaction, the positive beta (β^{+}) of ^{18}F decay has a crucial role in destroying this element and producing ^{18}O isotopes, and this is one of the main reasons behind the almost zero abundances of ^{18}F isotope in the universe.

The kinetic energy of α particles can exceed 20 keV as the temperature reaches more than about 0.3 GK inside stellar regions. Therefore, most particles can penetrate the Coulomb barrier of the target nucleus, and the reaction $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ will start to act in the weak *s-process*. The reaction $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+},\upsilon)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ consists of a chain of sub-reactions, therefore it is more complicated to examine it by an approximate approach. It is better if one could separate the effects of each stage on the final product of ^{19}F, starting with the most effective sources.

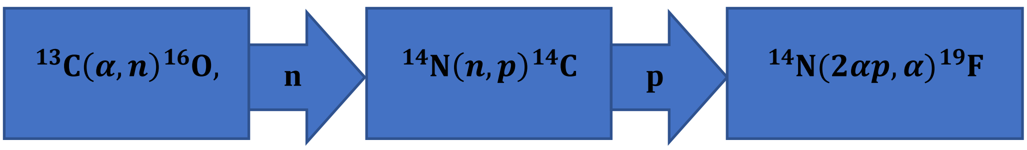

Figure 1: Proton source of $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+})^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ reaction is depending on the neutron source from alpha particle reaction with ^{13}C.

Thus, this work will focus on determining the general conditions that impact the strongest of the neutron source reactions especially in AGB stars, namely $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$, on ^{19}F abundances. To do this, we first theoretically calculate the neutron yield from $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$, then the sensitivity of this on the proton yield of $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ reaction. This could give a rough estimate of the effects that stellar neutron sources on ^{19}F final production, Figure (1). Then, reaction rates will be calculated for both $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$, and $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ for the temperature range ~ 10 GK. Few programs have been written to perform the present calculations using the MATLAB program, and cross-section values have been calculated from EMPIRE program. The experimental comparison shall be made with available standard libraries, namely NACRE II and Reaclib.

2. Theory

The basic quantity describing the probability of any nuclear reaction is the nuclear cross-section of certain reactions (channels), and many theoretical models are there to perform such calculations, of which Hauser-Feschbach model [6]

$$\sigma(E) = \sum_{J_\pi} \sigma_{CN}(E,J_\pi)\frac{T(E,J_\pi)}{T_c(E,J_\pi)} \tag{1}$$

Here σ is Hauser-Fischbach cross-section, $\sigma_{CN}(E,J_\pi)$ is the compound nucleus' cross-section of formation, J_π is the spin-parity space, and c is the optical model exit channel. T denotes the transmission coefficient of exit particle. Note that T_c is summed over all possible J space for the c-states.

In stellar physics, cross-sections are relatively hard to evaluate, thus these are transformed into a more easy-to estimate quantity in stellar nuclear physics, and the *reaction rate* $\langle\sigma v\rangle$. It's the velocity averaged cross-section of a specific reaction [6]

$$\langle\sigma v\rangle = 4\pi\left[\frac{\mu}{2\pi kT}\right]^{3/2}\int_0^\infty \sigma v^3\, e^{-\frac{\mu v^2}{2kT}}\, dv \tag{2}$$

Where v is the velocity, μ is the reduced mass and T is the temperature. For astrophysical interest, a thermonuclear reaction occurs in the range of 0.1 to 1 GK (E~130 keV), while in supernovae the temperature might reach up to 10 GK [6, 9]. $\langle\sigma v\rangle$ is the total rate of a particle's reaction with a specific target [6],

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}}(kT)^{-3/2}\int_0^\infty E\,\sigma(E)\,e^{-E/kT}dE \tag{3}$$

The quantity $\langle\sigma v\rangle$ can be made in terms of $N_A\langle\sigma v\rangle$, where N_A is being Avogadro's number, then $\langle\sigma v\rangle$ will represent reaction [9]. If we use T_9 for temperature in GK and substitute the numerical values then

$$N_A\langle\sigma v\rangle \cong \frac{3.732\times 10^9}{(\mu {T_9}^3)^{1/2}}\int_0^\infty E\,\sigma(E)\,e^{-11.61E/T_9}dE \quad \mathrm{cm^3mol^{-1}sec^{-1}} \tag{4}$$

To eliminate the strong dependence of σ on the entrance energy E (or temperature T), it is usual [7] to use the *Astrophysical S-Factor* using the transformation $E\sigma(E) = S(E)\exp[-2\pi\eta\,(E)]$ where [10],

$$S(E) = \sigma(E)Ee^{-2\pi\eta(E)} \tag{5}$$

$\eta(E)$ is Sommerfeld parameter, $\eta(E) = 0.1575\, Z_1 Z_2 (\frac{\mu}{E})^{1/2}$ and Z_1 and Z_2 are the atomic numbers of the incident and target nuclei. Then:

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}}\left(\frac{1}{kT}\right)^{\frac{3}{2}}\int_0^\infty S(E)\exp\left[-\frac{E}{kT}-2\pi\eta(E)\right]\; dE \quad (6)$$

Eq.(6) depends on $\exp(-E\,/\,kT)$ and $\exp(-E^{-\frac{1}{2}})$ which give us an energy region of interest known as the *Gamow window*. The width of this window is $\Delta = 0.2368(Z_1^2Z_2^2\mu\, T_9^5)^{1/6}$ MeV, and the center is $E_o = 0.122\,(Z_1^2Z_2^2\mu\, T_9^2)^{1/3}$MeV [10]. Furthermore, $S(E)$ in Eq.(5) can be approximated by terms of Taylor series at $E = 0$ [6]

$$S(E) = \sum_{n=0}^{\infty}\frac{(E-E_o)^n}{n!}\frac{\partial^n S(E)}{\partial E^n} = S(0) + \dot{S}(0)E + \frac{1}{2}\ddot{S}(0)E^2 + \cdots \quad (7)$$

An effective *S*-factor, $S_{\rm eff}$ can be introduced for non-resonant stellar reactions [6] as

$$S_{\rm eff} = S(0)\left[1+\frac{5}{12\tau}+\frac{\dot{S}(0)}{S(0)}\left(E_0+\frac{35}{36}kT\right)+\frac{\ddot{S}(0)}{2S(0)}\left(E_0^2+\frac{89}{36}E_0kT\right)\right]\ \mathrm{MeV.b} \quad (8)$$

Where τ is a correction parameter given as $\tau = \frac{3E_0}{2kT} = 4.248(Z_1^2Z_2^2\mu/T_9)^{1/3}$. The final form of the non-resonant reaction rate is [6]

$$N_A\langle\sigma v\rangle = \frac{4.34\times10^8}{\mu\, Z_1Z_2}S_{\rm eff}\,\tau^2e^{-\tau}\ \ \mathrm{cm^3mol^{-1}sec^{-1}} \quad (9)$$

In Table (1) we list *Q*-values and *S*(0) found in the literature for the present calculations. When considering neutron nuclear reactions near stellar cores or in other extreme density sites, the reaction rates of Eq. (4) should be reconsidered by taking into account the Maxwellian Averaged Cross-section σ_{MACS} [6], thus,

$$N_A\langle\sigma v\rangle = N_A\sigma_{MACS}v_T\times10^{-24}\quad \mathrm{cm^3mol^{-1}sec^{-1}} \quad (10)$$

Where $v_{\rm T}$ is the average velocity at *T*. There are few experimental techniques to calculate σ_{MACS} [8, 16].

Table 1: Calculated Q-values [11] of ^{13}C and ^{14}N for present calculations at $E_{\rm lab}$=130 keV. Also, *S*(0) values from the literature are listed.

Reaction	*Q* value(keV)	*S*(0) keV.b	Remarks
$^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$	2215.61	3×10^6 [12]	*S*(0) is taken as the average value.
$^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$	625.87	1.00 [13] (not certain, see text)	Poisoning n reaction – see text.

3. Results and Discussions

3.1. Cross-section and *S*-Factor Calculations

EMPIRE Program [17] is a well-known code used for cross-section calculations, mainly using the statistical approach with the utility to add many input parameters. The code gives the ability to compare resultant calculations with experimental data from EXFOR library saved in the ENDF format [18]. However, EMPIRE compares all available experimental data in EXFOR, which can add a few results that are incomplete or with a different energy range. Thus, to extract experimental cross-section values, a part of the present research is to write MATLAB library to extract only the required experimental data from EXFOR provided files with ENDF format by employing a user-controlled code. The code consists of few subroutines

and the whole library, called **E**XFOR **N**uclear **E**xtraction **L**ibrary (*ENEL*), is under development to include all possible reaction forms. It will be described in details in a forthcoming paper [19].
As for present *S*-factor calculations, the values listed in Table (1) were used in Eq. (8) taking E_o and τ into consideration. Again, MATLAB code was written for this task. In the coming sections, details of calculating the cross-section and S-factor calculations will be presented and discussed for each involved reaction.

3.2. $^{13}C(\alpha,n)^{16}O$ Reaction

For this reaction, the optical model parameters used were defaulted in EMPIRE [17] for the reaction, namely, OMP=9600. In Figure (2) the reaction cross-section results for this reaction are presented. In this figure and the rest of figures, the energy scale is fixed at 10 keV to 2.5 MeV. The reaction was calculated by taking the incident energy from 0.1 to 2.0 MeV. In the range *E*=0.6 to 1.4 MeV the results were in a good agreement with experimental data taking into account that no modifications have been applied to the program's input, *i.e.*, all the input of EMIRE was the default except energy, mass, and atomic numbers. However, few possible modifications could be made [7]. Ali [20] made a few modifications to better improve these results. For simplicity and since these modifications contributed within less than ~ 5%, we have ignored them in the present research. Other methods could even get the accuracy up to about 10% when using various methods – see for example Cristallo et al. [5]. Expermental data, although found in EMPIRE library, were taken from the original EXFOR library [18] as above. We wrote and used a library of programs in MATLAB to read the cross-section file for this reaction with all its details, then extrtacted the required data. In this case, the reaction was described with MF=3 and MT=4, which were used as input parameters. Extracted data have been carefully examined for a few examples to assure the accuracy of the program. We took only those data that were useful for the present comparison.

In Figure (3) the present results of reaction rates are shown, compared with those of NACRE II [21] experimental library as well as theoretical calculations of Ali and Selman [7]. Again, there have been no modifications used in the calculations of the reaction rates; therefore, it can be seen that the present results differ from that of the literature in the range $1 \leq T_9 \leq 8$. However, since the region of interest in the present research is less than T_9<1, the results of Figure (3) are generally acceptable.

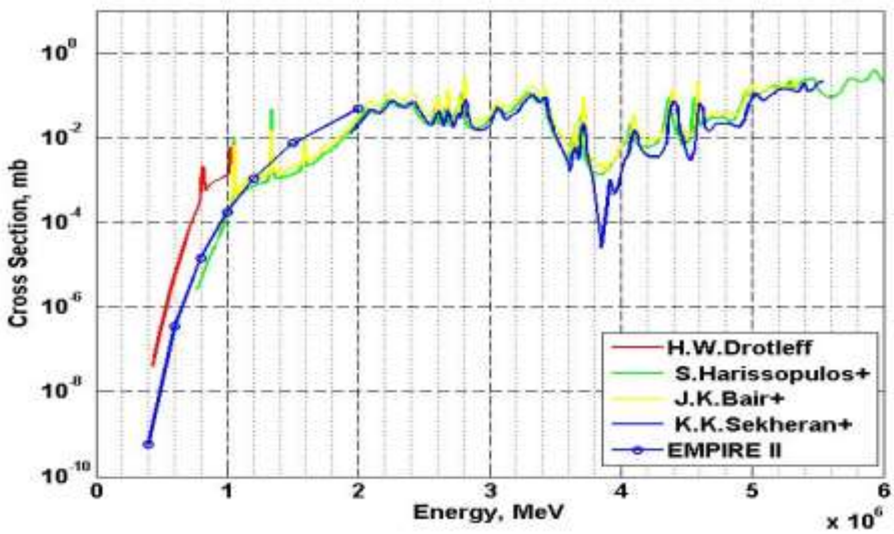

Figure 2: Present reaction cross-section calculations using EMPIRE code for $^{13}C(\alpha,n)^{16}O$ compared with experimental data from EXFOR library [18].

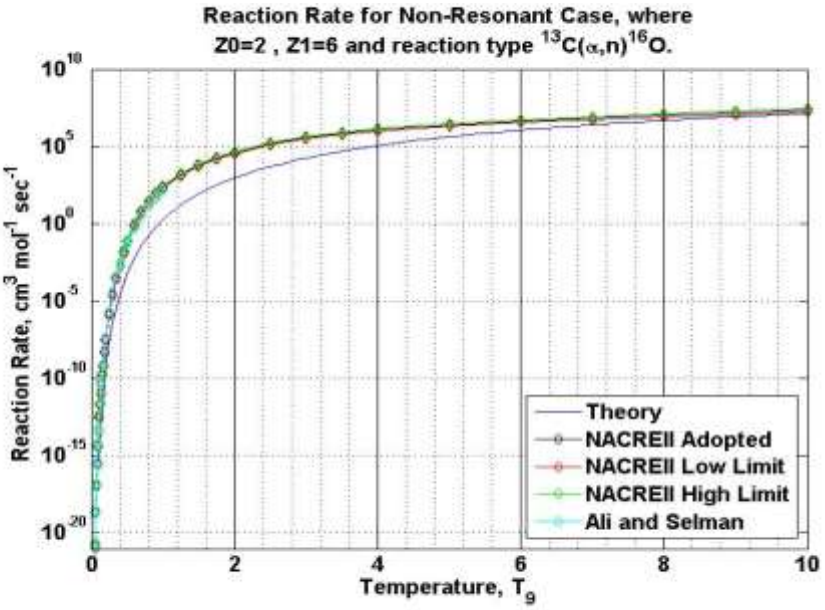

Figure 3: Reaction rates calculated from the present research for $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ compared with experimental data of NACRE II [21], and Ali and Selman [7].

Present calculations show a large sensitivity of the cross-section of $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction. It is one of the most studied astrophysical reactions since it is one of the main neutron sources in the *s*-process because this reaction ignites at the helium inter-shell when enough density and temperature are available for α particle to overcome Coulomb barrier of the ^{13}C nucleus. The availability of the target nucleus is one of the most important conditions for such a reaction to perform, thus it is generally accepted that there should be a ^{13}C pocket (or pockets) in AGB stars that provide such conditions.

Present calculations also show the necessity of extensive studies that were made to investigate the amount of ^{13}C in such stars, especially the work of Gallino et al.– see [8]. It was previously found that at least 4x10^{-6} M_Θ of ^{13}C isotope should be enough to perform the ideal environment for this reaction to continue in regions close to the stellar core of stars in CNO cycle with a mass at least 1.2 M_Θ. Other studies [14] suggested a factor of magnitude less abundant of this isotope which is more acceptable to our present results since the rates of reaction are found to be less than the previous one.

3.3. $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ Reaction

Figure (4) shows the reaction cross-section from EMPIRE code compared with few experimental data. The same procedure described in $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction has been followed to run EMPIRE and extract experimental data. In Figure (5) the reaction rates found from the Reclib database are plotted [22]. Theoretical values of rates for this reaction cannot be found utilizing the current code since it has great resonances at interested temperatures, nor they can be found in experimental data sites for reaction rates such as NACREII [21]. Thus, we adopt only the values shown in Figure (4) for the present purpose. It should be emphasized that $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ reaction has its significance due to the abundant ^{14}N isotope, however, this reaction can have rates affecting the final one, $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}v)^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ – see below.

We have an attempt to find the values of S_{eff} for this reaction from the data of Reaclib, and the results are shown in Figure (6), also tabulated in Table (2). These results have been obtained from reversing Eq. (9) and writing another MATLAB code to read the data file from the Reclib library for this reaction, then fits the data to Eq. (9).

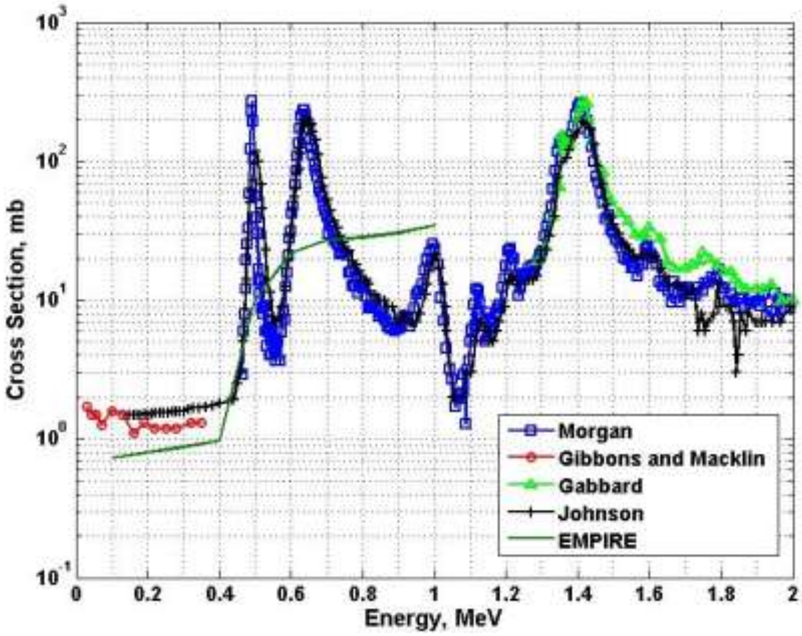

Figure 4: Present reaction cross-section calculations using EMPIRE code for $^{14}N(n,p)^{14}C$ compared with experimental data from EXFOR library [18].

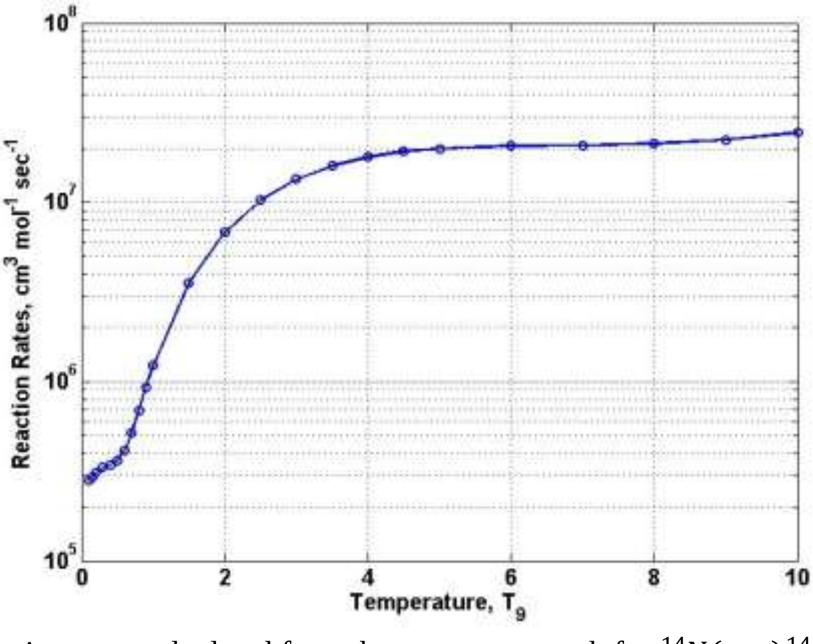

Figure 5: Reaction rates calculated from the present research for $^{14}N(n,p)^{14}C$ compared with experimental data of Reaclib library [22].

Results of Figure (6) show a significant drop after high values which greatly alters the reaction rates at energies of interest around 130 keV which explains the effect of the constant increase of reaction rates at lower energies. The approximate $S(0)$ is 5.235 MeV.b.

3.4. The Final Impact on ^{19}F Isotope

There are few poisoning reactions in the *s*-process in AGB stars that consume the neutrons, slowing and making the *s*-process less efficient. The most important poisoning reactions are thought to be ^{14}N$(n,p)^{14}$C and ^{26}Al$(n,p)^{26}$Mg.

Table 2: The present S_{eff} values found from the reverse fitting of Eq.(9) with reaction rate data from Reaclib [22] for ^{14}N$(n,p)^{14}$C reaction.

E (MeV)	S_{eff} (MeV.b)	*E* (MeV)	S_{eff} (MeV.b)
0.1	5.235	1.3	896.35
0.2	7.114	1.4	1567.92
0.3	9.017	1.5	2313.28
0.4	12.599	1.6	3051.08
0.5	15.383	1.7	3727.9
0.6	19.163	1.8	4319.28
0.7	24.593	1.9	4823.05
0.8	34.124	2.0	5622.68
0.9	49.585	2.1	6286.64
1.0	72.247	2.2	6997.02
1.1	102.89	2.3	7938.52
1.2	388.955	2.4	9328.25

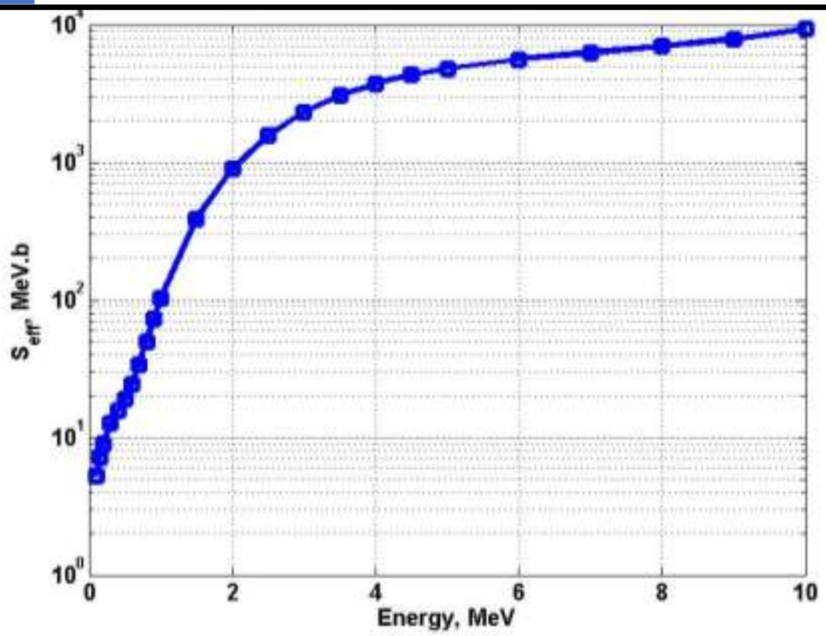

Figure 6: Presently calculated S_{eff} values for ^{14}N$(n,p)^{14}$C reaction from the reaction rates Reaclib [22].

At low energies, the low values of present S_{eff} from Figure (6) suggest that $^{14}N(n,p)^{14}C$ contributes more to the poisoning process. Also, we expect from the present results and the scheme in Figure (1) that proton yield from $^{14}N(n,p)^{14}C$ when contributing to the reaction $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$ that the final product of ^{19}F isotope is low due to the low density of protons from $^{14}N(n,p)^{14}C$ reaction. This could explain that regardless of the abundant ^{14}N isotope in AGB stars, the reaction $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$ suffers from important drawbacks due to neutron consumption by other cosmological reactions.

4. Conclusions and Future Work

To detect the sensitivity of ^{19}F production in AGB stars, reaction rates for $^{13}C(\alpha,n)^{16}O$ were calculated and found lower than previously calculated rates, thus this might affect the next step in the chain of ^{19}F production which highly depends on protons from $^{14}N(n,p)^{14}C$ reaction. As for $^{14}N(n,p)^{14}C$, only theoretical calculated rates were found and they suggested, along with those of the previous reactions, that ^{19}F is highly affected by neutron consumption by poisoning reactions. The approximate $S(0)$ value for $^{14}N(n,p)^{14}C$ was found to be 5.235 MeV.b, which also made a concluding remark about the weakness of ^{19}F productivity regardless of the abundant ^{14}N isotope in these stars. We suggest to develop this work by reexamining the values of S_{eff} and $S(0)$ for $^{14}N(n,p)^{14}C$ reaction by fitting procedure. Also, taking other mechanisms illustrated in Figure (1) can add important knowledge about the process of ^{19}F production in the universe.

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