Calculation of (p,γ) and (p,α) nuclear reaction cross sections in stars up to 10 MeV

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Abstract. In Knowledge of the proton-proton (p-p) chain and CNO cycle are required for the evolution of main sequence stars during the early formation of the universe. In this study, we summarized the excitation functions of (p,γ) and (p,α) reactions for ^{7}Be(p,γ)^{8}B, ^{12}C(p,γ)^{13}N, ^{13}C(p,γ)^{14}N, ^{14}N(p,γ)^{15}O and ^{15}N(p,α)^{15}O in p-p chain and CNO cycle using EMPIRE and TALYS computer up to 10 MeV. The calculated data on nuclear fusion cross sections in hydrogen-burning stars were compared with theoretical TENDL-2014 and ENDF/B-VII data from EXFOR. The calculation results show closed agreement between the calculations and the data from literature.

1 Introduction

Animals, plants, soil, air, planets, stars like everything formed by the basic blocks of matter called atoms. After the big bang, approximately 13.7 billion years ago, a large part of atoms formed in the early formation of the universe and came unchanged until the present day. Since the universe includes everything from subatomic particles to galaxies, from planets to stars, it is needed to be explored in detailed.

All stars are born from collapsing clouds of gas and dust the interstellar medium (ISM). During their lives, they deposit energy into the ISM in the form of electromagnetic radiation and stellar winds. When they die, they return some of their matter and energy back into the ISM. The life time of stars range from a few million years for the most massive to trillions of years for the least massive [1-3].

The amount of H and He elements in the universe are approximately 73% and 25% of the mass, respectively. After H and He, C, N and O elements are the most abundant elements in the Universe. Energy production in massive stars is governed by the CNO cycles throughout most of their lifetimes [4]. Hydrogen and helium elements having low-mass were produced in the hot and dense conditions of the birth of the universe itself. The life of stars is described in terms of nuclear reactions.

The Hydrogen burning mechanism is essentially the nuclear fusion of four protons into one ^{4}He nucleus. There are two reaction chains that can convert hydrogen to helium, namely the proton–proton (or pp chain) chain, also called pp reaction, and the CNO cycle. The pp chain is more important in stars the mass of the Sun or less and stars of similar mass The CNO cycle by which stars convert hydrogen to helium is the dominant source of energy in more massive stars [5].

The p-p fusion is the nuclear fusion process which fuels the Sun and other stars which have core temperatures less than 15×10^{6} K and a reaction cycle at energy of 25 MeV. The p-p chains occur under lower temperature than the carbon-nitrogen-oxygen cycle. The pp chain in stars like our Sun divides into three main branches, called as the ppI, ppII and ppIII chains. These are given Eq. 1-3. According to Eq. 1, in the *proton-proton* fusion reaction inside stars like the sun, the first step in ppI process is the collision of two protons (p or ^{1}H) to make an atom of heavy hydrogen (^{2}H). The second step containing the weak interaction involves the collision of a ^{2}H nuclei with a proton to make a nucleus of ^{3}He, and then gamma ray is emitted having very high energy. In the final third step, a normal ^{4}He nucleus are created with combining two ^{3}He nuclei and two extra protons (2^{1}H) are released to start the whole process again. Inside the Sun, about 655×10^{6} tons of H are converted into 650×10^{6} tons of ^{4}He every second. In stars heavier than about 2 solar masses, in which the core temperature is more than about 18×10^{6} K, the dominant process in which energy is produced by the fusion of hydrogen into helium is a different reaction chain known as the carbon-nitrogen cycle. The former case is the last reaction of the ppI chain, whereas the latter reaction leads into either the ppII or the ppIII chain, as given Eq. 2-3.

The second process of stable hydrogen burning reaction in stars is the CNO cycle, dominates from 20×10^{6}K to 130×10^{6}K. This cycle for star more massive than the Sun converts hydrogen to helium according to the following sequence of reactions in Eq. 4. The CNO cycle occurs from the following steps. After ^{12}C element captures a proton, ^{13}N is produced and gamma-ray is emitted. ^{13}N is unstable and decays to the ^{13}C with a half-life of about 10 minutes. The ^{13}C isotope captures a proton and a gamma-ray is emitted to become ^{14}N isotope. ^{14}N isotope captures a proton and a gamma-ray is emitted to become ^{15}O. ^{15}O isotope undergoes a β^+ decay to become ^{15}N. Finally, ^{15}N isotope captures a proton and then it emits a ^{4}He to close the cycle and return to ^{12}C.

ppI chain:

$$\begin{aligned} &{}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu_e \\ &{}^2_1H + {}^1_1H \rightarrow {}^3_2He + \gamma \\ &{}^3_2He + {}^3_2He \rightarrow {}^4_2He + 2\,{}^1_1H \end{aligned} \qquad (1)$$

ppII chain:

$$\begin{aligned} &{}^3_2He + {}^4_2He \rightarrow {}^7_4Be + \gamma \\ &{}^7_4Be + e^- \rightarrow {}^7_3Li + \nu_e \\ &{}^7_3Li + {}^1_1H \rightarrow 2\,{}^4_2He \end{aligned} \qquad (2)$$

ppIII chain:

$$\begin{aligned} &{}^3_2He + {}^4_2He \rightarrow {}^7_4Be + \gamma \\ &{}^7_4Be + {}^1_1H \rightarrow {}^8_5B + \gamma \\ &{}^8_5Be \rightarrow {}^8_4Be + e^+ + \nu_e \\ &{}^8_4Be \rightarrow 2\,{}^4_2He \end{aligned} \qquad (3)$$

CNO Cycle

$$\begin{aligned} &{}^{12}_6C + {}^1_1H \rightarrow {}^{13}_7N + \gamma \\ &{}^{13}_7N \rightarrow {}^{13}_6C + e^+ + \nu_e \\ &{}^{13}_6C + {}^1_1H \rightarrow {}^{14}_7N + \gamma \\ &{}^{14}_7N + {}^1_1H \rightarrow {}^{15}_6O + \gamma \\ &{}^{15}_6O \rightarrow {}^{15}_7N + e^+ + \nu_e \\ &{}^{15}_7N + {}^1_1H \rightarrow {}^{12}_6C + {}^4_2He \end{aligned} \qquad (4)$$

TALYS computer code system in the from 1 keV to 1 GeV energy range [6] and EMPIRE computer code over from keV up to few hundred MeV energy range [**7**] have been widely used in order to calculate nuclear reactions. In this study, in order to calculated the excitation functions of (p,γ) and (p,α**)** cross section for some reactions ^{15}O in pp chain and CNO cycle, we used EMPIRE and TALYS computer up to 10 MeV. Results were compared with theoretical TENDL-2014 and ENDF/B-VII data from EXFOR [8].

2 Results and Discussions

In this study, in order to calculated the excitation functions of (p,γ) and (p,α**)** cross section for some reactions such as $^{7}Be(p,\gamma)$, $^{12}C(p,\gamma)$, $^{13}C(p,\gamma)$, $^{15}N(p,a)$, $^{14}N(p,\gamma)$ in pp chain and CNO cycle, we used two computer code systems called as TALYS-1.6 [6], EMPIRE-3.2.2-Malta [7] up to 10 MeV. Results were compared with theoretical TENDL-2014 and ENDF/B-VII data from EXFOR from EXFOR library [8].

Our results from calculations are given Figure 1-5. Theoretical calculated cross sections of $^{7}Be(p,\gamma)$ reaction in ppIII chain between 0-10 MeV is shown in the Fig. 1. This reaction's cross section data obtained from EMPIRE and ENDF that shows to us increasing values with 0.75-5 MeV energy ranges. However, in spite of increasing these values, reaction cross section value from TALYS was a pick at about 5 MeV energy. At the same time, the data from EMPIRE and TALYS computer code, and also ENDF systems have showed increasing values in the 6.5 MeV with 10 MeV energy range.

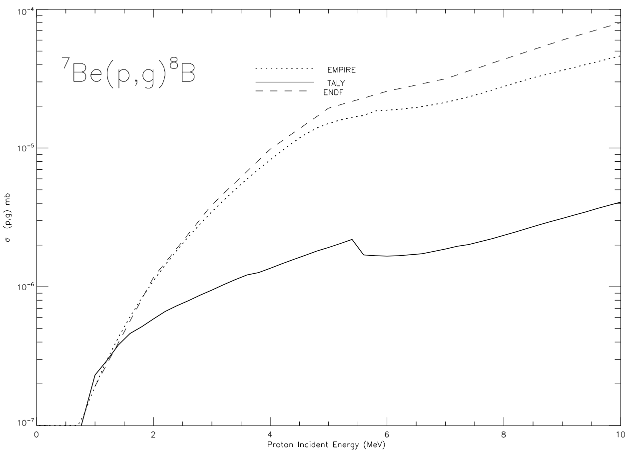

Fig. 1. Theoretical cross sections calculation of $^{7}Be(p,\gamma)$ reaction up to 10 MeV.

Reaction cross section of $^{12}C(p,g)$ accruing in the CNO cycle is given in Fig. 2. As seen from Fig. 2, ENDF and TALYS theoretical data are in harmony between 2 and 5 MeV. The data from EMPIRE also joins at this harmony between 3 and 5 MeV. Only one experimental data of Burtebaev [9] could be found from EXFOR in literature at approximately 4.27 MeV. This data is closed agreement with ENDF at around 4 MeV.

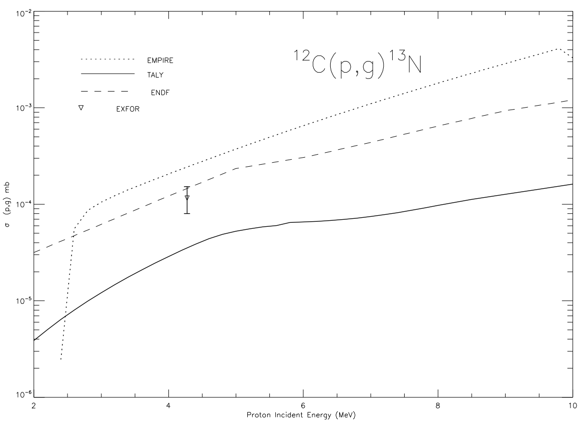

Fig. 2. Theoretical cross sections calculation of $^{12}C(p,\gamma)$ reaction up to 10 MeV.

Reaction cross section of $^{12}C(p,\gamma)$ in the CNO cycle is given in Fig. 3. When $^{13}C(p,g)$ reaction was analyzed, while it can be seen disharmony between EMPIRE, TALYS, and ENDF computer data up to 2.5 MeV, there is a good harmony over 2.5 MeV. Also, while the line from EMPIRE decreases up to 2.5 MeV, the line from

TALYS increases. There is no experimental data for $^{12}C(p,g)$ reaction from literature. The fourth reaction cross section in the CNO cycle is $^{14}N(p,\gamma)$ given in Fig. 4. It can be seen from Figure 4, EMPIRE line decreases up to about 5 MeV while TALYS and ENDF lines increase. All cross sections data are approximately the same values between 5-10 MeV. The fifth and final reaction cross section calculation in the CNO cycle is $^{15}N(p,\alpha)$ as given in Fig. 5. For three lines, it can be seen that there is a good relation from 0 to 10 MeV. All cross section data have a rising trend up to about 5 MeV but having a stable and constant values after 5 MeV.

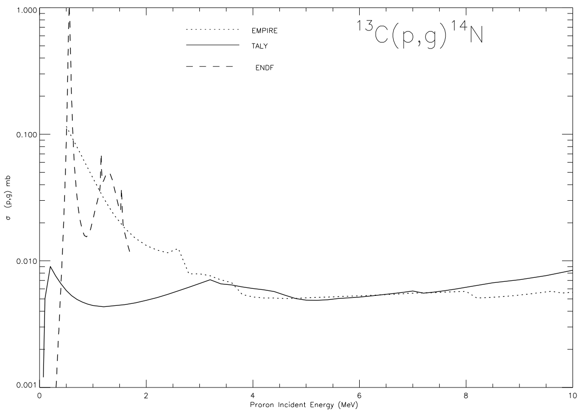

Fig. 3. Theoretical cross sections calculation of $^{13}C(p,\gamma)$ reaction up to 10 MeV.

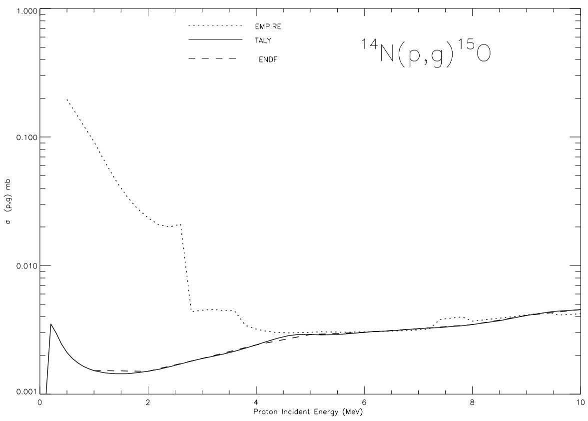

Fig. 4. Theoretical cross sections calculation of $^{14}N(p,\gamma)$ reaction up to 10 MeV.

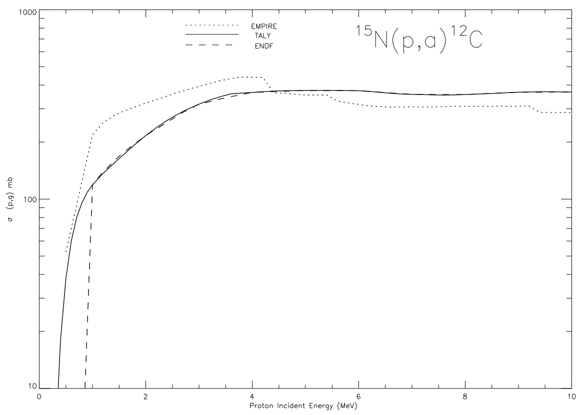

Fig. 5. Theoretical cross sections calculation of $^{15}N(p,\alpha)$ reaction up to 10 MeV.

3 Conclusion

We know that it is necessary hydrogen burning to be able to start the nuclear fusion of four protons into one ^{4}He nucleus in stars. In this work, (p,γ) and (p,γ) cross section reactions for ^{7}Be, ^{13}C, ^{15}N, and ^{14}N nuclei in pp chain and CNO cycle in stars were calculated in the energy range from 0 to 10 MeV using TALYS 1.6 [7] and EMPIRE-3.2.2 [8] computer codes. Since these reactions in pp chain and CNO cycle occur in low energies, it is difficult to calculate cross sections in these nuclei. We were able to calculated only five limited elements in in pp chain and CNO cycle. We suggest that we can achieve better results when added resonance effects or resonance parameters in nuclear code calculating programs.

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