^{13}C(α,n)^{16}O : The Source of Neutrons for the s-process main component

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Abstract. The ^{13}C(α, n)^{16}O reaction operates in the He intershell of low-mass (M < 4 $M_{\odot}$) AGB stars and it is the neutron source that allows the creation of the main component of the s-process elements. The reaction rate is then required to be well known in the energy range of astrophysical interest. Therefore, the ^{13}C(α, n)^{16}O reaction rate has been calculated in stellar like conditions using a nuclear-model based computer code TALYS. The results have been compared with available literature data and found to be in good agreement with experimental data and, evaluated data NACRE II as well.

1 Introduction

Asymptotic Giant Branch (AGB) stars play an important role in determining the galactic chemical evolution [1]. In their interiors, the main components of the s-process [2] is synthesized [3], namely the slow neutron capture process allows the production of several isotopes of elements from Sr to Pb. The s-process path runs along the stability valley due the competition between n-captures and beta decays [4]. The ^{13}C(α, n)^{16}O reaction is the main source of neutrons in low-mass AGB stars, which is active in the He intershell below the H shell [5]. It is well known that the ^{13}C pocket forms at the beginning of each interpulse [3] period in the He rich layers thanks to a special injection of a protons. When H shell re-ignites ^{13}C forms through the ^{12}C(p, γ)^{13}N (β^{+})^{13}C and then starts capturing α particles and, as a consequence, releases neutrons [3]. This process provides relatively low neutron densities [$\approx 10^7 neutrons/cm^3$] for $10^4 - 10^5$ years each time. Starting from seed nuclei in the iron region, this neutron flux slowly builds up heavy elements along the line of stability. The^{13}C(α, n)^{16}O reaction takes place at 90 MK corresponding to effective energy range (i.e, Gamow window) of 140 - 230 keV. In few cases,^{13}C pocket also delivers neutrons at lower temperature down to 50 MK [1]. Fig.1 shows the normalized probability using Maxwell-Boltzmann distribution versus center-of-mass energy E for the^{13}C(α, n)^{16}O reaction at three different temperatures. It can be seen from Fig. 1 that slight variation in temperature shifts the Gamow window and peaks as well. In order to constrain this important nucleosynthesis process, the reaction rate of the ^{13}C(α, n)^{16}O neutron source needs to be known in the astrophysical energy

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window. A detailed literature [6–12] survey indicates that the ^{13}C(α, n)^{16}O reaction has been studied extensively. Most of the authors have reported cross-sections or astrophysical factors in stellar environments for this reaction. Only few of them have reported thermonuclear reaction rates. In this context, ^{13}C(α, n)^{16}O reaction rate has been calculated using nuclear model based computer code TALYS [13] at the temperatures of astrophysical interest. The calculated reaction rates have been compared with some of the available experimental and evaluated data set NACRE II [14].

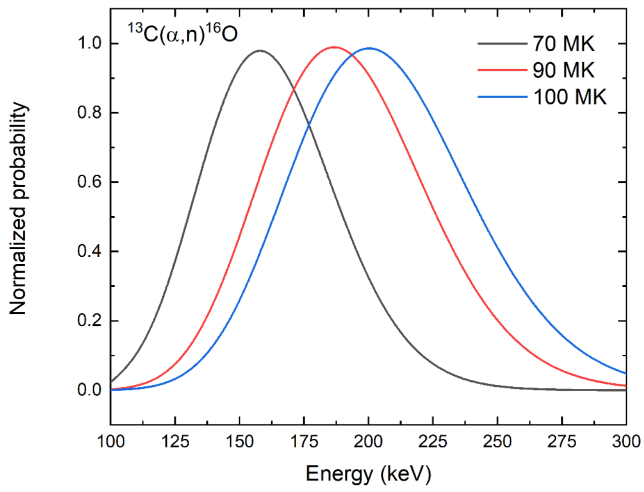

Figure 1. Maxwell-Boltzmann distribution versus energy E for the ^{13}C(α, n)^{16}O reaction at three different temperature T.

2 Nuclear Model based Calculations

TALYS performs simulation of nuclear reactions that involve neutrons, protons, deuterons, tritons,^{3}He- and alpha- particles, in the 1 keV-200 MeV energy range and for target nuclides of mass 12 and heavier. It adopts Hauser-Feshbach (HF) statistical model [15] to estimate the reaction rates that are of astrophysical relevance. HF model relies on the fundamental assumption (Bohr hypothesis) that capture process occurs by means of the intermediary production of a compound nucleus (CN) that can reach a state of thermodynamic equilibrium. TALYS estimates the corresponding cross-section by the compound nucleus formula for the binary cross-section [16] as given in eq. 1,

$$\sigma^{\mu}_{\alpha\alpha'} = D^{comp}\pi\lambda\!\!\!^{-2} \sum_{J=mod(I^{\mu}+s,1)}^{l_{nax}+I^{\mu}+s} \sum_{\Pi=-1}^{1} \frac{2J+1}{(2I^{\mu}+1)(2s+1)} \sum_{j=|J-I^{\mu}|}^{J+I^{\mu}} \sum_{l=|j-s|}^{j+s} \sum_{j'=|J-I'|}^{J+I'}$$
$$\sum_{l'=|j'-s'|}^{j'+s'} \delta_{\pi}(\alpha)\delta_{\pi}(\alpha') \frac{\langle T^{J}_{\alpha l j}(E_a)\rangle\langle T^{J}_{\alpha' l' j'}(E_{a'})\rangle}{\sum_{\alpha'',l'',j''} \delta_{\pi}(\alpha'')\langle T^{J}_{\alpha'' l'' j''}(E_{a''})\rangle} W^{J}_{\alpha l j \alpha' l' j'} \quad (1)$$

In the above equations, E_a, s, π, l and j represent the projectile energy, spin , parity, orbital and total angular momentum, respectively. The same symbols but labeled by a prime correspond to ejectile. The symbols $I^\mu, \Pi^\mu(I^{'}, \Pi^{'})$, represent the spin and parity of target nucleus, while J, and Π correspond to the spin and parity of compound system. A thermodynamic equilibrium holds locally to good approximation inside stellar interiors. Consequently, the energies of both target and projectiles, as well as their relative energies, obey a Maxwell-Boltzmann distribution corresponding to the temperature T. In such conditions, the astrophysical rate is obtained by integrating the cross-section given by eq. 1 over a Maxwell-Boltzmann distribution of energies at the given temperature T. The stellar rate per pair of particles in the entrance channel at temperature T, taking account of the contributions of various target excited state, is expressed in classical notation as given eq. 2.

$$N_A\langle\sigma v\rangle_{\alpha\alpha'}(T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2}G_I(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu + 1)}{(2I^0 + 1)} \sigma^\mu_{\alpha\alpha'} E(E) exp\left(-\frac{E + E_x^\mu}{kT}\right) dE \quad (2)$$

where k is the Boltzman constant, m is the reduced mass and N_A the Avogadro Number. Using the above adopted formalism in TALYS code, the rate of ^{13}C(α, n)^{16}O reaction has been calculated. In statistical models, nuclear level densities are used at excitation energies where discrete level information is not available or incomplete. TALYS uses several models for level density, which range from phenomenological analytical expressions to tabulated level densities derived from microscopic models. In the present calculations, the level density corresponding to Constant Temperature + Fermi gas model introduced by Gilbert and Cameron [17] was used. In this model, the excitation energy range is divided into a low energy and high energy parts. Low energy part from 0 MeV up to matching energy E_M, where the so-called constant temperature law applies and high energy part above E_M, where the Fermi Gas model applies. The optical model parameters (OMP) are calculated using local and global parameterisations of Koning and Delaroche [18]. In addition, the alpha spherical local optical potentials of Avrigeanu et al [19] has been used. The theoretically calculated ^{13}C(α, n)^{16}O reaction rate has been plotted along with a selected experimental data [11, 12] as well as the nuclear reaction rates compilation NACRE II as shown in Fig. 2. NACRE compiles a number of cross-section measurements and subsequently calculates a comprehensive reaction rates. Fig. 2 shows that the theoretically calculated reaction rates agrees very well with direct experimental data reported by G. F. Ciani et al [11] and NACRE II within the experimental errors. Moreover, Fig. 2 also report the data by O.Trippella et al, [12] whose have investigate the ^{13}C(α, n)^{16}O reaction by combining two indirect approaches: the Asymptotic Normalization Coefficients [20] and Trojan Horse Method [21, 22]. In this case theoretical estimate matches the experimental data only at low and high temperature, and not in the central part of the investigated range. Therefore, we can conclude that TALYS provides a reasonable evaluation for the ^{13}C(α, n)^{16}O reaction rates, even if it matches only experiential data directly measured. Keeping this warning in mind, we can state that TALYS might be used to estimate thermonuclear reaction rates in case of reactions where no experimental data are available (e.g. processes involving short lived nuclei interacting with neutrons) at the energies of typical astrophysical processes.

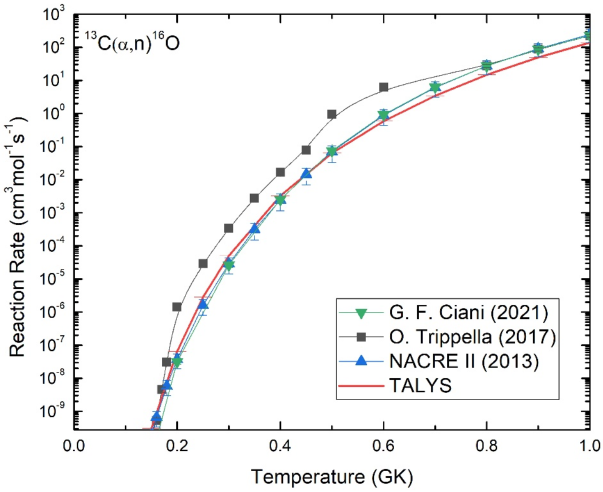

Figure 2. Theoretically calculated thermonuclear reaction rate for ^{13}C(α, n)^{16}O reaction along with experimental data and NACRE II.

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