

Radiative capture of proton through the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction at low energy

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Abstract: The CNO cycle is the main source of energy in stars more massive than our Sun. This process defines the energy production, the duration of which can be used to determine the lifetime of massive stars. The cycle is an important tool for determining the age of globular clusters. Radiative proton capture via $p + ^{14}\text{N} \rightarrow ^{15}\text{O} + \gamma$, at energies of astrophysical interest, is an important process in the CNO cycle. In this project, we apply a potential model to describe both non-resonant and resonant reactions in the channels where radiative capture occurs through electric $E1$ transitions. We employed the R -matrix method to describe the ongoing reactions via $M1$ resonant transitions, when it was not possible to correctly reproduce the experimental data using the potential model. The partial components of the astrophysical S -factor are calculated for all possible electric and magnetic dipole transitions in ^{15}O . The linear extrapolated S -factor at zero energy ($S(0)$) agrees well with earlier reported values for all transition types considered in this work. Based on the value of the total astrophysical S -factor, depending on the collision energy, we calculate the nuclear reaction rates for $p + ^{14}\text{N} \rightarrow ^{15}\text{O} + \gamma$. The computed rates agree well with the results reported in the NACRE II Collaboration and most recent existing measurements.

Keywords: CNO cycle, potential model, R -matrix method, cross-section, astrophysical S -factor, nuclear rates.

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I. INTRODUCTION

The CNO cycle is a proton capture catalytic sequence that serves as the secondary mechanism for converting hydrogen into helium in the stellar environment [1, 2]. The hydrogen burning rate of the CNO cycle is significant for both nucleosynthesis and elemental production, as well as determining the lifetime of stars [3]. The $^{14}\text{N}(p, \gamma)^{15}\text{O}$ is the slowest reaction in the cycle, which determines the rate of energy production [4]. The continuous enrichment of ^{14}N in the solar component is maintained based on the rate of $^{14}\text{N}(p, \gamma)^{15}\text{O}$. Solar neutrino's spectral composition is also impacted by this reaction [5, 6]. Because of the shorter lifetime of ^{15}O in comparison to ^{13}N , the β decay of ^{15}O is predicted to dominate the production of CNO neutrinos [7].

Numerous researchers [7–11] have examined the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ cross-section for over 50 years. It was noted that only the measurements conducted by Schröder *et al.* [11] covered a broad energy range. It was also suggested that the $E1$ transitions to the ground state ($1/2^-$) and $M1$ transitions to the 4th excited state ($3/2^+$) play a crucial role in the $S(0)$ measurements. Bertone *et al.* [12] meas-

ured the lifetime of $E_x=6.7931 \text{ MeV} \pm 1.7 \text{ keV}$ state in ^{15}O . Based on their new value for the lifetime of this state, cross-section for the direct transition to the ground state of ^{15}O was substantially reduced at a lower energy level. According to their measurements, the major contributions to the reaction rate at low temperatures were the 259 keV resonant and direct capture (DC) of the $E_x=6.7931 \text{ MeV} \pm 1.7 \text{ keV}$ state. Later, in Ref. [13], the authors determined the spectroscopic factors and asymptotic normalization coefficients (ANCs) for bound states in ^{15}O based on the $^{14}\text{N}(^3\text{He}, d)^{15}\text{O}$ reaction. Their results were used to compute the astrophysical S -factor for DC in the $^{14}\text{N}(^3\text{He}, d)^{15}\text{O}$ reaction. Angulo *et al.* [14] analyzed the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ using the R -matrix model and confirmed that the ground state $S_{\text{g.s.}}(0)$ contribution was smaller than that reported earlier. Mukhamedzhanov *et al.* [15] considered four transitions: from the low-lying resonant state ($E_x=7.5565 \text{ MeV} \pm 0.4 \text{ keV}$) to ground, third, fourth, and fifth excited states. They extracted the ANCs by comparing the distorted-wave Born approximation with coupled-channel Born approximation calculations. Utilizing the obtained ANCs, they computed the astrophysical S -factor and rates for the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction. Their investiga-

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