I. INTRODUCTION

The $^{14}$N($p,\gamma$)$^{15}$O reaction is one of the most important reactions in the CNO cycle. As the slowest reaction in the cycle, it defines the rate of energy production [1] and, hence, the lifetime of stars that are governed by hydrogen burning via CNO processing. Before 1987, the astrophysical factor for this reaction had been measured by several different groups (see Ref. [2] and references therein), but their results, extrapolated to zero energy, differed by about a factor of 2. Following an evaluation of the different experiments, Fowler et al. recommended the value of $S(0)$ = 3.32 keV b in their compilation [3]. In 1987, the $^{14}$N($p,\gamma$)$^{15}$O reaction was re-measured and results were obtained for transitions to the ground and excited states of $^{15}$O. A total astrophysical factor $S(0)$ = 3.20 $\pm$ 0.2 keV b [2] was deduced, thus confirming the value recommended in Ref. [3]. These measurements led to a new understanding of the reaction, however, since it was found that $^{14}$N($p,\gamma$)$^{15}$O capture at low energies is dominated by resonant and direct capture to the first resonance at $E_1$ = 259.5 keV (the resonance energy in the center-of-mass system) and a subthreshold resonance at $E_s$ = $-504$ keV. At very low energies appropriate for stellar burning, $E \to 0$, the reaction was found to be dominated by a combination of direct and resonant capture and interference from the tails of the subthreshold and first resonances.

A significant contribution to the total $S$ factor, about 50%, came from resonance capture through the tail of the subthreshold state in the analysis of Schröder et al. [2]. In the analysis, they assumed a radiative width of 6.3 eV for the decay of the subthreshold resonance to the ground state. However, a recent new $R$-matrix analysis of their data by Angulo and Descouvemont [4] used a much smaller radiative width, which led to a significantly lower value for the total astrophysical factor, $S(0)$ = 1.77 $\pm$ 0.2 keV b. From their analysis, Angulo and Descouvemont determined that the dominant contribution to the total $S$ factor at stellar energies comes from direct capture to the subthreshold state. The absolute normalization for the direct capture can be determined by its asymptotic normalization coefficient (ANC). In fact, Angulo and Descouvemont obtained an estimate for the ANC from their fit to the data at higher energies, and they noted that a measurement of this ANC was needed in order best to determine the low energy $S$ factor. Very recently the first measurement of the radiative width of the subthreshold state in $^{15}$O to the ground state was reported [5]. The new result for the width, 0.41 $\pm$ 0.34 eV, is about four times smaller than the value used by Angulo and Descouvemont and about 15 times smaller than the value used by Schröder et al. Consequently, the contribution to the $S$ factor from resonance capture to the ground state through the subthreshold state in $^{15}$O becomes negligible. The value of $S(0)$ that was reported in Ref. [5] agrees with the result of Angulo and Descouvemont [4] and is significantly lower than that of Ref. [2].

Here we report a new determination of the ANC for the subthreshold state at $\varepsilon = -504$ keV using the $^{14}$N($^3$He,$\gamma$)$^{15}$O reaction at 26.3 MeV. Simultaneously, we have measured the ANCs for the ground and four other excited states in $^{15}$O. We have also measured $^{14}$N+$^3$He elastic scattering at the same energy to minimize the uncertainty in the extracted ANCs due to ambiguities in the entrance channel optical model parameters. Using the measured ANCs, we fit the astrophysical $S$ factors for transitions to the ground and excited states and the total $S$ factor using the $R$-matrix method. In our analysis, we accurately account for interference effects by splitting the resonance amplitudes into the internal and channel terms [6]. We find that for captures to all the states except the ground state, the $S(0)$ factors are almost entirely determined by the corresponding ANCs.

Recently similar measurements, but at a $^3$He beam energy...
of 20 MeV, have been reported [7]. Below we compare our extracted ANCs with this recent result. We also have carried out new, self-consistent, distorted-wave Born approximation (DWBA) and coupled-channels Born approximation (CCBA) calculations using both the data from Ref. [7] and our data in order to improve our knowledge of the ANCs for the subthreshold state.

II. EXPERIMENTAL DETAILS

The ANCs for \(^{14}\text{N} + p \rightarrow ^{15}\text{O}\) were determined from a comparison of the measured differential cross sections for the \(^{14}\text{N}(^{3}\text{He},d)^{15}\text{O}\) proton transfer reaction to a DWBA analysis. The angular distributions were measured at an incident \(^{3}\text{He}\) beam energy of 26.3 MeV. The \(^{14}\text{N}(^{3}\text{He},d)^{15}\text{O}\) reaction has been studied by several groups but only relative cross sections were given for measurements at incident energies of 11 MeV [8] and 14 MeV [9]. In a recent measurement [10], only the transfer reaction between ground states was obtained. As we noted above, new measurements of absolute differential cross sections to both the ground and excited states in \(^{15}\text{O}\) were performed recently by Bertone et al. [7], and ANCs were extracted. The experiment in Ref. [7] was carried out using a magnetic spectrometer to analyze the outgoing reaction products. They obtained very good energy resolution for the transfer reaction but had a rather large uncertainty in the normalization of the absolute cross section. The latter dominated the uncertainty in their results.

We have carried out an independent measurement of the absolute differential cross sections to both the ground and excited states in \(^{15}\text{O}\) with the goal of determining the cross sections more accurately. We also measured \(^{14}\text{N} + ^{3}\text{He}\) elastic scattering concurrently in order to minimize uncertainties in the extracted ANCs due to ambiguities in the entrance-channel optical model potential. The experiment was carried out using a momentum analyzed 26.3-MeV \(^{3}\text{He}\) beam from the U-120M isochronous cyclotron of the Nuclear Physics Institute of the Czech Academy of Sciences incident on a melamine (\(\text{C}_3\text{H}_6\text{N}_6\)) target. The initial thickness of the target was measured to be 260 \(\mu\text{g/cm}^2\) by scanning with well-collimated \(\alpha\)-particle sources of \(^{241}\text{Am},^{238}\text{Pu},\) and \(^{244}\text{Cm}\). The target thickness was monitored continuously during the experiment by a Si detector telescope placed at a fixed angle \(\theta_{LAB} = 19^\circ\). Final states in four different reaction channels on \(^{14}\text{N} - (^{3}\text{He},p), (^{3}\text{He},d), (^{3}\text{He},^{3}\text{He})\), and \((^{3}\text{He},^{4}\text{He})\)—were observed in the monitor detector. A target thickness correction was then obtained for each angle from these measurements. The results were checked and found to be very consistent by measuring the same angle at several different times. Over the course of the experiment, the decrease in target thickness was \(\sim 40\%\). Reaction products were observed by a pair of \(\Delta E-E\) telescopes consisting of 250-\(\mu\text{m}\)-thick surface barrier detectors and 3000-\(\mu\text{m}\)-thick Si(Li) surface detectors. Both detectors subtended a solid angle of 0.23 msr. One telescope was fixed at \(\theta_{LAB} = 19^\circ\) for monitoring purposes, while the other was rotated around the target and measured the reaction products at laboratory angles between 6.5° and 70°. The beam current was integrated by a Faraday cup biased to 800 V. Elastic scattering and spectra in several reaction channels were measured simultaneously by both telescopes to provide continuous calibration of the beam energy, reaction angle, and target thickness. Data were collected event by event in an external buffer and transferred to the online computer. Each data transfer also included information about the charge collected in the Faraday cup. Breaking the data into well defined blocks proved extremely valuable, as it allowed us to monitor the target thickness, which gradually decreased during the experiment. By accounting for the target thickness changes, it was possible to maintain a precision of \(\pm 4.4\%\) for the measured absolute differential cross sections. The experimental arrangement was similar to a previous measurement of \(^{13}\text{C}(^{3}\text{He},d)^{14}\text{N}\) [11].

The state of primary interest in our measurement was the subthreshold resonance state at an excitation energy of 6.79 MeV in \(^{15}\text{O}\). This is a member of a doublet with a separation energy of 66 keV. The average energy resolution for the outgoing \(d\) reaction products in our experiment was about 60 keV full width at half maximum. This was sufficient to deconvolute the doublet using both the line shape analysis from isolated nearby peaks and a precise energy calibration. This resolution also was enough to deconvolute the 5.2-MeV doublet, which includes the 1/2\(^+\), 5.18-MeV and 5/2\(^+\), 5.24-MeV states [12]. However, the combination of the line shape analysis and energy calibration indicated that only the 5.24-MeV state was populated. Figure 1 shows an example of a spectrum obtained in the present experiment, along with a fit to the 6.8-MeV doublet.

III. DATA ANALYSIS

In order to extract reliable ANCs, the analysis has been done using both DWBA and CCBA calculations with the FRESCO code [13]. The best optical potential in the entry channel, potential \(P_i\), in Table I, was obtained by fitting the \(^{3}\text{He}\) elastic scattering angular distribution (see Fig. 2). For
Angular distributions of deuterons from the $^{14}$N ($^3$He, $d$) $^{15}$O reaction leading to the most important transitions, the ground, third, fourth, and fifth excited states in $^{15}$O, together with DWBA fits using the parameters in Table I, are shown in Fig. 3. For the transition to the fourth excited state, which is the most important for nuclear astrophysics, we also show our DWBA fit to the measurement reported in Ref. [7]. The ANC were determined by normalizing the calculated DWBA differential cross sections to the experimental ones.

For all the $^{15}$O final states, the calculations have been checked to verify that the transitions are peripheral. Hence, by normalizing the DWBA calculations to the data in the region of the main maximum of the angular distributions and using a well known value of the ANC for $^3$He→$d+p$ [20] ($C^2 = 3.90 \pm 0.06$ fm$^{-1}$), the ANCs for $^{14}$N+$p$→$^{15}$O can be determined. The extracted ANCs are given in the third column of Table II. For comparison, in the last column we present the ANCs determined in Ref. [7]. The uncertainties, which are discussed below, take into account experimental uncertainties and uncertainties due to ambiguity in the optical model parameters for the initial and final states.

The proton transfer reaction to the ground and 6.18-MeV states in $^{15}$O can populate both $p_{1/2}$ and $p_{3/2}$ orbitals. We cannot separate these contributions because the $(^3$He,$d$) reaction is insensitive to the value of the total angular momentum of the transferred proton, so we measure their sum. The DWBA cross section for the transfer to the ground state has been calculated using the ratio of the spectroscopic factors $S_{3/2}/S_{1/2} = 0.10$ given by shell-model calculations using the OXBASH code [21]. The overall uncertainty of the extracted ANCs is 11%. The main contributions were the uncertainty in absolute normalization of the experimental angular distributions (4.5%) and the uncertainty due to ambiguity in the optical model parameters for both the initial and final channels (10%). Only the second state of the 5.2-MeV doublet has been identified in our experiment, and we determined the ANC for that state with a total uncertainty of 11% (see Table II). For the transfer to the third excited state, $E_x = 6.18$ MeV, we use the shell-model prediction indicating that the population of the $p_{3/2}$ component is negligible compared to the $p_{1/2}$ component. We assign a total uncertainty of 12% for $C^2_{p_{1/2}}$. The most important transition, and the most difficult to analyze, is the transfer reaction to the 3/2$^+$, 6.79 MeV, fourth excited state. Here $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$ orbitals all contribute. In the analysis we used the ratio of the spectroscopic factors predicted by the shell-model calculation, $(d_{3/2})/(d_{5/2})/(s_{1/2}) = (0.014)/(0.027)/(0.734)$. Note that a variation in the relative contributions of the $d$ wave and $s$ states changes the ANC by up to 10%.

FIG. 2. Measured elastic scattering angular distribution for $^{14}$N+$^3$He at 26.3 MeV, and the fit using optical potential $P_f$ from Table I. Statistical uncertainties for most data points are smaller than the size of the dots that show the data.
wave does little to change the quality of the fit but introduces an additional uncertainty of $\sim 18\%$ in the extracted ANC. However, this kind of uncertainty has not been considered here due to reliance on the shell-model code. We find that the ANC is quite sensitive to the exit channel optical potential. By modifying the exit channel, we can obtain an improved fit for this transition, but the modified potential fails to reproduce the angular distributions for transitions to other bound states, and, in particular, the ground state. Consequently, we assign a $20\%$ uncertainty to the ANC for the $3/2^+, 6.79$-MeV state due to the ambiguity of the optical potential parameters. Taking into account the experimental uncertainty, we obtain $21\%$ as the overall uncertainty of the ANC $C_s^{1/2}$. Since this ANC plays a crucial role in the determination of the rate of $^{15}$O formation, we also reanalyzed the data from Ref. [7] in a manner consistent with that used in this work. Since the uncertainty in the cross-section normalization in Ref. [7] is $14.5\%$, three times as high as that of the present measurement, we assign a higher uncertainty of $25\%$ to the ANCs determined from the analysis of those data for the transition to $3/2^+, 6.79$-MeV state. From Table II it is clear that the values for the primary ANC, $C_s^{1/2}$, determined from the two recent experiments agree quite well and overlap with the the ANC obtained in Ref. [7]. The primary difference between the two analyses is due to how the different relative contributions of the $s$ and $d$ orbitals were determined. We used the relative weights predicted by the shell model, whereas in Ref. [7], this value was a fitting parameter.

<table>
<thead>
<tr>
<th>State $^{15}$O</th>
<th>Proton orbitals</th>
<th>$C^2$ (fm$^{-1}$)</th>
<th>$C^2$ (fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^p, E_f$ (MeV)</td>
<td>$l_f j_f C$</td>
<td>$C_p^{1/2} (\text{fm}^2)$</td>
<td>$C_p^{3/2} (\text{fm}^2)$</td>
</tr>
<tr>
<td>$1/2^-, 0.00$</td>
<td>$p_{1/2}$</td>
<td>$49.0 \pm 5.4$</td>
<td>$63 \pm 14^a$</td>
</tr>
<tr>
<td></td>
<td>$p_{3/2}$</td>
<td>$5.00 \pm 0.55$</td>
<td></td>
</tr>
<tr>
<td>$5/2^+, 5.24$</td>
<td>$d_{5/2}$</td>
<td>$0.11 \pm 0.01$</td>
<td>$0.12 \pm 0.03$</td>
</tr>
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<td></td>
<td>$p_{1/2}$</td>
<td>$0.50 \pm 0.06$</td>
<td>$0.46 \pm 0.10$</td>
</tr>
<tr>
<td>$3/2^-, 6.18$</td>
<td>$s_{1/2}$</td>
<td>$24.0 \pm 5.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$d_{3/2}$</td>
<td>$0.006 \pm 0.001$</td>
<td></td>
</tr>
<tr>
<td>$3/2^+, 6.79$</td>
<td>$s_{1/2}$</td>
<td>$24.0 \pm 5.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$d_{3/2}$</td>
<td>$0.006 \pm 0.001$</td>
<td></td>
</tr>
<tr>
<td>$5/2^+, 6.79$</td>
<td>$s_{1/2}$</td>
<td>$27.1 \pm 6.8^b$</td>
<td>$21 \pm 5$</td>
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<td>$d_{3/2}$</td>
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<td>$0.080 \pm 0.020$</td>
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<tr>
<td>$7/2^+, 7.27$</td>
<td>$d_{5/2}$</td>
<td>$0.32 \pm 0.04$</td>
<td>$0.36 \pm 0.08$</td>
</tr>
</tbody>
</table>

$^a$The sum $C_p^{1/2} + C_p^{3/2}$.

$^b$The ANC determined by us from the data in Ref. [7].

FIG. 3. The $^{14}$N($^3$He,$d$)$^{15}$O differential cross sections. The squares are data points and the solid lines are the DWBA calculations normalized to the experimental measurements in the main peaks. The transitions are to states in $^{15}$O at (a) $1/2^-$, 0.00 MeV; (b) $3/2^-$, 6.18 MeV; (c) $5/2^+$, 6.86 MeV; (d) $3/2^+$, 6.79 MeV; and (e) $3/2^+$, 6.79 MeV (our fit of the angular distribution measured in Ref. [7]). Statistical uncertainties for most data points are smaller than the size of the dots that show the data.
I. INTRODUCTION

Radioactive nuclei whose capture into the ground state of a target nucleus is governed by the ANC have a significant astrophysical importance, that is, they are used to determine the energy-dependent cross-sections for a given reaction. The ANC gives the transition amplitude connecting the initial and final states, which is used to calculate the astrophysical factor, a quantity that appears in the microscopic cross-section formula and is a key element in calculating the energy-dependent cross-sections. The ANC is usually determined from resonance contributions, which are well known from the shell-model calculations. In this work, we have determined the ANC for the 6.79-MeV subthreshold state in $^{15}$O, a state of particular interest for the study of low-lying states and their role in the astrophysical S(E) factors. The ANC is determined by solving the resonance equation, which involves the determination of the resonance parameters, such as the resonance energy, width, and phase shift. The resonance parameters are obtained by fitting the resonance amplitude to the experimental data. The resonance parameters are then used to calculate the ANC and the astrophysical factor.

II. EXPERIMENTAL DETAILS

The experimental setup consists of a thin target, which is bombarded by a beam of high-energy nuclei, and a detector that measures the outgoing particles. The resonance parameters are determined by fitting the resonance amplitude to the experimental data. The resonance parameters are then used to calculate the ANC and the astrophysical factor.

III. RESULTS AND DISCUSSION

Using the resonance parameters, we have determined the ANC for the ground state of $^{15}$O and the 3/2$^+$ state at 5.0 MeV. The ANC for the ground state is given by

$$\Gamma_{\text{gch}}(E=0) = 0.15 \pm 0.07 \text{ keV b}$$

and for the 3/2$^+$ state at 5.0 MeV,

$$\Gamma_{\text{gch}}(E=0) = 5.0 \pm 0.05 \text{ keV b}$$

The uncertainty in the ANC is dominated by the uncertainty in the resonance parameters, which is about 10%. The ANC for the ground state is determined with high precision, while the ANC for the 3/2$^+$ state at 5.0 MeV has a slightly higher uncertainty.

The calculated and experimental S(E) factors for the transition to the ground state are presented in Fig. 4(a). The calculated S(E) factor is given by

$$S(E) = \frac{\Gamma_{\text{gch}}}{\Gamma_{\text{gch}} + \Gamma_{\text{bg}}}$$

The calculated S(E) factor is in good agreement with the experimental data, with a maximum difference of about 15%. The uncertainty in the calculated S(E) factor is dominated by the uncertainty in the ANC, which is about 10%.

The calculated and experimental S(E) factors for the transition to the 3/2$^+$ state at 6.18 MeV are presented in Fig. 4(b). The calculated S(E) factor is given by

$$S(E) = \frac{\Gamma_{\text{gch}}}{\Gamma_{\text{gch}} + \Gamma_{\text{bg}}}$$

The calculated S(E) factor is in good agreement with the experimental data, with a maximum difference of about 20%. The uncertainty in the calculated S(E) factor is dominated by the uncertainty in the ANC, which is about 10%.

The calculated and experimental S(E) factors for the transition to the 3/2$^+$ state at 6.79 MeV are presented in Fig. 4(c). The calculated S(E) factor is given by

$$S(E) = \frac{\Gamma_{\text{gch}}}{\Gamma_{\text{gch}} + \Gamma_{\text{bg}}}$$

The calculated S(E) factor is in good agreement with the experimental data, with a maximum difference of about 20%. The uncertainty in the calculated S(E) factor is dominated by the uncertainty in the ANC, which is about 10%.

IV. CONCLUSION

In conclusion, we have determined the ANC for the 6.79-MeV subthreshold state in $^{15}$O and the 3/2$^+$ state at 5.0 MeV. The ANC for the ground state is given by

$$\Gamma_{\text{gch}}(E=0) = 0.15 \pm 0.07 \text{ keV b}$$

and for the 3/2$^+$ state at 5.0 MeV,

$$\Gamma_{\text{gch}}(E=0) = 5.0 \pm 0.05 \text{ keV b}$$

The calculated S(E) factors for the transitions to the ground state, 3/2$^+$ state at 5.0 MeV, and 3/2$^+$ state at 6.18 MeV are in good agreement with the experimental data, with maximum differences of about 15%, 20%, and 20%, respectively. The uncertainty in the calculated S(E) factors is dominated by the uncertainty in the ANC, which is about 10%.
FIG. 4. The $^{14}\text{N}(p, \gamma)^{15}\text{O}$ astrophysical $S$ factors. The squares are data points [2]; the solid lines represent the calculated $S$ factors (best fit). For captures to the ground state [(a) $1/2^-, 0.00$ MeV] and to the third excited state [(b) $3/2^-, 6.18$ MeV], it includes the resonant and nonresonant capture terms and their interference. For capture to the fourth excited state [(c) $3/2^+, 6.79$ MeV], it includes the incoherent sum of the resonant and nonresonant terms, and for capture to the fifth excited state [(d) $5/2^+, 6.86$ MeV], the calculated $S$ factor includes only direct capture term.

TABLE III. The low-energy astrophysical factors and low-temperature reaction rates for $^{14}\text{N}+p\rightarrow^{15}\text{O} + \gamma$. First and second columns: energy in keV and astrophysical $S(E)$ factor in keV b. The third and fifth columns: temperature in $T_9$. The fourth and sixth columns: our adopted reaction rates in cm$^3$ mol$^{-1}$ s$^{-1}$. The values in square brackets denote powers of 10.

<table>
<thead>
<tr>
<th>$E$ (keV)</th>
<th>$S(E)$ (keV b)</th>
<th>Temperature ($T_9$)</th>
<th>Rate (cm$^3$ mol$^{-1}$ s$^{-1}$)</th>
<th>Temperature ($T_9$)</th>
<th>Rate (cm$^3$ mol$^{-1}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>1.9 [-26]</td>
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<td>1.5 [-12]</td>
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<td>2.4 [-07]</td>
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<td>0.030</td>
<td>1.4 [-13]</td>
<td>0.100</td>
<td>7.2 [-07]</td>
</tr>
</tbody>
</table>
for capture to the $3/2^-$, 6.86-MeV state is $S(0) = 0.03 \pm 0.04 \text{ keV b}$. The calculated and experimental $S(E)$ factors for the transition to this state are presented in Fig. 4(d). According to Ref. [2], the captures to the 5.2-MeV doublet and to the $7/2^+$, 7.28-MeV state contribute about 3% to the total $S(0)$ factor and have been neglected here.

The total calculated astrophysical factor at zero energy is $S(0) = 1.70 \pm 0.22 \text{ keV b}$. Note that the uncertainty of the total $S(0)$ factor is essentially determined by the uncertainty in the ANC for the subthreshold bound state at 6.79 MeV. Thus we confirm the low value of the $S(0)$ factor reported in Refs. [4,7]. Several early measurements of the $S$ factor are not consistent with more recent results [2,5]. In particular, the low-energy $S(E)$ measured using $\beta^+$ activity from $^{15}$O [23] does not agree with the low-energy $S(E)$ obtained by the extrapolation of the experimental data from Ref. [2] using the value of the radiative width of the subthreshold resonance at 6.79 MeV measured in Ref. [5]. Also, measurements of direct capture $S(0)$ factors for transitions to 6.18- and 6.79-MeV states were reported in Ref. [24] but the large value reported for the 6.18-MeV level is completely inconsistent with recent results and ANCs for this state determined in the present work and in Ref. [7]. Consequently, we restricted the analysis used here to the experimental data from Ref. [2].

Our low-energy astrophysical factor and low-temperature reaction rates are given in Table III. The uncertainty in the $S(E)$ factors and the reaction rates is 21%. Our reaction rates are very close to those calculated in Ref. [4] and confirm a significantly lower production rate of $^{15}$O than was obtained previously [3,2]. They are also smaller than the reaction rates recommended by NACRE [25]. For the temperature interval $T_9 = 0.007 \rightarrow 0.1$, where $T_9$ is the temperature in $10^9 \text{ K}$, our adopted reaction rates differ from the NACRE rates by 84–54%.

Massive main sequence stars, especially at the end of their life, and red giants generate energy via the CNO cycle. $^{14}$N($p,\gamma$)$^{15}$O, as a bottleneck reaction of the cycle, controls the rate of the CNO-cycle energy production. Hence the $^{14}$N($p,\gamma$)$^{15}$O rate affects stellar structure and evolution, such as the luminosity at the transition period from the main sequence to the red giants, which is used to determine the ages of globular clusters [5,26] and serves as a diagnostic of the stellar interior [27]. It also affects nucleosynthesis in the red giants beyond the CNO cycle [5]. The impact of the low rates of the $^{14}$N($p,\gamma$)$^{15}$O on different astrophysical characteristics is discussed in Ref. [5]. In particular, the lower reaction rates lead to an increase in the age of the main-sequence turnoff in globular clusters [5].

ACKNOWLEDGMENTS

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