

$^{16}\text{O}(p,\gamma)^{17}\text{F}$ Reaction and the C and O Isotopic Ratios in Red Giant Branch Stars

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The ^{16}O : ^{17}O isotopic ratio is a widely used tracer of nucleosynthesis and mixing processes in red giant stars. Its value depends on the rates of the proton-capture reactions responsible for the production and destruction of ^{16}O and ^{17}O among which the $^{16}\text{O}(p,\gamma)^{17}\text{F}$ reaction plays a central role, as it involves both isotopes. This work reports on a new measurement of the $^{16}\text{O}(p,\gamma)^{17}\text{F}$ cross section carried out at the Laboratory for Underground Nuclear Astrophysics (LUNA) over a center-of-mass energy range of 200–380 keV, a region previously unexplored by experimental studies. Two complementary techniques were

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employed: prompt gamma-ray detection and activation. The results obtained with the two techniques are consistent within experimental uncertainties. From the measured cross sections and existing literature data, we evaluate a new thermonuclear reaction rate, which is then used to demonstrate how simultaneous measurements of stellar carbon and oxygen isotopic ratios constrain the initial mass and the extent of the mixing events in red giant branch stars. In particular, we demonstrate how the $^{12}\text{C}:^{13}\text{C}$ abundance ratio is primarily sensitive to the temperature T_{max} attained during mixing, whereas the $^{16}\text{O}:^{17}\text{O}$ abundance ratio is highly sensitive to the initial stellar mass M_i . Therefore, simultaneous measurements of these isotopic ratios can disentangle and place stringent constraints on M_i and T_{max} , and the remaining uncertainty is now dominated by stellar abundance measurements rather than nuclear-physics inputs.

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Introduction—The isotopic ratios of carbon, nitrogen, and oxygen measured in stellar atmospheres are sensitive tracers of the interplay between nuclear burning and mixing processes due to convection and/or other dynamical or secular instabilities. In particular, the photospheric $^{16}\text{O}:^{17}\text{O}$ ratio changes when the star reaches the red giant branch (RGB) and convective mixing extends from the stellar surface down to the layers where proton-capture reactions on oxygen isotopes are or have been previously active. Under such conditions, ^{16}O is depleted, while the ^{17}O is enhanced, leading to a net decrease in the isotopic ratio. Similarly, a reduced $^{12}\text{C}:^{13}\text{C}$ ratio indicates mixing into regions where proton-capture reactions on carbon isotopes are or have been previously active.

Carbon isotopic ratios measured in low-mass RGB stars ($M \leq 2M_{\odot}$) are often lower than predicted by stellar models [1], supporting the existence of extra mixing in addition to the first dredge-up [2,3]. Simultaneous measurements of both carbon and oxygen isotopic ratios offer a powerful tool for constraining the extent and efficiency of mixing events, provided that the nuclear reaction rates governing the production and destruction of the relevant isotopes are known with sufficient precision. Moreover, those rates are needed to interpret oxygen isotopic ratios measured in presolar grains from Asymptotic Giant Branch stars, which carry the fingerprint of mixing processes in these stars [4,5].

One key reaction in this context is $^{16}\text{O}(p,\gamma)^{17}\text{F}$, which governs the destruction of ^{16}O and produces ^{17}O via ^{17}F decay. At astrophysical temperatures (10–500 MK), this reaction proceeds via direct capture either to the $5/2^+$ ground state or to the $1/2^+$ excited state at 495 keV of ^{17}F . A comprehensive evaluation of the available experimental data was conducted by Iliadis *et al.* in 2008 [6], who identified and, in some cases, corrected systematic issues in earlier measurements. The currently adopted reaction rate [7,8] is based on a fit of existing data with a single-particle potential model combined with Bayesian statistical methods and carries an estimated uncertainty of 4.2%. However, alternative fits to the data provide results differing by up to 10% [9]. Moreover, the only data set extending to center-of-mass energies below 350 keV [10] is affected by

uncertainties as large as 50%. In this Letter, we present a new measurement of the $^{16}\text{O}(p,\gamma)^{17}\text{F}$ cross section at center-of-mass energies between 200 and 380 keV, thereby addressing a critical gap in the experimental data relevant to stellar nucleosynthesis and deep mixing in red giants.

Experiment—The experiment was carried out by bombarding solid oxygen targets with an intense ($\sim 200 \mu\text{A}$) proton beam from the LUNA 400 kV accelerator [11] at Laboratori Nazionali del Gran Sasso (LNGS), with beam energies ranging from 230 to 400 keV. The targets were produced either through anodic oxidation of tantalum backings [12] or via reactive sputtering. Oxidized targets were enriched to between 4% and 8% in ^{18}O to allow characterization by nuclear resonant reaction analysis (NRRA) [13], using the well-known resonance in $^{18}\text{O}(p,\gamma)^{19}\text{F}$ at $E_p = 151 \text{ keV}$ [12]. The measured energy loss at this energy was between 13 and 21 keV, depending on the target, corresponding to 1.24×10^{17} to 2.04×10^{17} atoms/cm², respectively. The use of targets with different thicknesses provided a cross-check for possible systematic effects associated with the energy loss within the target. The NRRA was repeated periodically to monitor target degradation.

Two complementary experimental techniques were employed, both based on the detection of gamma rays. The first used a segmented Bismuth Germanium Oxide (BGO) detector to perform an activation measurement exploiting the β^+ decay of ^{17}F (half-life of 64.4 s [14]). Each data-acquisition run was carried out alternating periods of target irradiation and decay counting, the latter conducted with no beam on target. The yield was determined by measuring the rate of the resulting annihilation radiation over time. The environmental background was effectively suppressed by selecting events corresponding to two 511-keV gamma rays detected in coincidence in diametrically opposed detector segments (180° apart) [15,16]. This approach enabled a total cross section measurement, free from uncertainties related to angular distribution or branching ratio effects.

In the second campaign, prompt gamma rays were detected directly using an HPGe detector positioned at 55° with respect to beam direction, together with two CeBr_3

scintillators placed nominally at 0° and 90° . This setup allowed for the determination of the direct-capture cross sections to the ground state and to the first excited state of ^{16}O , hereafter denoted as $\text{DC} \rightarrow 0$ and $\text{DC} \rightarrow 495$, respectively.

Both setups employed passive shieldings consisting of lead and polyethylene to reduce environmental background [15]. Combined with the deep underground environment of LNGS, this configuration suppressed both cosmic-ray-induced and environmental backgrounds [15,17].

The absolute gamma-ray detection efficiencies for both experimental setups were measured using calibrated radioactive sources (^{60}Co , ^{133}Ba , and ^{137}Cs) and the well-known resonance at $E_p = 278$ keV in the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction. These measurements were used to validate Monte Carlo simulations of the experimental configurations, implemented within the LUNA Geant4 [18] framework SimLUNA. For the activation campaign, the detection efficiency for 511-keV gamma rays in coincidence was 29.6%. For the prompt-gamma experiment, the simulations were employed to determine the efficiency at the gamma-ray energies relevant to the $^{16}\text{O}(p, \gamma)^{17}\text{F}$ reaction, yielding values between 0.78% and 2.66%, depending on the detector and gamma-ray energy. The simulations were also used to quantify true-coincidence summing corrections.

Data analysis—In the activation experiment, the $^{16}\text{O}(p, \gamma)^{17}\text{F}$ reaction yield was found as described in [15], by solving the differential equation as follows:

$$\frac{dN_i}{dt} = Y_i I(t) - \lambda_i N_i(t), \quad (1)$$

where $N_i(t)$ is the number of nuclei of species i at time t , λ_i is the decay constant of species i , Y_i is the yield of isotope i , expressed in counts per incident proton, and $I(t)$ is the number of incident protons over time. The annihilation rate was then fitted with the following equation:

$$A(t) = KI(t) + \sum_i \lambda_i N_i(t). \quad (2)$$

The term $KI(t)$ represents the contribution from prompt gamma rays, originating primarily from annihilation radiation caused by e^-e^+ pair production of high-energy gamma rays [15]. This term was treated as a free parameter in the fitting procedure. The sum term in Eq. (2) accounts for the presence of β^+ emitters produced by proton-induced reactions on contaminants in the target, in addition to the expected ^{17}F . Two β^+ -emitting isotopes were identified: ^{13}N , half-life 597.2 s [19], produced by proton capture on ^{12}C ; and ^{15}O , half-life of 122.3 s [20], from proton capture on ^{14}N . The latter produced a detectable signal only at energies above the intense $^{14}\text{N}(p, \gamma)^{15}\text{O}$ resonance at 278 keV. Because these background reactions emit gamma rays that are visible in the BGO prompt gamma-ray

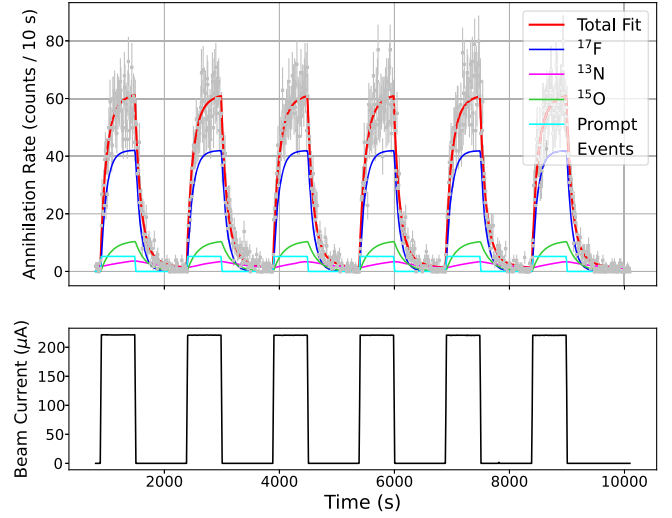


FIG. 1. Top panel: sample annihilation-rate plot, at $E_p = 330$ keV, fitted with Eq. (2). The red line shows the total fit, while the contributions of the different terms in Eq. (1) are plotted with different colors. Bottom panel: Beam current as a function of time.

spectrum, the event counts in the corresponding peaks were used to constrain the yields of ^{13}N and ^{15}O in the fit. Figure 1 shows a representative annihilation-rate plot.

For the prompt gamma-ray experimental campaign, the reaction yield was calculated from the number of observed counts from each of the two primary transitions. Figure 2 shows a sample spectrum from the HPGe detector.

The yields from each detector were corrected for the angular distribution factor $W(\theta) = 1 + \sum_{n=1}^4 \{Q_n A_n P_n[\cos(\theta)]\}$, where P_n are the Legendre polynomials of order n and the terms Q_n are attenuation coefficients due to the finite solid angle covered by each detector, evaluated from Geant4 simulations. The angular distribution coefficients A_n were derived by extrapolating the coefficients from Ref. [21] to the relevant beam energies. The validity of the extrapolation was verified by comparing the yields from the three detectors at

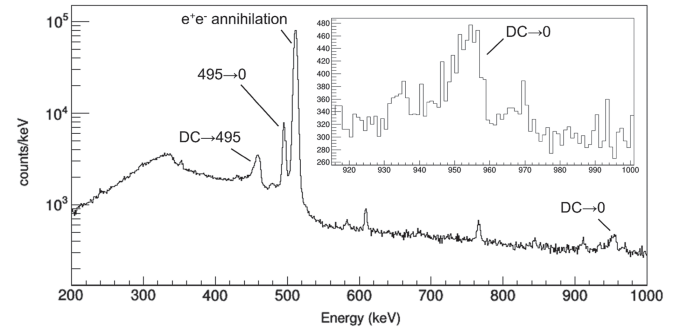


FIG. 2. HPGe spectrum obtained at $E_p = 380$ keV. The $\text{DC} \rightarrow 0$ peak is shown in the inset. The peaks at 583, 609, 768, and 911 keV stem from the decay chains of environmental ^{238}U and ^{232}Th .

$E_{\text{cm}} 370$ keV, where the gamma-ray peaks from the capture to the first excited state and to the ground state were clearly visible in all three detectors. More details on the analysis will be provided in a forthcoming publication.

The astrophysical S factor was calculated as [22]

$$S(E_{\text{cm}}) = Y \left(\int_{E_0 - \Delta E}^{E_0} \frac{e^{-2\pi\eta} P(E)}{\epsilon_{\text{eff}}(E) E} dE \right)^{-1}, \quad (3)$$

where ϵ_{eff} is the effective stopping power of the target calculated using SRIM-2013 stopping powers [23] and $P(E)$ is the distribution of ^{16}O atoms as a function of the depth inside the target, determined with the NRRA technique and corrected at each beam energy for the different stopping power. The results are shown in Fig. 3 and provided in tabular form in Supplemental Material [24], with statistical and systematic uncertainties reported separately. Statistical uncertainties on the activation data are below 2.5%. On the other hand, the statistical uncertainty on the prompt-gamma data range from 1.0% to 42%, depending on the transition observed and the center-of-mass energy. Systematic uncertainties were evaluated independently for the prompt-gamma and activation experiments, and the systematic effects common to both techniques were identified, as summarized in Table I. Specifically, the uncertainties on beam energy [11], accumulated charge [25], and effective stopping power (calculated from the mean errors quoted by SRIM [23]) are the same for the two experimental approaches.

The effects of the uncertainties on beam energy and target thickness were evaluated by varying the integration limits in Eq. (3) within their respective uncertainty ranges. It was found that the beam energy uncertainty had negligible impact ($\ll 1\%$), while the uncertainty due to target thickness depends on the precision achieved with the NRRA technique. The latter varied between the two experimental campaigns, due to the significantly different gamma-ray detection efficiencies of the setups used.

S factor fit and reaction rate evaluation—The $^{16}\text{O}(p, \gamma)^{17}\text{F}$ reaction occurs by direct capture in a single-step process [7,26,27]. Such direct processes are described accurately within a single-particle potential model, treating ^{16}O and the proton as structureless, with their wave functions generated considering single-particle Woods-Saxon (WS) potentials. The radiative capture cross section is obtained by computing electromagnetic transitions between bound and scattering wave functions. In this Letter, we consider the E1 transition using the exact expression for the radial operator [28]. We found, as in Ref. [7], that E2 transitions are negligible and the reaction is driven by E1 transitions.

In this two-body model, the $5/2^+$ ground state and $1/2^+$ excited state of ^{17}F are seen, respectively, as a proton bound in a d and an s wave to the 0^+ ground state of ^{16}O . The depths of the WS potentials in these partial waves are

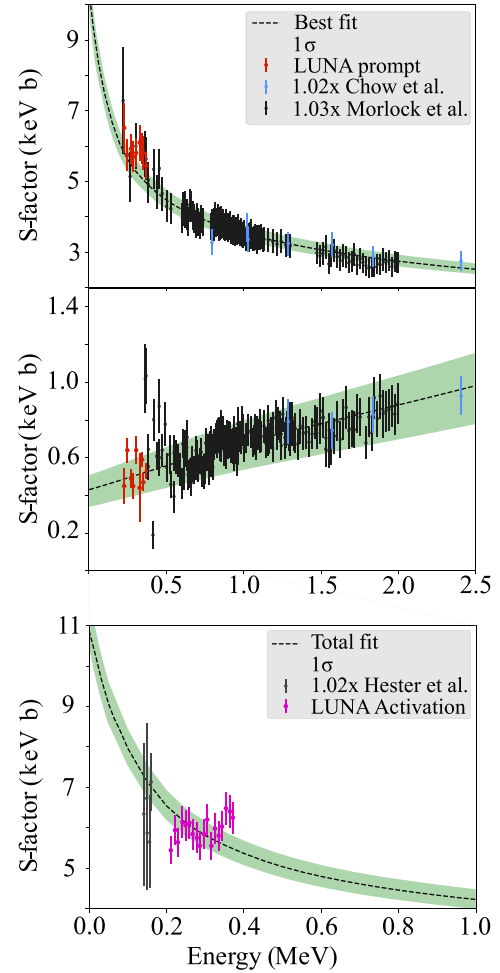


FIG. 3. S factors for the $^{16}\text{O}(p, \gamma)^{17}\text{F}$ radiative capture reaction to the $1/2^+$ excited state of ^{17}F (top), $5/2^+$ ground state of ^{17}F (middle), and the total S -factor (bottom). The error bars include both statistical and systematic errors. The black dashed lines are the evaluation obtained with the best-fit parameters and the green bands the corresponding 1σ uncertainties. To assess whether the observed fluctuations could indicate significant peak-like structures, we repeated the fits by adding a positive localized component with variable centroid and width to the smooth S -factor parameterization. The inclusion of this term did not lead to a statistically significant improvement of the fits in the energy region under discussion, and its fitted amplitude was compatible with zero within the uncertainties.

adjusted to the experimental proton separation energies of 600.27(25) keV for the $5/2^+$ ground state [29] and 104.94 (27) keV for the $1/2^+$ excited state [30]. The normalization of the bound-state wave functions and the radius of the WS potentials are adjusted to reproduce the S -factor data. As in Ref. [7], we have found that the radiative capture is mainly peripheral, i.e., the total S factor is sensitive only to the asymptotic normalization coefficients (ANCs) of the ground states, especially at low energies in the range of astrophysical interest. These ANCs are determined in the single-particle potential model by the geometry of the

TABLE I. Systematic uncertainties on the S factors.

Source	Activation	Prompt gamma
Beam energy		$\ll 1\%$
Beam charge		2%
Effective stopping power		3%
Target thickness	$\sim 1\%$	$\sim 5\%$
Detection efficiency	5%	3%–5%
Angular distributions		2.5%

potentials generating the wave function, the binding energy of the states, and the spectroscopic factors. Owing to the high correlation between the radius and diffuseness of the potentials, we consider a fixed diffuseness $a = 0.65$ fm in all partial waves to avoid overfitting.

Since the capture occurs mainly through E1 transitions, captures to the ground and excited states occur from scattering states in p and f waves. As in Ref. [7], we found the capture at low energies (< 1 MeV) to be insensitive to the choice of the potentials used to generate the scattering waves. In this Letter we use the scattering wave functions generated using a hard sphere potential in the p and f waves, because they reproduce accurately the energy dependence of the data at energies greater than 1 MeV. The only adjustable parameters of the theoretical model are the ANCs of the bound state and the radii of the WS potentials. These parameters are constrained with the S -factor data measured in this work and datasets from Refs. [10,21,31]. The best-fit parameters and their uncertainties are obtained with a frequentist approach. This choice is motivated by the results of a recent Bayesian analysis of this reaction [7], which obtained posterior distributions exhibiting an approximate Gaussian shape. In such conditions, we expect that both Bayesian and frequentist approaches will lead to similar optimal parameters and uncertainties [32,33].

In a frequentist approach, the choice of the χ^2 function to minimize can influence the final results [32,33]. We choose to scale the contribution of each dataset to the χ^2 by their number of data points, so that larger datasets do not dominate the fit. Separately, we introduced normalization factors for the datasets from Refs. [10,21,31] to account for their systematic errors. The χ^2 includes a penalty from the normalization factor, which is treated as a data point with a mean of 1 and an error equal to the systematic uncertainty of the associated dataset.

Figure 3 shows the experimental S factors for the transition to the $1/2^+$ state, the $5/2^+$ state, and the total S factor. Because the fitted ANCs and potential depths for the two transitions are independent of each other, the χ^2 takes into account simultaneously the quality of the fits of the two partial S factors and the total S factor, compared with the respective available datasets. Compared to other datasets, the prompt and activation data measured in

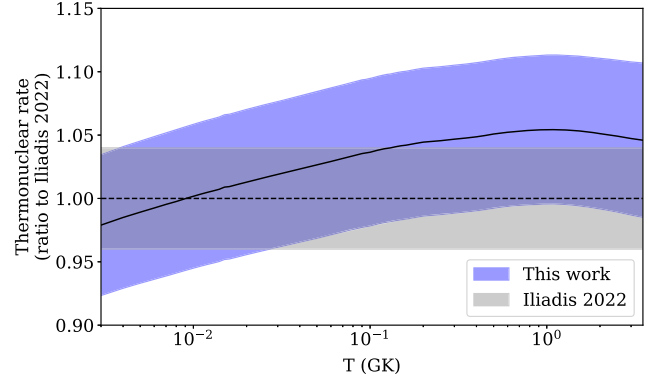


FIG. 4. Ratio of the $^{16}\text{O}(p, \gamma)^{17}\text{F}$ reaction rate obtained in this work (blue) with the evaluation of [7] (gray). The bands represent the 1σ uncertainties.

this work lie at lower energies and exhibit reduced uncertainties. Including the activation data does not significantly change the overall fitted S factor and its uncertainties. A future publication will discuss the difference between fitting the LUNA prompt data only or both prompt-gamma and activation data. The resulting ANCs of the $1/2^+$ and $5/2^+$ states are $C^{1/2^+} = 80(2) \text{ fm}^{-1/2}$ and $C^{5/2^+} = 0.96(6) \text{ fm}^{-1/2}$, and the total S factor at 0.01 MeV is $10.4(1.0) \text{ keV b}$. (By construction, the uncertainties on the ANCs incorporate those of the spectroscopic factors.) A comparison of the present results with those obtained by fitting only non-LUNA data and with literature fits is provided in Supplemental Material [24]. The inclusion of our data in the evaluation leads to more precise S factors and ANCs that are closer to the values extracted from transfer reaction data on ^{16}O [34].

The astrophysical reaction rate was evaluated using the fitted S factor including all literature data. Figure 4 shows a comparison of the present rate with the previous evaluation of Ref. [7]. Our evaluation exhibits larger uncertainties than [7], although it includes additional low-energy data, which constrain the low-energy behavior of the S factor. This difference is mostly due to the use of different statistical and theoretical frameworks: Ref. [7] uses a Bayesian approach that incorporates prior knowledge, resulting in a different choice of likelihood function. A detailed analysis considering various choices of likelihood functions and scattering potentials will be provided in a forthcoming publication.

Astrophysical implications—The new $^{16}\text{O}(p, \gamma)^{17}\text{F}$ rate was used to explore if simultaneous measurements of stellar carbon and oxygen isotopic ratios can provide a new pathway to constrain the initial mass and the maximum temperature attained during mixing events. These parameters are interdependent, making their individual effects difficult to isolate. A good target for this kind of investigation is α -Boo (Arcturus), the brightest star in the northern celestial hemisphere. Arcturus is a typical RGB

star, with mass in the range of 1 to 2 $M/M_{\odot}$ (see Ref. [35] and references therein). Reported carbon and oxygen isotopic ratios for this star are $^{12}\text{C}:^{13}\text{C} = 9 \pm 1$ and $^{16}\text{O}:^{17}\text{O} = 3030 \pm 530$ [35]. After the first dredge-up, the carbon isotopic ratio should be $\sim 25(\pm 5)$, where the quoted range accounts for variations of the initial mass and metallicity [36,37]; therefore, the substantially lower value measured for Arcturus proves the activation of some form of extra mixing during the RGB phase. By means of the FuNS code [38], we computed a set of evolutionary tracks for stars of initial mass between 1 and $2M_{\odot}$ and chemical composition in agreement with available spectroscopic studies of Arcturus, specifically, $[\text{Fe}/\text{H}] = -0.52$ and $[\text{O}/\text{Fe}] = 0.4$ [39]. The adopted nuclear network includes 35 isotopes and 29 reactions, whose rates are from the latest release of the STARLIB database [40], except for the proton captures on ^{12}C and ^{13}C , for which we adopt the updated rates from [16], the $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ and $^{17}\text{O}(\text{p}, \gamma)^{18}\text{F}$ reactions from [41], and the new $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}$ rate presented in this Letter.

According to the extant spectroscopic analysis, a solar $^{12}\text{C}:^{13}\text{C}$ (95.5 [42]) and an enhanced $^{16}\text{O}:^{17}\text{O}$ (7165 [35,39]) were adopted as initial abundance ratios in all our models. After the first dredge-up, depending on the assumed initial mass, the $^{12}\text{C}:^{13}\text{C}$ and the $^{16}\text{O}:^{17}\text{O}$ ratios are reduced down to 23–27 and 500–6000, respectively. A further reduction can occur after the RGB bump, when the H-burning shell reaches the steep molecular-weight gradient left by the first dredge-up, and the extra mixing switches on. We assume the extra mixing starts from the inner border of the convective envelope and extends down to a layer where the temperature attains T_{max} . A constant mixing velocity (v_{mix}) is assumed. In practice, this simplified description of the extra-mixing phenomenon depends on three input parameters: v_{mix} , T_{max} , and the initial mass (M_i). Actually, when v_{mix} is varied between 0.01 and 0.0001 times the average turbulent velocity in the innermost layer of the convective envelope, both $^{12}\text{C}:^{13}\text{C}$ and $^{16}\text{O}:^{17}\text{O}$ change very little. In contrast, these isotopic ratios are sensitive to variations in T_{max} and M_i .

As a result, the simultaneous fit of $^{12}\text{C}:^{13}\text{C}$ and $^{16}\text{O}:^{17}\text{O}$, as shown in Fig. 5, provides stringent constraints for $T_{\text{max}} = 20.2 \pm 0.5$ MK and $M_i = 1.24 \pm 0.04$. Here, the quoted errors account for the uncertainties on the measured C and O isotopic ratios, while the rates of CNO reactions, specifically, the $^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}$, $^{13}\text{C}(\text{p}, \gamma)^{14}\text{N}$, $^{14}\text{N}(\text{p}, \gamma)^{15}\text{O}$, $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}$, and $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$, imply a further 3% uncertainty in the predicted M_i and a 2% in T_{max} . Noteworthy, a $\pm 2\sigma$ variation of the $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}$ reaction rate results in a change of less than 1% in M_i , indicating that this rate is now well constrained.

In summary, we presented new measurements of the $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}$ reaction at energies between 200 and 380 keV. Two complementary techniques were employed: prompt gamma-ray detection, yielding partial cross sections for

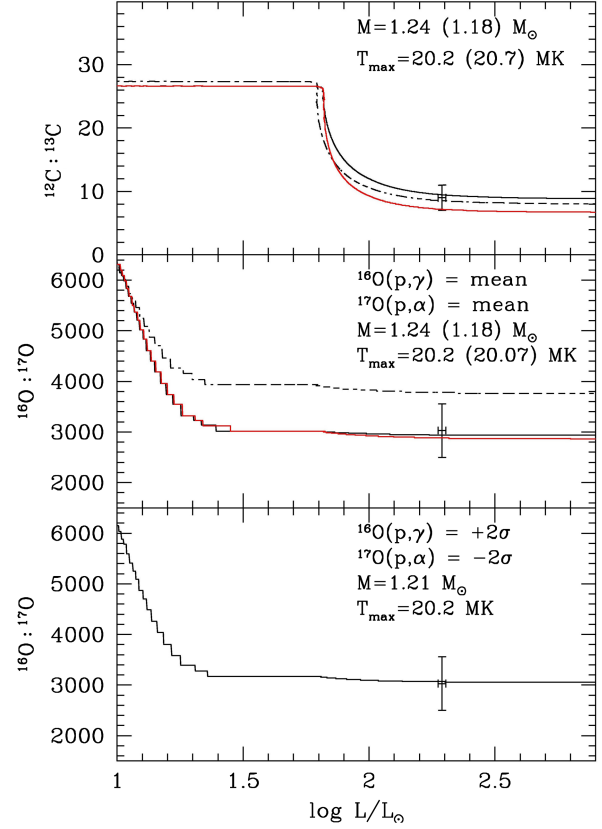


FIG. 5. Best fits of the $^{12}\text{C}:^{13}\text{C}$ (top panel) and $^{16}\text{O}:^{17}\text{O}$ (middle and bottom panels) ratios of Arcturus as a function of the stellar luminosity. The ratios from spectroscopic observations are reported as points with error bars. In the top and middle panel, the black-solid and the black-dashed lines represent model predictions for $M_i = 1.24$ and 1.18 , respectively, and $T_{\text{max}} = 20.2$ MK, while the red line was obtained assuming $M_i = 1.24$ and $T_{\text{max}} = 20.7$ MK. The bottom panel shows a fit obtained increasing the $^{16}\text{O}(\text{p}, \gamma)^{17}\text{F}$ by 2σ and decreasing the $^{17}\text{O}(\text{p}, \alpha)^{14}\text{N}$ rate by 2σ with respect to the mean values. The corresponding best-fit mass is $1.21M_{\odot}$.

capture to the ground and first excited states of ^{17}F , and activation, which allowed us to determine the total cross section. A global fit of our data together with existing literature data was performed using a single-particle potential model. The resulting S factor was used to derive an updated astrophysical reaction rate and to infer the initial mass and maximum temperature attained during deep-mixing events in the Arcturus RGB star, based on measured $^{12}\text{C}:^{13}\text{C}$ and $^{16}\text{O}:^{17}\text{O}$ ratios. We find that simultaneous measurements of these isotopic ratios can disentangle and place stringent constraints on M_i and T_{max} , and that the uncertainty is now dominated by stellar abundance measurements. This technique could be applied in the future to any RGB star, provided that a precise spectroscopic abundance analysis is available.

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Data availability—The numerical values for data shown in Fig. 3 are given in Supplemental Material [24], and will be publicly available through the EXFOR database.

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