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Improved thermonuclear reaction rate for ^{18}O(p,γ)^{19}F

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For 0.8 $M_\odot \leq M \leq 8.0\ M_\odot$ stars, the final phase of nucleosynthesis occurs during the asymptotic giant branch (AGB) stage. Grain condensation and significant mass loss transpires during this stellar evolutionary period, and presolar grains recovered from comet and meteorite samples can often be attributed to this unique stellar environment. A subset of presolar oxide grain specimens exhibit dramatic ^{18}O depletion that cannot be explained by standard AGB stellar burning stages and dredge-up models. An extra mixing process, referred to as *cool bottom processing* (CBP), was proposed for low-mass AGB stars to explain similar isotopic anomalies. The ^{18}O depletion observed within certain stellar environments and within presolar grain samples may result from the ^{18}O+p processes during CBP, and we report here on a study of the ^{18}O(p,γ)^{19}F reaction at low energies. The (p,γ) reaction rate at low temperatures was found to not be affected by a low-energy, unobserved, narrow resonance—E_R^{lab} = 95 keV—near the CBP Gamow peak. A new strength upper limit measurement was performed at TUNL's Laboratory for Experimental Nuclear Astrophysics, and an improved reaction rate was calculated. In addition, non-resonant cross section and astrophysical S-factor upper limits were measured at low bombarding energies.

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1. Introduction

A search for the unobserved 95 keV resonance in the $^{18}\mathrm{O}(p,\gamma)^{19}\mathrm{F}$ reaction was performed at the Laboratory for Experimental Nuclear Astrophysics (LENA). Because $^{18}\mathrm{O}(p,\gamma)^{19}\mathrm{F}$ is a process that destroys $^{18}\mathrm{O}$, we hypothesized that this reaction might contribute to the depletion of $^{18}\mathrm{O}$ observed in low-mass asymptotic giant branch stars and certain presolar oxide grains [1]. This depletion has been attributed to *cool bottom processing* (CBP), an extra-mixing process that occurs by some unknown driving mechanism [2]. We were also motivated by evidence that the theoretical stellar plasma temperature regime of this extra-mixing process [3] may cover the $^{18}\mathrm{O}(p,\gamma)^{19}\mathrm{F}$, E_R^{lab} = 95 keV resonance. The studies performed by Ref. [4] and then by Ref. [5] were unable to directly measure the 95 keV resonance, and resonance strength upper limits of $\omega\gamma \leq 5.0\times10^{-8}$ eV and $\omega\gamma \leq 4.0\times10^{-8}$ eV were established, respectively.

To improve upon the previous upper limits, several key tools were utilized at LENA. The LENA Electron Cyclotron Resonance Ion Source (ECRIS)—an accelerator capable of $E_p^{lab} = 50-215$ keV proton beams and an average current at the target of I_p = 1.5 mA—was employed to increase the reaction yield [6]. Our $\gamma\gamma$-coincidence spectrometer was assembled by placing the 135% HPGe detector in close running geometry with the target and centering the target within a 16-segment NaI(Tl) annulus [7]. This configuration allowed significant background reduction (a factor of 100) by excluding events that did not occur simultaneously in both the HPGe detector and the annulus. $\mathrm{Ta_2{}^{18}O_5}$ targets were prepared by the anodization of ultra-pure tantalum backings in a solution of enriched $\mathrm{H_2{}^{18}O}$.

2. Results

After analyzing 80 C of on-resonance data collected at E_p^{lab} = 105 keV with an average beam current of I_p = 754 μA, we concluded that we had not observed the resonance; however, we could constrain the upper limit. To determine the new upper limit, a relative resonance strength calculation was performed by constructing the ratio between the resonance strength of the well known E_R^{lab} = 151 keV resonance [8] and the unobserved resonance. All $^{19}\mathrm{F}$ levels will decay through the second excited state ($2 \rightarrow 0$) [9], and in our calculations, we included the possibility that the E_x = 8084 keV [9] level can decay directly to the ground state. We used the following expression to estimate an upper limit for the number of $^{19}\mathrm{F}$ compound nuclei produced [10, 11]:

$$\left(\frac{\mathcal{N}_{max}}{\mathcal{B}\eta\mathcal{W}}\right) = \frac{\mathcal{N}_{\mathrm{R0}}}{\eta_{\mathrm{R0}}^{\mathrm{Ge,P}}} + \frac{\mathcal{N}_{20}}{\eta_{20}^{\mathrm{Ge,P}}\, f_\gamma} \tag{2.1}$$

where $\mathcal{N}_{\mathrm{R0}}$ is the upper limit on the intensity of the ground state transition, $\mathcal{N}_{20}$ is the upper limit on the intensity of the decay from the $^{19}\mathrm{F}$ second excited state to the ground state ($2 \rightarrow 0$) in the coincidence-gated HPGe spectrum, $\eta_{\mathrm{R0}}^{\mathrm{Ge,P}}$ is the HPGe peak efficiency for the ground state transition, $\eta_{20}^{\mathrm{Ge,P}}$ is the HPGe peak efficiency of the $2 \rightarrow 0$ transition, and f_γ is a $\gamma\gamma$-coincidence correction factor that depends on the γ-ray decay scheme and the coincidence gate selected. The intensity upper limits were all calculated using the Bayesian statistical method outlined by Ref. [12].

Based on the known decays and their branching ratios, GEANT4 (and a post-processing code that incorporated our coincidence gates) was used to determine the f_γ correction factor for every

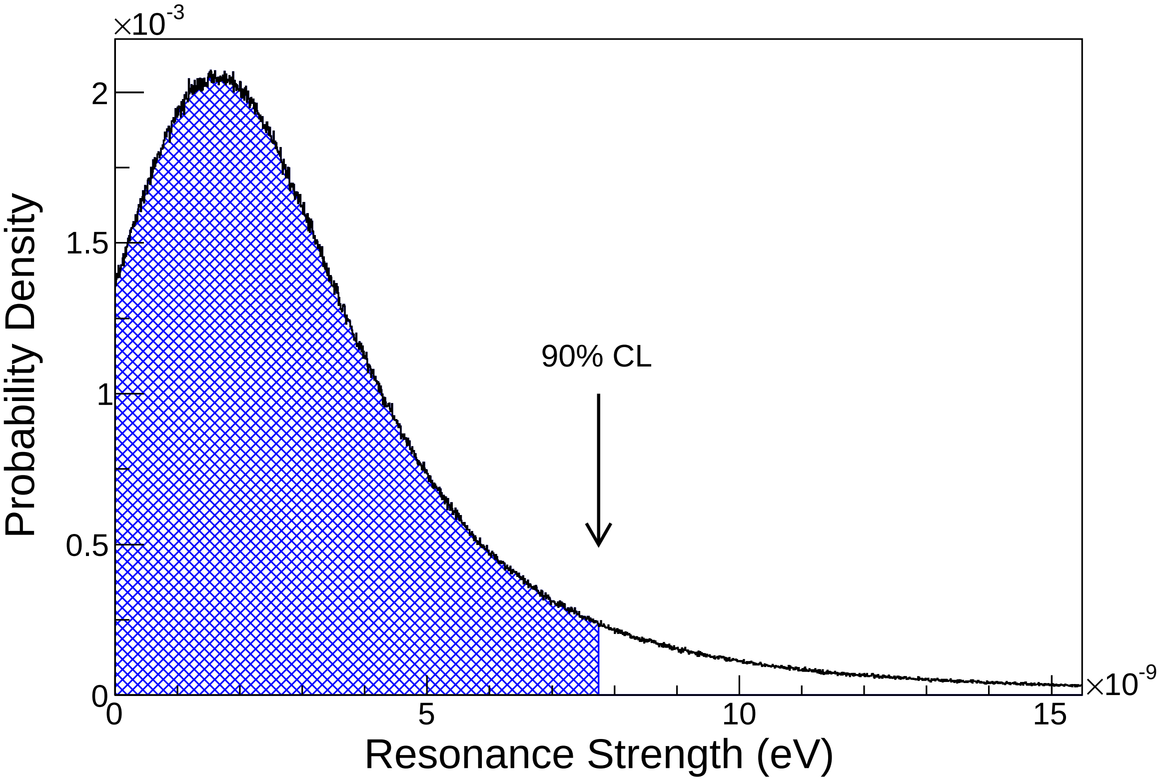

Figure 1: Resonance strength probability density function generated by solving the relative resonance strength equation iteratively. Normal distributions were constructed for each value that entered into the strength calculation; these distributions were randomly sampled during each iteration. The histogram created was then integrated to the 90% confidence level, and a new upper limit of $\omega\gamma \leq 7.8\times10^{-9}$ eV was extracted.

^{19}F level that satisfied our spin and energy criteria ($J \leq 7/2$ and $E_x \geq 5500$ keV). The following equation was used to extract the correction factor for each level:

$$\mathscr{N}'_{20} = \mathscr{N}_R \eta_{20}^{\mathrm{Ge,P}} f_\gamma \tag{2.2}$$

where $\mathscr{N}'_{20}$ is the simulated intensity of the 197 keV peak in the gated coincidence spectrum, $\mathscr{N}_R$ is the total number of simulated reactions, and $\eta_{20}^{\mathrm{Ge,P}}$ is the $2 \rightarrow 0$ singles peak efficiency. The mean of this set of f_γ values was adopted as a reasonable estimate of the E_x = 8084 keV correction factor.

An analysis Monte Carlo code was written that generated a probability density function for every value that was inputted into the relative resonance strength calculation and Eq. (2.1). These probability densities where then randomly sampled and the relative resonance strength equation was iteratively solved to fill a new resonance strength pdf. This probability density function was then integrated to the 90%, 95% and 99% confidence levels. Our calculations yielded an improved upper limit on the E_R^{lab} = 95 keV resonance strength of $\omega\gamma \leq 7.8\times10^{-9}$ eV (90% CL) for a rectangular coincidence gate of 4.25 MeV $\leq E_\gamma^{\mathrm{NaI(Tl)}} \leq$ 10.0 MeV. Our new upper limit is a factor of 5 lower than the upper limit reported by Ref. [5] .

No direct capture transitions were observed in the accumulated singles or coincidence spectra at E_p^{lab} = 105 keV. However, an upper limit on the total direct capture cross section was obtained by assuming a constant S-factor over the target thickness and using numerical integration techniques to extract σ(E) and S(E). This set of calculations was performed for the same $\gamma\gamma$-coincidence gate used for the relative resonance strength upper limit calculation. We obtained an astrophysical S-factor upper limit of $S_{\mathrm{total}}^{\mathrm{DC}} \leq 8.1$ keV b (90% CL), corresponding to a direct capture cross section upper limit of $\sigma_{\mathrm{total}}^{\mathrm{DC}} \leq 1.8$ pb (90% CL).

It is interesting to compare our measured upper limit values with direct capture model calculations. We compared the total S-factor predicted by Ref. [4] and the output of the direct capture codes `TEDCA` [13] (zero scattering potential) and `DIRCAP` [14] (hard sphere scattering potential). The `TEDCA` and `DIRCAP` output was normalized to the measured direct capture cross sections at E_p^{lab} = 1850 keV [4]. At E_p^{lab} = 105 keV, our measured upper limits were smaller than the prediction from Ref. [4] by about a factor of 2. Our experimental results were also consistent with the direct capture model output at E_R^{lab} = 105 keV.

Based on the argument made by Ref. [14] that a zero scattering potential provides better direct capture estimates as opposed to a hard sphere scattering potential, we adopted the `TEDCA` extrapolation of the total direct capture S-factor to calculate the reaction rates. Figure 2 compares our new reaction rate with the ^{18}O(p,γ)^{19}F reaction rate published by Ref. [15]. The solid lines are the ratios between the present (p,γ) high and low reaction rates and the recommended (p,γ) reaction rate from Ref. [15]. The dotted lines are the same ratios calculated from the high and low rates presented in Ref. [15]. The dashed line at 44.7 MK represents the highest minimum threshold on CBP stellar plasma temperatures according to Ref. [3]. A second dashed line at 5.5 GK represents the matching temperature [16] beyond which our experimentally-based rates have to be matched to Hauser-Feshbach predictions. Major deviations between the previously accepted reaction rates and our new rates can be attributed to our dramatically improved total astrophysical S-factor; the rates published by Ref. [15] relied upon the S-factor fit from Ref. [4]. At high temperatures an additional deviation between the new and previous rates is evident in Fig. 2. This deviation occurs because we provide a higher cutoff energy for our S-factor fit than Ref. [4] ($E_{\mathrm{cutoff}}^{\mathrm{cm}}$ = 2.5 MeV versus $E_{\mathrm{cutoff}}^{\mathrm{cm}}$ = 1.0 MeV, respectively).

Further constraint on the E_R^{lab} = 95 keV resonance strength has not increased the reaction rates at the CBP stellar plasma temperature threshold. In fact, as Fig. 2 shows, the ^{18}O(p,γ)^{19}F reaction rate calculated from our new upper limit is lower than the recommended rate at CBP temperatures. This further reduces the likelihood that ^{18}O(p,γ)^{19}F is a significant contributor to the depletion of ^{18}O seen in stellar atmospheres and presolar grain samples. Based on our calculations, the reaction rate contribution from the E_R^{lab} = 95 keV resonance is $<$3% in the temperature region relevant to cool bottom processing and can be considered negligible.

3. Conclusion

An improved ^{18}O(p,γ)^{19}F astrophysical S-factor upper limit was determined at low bombarding energies. Our new upper limit, $S_{\mathrm{total}}^{\mathrm{DC}} \leq 8.1$ keV b (90% CL), improves upon the previous value from Ref. [4] by about a factor of 2 at E_p^{lab} = 105 keV. We were also able to further constrain the upper limit on the ^{18}O(p,γ)^{19}F, E_R^{lab} = 95 keV resonance strength to $\omega\gamma \leq 7.8\times10^{-9}$ eV—a factor

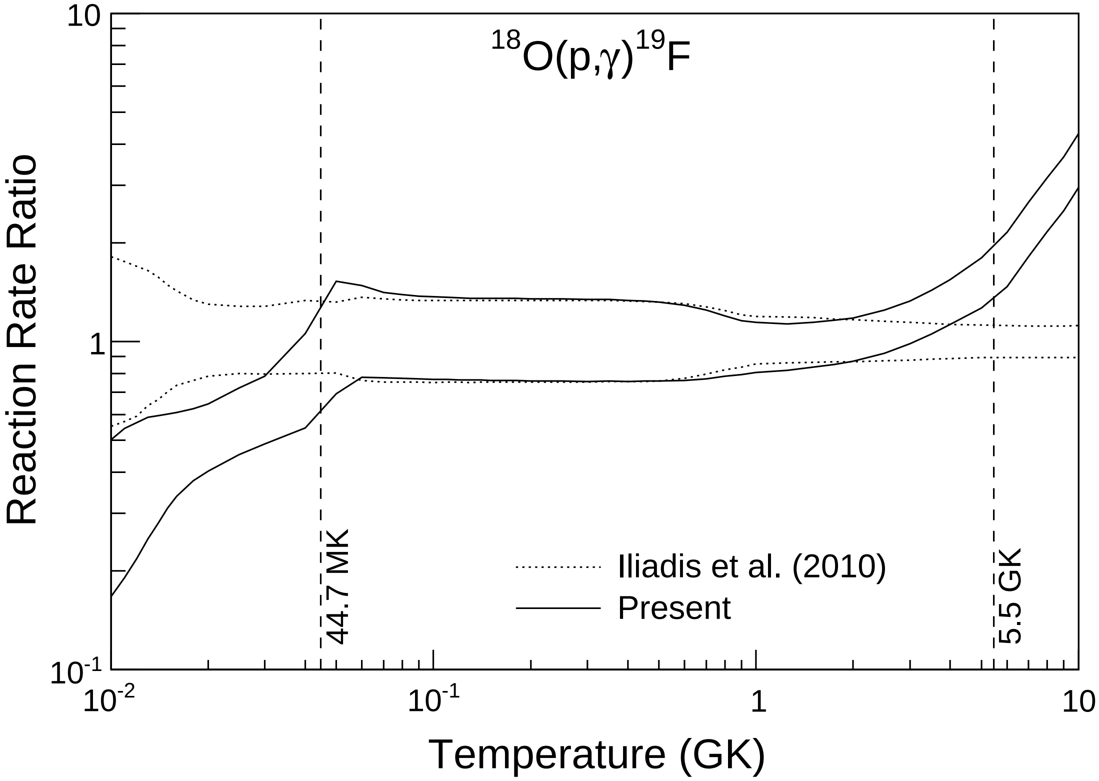

Figure 2: The reaction rate ratio between the (p,γ) rates from the current study and the recommended rates (solid line) are shown. The ratio between the Iliadis *et al.* [15] rates and the recommended rates (dotted line) are also shown.

of 5 improvement. Direct capture model calculations, paired with the new resonance strength upper limit, were used to arrive at significantly improved reaction rates. Based on these calculations, it is clear that at E_R^{lab} = 95 keV, the (p,γ) reaction is not a significant contributor to the reaction rate. Therefore, we were able to conclude that $^{18}O(p,\gamma)^{19}F$ is not a major source of ^{18}O depletion during cool bottom processing.

Acknowledgments

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