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The impact of the ^{18}F(α,p)^{21}Ne reaction on fluorine production in AGB stars

Amanda I. Karakas[*a], **H. Y. Lee**[b,d], **Maria Lugaro**[c], **J. Görres**[d] **and M. Wiescher**[d]

a Research School of Astronomy & Astrophysics, Mt Stromlo Observatory, Weston Creek ACT 2611, Australia

b Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843

c Sterrenkundig Instituut, University of Utrecht, Postbus 80000, 3508 TA Utrecht, The Netherlands

d Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, IN 46556

E-mail: akarakas@mso.anu.edu.au, hylee@phy.anl.gov, M.Lugaro@phys.uu.nl jgoerres@nd.edu, mwiesche@nd.edu

The recent experimental evaluation of the ^{18}F(α,p)^{21}Ne reaction rate, when considering its associated uncertainties, presented significant differences compared to the theoretical Hauser-Feshbach rate. This was most apparent at the low temperatures relevant for He-shell burning in asymptotic giant branch (AGB) stars. Investigations into the effect on AGB nucleosynthesis revealed that the upper limit resulted in an enhanced production of ^{19}F and ^{21}Ne in carbon-rich AGB models, but the recommended and lower limits presented no differences from using the theoretical rate. This was the case for models spanning a range in metallicity from solar to [Fe/H] ~ -2.3. The results of this study are relevant for observations of F and C-enriched AGB stars in the Galaxy, and to the Ne composition of mainstream silicon carbide grains, that supposedly formed in the outflows of cool, carbon-rich giant stars. We discuss the mechanism that produces the extra F and summarize our main findings.

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*Speaker.

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1. Introduction

Until 2006 the only rate for the ^{18}F(α,p)^{21}Ne reaction was the theoretical estimate available in the Brussels nuclear reaction-rate library [1]. The first experiment aimed at determining the ^{18}F(α,p)^{21}Ne rate over a large range of stellar temperatures was carried out by Lee [2]. This experimental evaluation, when considering its associated uncertainties, presented significant differences compared to the theoretical rate, especially at the low temperatures relevant for He-shell burning in asymptotic giant branch (AGB) stars ($T \approx 0.3$ GK). We investigate the effect of such differences on the nucleosynthesis occurring in AGB models of various initial mass and composition.

The theoretical estimate of the ^{18}F(α,p)^{21}Ne rate was not present in previous studies e.g., [3], although we had included the species ^{18}F because of its important role in the reaction chain ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^{+}\nu)^{18}$O, leading to the production of ^{18}O in the He shell. It was found that the inclusion of the ^{18}F(α,p) reaction resulted in an increase in the production of the stable ^{19}F; see §3 for more details on the production mechanism. This is of interest because AGB models do not synthesize enough ^{19}F to match the [F/O] abundances observed in AGB stars [4]. Also, the cosmic origin of fluorine is still uncertain, with massive stars [5] playing a significant role in producing fluorine alongside AGB stars. However, AGB stars and their progeny (e.g., post-AGB stars, planetary nebulae) are still the only confirmed site of fluorine production thus far [6, 7]. Observations of an enhanced F abundance ([F/Fe] = 2.90) in a carbon-enhanced metal-poor halo star [8] is further motivation to understand the details of F production in AGB stars [9].

In this proceedings, we summarize the results of calculations published in Karakas et al. [10].

2. The ^{18}F$(\alpha,p)^{21}$Ne reaction rate

The measurement of the ^{18}F(α,p)^{21}Ne reaction cross section is made difficult by the short half-life ($T_{1/2} \sim 109$ min) of ^{18}F. The time-reversed reaction of ^{21}Ne$(p,\alpha)^{18}$F was investigated at the Nuclear Science Laboratory in the University of Notre Dame [2]. The cross section was measured in the energy range of 2.3 MeV to 4.0 MeV using the activation method. The lower limit of the cross-section measurement is mainly determined by the statistical uncertainty of the activation data, while the upper limit is based on the uncertainty associated with the ^{18}O induced background. We refer the reader to [10] for further details.

3. Results

We computed the stellar structure first using the Mt Stromlo Stellar Structure code, and then performed post-processing on that structure to obtain abundances for 77 species, most of which are not included in the small stellar-structure network. See [10] and references therein for more details. This technique is valid for studying reactions not directly related to the main energy generation. This is certainly the case for studying the effect of the ^{18}F$(\alpha,p)^{21}$Ne reaction on AGB nucleosynthesis. We included models in our study with masses between 1.9 to $5M_{\odot}$, with initial metallicities from solar ($Z = 0.02$) to $Z = 0.0001$ ([Fe/H] -2.3), computed previously in [11]. A partial mixing zone (PMZ) is required to produce a ^{13}C *pocket* and free neutrons in the He-intershell via the ^{13}C$(\alpha,n)^{16}$O reaction. Neutrons are necessary for the chain ^{14}N$(n,p)^{14}$C, where free protons are

Table 1: Results from the AGB models. For each mass and Z value, we show the mass of the partial mixing zone used in the computation, the yield (y) of ^{19}F, and the multiplication factor (X) needed to obtain the upper limit ^{19}F yield from the recommended-rate yield. All yields are in solar masses, and the multiplication factors are dimensionless quantities. The same information is also presented for ^{21}Ne for each model.

Mass	Z	PMZ	$y(^{19}\mathrm{F}_{\mathrm{rec}})$	$X(^{19}\mathrm{F})$	$y(^{21}\mathrm{Ne}_{\mathrm{rec}})$	$X(^{21}\mathrm{Ne})$
3.0	0.02	0.002	5.84(−6)	1.526	1.25(−6)	4.423
3.0	0.012	0.002	5.66(−6)	1.736	1.39(−6)	5.330
1.9	0.008	0.002	9.35(−7)	1.178	1.60(−7)	2.340
3.0	0.008	0.002	1.71(−5)	2.407	4.52(−6)	9.609
2.5	0.004	0.002	1.33(−5)	2.061	2.81(−6)	8.364
5.0	0.004	0	1.45(−7)	4.582	−2.58(−6)	−1.965
2.0	0.0001	0.002	1.67(−5)	1.975	3.23(−6)	8.551

then used by ^{18}O$(p,\alpha)^{15}$N. We include a PMZ of $0.002M_\odot$ for all lower mass cases. The protons in the PMZ are captured by the abundant ^{12}C to form a ^{13}C pocket that is $\approx 10-15$% of the mass of the He-intershell. We note that the extent in mass and the proton profile of the partial mixing zone are very uncertain parameters (see discussions in [12, 13]).

From Table 1 it is evident that employing the upper limit of the ^{18}F$(\alpha,p)^{21}$Ne reaction results in an increase in the production of ^{19}F and ^{21}Ne, compared to using the recommended rate. The change in the yield increases with decreasing metallicity, at a given mass, with the largest change found in the $5M_\odot$, $Z = 0.004$ model. Note that the amount of ^{19}F produced in the intermediate-mass models (at a given Z) is much less than the amount produced in the lower-mass $3M_\odot$ model, by factors of $\sim$3–40. This is because ^{19}F is destroyed by HBB in the $5M_\odot$ models.

The enhanced abundance of ^{19}F as a result of using the upper limit may be explained by considering the ^{18}O$(p,\alpha)^{15}$N$(\alpha,\gamma)^{19}$F reaction chain. Including the ^{18}F$(\alpha,p)^{21}$Ne reaction reduces the abundance of ^{18}O because it competes with ^{18}O production via the ^{18}F$(\beta^+\nu)^{18}$O decay. However, the extra amount of protons from (α,p) enhances the ^{18}O$(p,\alpha)^{15}$N reaction rate, even though ^{18}O production has been deprived from the decay. In other words, the sum $N_{^{18}\mathrm{O}} + N_p$ (where N_i is the abundance by number of nucleus i) remains constant, however, the product $N_{^{18}\mathrm{O}}N_p$, on which the number of ^{18}O+p reactions depends, is maximized when $N_{^{18}\mathrm{O}}$ is equal to N_p. In [10] we analyzed the effect of the extra protons on the ^{19}F production in the He-shell. It was found that the overall ^{19}F production increases as long as $N_{^{14}\mathrm{N}}/N_{p_0} > 1$, where N_{p_0} is the original number density of protons without the inclusion of the ^{18}F$(\alpha,p)^{21}$Ne reaction, and this condition is well satisfied in the He-burning shell. During the network calculation a realistic $N_{^{14}\mathrm{N}}/N_{p_0} \approx 10^{10}$; this ratio is large enough to explain the enhanced fluorine production in the stellar models.

4. Discussion and conclusions

From Fig. 4, we see that the surface [^{19}F/^{16}O] ratios from the $3M_\odot$, $Z = 0.008$ model are a factor of ~ 2.2 times higher when employing the new upper limit of the ^{18}F$(\alpha,p)^{21}$Ne reaction. We chose to show this model because it produces the largest F abundances, although the metallicity

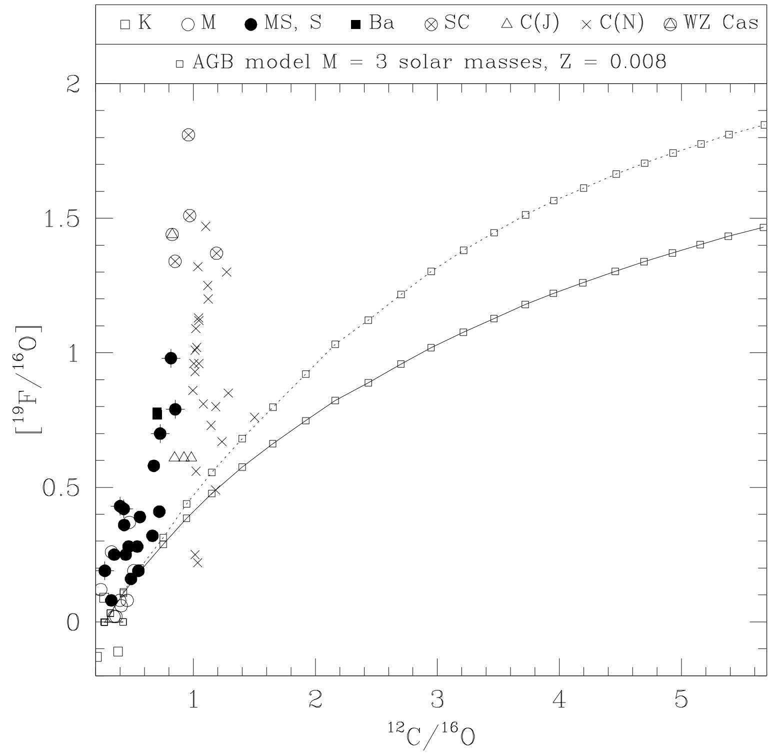

Figure 1: Comparison of fluorine abundances observed by [4] and model predictions for the $3M_\odot$, $Z = 0.008$ model. The predictions are normalized such that the initial ^{19}F abundance corresponds to the average F abundance observed in K and M stars. Each symbol on the prediction lines represents a TDU episode. Solid lines represent calculations performed using no ^{18}F(α, p)^{21}Ne reaction, which are equivalent to using the current lower limit, recommended value and Brussels library rate. Dotted lines are calculations performed using the current upper limit of the rate.

of this model is probably at the lower end of the distribution of Galactic carbon stars. Table 1 and Fig. 4 shows that a match between the stellar models and the stars with the highest observed ^{19}F abundances is possible, but only for very high C/O ratios of $\sim 4-5$ found in the $3M_\odot$, $Z = 0.008$ model. These high C/O ratios are likely not realistic, and the inclusion of carbon-rich, low-temperature opacities into the stellar models would cause the TP-AGB evolution to end before the model star reached such C/O ratios. A solution to the mystery of the high F abundances at modest C/O ratios is still missing, but a re-evaluation of the F and C abundances in the sample of AGB stars considered by [4] may help, along with a detailed examination of model uncertainties.

The ^{18}F(α,p)^{21}Ne reaction also affects the abundance of ^{21}Ne in the He-shell of AGB stars. There is a long-standing puzzle concerning the isotopic composition of Ne measured in stellar silicon carbide (SiC) grains extracted from meteorites, which formed in the envelopes of carbon-rich AGB stars e.g., [14, 15]. Models computed with the upper limit of the ^{18}F(α, p)^{21}Ne reaction rate show an increase in the ^{21}Ne abundance, and hence in the ^{21}Ne/^{22}Ne ratio in the intershell of up to a factor of 6; see [10] for further details. We conclude that the ^{18}F(α, p)^{21}Ne reaction rate being closer to its upper limit may be a promising explanation for the ^{21}Ne/^{22}Ne ratios in SiC grains. The modeling uncertainties related to convection and mass loss do not affect the intershell compositions and thus do not apply to the discussion of the Ne composition of stellar SiC grains. For this reason, the results for Ne are also a more reliable hint that the ^{18}F(α,p)^{21}N reaction is indeed closer to its upper limit than the comparison of F in AGB stars. However, more experimental data for this reaction at temperatures below 0.4 GK are required to help verify this result.

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PoS(NIC X)015