The effect of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction rate uncertainty on the yield of fluorine from Wolf-Rayet Stars

Richard J. Stancliffe, Maria Lugaro, Claudio Ugalde, Christopher A. Tout, Joachim Görres and Michael Wiescher

1 Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA, U.K.
2 Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, U.S.A.

Accepted 0000 December 00. Received 0000 December 00; in original form 0000 October 00

ABSTRACT

In the light of recent recalculations of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction rate we present results of the expected yield of $^{19}\text{F}$ from Wolf-Rayet (WR) stars. We have computed models using the upper and lower limits for the rate in addition to the recommended rate and hence we constrain the uncertainty in the yield with respect to this reaction. We find a yield of $3.1 \times 10^{-4} M_\odot$ of $^{19}\text{F}$ with our recommended rate and a difference of a factor of two between the yields computed with the upper and lower limits. In comparison with previous work we find a difference in the yield of approximately a factor of 4, connected to a different choice of mass loss. Model uncertainties must be carefully evaluated in order to obtain a reliable estimate of the yield of fluorine from WR stars together with its uncertainties.

Key words: stars: evolution, stars: Wolf-Rayet, stars: interiors, nucleosynthesis, fluorine

1 INTRODUCTION

The production site of $^{19}\text{F}$ has been a major puzzle for nucleosynthesis for a long time. It was predicted by Goriely et al. (1980) that $^{19}\text{F}$ should be manufactured in asymptotic giant branch stars, and these are currently the only observationally confirmed site for fluorine production (Jorissen et al. 1992). Other sites and mechanisms for the galactic production of fluorine have been proposed. The neutrino process operating during type-II supernova explosions can produce fluorine (Woosley & Weaver 1995). Moreover, fluorine can be synthesised during core He-burning and ejected via the strong winds of Wolf-Rayet (WR) stars (Meynet & Arnould 1993, 2004). It appears that the contributions of asymptotic giant branch and WR stars have to be included in the computation of the chemical evolution of the Galaxy to account for the observations of fluorine in the Milky Way (Renda et al. 2004).

The uncertainties of the nuclear reaction rates involved in the production and destruction of $^{19}\text{F}$ in the case of asymptotic giant branch stars have been studied in detail by Lugaro et al. (2004). Here we examine fluorine production in WR stars with regard to the uncertainties of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ rate.

Fluorine production in WR stars is of secondary nature because it relies on the presence of $^{13}\text{C}$ and $^{14}\text{N}$ produced during H burning. During core helium burning the production mechanism for $^{19}\text{F}$ is as follows. The seed $^{14}\text{N}$ undergoes $\alpha$ capture to produce the unstable nucleus $^{18}\text{F}$ which $\beta$-decays to $^{18}\text{O}$. In the presence of protons the reaction $^{18}\text{O}(p, \alpha)^{15}\text{N}$ can occur which then leads to the formation of $^{19}\text{F}$ via the reaction $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$. Protons may be present in a helium burning core from the reaction $^{14}\text{N}(n, p)^{14}\text{C}$, with the neutrons coming from the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$. The important destruction mechanism associated with the core helium burning phase is the reaction $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$. New estimates for the rate of this reaction have been presented by Lugaro et al. (2004). It is very difficult to gather experimental data at low energies so the estimated uncertainties are of fourteen orders of magnitudes at a temperature of about $2 \times 10^8$ K, typical of core helium burning. Thus it is necessary to investigate the impact of such a large uncertainty on the yield of fluorine from WR stars.

In section 2 we describe the details of the evolution code used and its nucleosynthesis routine. We briefly review the details of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction in section 3. In section 4

* E-mail: rs@ast.cam.ac.uk
2 THE STELLAR EVOLUTION CODE

Calculations were made using the evolution code STARS originally developed by [Eggleton 1972] and updated by many contributors (e.g. Pols et al. 1995). The current version of the code employs a fully simultaneous solution of the equations of stellar structure, nuclear burning and mixing [Stancliffe, Tout & Pols 2004]. Opacities are taken from Rogers & Iglesias (1992) and Alexander & Ferguson (1994). The evolution code uses an approximate reaction network comprising only those elements – namely $^1$H, $^4$He, $^{12}$C, $^{14}$N, $^{16}$O, $^{18}$O, $^{19}$F, $^{20}$Ne, $^{22}$Ne, $^{23}$Na, $^{24}$Mg, $^{25}$Mg, $^{26}$Mg, $^{26}$Al, $^{26}$Si, $^{27}$Al, $^{28}$Si, $^{29}$Si, $^{30}$Si, $^{31}$P, $^{32}$S, $^{33}$S, $^{34}$S, $^{56}$Fe, $^{57}$Fe, $^{58}$Fe, $^{60}$Fe, $^{59}$Co, $^{58}$Ni, $^{59}$Ni, $^{60}$Ni, $^{61}$Ni, $^{56}$Fe, $^{57}$Fe, $^{58}$Fe, $^{59}$Fe, $^{60}$Fe

| Light isotopes |
|----------------|
| $^1$H, $^2$H, $^3$He, $^4$He, $^7$Li, $^{11}$B, $^{12}$C, $^{13}$C, $^{14}$N, $^{15}$N, $^{16}$O, $^{17}$O, $^{18}$O, $^{19}$F, $^{20}$Ne, $^{21}$Ne, $^{22}$Ne, $^{23}$Na, $^{24}$Mg, $^{25}$Mg, $^{26}$Mg, $^{26}$Al, $^{26}$Si, $^{27}$Al, $^{28}$Si, $^{29}$Si, $^{30}$Si, $^{31}$P, $^{32}$S, $^{33}$S, $^{34}$S |

| Iron group isotopes |
|---------------------|
| $^{56}$Fe, $^{57}$Fe, $^{58}$Fe, $^{59}$Fe, $^{60}$Fe, $^{59}$Co, $^{58}$Ni, $^{59}$Ni, $^{60}$Ni, $^{61}$Ni |

Table 1. Isotopes included in the nucleosynthesis code. Isotopes also included in the structural part of the code are highlighted in bold. Unstable isotopes are in italics.

we present the results of the simulations. Conclusions and directions for further work are outlined in section 9.

2.1 The nucleosynthesis routine

The nucleosynthesis routine deals with 40 isotopes. These include all stable particles, and a few unstable ones, from neutrons and deuterium up to $^{34}$S and some isotopes from the iron group. It also computes its own values for the isotopes included in the evolutionary code as the compositions from the evolutionary part of the code will deviate slightly from those of the nucleosynthesis part. A list of all isotopes included in the nucleosynthesis code is given in Table 1. Unstable nuclei that are not included in the network are treated as if their decay were instantaneous. This approximation is fair for all light isotopes with half-lives from seconds to hours in conditions of core helium burning. For the unstable isotopes considered in the network, the decay lifetimes are the terrestrial values given by Krane [1988].

2.1.1 Charged particle reaction rates

In order to couple the nucleosynthesis network 63 charged particle reactions are required. The rates are taken from a variety of sources and are listed in Table 2 (proton captures) and Table 3 (α captures). The rate of the reaction $^3$He($^4$He,2$p$)$^4$He is that given by Caughlan & Fowler [1988], as are the rates for carbon and oxygen burning reactions.

The nucleosynthesis routines were designed to employ the ready-to-use fits to the reaction rates from the REACLIB library (1991 updated version of Thielemann et al. 1984), updated where possible to include the latest experimental results (see Lugardo et al. 2004, for full details). For some of the rates involved in the production of $^{19}$F, such as $^{15}$N($^8$N,$^7$Be) or $^{15}$N($^8$Be,$^7$Li), the rates are virtually the same as those presented in the NACRE compilation [Angulo et al. 1990]. In other cases, such as the rates $^{14}$N($^8$N,$^7$Be) or $^{18}$O($^7$Be,$^2$H), the rates used are updates with respect to the NACRE rates.
The effect of the $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$ reaction rate uncertainty on the yield of fluorine from Wolf-Rayet Stars

2.1.2 Neutron capture rates

A total of 45 neutron capture reactions are required for the network. The work of Bao et al. (2004) was used as the main source. Supplementary $(n,\gamma)$ data are taken from Rauscher & Thielemann (2000) for captures by $^{59,60}\text{Fe}$. Rates for the reaction $^{33}\text{S}(n,\gamma)^{34}\text{S}$ were taken from Schatz et al. (1995). For the reactions $^{26}\text{Al}(n,p)^{26}\text{Mg}$ and $^{26}\text{Al}(n,\gamma)^{27}\text{Al}$ rates are from Koehler et al. (1997). The important reaction rate for $^{15}\text{N}(n,p)^{14}\text{C}$ is from Gledenov et al. (1995), which is in agreement with previous experimental (Koehler & O'Brien 1989) and theoretical (Bahcall & Fowler 1963) estimates. This rate is approximately a factor of two higher than the rate proposed by Brehm et al. (1988) and used by Meynet & Arnould (1993, 2004).

For neutron captures by $^{59}\text{Ni}$ we take reaction rates from Holmes et al. (1976) and this is also the source of the rate of the reaction $^{17}\text{O}(n,\alpha)^{14}\text{N}$.

In addition to this, two neutron sinks are included to account for neutron captures by those elements not included in the network. The first sink is emulated by the reaction $^{34}\text{S}(n,\gamma)^{35}\text{S}$ and represents nuclei between $^{34}\text{S}$ and the iron group. The second sink is emulated by the reaction $^{61}\text{Ni}(n,\gamma)^{62}\text{Ni}$ and represents captures by all the heavy elements above $^{61}\text{Ni}$. In any case these reactions are not very important in core He-burning conditions where the main neutron absorber is $^{14}\text{N}$.

3 THE $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$ REACTION RATE

The $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$ reaction rate is the main destruction channel of $^{19}\text{F}$ in WR stars. However there is very little experimental data available at low energies. As described in detail by Lagarde et al. (2004), the level density in the compound nucleus $^{24}\text{Na}$ has been analysed on the basis of, as yet unpublished, low-energy $^{19}\text{F}(\alpha,p)$ resonance measurements by Ugalde (2004). We found that the level density is too low to apply the Hauser-Feshbach approach (Rauscher et al. 1997), which yields a rate in reasonable agreement with the estimate by Caughlan & Fowler (1988). Thus the rate needs to be calculated from determination of the strengths, $\omega_{\gamma}$, for the single resonances. The recommended rate is shown in Figure 1 together with the upper and lower limits. In the temperature range of core He burning the recommended rate is more than one order of magnitude smaller than the rate estimated by Caughlan & Fowler (1988) and used in the previous calculations. The lower limit for the rate is several orders of magnitude smaller than the recommended rate.

4 RESULTS

To test the effects of varying the $^{19}\text{F}(\alpha,p)^{22}\text{Ne}$ reaction rate a 60 $M_\odot$ model of $Z = 0.02$ was evolved from the pre-main sequence through to the WR phase with the recommended reaction rate and the upper and lower limits. Initial abundances for all the elements considered are taken from Anders & Grevesse (1989). This means we take the initial $^{19}\text{F}$ mass fraction as $4.051 \times 10^{-5}$.
10^{-7}. Mass loss was applied by the mass-loss rates of de Jager, Nieuwenhuizen & van der Hucht (1988) for pre-WR evolution and the rates of Langen (1984) for the WR phase. The switch to WR mass loss is made when the surface hydrogen abundance by mass fraction reaches 0.4 and the surface temperature exceeds 10^4 K. These may not be the ideal prescriptions to use (see Eldridge & Tout 2004) but our aim is to investigate the effect of varying the 19F(α,p)22Ne reaction rate not the influence of mass-loss rate on WR evolution.

Figure 2 shows the mass fraction of 19F in the core and at the surface as a function of time. Initially a rapid increase in the core fluorine abundance occurs because all the available 13C and 14N undergo α captures, opening the path to 19F production. It takes about 8 × 10^4 yr from this time to have a notable increase in the abundance of 19F at the surface when stellar winds have stripped away the stellar surface exposing the formerly convective core. Between this point and the end of the life of the star (the WC phase) approximately 9 M⊙ of material is lost from the surface.

A plot of the core temperature as a function of time during the He-burning is shown in Figure 2. In the case of the upper limit of the 19F(α,p)22Ne reaction, we see that temperatures are sufficiently high for the reaction to be active in the core soon after the maximum abundance of 19F has been reached and the fluorine abundance in the core rapidly drops from its peak value. For the recommended rate the initial decline is much slower and becomes steeper after 4.4 × 10^6 yr. The lower limit to the rate leads to an almost constant core abundance of 19F until about 4.4 × 10^6 yr later at which point fluorine is appreciably destroyed. The destruction of fluorine in the lower-limit case, and the steeper decline in the recommended case, that occur at a time of about 4.4 × 10^6 yr are to be attributed to another destruction channel that is opening at around such a time in the centre of the star, the 19F(n,γ) reaction where the neutrons are provided by the activation of the 22Ne(α,n)25Mg reaction rate. The rate we use for this neutron source reaction is practically the same as that recommended by NACRE. Such a rate is comparable to the recommended limit of the 19F(α,p)22Ne reaction and it is much higher than the lower limit for this reaction, as illustrated in Figure 1. The estimate of the neutron capture cross section of 19F is relatively old and needs to be revaluated (Bao et al. 2000) but a different rate is unlikely to have a large impact on the 19F yield from WR stars as the surface abundance is not affected by this destruction channel, as shown by the left panel of Figure 3.

The yield of 19F from each of the evolution runs is presented in Table 4. It is defined as

\[ p = \int_0^\tau \dot{M}(t)[X_a(t) - X_0]dt \]  

where \( \tau \) is the lifetime of the star, \( \dot{M}(t) \) the mass-loss rate at age \( t \), \( X_a(t) \) the surface fluorine abundance at time \( t \) and \( X_0 \) the initial abundance of fluorine. The rapid destruction of fluorine that occurs with the upper limit of the 19F(α,p)22Ne rate leads to a yield approximately a factor of two lower than the cases computed using the recommended and the lower limit for the rate.

In order to compare our results with those presented by Meynet & Arnould (1993, 2000) for the equivalent model we must consider the results of our calculation computed with the upper limit for the rate. This is equivalent to the rate proposed by Caughlan & Fowler (1988). Our yield is very close to the value of 1.2 × 10^{-4} M⊙ calculated by Meynet & Arnould (1993), who used the standard mass-loss rate that we adopted. This yield is approximately a factor of four smaller than that calculated by Meynet & Arnould (2000), who adopted an enhanced mass-loss rate. The enhanced mass loss rates used by Meynet & Arnould (2000) will expose the He core sooner and so provide a higher 19F yield. The comparison underlines the importance of mass-loss rates on the calculations of yields from these stars.

We also note that many reaction rates that influence the production of fluorine have been updated in our calculations with respect to those of Caughlan & Fowler (1988) that were used by Meynet & Arnould. Moreover, we have not included any convective overshooting. This means that we have a smaller convective core than Meynet & Arnould, which affects the luminosity of the star and thus the mass-loss rate.

5 CONCLUSIONS

We have calculated the yield of 19F from a Wolf-Rayet star of 60 M⊙ at \( Z = 0.02 \) with the upper, recommended and lower limits for the rate of the 19F(α,p)22Ne reaction. We find that there is a difference of a factor of two between the yields computed with the upper and lower limits for the rate. As future work the effects of the new rates for the 19F(α,p)22Ne reaction need to be determined across a wide range of stellar masses and metallicities and the effect of the uncertainties associated with the other rates affecting the production of fluorine should also be analysed.

We also find that, for a given rate of the 19F(α,p)22Ne reaction,

| Reaction Rate | Yield (10^{-4} M⊙) |
|---------------|--------------------|
| Upper limit   | 1.7                |
| Recommended   | 3.1                |
| Lower limit   | 3.4                |

Table 4. The yield of 19F obtained with the indicated 19F(α,p)22Ne reaction rates.
reaction, the $^{19}\text{F}$ from Wolf-Rayet stars is reduced by a factor of about 4 with respect to previous calculations, made with an enhanced mass-loss rate (Meynet & Arnould 2000). These model uncertainties should be carefully evaluated.

6 ACKNOWLEDGEMENTS

We thank the anonymous referee for helpful remarks that have corrected and improved this paper. RJS wishes to thank PPARC for a studentship and John Eldridge for assistance with mass-loss rates. CAT thanks Churchill College for a fellowship.

REFERENCES

Alexander D. R., Ferguson J. W., 1994, ApJ, 437, 879
Anders E., Grevesse N., 1989, Geochimica et Cosmoehimica Acta, 53, 197
Angulo C., Arnould M., Rayet M., Descouzemont P., Baye D., Leclercq-Wilain C., Coc A., Barhoumi S., Aguer P., Rolfs C., et al. 1999, Nuclear Physics A, 656, 3
Bahcall N. A., Fowler W. A., 1969, ApJ, 157, 659
Bao Z. Y., Beer H., Käppeler F., Voss F., Wisshak K., Rauscher T., 2000, Atomic Data and Nuclear Data Tables, 76, 70
Blackmon J. C., Champagne A. E., Hofstee M. A., Smith M. S., Downing R. G., Lamaze G. P., 1995, Phys. Rev. Lett., 74, 2642
Brehm K., Becker H. W., Rolfs C., et al. 1988, Z. Phys., 330, 167
Caughlan G. R., Fowler W. A., 1988, Atomic Data and Nuclear Data Tables, 40, 283
Champagne A. E., Cella C. H., Kouzes R. T., Lowry M. M., Magnus P. V., Smith M. S., Mao Z. Q., 1988, Nuclear Physics A, 487, 433
Dababneh S., Heil M., Käppeler F., Görrès J., Wiescher M., Reifarth R., Leiste H., 2003, Phys. Rev. C., 68, 025801
de Oliveira F., Coc A., Aguer P., Angulo C., Bogaert G., Kiener J., Lefebvre A., Tatischeff V., Thibaud J.-P., Fortier S., Maisan J. M., Rosier L., Rotbard G., Vernotte J., Arnould M., Jorissen A., Mowlavi N., 1996, Nuclear Physics A, 597, 231
Denker A., Drotleff H. W., Grosse M., Knee H., Kunz R., Mayer A., Seidel R., Soiné M., Wöohr A., Wolf G., Hammer J. W., 1995, in Busso M., Raiteri C. M., Gallino R., eds, AIP Conf. Proc. 327: Nuclei in the Cosmic III . p. 255ff
Eggleton P. P., 1971, MNRAS, 151, 351
El Eid M. F., Champagne A. E., 1995, ApJ, 451, 298
Eldridge J. J., Tout C. A., 2004, MNRAS, 353, 87
Görrès J., Arlandini C., Giesen U., Heil M., Käppeler F., Leiste H., Stech E., Wiescher M., 2000, Phys. Rev. C, 62, 055801
Görrès J., Graff S., Wiescher M., Azuma R. E., Barnes C. A., Becker H. W., T. R. W., 1990, Nuclear Physics A, 517, 329
Gledenov Y. M., Salatski V. I., Sedysheva P. V., Sedysheva M. V., Kohler E. P., Vesna V. A., Okunev I. S., 1995, in Busso M., Raiteri C. M., Gallino R., eds, AIP Conf. Proc. 327: Nuclei in the Cosmic III . p. 173ff
Goriely S., Jorissen A., Arnould M., 1989, in Proc. 5th Workshop on Nuclear Astrophysics . p. 60
Holmes J. A., Woosley S. E., Fowler W. A., Zimmerman B. A., 1976, Atomic Data and Nuclear Data Tables, 18, 305ff
Illicis C., Buchmann L., Endt P. M., Herndl H., Wiescher M., 1996, Phys. Rev. C, 53, 475
Illicis C., Schange T., Rolfs C., Schröder U., Somorjai E., Trautvetter H. P., Wolke K., Endt P. M., Kikstra S. W., Champagne A. E., Arnould M., Paulus G., 1990, Nuclear Physics A, 512, 509
Jorissen A., Goriely S., 2001, Nuclear Physics A, 688, 508
Jorissen A., Smith V. V., Lambert D. L., 1992, A&A, 261, 164
Kaeppler F., Wiescher M., Giesen U., Goerres J., Baraffe I., El Eid M., Raiteri C. M., Busso M., Gallino R., Limongi M., Chieffi A., 1994, ApJ, 437, 396
Kochler P. E., Kwanagh R. W., Vogelaar B., Y. Popov Y. P., 1997, Phys. Rev. C, 56, 1138

Figure 3. Left panel: mass fraction of $^{19}\text{F}$ present in the core as a function of time. The sharp increase in the mass fraction at $4.1 \times 10^6$ yr is the onset of core He-burning. Right panel: mass fraction of $^{19}\text{F}$ at the stellar surface as a function of time.
6 R.J. Stancliffe, M. Lugaro, C. Ugalde et al.

Koehler P. E., O’Brien H. A., 1989, Phys. Rev. C., 39, 1655
Krane K. S., 1988, Introductory Nuclear Physics. John Wiley & Sons
Landre V., Prantzos N., Ager P., Bogaert G., Lefebvre A., Thibaud J. P., 1990, A&A, 240, 85
Langer N., 1989, A&A, 220, 135
Lugaro M., Ugalde C., Karakas A. I., Görres J., Wiescher M., Lattanzio J. C., Cannon R. C., 2004, ApJ, 615, 934
Meynet G., Arnould M., 1993, in Kaeppeler F., Wisshak K., eds, Nuclei in the Cosmos II . pp 487–492
Meynet G., Arnould M., 2000, A&A, 355, 176
Pols O. R., Tout C. A., Eggleton P. P., Han Z., 1995, MNRAS, 274, 964
Rauscher T., Thielemann F., 2000, Atomic Data and Nuclear Data Tables, 75, 1
Rauscher T., Thielemann F., Kratz K., 1997, Phys. Rev. C., 56, 1613
Renda A., Fenner Y., Gibson B. K., Karakas A. I., Lattanzio J. C., Campbell S., Chieffi A., Cunha K., Smith V. V., 2004, MNRAS, 354, 575
Rogers F. J., Iglesias C. A., 1992, ApJS, 79, 507
Schatz H., Jaag S., Linker G., Steininger R., Käppeler F., Koehler P. E., Graff S. M., Wiescher M., 1995, Phys. Rev. C, 51, 379
Schmidt S., Rolfs C., Schulte W. H., Trautvetter H. P., Kavanagh R. W., Hategan C., Faber S., Vănilion B. D., Graw G., 1995, Nuclear Physics A, 591, 227
Stancliffe R. J., Tout C. A., Pols O. R., 2004, MNRAS, 352, 984
Stegmüller F., Rolfs C., Schmidt S., Schulte W. H., Trautvetter H. P., Kavanagh R. W., 1996, Nuclear Physics A, 601, 168
Thielemann F., Truran J. W., Arnould M., 1986, in Advances in Nuclear Astrophysics Thermonuclear reaction rates from statistical model calculations. pp 525–540
Timmermann R., Becker H. W., Rolfs C., Schröder U., Trautvetter H. P., 1988, Nuclear Physics A, 477, 105
Ugalde C., 2004, PhD thesis, University of Notre Dame
Wiescher M., Görres J., Thielemann F., 1990, Ap.J., 363, 340
Woosley S. E., Weaver T. A., 1995, ApJS, 101, 181