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Rates for reactions relevant to fluorine nucleosynthesis

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Abstract. We have recently updated the rates of reactions that lead to the nucleosynthesis of fluorine by using the latest experimental results, where available, together with a detailed analysis of the reactions when no or few experiments have been done. Some rates hold large uncertainties and in some cases these may translate into large abundance variations at the stellar surface.

Key words. Fluorine – Reaction rates – Nucleosynthesis

1. Introduction

The only stable isotope of fluorine, ^{19}F, is by far the least abundant of stable nuclides in the 12-32 atomic mass range. Useful atomic lines of flourine are nonexistent in the visible region of the spectrum and as a result information on the stellar abundance of fluorine is scarce. However, available data from infrared HF lines provide strong evidence that fluorine is produced deeply within the interiors of AGB stars during helium flashes (Jorissen et al. 1992).

Thermal pulses of the He-burning shell in low-mass AGB stars have been proposed (Jorissen et al. 1992) as a scenario for ^{19}F production through the chain ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^+)^{18}$O(p,α)^{15}N$(\alpha,\gamma)^{19}$F. Protons are produced by ^{14}N(n,p)^{14}C while the required neutrons come from ^{13}C(α,n)^{16}O. An alternate way of making ^{18}O is through the ^{14}C$(\alpha,\gamma)^{18}$O reaction; on the other hand, the ^{18}O$(\alpha,\gamma)^{22}$Ne reaction may poison the synthesis of fluorine. ^{19}F could be destroyed in stars by ^{19}F(p,α)^{16}O and ^{19}F(α,p)^{22}Ne. However, in a helium-rich environment protons have been depleted by hydrogen burning and the ^{19}F(p,α) reaction is not likely to occur. There has been considerable effort and improvement in the determination of the nuclear reaction rates over the last few years since the early ^{19}F nucleosynthesis studies. In particular new measurements of key reactions such as ^{14}C$(\alpha,\gamma)^{18}$O and ^{18}O$(\alpha,\gamma)^{22}$Ne provided new information on low energy resonances which were ignored or only insufficiently included in previous simulations of ^{19}F nucleosynthesis. The main implication for the present study is that the new experimental results put a more stringent limit on the reaction rates and therefore reduce considerably the associated uncertainties (Lugaro et al. 2004) compared to the uncertainties listed in the NACRE compilation (Angulo et al. 1999).

There has been very little experimental effort in the study of ^{19}F(α,p)^{22}Ne. We therefore will discuss the present nuclear physics related uncertainties associated with the rates. For the latter case we will also give a new reaction rate estimate based on experimental information and nuclear structure information on the compound nucleus ^{23}Na rather than on simple penetrability arguments.

2. The reaction rate of ^{14}C(α,γ)^{18}O

The reaction ^{14}C(α,γ)^{18}O has been studied experimentally in the energy range of 1.13 to 2.33 MeV near the neutron threshold in the compound nucleus ^{18}O by Görres et al. (1992). The reaction rate is dominated at higher temperatures by the direct capture and the single strong 4^+ resonance at E_{cm}=0.89 MeV. Toward lower temperatures, which are of importance for He shell burning in AGB stars, important contributions may come from the 3^- resonance at E_{cm}=0.176 MeV (E_x=6.404 MeV) and a 1^- subthreshold state at E_x=6.198 MeV. It has been shown in detailed cluster model simulations that neither one of the two levels is characterized by a pronounced α cluster structure (Descouvemont & Baye 1985). The strengths of these two contributions are unknown and have been estimated by Buchmann, d'Auria, & McCorquodale (1988) adopting an α spectroscopic factor of Θ_α^2=0.02, 0.06 for the 6.404 MeV and the 6.198 MeV states, for determining the 0.176 MeV resonance strength and the cross section of the high energy tail of the subthreshold state. While the value for the 6.404 MeV state is in agreement with the results of a ^{14}C(^{6}Li,d)^{18}O α-transfer experiment (Cunsolo et al. 1981) the value for the 6.2 MeV state appears rather large since the corresponding α transfer was not observed. This reflects the lack of appreciable α strength in agreement with the theoretical predictions. We therefore adopted an upper limit for the spectroscopic factor of this resonance of Θ_α^2=0.02. The upper limit for the reaction rate is based on the experimental data (Görres et al. 1992) plus the low energy resonance contributions calculated from the upper limit for the α spectroscopic factor. For the recommended reaction rate we adopted a considerably smaller spectroscopic factor Θ_α^2=0.01 for calculating the $\omega\gamma$ strength of the 0.176 MeV resonance. In this we followed the recommendations by Funck & Langanke (1989). The lower limit of the reaction rate neglects the contribution of this resonance altogether and corresponds directly to the experimental results (Görres et al. 1992). It should be noted however that the uncertainty for the resonance strength and therefore its contribution to the reaction rate is up to five orders of magnitudes as shown in figure 1.

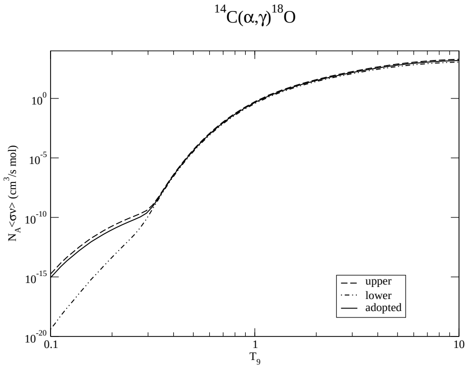

Fig. 1. The reaction rate and uncertainties for ^{14}C(α,γ)^{18}O

The ^{14}C(α,γ)^{18}O reaction can be activated together with the ^{13}C(α,n)^{16}O during the interpulse period, both in the partial mixing zone as well as in the deepest layer of the region composed by H-burning ashes, when ^{14}N(n,p)^{14}C occurs, and represents the main path to the production of ^{18}O, and subsequently of ^{15}N. The importance of the nucleosynthesis of ^{15}N during the interpulse period is very much governed by the choice of the rate of the ^{14}C(α,γ)^{18}O reaction. The closer, or higher, this rate is to that of the ^{13}C(α,n)^{16}O reaction the more efficient is the production of ^{15}N because ^{18}O and protons are produced together. The effect of the partial mixing zone, and hence the uncertainties related to it, are in fact much less important when using our recommended rate, since in the temperature range of interest our rate is more than an order of

Table 1. Reaction rate for $^{14}C(\alpha,\gamma)^{18}0$ in units of cm^3 s^{-1}mol^{-1}.

T_9	lower	recomm	upper
0.10	4.153E-20	9.138E-16	1.820E-15
0.15	2.116E-16	4.682E-13	9.326E-13
0.20	4.498E-14	9.370E-12	1.862E-11
0.25	2.113E-12	5.418E-11	1.058E-10
0.30	1.172E-10	2.901E-10	4.618E-10
0.35	9.055E-09	1.122E-08	1.337E-08
0.40	2.837E-07	3.434E-07	4.032E-07
0.50	3.465E-05	4.193E-05	4.922E-05
0.60	8.142E-04	9.856E-04	1.157E-03
0.70	7.496E-03	9.073E-03	1.065E-02
0.80	3.859E-02	4.672E-02	5.484E-02
0.90	1.354E-01	1.639E-01	1.923E-01
1.0	3.639E-01	4.405E-01	5.171E-01
1.5	6.424E+00	7.786E+00	9.148E+00
2.0	2.616E+01	3.190E+01	3.765E+01
2.5	6.315E+01	7.798E+01	9.281E+01
3.0	1.190E+02	1.491E+02	1.793E+02
3.5	1.925E+02	2.448E+02	2.972E+02
4.0	2.800E+02	3.604E+02	4.409E+02
4.5	3.760E+02	4.889E+02	6.017E+02
5.0	4.752E+02	6.228E+02	7.704E+02
6.0	6.664E+02	8.838E+02	1.101E+03
7.0	8.315E+02	1.112E+03	1.392E+03
8.0	9.632E+02	1.295E+03	1.628E+03
9.0	1.062E+03	1.435E+03	1.807E+03
10.0	1.132E+03	1.534E+03	1.937E+03

magnitude lower than our standard rate from NETGEN (Jorissen & Goriely 2001), which was also used in the previous study by Goriely & Mowlavi (2000) (see figure 1). At the temperature of interest the NETGEN rate is based on previous theoretical studies by Funck & Langanke (1989) and Hashimoto et al. (1986).

3. The reaction rate of ^{18}O(α,γ)^{22}Ne

The ^{18}O(α,γ)^{22}Ne is of interest for the discussion of ^{19}F production in AGB stars since it competes with the ^{18}O(p,α)^{15}N process. A strong rate might lead to a reduction in ^{19}F production. The reaction rate of ^{18}O(α,γ)^{22}Ne has been last summarized and discussed by Käppeler et al. (1994) and by the NACRE compilation. The main uncertainties result from the possible contributions of low energy resonances which have been estimated on the basis of α-transfer measurements by Giesen et al. (1994). A recent experimental study of ^{18}O(α,γ)^{22}Ne by Dababneh et al. (2003) led to the first successful direct measurement of the postulated low energy resonances at 470 keV and 566 keV thus reducing to 33% the previous uncertainty of about a factor of 30 given by NACRE at the temperature of interest which was given by taking the previously available experimental upper limit for the 470 keV resonance strength (Giesen et al. 1994). The new rate is shown in figure 2. Not measured still is the 218 keV resonance which is expected to dominate the rate at temperatures of T≤0.1 GK, well below the temperature in typical He-burning conditions. The resulting reaction rate is in very good agreement with the previous estimate by Käppeler et al. (1994).

Table 2. Reaction rate for ^{18}O(α,γ)^{22}Ne in units of cm^3 s^{-1}mol^{-1}.

T_9	lower	recomm	upper
0.10	1.333E-20	3.573E-20	1.076E-19
0.15	1.972E-14	2.955E-14	3.942E-14
0.20	2.260E-11	3.329E-11	4.398E-11
0.25	1.894E-09	2.600E-09	3.305E-09
0.30	5.258E-08	6.540E-08	7.822E-08
0.35	7.233E-07	8.445E-07	9.657E-07
0.40	5.711E-06	6.470E-06	7.230E-06
0.50	1.107E-04	1.229E-04	1.351E-04
0.60	8.058E-04	8.900E-04	9.740E-04
0.70	3.282E-03	3.622E-03	3.958E-03
0.80	9.274E-03	1.024E-02	1.119E-02
0.90	2.058E-02	2.279E-02	2.489E-02
1.0	3.872E-02	4.302E-02	4.699E-02
1.5	2.781E-01	3.180E-01	3.492E-01
2.0	9.828E-01	1.150E+00	1.276E+00
2.5	2.579E+00	3.043E+00	3.406E+00
3.0	5.338E+00	6.309E+00	7.100E+00
3.5	9.199E+00	1.087E+01	1.228E+01
4.0	1.386E+01	1.637E+01	1.853E+01
4.5	1.896E+01	2.238E+01	2.538E+01
5.0	2.416E+01	2.851E+01	3.236E+01
6.0	3.394E+01	4.002E+01	4.550E+01
7.0	4.208E+01	4.961E+01	5.645E+01
8.0	4.832E+01	5.696E+01	6.485E+01
9.0	5.282E+01	6.224E+01	7.090E+01
10.0	5.584E+01	6.580E+01	7.498E+01

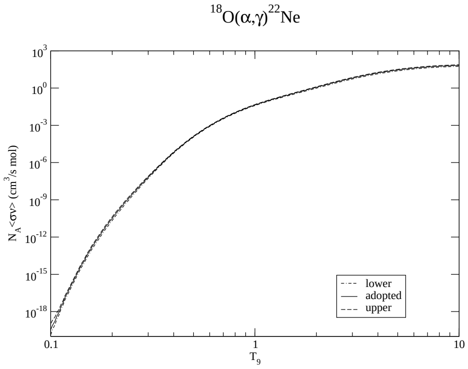

Fig. 2. The reaction rate and uncertainties for $^{18}O(\alpha,\gamma)^{22}Ne$

4. The reaction rate of $^{19}F(\alpha,p)^{22}Ne$

The reaction rate of $^{19}F(\alpha,p)^{22}Ne$ is one of the most important input parameters for a reliable analysis of ^{19}F nucleosynthesis in AGB stars. Yet, there is very little experimental data available for the $^{19}F(\alpha,p)^{22}Ne$ reaction cross section at low energies. Experiments were limited to the higher energy range above E_α=1.3 MeV (Kuperus 1965). Caughlan & Fowler (1988) suggested a rate which is based on a simple barrier penetration model previously used by Wagoner (1964). This reaction rate is in reasonable agreement with more recent Hauser-Feshbach estimates assuming a high level density (see Thielemann et al. 1986) and has therefore been used in most of the previous nucleosynthesis simulations. The applicability of the Hauser-Feshbach model, however, depends critically on the level density in the compound nucleus system (Rauscher, Thielemann & Kratz 1997). We analyzed the level density in the compound nucleus ^{23}Na above the α-threshold of Q_α=10.469 MeV as compiled by Endt & Van der Leun (1978) and Endt (1990). The typical level density is ≈0.02 keV^{-1}. This level density is confirmed directly for the $^{19}F(\alpha, p)$ reaction channel by direct studies from Kuperus (1965) at resonance energies above 1.5 MeV and further confirmed by as yet unpublished low energy $^{19}F(\alpha,p)$ resonance measurements of Ugalde (2004). This low resonance density translates into an averaged level spacing of D ≈ 50 keV which is considerably larger than the average resonance width of $\Gamma \approx 8$ keV in this excitation range. Based on these estimates the requirement of $D \leq \Gamma$ for the applicability of the Hauser-Feshbach approach (Rauscher et al. 1997) is not fulfilled. The reaction rate for $^{19}F(\alpha,p)^{22}Ne$ therefore needs to be calculated from determining the strengths $\omega\gamma$ for the single resonances,

$$\omega\gamma = \frac{(2J+1)}{2} \cdot \frac{\Gamma_\alpha \Gamma_p}{\Gamma_{tot}}. \quad (1)$$

We estimated the α partial width Γ_α using a simple WKB approximation with an average α-spectroscopic factor of C^2S_α=0.001. This average spectroscopic factor was determined from determining the average α-strength distribution from the strengths of observed α capture resonances at higher energies (Kuperus 1965) and from the α spectroscopic strengths of bound states in ^{23}Na (Fortune et al. 1978). The total widths Γ_{tot} of the levels correspond in all cases to the proton partial widths Γ_p, therefore, the resonance strength depends entirely on the spin J and the α partial width Γ_α of the resonance levels. For the higher energy range $E_\alpha \geq 1.5$ MeV we used directly the experimentally determined resonance strengths by Kuperus (1965). The resulting reaction rate is shown in figure 3 and deviates considerably from the Hauser-Feshbach prediction, in the temperature range of intershell He burning it is more than one order of magnitude smaller than predicted in the Hauser-Feshbach estimate. The possibility of "missing strength" in as yet unobserved resonances seems unlikely as shown by the previous $^{19}F(\alpha,p)^{22}Ne$ studies but cannot be completely excluded. However a substantial increase in the reaction rate would rather be associated with a large α strength of the low energy unbound states in ^{23}Na. Therefore an experimental confirmation of the here predicted resonance strength distribution is desirable for a wide energy range.

5. Conclusions

In this paper we have updated the rates for the $^{14}C(\alpha,\gamma)^{18}O$, $^{18}O(\alpha,\gamma)^{22}Ne$, and $^{19}F(\alpha,p)^{22}Ne$

Table 3. Reaction rate for $^{19}F(\alpha,p)^{22}Ne$ in units of $cm^3\ s^{-1} mol^{-1}$.

T_9	lower	recomm	upper
0.10	1.791E-60	1.21E-23	1.81E-22
0.15	6.754E-39	3.64E-18	3.10E-17
0.20	3.651E-28	7.23E-15	4.70E-14
0.30	1.664E-17	4.04E-11	3.94E-10
0.40	3.334E-12	7.70E-09	1.13E-07
0.50	5.637E-09	4.37E-07	6.27E-06
0.60	9.650E-07	1.02E-05	1.33E-04
0.70	4.401E-05	1.42E-04	1.51E-03
0.80	8.410E-04	1.48E-03	1.11E-02
0.90	8.745E-03	1.16E-02	5.91E-02
1.00	5.852E-02	6.85E-02	2.47E-01
1.50	1.980E+01	2.02E+01	3.37E+01
2.00	3.746E+02	3.77E+02	6.29E+02
2.50	2.132E+03	2.14E+03	4.47E+03
3.00	6.597E+03	6.61E+03	1.83E+04
3.50	1.440E+04	1.44E+04	5.27E+04
4.00	2.530E+04	2.53E+04	1.21E+05
4.50	3.852E+04	3.86E+04	2.35E+05
5.00	5.312E+04	5.32E+04	4.06E+05
6.00	8.320E+04	8.32E+04	9.51E+05
7.00	1.108E+05	1.11E+05	1.80E+06
8.00	1.339E+05	1.34E+05	2.96E+06
9.00	1.521E+05	1.52E+05	4.46E+06
10.00	1.656E+05	1.66E+05	6.30E+06

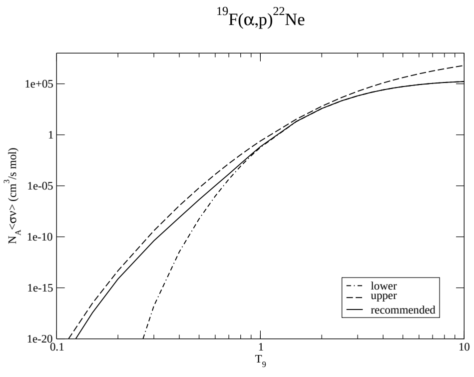

Fig. 3. The reaction rate and uncertainties for $^{19}F(\alpha,p)^{22}Ne$

reactions. We found that for temperatures relevant to helium flashes in AGB stars the $^{14}C(\alpha,\gamma)^{18}O$ reaction rate is close to one order of magnitude lower than the NETGEN rate. The rate for the $^{18}O(\alpha,\gamma)^{22}Ne$ reaction is in very good agreement with the rate from NACRE, while the rate for $^{19}F(\alpha,p)^{22}Ne$ is one order of magnitude smaller than those obtained from Hauser-Feshbach calculations.

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