The Nucleosynthesis and Reaction Rates of Fluorine 19 ($^{19}F$) in the Sun

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Abstract. We investigate the abundance of $^{19}F$ in the Sun through the nucleosynthesis scenario. In addition, we calculate the rate equations and reaction rates of the nucleosynthesis of $^{19}F$ at different temperature scale. Other important functions of this nucleosynthesis (nuclear partition function and statistical equilibrium conditions) are also obtained. The resulting stability of $^{19}F$ occurs at nucleus with $A = 19$ and Mass Excess= -1.4874 MeV. As a result, this will tend to a series of neutron captures and beta-decay until $^{19}F$ is produced. The reaction rate of $^{15}N$ ($\alpha$, $\gamma$) $^{19}F$ was dominated by the contribution of three low-energy resonances, which enhanced the final $^{19}F$ abundance in the envelope.

1. Introduction

The Fluorine abundances is playing a crucial role in the hotly debated nucleosynthesis scenarios in stellar populations. However, the Fluorine ($^{19}F$) is considered to be the only stable isotope of the fluorine element in the Sun. In addition, it is very sensitive to the physical conditions within stars in general, where the least abundant of stable nuclides in the 12-32 atomic mass range (1). Despite its importance, a detailed understanding of observational phenomena of fluorine nucleosynthesis (which can occur through the $^{15}N$ ($\alpha$, $\gamma$) $^{19}F$ reaction is still under development and, the reaction rate still retains with large uncertainties due to the lack of experimental studies available. Several possible explanations were offered by many researchers to explain its production (2).

There are several astronomical cites that contain extremely hot gases, in order to let the $^{19}F$ production be detected there, such as supernovae Type II (3; 4), WolfRayet stars (5), and within the interiors of Asymptotic Giant Branch (AGB) stars during helium flashes (6; 7).
However, available data from the Joint Institute for Nuclear Astrophysics (JINA) provides databases of nuclear data and reaction rates. We study the nuclear masses and nuclear partition functions to compute nuclear statistical equilibria which is a free energy minimum state with some number of constraints, and then to compute the reaction rates of $^{19}F$. The aim of this work is to study the process responsible for fluorine nucleosynthesis and their reaction rates, which may help us into understanding its origin in the Sun via H- and He-burning sequences. A quantitative comparison of observations with this process will lead the results from more detailed chemical evolution models incorporating the yields from very hot stellar interior.

Deriving the light element fluorine abundances are focused on using the HF line at $23358\;\text{Å}$ (8, and references therein). At this crowded/blended (CO lines) region, the detection of $^{19}F$ becomes harder. Moreover, $^{19}F$ has very fragile nuclide, which can be easily destroyed by the most abundant species in stellar interiors (proton or $\alpha$). Thus, the production site(s) of this element has been widely debated in literature (9; 10; 11; 12; 13; 14; 15). Jorissen et al (6) reported the leading work in this field, by presenting the first $^{19}F$ abundances of 49 K giants. A new scenario for $^{19}F$ production after $\sim 1\;\text{Gyr}$ was suggested by Renda et al (11), this model treated AGB stars as the major contributors of $^{19}F$ production; moreover SNe II considered as the only contributor to the $^{19}F$ abundance in the early universe. To solve the discrepancy between the theoretical and observed $^{19}F$ abundance in Galactic giants, recently, Kobayashi et al (15) adopts the yields of AGB stars and the $\nu$-process yields. This model expects fluorine-to-iron plateau at low metallicities, relying on the neutrino luminosities. However, considering $\nu$-process yields enhanced $^{19}F$ production, and served us to fit the high observed abundances in very hot stellar populations.

2. NUCLEOSYNTHESIS OF $^{19}F$

The synthesis of $^{19}F$ can be produced by consisting of a CNO H-burning sequence. A series of proton captures and beta-decays, initiated on $^{14}N$, leads to a finite abundance of $^{19}F$, with $^{19}F(p,\alpha)^{16}O$ being the destructive reaction through the reaction chain

$$^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\gamma)^{16}O(p,\gamma)^{17}F,\;^{17}F(\beta^+)^{17}O(p,\gamma)^{18}F(\beta^+)^{18}O(p,\gamma)^{19}F(p,\alpha)^{16}O.$$  

The adopted $^{19}F(p,\alpha)^{16}O$ rate is the geometrical mean of the lower and upper limits to that rate proposed by (16). Fluorine can also be produced and destroyed during He-burning through the chains (17).

$$^{14}N(\alpha,\gamma)^{18}F \xrightarrow{(\beta^+)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F} (n,p)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F(p,\alpha)^{22}Ne$$

As a result, the synthesis of $^{19}F$ thus requires the availability of neutrons and protons. They are mainly produced by the reactions $^{13}C(\alpha,n)^{16}O$ and $^{14}N(n,p)^{14}C$.

3. Computational Tool

We used nucnet tools to explore the abundance of $^{19}F$ in the Sun. This code was built by the Astronomy and Astrophysics group at Clemson University, South Carolina, USA 1.

The Joint Institute for Nuclear Astrophysics (JINA) provides databases of nuclear data and reaction rates. We were focused on the Snapshots, in order to study the nuclear masses and reaction rates. We used sourceforge.net/p/nucnet-tools/home/Home/
nuclear partition functions. It was also used to compute nuclear statistical equilibria and finally to compute the reaction rates of $^{19}F$.

### 4. Results and discussion

#### 4.1. Nuclear Masses

Here, the stability of $^{19}F$ can be studied by the mass excess (See figure 1), the expected parabola shape of the mass distribution for a given set of isobars suggest that nucleus with $A = 19$ will tend to beta decay until the $^{19}F$ produced.

Our calculation shows that if the nucleus ($A = 19$) has $Z < 9$, it will turn some of its neutrons into protons by $\beta^-$ decay until $Z = 9$. On the other hand, if $Z > 9$ it will turn protons into neutrons by $\beta^+$ decay until $Z = 9$.

#### 4.2. The Nuclear Partition Function

(i) We have considered the $^{13}C(\alpha,n)^{16}O$ reaction, by adopting the rate from (18) and (19), which is about 50% lower than the rate recommended by NACRE in the temperature range of interest. 

(ii) The reaction $^{14}C(\alpha,\gamma)^{18}O$ has been studied experimentally in the energy range of 1.13-2.33 MeV near the neutron threshold in the compound nucleus $^{18}O$ by (20). The reaction rate is dominated at higher temperatures by the direct capture and the single strong $4^+$ resonance at center-of-mass energy $E_{cm} = 0.89 MeV$ toward lower temperatures. As a result, the contributions may come from the $3^-$ resonance at $E_{cm} = 0.176 MeV E_x = 6.404 MeV$ and a $1_-$ subthreshold state at $E_x = 6.198 MeV$, which are important for He shell burning in AGB stars. It has been shown in detailed cluster model simulations that neither one of the two levels is characterized by a pronounced $\alpha$ cluster structure(21). The strengths of these two contributions are unknown and have been estimated by (22).

The $^{14}C(\alpha,\gamma)^{18}O$ reaction can be activated together with $^{13}C(\alpha,n)^{16}O$ reaction during the interpulse period. This could be happened in both the partial mixing zone and the deepest layer of the region composed by H-burning ashes, when $^{14}N(n,p)^{14}C$ occurs. This represents the main path to the production of $^{18}O$ and subsequently $^{15}N$. The importance of the nucleosynthesis of $^{15}N$ during the interpulse periods is very much governed by the choice of the rate of the $^{14}C(\alpha,\gamma)^{18}O$ reaction. The closer, or higher, this rate is to that of the $^{13}C(\alpha,n)^{16}O$ 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 magnitude lower than our standard rate from (23).

| Index | Z | A | Name | Mass Excess (MeV) | Spin | Data Source |
|-------|---|---|------|------------------|------|-------------|
| 0     | 5 | 19| $^{19}B$ | 59.3640          | 3/2  | reac1       |
| 1     | 6 | 19| $^{19}C$ | 32.4207          | 3/2  | reac1       |
| 2     | 7 | 19| $^{19}N$ | 15.8621          | 1/2  | reac1       |
| 3     | 8 | 19| $^{19}O$ | 3.3349           | 5/2  | reac1       |
| 4     | 9 | 19| $^{19}F$ | -1.4874          | 1/2  | reac1       |
| 5     | 10| 19| $^{19}Ne$ | 1.7514           | 1/2  | reac1       |
| 6     | 11| 19| $^{19}Na$ | 12.9268          | 3/2  | reac1       |
| 7     | 12| 19| $^{19}Mg$ | 33.0401          | 1/2  | reac1       |

Table 1. Nuclides with $A = 19$, the collection has 8 species.
(iii) The low-energy resonances in $^{14}N(\alpha, \gamma)^{18}F$ have recently successfully been measured by (24). Previous uncertainties about the strengths of these low-energy resonances were removed. Because of these results, the reaction rate is reduced by about a factor of 3 compared to NACRE. The $^{14}N(\alpha, \gamma)^{18}F$ reaction is inefficient at the temperature of neutron release in the partial mixing zone while it is activated in the convective pulse. Hence, its rate only affects the production of $^{19}F$ in the pulse. Using the new rate by (24) with respect to the rate by (25)

(iv) The reaction rate of $^{15}N(\alpha, \gamma)^{19}F$ was taken from NACRE. The rate is dominated by the contribution of three low-energy resonances. The resonance strengths are based on the analysis (10). It should be noted, however, that there were several recent experimental studies that point toward a significantly higher reaction rate. (26) already suggested higher resonance strengths than given in their earlier paper. The final $^{19}F$ abundance in the envelope increased by a few percent only. This is because the temperature in the thermal pulses is high enough that in any case all $^{15}N$ is transformed in $^{19}F$ as shown in Figure 2

(v) The $^{15}N(p, \alpha)^{14}C$ reaction has been investigated by (27), and more recently by (28) at $E_p(\text{lab}) = 78 - 810$ Kev.

(vi) The $^{18}O(\alpha, \gamma)^{22}Ne$ reaction is of interest for the discussion of $^{19}F$ production in AGB stars since it competes with the $^{18}O(p, \alpha)^{15}N$ process. A strong rate might lead to a reduction in $^{19}F$ production. The reaction rate of $^{18}O(\alpha, \gamma)^{22}Ne$ (29). The main uncertainties result

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**Figure 1.** Beta valley stability for $A = 19$ nuclides
(vii) The reaction $^{18}O(p,\alpha)^{15}N$ provides a major link for the production process of $^{19}F$. The reaction cross section has been measured by (32) down to energies of $\approx 70$ KeV. Possible contributions of low energy near threshold resonances were determined by (9) and (33) using direct capture and single-particle transfer reaction techniques.

(viii) 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 at AGB stars. However, 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 $E_{\alpha} = 1.3$ MeV (34). CF88 suggested a rate that is based on a simple barrier penetration model previously used by (35). This reaction rate is in reasonable agreement with more recent Hauser-Feshbach estimates assuming a high level density see also (36) and has therefore been used in most of the previous nucleosynthesis simulations (See Figure 3).

References for $\alpha$ and neutron captures that we have used in this paper are presented in Tables 2 and 3 respectively. All of the reactions not listed in the tables are taken from the REACLIB Data Tables.
Figure 3. Reaction rate of $^{19}F(^4He, p)^{22}Ne$

Table 2. $\alpha$-Capture

| Reaction | References |
|----------|------------|
| $^{13}C(\alpha, n)^{16}O$ | (18), (19) |
| $^{14}C(\alpha, \gamma)^{18}O$ | (23) |
| $^{15}N(\alpha, \gamma)^{19}F$ | (10) |
| $^{17}O(\alpha, n)^{20}Ne$ | (19) |
| $^{18}O(\alpha, \gamma)^{22}Ne$ | (29), (30) |
| $^{18}O(\alpha, n)^{21}Ne$ | (19) |

Table 3. Neutron Capture

| Reactions | References |
|-----------|------------|
| $^{12}C(n, \gamma)^{13}C$ | (37) |
| $^{13}C(n, \gamma)^{14}C$ | (16) |
| $^{14}N(n, p)^{14}C$ | (38) |
| $^{16}O(n, \gamma)^{17}O$ | (39) |
| $^{18}O(n, \gamma)^{19}O$ | (40) |
5. Conclusion
We studied the nuclear masses, nuclear statistical equilibria, and nuclear partition functions of the $^{19}F$ in the Sun. In this work, we have concentrated more on the study and interpretation of the evolution of the $^{19}F$ by utilizing the entire observational data of the solar system. Our results are in good agreement with other recent $F$ abundance determinations.

Our conclusions confirmed the stability of $^{19}F$, with atomic mass number, $A= 19$, atomic number, $Z= 9$ and Mass Excess, $\Delta= -1.4874$ MeV. This will lead to some characteristic of “valley of beta stability” (see Fig. 1). One can relate this stability due to the $^{19}F$ has the minimum mass excess. This feature will be scaled by the same factor of $m_U c^2 A$. More detailed theoretical studies are required to explain this behavior.

During the course of this study, we found that the reaction rate of $^{15}N(\alpha, \gamma)^{19}F$ was dominated by the contribution of three low-energy resonances, which enhanced the final $^{19}F$ abundance in the envelope. In addition, we found that $^{56}Ni$ has the most of the mass during to nuclear statistical equilibrium, because the $^{56}Ni$ species has the largest binding energy per nucleon.

It is noteworthy to mention here that, despite the lack of data, we limited the $^{19}F(\alpha, p)^{22}Ne$ reaction, to higher energy range above $E_\alpha = 1.3$ MeV, to achieve better agreement with Hauser-Feshbach (36).

More details and results on nuclear statistical equilibrium and the expansion time are required to control the dynamical calculations and characteristics.

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