PROCEEDINGS OF SCIENCE

PoS(NIC XII)161

^{19}F production in stars: toward an experimental study of key reactions ^{14,15}N$(\alpha,\gamma)^{18,19}$F

A. Di Leva[*ab], **G. Imbriani**[ab],**C. Abia**[c], **S. Cristallo**[e], **N. De Cesare**[eb], **I. Dominguez**[c], **A. D'Onofrio**[eb], **L. Gialanella**[eb], **M. Romano**[ab], **M. Romoli**[b], **A. Pezzella**[ab], **L. Piersanti**[d], **D. Schürmann**[ab], **O. Straniero**[c], **F. Terrasi**[eb]
[a]*Università degli Studi di Napoli Federico II*
Naples, Italy
[b]*INFN Sezione di Napoli*
Naples, Italy
[c] *Dpto. Física Teórica y del Cosmos, Universidad de Granada*
Granada, Spain
[d] *INAF-Osservatorio di Collurania*
Teramo, Italy
[e]*Seconda Universitá di Napoli*
Caserta, Italy
E-mail: `antonino.dileva@unina.it`

The origin of fluorine is a longstanding problem in nuclear astrophysics. There are three promising astrophysical sites where ^{19}F, the only stable fluorine isotope, can be synthesized: Type II Supernovae, Wolf Rayet stars, and Asymptotic Giant Branch stars. To determine the contribution of WR and AGB stars, models are mandatory. Fundamental ingredients for these models are the nuclear reaction rates invoved in the fluorine production. Aim of the present work is to improve the experimental knowledge of the ^{14}N$(\alpha,\gamma)^{18}$F and ^{15}N$(\alpha,\gamma)^{19}$F cross section by using the ERNA recoil separator recently installed at the CIRCE laboratory of Caserta (Italy).

XII International Symposium on Nuclei in the Cosmos,
August 5-12, 2012
Cairns, Australia

---

[*] Speaker.

1. Introduction

The origin of ^{19}F, the only stable isotope of fluorine, is a longstanding problem in nuclear astrophysics. Three promising sites have been proposed [1]:

1. Type II Supernovae [2, 3];
2. He-burning regions of Wolf Rayet stars [4];
3. Asymptotic Giant Branch (AGB) stars [5, 6, 7].

In type II supernovae the fluorine production proceeds via spallation of ^{20}Ne by μ and τ neutrinos, in the other two cases it involves a complex network of thermonuclear reactions, namely: $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$.

Protons are required in the He-burning region to activate the $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$, and for this reason the $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ reaction should be active. This requires the production of neutrons. Currently, only for low mass AGB stars there exist direct observational evidences of an in-situ Fluorine production [8, 9, 10, 11]. In this case the main neutron source is the $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction.

In this work we present the experimental setup and the preparation of a new determination of the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}$ and $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ cross sections, using the European Recoil Separator for Nuclear Astrophysics (ERNA) [12], recently moved at the CIRCE laboratory of the CRdC INNOVA [13] (Caserta, Italy).

2. Status of the knowledge of the $^{14,15}\mathrm{N}(\alpha,\gamma)^{18,19}\mathrm{F}$ cross sections

The rate of the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}$ reaction (Q=4.415 MeV), for temperatures of astrophysical interest T between 0.1 GK and 0.5 GK (see figure 1), is dominated by the contribution of a $J^\pi = 1^-$ resonance at $E_\mathrm{cm} = 445$ keV. At higher temperatures the contributions of the resonances $E_\mathrm{cm} = 883, 1088, 1189$ and 1258 keV become more important. Below 0.1 GK additional contributions

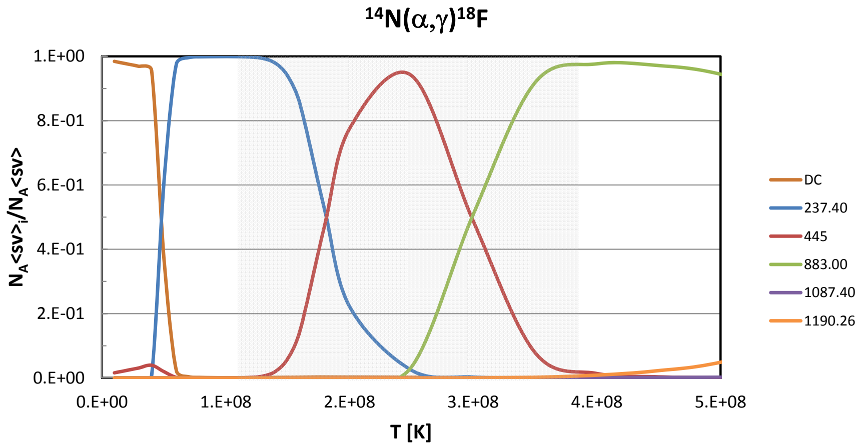

Figure 1: Ratio of individual reaction rate contributions from different resonances and total recommended value. The grey shaded area represents the relevant AGB temperature.

are possible from the low-energy tail of the 445 keV resonance, the direct capture (DC), and the $J^{\pi} = 4^{+}$ resonance at 237 keV. The lowest directly measured resonance is the one at 445 keV, which was measured together with the resonance at 1136 keV using thick solid TiN target and direct kinematics [14]. The strength of the $E_{\rm cm} = 237$ keV resonance has never been measured, it is argued [14] that it is extremely small $\omega\gamma \sim 1.5 \cdot 10^{-18}$ keV. Moreover, it is worth to measure DC component, since up to now it is only estimated through theory. DC is supposed to be $\sim 0.7 - 0.8$ keV b, as calculated from spectroscopic factors using some crude approximations, see comments in Iliadis et al. reaction rate compilation [15].

The rate of the ^{15}N$(\alpha,\gamma)^{19}$F reaction (Q=4.014 MeV) is dominated by resonance contributions of several low-lying states in ^{19}F. In a previous work all the resonances in the energy window from 0.6 MeV to 2.7 MeV have been studied [16], but at astrophysical energy contributions from the lower energy resonances, 364, 536 and 542 keV, are important, see figure 2. The strength of the 364 keV resonance, which directly influence the reaction rate at the relevant astrophysical temperature, has been measured indirectly [17] using the ^{15}N$(^{7}$Li$,p)^{19}$F reaction at 28 MeV, with an uncertainty in the order of a factor 2.

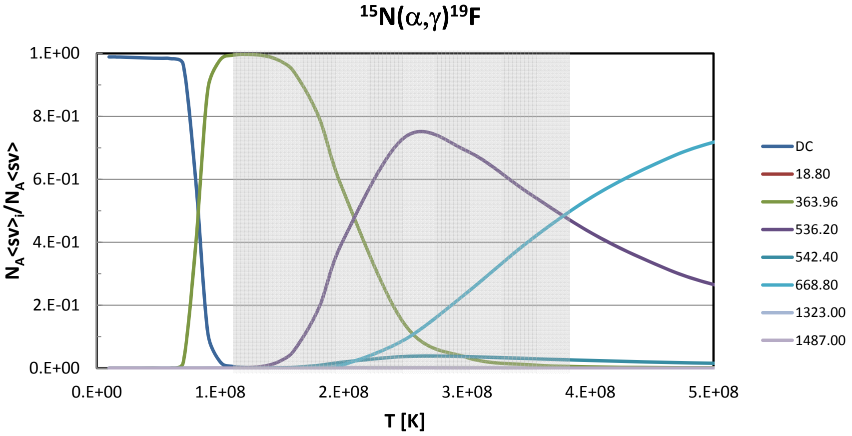

Figure 2: Ratio of individual reaction rate contributions from different resonances and total recommended value. The grey shaded area represents the relevant AGB temperature.

3. Measurement of ^{14,15}N$(\alpha,\gamma)^{18,19}$F cross sections with ERNA

The study of nuclear reaction cross sections in inverse kinematics is particularly important in the field of nuclear astrophysics with Recoil Mass Separators (RMS) [18, and references therein]. ^{14}N$(\alpha,\gamma)^{18}$F and ^{15}N$(\alpha,\gamma)^{19}$F can be studied with the RMS method with the ERNA recoil separator, [12, and references therein]. The maximum angle for the F recoils emerging from the target is determined by the reaction kinematics. Also additional straggling due to interaction with the target and post-stripper gases has to be taken into account. For both reactions to be studied the maximum angle should not exceed the maximum angular acceptance of ERNA, that means that 100% of the recoils, in a selected charge state, can be collected in the end detector.

Generally, the cross sections measured in nuclear astrophysics are very small and, therefore, it is very important to use intense ion beams, of the order of at least several μA. For the measurement of the cross section of ^{14,15}N$(\alpha,\gamma)^{18,19}$F at astrophysical relevant energies a nitrogen beam intensity on target of 5 to 10 pμA is desired.

Nitrogen ion beam generation with a source of negative ions by cesium sputtering (SNICS), with intensities of several μA, suffers difficulties connected with its own electron negativity, which hampers the formation of a stable negative ion. We investigated alternative materials to be sputtered in order to produce a more intense N beam [19]. We found that from three of the investigated compounds it is possible to obtain a more intense N beam with respect to the widely used boron nitrate mixed with graphite (BN+C). In particular, using ferricyanide we got an analyzed N beam having about double current intensity. Also thiocynide and azide have better performances than BN. Furthermore these materials are particularly interesting for the production of ^{15}N beam, since they are easily accessible in ^{15}N enriched forms.

As regards ^{14}N$(\alpha,\gamma)^{18}$F, we plan to measure the strength of the resonances down to 445 keV, see table 1. Unfortunately the $E_{\mathrm{cm}} = 237$ keV due to the extremely small $\omega\gamma$ would make $4 \cdot 10^{-7}$ recoils/day/μA, far below the ERNA measurement possibilities. The direct capture component can be measured at higher energies, in fact the recoils production rate at $E_{\mathrm{cm}} = 1.5$ MeV is calculated to be ~ 70 recoils/day/μA .

E_{CM} [keV]	237^1	445	535^1	883	1088
$\omega\gamma$[keV]	$1.48{\cdot}10^{-18}$	$(4.6\pm0.3)\cdot10^{-8}$	$1.0\cdot10^{-9}$	$(2.1\pm0.3)\cdot10^{-5}$	$(7\pm1)\cdot10^{-6}$
recoils/day/μA	$4\cdot10^{-7}$	$5\cdot10^{3}$	$8.7\cdot10^{1}$	$1.0\cdot10^{6}$	$2.8\cdot10^{5}$

1) Upper limit.

Table 1: Strength of the resonances of astrophysical interest in^{14}N$(\alpha,\gamma)^{18}$F and expected recoils production rate.

As regards ^{15}N$(\alpha,\gamma)^{19}$F, thanks to the improvements in the intensity of N beam we plan to directly measure with ERNA the strength of the 364 keV resonance, see table 2. Being the first direct determination of the resonance strength this measurement is of great importance, even if it will have limited counting statistics it is still a big improvement with respect to present situation.

E_{CM} [keV]	363.9^1	536.1	542.3	668	1091.2
$\omega\gamma$[keV]	$6.0\cdot10^{-12}$	$(9.5\pm1.2)\cdot10^{-8}$	$(6.4\pm2.5)\cdot10^{-9}$	$(5.6\pm0.6)\cdot10^{-6}$	$(9.7\pm1.6)\cdot10^{-6}$
recoils/day/μA	1	$8.5\cdot10^{3}$	$5.6\cdot10^{2}$	$3.8\cdot10^{5}$	$3.9\cdot10^{5}$

1) Upper limit.

Table 2: Strength of the resonances of astrophysical interest in ^{15}N$(\alpha,\gamma)^{19}$F and expected recoils production rate.

The measurement will start soon, accordingly with the ERNA program, which is started this year at CIRCE laboratory with the measurement of ^{7}Be$(p,\gamma)^{8}$B.
This work is part of a larger project devoted to a better understanding of the fluorine origin. The project plan includes the described experimental investigations as well as a theoretical study, based on the revised reaction rates, to obtain more reliable stellar nucleosynthesis models.

Acknowledgments

This work is supported by the MIUR under the grant FIRB RBFR08549F.

References

[1] A. Renda *et al.*, *On the origin of fluorine in the Milky Way*, MNRAS,**354**(1992)575

[2] S.E. Woosley and W.C. Haxton, *Supernova neutrinos, neutral currents and the origin of fluorine* Nature **334** (1988)45

[3] C. Kobayashi, et al. *Evolution of fluorine in the Galaxy with* ν*-process* ApJL **739** (2011)57

[4] G. Meynet and M. Arnould *Synthesis of F-19 in Wolf-Rayet stars* A&A **335** (2000)176

[5] M. Forestini *et al.*, *Fluorine production in thermal pulses on the asymptotic giant branch* A&A **261** (1992)157

[6] M. Lugaro *et al.*, *Reaction Rate Uncertainties and the Production of* ^{19}F *in Asymptotic Giant Branch Stars* ApJ **615** (2004)934

[7] S. Cristallo *et al.*, *Evolution, nucleosynthesis, and yields of low-mass asymptotic giant branch stars at different metallicities* ApJ **696** (2009)797

[8] A. Jorissen, V.V. Smith and D.L. Lambert, *Fluorine in red giant stars - Evidence for nucleosynthesis*, A&A **261**(1992)164

[9] C. Abia, *et al.*, *Fluorine in Asymptotic Giant Branch Carbon Stars Revisited*, ApJ **694**(2009,)971

[10] C. Abia, *et al.*, *Fluorine Abundances in Galactic Asymptotic Giant Branch Stars*, ApJL, **715**(2010) 94

[11] S. Lucatello *et al.*, *Fluorine and Sodium in C-rich Low-metallicity Stars*, ApJ **729**(2011)40

[12] A. Di Leva *et al.*, *Recoil separator ERNA: Measurement of* ^{3}He$(\alpha,\gamma)^{7}$Be, NIM A **595**(2008)381

[13] F. Terrasi *et al.*, *A new AMS facility in Caserta/Italy*, NIM B **259**(2007)14

[14] J. Görres *et al.*, *Low-energy resonances in* ^{14}N$(\alpha,\gamma)^{18}$F *and their astrophysical implications*, Phys.Rev: C **62**(2000)055801

[15] C. Iliadis *et al.*, *Charged-particle thermonuclear reaction rates: III. Nuclear physics input*, Nucl.Phys. A **841**(2010)251

[16] S. Wilmes *et al.*, *The* ^{15}N$(\alpha,\gamma)^{19}$F *reaction and nucleosynthesis of* ^{19}F, Phys.Rev. C **66**(2002)65802

[17] F. de Oliveira *et al.*, *Determination of* α*-widths in* ^{19}F *relevant to fluorine nucleosynthesis*, Nucl.Phys. A **597**(1996)231

[18] A. Di Leva *et al.*, *Recoil separator ERNA: Measurement of* $^{3}He(\alpha,\gamma)^{7}Be$, Phys. Rev. Lett. **102**(2009)232502 [erratum: Phys.Rev.Lett. 103(2009)159903]

[19] A. Di Leva *et al.*, ^{14,15}N *beam from cyanide compounds*, NIM A **689**(2012)98