Mem. S.A.It. Vol. 78, 486

Memorie della

Fluorine production in AGB stars: the role of the $^{15}N(p,\alpha)^{12}C$ reaction

M. La Cognata[1,2], S. Romano[1,2], C. Spitaleri[1,2], S. Cherubini[1,2], V. Crucillà[1,2], M. Gulino[1,2], L. Lamia[1,2], R.G. Pizzone[1,2], A. Tumino[1,2], R. Tribble[3], L. Trache[3], Changbo Fu[3], V. Goldberg[3], A. Mukhamedzhanov[3], G. Tabacaru[3], and S. Typel[4]

[1] Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria - Università di Catania, Catania, Italy e-mail: `Spitaleri@lns.infn.it`
[2] Laboratori Nazionali del Sud - INFN, Catania, Italy
[3] Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA
[4] GSI, Darmstadt, Germany

Abstract. The low-energy bare-nucleus cross section for $^{15}N(p,\alpha)^{12}C$ is extracted by means of the Trojan-horse Method applied to the $^{2}H(^{15}N,\alpha^{12}C)n$ reaction at E_{beam}=60 MeV. The astrophysical S-factor is deduced and compared to the direct data in the same energy region. A fair agreement with direct data down to 80 keV is found if energy resolution effects are taken into account.

Key words. Stars: abundances – Stars: Asymptotic Giant Branch – Stars: Fluorine Nucleosynthesis – Nuclear Reactions: Astrophysical S-Factor

1. Introduction

An open question in nuclear astrophysics is the ^{19}F abundance in the Milky Way and its production sites. This isotope is synthesized in type II supernovae explosions, in Wolf-Rayet stars and during the AGB phase of stellar evolution (Renda et al. 2004). In particular spectroscopic observations show that in low-mass AGB stars fluorine abundance is enhanced with respect to the solar one (Jorissen et al. 1992). Large efforts has been devoted in understanding ^{19}F nucleosynthesis since fluorine abundance observed in giants can constrain AGB star models (Lugaro et al. 2004). In particular a detailed study of nuclear reaction rates involved in ^{19}F production and destruction can play an important role. A key isotope for ^{19}F production in AGB stars is ^{15}N from which ^{19}F is synthesized via $^{15}N(\alpha,\gamma)^{19}F$ in the intershell region during a thermal pulse (Jorissen et al. 1992). The $^{15}N(p,\alpha)^{12}C$ reaction is then of primary importance since it removes both proton and ^{15}N nuclei from ^{19}F production chain (Lugaro et al. 2004).

The astrophysical S-factor of the $^{15}N(p,\alpha)^{12}C$ reaction has been measured down to 73 keV (Schardt et al. 1952; Zyskind et al. 1979; Redder et al. 1982) and a Breit-Wigner extrapolation has been performed to derive its trend down to zero energy (Redder et

Send offprint requests to: C. Spitaleri al. 1982). This extrapolation has also been employed to calculate the reaction rate (Angulo et al. 1999) to be introduced in astrophysical stellar evolution codes. In general the exponential suppression of the cross section due to the Coulomb barrier in the entrance channel makes the measurement of the low-energy tail of the S-factor very difficult or, sometimes, even impossible. Of course this simple extrapolation does not take into account the presence of subthreshold or low-energy resonances, neither the enhancement of the S-factor due to the presence of atomic electrons. Indeed the electron screening effect introduces at least a 10% increase of the S-factor at 80 keV for the ^{15}N + p system (Assenbaum, Langanke, & Rolfs 1987), which can modify the low energy behaviour of the S-factor.

In order to derive the low-energy bare-nucleus S-factor, which is the parameter of interest for astrophysics, with no need of extrapolation, a number of indirect techniques has been developed, e.g. the Coulomb dissociation (Baur & Rebel 1994), the ANC (asymptotic normalization coefficient) method (Mukhamedzhanov et al. 1997; Mukhamedzhanov & Tribble 1999), and the Trojan-horse method (THM) (Baur 1986; Spitaleri 1990; Cherubini et al. 1996; Typel & Wolter 2000; Typel & Baur 2003). In particular, the THM allows to extract a charged-particle two-body cross section at astrophysical energies free of Coulomb suppression and electron screening enhancement by selecting the quasi-free (QF) contribution to an appropriate three-body reaction performed at energies well above the Coulomb barrier. In the next section the method is briefly discussed while its application to the experimental study of the ^{15}N(p,α)^{12}C reaction is described in subsequent sections.

2. The Method

The THM theory is extensively discussed in many papers (Spitaleri 1990; Cherubini et al. 1996; Typel & Wolter 2000; Typel & Baur 2003). Recently the validity of the method has been discussed by Mukhamedzhanov et al. (2006a,b). Here only the essential details are briefly reviewed.

A reaction $A + a \rightarrow C + c + s$, with nucleus a having a strong $x \oplus s$ cluster structure, can proceed via a number of reaction mechanisms. In THM application the reaction mechanism is selected where the Trojan horse nucleus a breaks up into a nucleus x, acting as the participant to the subreaction $A + x \rightarrow C + c$, and a nucleus s which can be regarded as a spectator. This direct reaction mechanism gives the dominating contribution to the cross section in a restricted region of the three-body phase space when the momentum transfer to the spectator s is small (QF conditions). The QF reaction is well described in the Impulse Approximation. In particular in the Plane-Wave Impulse Approximation (PWIA) the cross section of the three-body reaction can be easily factorized as follows (Jain et al. 1970; Spitaleri et al. 1999):

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF \, |\Phi(\boldsymbol{p}_s)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\text{off}} \quad (1)$$

where KF is a kinematical factor (Spitaleri et al. 2001), $\Phi(\boldsymbol{p}_s)$ is the Fourier transform of the radial wave function $\chi(\boldsymbol{r})$ for the $x - s$ intercluster relative motion, $[(d\sigma/d\Omega)_{c.m.}]^{\text{off}}$ is the off-energy-shell differential cross section for the two-body $A(x,c)C$ reaction at the center of mass energy $E_{c.m.}$. Since $|\Phi(\boldsymbol{p}_s)|^2$ is known from nuclear clustering studies the product $KF \cdot |\Phi(\boldsymbol{p}_s)|^2$ is evaluated via a Montecarlo calculation and therefore $[(d\sigma/d\Omega)_{cm}]^{\text{off}}$ is deduced from a measurement of $d^3\sigma/dE_c d\Omega_c d\Omega_C$.

In the present work the cross section of the ^{15}N(p,α)^{12}C reaction is derived by selecting the QF contribution to the ^{2}H(^{15}N,α^{12}C)n three-body process. Because of the approximations adopted, the absolute value of the two-body cross section cannot be extracted. However, the normalization factor is determined by scaling THM data to the direct ones which are available at energies above the Coulomb barrier. In particular, an improved analysis of the same partial data set as the one reported in La Cognata et al. (2006) is discussed, in which the effect of finite energy resolution is taken into account.

3. The Experiment

The experiment was performed at Texas A&M University Cyclotron Institute. A 60 MeV ^{15}N beam, with a spot size on target of 1 mm and intensities up to 5 enA, was impinging onto a $\sim 100\mu g/cm^2$-thick CD_2 target. A telescope (A) made up of an ionization chamber and a silicon position sensitive detector (PSD A) is used to detect and discriminate carbon nuclei while two silicon PSD's (B, C) are placed on the opposite side with respect to the beam direction, their position being optimized to detect α's from the ^{2}H(^{15}N,α^{12}C)n QF process. The ionization chamber, closed by two 1.5 μm thick Mylar foil windows, was filled with 60 mbar buthane gas.

Before proceeding to the extraction of the cross section and of the astrophysical S-factor of the ^{15}N(p,α)^{12}C reaction two steps are necessary: (i) by investigating the kinematics of the three-body process the ^{2}H(^{15}N,α_0^{12}C)n channel has to be disentangled from other reactions taking place in the same target; (ii) from the study of the three-body reaction dynamics and in particular from the analysis of the correlation between the $\alpha_0 -^{12}$ C coincidence yield and the neutron momentum the presence of the QF mechanism is deduced. Its contribution is then separated from the one of different reaction mechanisms feeding the same exit channel.

3.1. Selection of the ^{2}H(^{15}N,α_0^{12}C)n Channel

In order to single out the contribution of the ^{2}H(^{15}N,α_0^{12}C)n reaction, the one which provides the S-factor relevant for astrophysics (since the α_1 channel shows a much lower cross section than the α_0 channel Rolfs & Rodney 1974), first a number of conditions is imposed to the data set. In detail, coincidences are selected by introducing a window on the Time-to-Amplitude Converter (TAC) parameter and the carbon locus is identified in telescope A. An additional cut is introduced in the $E_{^{12}C}$ vs. E_α 2D spectrum to single out the kinematic locus of the three-body reaction. Finally the $Q-$value spectrum of the three-body process is deduced through energy conservation (see Figure 1). Two peaks show up, corresponding to the ^{2}H(^{15}N,α_0^{12}C)n channel (the one at higher energy, $Q_{3-body} = 2.74$ MeV) and to the ^{2}H(^{15}N,α_1^{12}C)n channel ($Q_{3-body} = -1.7$ MeV). The absence of additional peaks and the good agreement between the theoretical and experimental $Q-$values make us confident that additional reaction channels have been disentangled from the ^{2}H(^{15}N,α_0^{12}C)n coincidence yield and that an accurate calibration procedure has been performed. Only the events belonging to the high energy peak are retained for further analysis.

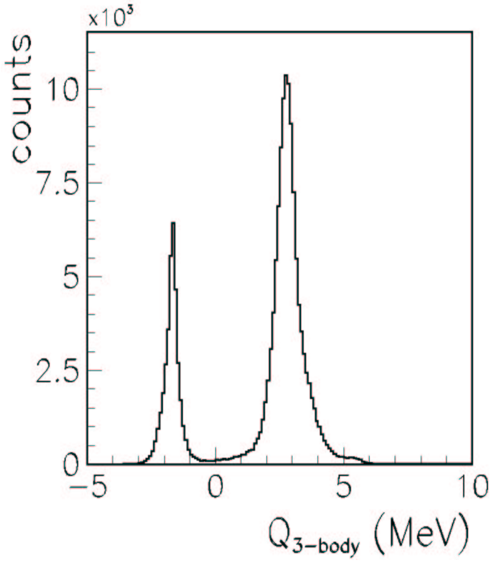

Fig. 1. $Q-$value spectrum for the three-body process.

3.2. Selection of the QF Mechanism

An extensive study of the processes feeding the exit channel is a necessary step in order to disentangle the QF component from other reaction mechanisms. In fact the analysis of the experimental results is often complicated by the presence of other reaction mechanisms yielding the same particles in the final state, e.g. sequential decay (SD) (La Cognata et al. 2005). SD contributions due to the $^{13}C^* \rightarrow {}^{12}C + n$ and $^5He^* \rightarrow {}^4He + n$ decays can be singled out by studying the $E_{\alpha-n}$ vs. $E_{\alpha-^{12}\mathrm{C}}$ and $E_{^{12}\mathrm{C}-n}$ vs. $E_{\alpha-^{12}\mathrm{C}}$ 2D plots and identifying the kinematic loci appearing in the spectra due to the excited levels of such intermediate nuclei (La Cognata et al. 2006). It is found that in the chosen phase space region (within a neutron momentum window $|\boldsymbol{p}_s| < 40$ MeV/c) SD processes give negligible contributions to the coincidence yield in the astrophysically relevant energy region (La Cognata et al. 2006). On the other hand the excited states of the ^{12}C+α system can be formed through a QF reaction mechanism or through a sequential one. The procedure to discriminate the two is more complicated and relies on the study of angular correlation spectra and of the $E_{c.m.}$ spectra as a function of the neutron momentum (La Cognata et al. 2006). An additional test is the comparison of neutron experimental and theoretical momentum distributions inside deuteron. Indeed, if direct break-up occurs, the experimental momentum distribution should resemble the one neutron has inside deuteron, given by the Fourier transform of the intercluster wave function in the PWIA approach. The momentum distribution deduced from the present data set is displayed in Figure 2. The theoretical one, the square of the Hulthén wave function in momentum space, is superimposed to the data (black line in Figure 2). The normalization constant, which is the only adjustable parameter, has been fitted to the experimental distribution. The nice agreement between the two demonstrates that in the $|\boldsymbol{p}_s| < 40$ MeV/c momentum window the QF contribution is dominant thus neutron can be regarded as a spectator to the ^{15}N$(p,\alpha)^{12}$C subreaction.

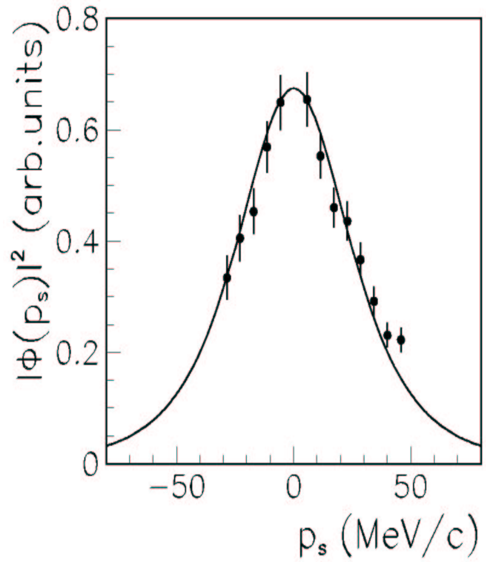

Fig. 2. Experimental neutron momentum distribution (black dots) compared with the theoretical distribution given by the square of the Hulthén wave function in momentum space (solid line).

4. Results and Discussion

Before extracting the $S(E)$−factor for astrophysical application, it is necessary to perform appropriate validity tests on the indirect two-body cross section. Thus angular distributions and excitation function are deduced and compared to the ones in literature (Schardt et al. 1952; Zyskind et al. 1979; Redder et al. 1982). In order to obtain the two-body cross section angular distributions are integrated over the full $\theta_{c.m.}$ angular range and multiplied by the Coulomb penetration function as given e.g. in (La Cognata et al. 2005). An error calculation was performed to derive the uncertainty affecting the relative energy $E_{^{15}\mathrm{N}-p}$ variable, leading to a value of about 40 keV for the AC coincidences. In the calculation energy and angular straggling in the target and in the ΔE detector were taken into account. Normalization to direct data is deduced by equating the areas subtended by the 314 keV peak, due to the 12.44 MeV 1^- ^{16}O excited state, in both data sets. In order to perform a coherent comparison, energy resolution of direct data was reduced to 40 keV too. The results are shown in Figure 3. THM and direct data are displayed as full dots and a full line respectively. A good agreement is apparent in the energy region where direct data are available.

It is worth to stress that the present result differ from the one reported in La Cognata et al. (2006) since the low energy region, $E_{c.m.} <$ 10 keV has been excluded from the analysis. Indeed the S−factor extracted from the three-body coincidence yield in that energy region turns out to be strongly model dependent

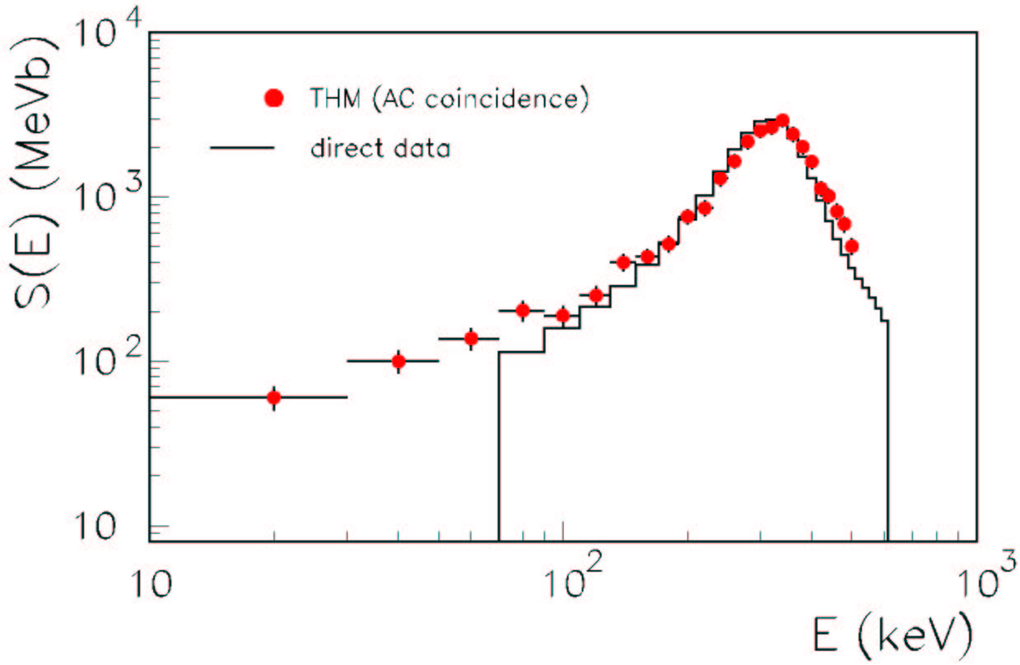

Fig. 3. Comparison between the THM $S-$factor (red dots) and the one deduced from direct data (Schardt et al. 1952; Zyskind et al. 1979; Redder et al. 1982) by reducing their resolution to the THM one (black line).

since its value is substantially influenced by the theoretical approach adopted in data reduction (PWIA or MPWBA). A further theoretical analysis, besides the inclusion of the full data set, is therefore required before providing our best estimate of the $S(0)$ parameter. In addition a technique has to be developed allowing to deduce the THM astrophysical $S(E)-$factor free of finite resolution effects to compare the THM $S(E)$-factor with the actual data in literature. These improvements will be the subjects of a forthcoming paper.

References

Angulo, C., et al. 1999, Nucl. Phys. A, 656, 3
Assenbaum, H.J., Langanke, K., & Rolfs, C. 1987, Z. Phys. A, 327, 461
Baur, G. 1986, Phys. Lett. B, 178, 135
Baur, G. & Rebel, H. 1994, J. Phys. G, 20, 1
Cherubini, S., et al. 1996, ApJ, 457, 855
Jain, M., et al. 1970, Nucl. Phys. A, 153, 49
Jorissen, A., et al. 1992, A&A, 261, 164
La Cognata, M., et al. 2005, Phys. Rev. C, 72, 065802
La Cognata, M., et al. 2006, Eur. Phys. J. A, 27, 249
Lugaro, M., et al. 2004, ApJ, 615, 934
Mukhamedzhanov, A., et al. 1997, Phys. Rev. C, 56, 1302
Mukhamedzhanov, A., & Tribble, R.E. 1999, Phys. Rev. C, 59, 3418
Mukhamedzhanov, A., et al. 2006, nucl-th/0602001
Mukhamedzhanov, A., et al. 2006, Eur. Phys J. A, 27, 205
Redder A., et al. 1982, Z. Phys. A, 305, 325
Renda, A., et al. 2004, MNRAS, 354, 575
Rolfs, C., & Rodney, W.S. 1974, Nucl. Phys. A, 235, 450
Schardt, A., et al. 1952, Phys. Rev., 86, 527
Spitaleri, C. 1990, Problems of Fundamental Modern Physics II, World Scientific, Singapore, 21

Spitaleri, C., et al. 1999, Phys. Rev. C, 60, 055802
Spitaleri, C., et al. 2001, Phys. Rev. C, 63, 055801
Typel, S., & Baur, G. 2003, Ann. Phys., 305, 228
Typel, S., & Wolter H., 2000, Few Body Syst., 29, 7
Zyskind, J.L., et al. 1979, Nucl. Phys. A, 320, 404