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^{19}F spectroscopy and implications for astrophysics

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Abstract. The spectroscopy of ^{19}F is of interest for nuclear astrophysics and nuclear structure. In these proceedings we will focus on the astrophysical implications and on the perspectives of the use of elastic scattering for the investigation of reactions of astrophysical importance. In astrophysics, fluorine and the reactions producing and destroying it play a key role in constraining models of stars in different evolutionary stages, such as the asymptotic giant branch (AGB) stars, responsible of the production of about half of the elements heavier than Fe. Indeed, s-nuclei are produced and brought to the surface thanks to mixing phenomena, together with fluorine that is produced in the same region from the same neutron source. Since the last stage in fluorine nucleosynthesis is the ^{15}N$(\alpha, \gamma)^{19}$F radiative capture, the study of the ^{15}N$+\alpha$ elastic scattering may cast light on the fluorine synthesis. Also, ^{19}F states are responsible of the appearance of resonances in the ^{18}O$(p, \alpha)^{15}$N reaction, leading to the production of ^{15}N, later burnt to ^{19}F in AGB stars through α-captures. Finally, the ^{19}F spectroscopy may help constraining nuclear properties of the radioactive mirror nucleus ^{19}Ne, whose states play a key role in novae modeling through the ^{18}F$(p, \alpha)^{15}$O reaction. In this work, the ^{15}N$-\alpha$ elastic scattering is studied using the thick target inverse kinematics approach, allowing us to span a very large fluorine excitation energy range ($\sim 6-10$ MeV). A R-matrix analysis of the measured differential cross sections was also carried out, making it possible to determine the spin-parity and widths of a number of ^{19}F states, including some previously not reported in the literature.

1. Astrophysical background

^{19}F is a key isotope in astrophysics, as its abundance might be used as a probe of stellar nucleosynthesis, since production and destruction rates are very sensitive to the stellar interior physical conditions (see Ref.[1] and references therein for an updated discussion on fluorine astrophysical relevance). In these proceedings, we mainly discuss two astrophysical environments, namely asymptotic giant branch (AGB) stars and classical novae.

In detail, AGB stars are presently considered a major source of Galactic fluorine, as demonstrated by direct observations in AGB stars [2] and in other environments, such as

planetary nebulae [3] and carbon-enhanced metal-poor stars [4]. In AGB stars, ^{19}F is synthesized through the chain of reactions [5]:

$$^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F} \qquad (1)$$
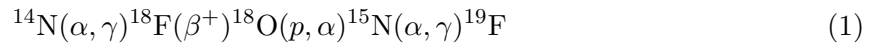
taking place in the intershell region where the s-process occurs as well, fed by neutrons from the ^{13}C$(\alpha,n)^{16}$O reaction. In turn, the ^{14}N$(n,p)^{14}$C reaction releases protons intervening in the fluorine production chain. Therefore, constraining fluorine abundance would make it possible to cast light on the s-process [6]. While recent direct and indirect studies have mainly focused on fluorine destruction by means of p- [7, 1, 8, 9] and α- [10] induced reactions, the latest work covering a broad energy region for the ^{15}N$(\alpha,\gamma)^{19}$F reaction dates back to 2002 [11] (a more recent work, ref.[12], only focuses on two narrow energy region around the 1323 and 1487 keV resonances). Therefore, the spectroscopic investigation of ^{19}F states may help constraining the nuclear properties entering the calculation of the ^{15}N$(\alpha,\gamma)^{19}$F reaction rate, especially because the uncertainty affecting fluorine production rate approaches a factor of 2 at $T \leq 0.2$ GK [11].

^{19}F level scheme also plays a crucial role in another reaction in the chain (1). Indeed, the ^{18}O$(p,\alpha)^{15}$N is a resonant reaction responsible of the production of ^{15}N, proceeding through fluorine excited states. The ^{18}O$(p,\alpha)^{15}$N reaction has been studied recently by means of the Trojan Horse Method (THM) [13, 14, 15, 16] and using direct methods [17]. This latest result shows some interesting features, firstly a new $1/2^-$ state at 8.0996 MeV in ^{19}F was introduced in the analysis; secondly, a number of discrepancies was observed with respect to the old but comprehensive review in Ref.[18]. In particular, Ref.[17] seems to suggest larger α-partial widths in the case of discrepancies. In this context, the study of ^{15}N + α elastic scattering can have very important implications, allowing us to assess the results provided by the most recent measurements. In particular, preliminary calculations tend to also show larger widths, in agreement with Ref.[17] and in disagreement with Ref.[18]. More details can be found in Ref.[27]; as it will discussed later on, more work is still necessary to get more definite results.

A second astrophysical environment where the measurement of the ^{15}N + α elastic scattering can play an important role is classical novae. These are known potential sources of γ radiation as first pointed out by [20, 19], in particular of the early (or prompt) γ-ray emission (511 keV line plus continuum) due to the disintegration of the short-lived, β-unstable isotope ^{18}F (and also of ^{13}N). However, only upper limits on the ^{18}F annihilation line have been derived to date, setting a maximum detectability distance of the 511 keV line equal to about 3 kpc [21]. Such estimates depend critically on an accurate knowledge of the multiple nuclear processes involved in the production and destruction of ^{18}F during nova outbursts, especially on the ^{18}F$(p,\alpha)^{15}$O reaction, that is the main ^{18}F destruction channel and also the most uncertain one. Since ^{19}F is the mirror nucleus of ^{19}Ne, being stable it has been routinely used to constrain states in the latter entering astrophysical considerations through the ^{18}F$(p,\alpha)^{15}$O reaction (see the two most recent works [22, 23] and references therein). Investigating ^{19}F has the advantage of using stable nuclei, making it possible to achieve higher precision and better resolution in the examination of ^{19}F spectroscopy and, using isospin symmetry considerations, ^{19}Ne as well.

2. Method

The ^{15}N$+\alpha$ elastic scattering excitation function was measured by using the Thick Target Inverse Kinematics (TTIK) method [24]. The ^{15}N beam at 40.23 MeV, produced by the Tandem at the Laboratori Nazionali del Sud in Catania (Italy), was sent into the CT2000 scattering chamber filled with helium gas at a pressure of 142 mbar. The gas pressure and the temperature were measured, respectively, by two capacitance manometers, with an accuracy of 0.3%, and with a thermocouple device, with 1 K sensitivity. The chamber was insulated from the beam line by means of a 4.3 μm thick Havar foil window. The detection apparatus consisted of five ΔE-E silicon telescopes used to measure the energy and identify the recoiling alpha particles, placed
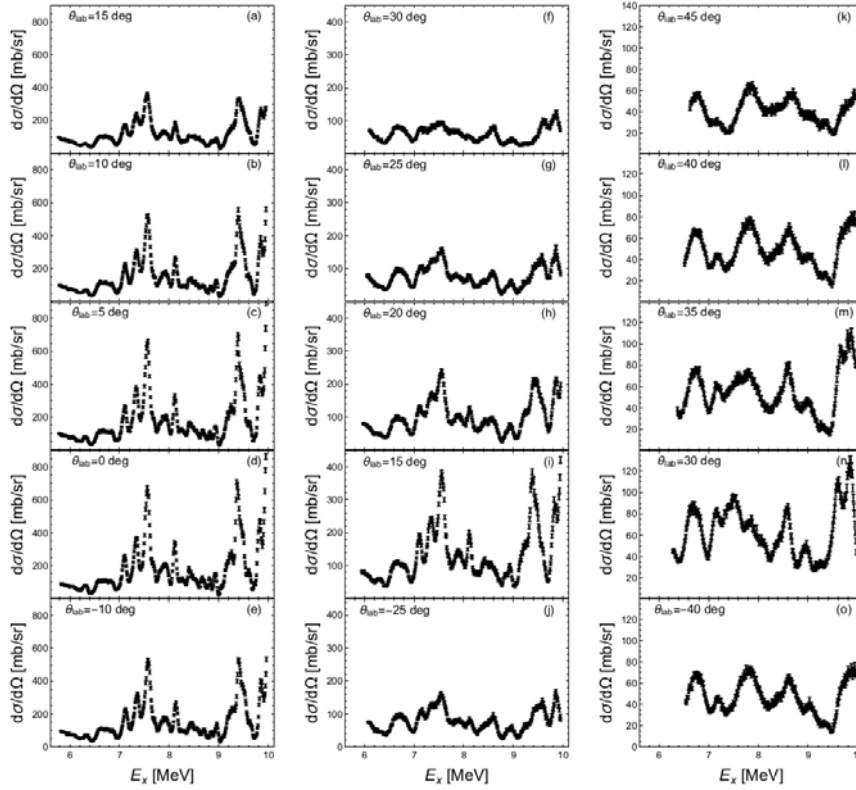
Figure 1. Excitation functions of the ^{15}N + α elastic scattering for different laboratory angles. Cross sections are in the ^{15}N + α c.m. system and expressed in function of the ^{19}F excitation energy E_x. Statistical errors only are reported. The displayed angles (θ_{lab}) are measured with respect to the center of the scattering chamber.

800 ± 2 mm away from the chamber center. Each telescope was made of a 10 μm thick silicon surface barrier detector, with an active area of 50 mm^2, as ΔE stage, and a 500 μm thick SBD to measure the residual energy. Two SBDs, 200 μm thick, were used to measure elastic scattering from a thin Au foil (200 μg/cm^2) placed downstream the Havar foil for normalization purposes. The monitor telescopes were placed at ±60° with respect to the gold foil. While monitor detectors were fixed, telescopes were set at different laboratory angles (with respect to the center of the chamber) to span a variety of c.m. angles.

The excitation functions were reconstructed by considering as first interaction energy of ^{15}N the one after the gold foil (E=28.3 MeV), removing the scattering events before it. Then elastic scattering excitation functions were reconstructed from the energy of the detected α-particles and their impact point on the detector. The first step was the identification of α-particles produced in elastic scattering events. The use of ΔE-E telescopes made it possible to get essentially background free spectra. As a second step, the energy and position of the detected α-particles were related with the c.m. energy and the elastic scattering angle. In this way, for each impact point on the detectors, relations were found between the energy of the detected α-particle and different quantities of interest: the position z of the interaction point along the beam direction, the c.m. energy $E_{c.m.}$, the angles θ_{lab} and $\theta_{c.m.}$, and the solid angle $\Delta\Omega_{lab}$ of the considered detector with respect to the interaction point. Finally, the center of mass differential cross sections $d\sigma/d\Omega_{c.m.}$ was calculated.

3. Results
In Fig.1, the c.m. excitation functions are given, for different angular setting and for each telescope, as a function of the ^{19}F excitation energy. All angles are measured with respect to the scattering chamber center.

We have then run the R-matrix code Azure [25] to simultaneously fit the fig.1 (a)-(e) spectra

and the $^{18}O(p,p)^{18}O$ elastic scattering data at $\theta_{c.m.} = 140.8°$ [26], taking into account the effect of energy resolution. The results are discussed at length in Ref.[27], here we will address only the main features.

Except in the critical region between 8.5 and 9 MeV, the overall agreement is fairly good, as it is apparent from the reduced $\tilde{\chi}^2$ mentioned in Ref.[27]. This was obtained by modifying the spin-parity assignment of the 7.364 MeV ^{19}F state. By setting $J^\pi = 5/2^+$ (as in Ref.[28]) in the place of $1/2^+$, we got a very nice reproduction of the state with total width $\Gamma = 100$ keV. The accuracy of such assignment is confirmed by the angular dependence of the cross section around a ^{19}F excitation energy of about 7.3 MeV. Experimental data cover $0 - 15°$ in the laboratory and $159 - 180°$ in the center-of-mass frame, a region very sensitive to the contributing angular momenta.

At higher excitation energies, around $E_x = 9.4$ MeV, a good fitting of the experimental data was achieved introducing in the analysis a novel state at 9.374 MeV, $J^\pi = 13/2^+$, $\Gamma_\alpha = 20$ keV and negligible p−width ($\Gamma_p = 7 \times 10^{-8}$ keV). Also, the spin-parity of the adjacent level at 9.509 MeV had to be fixed to reach good agreement with the experimental spectra. Of the two values for spin and parity suggested in the literature [18], $J^\pi = 5/2^+$ and $7/2^+$, we considered $J^\pi = 5/2^+$ since it led to a better fit. Also in this case the possibility to span the $165° - 180°$ center-of-mass angular range helped to single out the most likely J^π assignment.

4. Outlook

At larger angles in the laboratory frame (see Fig.1, panels (f)-(o)), energy resolution progressively washes out the contribution of the individual levels, and were not used in the data fitting at this stage. Yet, the analysis of the complete angular range is very important to better constrain spin and parities of the contributing states, so it is presently ongoing. A special mention deserves the fitting of the $E_{c.m.} = 4.4 - 5$ MeV energy interval, corresponding to ^{19}F excitation energies in the range $8.4 - 9$ MeV. The fitting of this energy region is still not satisfactory, though it is close to the p-emission threshold and so it has a particular importance for astrophysics. More work is therefore necessary on the ^{19}F spectroscopy in this energy interval, especially in view of the astrophysical applications.

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