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Direct measurement of the ^{18}F(p,α)^{15}O reaction for application to nova γ-ray emission

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The ^{18}F nucleus is one of the radioactive isotopes produced during nova explosions. It is of particular interest since it is mainly responsible for the 511 keV gamma-ray emission of novae that could be detected with the INTEGRAL satellite or future gamma-ray telescopes. The amount of ^{18}F synthesised still suffers from large uncertainties coming from missing nuclear information concerning the ^{18}F destruction reaction ^{18}F(p,α)^{15}O. In particular, the interference sign between three 3/2$^+$ resonances in ^{19}Ne, situated slightly above the proton threshold (8 keV and/or 38 keV) and at higher energy (665 keV), is unknown. The maximum effect of these interferences is lying in the energy range corresponding to the Gamow peak region and has a strong impact on the ^{18}F(p,α)^{15}O reaction rate. We report here on the direct measurement at low energy (down to 400 keV in the center-of-mass) of the ^{18}F(p,α)^{15}O total cross section that we performed at the Louvain-la-Neuve CRC-RIB facility with the high-intensity and -purity ^{18}F radioactive beam ($T_{1/2}$ = 110 min). The total cross section for the different incident energies will be presented and compared to previous experimental data.

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1. Introduction

Gamma-ray emission from classical novae is dominated during the first hours by positron annihilation following the β^+ decay of radioactive nuclei. The main contribution comes from the decay of ^{18}F (half–life of 110 min) and hence is directly related to ^{18}F formation during the outburst [1, 2, 3]. A good knowledge of the nuclear reaction rates for the production and destruction of ^{18}F is required to calculate the amount of ^{18}F synthesized in novae and the resulting gamma-ray emission at and below 511 keV. In the following, we focus on the ^{18}F destruction through the reaction ^{18}F(p,α)^{15}O whose cross section still remains highly uncertain.

The calculation of the reaction rate of the ^{18}F(p,α)^{15}O reaction involves several resonances in the ^{19}Ne compound nucleus below 1 MeV above the proton threshold. Apart from a 3/2$^-$ resonance (E_r = 330 keV), most of the involved resonances have a 3/2$^+$ spin and parity. One of them is the $E_r = 665$ keV resonance which has been extensively studied in the past [4, 5, 6, 7, 8, 9, 10] and for which the properties (Γ_p, Γ_α, Γ_{tot}) are now well established. Due to its large total width, Γ_{tot} = 40 keV, it is a large contributor to the reaction rate. At much lower energy and close to the proton threshold, the proton width of two 3/2$^+$ resonances (E_r = 8 and 38 keV) have been recently determined through the study of their analog levels in the ^{19}F miror nucleus [11, 12]. Uncertainties in the properties of these two resonances and their impact on the reaction rate has been recently discussed [13]. The most important effect is the interferences between the low-lying and high-energy resonances whose signs are totally unknown and which lies in the Gamow peak region.

We report here on a direct measurement at low energy of the ^{18}F(p,α)^{15}O reaction cross section with the goal of constraining the interference sign of the 3/2$^+$ resonances. Two data points were measured on the top of the $E_r = 665$ keV resonance ("on-resonance") and others two were measured at lower energies ("off-resonance").

2. Experimental method

The experiment was performed at the CYCLONE RIB facility at the *Centre de Recherches du Cyclotron*, UCL, Louvain–la–Neuve, Belgium. We used a high purity 13.8-MeV ^{18}F radioactive beam which was produced using the ISOL technique [14]. ^{18}F was produced in the batch mode and an average of 1.0×10^6 ^{18}F ions per second on target was delivered for a total of 50 hours, representing 17 ^{18}F batches. The beam properties (nominal energy, energy resolution and beam purity) were studied using a 1 cm^2 silicon PIPS detector placed at zero degrees downstream from the target position (see Ref [15]). The ^{18}F beam bombarded a 70 μg/cm^2 polyethylene (CH$_2$) target and the products of the ^{18}F(p,α)^{15}O reaction were detected using two LEDA silicon strip detectors [16]. These detectors are composed of 8 sectors, each divided into 16 radial strips. The energy calibration of the 256 strips was performed with a 3α–source (^{239}Pu, ^{241}Am and ^{244}Cm) whereas the time–of–flight calibration was performed with a precision pulser.

The experimental set–up is shown in Figure 1. The α-particles from the ^{18}F(p,α)^{15}O reaction were detected in the LEDA1 detector positioned 8.5 cm downstream from the target covering laboratory angles between 30.5° and 56.8°. Due to the properties of inverse kinematics, the ^{15}O nuclei are emitted in a forward cone of limiting laboratory angle $\theta = 23°$. Hence the LEDA2 detector was positioned 32 cm downstream from the target covering the laboratory angles between 8.9° and

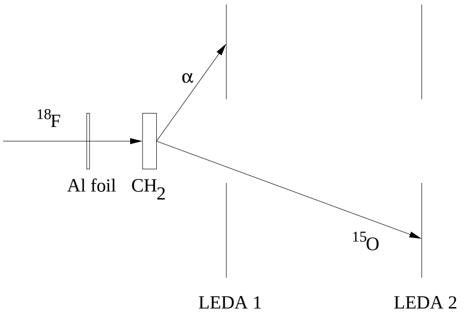

Figure 1: The experimental set–up is shown with ^{18}F ions impinging on a CH$_2$ target after passing through the aluminium degraders. Alpha particles were mainly detected in the first LEDA detector while ^{15}O were detected in coincidence in the second LEDA detector.

22.1°. The positions of the detectors were determined by Monte-Carlo simulations: for the LEDA1 detector, the angular range and detection efficiency were maximized and for the LEDA2 detector, the coincidence efficiency between α–particles and ^{15}O was optimized.

The ^{18}F(p,α)^{15}O cross section was measured at four different energies corresponding to beam energies ranging from 0.77 to 0.48 MeV/u. In order to obtain the four different energies there are in our case two possibilities: either the cyclotron is tuned for each energy, or only one nominal energy is used in conjunction with degraders. In the first solution, the beam properties (spatial and energy resolution) remain similar in all cases, however for the lowest two energies the acceleration efficiency is reduced as compared to the highest two energies leading to a decrease in the beam intensity by at least a factor of two. In the second solution, the beam intensity is the same for each center-of-mass energy, but for the lowest energies the energy and spatial resolution of the beam on target are worse due to the straggling in the degraders. However in the present experiment the energy resolution is not crucial since the cross section is not affected by narrow resonances and since only the number of coincidence events is needed. Hence we used a nominal ^{18}F beam of 13.8 MeV together with aluminium foils of different thickness as degraders before the target position. Home-made (evaporated) aluminium foils of 95, 500 and 670 μg/cm^2 were used, corresponding to ^{18}F energies incident on target of 13.1, 9.9 and 8.6 MeV, respectively. These energies as well as the beam energy profile were measured directly with the zero degree silicon PIPS detector. Comparison of the different beam energies allowed us to check the thickness of the degraders which were found to be within 10% of their nominal values.

Data were collected in event–by–event mode where the multiplicity, the angle, the deposited energy and the time of flight relative to the cyclotron radio–frequency were recorded, allowing an off–line analysis of single and coincidence events.

3. Data Analysis

3.1 Data reduction

"On-resonance" coincidence spectra using the 95 μg/cm^2 aluminium degrader are shown in Figure 2. The coincidence condition between the two LEDA detectors allow us to identify easily the events from the ^{18}F(p,α)^{15}O reaction in the $E_1 \times E_2$ two-dimensional spectrum (Figure 2a). The linear correlation observed between the detected energies in the two LEDA detectors is characteristic of a two–body reaction which after reconstructing its Q–value was identified as the ^{18}F(p,α)^{15}O reaction. The same coincidence events are displayed in a $E \times \theta$ spectrum for LEDA1 and LEDA2 (see Figure 2b and 2c, respectively) where kinematical bands of α-particles and ^{15}O are clearly observed. A full Monte–Carlo simulation of the experimental set–up including energy losses in the degraders and the target as well as the spatial and energy resolution of the beam was performed and a very good agreement with the three spectra of Figure 2 was observed providing high confidence in the identification of the ^{18}F(p,α)^{15}O reaction. An additional check of the reaction identification was performed by verifying that the reaction products were detected in the same reaction plane. Selection of the ^{18}F(p,α)^{15}O events in the $E_1 \times E_2$ spectrum leads to approximatively 1400 and 4100 events for the beam energies of 13.9 and 13.1 MeV, respectively. These events are clearly separated from the coincidence events coming from the ^{18}F + ^{12}C elastic scattering which are found below 2 MeV in LEDA1.

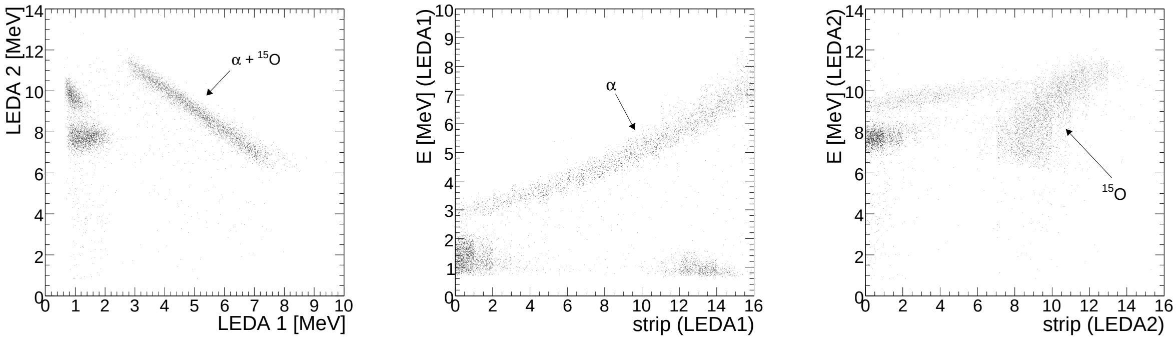

Figure 2: Coincidence spectra $E_1 \times E_2$, $E_1 \times \theta_1$ and $E_2 \times \theta_2$ where 1 and 2 represent the first and second LEDA detector, respectively. The three regions correspond to the α–^{15}O events from the ^{18}F(p,α)^{15}O reaction, and to ^{18}F + ^{12}C events from elastic scattering.

In order to be sensitive to the interference effect of the 3/2^{+} resonances, the ^{18}F(p,α)^{15}O cross section was measured "off-resonance" at two different beam energies (E_{lab} = 9.9 MeV and E_{lab} = 8.6 MeV). In this case the selection of the coincidence events is slightly more difficult since the ^{18}F(p,α)^{15}O cross section is decreasing due to the Coulomb penetrability and the ^{18}F + ^{12}C elastic scattering cross section is increasing due to the lower center-of-mass system energy. Hence the α–^{15}O coincidence events are no longer well separated from the ^{18}F + ^{12}C elastic scattering events in the $E_1 \times E_2$ spectrum. However the kinematical band $E_1 \times \theta_1$ for the α–particles is well separated from other events and an additional selection was performed along this kinematical band. After applying these two simultaneous selections, the α–^{15}O coincidence events were properly selected; 180 and 39 events were obtained at E_{lab} = 9.9 and 8.6 MeV respectively. Background measurements were also run and no coincidence events were observed in the region of interest.

3.2 Cross section

The total cross section in the center-of-mass system was calculated from the observed yield at each energy following the relation

$$\sigma(E) = \frac{1}{IN_p} \sum_s \left(\frac{Y_s(E)}{\Delta\Omega_s \varepsilon_s} \right) \times 4\pi$$

where I is the number of incident ^{18}F ions and N_p the proton content of the target per unit area. The sum is performed over the 16 strips s of the LEDA1 detector where $Y_s(E)$ is the number of α–particles detected in a given strip from the ^{18}F(p,α)^{15}O reaction in coincidence with ^{15}O ions, $\Delta\Omega_s$ is the geometrical solid angle subtended by the strip in the center-of-mass and ε_s is the coincidence efficiency. The coincidence efficiency was determined by Monte–Carlo simulations assuming that the angular distribution in the center-of-mass is isotropic as would be expected from an $\ell = 0$ resonance. The angular distribution obtained from the two data points "on-resonance" supports this assumption and the total cross section is obtained by multiplying by 4π.

The number of incident ^{18}F ions was determined from the ^{18}F + ^{12}C elastic cross section detected in the LEDA2 detector using the strips at 19.4° because they have the maximum solid angle and are not very sensitive to the exact position of the beam on the target. Furthermore, the elastic scattering peaks of ^{18}F and ^{12}C are well separated in a time-of-flight v. energy spectrum. Since the beam intensity is deduced from elastic scattering on the ^{12}C and since the ^{18}F(p,α)^{15}O cross section depends on the hydrogen content of the target, the normalization does not depend on the target thickness but on the target stoichiometry. This quantity was determined from the well known cross section of the ^{1}H(^{18}O,α)^{15}N reaction whose cross section was also measured here. The hydrogen content of the target was monitored during the experiment by checking the ratio of the number of protons and ^{12}C elastically scattered. No hydrogen depletion was observed as it could be expected from the low ^{18}F beam intensity.

The ^{18}F(p,α)^{15}O cross section deduced from the present experiment is shown in Figure 3 as well as the available data from the literature [9, 17]. For the present data, the error bars mainly come from statistical and coincidence efficiency uncertainties. Each data point is represented at a center-of-mass energy corresponding to the beam energy in the middle of the target. Each measurement is an averaged cross section taken over the beam energy loss in the target (i.e. about 50 keV in the center-of-mass). For the data from the lowest two energies this effect was taken into account as an additional vertical error bar which was added quadratically to the previous uncertainties. This effect results in a smaller uncertainty at lower energy since the energy dependence (slope) of the cross section is less important "off-resonance".

4. Preliminary analysis and perspectives

The solid (dashed) lines on Figure 3 represent the results of R-matrix calculations for constructive (destructive) interferences between the $E_r = 665$ keV resonance and the low-lying resonances $E_r = 8$ or 38 keV using adopted parameters from the literature [11, 9]. The target thickness has been taken into account for these calculations. Interferences with two resonances are a simple case but seem a good approximation since previous (d,p) transfer reaction studies [11, 12] showed that only one of the two low-lying resonance is dominating the reaction rate. However one cannot exclude a small contribution from the other resonance and a full R-matrix analysis taking into account interference effects between the three 3/2$^+$ resonances is underway and will be presented

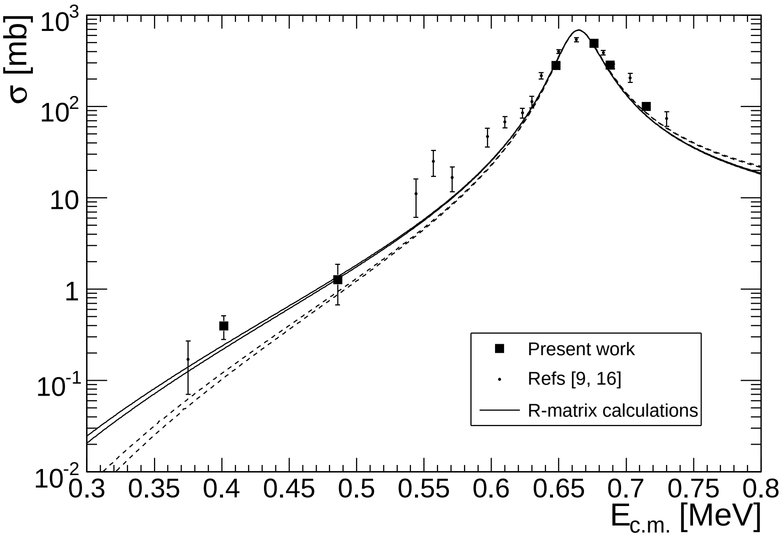

Figure 3: Cross section of the ^{18}F(p,α)^{15}O reaction. The experimental data consists in the present data (full squares) and previous data (dots) for comparison purposes. The solid (dashed) lines are R-matrix calculations for constructive (destructive) interferences (see text for details).

elsewhere [18]. However, as a preliminary result it seems that if only two interfering resonances are considered, the constructive case is favored. The result of this ongoing analysis is expected to reduce significantly the uncertainty associated to the production of ^{18}F in novae events.

Acknowledgments

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