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ANL/PHY/CP--90200
CONF-9606248--1

The Influence of ^{18}F Induced Reactions in the Hot CNO Cycle

K. E. Rehm[a], M. Paul[b], A. D. Roberts[c], C. L. Jiang[a], D. Blumenthal[a], C. N. Davids[a], P. DeCrock[a], S. M. Fischer[a], J. Gehring[a], D. Henderson[a], C. J. Lister[a], J. Nickles[c], J. Nolen[a], R. C. Pardo[a], J. P. Schiffer[a] R. E. Segel[d] and D. Seweryniak[a]

[a]Argonne National Laboratory, Argonne, IL
[b]Hebrew University, Jerusalem
[c]University of Wisconsin, Madison, WI
[d]Northwestern University, Evanston, IL

The contribution of the ^{18}F(p,γ) reaction to the production of ^{19}Ne, which is an important isotope in connection with the breakout from the hot CNO cycle, has been investigated in experiments with ^{18}F beams. Measurements of the cross sections for the ^{18}F(p,α)^{15}O and ^{18}F(p,γ)^{19}Ne reactions indicate that the contribution of the ^{18}F(p,γ) route to the formation of ^{19}Ne is small.

1. INTRODUCTION

The synthesis of heavier elements in explosive nucleosynthesis in a proton-rich environment is believed to proceed through the nuclide ^{19}Ne which is is produced either directly via the ^{15}O(α,γ)^{19}Ne reaction or via the ^{14}O(α,p)^{17}F reaction followed by the sequence ^{17}F(p,γ)^{18}Ne(β^+) ^{18}F(p,γ)^{19}Ne[1]. ^{19}Ne is then the starting point for the rp-process where, in a series of radiative capture reactions followed by β^+ decays, nuclei up to ^{56}Ni and beyond are produced[2]. Since ^{18}F can also be destroyed via the ^{18}F(p,α)^{15}O reaction the 'breakout' from the hot CNO cycle via ^{18}F is controlled by the ratio of the reaction rates R[^{18}F(p,α)]/R[^{18}F(p,γ)]. In a series of experiments using radioactive ^{18}F beams we have therefore studied the astrophysical reaction rates for the (p,α) and the (p,γ) reactions on ^{18}F.

2. EXPERIMENTAL DETAILS

The experiments were performed at the ATLAS accelerator system of Argonne National Laboratory using a two-accelerator method for generating the ^{18}F ion beam. The ^{18}F material ($T_{1/2}$=110 min) was produced at the medical cyclotron of the University of Wisconsin via the ^{18}O(p,n)^{18}F reaction with 11 MeV protons bombarding an enriched [^{18}O] water target. After chemical separations the material was flown to Argonne National Laboratory and installed in the negative ion sputter source of the tandem accelerator which is one of the two injectors of the superconducting linear accelerator ATLAS. A

more detailed description of the production method can be found in Ref. [3].

The tandem accelerator produced ^{18}F ions in their 4^+ state with energies between 11.7-15.1 MeV. For a typical run of 2h the average beam current on target was $\sim 5\times10^5$ ^{18}F/sec. The resulting beam is a mixture of radioactive $^{18}F^{4+}$ and $^{18}O^{4+}$ ions from the production target with the ^{18}O being 500-2000 times more intense than the ^{18}F.

For the (p,α) reaction, particle identification was obtained using the gas-filled magnet method which gives clean mass and Z identification even for particles with energies of about 500 keV/nucleon. Details of this technique are given in Ref. [4]. To improve background suppression the α particles from the p(^{18}F,^{15}O)α reaction were detected in kinematic coincidence with a large area Si detector, mounted at the appropriate scattering angle.

The (p,γ) measurements were performed with the Fragment Mass Analyzer (FMA) [5] which has a high ($\sim$ 30 %) efficiency for radiative capture measurements. In the focal plane of the FMA the incoming particles were identified in a position-sensitive parallel-grid avalanche counter according to their m/q ratio. This detector was followed by a large-volume ionization chamber for Z identification. With this arrangement a suppression ratio of 10^{-12} for (p,γ) reaction products relative to the incident beam has been achieved.

In both experiments thin stretched polypropylene foils ($\sim$ 60-100 μg/cm^2) were used as targets. The detection efficiencies of the two experimental setups were determined by measuring the excitation functions for the ^{18}O-induced reactions p(^{18}O,^{15}N)α and p(^{18}O,^{19}F)γ, respectively.

3. EXPERIMENTAL RESULTS

Figure 1 shows the cross sections for the ^{18}F(p,α)^{15}O reaction measured in the energy region E_{cm}=550-800 keV. The resonance corresponds to a state in ^{19}Ne at an excitation energy E_x= 7.063 MeV. The horizontal bars represent the energy range due to the energy loss in the target. The solid line represents a Lorentzian averaged over an energy range of 55 keV with parameters obtained from a least-squares fit to the energy-averaged yields as described below. The energy range of 55 keV represents an average value for the different target thicknesses used in the experiments. From a comparison of the measured proton width Γ_p with its Wigner limit and the results of (^{3}He,d) measurements[6] populating states in the mirror nucleus ^{19}F, a spin value of $3/2^+$ for this state has been derived[7]. This assignment agrees with the results from a thick target measurement for the ^{18}F(p,α)^{15}O reaction in Ref. [8]. From a least squares fit to the data, values of $\omega\gamma$=2.1$\pm$0.7 keV, Γ_p=5$\pm$1.6 keV, Γ_α=8.6$\pm$2.5 keV, and Γ_t=13.6$\pm$4.6 keV were obtained.

Five runs were carried out with ^{18}F beams to study the ^{18}F(p,γ)^{19}Ne reaction at a bombarding energy of E_{cm}= 670 keV, i.e. slightly above the s-wave resonance found in the

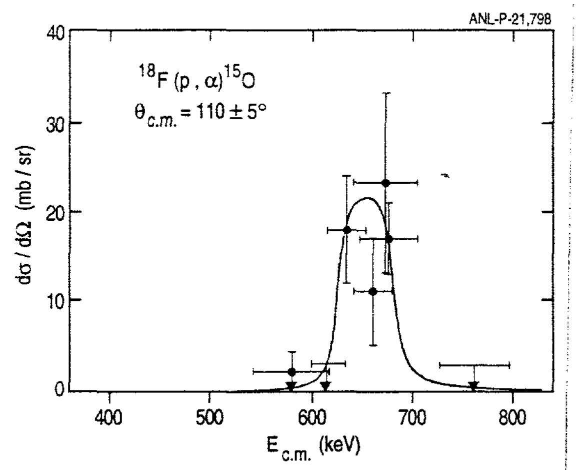

Figure 1. Excitation function for the ^{18}F(p,α)^{15}O reaction. The horizontal error bars represent the various target thicknesses. The solid line represents the cross section from a resonance with parameters given in the text averaged over an energy interval of 55 keV.

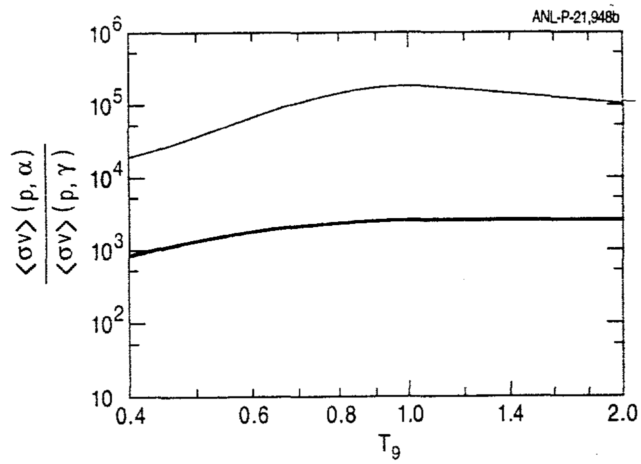

Figure 2. Ratio of the reaction rates between the ^{18}F(p,α)^{15}O and the ^{18}F(p,γ)^{19}Ne reactions. The two solid lines represent the upper and lower limits for this ratio.

^{18}F(p,α)^{15}O reaction. The ^{18}F beam intensity was monitored by collecting elastically scattered ^{18}F particles on a circular aperture which covered the angular range Θ_{lab}=3.6-10°. The β^+ activity of each collimator was measured off-line after each run with a calibrated Ge detector. From the integrated charge associated with the ^{18}F beam (2.8 pnC) and the total detection efficiency of the FMA an upper limit for the ^{18}F(p,γ)^{19}Ne reaction at E_{cm}= 670 keV of 42 μb has been deduced. Assuming the widths for the $3/2^+$ resonance as given above, upper limits for the resonance strength $\omega\gamma$= 740 meV and the gamma width Γ_γ= 3 eV have been calculated.

4. DISCUSSION

As shown in Ref. [9], the $3/2^+$ s-wave resonance in ^{19}Ne has a strong influence on the astrophysical reaction rate for the ^{18}F(p,α) reaction. At temperatures above T_9=0.5 the reaction rate is dominated by the new $3/2^+$ state at 7.063 MeV. Only at temperatures T_9 <0.5 do contributions from other states start to be significant, with the $3/2^-$ level at 6.742 MeV excitation energy being the most important.

From the limit for the resonance strength for the ^{18}F(p,γ)^{19}Ne reaction given above, an upper limit for the astrophysical reaction rate can be calculated which is smaller than the corresponding (p,α) value by at least three orders of magnitude. A lower limit for the reaction rate is provided by the cross section for direct proton capture as calculated in Ref. [10]. The ratio of the reaction rates R[^{18}F(p,α)]/R[^{18}F(p,γ)] which is the controlling factor for the breakout from the hot CNO cycle to the rp-process is plotted in Fig. 2. The two solid lines represent the lower and upper limits for this ratio caused by the limits of the (p,γ) reaction rate mentioned above. Due to the large value of the $^{18}F(p,\alpha)^{15}O$ cross section, the ratio of the reaction rates is larger than $\sim 10^3$ over the whole range of temperatures. This means that for the production of ^{19}Ne the $^{18}F(p,\gamma)$ route is small, and the dominant mechanism for generating this isotope must be the $^{15}O(\alpha,\gamma)$ reaction.

5. SUMMARY

This work provides the first experimental limit for the ratio of the astrophysical reaction rates between the $^{18}F(p,\alpha)^{15}O$ and the $^{18}F(p,\gamma)^{19}Ne$ reactions. The large cross section for the first reaction makes the (p,γ) route a small branch for the production of ^{19}Ne which is more effectively produced via the $^{15}O(\alpha,\gamma)$ reaction. The gas-filled magnet technique allowed a clean mass and Z identification for reaction products with energies below 1 MeV/u. The use of the Fragment Mass Analyzer for the measurement of radiative capture reactions results is a considerable improvement over gamma detection techniques, especially when unstable reaction products have to be detected. Improvements in beam intensity, which should be possible for less chemically reactive unstable isotopes, should allow the use of thinner targets and thus the measurement of excitation functions in finer steps than was done in these first experiments with radioactive ion beams.

This work was supported by the U.S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38 and the National Science Foundation.

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