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Astrophysically important ^{19}Ne states studied with the ^{2}H(^{18}F, $\alpha+^{15}$O)n reaction*

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The nuclear structure of ^{19}Ne near the proton threshold is of interest for understanding the rates of proton-induced reactions on ^{18}F in novae. Analogues for several states in the mirror nucleus ^{19}F have not yet been identified in ^{19}Ne indicating the level structure of ^{19}Ne in this region is incomplete. The ^{18}F$(d,n)^{19}$Ne and ^{18}F$(d,p)^{19}$F reactions have been measured simultaneously at $E_{\text{c.m.}}$ = 14.9 MeV. The experiments were performed at the Holifield Radioactive Ion Beam Facility (HRIBF) of Oak Ridge National Laboratory (ORNL) by bombarding a 720-μg/cm$_2$ CD_2 target with a radioactive ^{18}F beam. The ^{19}Ne states of interest near the proton threshold decay by breakup into α and ^{15}O particles. These decay products were detected in coincidence with position-sensitive E$-\Delta$E silicon telescopes. The α and ^{15}N particles from the break up of the mirror nucleus ^{19}F were also measured with these detectors. Particle identification, coincidence, and Q-value requirements enable us to distinguish the reaction of interest from other reactions. The reconstruction of relative energy of the detected particles reveals the excited states of ^{19}Ne and ^{19}F which are populated. The neutron (proton) angular distributions for states in ^{19}Ne (^{19}F) were extracted using momentum conservation. The observed states in ^{19}Ne and ^{19}F will be presented.

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1. Introduction

The ^{18}F$(p,\alpha)^{15}$O reaction predominantly destroys the ^{18}F produced during stellar explosions such as novae and X-ray bursts. The most probable source of positrons which lead to electron-positron annihilation radiation in the expanding envelope of novae in the first few hours of explosion is the decay of ^{18}F. This is due to its relatively long length half-life ($\sim$ 110 minutes) and its relatively large abundance. However, the amount of ^{18}F produced and transported to the novae envelope is severely constrained by its destruction through ^{18}F$(p,\alpha)^{15}$O in the burning shells. Uncertainty in this reaction rate results in significant uncertainty in the amount of ^{18}F produced in these explosions that is predicted theoretically [1, 2]. The proton-induced reactions on ^{18}F are also important for understanding the production of heavier elements, especially in the regions with higher temperatures and densities. In order to reduce the uncertainty in model predictions of ^{18}F production, a more precise understanding of ^{18}F$(p,\alpha)^{15}$O reaction rate is needed. The rate is dominated by contributions from resonances in ^{19}Ne near the proton threshold. Our present understanding of the energy level structure of ^{19}Ne is incomplete. According to Bardayan *et al.* [3], Kozub *et al.* [4], and most recently Nesaraja *et al.* [5], there are eight levels in the mirror nucleus ^{19}F for which analogs have not been seen in ^{19}Ne above the proton threshold of 6.411 MeV. The properties of these unobserved states may influence the ^{18}F$+p$ reaction rates.

Our approach to studying the proton widths and excitation energies of states in ^{19}Ne is to measure proton transfer on ^{18}F. These measurements have appeared however to present significant technical challenges, e.g. neutron detection for $(\mathrm{d,n})$ or difficult targets and the detection of very low-energy charged particles for $(^{3}\mathrm{He,d})$ and other proton transfer reactions. Instead we have utilized the $(\mathrm{d,n})$ proton transfer reaction but have detected the charged reaction products rather than the neutron. The ^{19}Ne excited states of interest decay by breaking up into $\alpha + {}^{15}$O. By detecting the energy and position of the α and ^{15}O, their momenta can be reconstructed. The excitation energy of the decaying state relative to the $\alpha + {}^{15}$O threshold ("relative energy") and the momentum of the undetected neutron can then be calculated.

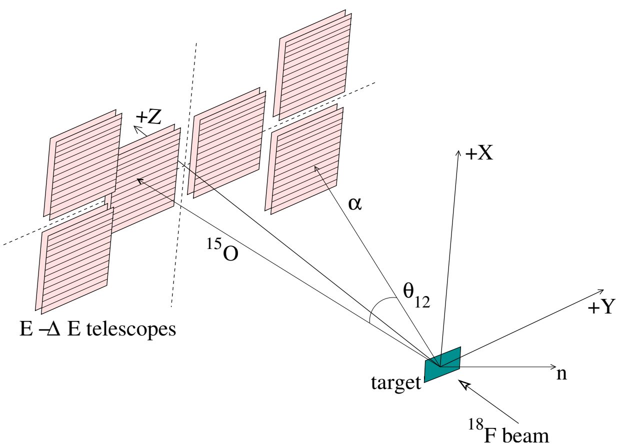

Figure 1: Schematic diagram of the six 5-cm $\times$ 5-cm $E-\Delta E$ detector telescopes employed for the measurement. The beam axis passes through the mid-point between the two inner telescopes.

2. Experiment

The ^{18}F beam was produced at the ORNL's HRIBF using the Isotope Separator On-line (ISOL) technique. A 720-μg/cm^2 CD_2 target was bombarded for 117 hrs with an isotopically pure, 150 MeV $^{18}F^{9+}$ beam at an intensity of $\sim 2\times10^6$ /s. The differential cross section of this reaction is large at $\theta_{c.m.} \leq 50^\circ$. Thus, in this angular region, nuclear information of astrophysical importance can be extracted. In inverse kinematics, the neutrons corresponding to this angular range are emitted at backward angles while the ^{19}Ne is limited to a narrow cone at forward angles. The ^{19}Ne ions of interest are highly excited and promptly decay into $\alpha+^{15}$O nuclei. The same holds true for states in ^{19}F which decays into $\alpha+^{15}$N. These charged particles were detected in coincidence in position sensitive $E-\Delta E$ telescope. The detection system is made up of six telescopes and each consists of a ΔE detector followed by an E detector, both of which are 5-cm $\times$ 5-cm. The ΔE's have 16 strips and are position sensitive while the rear detectors simply measure energy. The use of these detectors allow for energy measurement as well as both position determination and particle identification. A schematic diagram of the configuration of the six telescopes is shown in Figure 1. They cover $2.5^\circ - 16.5^\circ$ on either side of the beam axis. The two inner telescopes are optimized to measure heavier particles while the remaining four telescopes are optimized to detect the α particles.The position and energy of the detected charged particles allow their momenta to be constructed. The excitation energy of the decaying state relative to the α threshold (relative energy) in ^{19}Ne or ^{19}F and the momentum of the undetected nucleon (neutron or proton respectively) can then be calculated. The relative energy is given by

$$E_{\rm rel} = \frac{E_1E_2+m_1E_2+m_2E_1-\cos\theta_{12}\sqrt{E_1^2+2m_1E_1}\sqrt{E_2^2+2m_2E_2}}{m_1+m_2}, \tag{2.1}$$

where E_1, m_1 and E_2, m_2 are the kinetic energies and masses of the α and ^{15}O (or α and ^{15}N), respectively, and θ_{12} is the laboratory angle between them.

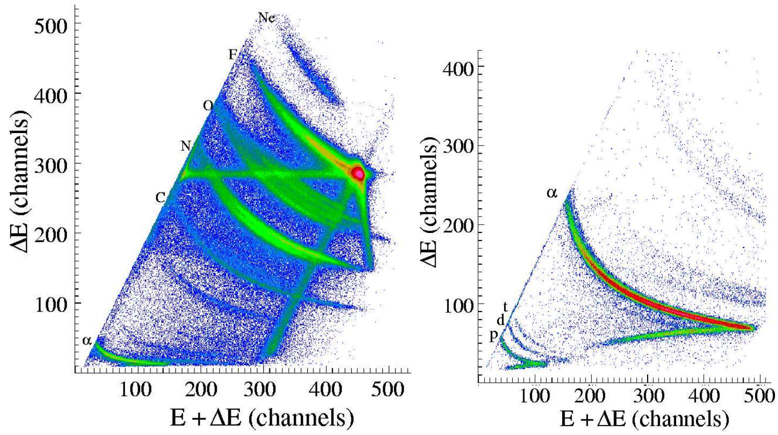

Figure 2: $E_{tot} - \Delta$E spectrum from the experiment for the inner detector (left) and outer detector (right). The loci of nuclei detected by the detectors are indicated. Complete isotope separation is observed for H and He while there is complete Z separation and partial isotope separation for the heavier nuclei.

3. Results and Conclusions

The particle identification histograms of our detectors are shown in Figure 2. We have found it useful to gate on the Q-value spectrum. The relative energy spectra obtained for $\alpha + {}^{15}$O and $\alpha + {}^{15}$N are shown in Figure. 3. The relative energies were determined using the fits shown in the figures. The excitation energies are determined by adding the appropriate threshold energy to the relative energy.

The observed excitation energies of ^{19}F compared reasonably well with the results from the ^{18}F(d,p) experiment of Kozub *et al.* [6]. The experiment of Kozub *et al.* was performed at a somewhat lower energy than the present one ($E_{c.m.} = 10.88$ MeV versus 14.94 MeV). We see all of the states reported by Kozub *et al.* for $E_x > 6$ MeV. It is interesting to note that both experiments see high-lying states at $E_x = 9.58$ and 10.5 MeV. The ^{18}F(d,p) experiment of de Sèrèville *et al.* [7, 8] observed particle groups corresponding to levels in ^{19}F at 6.1, 6.3, 6.5, 6.8, and 7.3 MeV which are also seen in the present experiment.

It is interesting to note that the two strongest peaks observed in ^{19}Ne, at E$_x$ = 6.09 and 6.29 MeV, are somewhat below the proton threshold of 6.411 MeV. The angular distribution for (d,n) transfer to these states are shown in Figure 4. We additionally show in Figure 4 the results of Distorted-Wave Born Approximation (DWBA) calculations using the code DWUCK4. The angular distribution of the ^{19}Ne(6.09 MeV) state is reasonably well reproduced by $l = 2$ transfer. Similarly, the angular distribution of the ^{19}Ne(6.29 MeV) state is well reproduced by $l = 0$ transfer with a small component of $l = 2$. Subthreshold resonances, in particular those near the particle threshold with low orbital angular momenta may contribute reasonably to a reaction rate [9]. The contribution of the high energy tail of these states may change our knowledge about ^{18}F$(p,\alpha)^{15}$O reaction rate. Until now, the calculation of the astrophysical reaction rate of ^{18}F$(p,\alpha)^{15}$O has been essentially calculated as a sum of contributions of resonant states above proton threshold, neglecting contributions that might be coming from high energy tail of states below proton threshold. Kozub *et. al.* [6] had earlier mentioned the possibility of l = 0 strength near the proton threshold in ^{19}Ne to be concentrated in a proton-bound state. We believe that the l = 0 strength in the 6.29-MeV state

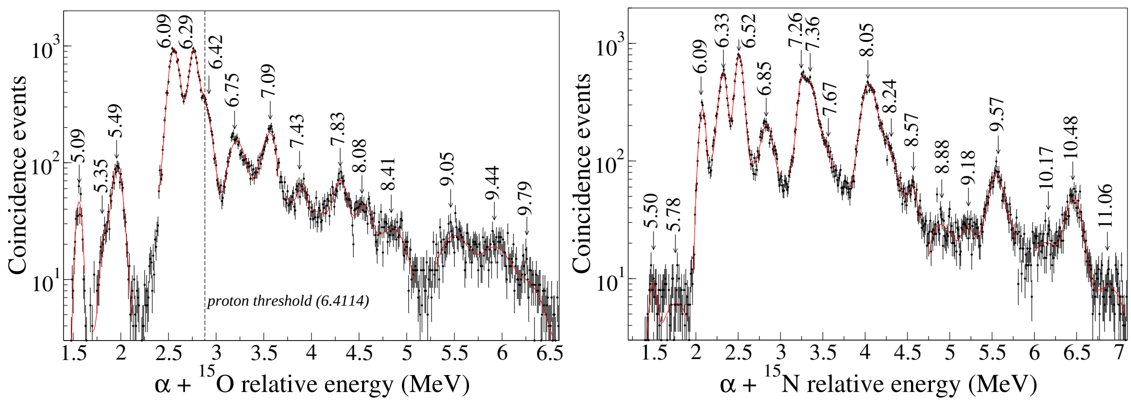

Figure 3: Relative energy spectra for $\alpha + {}^{15}$O (left) and $\alpha + {}^{15}$N (right) The dots are experimental data and the red curves are the MINUIT fit. The corresponding excitation energies (units in MeV) are written against the peaks.

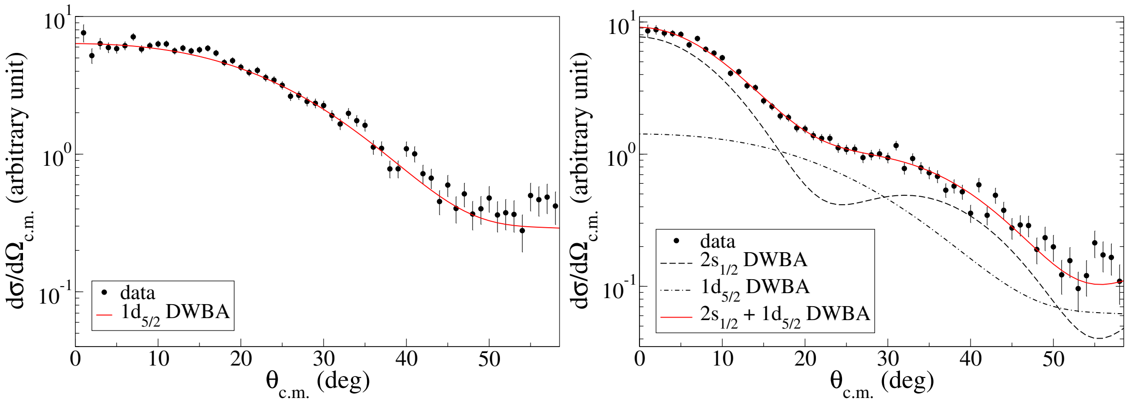

Figure 4: The angular distribution for (d,n) transfer to the 6.09- (left) and 6.29-MeV (right) levels in ^{19}Ne with shaded circles from this work. The curves show the DWBA calculations.

will make it relevant for the ^{18}F$(p,\alpha)^{15}$O process. We have started to study the contribution of its high energy tail to the ^{18}F$(p,\alpha)^{15}$O astrophysical S-factor. In addition, we are investigating how this contribution interferes with the $3/2^{+}$ resonances. We will utilize the new information from this experiment as well as other recent measurements to calculate an improved ^{18}F$(p,\alpha)^{15}$O reaction rate.

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