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Study of interference effects in the ^{18}F(p, α)^{15}O reaction

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The ^{18}F(p,α)^{15}O reaction plays a crucial role in understanding γ-ray emission from novae. Because of the importance of understanding the ^{18}F + p reactions, a number of studies of the A=19 isobars have been made using stable and exotic beams. The interference effects among $J^{\pi} = \frac{3}{2}^{+}$ resonances in the $^{18}F + p$ system, however, have never been measured, but they can change the S-factor by a factor of 20 at nova energies. R-matrix calculations indicate that the cross sections above the $E_{c.m.}$ = 665 keV resonance are sensitive to the interference between the $E_{c.m.}$ = 8, 38, and 665 keV resonances. In order to study the interference effects, an excitation function for the ^{1}H(^{18}F,α)^{15}O reaction has been measured in the energy range of $E_{c.m.}$ = 663-877 keV using radioactive ^{18}F beams at the Holifield Radioactive Ion Beam Facility. By measuring the ^{18}F(p,α)^{15}O cross section off resonance and comparing the cross section with theoretical calculations, we provide the first experimental constraints on the interference of $\frac{3}{2}^{+}$ resonances.

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The decay of radioactive ^{18}F nuclei in the expanding envelope of novae is the most important positron annihilation source of γ-rays during the first several hours after the expansion [1, 2]. The ^{18}F(p, α)^{15}O reaction plays a crucial role in understanding the destruction of ^{18}F that is synthesized in novae via proton capture on ^{17}O or through the sequence ^{17}F(p,γ)^{18}Ne($e^+ \nu_e$)^{18}F [3]. Although a number of studies on the ^{18}F + p system have substantially improved our understanding of the ^{18}F(p,α)^{15}O reaction [3-11], the interference among J^π = 3/2$^+$ resonances could not be taken into account in the reaction rate calculations due to the lack of experimental knowledge about the relative signs of the effect. These interference effects can, however, change the astrophysical S-factor by up to a factor of 20 at nova energies.

The ^{1}H(^{18}F,α)^{15}O excitation function was measured over the energy range $E_{c.m.} \simeq$ 663 - 877 keV at the Oak Ridge National Laboratory (ORNL) Holifield Radioactive Ion Beam Facility (HRIBF) [12]. The production of ^{18}F radioactive ion beams at HRIBF is based on the Isotope Separation On-Line (ISOL) technique [13]. A beam of ^{4}He ($\sim 1\mu A$, 85 MeV) from the Oak Ridge Isochronous Cyclotron (ORIC) bombarded a thick HfO_2 target to produce ^{18}F atoms via ^{16}O(α,pn)^{18}F reaction [14]. The ^{18}F atoms were then mass analyzed and post accelerated by the tandem electrostatic accelerator to the appropriate energies for this experiment. A schematic diagram of the experimental setup is shown in Figure 1. A beam of ^{18}F/^{18}O impinged on a 70 μg/cm^2 polypropylene CH_2 target (5.5×10^{18} ^{1}H atoms/cm^2). The average ^{18}F current was $\sim 10^5$ ions per second, and total of 4×10^{10} ^{18}F ions were delivered to the target during the experiments. Energy steps of $\Delta E_{c.m.} \simeq$ 50 keV (ΔE_{lab} = 1 MeV) were taken because the ^{18}F ions lose about 970 keV in the target at this energy range. The recoil particles from the ^{1}H(^{18}F, α)^{15}O reaction (α particles and ^{15}O ions) were detected in coincidence by two large area silicon detector arrays. The ^{18}F and ^{18}O ions which were scattered from the carbon component of the CH_2 target were also continuously detected by a gas-filled ionization counter enabling a constant monitor of the beam composition. The cross sections measured in this experiment are plotted in Figure 2.

To study the interference effects on the cross section, the R-matrix code MULTI [15] was used. The free parameters were the signs of three J^π = 3/2$^+$ resonance terms for the levels at $E_{c.m.}$ = 8, 38, and 665 keV, where we use the sign convention adopted in Eq. (XII. 5. 15) of Lane and Thomas

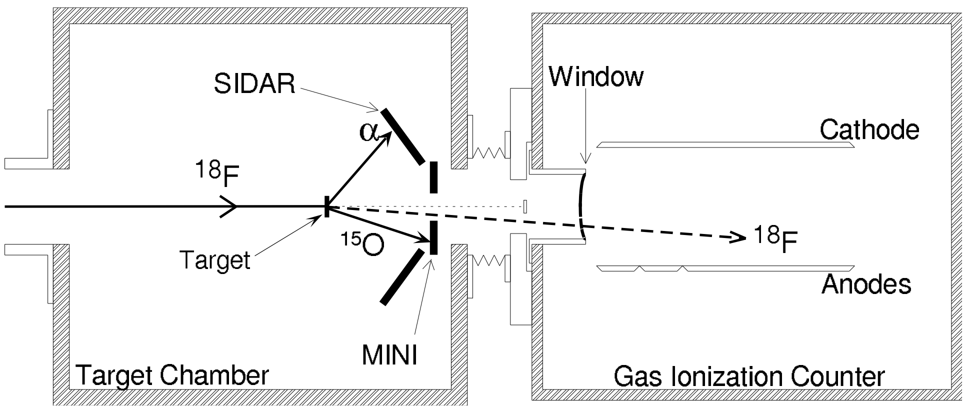

Figure 1: A schematic diagram of the experimental setup is shown.

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[16]. The results show that four out of eight possibilities could be ruled out, and all four of the "allowed" possibilities produce nearly identical cross sections above the 665-keV resonance. The allowed possibilities are $(+++)$, $(+--+)$, $(-++)$, and $(--+)$, where the signs in parenthesis are the signs of the 8-, 38-, and 665-keV resonances, respectively. We compare in Figure 2 the ^{18}F(p, α)^{15}O excitation function to theoretical cross section calculations from the *R*-matrix code MULTI. Two cases of the relative signs are shown in the figure for illustration purposes. The theoretical cross sections were calculated over the complete range of energies and then averaged over the energy loss in the target as well as over the angles covered by the detectors ($56^\circ \leq \theta_{c.m.} \leq 138^\circ$) for direct comparison with the data. Only upper limits on the cross section could be obtained at $E_{c.m.}$ = 770 and 824 keV due to the large ^{18}O contamination of the beam (^{18}F/^{18}O $\sim$ 0.04). Since all four cases with a negative sign for the 665-keV were ruled out, it is clear that the two resonances at $E_{c.m.}$ = 8 and 38 keV do not strongly affect the cross section above 665-keV. Interference effects from these resonances, however, become more important at the lower energy range ($E_{c.m} \leq$ 600 keV) as shown in Figure 3, where we show the astrophysical S-factor plots for 4 allowed possibilities.

New upper limits on the proton widths (Γ_p) of the $E_{c.m.}$ = 827 and 842 keV resonances have also been set. For a given set of resonance parameters [17], the upper limits on Γ_p were calculated at 90% confidence level from the χ^2 distribution. Upper limits were found to be $\Gamma_p \leq$ 1.17 keV at $E_{c.m.}$ = 827 keV and $\Gamma_p \leq$ 1.65 keV at $E_{c.m.}$ = 842 keV, respectively. The upper limit at $E_{c.m.}$ = 842

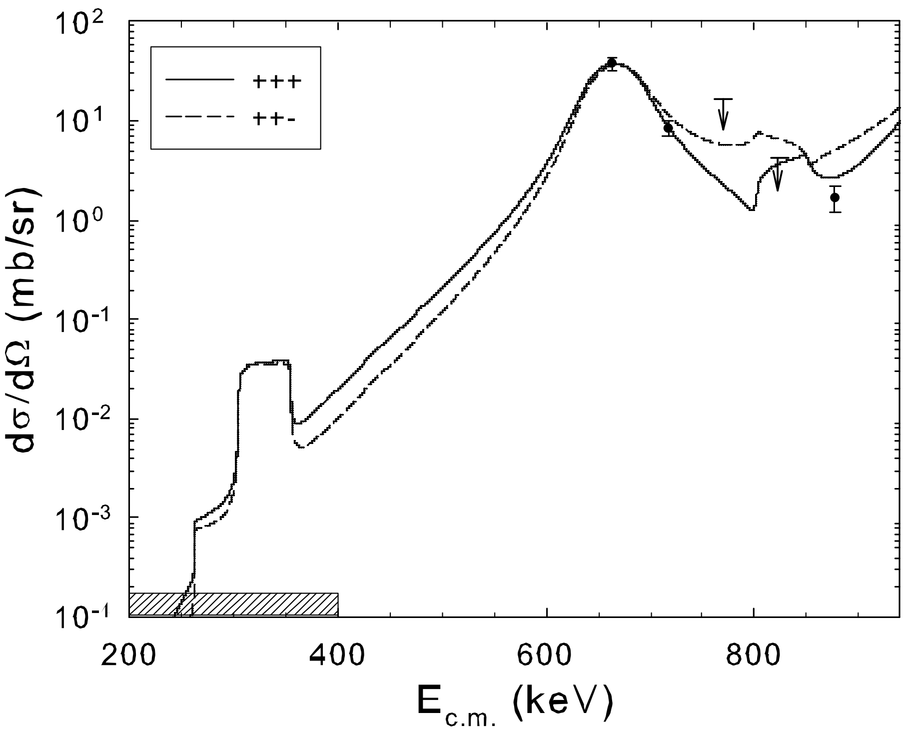

Figure 2: The ^{18}F(p, α)^{15}O excitation function is shown along with theoretical cross section calculations from the *R*-matrix code MULTI. Most effective energy range for novae is indicated by the shaded box.

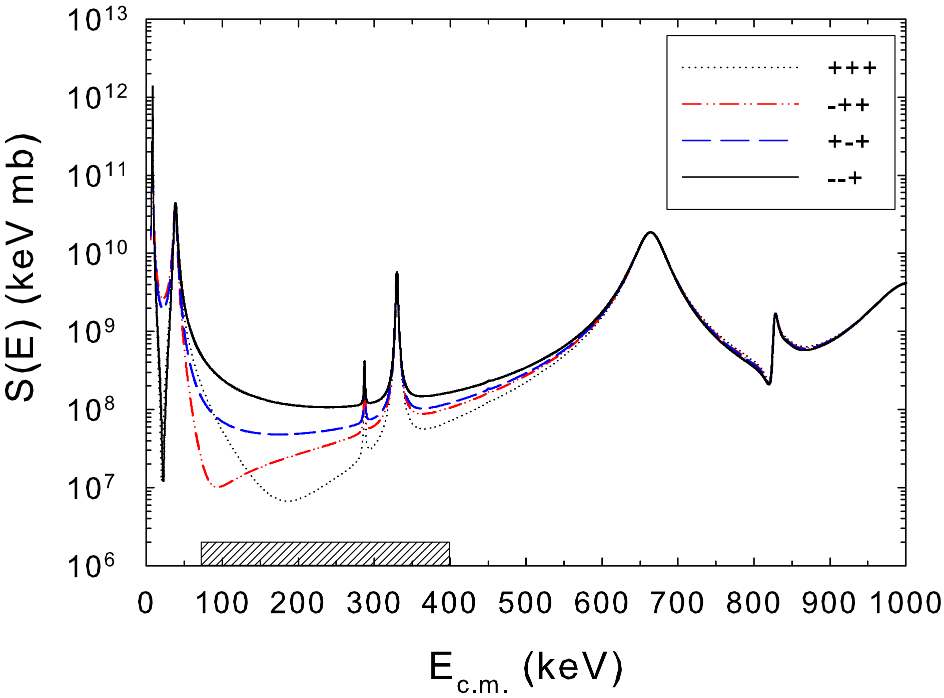

Figure 3: Astrophysical S-factor vs. center of mass energy plots for allowed four possibilities.

keV is consistent with the previously determined values from a ^{18}F(p,p)^{18}F measurement in Ref. [10], while the other upper limit is less stringent than the previous one.

To investigate how this uncertainty in interference propagates to uncertainties in ^{18}F production in novae, we have performed element synthesis calculations in the framework employed in the *Computational Infrastructure for Nuclear Astrophysics* [18], where the ejected envelope of nova is divided into 28 zones, each with its own thermodynamic history (time histories of the temperature and density). The result shows that the uncertainty in the ^{18}F(p, α)^{15}O reaction rate due to the interference produces roughly a factor of 2 variation in the amount of ^{18}F produced.

In conclusion, the ^{18}F(p,α)^{15}O reaction rate was uncertain partly because of the lack of experimental knowledge about the relative signs of the interference of three $3/2^+$ resonances. By measuring the ^{1}H(^{18}F,α)^{15}O cross sections in the energy range of $E_{c.m.}$ = 663-877 keV using radioactive ^{18}F beams at the HRIBF, we provide the first experimental constraints on the interference effects. Our results show that the uncertainty in the reaction rate at the temperature range 0.3 GK $\leq T \leq$ 0.6 GK is reduced by up to 37% compared to previous work [11]. We also set new upper limits on proton widths at $E_{c.m.}$ = 827 keV ($\Gamma_p \leq$ 1.17 keV), and $E_{c.m.}$ = 842 keV ($\Gamma_p \leq$ 1.65 keV).

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