Recent Accomplishments in Nuclear Astrophysics with Radioactive Beams at HRIBF

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Unstable nuclei play an influential, and in some cases dominant, role in many phenomena in the cosmos such as novae, supernovae, X-ray bursts, and other stellar explosions [1]. In the extremely high temperatures (>10^8 K) of these astrophysical environments, the interaction times between nuclei can be so short (~ seconds) that unstable nuclei formed in a nuclear reaction can undergo subsequent reactions before they decay. Sequences of (predominantly unmeasured) nuclear reactions occurring in exploding stars are therefore quite different than sequences occurring at lower temperatures characteristic of, for example, our Sun. Measurements of the structure and reactions of unstable nuclei are therefore required to improve our understanding of the astrophysical origin of atomic nuclei and the evolution of stars and their (sometimes explosive) deaths. We are utilizing a combination of experimental measurements, data evaluations, and astrophysical simulations to improve our understanding of these cosmic phenomena.

At the HRIBF, we are making some of the first precision measurements of reactions needed to probe the details of exploding stars [2-9]. We have used radioactive beams of ^{17}F and ^{18}F to study the ^{14}O(α,p)^{17}F, ^{17}F(p,γ)^{18}Ne, ^{18}F(p,α)^{15}O, and ^{18}F(p,γ)^{19}Ne reactions, and a stable beam to study the ^{25}Al(p,γ)^{26}Si reaction [9]. We have successfully demonstrated that precision nuclear spectroscopy measurements can be made with impure radioactive ion beams of intensities as low as 10^3 pps. When possible, we have detected all reaction products in coincidence, removing any ambiguities from reactions off stable ion isobaric contaminants in the radioactive ion beam (Figure 1). We have made measurements with radioactive ion beams that are contaminated by up to a factor of 100. We have studied multiple reaction channels, such as ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O, to significantly improve our reaction rate determinations (Figure 2). We have utilized a large solid angle detection scheme (such as our Silicon Detector Array SIDAR [3]) to make kinematically complete measurements for low-yield reactions with modest beam intensities. Our techniques are providing information that will facilitate nuclear spectroscopy studies at future radioactive beam facilities such as the Rare Isotope Accelerator. For example, we have developed equipment and techniques to monitor radioactive beam intensity and purity online during our experiments, and have studied the beam-induced degradation of polypropylene (CH_2) target foils that are used for many scattering and capture measurements.

Several HRIBF measurements to date [2-7] have utilized the SIDAR highly-segmented array of transmission silicon strip detectors to measure scattering and (p,α) reactions with radioactive beams. The geometric efficiency of ~25 % or more is increased substantially for some reactions because of the kinematic focusing of the reaction products. Detectors with a transmission geometry are stacked to enable particle identification by measuring both energy loss and total energy. In all cases, heavy ion products of (p,p) and (p,α) reactions have been detected in coincidence through the use of additional Si strip detectors or a gas ionization counter placed further downstream of the target. Coincidence measurements with gas ionization counters (providing Z-identification) are particularly useful because they enable measurements to be made with beams having isobaric impurities.

To reduce the (orders of magnitude) uncertainty in the ^{17}F(p,γ)^{18}Ne reaction rate, we measured the ^{17}F(p,p)^{17}F elastic scattering excitation function with a radioactive ^{17}F beam and a thin polypropylene (CH_2) target [2,3]. The availability of this beam enabled us to readily find the crucial s-wave resonance in the ^{17}F + p system which had not been found in 9 different stable beam studies spanning 30 years. Our precision measurement of the excitation energy and total width of this level resolved the major uncertainty in the ^{17}F(p,γ)^{18}Ne reaction rate at high temperatures. We are currently using a proton transfer reaction, ^{14}N(^{17}F, ^{18}Ne)^{13}C, to determine the direct capture component of the reaction rate, which we now know dominates at temperatures characteristic of novae, by measuring the asymptotic normalization coefficient (ANC).

The ^{14}O(α,p)^{17}F reaction rate is thought to influence the dynamics of an X-ray burst and the subsequent synthesis of heavier nuclei. To improve the determination of this rate, we measured an excitation function of the time-inverse reaction ^{17}F(p, α)^{14}O at 21 beam energies, spanning the energy range needed for stellar explosions [6]. Measurements of ^{17}F(p,p)^{17}F and ^{17}F(p,p')^{17}F were also made to constrain the ^{14}O(α,p)^{17}F reaction proceeding to both the ground and excited states of ^{17}F [7]. Measuring multiple reaction channels is crucial for an R-matrix analysis of this reaction rate.

We have also put considerable effort into improving the rates of the ^{18}F(p,α)^{15}O and ^{18}F(p,γ)^{19}Ne reactions. These are important for understanding the production of the long-lived radioactive isotope ^{18}F in novae, which may serve to constrain nova models via observations of the decay 511-keV gamma rays. We have measured ^{18}F(p,p)^{18}F, with both thin [4] and thick targets, and ^{18}F(p,α)^{15}O, at energies corresponding to two important ^{19}Ne resonances (330-keV [8] and 665-keV [5] in the center of mass). We have resolved a serious discrepancy in the literature concerning the 665-keV level (Figure 2), and made the first statistically significant measurement of the strength of the 330-keV resonance. Further investigations to search for missing ^{19}Ne resonances are planned.

Future experimental work will involve direct measurements of capture reactions with a mass spectrometer optimized for astrophysics – the Daresbury Recoil Separator (DRS) [10]. This device is coupled to a windowless, differentially-pumped hydrogen gas target system, and will enable the detection of the capture reaction recoils with high efficiency. One reaction we will study with the DRS is ^{17}F(p,γ)^{18}Ne to determine the gamma partial width of the dominant s-wave resonance. We will also measure the ^{7}Be(p,γ)^{8}B reaction with the DRS to help understand measurements of the solar neutrino flux. Other future work will involve transfer reaction measurements with neutron-rich radioactive beams to understand r-process nucleosynthesis in supernova explosions. Additionally, a number of nuclear structure measurements at the proton- and neutron-driplines are planned to improve calculations of reaction rates that cannot presently be measured.

The experimental nuclear astrophysics effort at HRIBF is closely coupled with nuclear data evaluations [11] through which the best rates of reactions based on all available information are determined. The new rates are disseminated in print and on the WWW [12], and new visualization tools are being developed to access reaction rate information. These new reaction rates are then incorporated into ORNL astrophysical simulations to determine the impact of our measurements, and to guide future experiments [13]. Having synergistic, onsite programs in measurements, data evaluation, and theory is very advantageous for nuclear astrophysics studies. For example, our new ^{17}F(p,γ)^{18}Ne rate changed the predicted amount of ^{17}O synthesized by up to a factor of 3 when averaged over the entire exploding star in comparisons to some previous predictions (Figure 3), and by up to a factor of 15000 in the hottest portions of the explosion [13]. Similarly, our new ^{18}F + p rates change the amount of the important radionuclide ^{18}F produced by a factor of 3 compared to other estimates [8]; this has an impact on future observational constraints on nova models.

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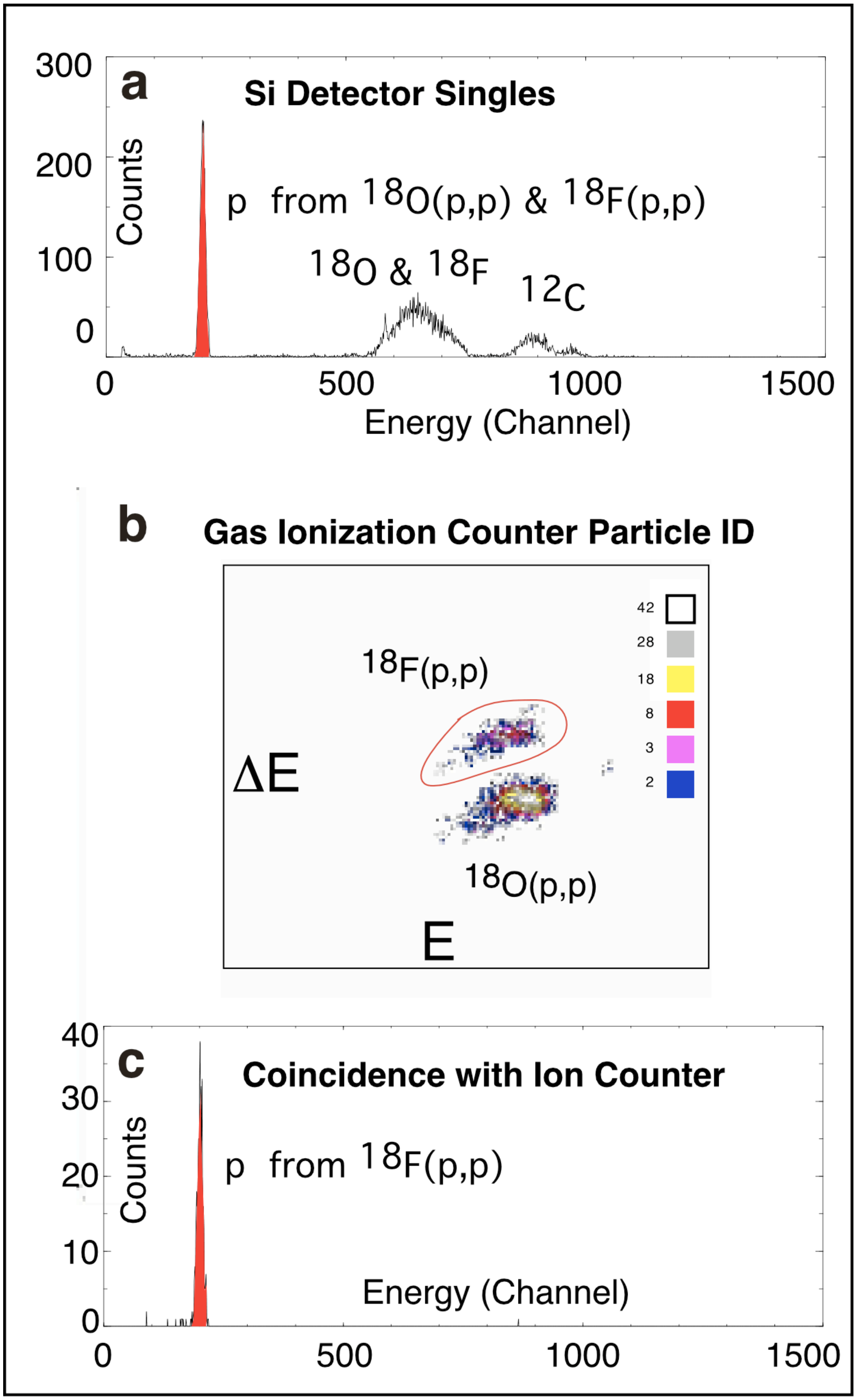

Figure 1: Kinematically Complete Measurement. (a) Singles energy spectrum from SIDAR showing scattering events from ^{18}F and ^{18}O beam particles; (b) Particle identification in a gas ionization counter at forward angles; (c) SIDAR energy spectrum in coincidence with ^{18}F in the ion counter.

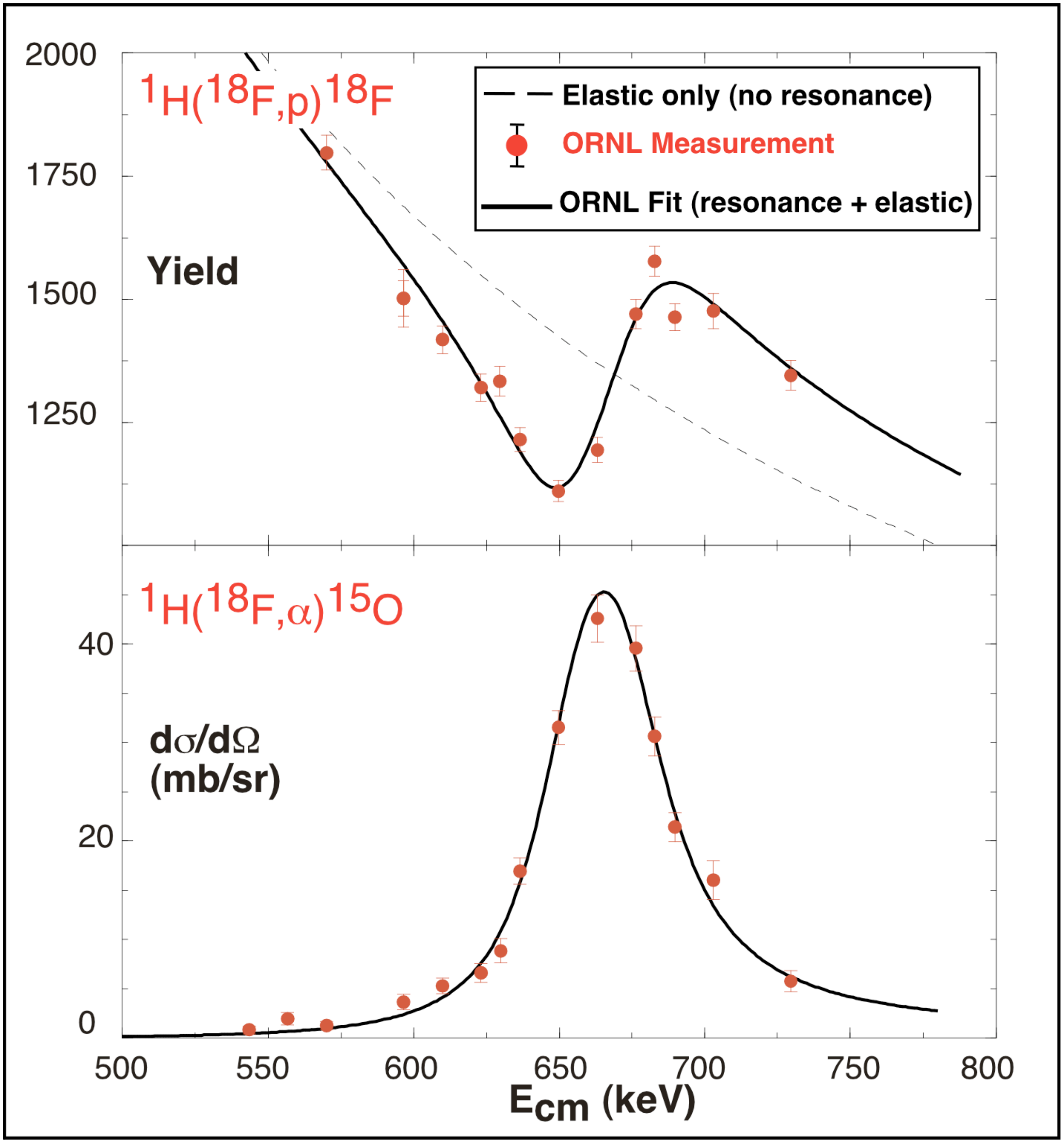

Figure 2: Excitation functions of the $^{18}F(p,p)^{18}F$ (top) and $^{18}F(p,\alpha)^{15}O$ (bottom) for the 665-keV ^{19}Ne resonance [5].

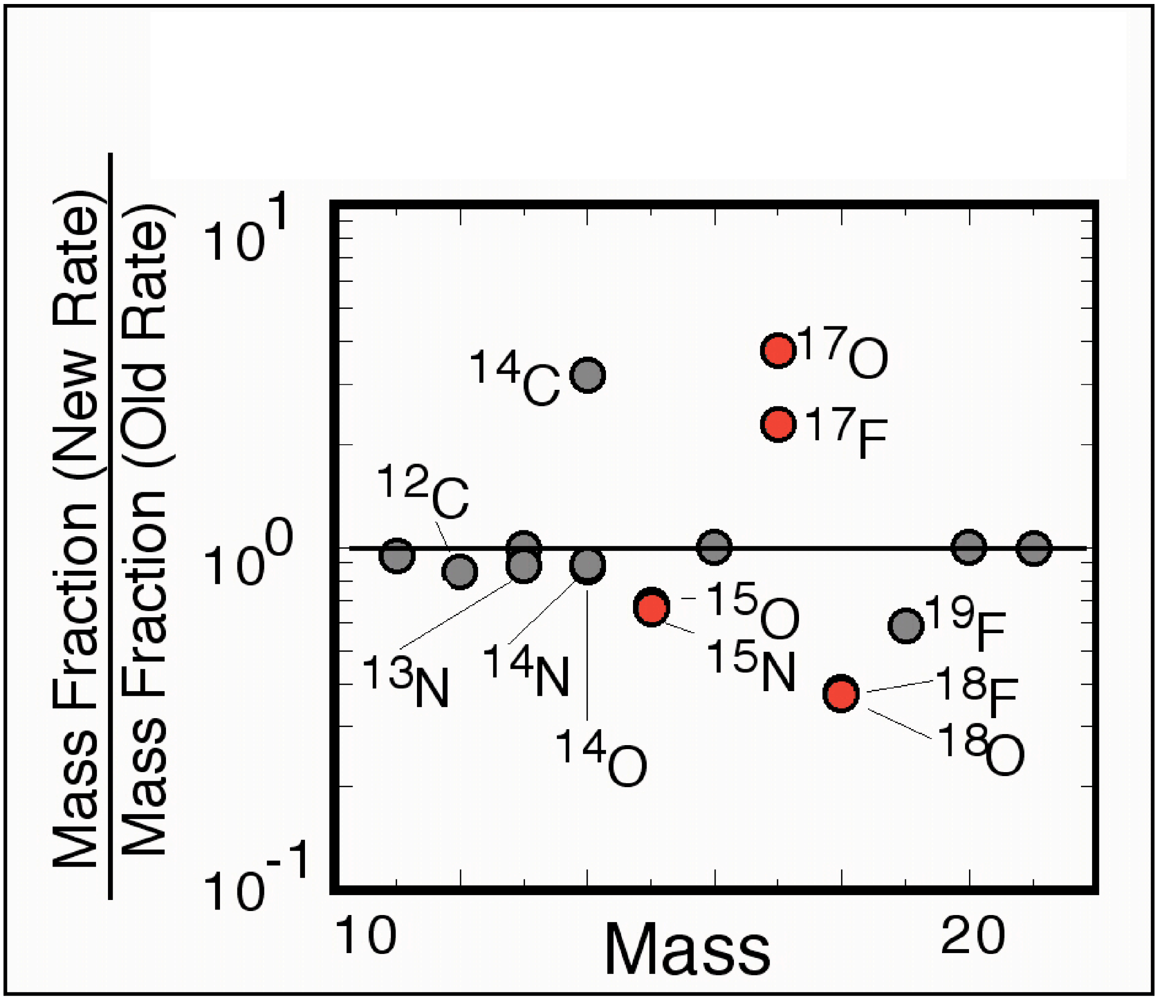

Figure 3: Astrophysical impact of the $^{17}F(p,p)^{17}F$ measurement as determined by the ratio of abundances predicted in two simulations of a nova outburst on the surface of a 1.35 solar mass white dwarf star, differing only in the $^{17}F(p,\gamma)^{18}Ne$ reaction rate. The ratio is of abundances predicted using the rate based on the HRIBF $^{17}F(p,p)^{17}F$ measurement to those predicted using the most widely-used rate [14].