**Production of High Quality $^7$Be Radioactive Beam for Nuclear Astrophysics Experiments.**

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Low energy $^7$Be radioactive beam has been produced at Nuclear Science Centre, New Delhi, using the existing 15UD Pelletron and the recoil mass spectrometer HIRA. For this purpose HIRA is operated in a new ion optical mode[1]. In this mode there is an intermediate focal plane where new slit system is installed to reject the primary beam without loosing the RIB. Optics has been experimentally tested for p($^7$Li,$^7$Be)n reaction in inverse kinematics to produce $^7$Be[2]. We obtained beam rejection of ~ $10^{10}$ at 0° with respect to the primary beam. A polypropylene $(CH_2)_n$ foil, mounted on a rotary/linear motion device, is used as production target. In the new optical mode we have unit magnification at intermediate focal plane as well as secondary target position. So beam spot size on secondary target is a replica of the primary beam spot i.e. ~ 3 mm(dia.). Purity of the RIB has been consistently found to be better than 99.9% in the energy range 11–21 MeV with yields of the order of 1kHz/pnA/mSr. Recently an $LN_2$ cooled gas cell has been tested as a production target. With this we expect to produce more RIBs like $^6$He,$^8$Li, $^8$B, $^{11}$C, $^{13}$N, $^{14,15}$O, $^{17,18}$F, $^{18,19}$Ne etc. with similar quality. As many of these beams at low energies may not be available from major ISOL/Fragmentation facilities, we have the opportunity to study the nuclear–astrophysical CNO cycle reactions and also to measure precise angular distributions in near barrier transfer, fusion etc. reactions.

Recently, $^7$Be beam was provided for a couple of experiments to measure astrophysical $S_{17}(0)$ factor using ANC method. In these experiments, we have measured angular distribution for d($^7$Be,$^7$Be)d and d($^7$Be,$^8$B)n reactions at $E_{cm}$=4.5 MeV. To our knowledge this is the lowest energy measurement of this kind.

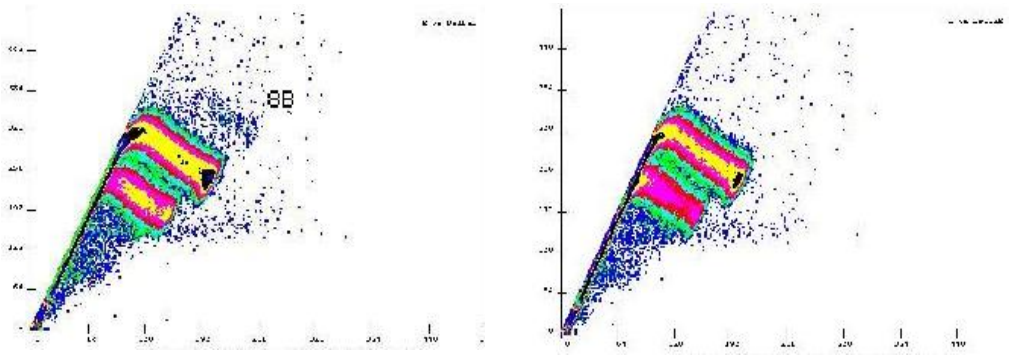


Figure 1: ΔE–E Spectra from d($^7$Be,$^8$B)n reactions at $E_{cm}$=4.5 MeV. The first spectrum is measured with $(CD_2)_n$ target which shows the $^8$B band and is not present in the other one is with $(CH_2)_n$ target

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# Yield studies of nuclei in the waiting-point regions of the $rp$ process at ISOLDE

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The astrophysical rapid proton capture process ($rp$ process) [1] is a part of the explosive hydrogen burning occurring during astrophysical events such as accretion in a close binary system. In high temperature and density conditions of $T_9 > 1$ and $\rho > 10^4$ g/cm$^2$ the $rp$ process can proceed beyond $A = 64$ and $Z = 32$ [2] and may continue possibly up to $A = 100$ via two-proton capture reactions bridging the waiting-points [3]. The speed of the process beyond $A = 64$ is defined largely by two of such waiting points along the process path at $^{68}$Se and $^{72}$Kr. Thus, experimental data on beta-decay half-lives and, in particular, nuclear masses and proton separation energies from this region are needed for reliable modelling of the process path, the resulting isotopic abundances and energy production.

In this paper we report on the status of the studies of the $N \sim Z$ nuclei close to the described bottleneck region at the ISOLDE on-line mass separator [4] concentrating on the yields of the isotopes of interest. The recent upgrade of the primary proton beam energy at ISOLDE from 1.0 GeV to 1.4 GeV was complemented by a test with 600 MeV energy at the beginning of December 2000. Particularly, the aim of this test measurement was to produce neutron-deficient Kr isotopes via spallation reactions in a Nb-foil target. In addition to their significance for near future experiments at ISOLDE, the results will possibly have significant consequences concerning the usable energies for producing the neutron-deficient isotopes in the future proton driver accelerators at ISOL facilities. A comparison of the yields to the available experimental and theoretical data will be given. In addition, the relevance of these tests for the future studies with nuclear spectroscopy and atomic mass measurements at ISOLDE [5] on the $rp$ process will be discussed.

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# A New $^{17}$F(p,$\gamma$)$^{18}$Ne Reaction Rate and Its Astrophysical Implications *

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The $^{17}$F(p,$\gamma$)$^{18}$Ne reaction is important in stellar explosions such as novae, X-ray bursts, and X-ray pulsars. This reaction influences the amount of $^{17}$O and $^{18}$O synthesized in novae, and is part of a crucial reaction sequence in X-ray bursts which leads to the synthesis of isotopes with mass greater than 20 and to a peak in the X-ray luminosity. It was thought that an unnatural parity, $J^{\pi} = 3^{+}$ state in $^{18}$Ne provides an $\ell = 0$ resonance in $^{17}$F + p capture which, depending on its excitation energy and resonance strength, could dominate the $^{17}$F(p,$\gamma$)$^{18}$Ne stellar reaction rate at stellar explosion temperatures. This level was expected from the structure of the $^{18}$O isobaric analog nucleus, but never conclusively observed despite nine previous experimental studies of the relevant $^{18}$Ne excitation energy region. Calculations of the properties of this level resulted in an uncertainty of more than a factor of 100 in the $^{17}$F(p,$\gamma$)$^{18}$Ne reaction rate.

We have observed [1,2] this missing $3^{+}$ state by measuring the $^{1}$H($^{17}$F,p)$^{17}$F excitation function with a radioactive $^{17}$F beam produced with the isotope separator on-line (ISOL) technique at ORNL's Holifield Radioactive Ion Beam Facility. We find that the state lies at a center-of-mass energy of $E_r = 599.8 \pm 2.5$ keV ($E_x = 4523.7 \pm 2.9$ keV) and has a width of $\Gamma = 18 \pm 2$ keV. Our measurement resolves the greatest uncertainty in the reaction rate, and indicates that the $3^{+}$ resonance dominates the capture rate at temperatures above 0.5 GK while the non-resonant direct capture dominates at lower temperatures. Details of the measurement will be presented. Further measurements to determine the direct capture rate and the gamma-width of the $3^{+}$ level will also be discussed.

We have used this new rate in calculations of the nucleosynthesis occurring in nova explosions on CO and ONeMg white dwarf stars. We find that the new rate changes the abundances of some isotopes (e.g., $^{17}$O) synthesized in the hottest zones of the explosion by over a factor of 1000 compared to some previous estimates, and up to a factor of 5 when averaged over zones of all temperatures [3]. Details of these nucleosynthesis calculations will also be presented.

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# SIDAR: A Silicon Detector Array for Astrophysics Studies With Radioactive Beams *

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Beams of radioactive nuclei are used at ORNL's HRIBF to study nuclei and measure cross sections of interest to astrophysics. In particular, proton-rich beams are used in scattering and transfer reaction studies in order to understand important reaction rates in explosive environments such as novae and x-ray bursts. Because radioactive beams are usually of low intensity, it is important that the detector system used cover a large solid angle. Furthermore, beams are often contaminated with stable isobars, and it is therefore desirable to perform kinematically-complete measurements to distinguish the events of interest. A high-efficiency segmented detector system is a necessity to perform such measurements with a reasonable efficiency and to verify the correct kinematical relationships are satisfied. We have developed the SIDAR silicon detector array using detectors manufactured by Micron Semiconductor [1] and pulse shaping electronics from Edinburgh University [2]. We have, in addition, developed a preamplifier system in collaboration with RIS Corporation [3]. This array has been used in conjunction with a gas ionization counter in several experiments [4,5,6] with radioactive beams at the HRIBF. Design and performance characteristics of the array will be presented along with future plans.

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# Determination of the $^{18}$F$(p,\alpha)^{15}$O Stellar Reaction Rate *

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In the standard model of a classical nova explosion, the energy source is explosive hydrogen burning in a degenerate layer on the surface of a white dwarf star. Proton-rich $\beta$-unstable nuclei are produced, and for those with longer lifetimes (greater than 100 s), convection can carry them to the top of the envelope before they decay. The $\gamma$-ray lines resulting from decays in the envelope are, in principle, observable and would provide a rather direct test of the model [1]. The most powerful emission in gamma rays from classical novae comes at energies of 511 keV and below, which originates from electron-positron annihilation. The main contributors to positrons in nova envelopes are $^{13}$N and $^{18}$F. When $^{13}$N decays, the nova envelope is still too opaque for $\gamma$-ray transmission; therefore, the decay of $^{18}$F is the most significant for observations. The amount of observable $^{18}$F which survives the runaway and is transported into the envelope is severely constrained by its destruction rate [2]. This destruction occurs most rapidly by the $^{18}$F(p,$\alpha$)$^{15}$O reaction which could be dominated by a resonance near 7.07 MeV in $^{19}$Ne, depending on the resonance properties. Recent experimental results [3,4,5] have differed by as much as a factor of three in their adopted resonance strength and by as much as 21 keV in their excitation energy for this state. This results in up to a factor of three variation in the $^{18}$F(p,$\alpha$)$^{15}$O rate at stellar temperatures. We have, therefore, measured the $^{1}$H($^{18}$F,p)$^{18}$F [6] and $^{1}$H($^{18}$F,$\alpha$)$^{15}$O [7] excitation functions with a thin (35-$\mu$g/cm$^2$) $CH_2$ target and a radioactive $^{18}$F beam at the Holifield Radioactive Ion Beam Facility. Proton and alpha yields were measured in coincidence with the heavy recoil nuclei at 15 bombarding energies between 10 and 14 MeV. Resonance parameters for the astrophysically important 7.07-MeV state have been extracted and will be discussed. Future measurements to determine the properties of other important resonances in $^{19}$Ne will also be discussed.

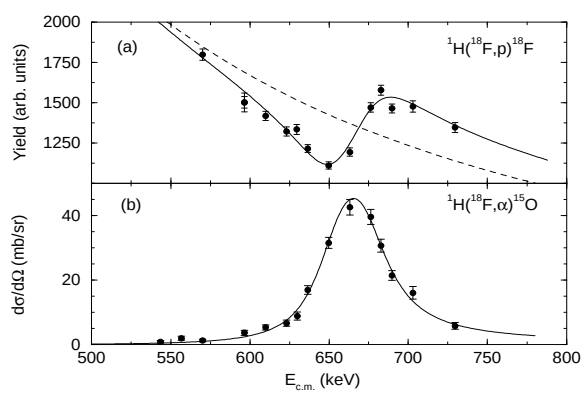


FIG. 1. A simultaneous fit of the $^{1}$H($^{18}$F,$p$)$^{18}$F and $^{1}$H($^{18}$F,$\alpha$)$^{15}$O excitation functions has been performed.

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# An experimental endstation for the measurement of capture reactions with radioactive ion beams at the HRIBF*

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The fusion of protons with other nuclei provides the energy that powers many astrophysical phenomena and the mechanism for element synthesis. Under extreme conditions, such as are found in accreting binary systems like X-ray pulsars and nova explosions, the rate of proton capture by certain radioactive nuclei may exceed their rate for radioactive decay. Knowledge of proton capture rates by radioactive nuclei is needed in order to understand energy generation and nucleosynthesis in these events. Due to the relatively short half-lives for decay, direct measurement of the proton capture cross sections requires radioactive heavy ion beams on hydrogen targets. The most sensitive technique for measuring these typically small cross sections involves the use of pure hydrogen gas targets with direct detection of the recoiling heavy nuclei in a recoil mass separator [1,2]. An experimental endstation optimized for such measurements is currently being developed at ORNL's Holifield Radioactive Ion Beam Facility (HRIBF) using the Daresbury Recoil Separator (DRS) with a windowless gas target system.

The DRS is a large-acceptance recoil separator that utilizes two 1.2-m-long crossed-field velocity filters and a 50° dipole magnet to separate beam particles from the recoils of interest [3]. Reaction products are detected at the (M/Q) focal plane in a gas ionization chamber. A large-area carbon foil microchannel plate detector is currently being constructed to provide timing and position information. The DRS has been installed at the HRIBF and is being commissioned in a series of measurements using stable ion beams and foil targets. Results of these measurements will be presented.

The use of a pure gas target provides about a factor of 3 increase in yield over plastic targets for the measurement of capture reactions in inverse kinematics. A windowless gas target has been constructed for use with the DRS in measurements of capture reactions. The special compact design of the gas target includes four differential pumping stages on each side of the target. Areal densities of $3 \times 10^{18}$ /cm$^2$ of helium have been achieved in the central target region without perceptible increases in the pressure in the fourth pumping stages, located only 0.5 m from the center of the target. Thus a high angular acceptance is achieved while maintaining the base vacuum in the nearby velocity filters. The operating parameters of the target as measured in a series of tests will be presented.

The combination of the DRS with the windowless gas target and large-area focal plane detectors provides a sensitive device for the measurement of capture reactions in inverse kinematics with radioactive beams. Plans for the first measurements with radioactive beams will also be presented.

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# Nuclear Reaction Rate Uncertainties and their effects on Nova Nucleosynthesis Modeling

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The observable consequences of a nova outburst depend sensitively on the details of the thermonuclear runaway which initiates the outburst. One of the more important sources of uncertainty is the nuclear reaction data used as input for the evolutionary calculations. It has been demonstrated that changes in the reaction rates used in a nova simulation can alter the production of individual isotopes (by an order of magnitude) and change global observables such as the peak luminosity and the amount of mass ejected by 10-30% [1].

We present the first systematic analysis of the full impact of reaction rate uncertainties on nova nucleosynthesis. The use of Monte Carlo techniques allows the translation of reaction rate uncertainties into uncertainties in nova model nucleosynthesis (see Fig. 1) and thereby quantifies the extent of disagreement between theory and observations.

By examining the relative importance of changes in individual reaction rates, our analysis can provide guidance in the selection of reactions for further experimental study. We will demonstrate the usefulness of this technique by determining the relative importance of the many individual reactions involved in the production of $^{22}$Na. Our analysis not only confirms the important reactions identified in [2], but also finds several additional reactions of similar importance.

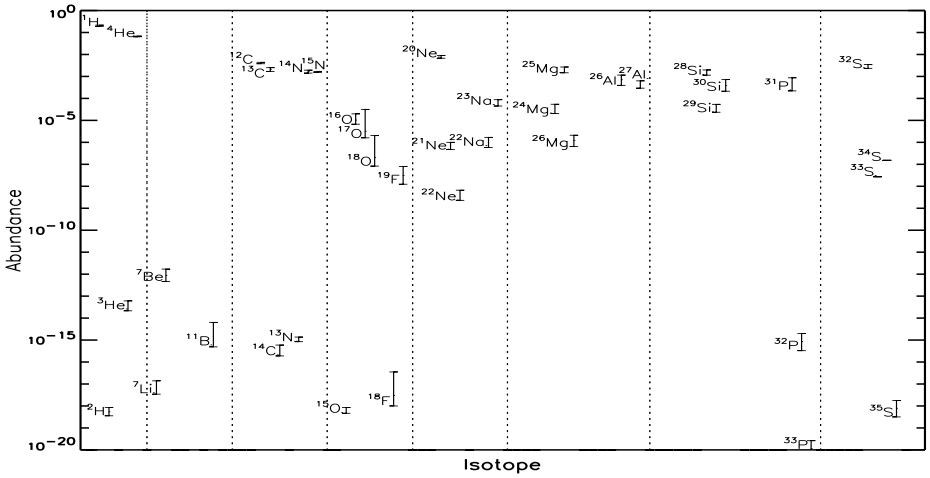


FIG. 1. Final Abundances (elapsed time = $4.7 \times 10^5$ sec after peak) for the innermost ejecta of a model for a nova outburst on a 1.25 $M_\odot$ ONeMg white dwarf. The error bars are derived from our Monte Carlo analysis.

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# Measurement of the $^7$Be(p,$\gamma$)$^8$B Cross Section at the HRIBF *

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There have been many measurements of the $^7$Be(p,$\gamma$)$^8$B reaction due to its importance in the solar neutrino problem [1]. The $^8$B decays produce the majority of the high energy neutrinos emitted from the solar core. Those high energy neutrinos provide most or all of the solar neutrino flux detected in many solar neutrino experiments[2,3]. Persistent discrepancies between the measured flux of solar neutrinos and the predicted flux have been observed in those experiments. The solution requires either radical alterations to the theory of stellar structure or new neutrino properties [1]. Neutrino oscillations have been proposed as one possible solution.

The current generation of solar neutrino experiments will measure the flux of $^8$B neutrinos from the sun with an uncertainty approaching 1%. A quantitative comparison of the measured neutrino flux with the standard solar model provides a rigorous contraint on neutino mixing parameters. The dominant uncertainty in the determination of these mixing parameters arises from the uncertainty in the $^7$Be(p,$\gamma$)$^8$B reaction rate. Numerous measurements of the $^7$Be(p,$\gamma$)$^8$B cross section have been performed using radioactive targets. However, the dominant uncertainties in the determination of the astrophysical reaction rate result from systematic uncertainties. Measurements using independent techniques are thus desired to better constrain the systematic uncertaintes. Measurements of the Coulomb dissociation of $^8$B and the Asymptotic Normalization Coefficient for $^7$Be+p are examples of successful approaches that have recently been applied to this problem. By combining the results obtained from numerous techniques, it may be possible to achieve the desired overall uncertainty of better than 5% in the $^7$Be(p,$\gamma$)$^8$B astrophysical S-factor.

We plan a direct measurement of the $^7$Be(p,$\gamma$)$^8$B cross section at the Holifield Radioactive Ion Beam Facility using a different experimental technique. The $^7$Li(p,n)$^7$Be reaction will be used to produce $^7$Be at the Triangle Universities Nuclear Laboratory, and the $^7$Be particles in a metal matrix will be shipped to ORNL. After a series of chemical processes[4], a pellet containing $^7$Be will then be mounted in a Cs sputter ion source to produce a beam of $^7$BeO$^-$. The $^7$BeO$^-$ will be accelerated in the 25 MV tandem accelerator and dissociated at the terminal to produce a $^7$Be beam. The $^7$Be beam will bombard a windowless hydrogen gas target. The windowless gas target has been constructed and is being tested. Areal densities of $3\times10^{18}$ /cm $^2$ of helium have been achieved in the central target region. A detailed description of the $^7$Be beam production and the gas target will be given. The DRS will be used to separate the unreacted beam particles from $^8$B recoils. Due to the forward focusing of the inverse kinematics and the large acceptance of the DRS, the $^8$B recoils can be detected with high efficiency. The DRS utilizes two crossed-field velocity filters and a 50° dipole magnet to separate primary beam particles from the recoils of interest. A rejection of $2\times10^{-11}$ of scattered beam particles has been achieved in a test run[5]. The $^8$B recoils are finally detected at the focal plan in a ionization counter which can give a further suppression of scattered beam particles. A detailed description of the experimental setup will be given.

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