Equipment and Facilities: RIB and Neutrons

This report summarizes the findings of the working group on *Equipment and Facilities: Radioactive beams, Neutrons* during the 2012 Nuclear Astrophysics Town meeting. The conveners of the working group were Aaron Couture (LANL), Ernst Rehm (ANL) and Remco Zegers (NSCL). Section 1 focuses on existing RIB facilities in North America (1.1) and the future capabilities of the Facility for Rare Isotope Beams (FRIB) (1.2). Section 2 focuses on neutron induced reactions at existing (2.1) and new/proposed (2.2) neutron facilities

1 Nuclear Astrophysics with Rare Isotope Beams

1.1 Existing RIB facilities in North America

The highest nuclear physics priority of the nuclear astrophysics community is the expiditious completion of the planned FRIB facility which is scheduled to be operational by the end of the decade. Until then it is crucial to pursue an active nuclear astrophysics program at existing radioactive beam facilities which will allow us to develop and test new equipment as well as to train the young researchers that will do the experiments at the next generation radioactive beam facility. All existing RIB facilities in North America are presently involved in a vibrant experimental program and at the same time undergo important upgrades that will increase the available beam intensities or give access to new nuclei that are critical to nuclear astrophysics. These facilities are briefly summarized below.

ANL: The CARIBU project has recently been completed providing access to new nuclei on the n-rich side of the mass valley. First experiments with a 400 mCi Cf source have started measuring masses with the Canadian Penning Trap. Transfer reaction studies using the HELIOS spectrometer and measurements of β-delayed n-branching ratios will start soon. The In-Flight radioactive beam program is planning to install a dedicated separator which together with liquid production targets will increase the beam intensities of experiments with radioactive isotopes by factors of $10^2 - 10^3$. With this upgrade (α,p) and (^{3}He,d) reactions (surrogates for (p,γ)) which are critical for novae and X-ray bursts will be measured.

FSU: The RESOLUT facility has started a new program with radioactive beams produced with the In-Flight technique. With the planned installation of additional resonators from KSU the range of radioactive beams will be extended towards heavier nuclei. An active target detector system (ANASEN) has been developed and plans for a neutron detector (ResoNeut) are being pursued. This will allow for (d,n) measurements as surrogate reactions of important (p,γ) processes.

NSCL: Nuclear astrophysics is presently being pursued with fast, stopped and soon also with reaccelerated beams. The experiments include mass measurements, direct reaction and structure studies, weak interaction studies as well as half-live and decay experiments with astrophysically important isotopes. Of particular importance to nuclear astrophysics are radioactive beams from the ReA3 project which, together with a dedicated recoil separator (SECAR) and a gas target (JENSA), will allow us to measure the resonance parameters of some of the critical (p,γ) reactions that play a role in explosive nucleosynthesis. Initially, the lower energy limit of beams available at ReA3 will be about 300 keV/u. It is foreseen that lower beam energies will be made accessible at a later stage, for example by placing the target at a high-voltage platform. The experience obtained in these experiments will be particularly important for similar studies with this device at the future FRIB facility, as discussed below.

TAMU: The radioactive beam program which in the past has used the In-Flight technique at the Mars recoil separator is presently going through an upgrade. Light stable beams from the K150 cyclotron will produce secondary particles which are stopped in a gas stopper and then transported to the K500 superconducting cyclotron for acceleration. Planned experiments will investigate g.s. properties and decay spectroscopy of astrophysically important isotopes as well as nuclear reactions.

TRIUMF: With the closing of the HRIBF facility ISAC is now the only operational ISOL facility in North America. In addition to the low-energy beams from ISAC-I which have been used to measure the rates for several astrophysically important reactions a new accelerator ISAC-II will provide higher energy beams. For astrophysics the Advanced Rare Isotope Laboratory (ARIEL) will open many new opportunities for nuclear astrophysics with n-rich beams produced through proton or photoninduced fission of actinides.

These facilities cover a large range of radioactive ion beams from low to high energies and are to a large extent complementary in their capabilities. This variety is an essential feature in order to identify the optimum conditions for future nuclear astrophysics experiments at FRIB.

1.2 Facility for Rare Isotope Beams (FRIB)

FRIB will produce a wide variety of short-lived isotopes with sufficient intensity to unlock the fundamental nuclear physics for understanding stellar explosions and the origin of the elements. At FRIB, the number of isotope species that can be produced is roughly double of what is known at present and approximately 80% of the isotopes that are are estimated to exist (see figure 1). These species include a very large fraction of those needed to accurately model the r-process path in the very neutron-rich regions of the table of isotopes, and all of those needed to extract detailed information on the rp-process and p-process paths in the very proton-rich regions (see figure 2). It will be possible to demarcate the neutron drip line up to sufficiently heavy masses to model the crusts of accreting neutron stars. And it will be possible to measure the masses and determine the decay and reaction rates of most of the isotopes that play significant roles in a wide variety of astrophysical phenomena. Given the unparalleled discovery potential of FRIB, it is no surprise that expeditious construction of FRIB is the highest nuclear physics priority for the nuclear astrophysics community.

At FRIB, unstable isotopes of interest for astrophysics will be available in the form of fast, stopped and reaccelerated beams. In addition, longer-lived unstable isotopes can be harvested and used in offline experiments, either at FRIB, or at other facilities. The experimental tools to most efficiently and accurately determine the nuclear physics properties of the unstable nuclei of interest for astrophysics have been developed, or will have been developed when FRIB comes online, at a wide variety of institutions by a wide range of collaborations, as briefly summarized in the section on existing facilities.

The availability of reaccelerated beams of unstable isotopes at astrophysical energies is of critical importance for the study of the rp-process in X-ray burts, novae and supernovae, as well as explosive Silicon burning in supernovae. Direct measurement of (p,γ) and (α,γ) reaction rates will be possible using the SECAR recoil separator, in combination with the JENSA gas-jet target. The construction of these devices is of acute importance for advancing the goals of the nuclear astrophysics community.

Active targets, such as the AT-TPC and ANASEN will be available for measurements of astrophysical reaction rates with charged-particle final exit channels, such as (α,p) reactions. A HELIOS-type spectrometer will also play an important role in the study of transfer and other direct reaction studies. And a variety of γ-ray spectrometers such as GRETINA, SeGA, HAGRID, CAESAR and SuN will be used for studying reactions involving γ-emission.

Reaccelerated beams of slightly higher energy (up to 15 MeV/u) also play an important role for extracting nuclear physics information for astrophysical purposes, mainly by using transfer reactions, e.g. (d,n) and (d,p), that serve as surrogates for proton and neutron transfer studies. Information about charged-particle direct-capture reactions can be obtained by measuring asymptotic normalization coefficients with unstable beams in inverse kinematics. A recoil separator for analyzing the forward-going recoils (at $\sim 6-15$ MeV/u) is required, in combination with charged-particle, γ and neutron detectors (such as VANDLE and/or LENDA).

Harvested nuclei could be used for the determination of (n,γ) rates on unstable nuclei and provide data for branching points in the s-process. Plans for isotope harvesting are underway, both for primary user experiments as well as for secondary harvesting from the primary beam dump, which enables true multi-user capability at FRIB. The availability of such long-lived experiments for secondary experiments is critical—in neutron capture, for instance, existing neutron facilities have reached a point where measurements on many s-process branch points are possible, but samples are not available.

The accurate determination of masses of neutron-rich isotopes is of critical importance for understanding the r-process. High-precision mass measurements can be performed at the LEBIT facility using stopped beams. Further developments, such as the single-ion Penning trap, will be of tremendous value to push further the limit of which neutron-rich masses can be measured.

The highest yields of the most exotic unstable isotopes at FRIB will be achieved for fast beams. Experiments utilizing fast beams will, therefore, be critical in providing nuclear structure and decay information for isotopes furthest from the valley of stability. Decay spectroscopy (β, γ, n and p) of implanted fast beams will be critical to measure half-lives and decay properties of astrophysically important nuclei. Ongoing improvements to the efficiency and accuracy of the detectors (such as the Beta Counting System, 3HeN, NERO for thermal neutrons, and MTAS and a community-supported Clover Array for stopped γ-rays) used to characterize the various decay products will be important to optimize decay experiments performed at FRIB. In-flight decay spectroscopy using knock-out, Coulomb excitation, pickup and transfer reactions provides high-precision information on the structure of unstable isotopes. This information is required to improve theoretical models used in astrophysical calculations. More central heavy-ion collision studies provide information on the equation of state of nuclear matter, which is important for understanding dense environments such as neutron stars. Charge-exchange reactions with fast beams provide the only way to effectively constrain theoretical models used for estimating weak interaction rates, which are critical for understanding core-collapse and thermonuclear supernovae. Time-of-flight mass measurements with fast beams will be used for mass regions where the life-time is too short for high-precision trap measurements. The measurement of fission excitation functions of importance for astrophysics can be performed with both fast and reaccelerated beams.

A wide variety of detection systems for experiments with fast-beams are, or will become available for early experiments at FRIB. Many of these experiments can be performed with the existing S800 spectrometer. However, the beam energy for such experiments would be constrained by the limited rigidity of the spectrometer and associated beam transfer lines. Therefore, an upgrade of the fast-beam experimental area with beam lines that can bend the most neutron-rich unstable isotopes at the energies where they are produced most abundantly and a high-rigidity spectrometer to perform the analysis of heavy fragments after the reaction is an important need.

2 Neutron Induced Reactions

The production of the elements beyond iron proceed primarily through neutron-capture reactions, either in explosive environments (via an r process) or in stellar atmospheres (via s-process nucleosynthesis). Further neutron-induced reactions, including (n, γ) and (n, α), are critical for modeling p-process environments as well providing needed nuclear physics underpinnings for γ-ray astronomy and solar system formation. While measurements are still needed in select cases on stable isotopes, the most critical present needs are on unstable isotopes.

Because of the lack of a Coulomb barrier for these reactions, the energies of interest are significantly lower than for competing charged particle reactions—in fact, the energies are directly the thermal particle distributions. This provides additional challenges for theoretical efforts to *calculate* neutron-induced reaction rates. While the reactions sample regions of relatively high excitation, the details of the nuclear structure at these energies strongly impact the cross sections.

As a result, the measurements of these cross sections have focused strongly on direct reaction measurements with neutron beams. The last 15 years have seen significant changes in the experimental facilities for these measurements. Two major facilities, Forschungszentrum Karlsruhe (FZK) and the Oak Ridge Electron Linear Accelerator (ORELA), have both closed. Taken together, these two facilities represented roughly 80% of the world activity for neutron capture measurements for nuclear astrophysics. While the closing of these facilities is an obvious loss, the measurement techniques they developed and pioneered have been incorporated in the new facilities which have begun operation in the last 15 years

2.1 Present Neutron Facilities

n_TOF The neutron time-of-flight facility at CERN (Switzerland) couples both C_6D_6 and BaF_2 detector arrays at the end of a ~200 m flightpath to a neutron source driven by 20 GeV proton-induced spallation on a Pb spallation target. This combination of long flight-path with intense production mechanism provides a combination of high neutron energy resolution, intense peak neutron flux, and moderate average neutron flux.
LANSCE The Los Alamos Neutron Science Center at Los Alamos (USA) is a facility with multiple neutron flightpaths driven by 800 MeV proton-induced spallation on tungsten. The primary capability for nuclear astrophysics comes from the Detector for Neutron Capture Experiments (DANCE), an 160 element, BaF_2 calorimeter located 20 m from the spallation target. DANCE was designed specifically with the goal of performing neutron capture cross-section measurements on short-lived (>100 d) isotopes. The combination of short flight-path with high-intensity neutron source offers a high neutron flux with moderate neutron energy resolution. In addition to DANCE, LANSCE offers several other neutron flightpaths for the measurement of $n, n')$, (n, p), and (n, α) reactions.
GELINA The Geel Electron Linear Accelerator in Belgium offers multiple flightpaths ranging from 10-400 m from the spallation target. Neutrons are produced via photo-neutron production from Brehmstrahlung from the 150 MeV electron beam. Detection capabilities include C_6D_6 detectors, ionization detectors for neutron-induced charged particle reactions, and ^{6}Li-glass detectors for total cross section measurements. GELINA offers modest flux, but very high energy resolution, which is needed far total cross-section measurements.
JPARC The Japan Proton Accelerator Research Complex includes a HPGe arrays and NaI(Tl) spectrometer for measurements of neutron induced reactions, however, the neutron energy resolution is limited by the quite broad (~800 ns) proton spallation pulse.

In addition to existing neutron facilities, multiple new facilities are either in the planning or construction phases, all designed to push farther from stability and to more exotic astrophysical scenarios.

2.2 New and Proposed Neutron Facilities

FRANZ The FRANZ facility at the University of Frankfurt is under construction and is expected to be running in 2013 and complete in 2014. It is focused on intense neutron beams specifically for nuclear astrophysics with keV time-of-flight beams of $> 10^7$ n/cm^2/s and activation beams of $\sim 10^{12}$n/s. Detection systems will include a 4-π BaF_2 array.
n_TOF EAR-2 This approved second experimental area located at 20 m for n_TOF will provide capabilities for more intense neutron fluxes at a cost of neutron energy resolution.
SARAF The Soreq Applied Research Accelerator Facility (Israel) will provide high intensity Maxwellian-averaged neutron fluxes for activation measurements.
LANSCE Pulse-Stacking This is a upgrade path for the LANSCE neutron beam facilities that is still in the proposal stage with NNSA. It would offer significantly enhanced (factors of 50-1000) neutron fluxes in the 1<E_n <500 keV regime relative to DANCE while simultaneously improving the neutron energy resolution. It would include the construction of a new

gamma-ray calorimeter for neutron capture measurements. Further, this redesigned neutron source would be ideal for (n,p) and (n,α) measurements.

NIF The National Ignition Facility (USA) is a plasma facility designed to produce intense bursts of neutrons in a 1-20 keV plasma environment. While the neutron spectrum is not not matched to a stellar energy distribution, the combination of extreme peak flux with a plasma environment offers a new method of measuring nuclear reactions. The environment is challenging and present a new set of systematic limitations. Development is underway to determine how to best exploit this new resource for nuclear astrophysics

Taken together, the future capabilities for neutron facilities is quite bright. As an additional benefit to the nuclear astrophysics community, the operation and construction of many of these facilities has been funded by agencies that are not traditional funding sources for nuclear astrophysics.

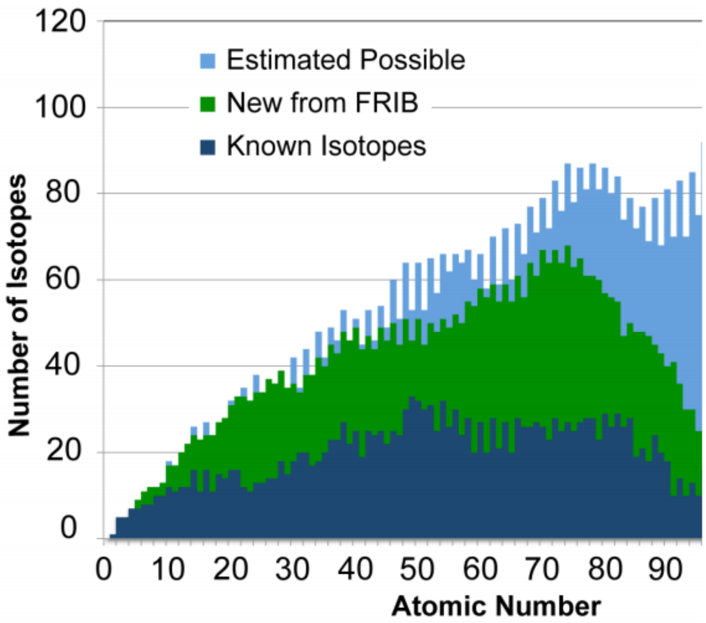

Figure 1

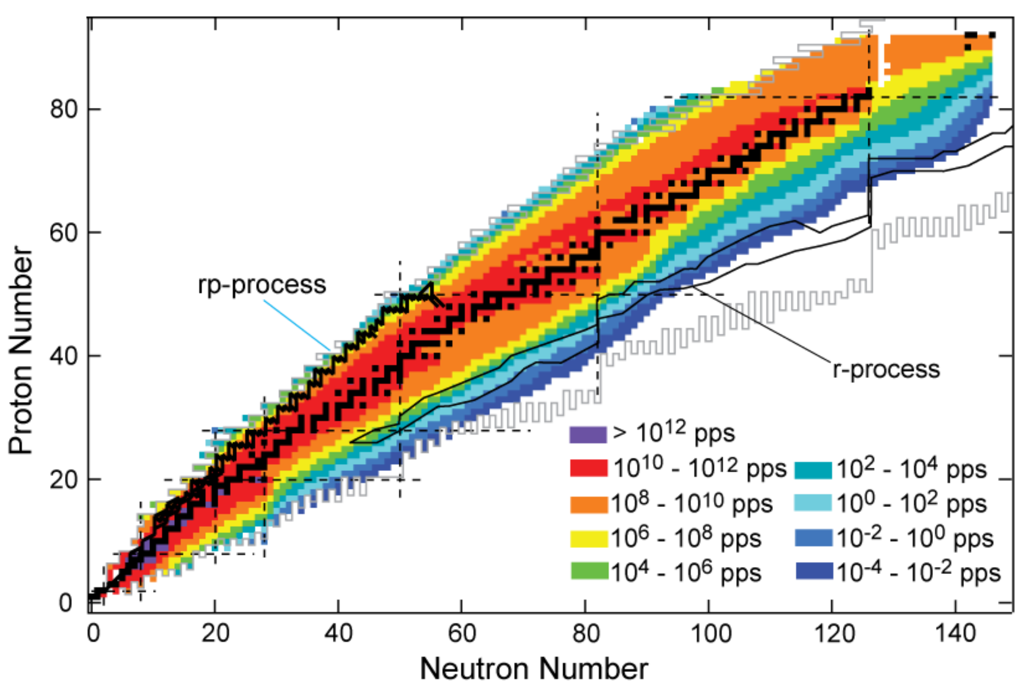

Figure 2