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Transfer of the Oak Ridge Enge Split-Pole Spectrograph to Notre Dame

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Abstract. The rates of nuclear reactions involving radioactive nuclei represent critical input parameters for models of explosive astrophysical events. These rates are largely determined by the nuclear structure of the exotic nuclei involved. An Enge Split-Pole Spectrometer is being transferred to Notre Dame to study the structure of exotic nuclei. Light-ion induced transfer reactions will be measured with high resolution using the combination of the spectrometer with high-quality tandem-accelerated beams. The spectrometer installation and plans are presented.

Introduction

There are a number of astrophysical events where hydrogen and helium nuclei are consumed in an explosive process [1]. During these events such as novae, X-ray bursts, and supernovae, exotic radioactive nuclei are produced that can be further transformed by subsequent nuclear reactions. Reactions on radioactive nuclei, therefore, have a central role not only in stellar nucleosynthesis but can also affect the explosion energetics and resulting light curves of astrophysical events. As such, critical comparisons between model predictions and observations depend heavily on astrophysical reaction rates involving radioactive nuclei.

The astrophysical reaction rates that provide critical input to these models are preferentially determined by measuring the reaction cross sections in the laboratory. For the cases involving radioactive nuclei, however, this is rarely possible as intense beams of these nuclei would be required, which is typically not possible for the current generation of exotic beam facilities [2]. Even in cases where intense beams are available, it is generally not feasible to measure the cross section at all energies required to completely characterize the astrophysical reaction rate.

An important alternative to directly measuring the rates is to determine the nuclear structure of the important exotic nucleus in order to estimate the cross section and the astrophysical rate. It is possible to determine the astrophysical reaction rate from the nuclear cross section since the energies of the interacting particles obey a Maxwell-Boltzman distribution (assuming non-degenerate conditions) at a given temperature, *T*. Consequently, the reaction rate will depend on the velocity-averaged cross section of the nuclear reaction

$$\langle \sigma(v)v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\left(\frac{1}{kT}\right)^{3/2}\int_0^\infty \sigma(E)E\exp\left(-\frac{E}{kT}\right)dE$$

where k is the Boltzmann constant and μ is the reduced mass of the initial reactants [3]. It is straightforward to calculate the astrophysical reaction rate if the reaction cross section is known. The reaction cross section as a function of energy usually exhibits rather sharp peaks due to resonances superimposed onto a slowly varying non-resonant background. The resonance cross sections can be parameterized with a Breit-Wigner formula leading to the expression for the reaction rate from a narrow isolated resonance

$$N_A < \sigma v >_r = 1.540 \times 10^{11}(\mu T_9)^{-3/2}\omega\gamma_r \exp\left(-\frac{11.605E_r}{T_9}\right)$$

where the reaction rate is in units of $cm^3mole^{-1}s^{-1}$, T_9 is the temperature in GK, μ is in amu, E_r is the center of mass resonance energy in MeV, and $\omega\gamma$ is the resonance strength in MeV [3]. The resonance strength is

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$$\omega\gamma_r = \frac{2J_r + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_a \Gamma_b}{\Gamma_r}$$

where J_r, J_1, J_2 are the spins of the resonance and interacting reactants in units of ħ, respectively and Γ_a, Γ_b, and Γ_r are the partial decays widths through channels *a, b*, and total width of the resonance, respectively. If there are multiple isolated narrow resonances that can contribute, the total reaction rate is the incoherent sum of such contributions. As can be seen above, if the resonance energies, spins, and partial widths can be determined, the astrophysical reaction rates of interest can be calculated. Such nuclear spectroscopic information can often be ascertained in the study of nuclear transfer reactions on stable nuclei.

Transfer Reactions

Nuclear transfer reactions have long been used to study the structure of nuclei. As discussed in the previous section, such studies are an important method for constraining astrophysically-important nuclear reaction rates [4]. Traditionally, such studies are initiated by bombardment of heavier targets by light ions. As a consequence, most studies have been limited to targets for which thin films can be made except for a handful of cases where gas targets or implanted targets have been utilized. The transfer reaction products are also light nuclei (or nucleons), which can be detected and analyzed to yield nuclear structure information for populated levels. The energy (or momentum) spectra of the emitted ejectiles allows for a rather direct determination of the resonance energies for a given reaction upon which the astrophysical reaction rate depends exponentially. The angular distributions of emitted ejectiles are characteristic of the transferred angular momentum and can thus be used to constrain the spins of nuclear levels. This is typically done by comparing the observed angular distributions with those calculated from models such as Distorted-Wave Borne Approximation (DWBA) [5] or Adiabatic Distorted Wave Approximation (ADWA) [6]. Partial widths can be estimated from particle-decay branching ratios or spectroscopic strengths measured in transfer reactions. Reactions that have been useful for such studies include *(p,d), (p,t), (d,p), (d,t), (^{3}He,d), (^{3}He,^{4}He), (^{6}Li,d), (^{7}Li,t)*, and more.

The extraction of useful information from studies of transfer reactions depends strongly on optimization of the experimental apparatus. The ability to resolve closely-lying states is greatly enhanced by obtaining good energy or momentum resolution for the outgoing particles. This typically requires the combination of low beam emittance, thin targets, and detection techniques with very good energy or momentum resolution. While this requirement can sometimes be mitigated by detecting γ rays in coincidence, there is usually an associated tradeoff in efficiency. Also γ-ray detection from unbound states may be difficult as the γ-ray branching ratio is often vanishingly small. It is also important to have reasonable angular resolution (~1-2^o) for the outgoing particles. Characteristic oscillations in the angular distribution pattern typically occur over the angular range of 10-15^o, and thus a reasonable angular resolution is required. Particle identification of the outgoing ejectiles is usually also required since many reaction channels may be open. Finally in order to measure particle-decay branching ratios, it is desirable to have detectors near the target that can detect the decay particles in coincidence with the transfer-reaction ejectiles.

All of these requirements can be met with the combination of an Enge split-pole spectrograph [7] and a high-resolution tandem accelerator beam. Because of their utility, Enge split-pole spectrographs have been and continue to be used at a number of facilities world-wide [8,9]. The Oak Ridge National Laboratory's Holifield Radioactive Ion Beam Facility (HRIBF) [10] was shut in 2012, which in turn left an Enge split-pole spectrograph available for transfer. In 2015, the Department of Energy approved transfer of the device to the Notre Dame Nuclear Science Laboratory (NSL). The refurbishment, installation process, and plans for its use are described below.

The Notre Dame Enge Split-Pole Spectrograph

The Notre Dame (previously HRIBF) Enge Split-Pole Spectrograph is a Scanditronix model ESP 90 device based upon the original design of H. A. Enge [7]. The main utility of the split-pole design is that the boundaries of the pole pieces are shaped such that transverse focusing is accomplished for the full 3.8-cm gap between the poles. The concept allowed for a greater acceptance (8-12 msr) while maintaining good energy resolution (~1%). This spectrometer had originally been installed at the ORNL EN Tandem [11] and then later moved to the Holifield Heavy Ion Research Facility [12]. A schematic of the device is shown in Fig. 1.

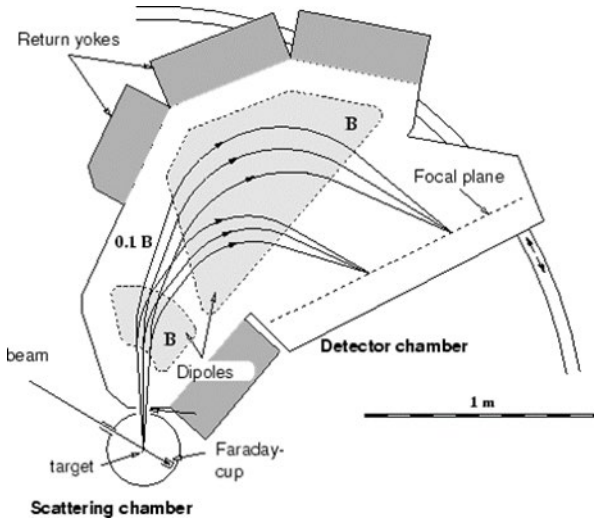

Figure 1: Top view of the Enge split-pole spectrograph [7].

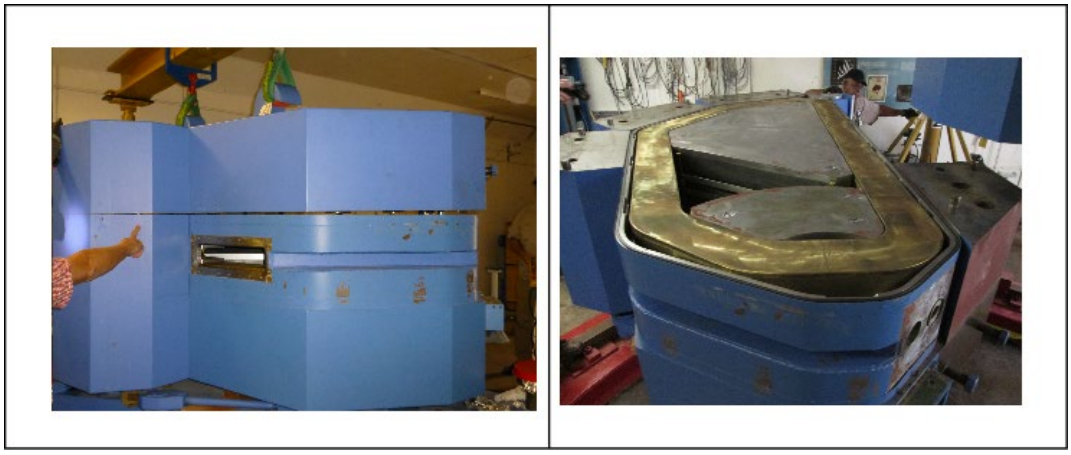

Figure 2: (Color online) Components of the spectrograph during disassembly in 2015.

The spectrometer was disassembled and removed from the HRIBF in the Fall of 2015. Disassembly was challenging as a result of the delicate nature of the components (e.g., the copper coils), the substantial weight (~66000 lbs), and the relatively low clearance in the experimental hall. A pair of 20000-lb capacity hydraulic lifts were used in conjunction with a cross beam to delicately lift and remove individual components of the spectrometer (Fig. 2).

Smaller components were packed in wooden crates while large components were loaded directly onto flatbed trailers for shipping. Exposed iron surfaces were coated lightly with diffusion pump oil to help protect the components from the elements. Unfortunately, complications in the approval, transfer, and shipping processes resulted in the spectrometer not actually being shipped until May 2016. Despite the best efforts to protect the components, significant rusting and degradation was observed on a number of critical systems when they arrived at Notre Dame (Fig. 3). Particularly troublesome was that the gears used to rotate the spectrometer were rusted, bound, and completely inoperable. All of the effected components were disassembled and treated with a glass bead blasting process to remove rust and corrosion. The bearings in the mounting trolley were also replaced to ensure smooth operation. The refurbishment was complete by Spring 2017, and the results are shown in Fig. 3.

Figure 3: (Color online) (Left) Components of the spectrograph exhibiting significant rust and corrosion as theyarrived at Notre Dame. (Right) The same components after refurbishment in 2017.

The spectrometer is currently in storage, but installation of the spectrometer at the NSL is expected to begin during the Spring of 2019. The project has been reviewed by BSA Lifestructures [13], and a siting location inside the NSL has been identified. The best location was deemed to be on the 30^{o} beamline in the East Target Room as shown in Fig. 4. This location has the advantages of good access to FN tandem beams, direct access to an outdoor staging area through a retractable shielding wall, and the availability of a 5-ton overhead lift which could be useful during installation. It is expected that operations of the spectrometer could commence by 2020. The combination of the spectrometer with the large number of intense stable ion beams (hydrogen, helium, as well as "heavy" ions) available at the NSL will nicely complement the handful of spectrometers operating world-wide.

Conclusions and Acknowledgments

Transfer reactions have a long history of being used to study the structure of nuclei. Constraining the nuclear structure of exotic nuclei would allow for better estimates of astrophysical reaction rates that occur during explosive nucleosynthesis. Studies of transfer reactions are facilitated by having a high-resolution spectrometer in conjunction with high-quality tandem accelerator beams. The HRIBF Enge Spectrometer has been transferred to the University of Notre Dame Nuclear Science Laboratory in order to perform such studies. The device is currently in storage, but installation at the NSL is expected to begin in the Fall of 2018 with operations becoming possible in 2020.

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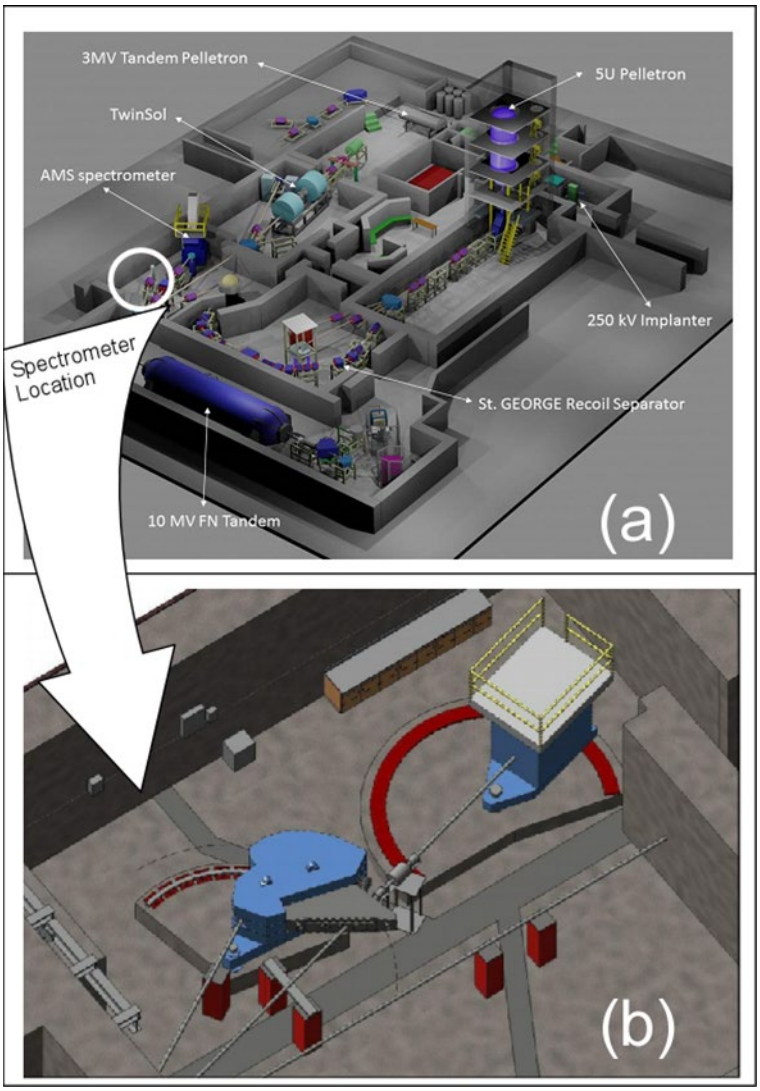

Figure 4: (Color online) (a) Facility layout of the Notre Dame Nuclear Science Lab. (b) Model drawing of the expected installation location of the spectrograph in the East Target Room. Removable beam line components will be installed on the adjacent beamline to allow rotation of the spectrograph to the 0° position.

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