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A Gas Jet Target for Radioactive Ion Beam Experiments

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Abstract. New radioactive ion beam (RIB) facilities, like FRIB in the US or FAIR in Europe, will push further away from stability and enable the next generation of nuclear physics experiments. Thus, the need for improved RIB targets is more crucial than ever: developments in exotic beams should coincide with developments in targets for use with those beams, in order for nuclear physics to remain on the cutting edge. Of great importance to the future of RIB physics are scattering, transfer and capture reaction measurements of rare, exotic, and unstable nuclei on light targets such as hydrogen and helium. These measurements require targets that are dense, highly localized, and pure, and conventional targets often suffer too many drawbacks to allow for such experimental designs. Targets must also accommodate the use of large area, highly-segmented silicon detector arrays, high-efficiency gamma arrays, and novel heavy ion detectors to efficiently measure the reaction products. To address this issue, the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) Collaboration led by the Colorado School of Mines (CSM) is in the process of designing, building and testing a supersonic gas jet target for use at existing and future RIB facilities. The gas jet target provides a high density and high purity of target nuclei within a tightly confined region, without the use of windows or backing materials. The design also enables the use of multiple state-of-the-art detection systems.

Keywords: Gas jet target; Transfer reactions; Capture reactions; Radioactive ion beams.
PACS: 21.10.-k, 29.90.+r, 24.10.-i, 26.30.-k

MOTIVATION

As the capabilities of both radioactive ion beam (RIB) facilities and detector systems increase, improvements are also necessary in the targets used for cutting-edge nuclear physics experiments. Experiments such as scattering, capture and transfer reaction measurements with radioactive beams on light gas targets like hydrogen and helium are and will continue to be an important part of the program of any RIB facility for many reasons. Such measurements are necessary to address open questions in nuclear structure and astrophysics, and to continue pushing the frontiers of nuclear science.

In nuclear astrophysics specifically, there are a number of astrophysical sites where proton- and helium-induced capture or transfer reaction rates are needed to help explain observed phenomena. For instance, the empirical elemental composition of classical novae [1] is sensitive to the composition and mass of accreted material, the mixing of accreted matter with white dwarf matter, and the temperatures and densities of the dwarf. The composition can therefore serve as a unique probe of the explosion, but only provided the underlying nuclear reactions are known. Accurate reaction rates are needed to test these models against observations of ejecta compositions and to identify potential issues in the models.

X-ray bursts [2] are the most frequent thermonuclear explosions observed and occur on the surface of accreting neutron stars. The shape of the light curve can be used both as a diagnostic of astrophysical parameters and model assumptions, provided the nuclear reactions that power it are known

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with sufficient precision. Hydrogen- and helium-induced reactions on neutron-deficient nuclei are also important in explosive burning during core collapse supernovae, where a quasi-statistical-equilibrium provides free protons and alpha particles that drive nuclear reactions through typical waiting points. This is important, for example, to predict the synthesis of ^{44}Ti [3], a gamma-ray emitter that has been detected in some supernova remnants, providing a unique isotopic probe to the burning conditions deep inside a supernova.

On a broader scale, improvements in light-ion targets are necessary as measurements in nuclear structure and nuclear reaction mechanisms are performed with more exotic nuclei. Since beam production rates drop farther from stability, low statistics are common, and therefore any background from contaminants in a target cannot be tolerated. Target materials which are isotopically and chemically pure and homogeneous are of utmost importance for the next generation of nuclear structure experiments.

EXPERIMENTAL TECHNIQUES

Measurements in Nuclear Astrophysics

Several types of measurements can be used to expand our knowledge of astrophysical reactions: proton scattering, (^{3}He,d) transfer reaction studies, (d,p) transfer reaction studies, and direct measurements of (α,p) reaction rates, for example. Astrophysically important proton capture reactions are especially difficult to study due to their low cross sections and low beam energies. Proton transfer reactions can be used to determine relevant proton capture information, without requiring the high beam intensities or low beam energies necessary for (p,γ). Utilization of the simplest proton transfer reaction, (d,n), is difficult due to the challenges of neutron measurement. However, the (^{3}He,d) reaction measured with a sufficiently dense, localized and pure ^{3}He target and appropriate charged-particle detectors overcomes these obstacles. In addition, proton scattering measurements can be used to locate specific proton capture resonances which may be previously unknown, before using the (^{3}He,d) transfer reaction to study the new resonances in more detail. Spectroscopic factors extracted from the cross sections can be used to constrain direct capture transition strengths and partial widths of resonances when consistent theoretical frameworks are applied [4]. Angular distributions can be used to constrain spin and parities of resonant states.

(α,p) reactions play a critical role in X-ray bursts [5,6]. It has long been argued that statistical model reaction rates used in current X-ray burst models are highly uncertain, as level densities for the natural parity states populated are too low for statistical approaches to be applicable. In addition, α-clustering effects in the structure of the compound nuclear states might lead to additional deviations from averaged statistical model predictions. Therefore, direct measurements of the reaction rate are needed.

The (d,p) transfer reaction in inverse kinematics is an excellent tool for extracting information about (n,γ) and even (p,γ) capture cross sections through the use of theoretical descriptions, as is evidenced by much recent work. Simultaneous measurements of (d,d) reactions can further constrain the derived capture cross sections through constraint of the optical model parameters.

Measurements in Nuclear Structure

One example of a nuclear structure measurement which benefits greatly from the use of improved targets is the study of two-proton decay [7]. The structure of ^{17}Ne and the decay properties of its ground state and excited states have been the subject of much attention, originally due to the possibility that the first excited state could directly decay by two-proton emission to the ground-state of ^{15}O. Interestingly, this state lies below the ^{16}F+p energy threshold but above the ^{15}O+2p energy, leading to the possibility that only a simultaneous two-proton emission could occur (other than gamma decay back to the ground state of ^{17}Ne). Thus, although ^{16}F+p channels are open, the decay may actually proceed through ^{15}O+p+p two-proton decay. More statistics are clearly required to confirm and to study further the simultaneous two-proton emission from the excited states of ^{17}Ne, which is possible via population of the excited states by the (^{3}He,t) charge exchange reaction with a pure ^{3}He target. In this context, any sequential/simultaneous proton decays could then be related to known states in the daughter nuclei, improving the knowledge of the nuclear structure and reaction mechanisms leading to multiple particle emission.

Examining the (d,p) or (d,t) neutron-transfer reactions is also useful for study of neutron single-particle systematics near closed shells, or examining neutron halos (see, for example, Ref. [8]). Aside from providing spin and parity information, such single-particle transfer reactions also provide spectroscopic information such as spectroscopic factors or asymptotic normalization coefficients, elucidating single particle strengths and allowing for benchmarking of reaction formalism.

TARGET DEVELOPMENT

In all of these cases, hydrogen- and helium-induced reactions on unstable nuclei are of great importance to nuclear physics research. Scattering and transfer reaction measurements as well as direct (capture) reaction rate experiments require targets that are well confined, having an optimum balance of density and thickness to maximize count rates but minimize reaction product straggling and energy loss. In inverse kinematics, target optimization is difficult to achieve, since the light target isotopes (hydrogen, helium) cannot be easily made into targets, and because outgoing reaction products tend to have very low energies making them susceptible to energy loss and straggling. Traditional solid targets are often plagued with both chemical (such as the carbon in CH_2) or environmental (such as water vapor) contaminants, or require backing materials which contribute substantially to straggling and background. Gas targets can eliminate some of the difficulties, but potentially introduce others: a gas cell requires thin windows which worsen energy and angular resolution, and a windowless gas target (achieved via differential pumping), while useful for capture reactions [9], is too extended along the beam axis to allow angular distributions to be measured.

An advantageous solution to these difficulties is the construction of a supersonic gas jet target, which allows for a high density and homogeneity of target nuclei within a highly confined region. No windows or backing materials are present to produce unwanted background, gas purity is high and the amount of contamination is well controlled, and the small target size allows for high resolution measurements of energy and angle. Laval nozzles provide the high density and small dimensions necessary for the jet target, and various pumping stages, in conjunction with a diaphragm compressor, handle the flow and recirculate the gas within the system. Targets of this type (though mostly smaller in scale) are well documented in the literature, using a wide variety of gases and target densities [10,11,12,13,14,15,16,17,18,19,20].

For the types of measurements desired, the use of a gas jet target with new, exotic radioactive ion beams presents different constraints than with previous experiments. Light target gases, with areal densities up to 1×10^{19} nuclei/cm^2 (roughly equivalent to solid foil targets), are required for use with low-intensity radioactive ion beams. To assist in different types of measurements, the density of the jet should be continuously variable. Also necessary is the use of large area, highly segmented silicon detector arrays, high-efficiency gamma arrays and novel heavy ion detectors to efficiently measure the reaction products. None of the existing (decades-old) gas jets to date fulfill all of these requirements. The JENSA (Jet Experiments for Nuclear Structure and Astrophysics) Collaboration, led by researchers at the Colorado School of Mines, is developing just such a jet target for use at both new and existing radioactive ion beam facilities[1].

DESIGN

There are four main considerations when designing, constructing and testing the gas jet: nozzle design, effective pumping outside the jet, accommodation of detector arrays and recoil detectors, and an effective recirculation and gas cleaning system (the necessary components are shown schematically in Figure 1).

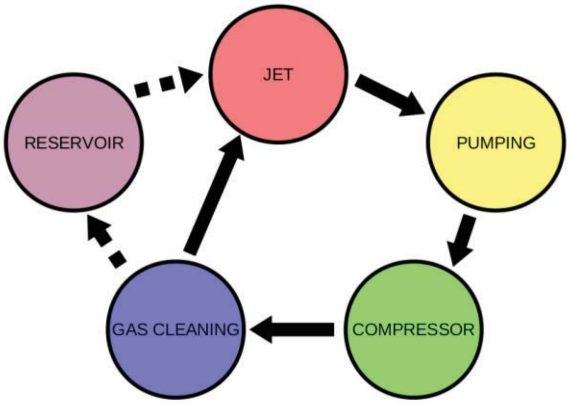

FIGURE 1. The basic components necessary for a recirculating gas jet target. Detectors for nuclear reaction products are included in the "JET" bubble.

The basic design of the gas jet target involves a Laval nozzle, to create the jet, with closely matched receiver nozzles to quickly collect the expanding gas. Laval nozzles, a standard design in many aerospace applications such as jet engines, provide the best throughput and shape for the jet, as demonstrated in Figures 2 and 3. The receivers are backed by a series of high-throughput roots blowers and dry multi-stage roots pumps, the exhaust of which feeds into a custom ~50 Nm^3/hr diaphragm compressor (Fig. 4). The compressor provides the reservoir pressure (up to 30 atm) necessary at the top of the jet, and can operate with as low as atmospheric pressure at the inlet. The remainder of the gas throughput, an estimated 1%, is handled by a series of upstream and downstream pumping stages separated by constrictive apertures (the backing of these pumping stages is also fed back

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[1] JENSA website: http://fribastro.org/5_EQUIPMENT/JENSA/JENSA.html

into the recirculating system, preventing gas losses over time). The flow rate through the system can be controlled by either restriction (via a needle valve) or by increasing the pressure compressor inlet by adding more gas; as the jet density varies with the flow rate, the jet can be continuously adjusted for the appropriate areal density. Actual jet profile and density measurements are planned for late 2012. Various pressure and flow diagnostics are located as necessary throughout the system for monitoring and feedback control, as well as safety considerations for the operation of compressed and/or explosive gases in the future. Gas cleaning and cooling systems will also be included to maintain homogeneity and prevent thermal straggling in the jet; the compressor itself has a built-in closed-loop cooling system which maintains the compressed gas at around 10 degrees Fahrenheit above ambient temperature.

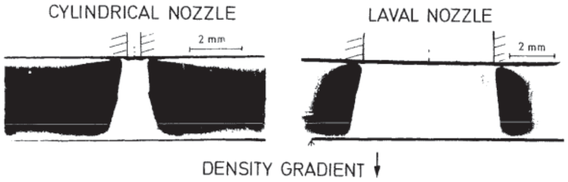

FIGURE 2. From Ref. [13], a Schlieren photograph of the jet profile from a cylindrical nozzle and a Laval nozzle using N_2 gas. The density gradient follows the direction of the arrow. Note that the Laval nozzle produces a straighter, more uniform profile.

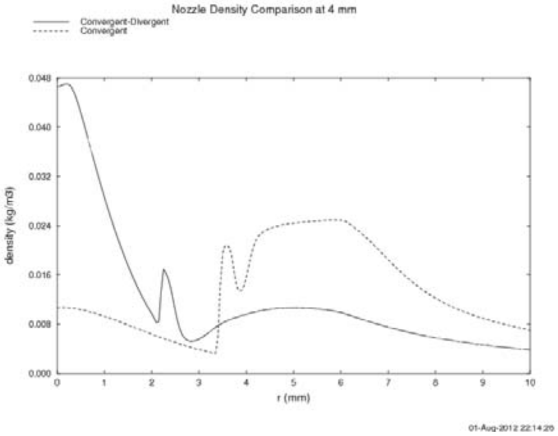

FIGURE 3. Hydrodynamic simulations of the jet density radial profile from a cylindrical (convergent) nozzle and a Laval (convergent-divergent) nozzle at 4mm from the nozzle opening, benchmarked against Ref. [20]. Note that the Laval nozzle creates a much more centralized jet.

FIGURE 4. The custom 50 m^3/hr compressor for the JENSA gas jet target as installed at the HRIBF.

Additionally, the design of the jet components and target chamber must be such that large silicon detector arrays, other charged particle arrays, and gamma-ray arrays can be accommodated and used. Different reaction studies will require slightly different arrangements of detector systems, but a general multi-array design will allow for further optimization as specific needs arise. For the proposed initial experimental program, a silicon detector array is needed with sufficient position resolution and angular coverage. We plan to use the SuperORRUBA detector system under development at ORNL [21] to begin our experimental campaign. The detectors will be mounted inside the jet target chamber around the jet-beam interaction point to detect outgoing charged particle reaction products, as in Figure 5. Since the pressure inside of the target chamber is expected to be in the milliTorr range, no issues with enhanced breakdown of the silicon detectors is anticipated. In addition, we plan to use for a subset of experiments a fast ionization chamber for identification of recoils downstream of the target; such a detector system is under development and testing at ORNL as well. We also plan to add gamma detection capability in the future, for example to tag excited states or to provide information about gamma cascades. We are exploring the construction of a dedicated high efficiency and cost-efficient HPGe array optimized for use with the gas jet target. One promising approach would be to enclose several germanium detectors within 2 custom cryostats to flank the gas jet; an example is the MARS array produced by Pacific Northwest National Laboratory. Also possible is the use of existing gamma detectors, or the new HAGRID detectors under development by a consortium of researchers at Rutgers University and the University of Tennessee Knoxville [22].

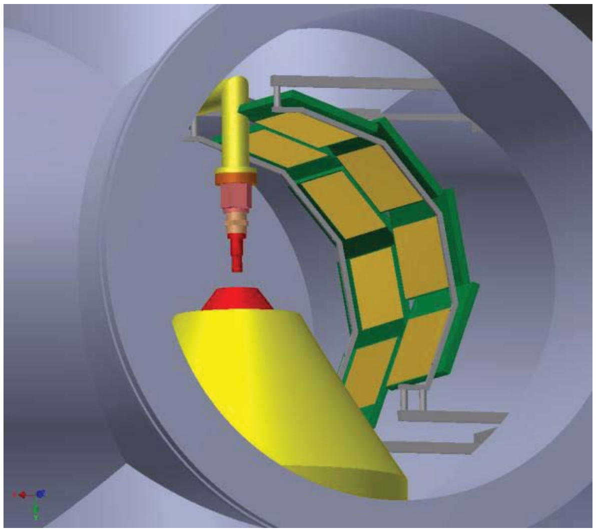

FIGURE 5. CAD drawing showing a possible implementation of the SuperORRUBA detectors around the gas jet target area.

Eventually, it is intended that the JENSA gas jet will become the main target for the SEparator for CApture Reactions (SECAR)[2], the next-generation recoil separator being designed for FRIB. Both JENSA and SECAR are considered as "having the highest scientific priority" for FRIB's future [23].

CURRENT STATUS

The JENSA gas jet target project including the SuperORRUBA silicon detector array has been fully funded by the US DOE, the design is finalized, and the construction is being completed. After initial installation and commissioning at ORNL, currently scheduled to be completed in early 2013, the target will be moved to the ReA3 hall at the NSCL as laboratory space becomes available and the necessary infrastructure is completed. Over the coming 1.5 years, the construction and commissioning of the gas jet target will be completed. In parallel, we will prepare the first full experimental proposals for its use at ReA3.

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[2] SECAR website: http://fribastro.org/5_EQUIPMENT/SECAR/SECAR.html