A Gas Jet Target for Radioactive Ion Beam Experiments

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With the development of new radioactive ion beam (RIB) facilities such as FRIB, which will push measurements further away from stability, the need for improved RIB targets is more crucial than ever. Important scattering, transfer and capture reaction measurements of rare, exotic, and unstable nuclei on hydrogen and helium require targets that are dense, highly localized, and pure. To this end, the JENSA Collaboration led by the Colorado School of Mines (CSM) is designing, building and testing a supersonic gas jet target for use at existing and future RIB facilities. The gas jet target allows for a high density and purity of target nuclei (such as ^{3}He) within a highly confined region, without the use of windows or backing materials, and will also enable the use of state-of-the-art detection systems. The motivation, specifications and status of the CSM gas jet target system is discussed.

Keywords: Gas jet target; Transfer reactions; Capture reactions; Astrophysics

1. Astrophysical Motivation

Scattering and transfer reaction measurements with radioactive beams on hydrogen and helium targets are an important part of the program of any radioactive beam facility for many reasons. For instance, there are a number of astrophysical sites where proton- and helium-induced capture or transfer reaction rates are needed to address open questions. The observed elemental composition of classical novae[1] is sensitive to accreted composition, mixing of accreted matter with white dwarf matter, mass of the accreted layer, temperatures, and densities and can therefore serve as a unique probe of the explosion, 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 measured shape of the light curve can be used as a diagnostic of system parameters and model assumptions, provided the nuclear reactions that power it are known with sufficient precision. Hydrogen- and helium-induced reactions on neutron-deficient nuclei are also important in explosive burning during core collapse supernovae, where quasi-statistical-equilibrium provides free protons and alpha particles that drive nuclear bottleneck reactions connecting clusters of equilibrium. 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.

2. Experimental Campaign

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.

Astrophysically important proton capture reactions specifically are difficult due to their low cross sections and low 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 (see, for example,[7]). The (d,p) reaction has long been used to study the spectroscopy and single-particle nature of nuclei. Simultaneous measurements of (d,d) reactions can further constrain the derived capture cross sections.

3. Target Development

In all of these cases, hydrogen- and helium-induced reactions on unstable nuclei are of great importance to nuclear astrophysics 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 energy loss and straggling. 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 contaminants (such as carbon and oxygen), or require backing materials which contribute substantially to straggling and background. Gas targets can eliminate some of the difficulties, but sometimes introduce others: a gas cell requires thin windows which worsen energy and angular resolution, and a windowless gas cell target (achieved via differential pumping) 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.[8–17]

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, are required for use with low-intensity radioactive ion beams. Also necessary is the use of large area, highly segmented silicon detector arrays, highly-efficiency gamma arrays and novel heavy ion detectors to efficiently measure the reaction products. None of the existing gas jets to date fulfills 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.

4. 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 basic design of the gas jet target involves a Laval nozzle, which provides the best throughput and shape for the jet, with closely matched receiver nozzles. The receivers are backed by a series of high-throughput roots blowers and dry screw pumps, which feed into a $\sim$50 Nm^3/hr diaphragm compressor (upgradeable). The compressor provides the reservoir pressure necessary at the top of the jet. Gas chillers minimize straggling due to thermal energy in the gas and maintain gas purity. The remainder of the gas throughput, roughly 1%, is handled by a series of upstream and downstream pumping stages separated by constrictive apertures. Various pressure and flow diagnostics will be located as necessary throughout the system for monitoring and feedback control, as well as safety considerations. Gas cleaning and cooling systems are also included.

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 HRIBF 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 1. 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 at HRIBF 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.

5. Status of the Gas Jet Target

The gas jet target project including the superORRUBA silicon detector array has been fully funded by the US DOE, and the design is being completed. After initial installation at HRIBF, the target will be moved to the ReA3 hall at the NSCL as soon as beamlines become available. Additional funding for a proof of concept gamma detection array along the lines of MARS is currently sought. We are preparing to move the JENSA gas jet target to the NSCL in the beginning of 2013. Over the coming 1.5 years, the gas jet target will be constructed and tested at HRIBF. In parallel we will prepare the first full experimental proposals for its use at ReA3.

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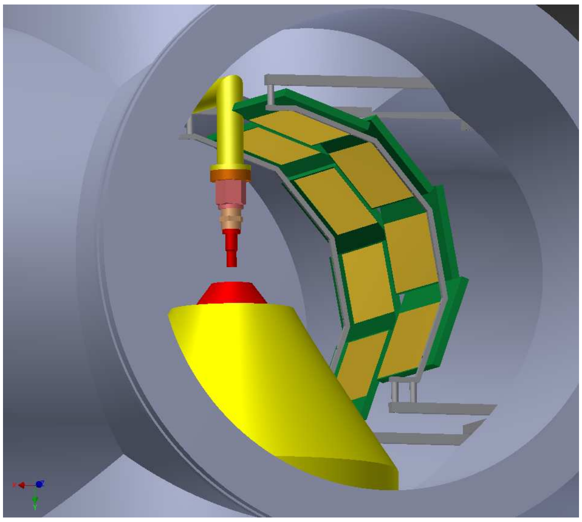

Fig. 1. CAD representation of the superORRUBA detectors mounted around the gas jet target.

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