Design and Construction of a Gas Jet Target for RIB Experiments

Jet Experiments in Nuclear Structure and Astrophysics (JENSA) Collaboration
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Introduction

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, and are needed to address important open questions in nuclear structure and astrophysics. For example, in nuclear astrophysics, the (^{3}He,d) reaction serves as a high resolution surrogate for the study of proton capture reactions, enabling access to the many reactions further away from stability, or with particularly low resonance strengths that cannot be measured directly. A hydrogen and helium gas target is needed at FRIB to take full advantage of the tremendous increase in available radioactive beam species suitable for scattering and transfer reaction measurements. In addition, FRIB will provide beam intensities that will enable the direct measurement of many proton- or alpha-induced reaction rates important in explosive hydrogen and helium burning in astrophysics, again requiring high density hydrogen and helium targets. The Gas Jet Target developed by this collaboration will form the heart of the proposed Separator for Capture Reactions (SECAR) at FRIB. Without a high-density, highly localized target of light ions, the reactions for which SECAR was designed will be tremendously difficult, if not unattainable. Developments in exotic beams should coincide with developments in targets for use with those beams, in order for the science of FRIB to continue moving forward.

Scattering and transfer reaction measurements as well as direct reaction rate experiments require targets that are well confined, having an optimum balance of target nucleus number 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 necessary (hydrogen, helium) cannot be easily made into targets. Traditional solid targets are often plagued with contaminants (such as carbon and oxygen), or require backing materials like aluminum or nickel which contribute substantially to straggling and background. Gas targets, such as are necessary with helium, can eliminate some of the difficulties, but introduce others: a gas cell requires thin windows which worsen energy and angular resolution, and an windowless gas 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 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 are well documented in the literature, using a wide variety of gases and target densities.

The use of a gas jet target with new, exotic radioactive ion beams such as those available at FRIB presents different constraints than with previous experiments. Light target gases, with areal densities up to $1x10^{19}$ nuclei/cm^2, are required for use with low-intensity (more exotic) radioactive ion beams. 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. No gas jet to date has been designed which fulfills all of these requirements. The Gas Jet Target Working Group, led by researchers at the Colorado School of Mines, is optimizing just such a jet target for construction and use at both new and existing radioactive ion beam facilities.

General Design Considerations

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 with two receiver stages. The receivers are backed by a series of high-throughput roots blowers and dry screw pumps, which feed into a ~50 Nm^3/hr diaphragm compressor. 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. A rough schematic is displayed in Figure 1.

The remainder of the gas throughput, roughly 1%, is handled by a large turbomolecular pump directly on the target chamber, as well as a series of upstream and downstream pumping stages separated by constrictive apertures. Design of the apertures and pumping stages determines the pressure gradient along the beamline, as well as providing the high vacuum (~10^{-6} Torr) needed to connect to the accelerator. Various pressure and flow diagnostics will be located as necessary throughout the system for monitoring and feedback control, as well as safety considerations.

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.

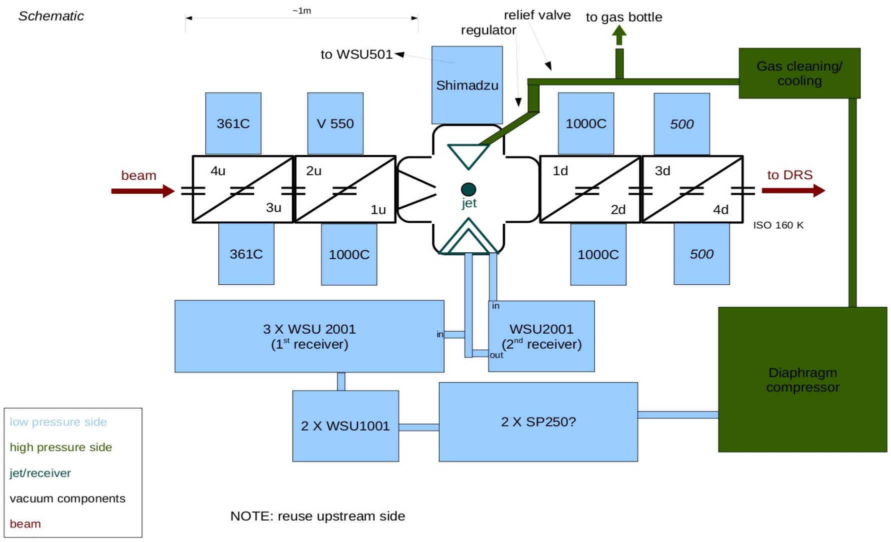

Figure 1: Preliminary schematic of the gas flow components

Optimization and Flexibility

Due to the various types of reaction studies which would benefit from the use of a gas jet target, several are likely to be constructed over the coming years. The first will be installed at the target position of the Daresbury Recoil Separator (DRS) at the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL. The design requires that the downstream apertures of the pumping stages be wide enough to admit any recoils which fall inside the angular acceptance of the DRS. This affects the pumping required on the downstream side of the jet. It is envisioned that this target may be moved to TRIUMF in Vancouver, Canada, for use with the new EMMA recoil separator being designed and built in the ISAC-2 hall.

A second jet will then be constructed for the ReA3 facility at the NSCL and will later be used at FRIB. The preliminary implementation of this target would not require downstream pumping stages, because a beam diagnostic or ionization chamber would be located just downstream of the target chamber. The downstream portion of the ReA3 gas jet target will be designed in conjunction with the finalization of designs for SECAR, the new recoil separator for FRIB, such that the target-detector system was optimized.

Contingent upon additional funding (external to this report), a third gas jet target may be built for the Dakota Ion Accelerators for Nuclear Astrophysics (DIANA) at the underground laboratory DUSEL in the Homestake Mine in South Dakota, in order to perform ultra-low-background reaction measurements. The DIANA facility is being designed to provide intense stable beam currents up to 100mA, and so a high-velocity gas jet target is absolutely necessary to handle the anticipated beam powers.

In each case, a balance must be found between the amount of flexibility desired (number of target gases the system is capable of handling, changes to pumping stages or apertures, changes to nozzle and thus jet dimensions, etc) and the amount of optimization desired (maximize density for one gas, design of apertures to complement recoil detectors, beam optics and infrastructure considerations, etc). This work is ongoing within the collaboration.

Detector Systems

It is envisioned that several detection systems will be either developed, adjusted or employed with the gas jet (be it at HRIBF, TRIUMF, ReA3 or FRIB). Existing detector arrays could be modified to fit around the jet for reaction studies, as described below. Arrays which are in the early stages, such as superORRUBA or SHARC, could also be modified for use with the jet, and designing mounts and feedthroughs for such arrays is planned. ANASEN or other heavy ion detectors could be placed downstream of the gas jet in place of pumping stages, and the jet could be used with or without a recoil separator.

Large arrays of charged-particle silicon-strip detectors will be implemented near the interaction point of the exotic beam with the gas jet target. These arrays are critical for determining the energy and angular distribution of ejectiles from the reactions of interest. The detection of the reaction products is required to extract the nuclear properties that determine the rates of reactions in astrophysical explosions.

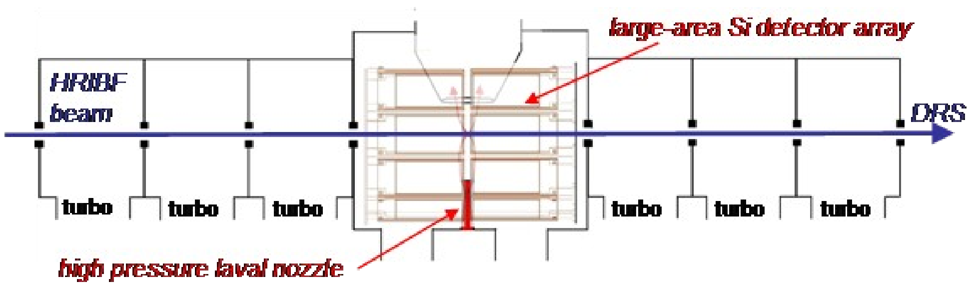

Figure 2: The ORRUBA array coupled to the gas jet target

In the early stages, existing arrays will be configured to surround the gas jet target at ORNL, as demonstrated in Fig. 2. New mounting and cabling will be required in order accommodate the nozzle and gas receivers of the gas jet target. Additional detectors and signal processing electronics will be procured so that a full implementation of the existing arrays can be instrumented. Similar setups will be used at NSCL ReA3. Based on these experiences, we will develop the optimum instrumentation for FRIB experiments.

As ion beams have become more exotic, the beam intensities and contamination have made the ability to detect a gamma coincidence at the target into a requirement for many experiments. Additionally, the DRAGON separator at TRIUMF and the DRS at HRIBF have demonstrated that gamma arrays at the target are not only useful for event tagging, but the spectroscopy information can be used to produce meaningful science directly (for example by measuring short lived excited states). Clearly, in the case of the gas jet target, a gamma spectroscopy array will be necessary in conjunction with the charged-particle detector arrays. We suggest the construction of a high efficiency and cost-efficient, close packed, HPGe array would best fill this need. One promising approach would be to enclose several germanium detectors within 2 custom cryostats to flank the gas jet. This gives great freedom in terms of custom geometry, crystal size, and crystal quality while maximizing detection efficiency by co-locating the crystals within distances of approximately 1cm and utilizing no internal shielding. One example is the MARS array produced by Pacific Northwest National Laboratory (see Figure 3).

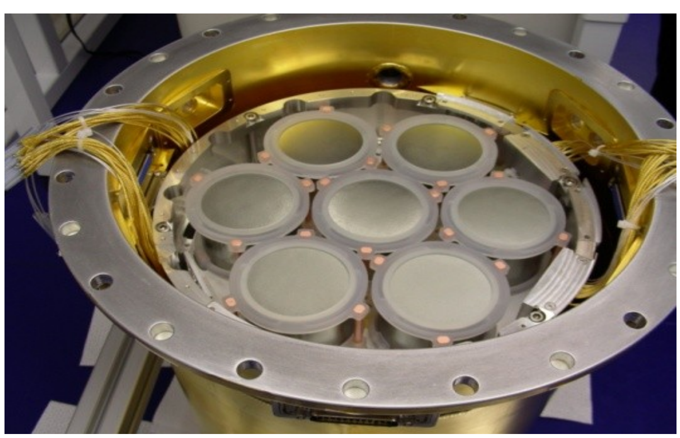

Figure 3: The PNNL MARS array

At this time, members of the JENSA collaboration are looking to secure external funding to run proof of concept measurements using the MARS array. This includes operating MARS at suitable beamline facilities such as ISAC1 at TRIUMF and also static laboratory tests with sources. Based on these results, a new array could be constructed at PNNL based on the same principles as the MARS array, but customized to the needs of the gas jet target. Additional funding would be required for this customized germanium array, but the necessary budget is not yet known, and thus not included in this report. Funding for the design and procurement of the superORRUBA and ANASEN arrays already exist, but ongoing funds for future operation or modification will be necessary if they are to be utilized with any of the gas jet targets. Implementation of these detection systems with the high-density gas jet target will create an opportunity for nuclear reaction studies unique in the world.

Next Steps

The acquisition of components, construction and testing of the first gas jet target at ORNL will take place in the next 1-2 years first at ORNL and then, based on the initial experience, at NSCL ReA3. Gas flow calculations have been completed, quotes for the necessary components are currently being acquired, and infrastructure requirements are being finalized. Members of JENSA will continue to work collaboratively on experimental campaigns, procurement of target gases, detector systems and specific design issues as they arise. A collaboration meeting is tentatively scheduled for March 25th, 2011.

Timelines, Budgets, Requirements

The JENSA collaboration anticipates acquisition, construction and testing of the first (ORNL) and second (ReA3) gas jet target within the next three years. This timeline is contingent upon appropriate levels of financial, engineering and administrative support; A DOE grant to the Colorado School of Mines provides funding for the design, purchase, construction and testing of one jet (ORNL). JINA provides equipment funding and some manpower for the second ReA3 target. Additional, modest funding for detectors at NSCL ReA3 has been requested within the NSCL operating grant proposal to NSF. This should be sufficient to establish a gas jet target setup for ReA3 and FRIB. In order to take full advantage of the target at FRIB, the SECAR recoil separator will be needed, for which funding is currently sought. Additional funds will also be needed for a gamma-ray detection array and modification of existing charged-particle arrays. The collaboration currently explores technical options, and it is too early for actual cost estimates.

Rough Timeline

2011: Begin acquiring components for ORNL gas jet target; machining of interior jet components; determination of infrastructure needs at ORNL and NSCL; acquisition of components (plus individual component testing); machining of downstream pumping stages

2012: Preliminary testing of gas jet central region (^{4}He); acquisition of components for additional gas jets (ReA3, DIANA?); acquisition and testing of compressor and gas purification systems; machining of pumping stages and jet components for additional gas jets

2013: Final on-site construction of ORNL gas jet; testing of full gas jet system; incorporation and testing of detector systems; construction of additional gas jets; in-beam testing of ORNL HRIBF and NSCL ReA3 gas jets

Rough Budget

Total: CSM+subcontractors, $1.025million (including contingency; see Gas Jet Project Management Plan for detailed information)

External Requirements

Engineering work to determine correct infrastructure requirements at ReA3/FRIB

Engineering work to determine feasibility of/requirements for moving gas jet between facilities