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EDITED BY
Alan Wuosmaa,
University of Connecticut, United States

REVIEWED BY
Alessandra Guglielmetti,
University of Milan, Italy

*CORRESPONDENCE
K. A. Chipps,
chippska@ornl.gov

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Gas jet targets for direct reaction studies

K. A. Chipps*

Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, United States

The study of direct reactions is of broad interest in nuclear physics, providing constraint to models of nuclear structure evolution and data to better understand the creation of the elements. In many cases, however, the data of interest are hindered by backgrounds and poor resolution from contaminants in either the beam, the target, or both. The use of a gas jet can overcome some of these issues through clever engineering, providing a reaction target that is chemically pure and thin enough to significantly reduce the impact on experimental resolution. This Perspective will discuss the effort to design, construct, and operate gas jet targets for direct reaction studies in the rare isotope era.

KEYWORDS

nuclear reactions, direct reactions, gas targets, gas jets, nuclear structure

1 Introduction

Direct reactions have long been a tool in nuclear physics to probe the evolution of nuclear structure and the role nuclei play in astrophysical events. With the development of rare isotope beams, however, new opportunities brought with them new challenges.

For one, beams of more and more exotic nuclei are less intense, due to the difficulty in producing them (increasing energy and decreasing production cross sections). To achieve the same results, then, either the time for a measurement or the target density must be increased, or indeed both. To ensure that the statistics that are collected do not suffer from backgrounds induced by unwanted target components (such as backing foils or spectator atoms in a chemical compound), pure targets are desired.

In addition to reduced intensities compared to stable beams, rare isotope beams are also more prone to be delivered on-target as "cocktail" beams, with multiple beam constituents alongside the nuclei of interest. This is due to production mechanisms like fragmentation and in-flight reactions. Because reactions are possible on any of the nuclei present in the beam, the purity of the targets is again a significant concern.

Lastly, as rare beams often result in decreased statistics, improvements in detectors are also needed–and need to be accommodated. Next-generation gamma arrays like GRETA [1], high-segmentation, high-coverage charged particle arrays like ORRUBA [2], and electromagnetic devices to separate reactions from unreacted beam like SECAR [3] or EMMA [4], all have strict mechanical and electronic requirements for interfacing with them. A new target technology loses value if it cannot accommodate the new detector technology needed to make use of it.

Gas jet targets take advantage of increased engineering–in the form of more complicated pumping schemes and fluid dynamics borrowed from aerospace–to achieve a dense, pure, and highly localized target of gas, as can be seen in Figure 1.

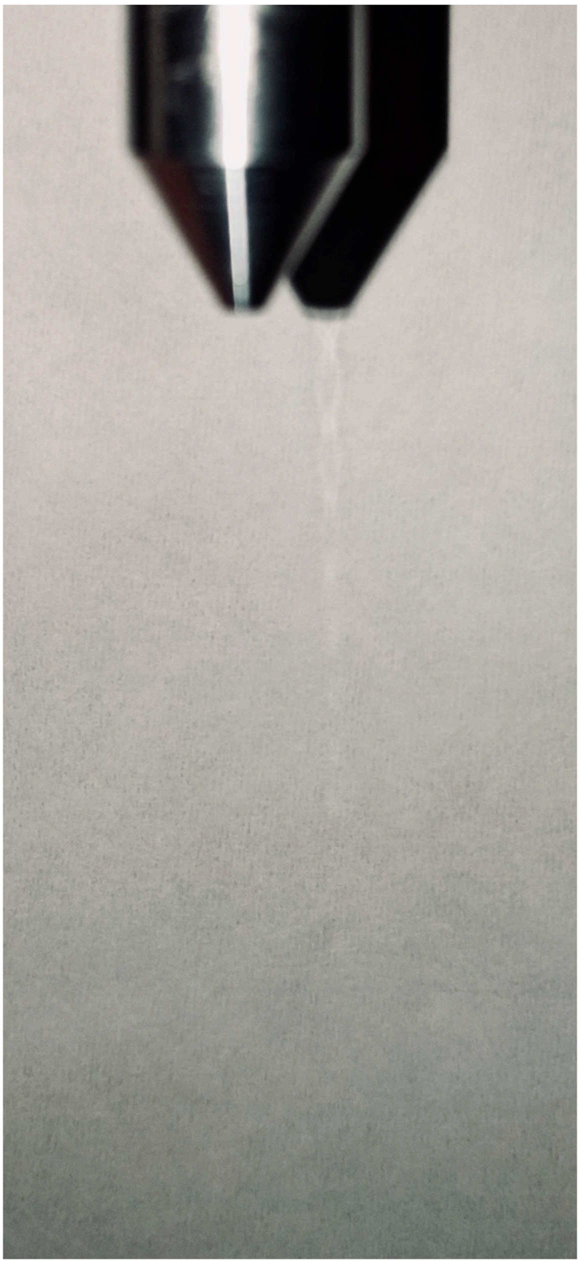

FIGURE 1
Photograph of a gas jet expanding into atmosphere.

Some of the earliest gas jets for nuclear reaction studies were built and operated in Germany in the 1970s through the early 2000s [5–17]. Others (e.g., Refs. 18–22) were built in the United States and abroad for various applications. Of these, the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target [23–25] is the most dense gas jet target for direct reaction studies in the world.

2 The JENSA gas jet target

To expand the use of gas jets to rare isotope facilities, such as the Argonne Tandem-Linac Accelerator System (ATLAS) facility or the Facility for Rare Isotope Beams (FRIB) in the United States, changes to the basic design of the target were needed. Beam intensities are, by their exotic nature, lower than for stable beams, necessitating an increase in the target density. Correspondingly, lower intensities require more detector coverage to maximize statistics, and the design of the target chamber has to accommodate this. Additional detectors to measure the heavy outgoing recoil or any gamma rays de-exciting the populated levels may also be desired. The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target system was designed and built to meet these new requirements.

2.1 $^{15}N(\alpha,\alpha)^{15}N$

While JENSA was designed explicitly for performing reaction studies in inverse kinematics with rare isotope beams, early science measurements focused on demonstrations of the system performance and comparison to existing reaction data. One such measurement was a study of ^{15}N elastic scattering on a ^{4}He jet target. This measurement was undertaken to constrain R-matrix analysis of the $^{15}N + \alpha$ entrance channel, relevant to the astrophysically-important $^{15}N(\alpha,p)$ and $^{15}N(\alpha,\gamma)$ reactions. The JENSA data, taken in inverse kinematics with a pure beam of ^{15}N produced “batch-mode” from the Holifield Radioactive Ion Beam Facility (HRIBF) and a pure target of research-grade ^{4}He–a difficult task as both beam and target species are naturally gaseous–were compared with normal kinematics data taken at the University of Notre Dame FN tandem using an alpha beam and melamine target enriched in ^{15}N. This comparison was done for 15 energies spanning roughly 3.9–4.8 MeV in the center of mass, with the elastically-scattered particles detected in the SIlicon Detector ARray (SIDAR).

Not only were the yields consistent between the two techniques, but the use of the JENSA gas jet target allowed for extension of the scattering data down to much lower center-of-mass angles: as the target exhibits cylindrical symmetry, detectors can be placed all the way to 90° in the laboratory frame without the target or target frame material impeding the reaction products.

2.2 $^{20}Ne(p,d)^{19}Ne$

A distinct benefit to the use of gas jets for direct reaction studies is the ability to enable reactions between two gaseous elements to be studied in high precision. A proton beam of 30 MeV, produced by the HRIBF, impinged on the JENSA target operating with natural neon. Deuterons from the (p,d) reaction, populating states in ^{19}Ne of astrophysical interest, were selected in the SIDAR detector array using standard energy loss techniques. An example spectrum is shown in Figure 2. In Figure 6 of Ref. 26, a similar spectrum is compared against the results of a test with a neon-implanted carbon foil. The reduction in background and improvement in the resolution due to JENSA is clear.

In the case of $^{18}F(p,\alpha)^{15}O$ reaction, which is known to destroy ^{18}F in novae, the spin and parity of a resonance at 6,288 keV in the compound nucleus ^{19}Ne was the largest unknown. By using the $^{20}Ne(p,d)^{19}Ne$ reaction to populate this level, with a pure neon gas target from JENSA, this uncertainty was removed. This resulted

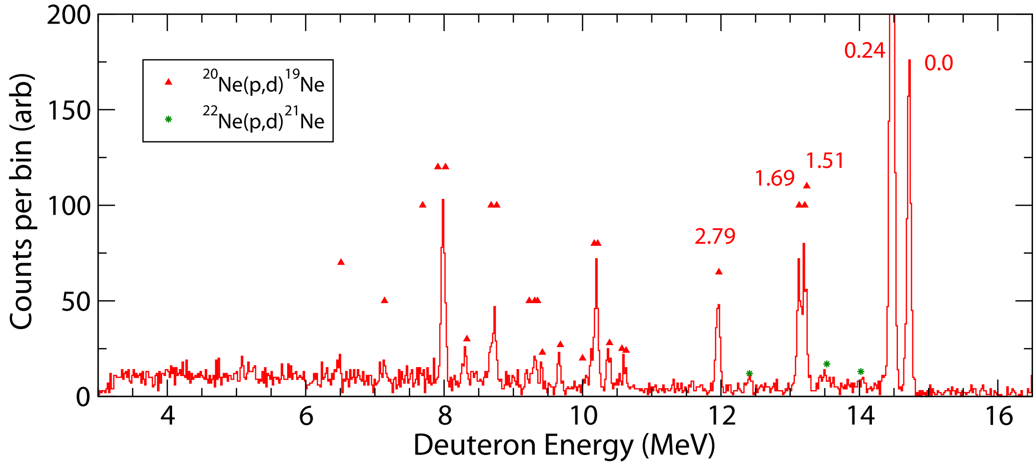

FIGURE 2
Example spectrum, taken for one angle, from the ^{20}Ne(p,d)^{19}Ne reaction measurement using JENSA. The first few states in ^{19}Ne are labeled. Peaks due to reactions on the naturally-occurring ^{22}Ne in the neon gas target (~9%) are labeled with green stars. Adapted from Ref. [27].

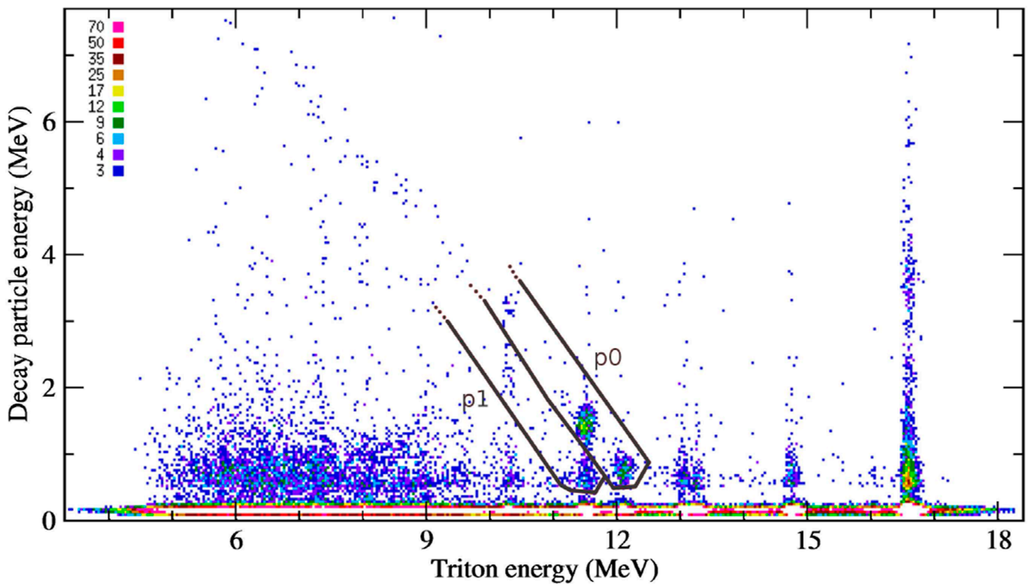

FIGURE 3
Preliminary matrix of the energy of any particle in coincidence with a reaction triton from JENSA (vertical axis) *versus* the triton energy (horizontal axis). Two bands, associated with the p0 and p1 decay channels from ^{18}Ne, are indicated with the black bands. Protons originating from the ~4,500 keV and 5,150 keV levels in ^{18}Ne form clearly visible groups in the spectrum.

in a factor of 2.8 reduction in the uncertainty of detection of astronomical ^{18}F due to the underlying nuclear reaction rate. These results, along with additional data from this measurement, were published by Bardayan et al. [27–29].

2.3 ^{14}N(p,t)^{12}N

As with gas jets in previous decades, the relatively thin jet (with respect to energy loss) allows for precision particle spectroscopy from direct reaction studies. JENSA was used with a natural nitrogen jet to study the ^{14}N(p,t)^{12}N reaction, looking for potential new levels in ^{12}N. Because the energy straggling of the incoming beam as well as the outgoing tritons through the jet was small, the resolution of the measurement was dominated by the resolution of the detectors (SIDAR in "lampshade" mode), and the width of broad, unbound levels in ^{12}N was immediately apparent in the spectra.

Two potentially new levels were observed in this direct reaction measurement with JENSA, including a strongly-populated level at ~4.5 MeV excitation energy with a width of approximately 500 keV. The results illuminated the ongoing need for spectroscopic

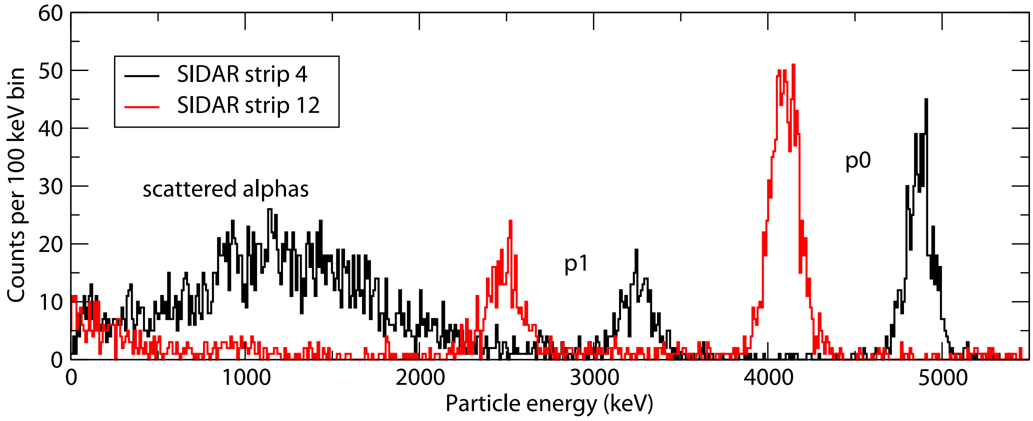

FIGURE 4
JENSA ^{14}N(α,p) spectra from two angles in SIDAR. The p0 and p1 channels are visible, as are the elastically-scattered alphas.

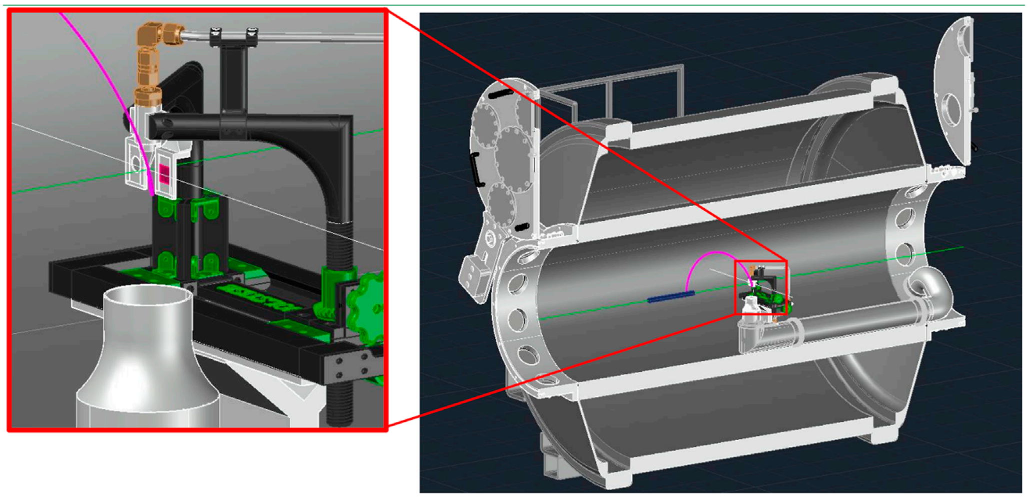

FIGURE 5
Computer aided design drawing of the SOLSTISE gas jet target setup inside of the SOLARIS solenoidal spectrometer magnet bore. CAD courtesy of M. Hall.

information of light-mass, weakly-bound nuclei. These results were published by Chipps et al. [30].

In addition to the direct spectroscopy capability, decay particles–such as protons or alphas emitted by the product of the reaction–are able to escape the thin jet target and potentially be detected. In the case of ^{12}N, protons corresponding to the p0 (to the ground state of ^{11}C), p1 (^{11}C $E_x = 2$ MeV), and p2 (^{11}C $E_x = 4.3$ MeV) decays, were observed in coincidence with the tritons of the reaction. Branching ratios for the decay channels as a function of energy can be extracted. This analysis was first done with JENSA data by Chipps et al. [31].

2.4 ^{20}Ne(p,t)^{18}Ne

Taking advantage of the unique combination of a gas jet target with a facility able to deliver high-energy proton beams, the ^{20}Ne(p,t)^{18}Ne reaction was studied, again at HRIBF. Due to the very high Q-value barrier for this reaction (~20 MeV), a 37 MeV proton beam was utilized. At these energies and angles, the reaction proceeded partially through direct reactions, and partially through a multi-step process. Tritons from the (p,t) reaction were detected in the SIDAR array using standard energy loss techniques.

The spin and parity of the level at 6,150 keV, which appeared as a shoulder on top of the 6,297 + 6,353 doublet, has been contested, as has the width of this level: depending on the spin assignment, variations of up to a factor of 2.4 in the ^{14}O(α,p) reaction rate are possible. The JENSA data favor a reassignment of the levels in this triplet versus the adopted ordering in the literature. This work was the thesis project of UTK PhD student Thompson [32].

As before, the thin jet target allowed for decay particles to escape and be detected in coincidence with reaction tritons. This is shown in Figure 3. A determination of the branching ratio from the 6,150 keV level to the ground state of ^{17}F will help to confirm whether the state contributes strongly to the ^{14}O(α,p) reaction rate in explosive proton-rich nucleosynthesis.

FIGURE 6
Size comparison between the SOLSTISE (center) and JENSA gas jet nozzles. Despite the difference in external size, the internal nozzle design is the same.

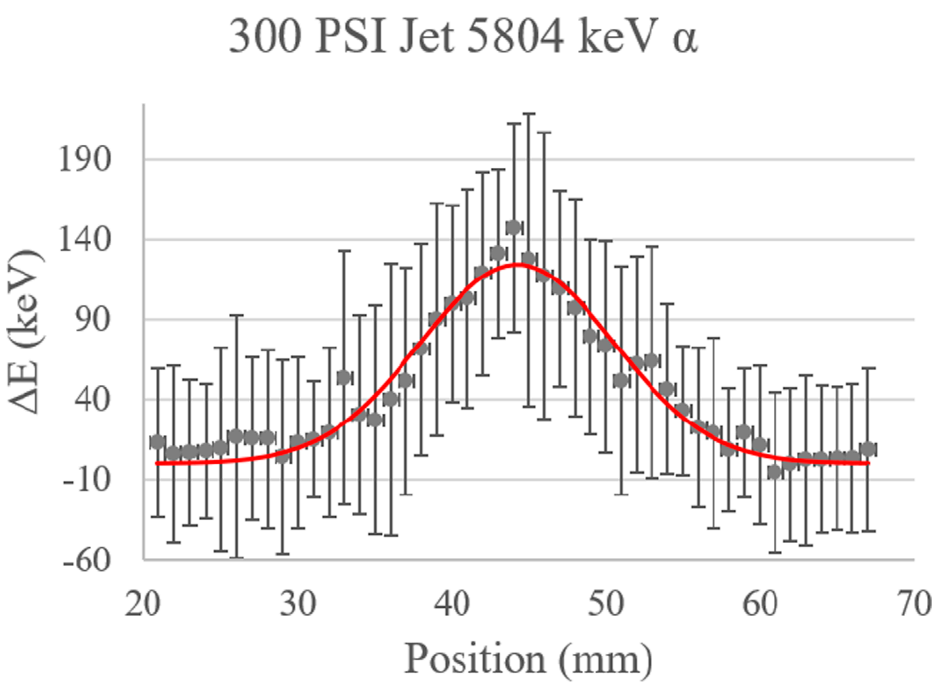

FIGURE 7
Energy losses for a known alpha source passing through a jet from SOLSTISE produced with 300 psi of nitrogen gas. For nitrogen, an energy loss of ~160 keV corresponds to an areal density of 10^{19} atoms/cm^2.

2.5 JENSA at ReA3: (α,p) studies

(α,p) reactions of relevance to astrophysical environments such as novae and x-ray bursts, while known to proceed through levels in the compound nucleus and hence falling outside of the scope of this review, nevertheless demonstrate the opportunities for studying direct reactions with rare isotope beams and gas jets.

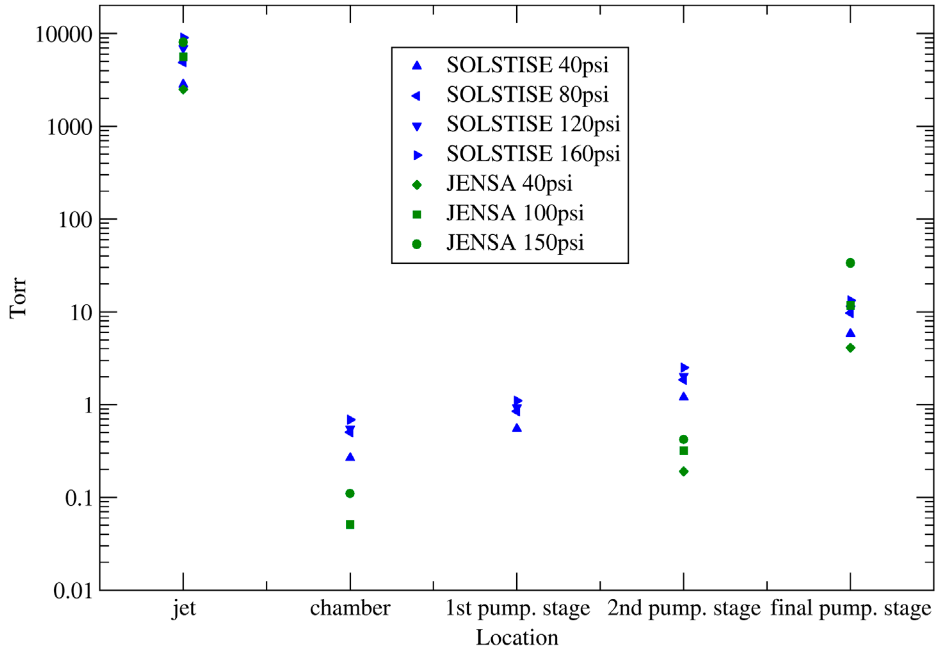

FIGURE 8
System pressures for SOLSTISE and JENSA compared at various stages, for nitrogen. For equivalent jet densities, the pressures inside the SOLSTISE system are comparable to JENSA.

During its tenure in the reaccelerated (ReA3) hall at the new Facility for Rare Isotope Beams (FRIB), JENSA has been used to study several (α,p) reactions, including ^{14}N, ^{34}Ar [33], ^{56}Ni, and ^{26}Al (α,p).

The ^{14}N(α,p)^{17}O reaction was first observed by accident: Ernest Rutherford, measuring the scattering of alpha particles from other light particles, was surprised to discover that protons were being produced when alpha particles hit air molecules in his test chamber. Almost 100 years later, the measurement was repeated with JENSA. The protons from the reaction are clearly visible (Figure 4).

A spectroscopic measurement of the ^{34}Ar(α,p)^{37}K reaction cross section was undertaken and published by Browne et al. [33]. The ^{56}Ni(α,p)^{59}Cu and ^{26}Al(α,p)^{29}Si reactions are under analysis. The latter measurement constitutes the first use of the JENSA gas jet target to study a reaction cross section into the Gamow window.

3 Combining technologies: the SOLSTISE gas jet

Gas jet targets offer several significant advantages to traditional targets, such as improved resolution, improved purity, and the ability to measure reactions near 90°, for a tradeoff in the scale of engineering required. One way to push the boundaries of particle spectroscopy even farther are to combine this target technology with other advances in beam production and particle detection: this is the goal of the SOLenoid and Supersonic Target In Structure Experiments (SOLSTISE) project. SOLSTISE is a gas jet target designed for operation inside of a solenoidal spectrometer such as HELIOS [34] or SOLARIS [35]. Figure 5 shows a CAD drawing of the SOLSTISE setup inside of the SOLARIS spectrometer at FRIB.

Due to the constraints of operating inside of a solenoidal magnetic field, the design of SOLSTISE is such that the amount of material–in particular, components made from materials which may impact the magnetic field lines–is minimized. In Figure 6, the impact of this design criterion on the size of the jet nozzle is apparent. In fact, the SOLSTISE project has taken significant advantage of additive manufacturing, producing many internal components such as receiver cones, frames, supports, and even jet nozzles using precision 3D printing techniques. Despite these design changes, the SOLSTISE system has been demonstrated to produce an equivalent jet to JENSA for nitrogen (see Figure 7). Additional changes to the pumping scheme between the two systems have resulted in improvements to the SOLSTISE pumping stage pressures, despite a lower overall pumping capacity. A comparison can be seen in Figure 8.

The SOLSTISE system has been designed to be compatible with both the HELIOS and SOLARIS spectrometers. Plans for first experimental measurements at ATLAS are underway.

4 Conclusion

Ongoing advances in rare isotope beam production, detector technology, analysis techniques, and reaction theory have given us unprecedented access to the nature of exotic nuclei. Gas jets can provide a pure, dense, and localized target to further improve the state of the art of direct reaction measurements.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data available upon request. Requests to access these datasets should be directed to chippska@ornl.gov.

Author contributions

KC: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

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