Advancing Target Science: Targetry for the Low Energy Nuclear Physics Community in the FRIB Era and Beyond

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In accelerator-based measurements of nuclear reactions of interest to nuclear physics and astrophysics, three ingredients are generally required: the beam of nuclei, the detector systems, and the target. The target acts as a source of one of the two reactants, with the beam providing the other, and the detector systems optimized to measure the resulting products from the reaction, be they charged particles, neutrons, or gamma rays. Fabrication and characterization of targets for such measurements is a critical endeavor in the nuclear physics community. In this brief whitepaper, an overview of the capabilities within the community and the current and future requirements for targets and target-making is provided.

INTRODUCTION

In carrying out most, if not all, accelerator-based, low-energy nuclear physics research, a continuous supply of specialized targets are necessary in addition to the high quality beams being produced. Depending on the experimental approach, stringent requirements are placed upon the production and preparation of such targets, based on the desired experimental outcome. A community of so-called "target practitioners" has grown in parallel therefore with many accelerator facilities. The extensive knowledge base, technical skills, target production equipment and laboratories are vital in maintaining a robust nuclear physics enterprise. Certainly, it should be mentioned that continued recruitment into the field of target preparation presents us with a high importance towards the workforce of the future. Within the framework of this Whitepaper we hope to discuss the steps necessary to ensure that the accelerator target needs of the nuclear physics community in the Facility for Rare Isotope Beams (FRIB) era are achieved.

A full review of the current state of accelerator targetry efforts is beyond the scope of this brief report. For the purposes of this whitepaper, we confine ourselves to the area of accelerator target development highlighted by a recent survey of the community. This survey was undertaken by the staff of the Center for Accelerator Target Science (CATS) [**?**] at Argonne National Laboratory (ANL) and the conveners of the FRIB Advanced Targets Working Group (AT-CATS) [**?**].

TARGETS FOR ACCELERATOR-BASED NUCLEAR PHYSICS EXPERIMENTS

For every accelerator-based measurement where targets are needed, different requirements - many of which can be contradictory - determine the target specifications. Sensitivity to contaminants (from environmental contamination to stoichiometric components or backing materials to isotopic impurity), beam energy requirements, the need for experimental resolution, and requirements for higher statistics are all considerations in the problem of optimizing the choice of target. Here, various types of target are introduced.

Stable targets

Long the workhorse of the nuclear physics community, stable targets remain a critical and ubiquetous component of both fundamental and applied nuclear physics research with ion beams.

Plastics

Due to the frequent need for hydrogen-induced reaction measurements, simple polymerized plastics have long been a mainstay of ion beam studies. More than half of the respondents to a 2022 survey by AT-CATS indicated a regular need for targets of this type.

Hydrogen isotopes, particularly protons and deuterons, are often the most appropriate probe of a given nuclear property, and hence are necessary as target material. However, pure hydrogen is naturally in its diatomic, gaseous form, and hence presents complications for use in nuclear reaction measurements. As a gas, it is difficult to localize at sufficient densities, particularly without the use of additional materials to enclose it. It is also both highly flammable and explosive with even small concentrations of oxygen, leading to strict safety regulations governing its use. The use of hydrogenated plastics gets around many of these issues, by providing a solid matrix that is hydrogen-dense and readily fabricated. Polyethylene (C_2H_4) is a common compound used for hydrogen-rich plastic targets in nuclear physics. It is easily and cheaply procured, even in its deuterated form (C_2D_4), and target fabrication is reasonably straightforward, even without a full chemistry laboratory setup. Polyethylene powder is dissolved in a heated solvent such as xylene and poured or spun onto glass slides, where it is allowed to cool in a controlled manner, producing flat, uniform films of the desired areal density [**?**]. The films can then be lifted or floated onto frames designed for the experiment. A large variation in the dissolved concentration is possible, and target films can even be folded or sandwiched to provide thicker targets or stretched thinner if desired. The process can be undertaken in any reasonable lab space with a small hood or appropriate ventilation (for the solvent). In addition, polyethylene films are reasonably shelf-stable, such that targets can be kept and utilized years after fabrication.

There are limits to the functionality of such polymerized plastic films as targets, however. Particularly thin films ($\simeq$100 μg/cm^2 or less) are fragile once removed from the glass substrate, and prone to tearing. Beam-induced damage, such as carbonization or melting [**?**], is possible; even weaker-intensity beams can cause depletion of the hydrogen content compared to carbon over the course of an experiment. The stoichiometric carbon in the targets increases the overall stopping power, worsening the experimental resolution of charged particle detection, and produces background reactions with the beam.

Enriched materials

For accelerator-based nuclear physics studies near Coulomb energies, thin, uniform, metallic target layers are employed, ideally prepared from highly enriched isotopes. Nearly 90% of the AT-CATS target needs survey respondents indicated that thin, isotopically-enriched stable targets were a requirement for their research programs.

For non-metals and instances where self-supporting films cannot be produced, enriched compounds on various carrier foils (target backings) are substituted instead. For the most part, the enriched target materials are obtained in chemical stable form from the National Isotope Development Center (NIDC) at Oak Ridge National Laboratory (ORNL). Targets of those elements which are mono-isotopic have the advantage of having a number of commercial sources available, though not directly in a form or thickness suitable for these accelerator experiments.

The method of choice for preparing thin free-standing foils of enriched isotopic metals is Physical Vapor Deposition (PVD), a common technique found throughout the field of solid state physics. Taking place under high vacuum in a deposition chamber (bell jar), a small quantity of enriched metal is heated in an evaporation source and allow to condense onto a suitable substrate where it can be later removed intact. Nowadays, these deposition systems, available worldwide, have grown in both complexity and expense using a variety of evaporation sources and thin film measurement tools. A wealth of knowledge regarding all manner of target preparations has been assembled under the auspices of the International Nuclear Target Development Society (INTDS), compiled from their Conference Proceedings [**?**].

Implanted targets

To address the need for gaseous targets while avoiding the technical difficulties introduced by using gases, implanted targets are often pursued. A stable matrix, traditionally a heavy metal such as titanium, is bombarded by extremely low energy light particles from an ion source, which collect in the interstitial regions of the matrix.

Implanted targets are inherently difficult to use, as the target material of interest is only weakly contained within the target matrix. Implanted helium or other noble gases tend to diffuse out of the target over time, with that diffusion accelerating under bombardment from the ion beam during the nuclear physics measurement. Deeper implantation into a thicker matrix provides some additional stability, but at the cost of the possible reactions which can be studied: thick implanted-target measurements are limited to neutron- or gamma-emitting reactions, as nearly all charged particles will experience high stopping powers and remain inside the target material. These high stopping powers (due to the high Z and high density of the target matrix) also impact the impinging beam; the beam will undergo energy loss as it traverses the target material, such that uncertainties in the stopping power translate into uncertainties in the energy at which a reaction occurred.

Newer target matrix materials are being pursued, which trap the implanted ions more effectively and reduce the stopping power of the target. More effort is needed to determine if such materials are a viable option for the broader community.

Radioactive targets

Targets made from unstable, or “radioactive,” isotopes present a myriad of auxiliary safety issues all their own; primarily the manipulation and handling sometimes highly radiological materials. In addition, the methods, procedures and laboratory equipment needed are regulated in order to assure against accidental release. Only a very few facilities are capable providing the targets required, and yet 47% of the target needs survey respondents indicated that radioactive target materials were needed for their research.

The preparation of thin radioactive target layers proceeds similarly to that of any stable compound via, for example, evaporation under vacuum. The additional requirement for radioactive target species is having access to a sequestered (expensive) deposition system contained within a radiological facility, perhaps dedicated to a single element or isotope (due to cross-contamination). This is therefore not usually the method of choice for such targets, but it is sometimes necessary. Instead, the simpler techniques of electrodeposition or molecular plating are employed. Here the apparatus necessary is a bench-top plating cell or bath starting from a nominal solution of the radioactive material and a metal target backing. Depending on the degree of activity or radiological hazard, the apparatus may be placed in a hood, glove-box or even a hot cell where the deposition may be carried out safely. Mechanical rolling, pellet pressing or drop casting are possible other methods for fabrication depending on the case.

Gas targets

Gas cells

Gas cells provide a straightforward means for studying nuclear reactions on target materials that naturally occur in gaseous form. The design of a gas cell can vary substantially based on the technical requirements of a given experiment; it may be a static gas volume or recirculating, it may have a variety of window materials and thicknesses, it may be cooled to increase the density, and so on. The basic design of a gas cell is a cylindrical main volume with relatively thin sheets or films of material over some portion of one or both ends, such that the gas is contained but the beam particles and reaction products can escape into detectors outside of the gas volume.

The choice of gas cell window material is of tremendous concern. Both the beam and the reaction products lose energy in the window(s) and suffer from energy and angular straggling, and the beam may react with the window material and produce undesired background in the detectors. The problem of energy loss and straggling is addressed by choosing the thinnest windows possible for a given target density (and hence gas pressure) requirement, and by choosing lighter-mass materials, such as plastic films (eg Kapton, mylar). Such plastic film windows are inexpensive and readily commercially available, but (as described for plastic targets) are prone to beam induced damage. Additionally, as the window serves to separate the gas volume from the vacuum of the target chamber around it, stretching can occur, leading to potential nonuniformity in the target density as a function of location in the gas cell. However, because the design of a gas cell is such that the window is larger than the beam spot but not substantially so, this bowing or stretching effect can be minimized.

The problem of undesired background reactions can be addressed in several ways. If possible, choosing a window material with a high mass and atomic number (such as a metal like titanium or alloys like HAVAR) such that the beam is below the Coulomb barrier for the given species and energy, will significantly suppress reactions between the beam and the window foil. Alternatively, an experiment may be designed such that both the light and heavy charged particle reaction products are detected in coincidence, which reduces the number of beam-window interactions that end up as background in the measurement. The reasonably common use of gas cells as a target for secondary in-flight beam production is thanks to a similar technique, where beamline components such as a magnetic chicane (e.g. [**?**]) are used to select the heavy recoil of interest and steer away any reaction products resulting from interactions with the windows. In the case of electron beams, the size of the beam spot may allow for a tiny hole to be made in the gas cell entrance window, such that the pressure differential was reasonably maintained but the entering beam had no window material to interact with.

It can be seen that the different issues with regard to window material can often result in conflicting requirements to address them. Reducing energy loss requires light-A materials, whereas reducing background producing interactions requires heavy-A materials, for example. In many cases, the density of the volume of gas contained within the gas cell is still orders-of-magnitude lower than the density of the windows holding it in. The use of cryogenics to cool the gas within a gas cell is one method to increase the gas density without increasing its pressure and hence the mechanical stress on the windows. Asymmetric gas cell designs (with respect to the beam axis) can also help to mitigate the conflicting technical requirements, by providing different entrance and exit windows. Ultimately, while gas cells can be used successfully, these limitations drove the field to consider other ways to study reactions on gaseous targets.

Extended gas targets

Differential pumping through restrictive apertures can also remove the need for window material. These differentially-pumped gas targets are traditionally designed to extend along the beam axis. These types of gas targets are generally used for recoil separators/spectrometers, where the decrease in acceptance due to the finite extent of the target along the beam axis is more than outweighed by the reduced energy straggling of the beam and heavy reaction recoils through a windowless gas volume. Their physical extent makes them unsuitable for measurements that require a localized target, but can be a benefit in direct reaction studies where the energy of a resonance is not precisely known.

Active targets, gas jets, and other technologies

To provide targets of isotopes which are naturally occurring as gases but without the detrimental issues seen with gas cells, alternative solutions have been pursued. Some of these include active targets, gas jet targets, and frozen targets. These technologies are being pursued by several research groups in the nuclear physics community, both in the US and abroad. Because such target technologies do not lend themselves well to transport, their development is far less centralized than for other (solid) target development.

Active targets work on the principle that the target and detection medium share the same volume. This is most often seen in the form of ionization chambers or time projection chambers, where the target gas can be either pure or a mixture with a quenching gas to improve the operation of the detection medium. Several such systems are in regular use in the US and in the wider nuclear physics community. Many of these detector systems have the benefit of allowing low energy measurements, such as those needed to understand reactions for explosive astrophysical environments, but these also tend to be rate limited due to the eventual buildup of space charges from the incident beam in the active region of the gas.

For a particle spectroscopy measurement, a gas target should exist in vacuum without window materials or containment, while still being localized to the beam-target interaction point, just as a normal (solid) target foil would be. This is the goal of gas jet targets. While generally providing a lower overall target density than gas cells or active targets, the very low energy loss and straggling seen with gas jets is sometimes necessary to warrant the tradeoff. Gas jets can provide a pure, windowless gaseous species target for precision measurements, but are also much more infrastructure-intensive than standard gas cells.

When gas targets do not provide a sufficient density of target atoms, but the incident beam energy is high enough that a thicker target can be used, alternatives such as liquid or frozen targets are being developed and utilized. Cells of liquid hydrogen [**?**] or extruded hydrogen ice [**?**] can be used to provide dense targets for fast beam experiments which are also more robust against beam damage than traditional hydrogenated plastics. Liquid lithium [**?**] can be used as both a charge stripper and beam-fragmentation target. Frozen hydrogen targets produced by spraying hydrogen gas onto a thin, supercooled substrate [**?**] have the benefit of being thinner than extruded hydrogen ice, more pure than hydrogenated plastics, and can be regenerated quickly during an experiment if necessary. These state-of-the-art targets demand a higher complexity of infrastructure than standard solid targets, however, with hydrogen safety and cryogenics requirements for operation.

EXISTING CAPABILITIES: CATS

Outside of the NIDC at Oak Ridge where, for the most part, any enriched stable and radioactive target may be specified and quoted on for production, a plethora of university-based target facilities also exist throughout the United States and Canada usually based on their own specific needs. A more widely based national approach is the Center for Accelerator Target Science (CATS), based on the ANL Physics Division existing target development laboratory. The objectives of the Center are as follows:

1. Serve the low-energy community by producing targets whenever possible by either manufacturing them or by directing requests to other facilities best able to perform the task;
2. Train individual investigators and students in target making in order to provide a workforce capable to address present and future needs;
3. Carry out R&D activities dedicated to novel production techniques and optimization of existing ones;
4. Develop and maintain an inventory of existing targets that will serve as a pool available to the community.

The Argonne Physics Division Target Laboratory has always strived to be of service to the entire low-energy nuclear physics community wherever possible. For any given year, a number of outside targets requests have been accommodated and continue to be addressed at present. This includes external experimental groups in need at the Argonne Tandem Linac Accelerator System (ATLAS) Facility as well as Argonne researchers conducting experiments at other facilities (such as FRIB). If resources allow, target development and fabrication for DOE-funded external groups performing research at other facilities will be provided.

Depending on the workload from the ATLAS research program and from outside demands, it has been difficult to carry out research and development activities dedicated to novel target production techniques and for optimization of existing ones. The addition of a new technician to the CATS Staff will enable efforts towards new R&D on several fronts, for example the manufacture of tritium foils and availability of isotopic carbon targets. Long term support for optimal staffing levels at CATS will ensure that development of new targetry is continued.

Available to the community are targets collected within the Argonne Target Library consisting of target inventories reclaimed from the Wright Nuclear Structure Laboratory at Yale University consisting of targets from BNL and LANL as well as those from Yale with their listings (.pdfs) appearing on the CATS target library website. In addition to these targets, collections from MSU, Daresbury Laboratory and numerous microball targets (Washington University) are also inventoried and listings compiled. Finally, there is a vast array of ATLAS targets, accumulated over the past three decades which have been systematically sorted and added to the assembled target collections. All these are made available to the low-energy physics community, requested on a first-come first-serve basis.

Outreach and workforce development

As enumerated in the second CATS objective, workforce development within the nuclear physics community is a priority. The target laboratory in the past has taken part in training a worldwide array of researchers, many of whom now lead their own target laboratories at their home institutions. These individuals have sought out ANL as a place they wish to visit and as a center of learning/education. CATS is rightfully proud of this heritage. Additions to the CATS staff also are now being trained as part of the workforce. We anticipate one or two visits from outside individual investigators per year going forward. In addition, our CATS outreach to the student community has formally commenced with a Student Target Workshop organized with Center for Excellence in Nuclear Training And University-based Research (CENTAUR) at Texas A&M University (TAMU) and Louisiana State University (LSU). This Workshop was opened nationwide to graduate students and postdoctoral researchers. CATS also participates in the Exotic Beam Summer School, held annually at one of the rotating host institutions (ANL/ATLAS, MSU/FRIB, ORNL, LBNL, and ARUNA).

In addition to the CATS-led efforts, outreach with the community is undertaken by the authors of this whitepaper under the auspices of AT-CATS [**?**]. Workshops and minisymposia at various community meetings, such as the Low Energy Community Meeting or annual APS Division of Nuclear Physics conference, are regularly organized.

COMMUNITY NEEDS FOR THE FUTURE

Looking to the future of accelerator-based nuclear physics measurements, such as those that will be performed at the ATLAS and FRIB DOE user facilities and the ARUNA university-based laboratories, several needs stand out:

1. Improved hydrogenated compounds for target material, which are straightforward to fabricate (such as C_2H_4) but which allow higher hydrogen concentration and more robustness against beam damage;
2. Improved implanted materials, which allow higher implantation density and lower matrix density to improve signal-to-background;
3. Improved techniques for isotopic purification and materials handling, to minimize losses when producing enriched and radioactive targets;
4. Increasing number of radioactive, specifically Actinide, targets and preferably not in oxide form on thin backings if not self-supporting;
5. Stronger and less dense materials for gas cell windows to improve signal-to-background;
6. R&D into novel gas mixtures for active targets, which, in addition to improvements in the electronics and mechanical design, could increase the rate capabilities of such devices;
7. Continued R&D into novel target technologies, to gain access to rare, unusual, or difficult-to-acquire isotopes for accelerator-based measurements.

In addition to these technical challenges, support for optimal staffing and operation of CATS at Argonne and for the various target fabrication and characterization efforts at colleges, universities, and national laboratories across the US, is necessary to maintain the experimental nuclear physics programs at our premier user facilities.

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