PROFILE ANALYSIS OF A GAS JET TARGET FOR INVERSE KINEMATIC NUCLEAR REACTIONS

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**Abstract:**

The study of rare nuclear reactions is an important goal in stellar astrophysics. However, reaction identification and analysis through gamma ray spectroscopy becomes a significant challenge when gamma decays from the nuclei of interest lack sufficient statistics to overcome the radiation background. This background comes from natural radioactivity, beam induced background, and cosmic rays. Inverse kinematics reactions are a precise way to study such rare processes while significantly reducing the background. In this technique, the incident particle is a heavy nucleus, whereas light nuclei act as the target (jet gas target). In order to detect the recoil nuclei from the reaction of interest, the recoils must be separated from the un-reacted beam particles and other products. This will be accomplished using the University of Notre Dame’s future mass recoil separator. The reaction in the gas jet should be as point like as possible in order to optimize the mass recoil separator operation, and to obtain angular distribution measurements of the recoil gamma rays. This work deals with the development of an experimental technique to characterize the jet gas target. The heavy ion beam, in this case neon, is provided by the 4MV KN Van de Graaf accelerator. Two sets of electrostatic steerers were designed and built in order to precisely translate the beam vertically and horizontally. This allows an indirect determination of the composition of the gas jet target, by monitoring the elastic scattering yield of helium nuclei with a silicon detector. Calculations are presented of the drift region and applied voltage necessary in steering the beam, as well as preliminary results from the gas jet profile analysis.
1. Background

The hundreds of nuclear isotopes known today, anything heavier than helium, the elements that are responsible for life, were created within stars. The behavior of nuclei far from the valley of stability is particularly valuable in understanding astrophysical processes in stars. Stars form when hydrogen gas condenses, and temperature and pressure lend enough energy to overcome the Coulomb barrier. Fusion processes create heavier elements, first helium, and then helium burning reactions (specifically the triple alpha process) lead to the production of carbon-12, and eventually oxygen-17. Of the most important characteristics of the reactions is the cross section, a measure of the probability of the reaction occurring. Thus, the goal in nuclear astrophysics is to accurately study the \((\alpha, \gamma)\) reactions so crucial in stellar evolution.2

Most nuclear laboratories accelerate a stable, light nucleus to collide into a heavy-nuclei target, creating nuclei of interest in some excited state. The nuclei may then decay by emitting gamma rays (essentially high-energy photons), which are then recorded by semiconductor detectors. However, for many stellar reactions, the cross section is very small, and so very few gamma rays are emitted, and background radiation can obscure the spectra. Reversing this paradigm, in a process known as inverse kinematics, avoids the problem of background. Instead of

Figure 1: Schematic of Gas Jet Target Operations
having a light projectile and a heavy target, inverse kinematics involves a heavy, stable beam incident on a light target, where the intermediate reaction products include these low cross section nuclei. As the target nuclei are so light, the nuclei of interest have enough momentum to be refocused, separated, and used in further reactions on the beam line. This separation is especially necessary because much of the beam passes through the gas jet without reacting, and so the products are mixed with a large number of slightly scattered, but essentially unchanged, beam particles.

Hence, development is underway at the University of Notre Dame’s Nuclear Structure Laboratory for a new inverse kinematics setup, in conjunction with a recoil mass separator. The recoil mass separator will use a series of quadrupole and dipole magnets to isolate one specific reaction product by mass/charge ratio. Each of these magnets will have to be tuned to specifically based on mass, momentum, and charge. Optimally, the reaction with the gas target is point-like, thus, confining the momentum and the scattering angle of the products. However, the gas jet is not one dimensional, not exactly spatially uniform, and so the reactions will generally occur within some confined area but with an error. In order to maximize the number of products, the reaction should have a high cross section – ie, the gas target needs to be as dense as possible. In other words, the gas jet target needs to have a large a number of particles per unit length as seen by the beam. Ideally, the particle density would also be homogenous throughout the gas jet.
Furthermore, these parameters must be known before reactions can be studied. It is thus necessary to test the profile of the gas jet target. This is indirectly determined by measuring the number of particles scattered off the gas jet target. A silicon scintillator detector monitors the scattered products at some fixed angle, which is directly proportional to the number of interactions. In order to accomplish this, the beam must scan the target area vertically and horizontally. The number of interactions is a function of the density of the gas target, so the scan will allow a precise measurement of the profile of the target.

2. Gas Jet Target

As the limits of nuclear physics advance, a simultaneous development of modern technology is often necessary to support experimental progress. Light targets are typically gaseous, and so the major concern for inverse kinematics setups is containment within a high-vacuum beam-line. The target needs to have as high a pressure as possible, in order to maximize the number of reactions. Many times, window gas targets are used, where the gas is contained in a small box with some very thin (often carbon film) window, which allows the beam to easily pass through. However, the beam will incur some energy loss through interactions with the window. These windows are fragile, and require caution when manufacturing as well as installing, as they can easily be blown out with sharp changes in pressure. Additionally, wear and tear on the window target will necessitate its replacement.
Windowless gas targets may be employed, but require additional technological considerations. Nevertheless, they offer numerous advantages. Beam energy loss is minimized and may even be considered negligible (depending on setup), all interactions are pure, and the target does not have to be replaced. There are two kinds of windowless gas targets, an extended windowless gas target, and as in this case, the jet gas target. The gas jet target is ideal as it allows much higher pressures than window targets, while keeping the surrounding vacuum pressure to a minimum. The two main components of the jet gas target are the nozzle, and the catcher. The nozzle sprays the gas perpendicularly to the beam, and helps keep the gas stream contained. The catcher, as the name suggests, recaptures the gas, and must meet exacting specifications: too big and the gas can splash out, too small and the gas will obviously spill into the beamline. A roots pump must be used to pump the catcher as well as pull a vacuum in each of the three target sections. Turbomolecular pumps are usually the standard high-vacuum pumps, but helium particles are small, high-speed particles, and so are not easily pulled out by the turbo fan. Roots
pumps operate completely differently, having two large paddles, and are ideal for helium.\(^4\)

The nozzle plays a large part in helping confine the jet. The type of nozzle used is a Laval nozzle, known for its convergent and divergent sections. The divergent section helps control and define the stream of gas, and also accelerates the gas to supersonic speeds. (The gas particles have a higher velocity are faster than the speed of sound within that medium.) To further insure that the pressure is kept as low as possible, the jet gas chamber has three different sections, separated by narrow apertures to allow the beam to pass through. Each section has a dedicated roots pump. In the central chamber with the gas target, argon gas is also circulated to suppress the dispersion of helium. Thus, the pressure may be rather high in the central chamber, but are orders of magnitude lower in the two flanking chambers. Argon is heavy, with a mass number of 36, so it is unlikely beam particles will react. Even if reactions do occur with argon, the location will occur well outside of the expected reaction region and thus won’t even be measured.\(^5\)

Figure 5: Experimental Setup
3. Design of the Deflection Plates

The steering plates operate in the same manner as a parallel plate capacitor. Two sets of plates are needed to deflect the beam in each direction. A high voltage is used to create an electric field. The first set of plates causes the beam to accelerate toward the negative plate. For the drift region, the beam does not undergo acceleration, of course, but it travels along a tangential path, thus incurring an even greater deflection. The second set of plates has the same magnitude of voltage but is reverse in polarity. This causes the beam to decelerate, and so the beam leaves perfectly parallel to its original direction. The amount of this translation ($\Delta T$) is related to the beam energy, mass and charge of the beam particles by:

$$\Delta t = \frac{-q}{2E_0} \frac{V}{x} (L + d)$$

where $q$ is the fundamental charge, $V$ is the voltage applied to the plates, $E_0$ is the original beam energy, $d$ is the drift distance (18.75 in), $L$ is the length of the plates (6.0 in), and $s$ is the separation of the plates (1.0 in). The steering plates fit exactly in the beam pipe, and the voltage connections are made through the beam line using SHV hermitic feedthroughs. A simple wire connection was soldered to the feedthrough connection, and had a ring connection on the other end, which was screwed into the center of each plate. Military grade ceramic standoffs insulate the plates from the electrically grounded supporting framework. In order to maximize the degree of translation possible, the drift region is made as large as possible. Thus, two sets of perpendicular plates are connected with ceramic standoffs, and placed at opposite ends of the available steering region.
4. Profile Analyses:

The steering plates must be tested before the gas jet profile can be analyzed. If deflection changes the beam, by making it more diffuse, or have a non-uniform in shape, for example, this would drastically affect scattering. Furthermore, these sorts of problems could indicate issues with the high voltage supply, rather than the plates themselves. Thus, the beam profile is monitored with a collimator, which is moved in increments to block the beam. If the beam is completely blocked within very few increments, then the beam has a confined, point-like cross section. This behavior is repeatable at different vertical distances, and so the steering plates are working properly and not affecting the beam composition. However, for the deflection 0.8842 mm down, the shape of the curve, and thus the beam, is slightly deformed. While not a large aberration, it does have an effect on the gas jet profile tests; most likely the plates need to be better aligned.
In the gas jet tests, the KN Van de Graaf accelerator provides a 2.0MeV beam of $^{20}$Ne ions, which are relatively heavy, to scatter off the $^4$He gas jet. A silicon semiconductor detector records the scattered particles at a certain angle. The number of scattered particles is proportional to the density of helium nuclei at that reaction site. The scattered particles are normalized against the remaining particles in the beam, so that any change in scattering can be attributed solely to the target and not variations in beam stability. The remaining beam is recorded as a current, which must also be normalized, because in interacting with the gas jet, the neon is further ionized. Thus, this reading likely represents an inflated value. So, the current is recorded with the jet off, and when the gas is turned on, the new current gives the inflated value. The factor between the two permits a normalization of the current reading. As the constant $q$ ($1.602 \times 10^{-19}$) and the beam charge (+1) are known, the number of beam particles is readily found. Fig. 8 shows the results of the first profile tests.

**Figure 8: Gas Jet Profile**
The x-axis of the plot is the degree of horizontal deflection, and the y-axis is the number of scattered particles/number of beam particles. Each curve represents a different vertical slice of the target; ±0.8842 mm (1000V) and ±0.4421 mm (500V), respectively.

In these initial tests, some issues are readily apparent. The peak of the curves shift as the beam moves vertically up, which is most likely due to the aforementioned alignment needed. Furthermore, if the gas jet truly did have a uniform density, then each of these curves would lie exactly on top of each other. The more the beam moves in the +y direction, toward the nozzle, a greater number of particles is scattered, indicating an increase in the density helium. This is not very surprising; as some diffusion would occur the further the gas travels from the nozzle. Several parameters can be adjusted to minimize this effect, including the pressure of the gas jet, the exact shape and size of the nozzle, and the pressure of argon suppressant. At the time of this writing, further tests are being conducted to experiment with these parameters.

5. Conclusions

The steering plates were shown to work well in translating the beam, and with a re-alignment should show much improvement. With the tests being carried out now, the gas jet target will be successfully analyzed. Work can then move forward in constructing the St. George Mass Recoil Separator, and eventually a new 5.0 MV single-ended Van de Graaf accelerator.
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References:


