The LEBIT Gas Stopping Station

Zachary Burton
2002 REU Student

Michigan State University
Department of Physics
National Superconducting Cyclotron Laboratory
Advisor: Dr. David Morrissey
Abstract:

The ability to make high precision mass measurements will soon be realized at the NSCL at Michigan State University. The LEBIT project will have the capabilities to measure masses of the most exotic nuclei produced in today’s world. At the NSCL, the coupled cyclotron facility will be able to produce beams of 100+ MeV/A. However, certain nuclear physics experiments require energies in the range of ~5 keV/A. In order to get these ions to the correct energy, the ions produced in the NSCL’s coupled cyclotrons will travel to the Gas Stopping Station where the nuclei will be stopped using two types of degraders and a gas cell, containing ~1 bar He. Upon being stopped in the gas the ions will be thermalized and extracted with a DC gradient and ejected into a RF multipole system, which will guide the ions to the Penning Trap for mass measurements. Efficient and quick extraction of ions from the gas cell will be required to measure the half-lives of nuclei as low as 10 milliseconds.

Introduction:

The ability to make high precision mass measurements of unstable nuclei will illustrate the nuclear structure of these ions. These measurements may now be achieved with the ion beam produced by the Coupled Cyclotron’s at the National Superconducting Cyclotron Laboratory (NSCL) (Fig. 5). Ions with half lives in the range of ~10 ms can be measured and studied [1].

In order to make these mass measurements, the radioactive ion beam needs to have low energy to meet the specifications of the 9.4 Tesla Penning Trap, which will be the device where measurements are made. For this reason, the Gas Stopping Station (GSS) (Fig. 7) was developed at the NSCL. There are three components which slow the beam and dissipates the energy: glass degraders, a beryllium window, and a gas cell, which contains ~1 bar of high pure helium. This station is the first step of the larger project called LEBIT (Low Energy Beam and Ion Trap) (Fig. 6). By using both the gas stopping station and the Penning Trap, high precision mass measurements will be made of exotic nuclei never achieved before [2].
The NSCL’s Coupled Cyclotron facility produces beams of radioactive ions. Recently, the two cyclotrons, the K500 and the K1200, were coupled to increase the intensities of the radioactive ion beams. The maximum energy produced by these coupled cyclotrons is ~200 MeV/A. Because of the recent coupling of the cyclotrons the NSCL is the premier facility in the world that produces beams at intermediate energy ranges. From the cyclotrons, the accelerated ions are directed at a target just after the K1200 and then the products from that reaction are sent through the A1900 Fragment Separator. The separation process is analogous to light optics, where white light sent through a prism is separated into its components to make the rainbow. The A1900 similarly works by using magnetic fields and apertures to bend and separate this mixed ion beam (Fig. 5).

When the ions are fragmented on the production target, they are typically stripped of their electrons and have a large positive charge. Passing these positively charged ions through a magnetic field will bend their path. The amount that the ion bends depends on the rigidity of the ion. The rigidity is how hard it is to bend an ion or rather how strong of a magnetic field needs to be present to bend them the appropriate amount. Magnetic rigidity is defined as the following:

$$B \rho = \frac{p}{q} = \frac{\gamma m_0 v}{q}$$  \[1\]

Where $B$ is the magnetic field, $\rho$ is the radius of the circular path the ion travels, $m_0$ is the mass, $v$ is the velocity and $q$ is the charge. The unit for the magnetic rigidity is the Tesla-meter (Tm). These formulas are valid with a uniform perpendicular magnetic field. After the A1900 device selects an ion, it is passed through the beam lines to an experimental vault for study.
Setup:

LEBIT is located in the N4 vault and outside of the vault in the LEBIT room. No extra shielding is used for the ion trap because the ion beam is at such low energy, no prompt radiation will be given off. When the radioactive beam enters the N4 vault it will encounter the first piece of equipment used to slow the ions, the glass degraders. There are six sets two glass degraders in the path of the beam. The degraders are capable of moving in two ways. They are able to rotate, which will change the thickness of the glass, and they are also able to traverse in the vertical direction so a different set of panes of glass can be used. Each set of panes has a different thickness in order to measure the stopping power for each set. This allows the experimenter the ability to change the only variable in the stopping portion of the experiment.

Fig. 1: The glass degraders with their respective thickness and location. Width of degrader is in millimeter.

There are two glass degraders for the purpose of symmetry. If the radioactive beam were to pass through a single degrader then each ion would have a different energy because
they had passed through a different thickness of glass. This is true because the ions in the beam do not travel perfectly straight. When they reach the glass they will have different trajectories and therefore will pass through different amounts of glass. If you have two degraders however, then that will compensate for the energy difference.

Once passing through the glass degraders, the ions will experience a dipole magnet, pass through the beryllium window, and then enter the gas cell. The initial object in the path of the beam will be the beryllium window. This is the second overall degrader for the beam. This window has a thickness of 1.50 mm and a diameter of 53.20 mm +/- 0.05 mm. The window also has a calculated density of 1.848 g/cm³. More energy will be lost from passing through this window where upon they will straggle into the gas cell, which immediately follows the window.

The third and final stopping mechanism will be a pressurized cell filled with high purity helium. The gas cell will have high-pressure, pure helium gas of ~1 bar contained inside and can be thought of as a radioactive ion source. When the ions straggle into the gas from the degrader, the helium will stop and thermalize the ions. An electric potential will be created along the gas cell and will, along with gas flow, extract the ions through a supersonic nozzle (Fig. 3). Helium is a light gas but is the ideal gas to stop these ions. Since these ions will have positive charges, they attract electrons from the surrounding atoms. Most atoms would give off their electrons easily because their ionization potentials are low. Helium, on the other hand, has the highest ionization potential at 24.6 eV. This is important because the helium atom will not give off its electrons to the ion beam. If the electrons were to leave the helium and bond with the ions then the ions, from the radioactive beam would be neutralized. If the ions are neutral, then it cannot be
controlled by electric or magnetic field. They would be pumped away with the surrounding helium.

Along with the gas flow that will occur in the gas to extract the ions through the nozzle, there will be ring electrodes that will have a DC gradient placed on them to guide the ions downstream. The rings are essential to having quick and efficient extraction from the gas cell. Along with the rings in the gas cell, another electrode will be placed directly before the nozzle in order to focus the ions correctly. This flange is known as the flower flange and is necessary to guide as many ions as possible without losing ions to pumping or actual stainless steel gas cell. Simulations have been done in determining the voltage drop on each electrode on the rings in order to have efficient amounts of ions but also fast enough where their decay will become a large factor. Below is a plot of the acceptance of the ions in the rings and also the time of flight plot that was determined.

![Graphs showing acceptance and time of flight](image)

Fig. 2: a) A plot of the acceptance which is very high in the first third of the gas cell but is low for the rest of it. b) Plot of the time of flight (TOF) that the ion will experience if it were stopped at that point. (The x-axis for the TOF is in mm)
The TOF is very important for this experiment because this system has to be able to handle ions with half lives on the order of ~10 ms. More calculations for the voltage are being made in order to have as large of an acceptance as possible but also a low TOF for the ions. It is important that the ions are stopping further downstream in the gas cell so their extraction time is much less. In order to have the ions stop further in the gas cell the correct combination of glass thickness and angle must be attained.

The next step in guiding the ions to the Penning Trap for mass measurements will be an RF multipole structure, which will focus and accelerate the ions to their final destination. This radio frequency quadrupole (RFQ) will be separated into three parts. The first section will occur in cross A of the GSS where the pressure will be ~50 mTorr. Between cross A and cross B, where the second section is placed, there is a skimmer that will deflect as much of the gas as possible. This device is a small orifice on the order of ~3mm. In the second cross the pressure will drop to ~10^{-3} Torr. Once again, there will be another small orifice allowing little gas flow, where the pressure will be ~10^{-6} Torr. This technique of vacuum usage is called differential pumping and is essential for the RFQ to work properly. If the pressure is too low in the first cross then the ions will not be able to thermalized in the helium, which acts as a buffer gas. If the pressure is too high in the second two crosses then the ions will take too long to be extracted and guided along their path. There will be decaying which will ruin the measurements further downstream.

The RFQ has two main purposes: to focus the ions as much as possible so no ions are lost to straggling and to move the ions downstream quickly and efficiently. In order to focus these ions a radio frequency is applied to the quadrupole. The resulting E-field
is inhomogeneous, which causes a non-zero force on the ions. First, the potential caused by an E-field needs to be looked at. The quadrupole in this system has two phases for the four rods. The rods across from each other are in phase while the two adjacent rods are then in their own phase. Ideally this will be a 90-degree phase difference. By looking at the potential due to just two of these rods that are in phase one can see that the potential looks like a saddle and the ions are not stable and will be lost due to vacuum or touching of the rod. The potential due to the other two rods is the same but rotated 90 degrees.

The way to fix this problem is oscillate these two potentials between the rods. Placing a radio frequency on the two groups of rods can do this. The resulting potential is a pseudo-potential because it is not real but the ions will assume it is real because the oscillation is fast enough. This pseudo-potential, \( D \), is shown below:

\[
D = \frac{e}{m} \frac{1}{4\Omega^2} \vec{E}^2 = \frac{e}{m} \frac{V^2 r^2}{\Omega^2 r_o^4} \quad [2]
\]

Shown below is a plot showing the two potentials initially and then after the RF is placed on it. There is also a small cartoon of the RFQ in two different phases.

Fig. 3: Two potentials of the rods resulting in the pseudo-potential that will confine the ions.
This potential will then confine the ions. Since the force on the ion is the negative gradient of the potential:

\[ < F >_T = -e \nabla D \quad [3] \]

The ions will then experience a force, which will bring them down to the middle of the RFQ where they can be moved downstream.

In order to put this RF on the quadrupole there must be a circuit driving this frequency. There are two options that can be taken in order to make this circuit. The traditional way is using a sine wave. Unfortunately, for this experiment, the frequency needs to be adjustable and sine waves are frequency dependent. Sine waves also have problems associated with high voltage resonant circuits. We need voltage separation in the wave of ~350V so the range of masses available to study is large, but for a sine wave in order to do this expensive amplifiers need to be purchased. A way to combat this is to use a square wave in place of the sine wave. By constructing a circuit driver using a square wave and placing it across a quadrupole 350V of separation was easily attainable. Amplifiers are not needed in order to complete this separation. There are problems with square waves but are minor in the face of money. It is difficult to produce “perfect” square waves and is also difficult to control the duty cycle of the wave. A 50% duty cycle would be ideal because it would be the most efficient.

\[ \text{Duty Cycle} = \frac{\text{Time spent at peak in one period}}{\text{Total time of period}} \quad [4] \]

Another problem associated with square waves is that the transmission percent of sine waves is better than that of square waves. Using simulations to show the percent of transmission, it is shown that a sine wave will have a transmission of 84.2% and a square
wave is at 67.7%. This is an acceptable loss due to the money saved by using square waves.

Experiment:

This project is under construction currently but progress is being made where stopping tests can be done within the gas cell. Experiments have been run seeing where the ions are stopping in the helium gas. These experiments were to see how the angle of the glass degraders affected the stopping within the Be window and helium and then compare them to previous calculations. The primary stopping tests were done for this purpose. By changing one variable, the angle of the degraders, essentially all three variables are being changed. If the angle is increased, more energy will dissipate in the glass, which will then allow more energy to dissipate in the Be window, and finally will stop further from the nozzle in the gas cell. Data from the experiment was collected and compared to that of previous calculations [6].

A primary beam (no nuclear reaction) of $^{40}\text{Ar}^{18+}$ at 100 MeV/A was used during the stopping test. The ions traveled through the glass degraders with a total thickness of 3mm. In place of the Be window a 600 micron stainless steel window was used. After passing through the stainless steel window and into the gas cell, the ions were then detected by a pair of silicon detectors, 100 and 500 microns respectively, 30 cm from the window. Calibration was done to these silicon detectors previously and the energy straggling was larger than calculations [7] had suggested. This was due to non-uniformity in the stainless steel window. The Be window is more uniform and will prevent energy straggling from the ions [8].
In another test with stopping the ions, a 140 MeV/A $^{36}$Ar was used. The change in energy causes in the change in the thickness and angle of the glass degrader. The first silicon detector was placed 43 cm from the Be window and two different tests were run. The first test was when the cell was evacuated to high vacuum and the second test was when there was 1200 Torr of helium. A plot (a) was made of the transmission of the two different tests vs. the angle of the degrader. Another plot (b) showing the fraction of the ions stopped in the gas when there was 1200 Torr was made showing which angles created the most amount of stopping [6]:

Fig. 4: Two plots showing the transmission of ions vs. the degrader angle
Conclusions:

The applications from this project will be very useful in the world of nuclear science. The measurements that will come from this project, like nuclear masses, half-lives, and decay studies, have not been measured for exotic nuclei and they will soon be realized with the LEBIT project. Along with LEBIT, there are a few other laboratories that are working on a gas-stopping project (Fig. 8). The LEBIT project is conducting this experiment with the highest beam energy of the other facilities so nuclei never seen before will be measured here at the NSCL [1]. All of these facilities are working to understand the structure of exotic nuclei that are far from stability. With these technologies, the testing of nuclear theories will now be possible.

Acknowledgements:

I would like to thank Prof. David Morrissey, Patrick Lofy, and the LEBIT group members for letting me work on this project. The REU program at Michigan State University gave me this opportunity to work in a lab and understand how research is conducted in an academic but also real world setting. I would like to also thank the National Science Foundation* for the funding of the REU program and the LEBIT project. The Department of Energy** also gives funding to the LEBIT project and to Michigan State University.

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References:


[8] – S. Schwarz et al., The low-energy-beam and ion-trap facility at NSCL/MSU, East Lansing, MI.
Fig. 5: A view of the two cyclotrons, the K500 & K1200, the A1900 Fragment Separator, the vaults, and the N4 vault with LEBIT room.
Fig. 6: The LEBIT project including the Gas Stopping Station and the 9.4 Tesla Penning Trap.
Fig. 7: The Gas Stopping Station including the gas cell, nozzle, RFQ, and crosses A, B, and C.
<table>
<thead>
<tr>
<th>Gas</th>
<th>Cell Size</th>
<th>Pressure</th>
<th>$E$ (MeV/A)</th>
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<tbody>
<tr>
<td>Argonne [3]</td>
<td>He</td>
<td>~20 cm</td>
<td>100 mbar</td>
</tr>
<tr>
<td>SHIPTRAP[4]</td>
<td>He or Ar</td>
<td>~15-20 cm</td>
<td>150-200 mbar</td>
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<tr>
<td>RIKEN[5]</td>
<td>He</td>
<td>200 cm</td>
<td>150 mbar</td>
</tr>
<tr>
<td>NSCL</td>
<td>He</td>
<td>~50 cm</td>
<td>1 bar</td>
</tr>
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Figure 8: Table showing the other facilities working on a gas stopping station of their own. The specifications of the facilities are displayed.