MoNA and initial measurements with $^7$He Resonance

Tina Leah Pike
REU
Summer 2004
Abstract

MoNA and initial measurements with $^7$He Resonance *

Of recent interest in the study of exotic nuclei are neutron rich nuclei near and beyond the drip line. Using radioactive beams produced at the National Superconducting Cyclotron Laboratory (NSCL), the Modular Neutron Array (MoNA) detector, and a 4 Tesla sweeper magnet it is possible to study these nuclei. MoNA is a large area, high-efficiency neutron detector consisting of 144 plastic scintillating bars. When used in tandem with the series of detectors and scintillators in the sweeper setup MoNA is capable of detecting neutrons in coincidence with reaction fragments detected at the sweeper. As an initial experiment to test the tandem setup of MoNA and the sweeper a secondary beam of $^8$Li was produced in the coupled cyclotron facility and the reaction of interest, stripping off a proton to observe the resonance of $^7$He immediately decaying to $^6$He+n, was studied with MoNA and the sweeper. The ground state of $^7$He resonance was observed in the relative velocities of $^7$He and the neutron.

*MoNA collaboration is supported by the NSF.
TP, RP acknowledge the support from the NSF Research Experience for Undergraduates program.
Introduction

Studying the properties of exotic nuclei can provide insight to fundamental laws and nuclear models of interest to the physics community. Of recent consideration is the study of neutron rich nuclei near and beyond the drip line. Bound systems are found in the valley of stability on the chart of the nuclides (see figure 1). Stability weakens while moving away from this valley of stability and unbound nuclear systems are found beyond the neutron and proton drip lines. Moving away from the valley of stability nuclei decay to those nuclei on the valley of stability. \( \beta \) unstable nuclei are those near the valley of stability that decay by \( \beta \) emission to the stable nuclei on the valley of stability. Proton and neutron unstable nuclei are those where the proton and neutron separation energies become negative and the last proton or neutron is said to be unbound. These are the nuclei beyond the proton and neutron drip lines. [1]

![Figure 1. The chart of the nuclides. The black nuclei are stable and make up the valley of stability. Stability decreases moving away from this valley starting with \( \beta \) unstable nuclei close to the valley and ending with the proton and neutron drip lines on the outer most edges.](http://www.nscl.msu.edu)

As the stability of nuclei decreases the level of difficulty to experimentally study them increases. However, using radioactive beams created at the National Superconducting Cyclotron Laboratory (NSCL), a Modular Neutron Array (MoNA) detector, and a sweeper magnet it is possible to study these exotic nuclei near and beyond the neutron drip line. It is necessary to study the detected neutrons in coincidence with detected charged fragments from reactions that are swept aside by the sweeper magnet for a more comprehensive understanding of the exotic nuclei studied.

MoNA is a large-area, high-efficiency neutron detector comprised of 144 plastic scintillating bars. (See figure 2). The scintillating material is sensitive to electrons, protons, alpha particles, gamma rays and
neutrons. Because a neutron has no charge it is detected indirectly. It must interact with a charged particle within the bar to cause scintillation in order to be detected. Each bar measures 200x10x10 cm³ and has two photomultiplier tubes, one at each end, which converts the internally reflected light into an electric signal. Currently, MoNA is arranged in nine columns each consisting of 16 detector bars making an array of 144 detectors covering an area of 2.0 m wide by 1.6 m high.

![MoNA Setup](image)

R. Pepin, August 2004

**Figure 2.** A picture of MoNA in its current position and configuration

MoNA does, however, have the ability to be rearranged to meet the needs of various experimental setups and is designed to have 70% efficiency at detecting single neutron events and 49% efficiency at detecting a double neutron hit. MoNA also has the capability of using passive iron converters, which increase nuclear interactions in the detector volume, to increase the efficiency of detecting neutrons of above 100 MeV. [2]

The sweeper magnet is a 4 Tesla large gap magnet that bends the charged reaction fragments 43 degrees to a vacuum chamber containing multiple detectors. The vacuum chamber contains two Cathode Readout Drift Chambers for position measurements, an ion chamber for energy loss measurements, and thin and thick plastic scintillators for additional energy measurements.

As an initial experiment a $^8$Li beam created by the coupled cyclotron facility was used to bombard a carbon target to test MoNA’s ability to detect neutrons from the reaction in coincidence with charged fragments from the reaction at the sweeper magnet. It was found that MoNA was, in fact, able to detect neutrons in coincidence with charged reaction fragments detected at the sweeper magnet.
**Experiment**

A primary beam was produced by creating $^{18}$O$^{+3}$ in the Electron Cyclotron Resonance (ECR) ion source and injecting it into the K500 cyclotron via the K500 Injection Line. An ion must be used because electromagnetic fields are used to accelerate the particles in the cyclotron and electromagnetic fields only accelerate charged particles. Once in the K500 the $^{18}$O$^{+3}$ was accelerated in a circular path and the energy was increased as it passed the same radio frequency and high voltage several times. At 10.91 MeV/nucleon the $^{18}$O$^{+3}$ was transferred to the K1200 cyclotron via the K500-to-K1200 Coupling Line. [3] Before entering the K1200 the $^{18}$O$^{+3}$ was ionized to $^{18}$O$^{+8}$. The $^{18}$O$^{+8}$ beam was then accelerated in the K1200 cyclotron using the same radio frequency and high voltage method of acceleration as that of the K500. Upon exiting the K1200 cyclotron at 120 MeV/nucleon the secondary beam was produced by projectile fragmentation when the primary beam ($^{18}$O$^{+8}$) struck a beryllium production target of 3,526 mg/cm$^2$ creating a large range of isotopes. After striking the production target the beam immediately proceeded to the A1900 fragment separator where the desired isotope, $^8$Li, was selected with a series of bending and focusing magnets. The beam was then directed to the N4 vault with another series of focusing and bending magnets in the transfer hall.

![Diagram of cyclotron](http://www.nscl.msu.edu)

**Figure 3.** A schematic of the cyclotron indicating various parts of the cyclotron.

In the N4 vault the $^8$Li beam was directed toward the sweeper magnet. While entering the sweeper magnet the $^{18}$O$^{+8}$ beam bombarded a carbon target of 75 mg/cm$^2$ creating charged fragment reaction products and neutrons. The reaction of interest was the proton stripping of the $^8$Li to unbound $^7$He decaying to $^4$He+n. The sweeper magnet is a 4 Tesla magnet that “sweeps” the charged fragments from the reaction away to the side while allowing the neutrons to continue at zero degrees toward MoNA. The sweeper magnet bends charged particles different amounts according to their mass-to-charge ratio and velocities. Once bent
through the sweeper the fragments pass two Cathode Readout Drift Chambers (CRDC’s) that are for position determination and then the fragments pass through an ion chamber for an energy loss measurement. After passing through the ion chamber the fragments pass through two scintillators, first a thin one and then a thick one. As a fragment passes through the thin scintillator it deposits a certain amount of energy providing a $\Delta E$ measurement and proceeds to the thick scintillator where it deposits its remaining energy giving a final energy measurement. Together these energy measurements are used for the identification of the charged fragments. They are also used in cooperation with mass-to-charge ratios and the CRDC’s to deduce the position of the reaction at the target. [4]

The neutrons, which continued at zero degrees, were detected by MoNA. The signals produced by the neutrons that interacted with a charged particle within the scintillating bars of MoNA and produced a signal for detection were recorded. Using the information provided by MoNA, identification of the charged fragments bent by the sweeper, and various methods of analysis it was possible to determine neutron events that occurred in coincidence with charged fragments at the sweeper.

Analysis

MoNA is used in cooperation with the sweeper magnet to measure various properties of reaction events occurring in coincidence. This is important in the study of exotic nuclei beyond the neutron drip line because it is possible to deduce the decay energies of reactions, including previously unknown decay energies, by using these various measured properties from MoNA and the sweeper. Because the MoNA-sweeper combination had not yet been used for an experiment to study reactions in tandem it was necessary to study a known reaction to determine if the experimental setup with the sweeper and MoNA worked as expected.

The reaction studied was that of $^6\text{Li}$ hitting a carbon target stripping off a proton creating unbound $^7\text{He}$ that immediately decayed into $^6\text{He}+n$. The $^6\text{He}$ and the neutron were detected by the sweeper setup and MoNA respectively. With preliminary analysis from the information provided by the sweeper and MoNA the relative velocities of the $^6\text{He}$ and the neutron were determined. These relative velocities can then be compared to the theoretical expectations to determine how well MoNA and the sweeper work in tandem.
We begin by looking at theoretical values for the velocities of the $^6$He and the neutron. Conservation of energy and momentum allows for calculation of the expected relative velocities. Because the decay energy is one of a known value, 450 KeV, and the masses of the $^6$He, $5.603 \times 10^3$ MeV/c$^2$, and the neutron, $9.39 \times 10^2$ MeV/c$^2$, are known it is possible to calculate the expected relative velocities of the $^6$He and the neutron. Initially, we have the kinetic energies of both the $^6$He and the neutron of which the sum is the energy of the decay of the $^7$He (see equation 1).

$$E_{\text{Decay}} = \frac{1}{2} m_{\text{He}} v_{\text{He}}^2 + \frac{1}{2} m_n v_n^2 \quad (\text{Eqn. 1})$$

We want to extract the velocities of each of the particles. Remembering conservation of momentum (see equation 2)

$$m_{\text{He}} v_{\text{He}} = m_n v_n \quad (\text{Eqn. 2})$$

we have two equations and two unknowns. Initially solving for the velocity of the $^6$He fragment yields the following (see equation 3)

$$v_{\text{He}} = \left[ 2 E_{\text{Decay}} \frac{m_n}{m_{\text{He}}} \left( \frac{1}{m_{\text{He}} + m_n} \right) \right]^{1/2} \quad (\text{Eqn. 3})$$

From equation 3 we obtain a velocity of 0.143 cm/ns for the $^6$He. Using this velocity in equation 2, from conservation of momentum, the velocity of the neutron is found to be 0.859 cm/ns. It must be noted that these calculations are under the assumption that MoNA covers only small angles and we are therefore only considering forward and backward emissions. (See figure 4). The relative velocity is then 1.002 cm/ns. The relative velocity found under the previously mentioned assumption can then be compared to the measured relative velocity of the $^6$He and the neutron to determine how well MoNA and the sweeper worked in tandem.

**Figure 4.** Diagram depicting forward and backward emissions.
Experimental Results

To determine the experimental relative velocities of the $^6$He and the neutron it must be determined whether the tandem setup actually measured the $^6$He and the neutron in coincidence. To determine this it must first be determined if MoNA detected neutrons. Examining a run done with the $^8$Li beam striking the steel viewer in the sweeper provides sufficient information to verify if MoNA performed suitably to detect neutrons. Looking at the time of flight spectrum for the first hit two distinct features are seen. (See figure 4).

![Time of flight spectrum for beam striking steel viewer. The gamma flash is observed to come before the neutron peak.](image)

First, a gamma flash is seen as expected. A gamma flash appears in the spectrum because as the beam strikes the viewer atoms in the viewer get excited and vibrate emitting gamma rays that are detected by MoNA. The distinctive gamma flash in the time of flight spectrum for the first hit indicates that MoNA detected gamma rays produced by the beam striking the viewer and also that MoNA has the capability of detecting gamma rays for future reactions. Another distinct feature in the time of flight spectrum for the first hit is the neutron peak. As the $^8$Li beam strikes the steel viewer reactions occur and charged reaction fragments are swept aside by the sweeper magnet while allowing uncharged particles to continue at zero degrees toward MoNA. The peak observed is known to be a neutron peak because of where it occurs relative to the gamma flash in the spectrum. This is a clear indication that MoNA has the capability of detecting neutrons and coincidence events may be examined.
To examine events in coincidence it is first necessary to know the identification of the fragments swept aside by the sweeper. Identification of these fragments is done by viewing data from the thin and thick scintillators within the sweeper setup. The thin scintillator allows fragments to pass through it depositing a certain amount of energy giving a $\Delta E$ (change in energy) measurement. The fragments then continue on to the thick scintillator where they deposit their remaining energy providing a final energy loss measurement. By viewing this data as $\Delta E$ vs. $E$ it is possible to identify the fragments.

![Figure 5. The $\Delta E$ vs. $E$ plot used for fragment identification at the sweeper magnet. Fragment identification is indicated on the spectrum.](image)

This $\Delta E$ vs. $E$ plot shows distinct bands, each one corresponding to a different fragment. The $\Delta E$ to energy ratio is a characteristic feature for the different isotopes of the elements and it is therefore possible to determine what fragment each band came from. Studying a known reaction allows us to know what reaction products to expect. Some possible reactions occurring are $^8Li \rightarrow ^6He + ^1H + ^1n$ and $^8Li \rightarrow ^3H + ^4He + ^0n$. The bands in the $\Delta E$ vs. $E$ plot can be identified because of the known reaction products and the characteristic $\Delta E$ to energy ratio for the isotopes of the elements. We know that the top band is from $^8Li$, the middle band is from $^6He$, and the bottom band is from $^3H$.

After identifying the fragments swept aside by the sweeper it is possible to identify the neutrons occurring in coincidence with those fragments by gating on the fragments in the $\Delta E$ vs. $E$ spectrum. This will identify MoNA events that occurred in coincidence with the gated fragment. Examining the time of flight hit spectrum for the total hits ungated yields the time of flight for all hits coming from any fragment.
and including background. (See blue spectrum in Figure 6.)

![Total Time of Flight](image)

**Figure 6.** The time of flight spectrum for the run of interest. The blue spectrum is completely ungated. The red one is gated on $^3$He, the yellow one is gated on the $^3$H, while the green is gated on the $^8$Li.

Gating on the $^8$Li band in the $\Delta E$ vs. $E$ plot from the sweeper thin and thick scintillators will show the events in the time of flight hit spectrum in coincidence with the $^8$Li. (See green spectrum in Figure 6). Applying the $^8$Li gate to the time of flight hit spectrum for the total hits results in random events. This indicates that there were no neutrons associated with the $^8$Li. This is expected because if portions of the $^8$Li do not react within the target then no neutrons detected in MoNA would be associated with the $^8$Li. Gating on the $^3$H and applying the gate to the time of flight hit spectrum will yield the neutrons associated with the $^3$H from the $^5$Li$\rightarrow^3$H$+^2$He$+^1$n reaction. (See yellow spectrum in Figure 6). These neutrons are evident in the gated time of flight hit spectrum, they are the tall peak in the center of the spectrum. To look at the reaction of interest, $^5$Li$\rightarrow^6$He$+^1$H$+^1$n, or essentially unbound $^7$He decaying to $^6$He$+n$, a gate on the $^6$He in the $\Delta E$ vs. $E$ spectrum is applied to the time of flight hit total spectrum. Applying this $^6$He gate to the time of flight hit spectrum yields a distinct peak of neutrons. (See red spectrum in figure 6).
asserts that the neutrons detected by MoNA gated on the $^6$He occurred in coincidence with the $^6$He as expected for the unbound $^7$He decay into $^6$He+n.

Further preliminary analysis on experimental results yields a relative velocity spectrum for the $^6$He and the neutron that can be compared to the expected value of +/-1.002 cm/ns.

The resulting relative velocity spectrum has two distinct peaks, one at 1.15 cm/ns and the other at –0.25 cm/ns. The peaks should be sharp and at the location of +/-1.002 cm/ns. They are not sharp because MoNA has a small angle of acceptance therefore accepting neutrons from reactions that do not result from directly forward or backward emissions. This is why the peaks are broad. The resulting difference in these two peaks is 1.4 cm/ns. The expected difference between the peaks is, however, 2.004 cm/ns (as mentioned previously, 1.002 cm/ns for a relative velocity). The peaks are not 2.004 cm/ns apart because of resolution. Convolution occurs because of the Gaussian distribution associated with the counts when making the spectrum. This causes an inward shift for the peaks resulting in a smaller distance between the peaks. The edges of the spectrum are expected to appear at about +/-1.002 cm/ns because of the convolution and resolution effects. The valley in the spectrum should also be centered at zero. However, the experimental results yield a spectrum centered at $V_{diff}=0.35$ cm/ns instead of 0.00 cm/ns. The

Figure 7. Relative velocity spectrum for the run of interest. The two peaks indicate a distinction between forward and backward emissions.
spectrum is not centered at zero because of some fine-tuning left to finish. When correcting for this factor the edges appear in the appropriate place. Therefore the experimental results agree considerably well with the expected relative velocities.

**Conclusion**

MoNA was able to detect neutrons in coincidence with fragments detected at the sweeper magnet. From this it was possible to look at a known reaction of the stripping of a proton from $^8\text{Li}$ to unbound $^7\text{He}$. $^7\text{He}$ decayed immediately into $^6\text{He}+\text{n}$ while observing the difference between forward and backward emissions of the $^6\text{He}$ and the neutron. It was necessary to observe the difference between forward and backward emissions because it indicates that MoNA worked in tandem with the sweeper at an appropriate resolution to observe the difference between these emissions. The experimental relative velocities agreed with the expected relative velocities again indicating that MoNA and the sweeper worked in tandem. Although, the tandem setup was able to detect forward and backward emissions there are still a few items that need fine-tuning for a completely satisfactory tandem setup.
References

2. http://groups.nscl.msu.edu/mona/ Thomas Baumann