An Energy Calibration of the FN Tandem Accelerator Magnet Analyzing System at Notre Dame

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ABSTRACT

This work established the groundwork for a proper calibration of the magnet analyzing system for the FN Tandem accelerator at the University of Notre Dame. The calibration utilized (p.n) reactions with well-known threshold energies to correlate NMR Frequency with beam energy. A neutron detector composed of three ^{3}He proportional counters with moderating polyethylene has been constructed to detect the neutrons. To maximize detection efficiency, GEANT4 was employed to determine the optimal dimensions of the moderator. The maximum efficiency was found to occur with a 3-inch moderator half-length, with the efficiency varying by 2.2% over an 11keV proton beam energy range. A preliminary analysis of data from the ^{27}Al(p,n)^{27}Si yields a result of 5.803MeV corresponding to a frequency of 14.64±.01MHz.

INTRODUCTION

Nuclear astrophysics investigates the nature of energy generation in stars, which consequently leads to examinations of matter creation in stars as well. The source of energy for stars once represented the biggest problem facing astrophysics. In 1920, however, Arthur Eddington suggested that stars generated energy through nuclear fusion, and in 1933, Hans Bethe developed the precise process describing the fusion of hydrogen into helium, for which he later won a Nobel Prize. Later, in the 50's and 60's, scientists including Fred Hoyle, William Fowler, and many others, developed models providing for the fusion of heavier elements. This process of stellar nuclear fusion which extracts energy from the fusing of two lighter elements into a heavier one is referred to as nucleosynthesis. Such a process lies fundamental to an understanding of all known life for two reasons. The first results from all life's dependence on the radiation emitted from the sun, or sunlight. Secondly, heavy elements, particularly carbon and oxygen, compose the chemical makeup of organic material. The source of most lithium and all heavier elements in the universe, including oxygen and carbon, are thought to result from this nucleosynthesis in other stars [1]. Thus a thorough knowledge of nucleosynthesis lies fundamental in our appreciation of the conditions necessary for life.

An understanding of the rate of particular nucleosynthesis reactions lies central to grasping the elemental composition of stars throughout their lifetime as well as the rate of energy production. Each reaction has a property called the cross section, which represents the probability of the given reaction occurring. A high cross section corresponds to high reaction probability, while a low cross section translates to a very small likelihood of the reaction taking place. The REACTION research group at Notre Dame University is examining many stellar nuclear reactions occurring within the sub-Coulomb nuclear barrier. The cross sections within this region display a very high sensitivity to energy. Therefore, in order to measure these cross-sections precisely, the energy at which reactions are experimentally observed must be known to a high degree of precision. To accomplish this high energy precision, the analyzing magnet system for the FN Tandem accelerator housed at the University of Notre Dame was calibrated using negative Q-Value (p,n) reactions. This paper discusses the design of this calibration for optimal efficiency, provides preliminary results from ^{27}Al(p,n)^{27}Si and offers future improvements for the continuation of this calibration.

EXPERIMENTAL SETUP

The FN Tandem particle accelerator at Notre Dame operates by creating a positive terminal voltage on a central electrode, which consequently creates an electric field in the accelerator. As negative ions from the Sputter Negative Ion Source enter the electric field, they accelerate until they hit a stripper foil at the center of the accelerator. This stripper foil removes multiple electrons from the particles, creating positive ions. These positive ions then feel the electrical field as well, but are accelerated away from the central electrode. When these positive ions with charge q exit the accelerator proper, for a given terminal voltage V they have energy $E=(q+1)V$ and exist in a plethora of charge states [3]. The analyzing magnet system then filters out the desired charge states, and consequently the desired energy, to be collided with the target in the target room. The magnetic rigidity (p/q) of a particle traveling in a magnetic field of strength *B* is described by $\frac{p}{q} = BR$, where *R* is the radius of the charged particle trajectory within the magnetic field. Considering the relationship between observed NMR Frequency *f* and magnetic field strength *B, B=cf*, utilizing Newton's second law it follows that $c^2 f^2 \frac{q^2 R^2}{2m} = (q+1)V$ and we conclude that the square of the measured NMR frequency is proportional to the energy of the outgoing particle. The NMR frequency is thus the observable quantity used to correlate with energy.

To find known energy values for this correlation, we turn to (p.n) reactions. These reactions have extremely well-studied and well-defined behaviors, and thus yield an excellent tool for determining precise energies. To break up a heavy stable nucleus, energy to overcome the strong nuclear force holding the particles together must be present. The term for this necessary energy is called the Q-Value or threshold energy. If the incoming particle does not have this energy, no reaction occurs. Above this energy threshold, however, reactions begin to occur at a predictable rate, with the reaction yield measured *Y* proportional to the energy above the threshold energy, or $Y = (E - E_{th})^{2/3}$ (see Fig. 1). Since the threshold energies and behavior of (p,n) reactions are both well-known, these threshold energies can be experimentally pinpointed and correlated with the square of NMR frequency, thus creating a calibration curve for the analyzing magnet system. This process has been widely used by other accelerator facilities [4], [5].

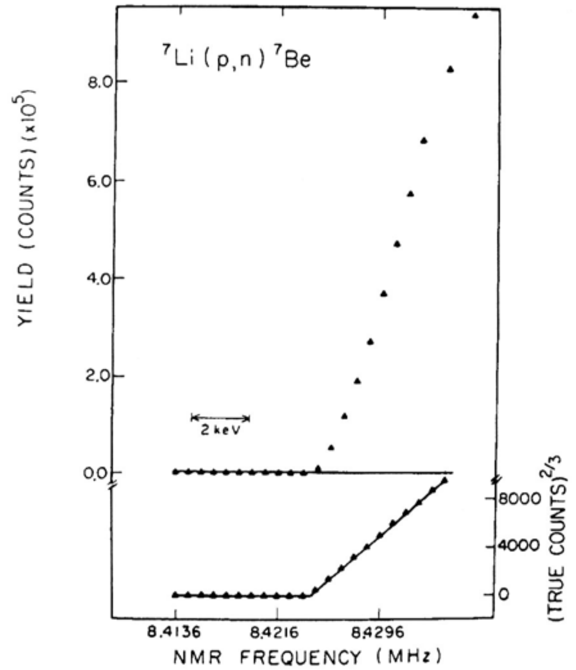

Figure 1: Yield vs. NMR Frequency for ^{7}Li(p,n)^{7}Be. Note the threshold frequency, before which no yield is observed, and after which the yield increases linearly with the 2/3 power of the energy difference (True Counts, lower plot). Also, the energy range for this plot is approx. 8 keV [4]

DETECTING NEUTRONS: GEANT4 SIMULATIONS

In order to properly conduct a calibration utilizing (p,n) reactions, one must have an apparatus which can properly detect neutrons. The neutron detector utilized consisted of ^{3}He proportional counters surrounded by moderating polyethylene to thermalize the neutrons. ^{3}He was selected for a proportional counter because ^{3}He(n,p)^{3}H has a cross section σ=5333 barns at thermal energy, which is extremely high. Thus these proportional counters yielded relatively high reaction yields resulting in counts for incoming thermal neutrons. The moderating material, polyethylene $(C_2H_4)_n$, was chosen for its high hydrogen content, since hydrogen easily slows neutrons to thermal energies (~meV) due to the similar masses of hydrogen and neutrons. The thickness of the moderator determines the extent to which neutrons are slowed before they reach the proportional counters. If the moderator were too thick, it would absorb the neutrons before they reach the proportional counters. Too thin a moderator results in neutrons passing through the apparatus without detection. To determine the optimal moderator thickness for our detector to maximize detection efficiency, we turned to the detector simulation program GEANT4.

GEANT4 is “a toolkit for the passage of particles through matter” [6]. It thus serves as the perfect framework for developing a system to simulate and test for optimal detector configurations. In order to confirm that this system produces valid results, however, GEANT4 was tested against literature values to confirm similar behavior in a known system. The known apparatus utilized for validating GEANT4 was a Bonner Sphere, perhaps the most common form of neutron flux monitor. Bonner Spheres consist of moderating polyethylene spheres with a neutron detector at the center. In our simulation, we fixed the radius of the spherical ^{3}He counter at 3.2 cm and varied the radius of moderator from 0 cm to 12.7 cm. Its response functions at various moderator thicknesses and energies were calculated and then compared to literature values calculated by *Vega-Carrillo et al.* utilizing MCNP [7]. Our values compared rather favorably with this literature values, as shown in Figure 2.

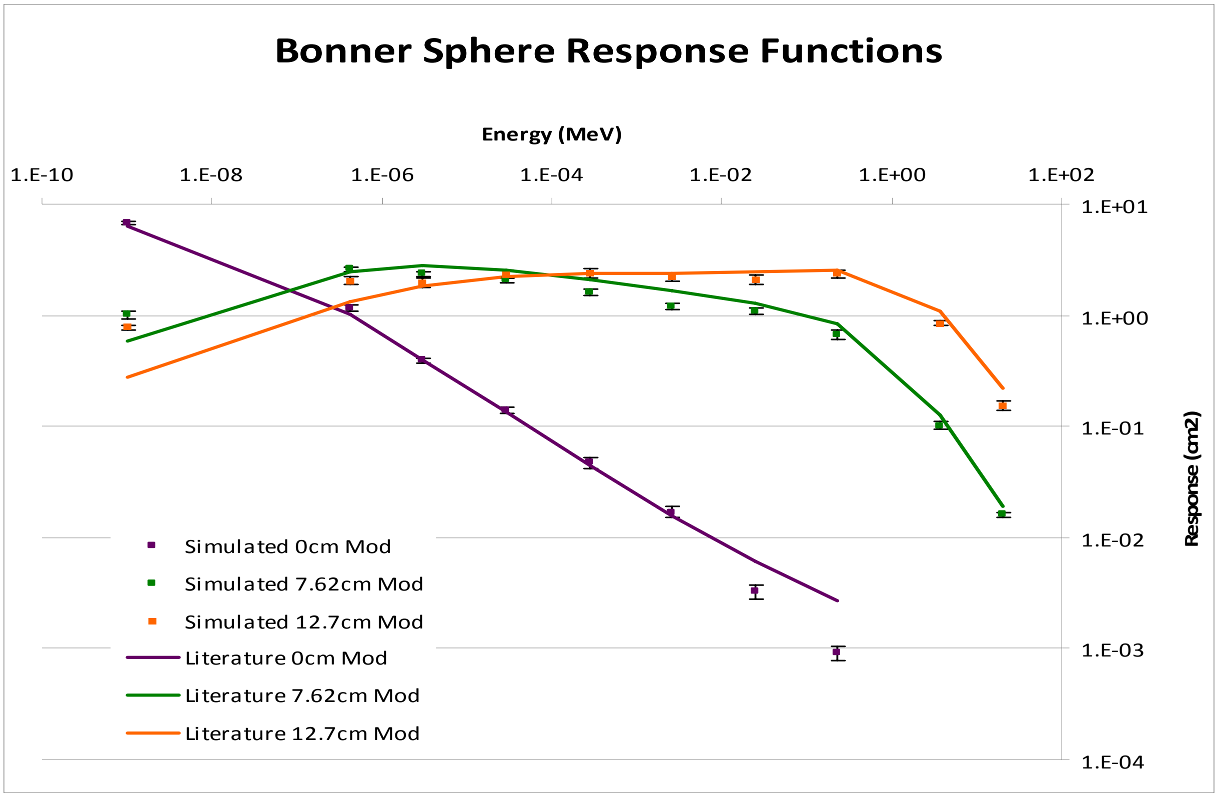

Figure 2: Simulated Bonner sphere response functions for varying energies. 3 thicknesses were examined. The simulated data shown by dots compares well with the lines of the literature data.

Having confirmed this data, the neutron detector was then configured. The configuration necessarily needed to consider the spatial range of neutrons emitted from the reaction. The neutrons emitted from the reaction created a cone of tracks, as the emitted neutrons displayed a range of angles from the reaction site (see Fig. 3). The maximum angles were determined by the maximum energy of the neutrons. The detector itself consisted of 3 ^{3}He detectors arranged in a vertical plane halfway through the moderating material (see Fig 4). This configuration allowed for optimal detection of the incoming neutrons from the beam point-source since the plane represented a ‘wall’ orthogonal to the track of the neutrons.

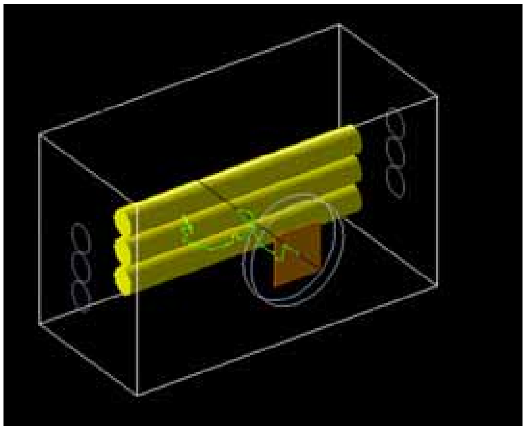

Figure 3. GEANT4 Image of the Neutron Detector Design. Yellow cylinders represent ^{3}He proportional counters.

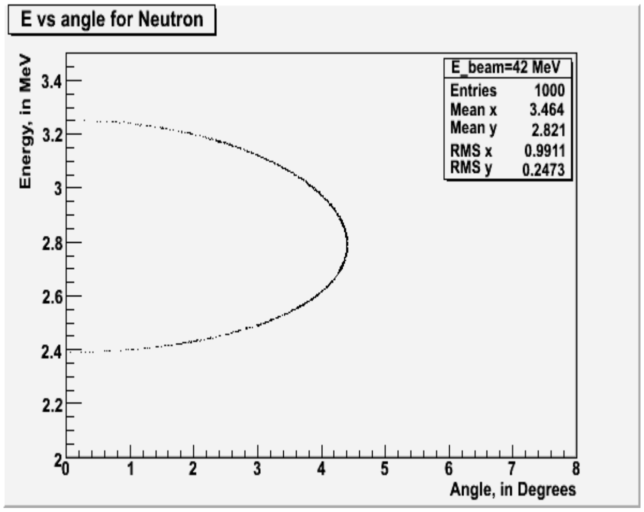

Figure 4. Angular Distribution of Neutrons from 13C(p,n)13n at 3.23MeV as a function of Energy. This angle is simply the angle of the neutron normal to the plane of collision; thus a cone of neutrons tracks is observed.

With this detector construction, the detector was then tested for efficiency at various moderator thicknesses to determine the optimal detector configuration. The detector was configured using incoming neutron energies from the ^{13}C(p,n)^{13}N reaction. Although other (p,n) reactions will be examined for calibration, this investigation provides a template for quickly determining the best moderator thickness for a given reaction. Optimal moderator thickness for the neutron detector was determined by simply testing for maximum counts per incoming neutrons at varying energy levels near the threshold energy. The simulated results are shown in Figure 5. The peak efficiency occurs at a 3-inch moderator half-length, which indicates the thickness used for detecting neutrons for the $^{13}C(p.n)^{13}N$ reaction.

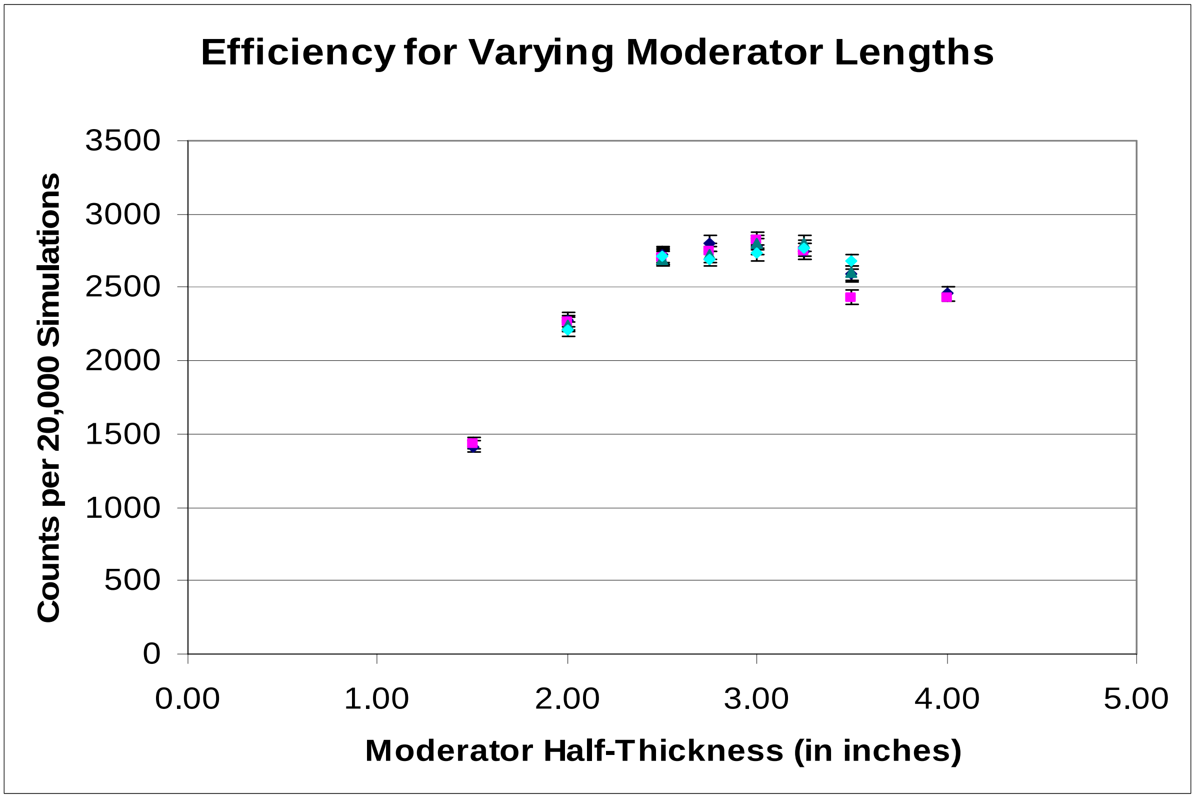

Figure 5: Neutron Detector Efficiency as a Function of Moderator Half-Thickness. The peak at 3” notes the optimal moderator thickness for our neutron detector.

Having obtained this maximum detector response, the efficiencies for this configuration were then tested across an 11keV range, from 1keV below the threshold energy to 10keV above the threshold energy. These results are shown in Figure 6, and indicate the efficiency to be statistically constant in this region, as all the efficiencies are within 1.5σ of each other. There does, however, appear to be a slight downward trend in this region, suggesting perhaps a slight decrease in detector efficiency towards the higher end of the energy range examined. Most importantly, however, it should be noted that the detector efficiency should *not* be assumed constant over a given energy range. This complicated the yield vs. energy dependence.

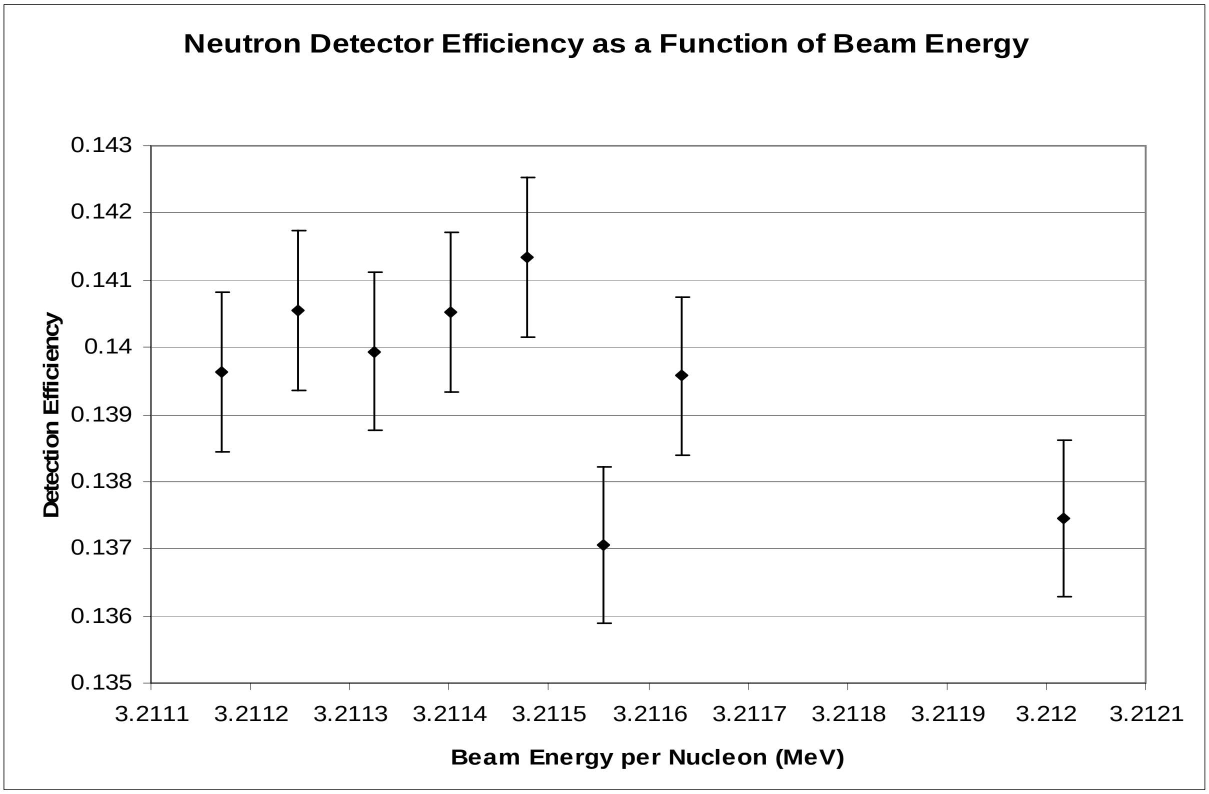

Figure 6: Detector Efficiency as a Function of Beam Energy. While the efficiencies do not vary with statistical significance, a slight decrease in efficiency is evident as energy increases.

PRELIMINARY RESULTS: ^{27}Al(p,n)^{27}Si

The results from a run of the reaction ^{27}Al(p,n)^{27}Si were obtained and initially analyzed. The raw data, seen in Figure 7, did seem to follow the expected behavior, however, significant background contributions can be concluded from this data, as seen by the positive sloping trend below the threshold energy. *Wilkerson et.al.* assumed a linear background and having fit a background to the raw data, subtracted off the background fit from the raw yield data [4]. Utilizing this approach, a linear background was fit, and then the yield data was taken to the 2/3 power, while squaring the frequency to plot $frequency^2$ *vs. Yield* $^{2/3}$. This represents the fundamental anticipated relationship between frequency and yield (see Experimental Setup).

Two linear fits were then performed on the data, neglecting data from the curved transition area around the threshold energy. The intersection of these points yielded the square of the threshold frequency, which was then transformed to obtain the final threshold frequency value (Fig. 8). The final calculated value was observed to be 14.6395±.01MHz.

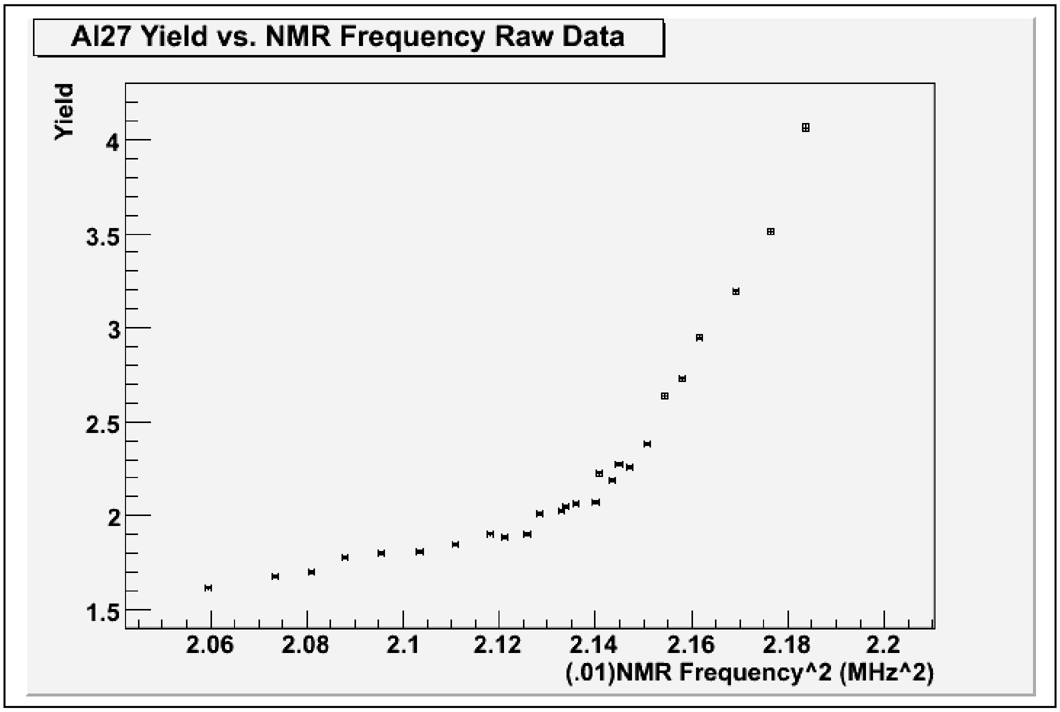

Figure 7: Raw Data, Frequency^2/100 Yield

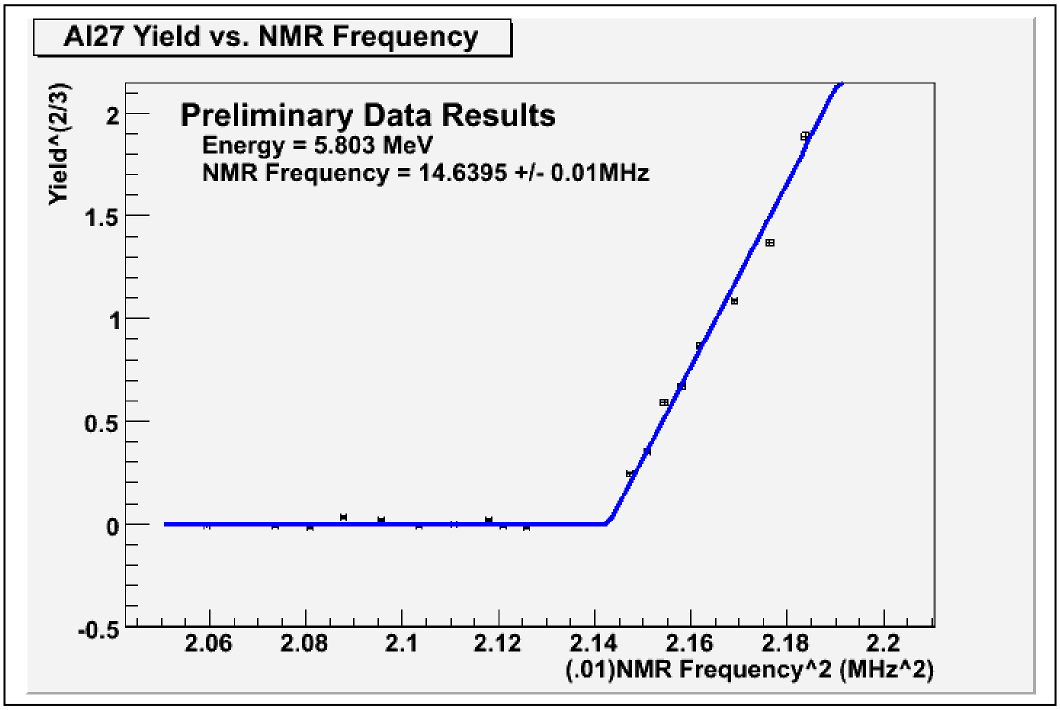

Figure 8: Yield $^{2/3}$ vs. Frequency^2/100 with fit, Showing Threshold Frequency

The Chi-Squared per degree of freedom for our fit was found to be 6.1. This high value clearly indicates a problem either with the uncertainty estimations or with the fit. Sources of uncertainty result from measurements of the yield and NMR frequency. The NMR frequency error was determined by fitting the frequency vs. terminal voltage with a linear fit, and then taking the maximum error from that fit to be the maximum uncertainty of NMR frequency. The yield was calculated by dividing counts from the neutron detector by counts from the Faraday Cup. The uncertainties for counts from the detector itself were calculated using simple statistical errors. The Faraday Cup uncertainty, however, presents a large problem, as there is no orthodox way of easily calculating this value. This value was estimated at a simple 1% error, but it is believed that this figure may be too low. Further investigations could be conducted into accurately determining the uncertainty of the counts from the Faraday Cup.

Varying methods of fitting have been experimented with, and all yield slightly different results. Some of these varied by as much as .02MHz, which results in the .01MHz uncertainty for the final value. Variations of the primary method include fitting to frequency instead of frequency squared, subtracting off the background after converting data to yields to the 2/3, and other combinations of a similar nature. It is difficult to determine the proper method of fit other than taking the best chi-squared value, and time constraints prevented a complete investigation into the best fit of the data. Furthermore, selecting which data range to fit to (ie. choosing data from the transition region to cut out) seemed to be somewhat arbitrary, as there is no definitive 'start' to the transition region. This raises big questions about the systematic uncertainty of the data that should be further investigated.

Other sources of error include the possibility of a nonlinear fit to the background, which the observed data slightly suggest in figure 8, and changes in the efficiency of the detector, as discussed in the previous section. Furthermore, since the beam is not monoenergetic, but contains a spread of energies, there will be a smearing effect in energy values since the incoming energy is not discrete. This explains the curved nature of the transition region. Furthermore, this energy smearing seems to lower the calculated threshold frequency from the actual value (see Fig. 9), but this effect as well requires further investigation.

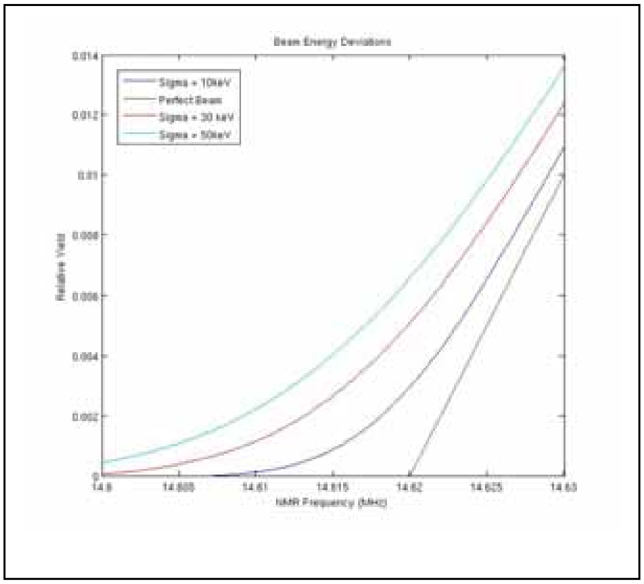

Figure 9: Effect of Beam Energy Distribution. Note the increased curvature for large values of sigma, as well as the slight decrease of the perceived threshold NMR frequency

CONCLUSION

Utilizing GEANT4, a successful detector configuration for neutron detection was designed and simulated to provide for optimal efficiency. Using a similar design in the detection of ^{27}Al(p,n)^{27}Si, data for this reaction was obtained and analyzed. A preliminary threshold frequency for this data was obtained, but much work remains to be done in completing the analysis of this data. Better uncertainty estimations concerning the output from the Faraday Cup would contribute towards improving these fits, as would a more in-depth analysis of various fitting processes over the various data ranges. It is unfortunate that time constraints have halted this data analysis from full fruition. Important groundwork, however, has been laid to contribute towards a highly accurate and precise energy calibration of the analyzing magnet system for this accelerator.

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