

Proton Transfer Reactions Studied Using the Versatile Array of Neutron Detectors at Low Energy (VANDLE)

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For my mother Christine.

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Abstract

Single nucleon transfer reactions are powerful tools for the study of nuclear structure. The spectroscopic properties of unstable nuclei help to constrain nuclear structure models for more exotic nuclei. In inverse kinematics, proton transfer reactions, such as (d,n), may be used to study the properties of short-lived radioactive ion beams (RIBs). By measuring the outgoing neutron, it is possible to extract spectroscopic information about the proton states of the recoil nucleus in much the same way as probing the neutron states of the recoil using neutron transfer (d,p). With the development of new accelerator facilities, such as the Facility for Radioactive Ion Beams (FRIB) in the U.S., comes the need for new spectroscopic tools for use with RIBs.

The versatile array of neutron detectors at low energy (VANDLE) is an array of plastic scintillator bars that are used to detect neutrons using a time-of-flight method. Stable beams of ^{12}C and ^{16}O were used to study proton transfer reactions in inverse kinematics using VANDLE at the University of Notre Dame. $^{12}\text{C}(d,n)$ was measured at eight energies between equivalent deuteron energies of 3.1 *MeV* and 7.0 *MeV* while $^{16}\text{O}(d,n)$ was measured at a single energy of 8.0 *MeV*. This work was the first successful proton transfer measurement using VANDLE. Angular distributions are shown for transfer to the ground state of ^{13}N at all eight energies and to the first excited state at the higher beam energies. Excitation functions for $^{12}\text{C}(d,n)$ are shown for center-of-mass angles between 3° and 70° . The angular distributions for population of the ground state and first excited state of ^{17}F are also shown. Developments of low energy proton transfer experiments in inverse kinematics are discussed and angular distributions are compared to literature.

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Chapter 1

Introduction

With the next generation of radioactive ion beam (RIB) facilities comes the opportunity to push the boundaries of nuclear structure research further from stability. Over the next decade, the Facility for Rare Isotope Beams (FRIB) in the U.S., the Selective Production of Exotic Species (SPES) in Italy, and the Facility for Antiproton and Ion Research (FAIR) in Germany will all be coming online. More exotic species will be available for study and new tools and techniques will be necessary to utilize them to their full potential. While these locations are still under construction, current facilities may be used to access exotic beams. The Nuclear Structure Laboratory (NSL) at the University of Notre Dame includes the TwinSol facility that can provide beams of isotopes a few nucleons from stability. The NSL was used for the study presented in this text.

Direct reactions such as proton transfer, in inverse kinematics, allow the study of short-lived radioactive nuclei which would normally decay too quickly to be made into a target. They provide an excellent way to study the shell structure of nuclei. The spectroscopic properties of these nuclei may be used to increase the understanding of nuclear structure by helping to better constrain theoretical nuclear models. Since a proton is transferred from one nucleus to another, these reactions may be used to study the single proton states of the resultant nucleus by extracting the energy and constraining the spin-parity and spectroscopic strength of the state which it is transferred into.

Measurements of proton capture reactions, (p, γ) , are used to study astrophysical reaction rates. The close proximity of the Coulomb barrier at astrophysical energy scales often

prevents measurement of these reactions in the laboratory. Transfer reactions are often used as an indirect way of measuring reactions of this type because the asymptotic overlap of the incoming and outgoing channels are the same in both cases. Extraction of asymptotic normalization coefficients (ANCs) makes it possible to compute these stellar reaction rates without measuring the proton capture reaction.

The work described in the following chapters is centered around the development of proton transfer reaction measurements using the Versatile Array of Neutron Detectors at Low Energy (VANDLE) [19, 20, 16].

1.1 Single Nucleon Transfer Reactions

Single nucleon transfer reactions have been used for decades as a way to study the structure of the nucleus [21]. In reaction notation, the transfer reaction is written as

$$A + a \rightarrow B + b + Q \tag{1.1}$$

Where A is referred to as the “target nucleus”, a as the “projectile”, B as the “residual”, b as the “ejectile”, and Q is referred to as the reaction Q-value. The Q-value is equal to the rest mass energy difference between $A + a$ and $B + b$ and is used to represent the amount of energy which is released during the reaction. This is typically a very complicated many-body problem. In nuclear physics notation, Equation 1.1 may be rewritten as Equation 1.2 and will be written in this form for the remainder of this dissertation.

$$A(a, b)B \tag{1.2}$$

The particles to the left of the comma in Equation 1.2 (A and a) are the reactants of the transfer reaction while those to the right (b and B) are the products.

When a transfer reaction occurs inside the target, excited states of the residual nucleus may be populated if the reaction is of sufficient energy. The energy released by the reaction is described, in terms of the particle rest masses, by the reaction Q-value.

$$Q_{g.s.} = c^2 [m_A + m_a - (m_B + m_b)] \quad (1.3)$$

Where $Q_{g.s.}$ is the Q-value to populate the ground state of all involved particles and m_A , m_a , m_B , and m_b are the rest masses of the target particle, the projectile, the residual, and the ejectile respectively.

Equation 1.3 may be used to deduce the mass of an unknown isotope, assuming that the other three are known. If the rest masses of all particles are known precisely, it is possible to extract a spectrum of excited states of the residual nucleus using Equation 1.4 below.

$$Q_{final} = Q_{g.s.} - (E_{x,ejectile} + E_{x,residual}) \quad (1.4)$$

Where Q_{final} is the Q-value to populate excited states $E_{x,ejectile}$ of the ejectile nucleon and $E_{x,residual}$ of the residual nucleus. If the reaction ejectile is a neutron, or a proton, the ejectile has no excitation energy and Equation 1.4 may be rewritten as

$$E_{x,residual} = Q_{g.s.} - Q_{final} \quad (1.5)$$

Due to its relatively low binding energy, two-body structure, and lack of excited states, it is common practice to use a deuteron (^2H) as the nucleus which donates the nucleon. Deuterons have the additional advantage of being relatively easy to accelerate with high beam intensities and are a good choice for reactions of this type. In the notation presented in Equation 1.2, single proton transfer may be written as (d,n) and single neutron transfer as (d,p).

In these cases, the mass of the deuteron and the neutron / proton ejectile are known precisely. If the mass of the target and residual (A and B) are also known, transfer reactions may be used to identify excited states in a residual nucleus since the final state Q-value directly reflects the energy of the excited state of the residual nucleus. An example of this is the case of the neutron transfer reaction $^{130}\text{Sn}(d, p)^{131}\text{Sn}$ detailed in R.L. Kozub et al. [2]. The relationship between the final state Q-value and the residual excitation energy is shown in Figure 1.1. For increasingly large residual excitation energies, the Q-value becomes

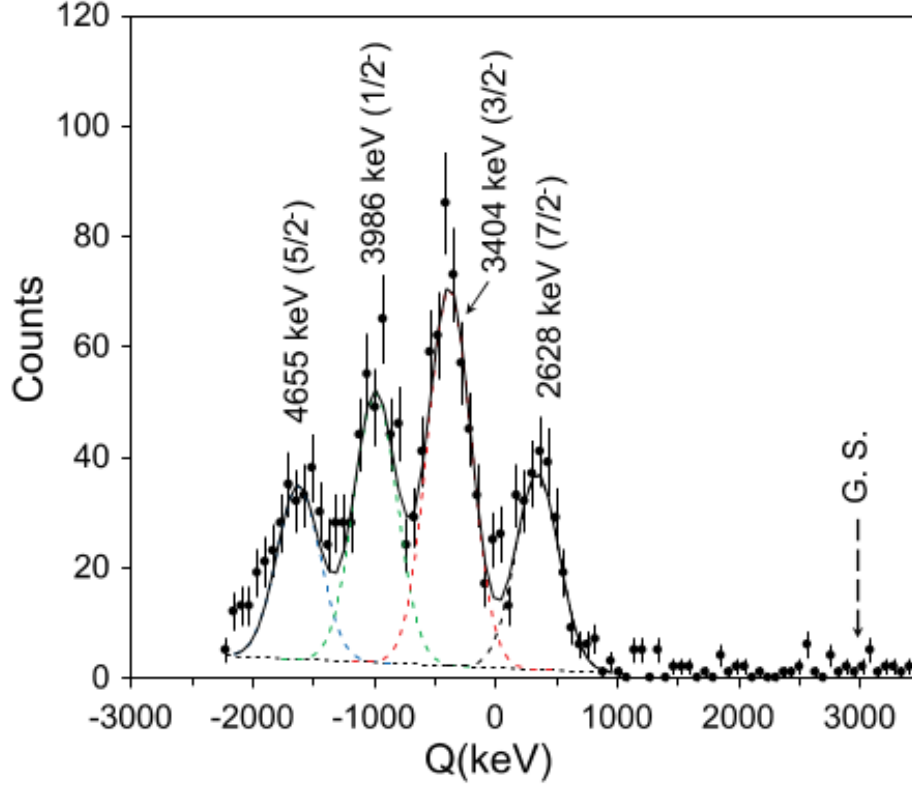


Figure 1.1: Q-value spectrum for the neutron transfer reaction $^{130}\text{Sn}(d, p)^{131}\text{Sn}$ showing population of various excited states of ^{131}Sn . This measurement was performed using a radioactive beam of ^{130}Sn and a deuterated polyethylene target (C_2D_4) as described in R.L. Kozub et al. [2].

increasingly small and eventually becomes negative, indicating an excitation energy that is greater than the ground state Q-value.

Transfer reactions are known as direct reactions or, less commonly, peripheral reactions, meaning the reaction occurs near the surface of the nucleus and are not deeply penetrating. Direct reactions occur on time scales of the order of 10^{-22} s and do not involve an intermediate compound nucleus [22]. This makes the single-nucleon transfer reaction a powerful tool for the measurement of single-particle proton or neutron states of the residual nucleus as well as demonstrating the validity of the shell model [22].

The angular distribution of transfer reactions are directly dependent upon the angular momentum transferred between particles during the reaction. This means that angular distributions extracted from transfer reaction measurements may be used to obtain information about the spin and parity of the state of the residual particle. As a simple

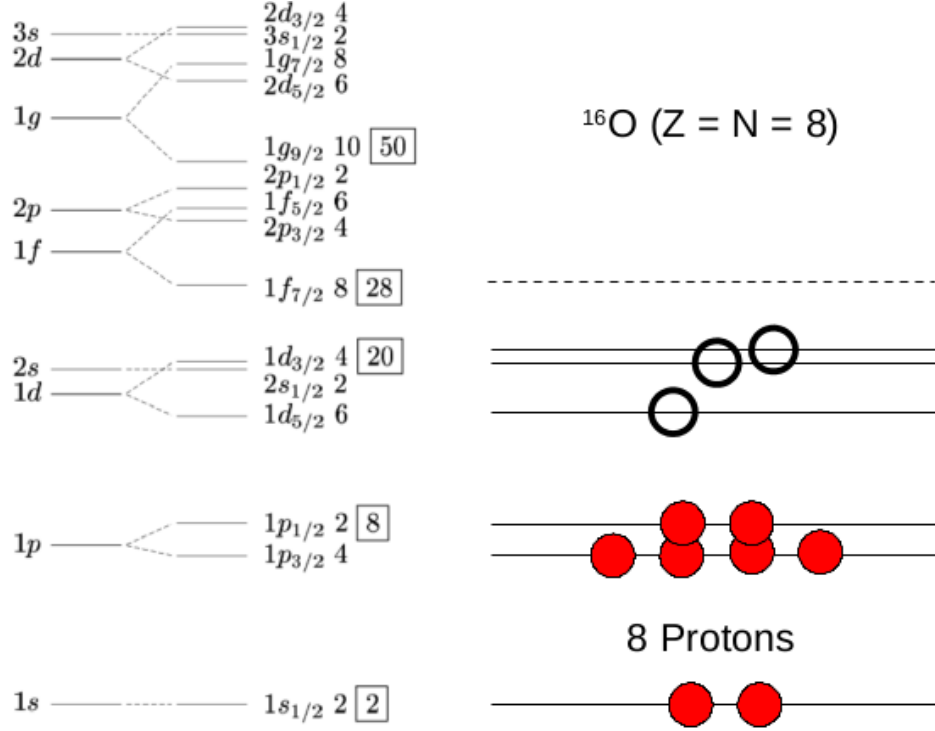


Figure 1.2: Cartoon showing the protonic shell structure of the doubly magic nucleus ^{16}O . The $1s$ and $1p$ proton shells are closed while the $1d + 2s$ shell is open to proton transfer.

example, one may examine the single proton transfer reaction $^{16}\text{O}(d, n)^{17}\text{F}$. In this example, ^{16}O is an isotope with both the neutron and proton shells closed. Therefore, a nucleon that is transferred to the oxygen nucleus must be placed in the next open shell. Figure 1.2 shows that the next available shell contains both s and d orbitals. Since ^{16}O has a spin-parity of $J^\pi = 0^+$, it would naturally be expected that angular momentum transfers of $l = 0$ and $l = 2$ would be observed for population of the s and d orbitals respectively. Table 1.1 shows the energy level diagram of the residual nucleus ^{17}F where the ground state, first excited state, and fifth excited states are built by placing a single proton in the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ orbitals respectively. Negative parity transitions are allowed but may not be populated using a single-step transfer.

In general, transfer reactions may populate more than one single-particle state of the residual nucleus. The various states may be separated by Q -value in order to obtain angular distributions. If the level density is high, or two or more levels happen to be very close together, the resulting angular distribution would be made up of contributions from all the

Table 1.1: Excitation energy and spin-parity (J^π) of the first four excited states of ^{17}F [1]. Also listed is the angular momentum transferred in a (d, n) reaction (Δl) as well as the total angular momentum (j) of the transferred proton.

Excitation (keV)	J^π	Δl	j
0.0	$5/2^+$	2 (d)	$5/2$
495.33(10)	$1/2^+$	0 (s)	$1/2$
3104(3)	$1/2^-$	1 (p)	$1/2$
3857(4)	$5/2^-$	3 (f)	$5/2$
4640(20)	$3/2^-$	1 (p)	$3/2$
5000(20)	$3/2^+$	2 (d)	$3/2$

allowed angular momentum transfers. If the total possible number of orbitals which are available to the transferred nucleon is large, the resultant ejectile angular distribution could become incredibly complex.

For single nucleon transfer reactions, where the transferred angular momentum is carried by a single nucleon, this is sometimes not the case. For the example of $^{16}\text{O}(d, n)^{17}\text{F}$ mentioned previously, the oxygen nucleus has a spin-parity of 0^+ in its ground state. The total angular momentum of the transferred nucleon is given by $j = l + s$ where l is the angular momentum of the nucleon and s is its spin. Since the transferred particle is a proton, its spin must be $1/2$. This restricts the possible angular momentum transfer to $|j - 1/2| < \Delta l < j + 1/2$. So for the case of ^{16}O and all other even-even nuclei, which have zero spin, the total angular momentum of the transferred nucleon must equal the spin of the final state of ^{17}F . Table 1.1 shows the possible angular momentum transfer (Δl) and the total angular momentum of the transferred proton (j) for population of the first four states of ^{17}F using (d, n) .

1.2 Motivation

1.2.1 Proton Transfer in Inverse Kinematics

This study focuses solely on proton transfer reactions in inverse kinematics, i.e. a reaction where the projectile is heavier than the target. In this arrangement, the target nucleus transfers a proton to the incoming beam nucleus. The residual nucleus, now with an atomic

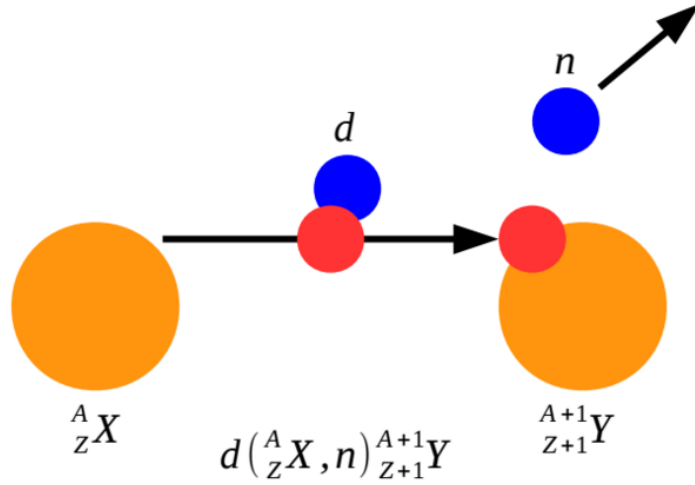


Figure 1.3: Simple cartoon demonstrating proton transfer in inverse kinematics.

charge of $Z+1$ with respect to that of the beam, recoils out of the target. The remaining neutron is ejected from the system and may be detected by a neutron detector. This is demonstrated by the cartoon in Figure 1.3. In the notation presented in Equation 1.2, the proton transfer reaction in inverse kinematics may be written as $d(^A_Z X, n)^{A+1}_{Z+1} Y$.

Due to the conservation of energy and momentum, the ejected neutron carries information from the state of the residual nucleus at the moment the proton was transferred to it. This makes it possible to study the properties of the residual nucleus by measuring only the ejected neutron. More specifically, it allows the study of proton states and the single-particle structure of the residual nucleus.

Inverse kinematics allows the use of radioactive ion beams (RIBs) since the heavy particle is now the projectile. The use of RIBs allows the study of isotopes which would normally be inaccessible due to radioactive instability. Transfer reactions can be used to produce unstable nuclei and excited states that are particle unbound, such as the first excited state of ^{13}N , making them otherwise difficult to study.

In a direct reaction, the heavy nucleus may be thought of as being grazed by the lighter particle. In normal kinematics, i.e. a reaction where the target is heavier than the projectile, the incoming light projectile (and thus the outgoing ejectile) will typically be scattered only to small angles making the ejected neutrons forward-focused about the beam trajectory.

In inverse kinematics however, the opposite is true. The neutrons are still forward-focused in the center-of-mass (CM) frame, but forward angles (angles less than 90°) in the CM frame correspond to backward angles in the laboratory frame. This means that in inverse kinematics, transfer reactions are backward focused in the laboratory frame. This is a very important distinction because of the differences in detector placement for the two cases.

1.2.2 Using VANDLE for Proton Transfer Reactions

Aside from a small number of dedicated neutron arrays such as the Low Energy Neutron Detector Array (LEND) [14] and the Modular Neutron Array (MoNA) [23] at the National Superconducting Cyclotron Laboratory, RESONEUT [24] at Florida State University, and the UofM array at the University of Michigan [25], few opportunities exist to take advantage of the increasing availability and intensity of RIBs.

The Versatile Array of Neutron Detectors at Low Energy (VANDLE) [19, 20, 16] was originally designed to be used for both decay and reaction studies and has been used extensively for beta delayed neutron spectroscopy measurements as well as several reaction measurements.

Performing proton transfer reaction experiments using VANDLE allows the study of single-particle proton states in exotic recoil nuclei in the same way that neutron transfer reactions (d, p) probe single-particle neutron states of nuclei. In this way, (d, n) measurements complement (d, p) measurements performed using high resolution instruments such as the Oak Ridge Rutgers University Barrel Array (ORRUBA) [26] and the Gammasphere and ORRUBA Dual Detectors for Experimental Structure Studies (GODDESS) [27].

1.3 Previous Work

VANDLE has been used extensively at both national and international facilities including the National Superconducting Cyclotron Laboratory (NSCL), the University of Notre Dame (UND), Argonne National Laboratory (ANL), the Isotope mass Separator On-Line facility (ISOLDE), Oak Ridge National Laboratory (ORNL), and RIKEN.

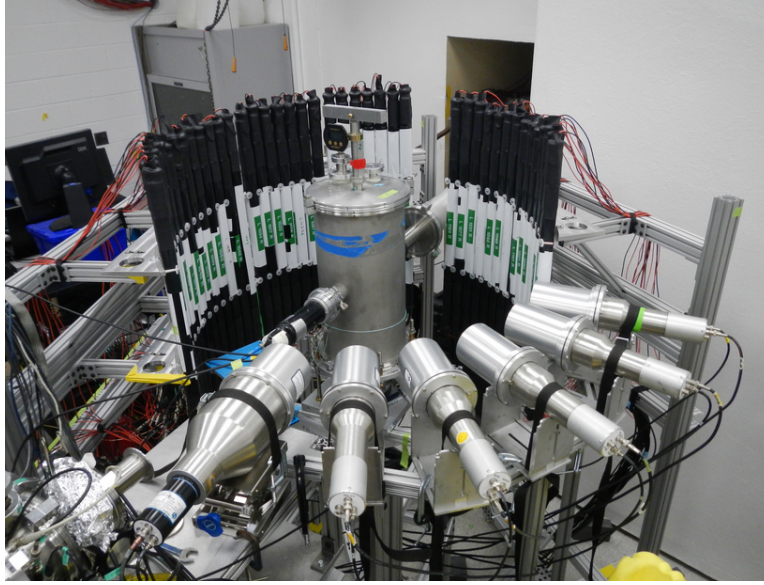
The Gamow-Teller decay of ^{78}Ni was studied by M. Madurga et al. [28] via β -delayed neutron emission from the neutron rich isotopes ^{83}Ga and ^{84}Ga . This measurement was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL. Beams of the Ga isotopes were produced via an Isotope Separation Online technique using a $10 - 18 \mu\text{A}$ beam of 50 MeV protons incident on a uranium carbide target. This measurement used 48 VANDLE bars at a radius of 0.5 m around the isotope implantation point. The neutron detectors were triggered using small β detectors situated near the implantation point.

The reaction $^{19}\text{F}(\alpha, n)^{22}\text{Na}$ was studied by W.A. Peters et al. [29] via two complementary measurements performed at UND and HRIBF. The UND measurement was performed in normal kinematics using pulsed beams of alpha particles with energies between 3.9 and 6.7 MeV incident on a $29 \mu\text{g}/\text{cm}^2 \text{ LaF}_3$ target backed with gold. The second measurement at HRIBF was performed in inverse kinematics using continuous beams of ^{19}F with energies between 12 and 38 MeV incident on a helium gas jet.

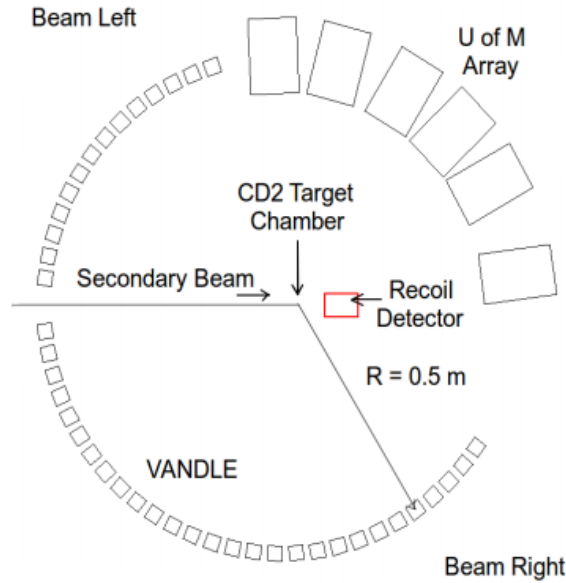
1.3.1 Previous VANDLE (d,n) Measurements

To date, a very small number of (d, n) measurements have been attempted using VANDLE. The first attempt was the indirect measurement of the proton capture reaction $^{56}\text{Ni}(p, \gamma)^{57}\text{Cu}$ using the proton transfer reaction $^{56}\text{Ni}(d, n)^{57}\text{Cu}$ in inverse kinematics in order to determine the proton width of the $1p_{1/2}$ resonance in ^{57}Cu at 1106 keV [30]. The measurement was performed at the NSCL with a $35 \text{ MeV}/u$ ^{56}Ni beam. Prior to that measurement, $^{40}\text{Ca}(d, n)^{41}\text{Sc}$ was performed at the NSCL in inverse kinematics using a $30 \text{ MeV}/u$ ^{40}Ca beam as a proof-of-principle for $^{56}\text{Ni}(d, n)$.

The second attempt was the measurement of $^7\text{Be}(d, n)^8\text{B}$ to study the proton halo state of ^8Be as well as to indirectly study the important astrophysical proton capture reaction $^7\text{Be}(p, \gamma)^8\text{B}$. This measurement was performed at UND in the spring of 2014 and used the superconducting solenoid recoil separator TwinSol [31]. To produce the radioactive beam of ^7Be , a stable beam of ^6Li impinged on a ^3He gas cell. The products from this primary reaction were then focused onto the secondary target of deuterated polyethylene (C_2D_4) using TwinSol. Figure 1.4a shows a photo of the VANDLE setup around the secondary target chamber.



(a) Photo of VANDLE ${}^7\text{Be}(d,n)$ at Notre Dame



(b) Top-down schematic of the VANDLE setup at Notre Dame

Figure 1.4: The VANDLE setup for the RIB experiment ${}^7\text{Be}(d,n)$ performed at the University of Notre Dame in 2014. VANDLE was placed at mostly back angles while forward angles were covered by liquid scintillator detectors from the University of Michigan Array.

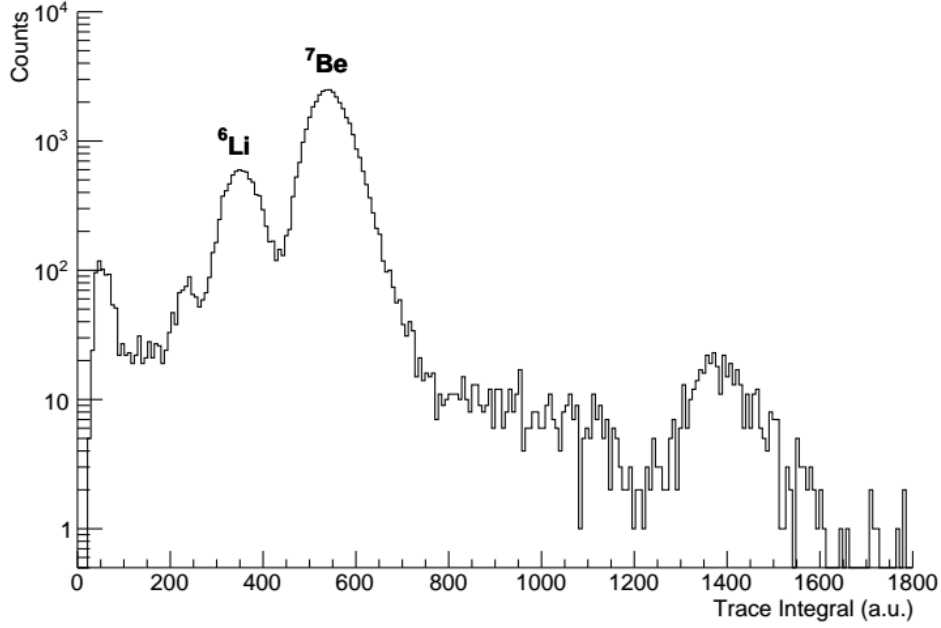


Figure 1.5: Typical beam-stop scintillator light response acquired during one of the ${}^7\text{Be}(d,n)$ runs. Prominent peaks are present for the unreacted ${}^7\text{Be}$ secondary beam as well as ${}^6\text{Li}$ contaminants from the primary beam.

A plastic scintillator placed directly downstream of the secondary target was used as a recoil beam-stop and provided the start signal for the neutron time-of-flight (TOF). Figure 1.5 shows the light response obtained from the beam-stop scintillator during one of the ${}^7\text{Be}(d,n)$ runs. Intense peaks are present for unreacted ${}^7\text{Be}$ secondary beam as well as unreacted ${}^6\text{Li}$ primary. Since TwinSol is a momentum separator, any particle which has the same magnetic rigidity as the desired ${}^7\text{Be}$ beam will make it through TwinSol into the secondary target chamber. Due to the reaction kinematics, the ${}^8\text{B}$ particle of interest will lie somewhere beneath the two intense peaks. With a simple light response spectrum like the one shown in Figure 1.5, there is no way to separate the ${}^8\text{B}$ reaction product from other beam contaminants.

Since the neutron TOF was triggered by the recoil scintillator, which measured the full beam intensity, the vast majority of all events in VANDLE were not related to the (d,n) reaction. Figure 1.6 shows a typical neutron time-of-flight spectrum obtained during one of the runs. A strong target γ -ray flash is visible on top of a featureless background. With no

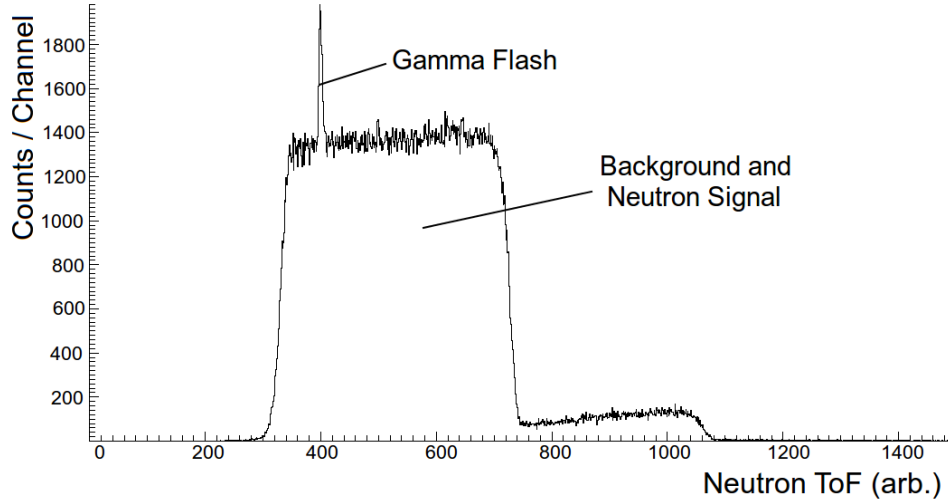


Figure 1.6: Typical VANDLE neutron TOF spectrum for ${}^7\text{Be}(d,n)$. Since no recoil identification was available, the vast majority of VANDLE events are from background.

recoil identification, there is no way to find which events are from the (d,n) reaction and which are simply background events.

1.4 Stable (d,n) Measurements

The two VANDLE proton transfer measurements using RIBs discussed in Section 1.3.1 were both largely unsuccessful due to high background rates. At the time, it was not even clear if plastic scintillator arrays (such as VANDLE) could be used on their own to measure (d,n) without some sort of recoil identification. Performing measurements using stable beams instead of RIBs with setups similar to those measurements mentioned above would allow the quick diagnosis of problems which would take orders of magnitude longer to discover during a RIB measurement.

Stable beams of ${}^{16}\text{O}$ and ${}^{12}\text{C}$ were selected since they have been well characterized in normal kinematics in the past (see sections 1.4.1 and 1.4.2). Since the center-of-mass frame is the same for both normal and inverse kinematics, the results obtained from VANDLE in inverse kinematics should be the same as those obtained using deuteron beams. This hypothesis provides a very important test for performing future proton transfer measurements using VANDLE.

The two stable proton transfer reactions $^{16}\text{O}(d, n)^{17}\text{F}$ and $^{12}\text{C}(d, n)^{13}\text{N}$ were selected for the proof-of-concept proton transfer measurements using VANDLE in inverse kinematics as extensive literature data exist for both.

1.4.1 Previous Oxygen-16 (d,n) Measurements

The unstable isotope ^{17}F is of interest because its first excited state ($1/2^+$) is bound by only 105 *keV* and is a known proton halo [32, 33, 34]. In broad terms, a halo state is a nuclear state in which one or more nucleons have a radial distribution that extends far outside the nuclear core. More precisely, halo nucleons are those which are weakly bound and are in low angular momentum state relative to the core [35, and references therein]. Proton halos have an additional constraint due to the Coulomb barrier, but may exist for atomic charges of $Z < 10$ [35].

In addition to possessing a proton halo state, the proximity of ^{17}F to the doubly-magic nucleus ^{16}O means that the structure of ^{17}F determines the single-particle energies of proton states near ^{16}O and is an important input for nuclear structure models [34].

The proton transfer reaction $^{16}\text{O}(d, n)^{17}\text{F}$ was well characterized in normal kinematics by S.T. Thornton [4] at the University of Wisconsin and was published in 1969. Pulsed deuterons at laboratory energies of 8.0 *MeV* and 9.3 *MeV* impinged on a gas cell filled with O_2 . Reaction neutrons were measured using NE-213 liquid scintillator detectors [12] with a diameter of 10.2 *cm* and a height of 2.5 *cm*. The neutron detectors were placed around the target at a radius of three meters. Neutrons were measured using time-of-flight (TOF), and pulse shape discrimination (PSD) was used to eliminate background gamma rays. The timing full width at half maximum (FWHM) for measured neutrons was somewhere between 1.2 *ns* to 1.5 *ns* throughout the measurement, values which are consistent with the time resolution of VANDLE [20].

Another measurement of $^{16}\text{O}(d, n)$ in normal kinematics was performed by C.J. Oliver et al. [3] at the University of Liverpool and published in 1969. Pulsed deuteron beams with energies of 7.73, 11.0, and 12.0 *MeV* were incident on a tantalum window gas cell filled with spectroscopically pure natural oxygen at a pressure of 60 *cm* of mercury. The deuterons were stopped by the tantalum lining of the gas cell. Neutrons were measured using a time-of-flight

Table 1.2: Energies of incident deuterons for the reaction $^{16}\text{O}(d, n)$ in normal kinematics with the corresponding CoM energy and ^{16}O energy for inverse kinematics (all in MeV).

Ref.	E_d (MeV)	E_{cm} (MeV)	$E_{^{16}\text{O}}$ (MeV)
Oliver et al. [3]	7.73	6.865	61.38
Thornton [4]	8.00	7.105	63.55
This work	8.06	7.158	64.00

spectrometer [36] using NE-213 liquid scintillator detectors with a diameter of 10 *cm* and thickness 5 *cm* at center-of-mass angles from 0° to 150°. A neutron flight-path of 3.46 *m* was used for the measurement at 7.73 *MeV*.

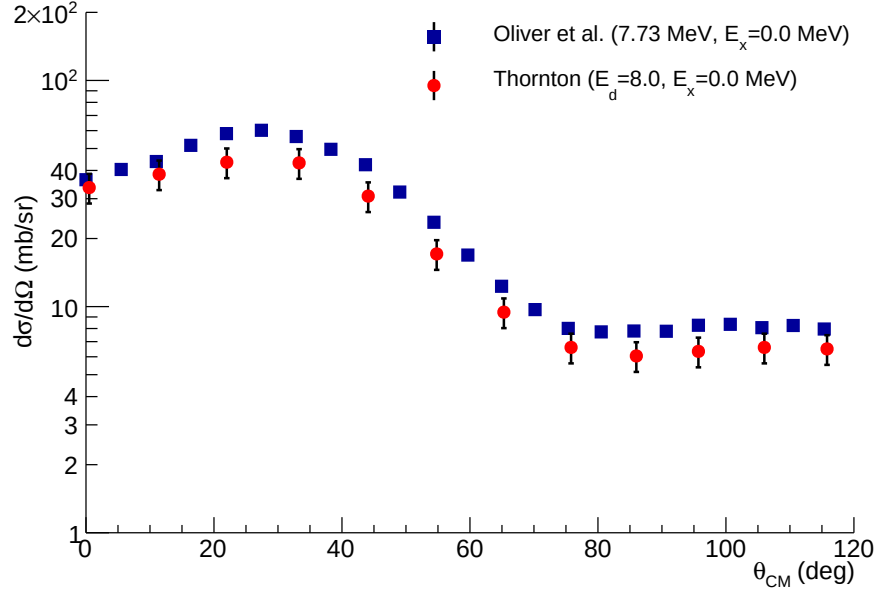
In inverse kinematics, the incident deuteron energies listed in Table 1.2 correspond to ^{16}O energies and correspond closely to the range of energies available at the University of Notre Dame (see Section 3.3).

Oliver and Thornton made measurements of the reaction cross-sections for $^{16}\text{O}(d, n)$ leading to the ground state and first excited state of ^{17}F . Figure 1.7 shows the (d, n) angular distribution at a deuteron energy of $E_d = 7.73$ *MeV* (blue) and $E_d = 8.0$ *MeV* (red) for population of the ground state (top) and first excited state (bottom) of ^{17}F .

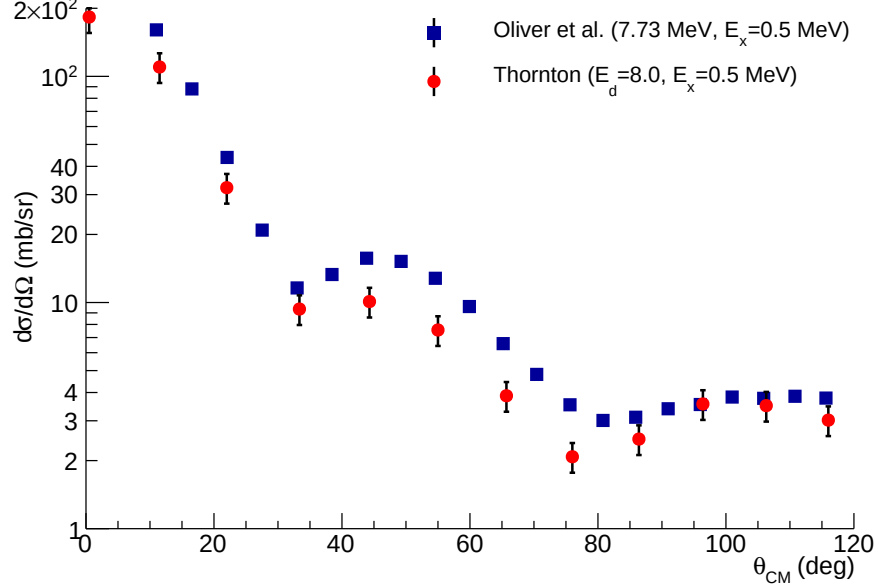
1.4.2 Previous Carbon-12 (d,n) Measurements

The proton transfer reaction $^{12}\text{C}(d, n)$ populates low-lying excited states in the unstable isotope ^{13}N ($T_{1/2} = 9.97$ *m* [37]). The first excited state of ^{13}N is proton unbound by ≈ 420 *keV* [37] making it difficult to detect and study by other means.

A measurement with deuteron energies in the range of 3.6 *MeV* to 12.0 *MeV* was performed by J.R. Davis and G.U. Din [5] at the Australian National University in the early 1970s. Beams of deuterons were incident on a thin 240 $\mu\text{g}/\text{cm}^2$ carbon target. Neutrons from the reaction were detected using a stilbene crystal, which provided discrimination against γ -rays. Excitation functions were measured at 0° for deuteron energies between 3.6 *MeV* and 12.0 *MeV* corresponding to excitation energies between 12.8 *MeV* and 20.6 *MeV* in the compound nucleus ^{14}N . Angular distributions were measured at various bombardment



(a) Population of the ground state of ^{17}F ($5/2^+$).



(b) Population of the first excited state of ^{17}F at 0.495 keV ($1/2^+$).

Figure 1.7: Angular distributions for $^{16}\text{O}(d,n)$ measured by C.J. Oliver et al. [3] at $E_d = 7.73 \text{ MeV}$ (blue) and by S.T. Thornton at $E_d = 8.0 \text{ MeV}$ (red) [4] leading to the ground state and first excited states of ^{17}F .

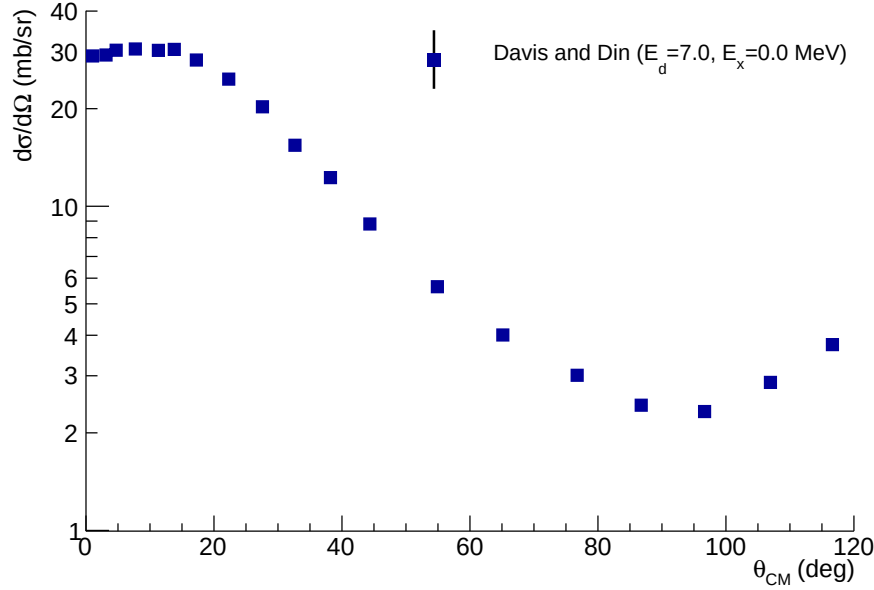


Figure 1.8: Reaction cross sections for the transfer reaction $^{12}\text{C}(d, n)$ at a deuteron energy of 7.0 MeV for population of the ground state of ^{13}N ($1/2^-$) as measured by J.R. Davis and G.U. Din [5].

energies between 7.0 MeV and 12.0 MeV. Figure 1.8 shows the angular distribution at a deuteron energy of 7.0 MeV.

A measurement described in H.R. Schelin et al. [6] used deuteron beams with energies ranging between 7.0 MeV and 13.0 MeV produced using the University of Sao Paulo Tandem Pelletron. Neutrons from the reaction were detected using a EJ-213 liquid scintillator detector 12.7 cm in diameter and 2.54 cm in thickness. The authors quote the mean deuteron beam intensity of 50 nA and the time resolution of the system as 1.5 ns. A typical TOF spectrum from this measurement is shown in Figure 1.9. This spectrum shows the target γ -flash on the far right as well as neutrons from the population of the ground state (n_0), the first excited state (n_1), and combined second and third excited states ($n_2 + n_3$) of ^{13}N . Figure 1.10 shows proton transfer cross-sections, at a deuteron beam energy of 7.0 MeV, for population of the ground state and first excited state of ^{13}N . It should be noted that there is considerable disagreement between the measurement by Davis and Din and that of Schelin et al. This will be discussed in more detail in the Results chapter.

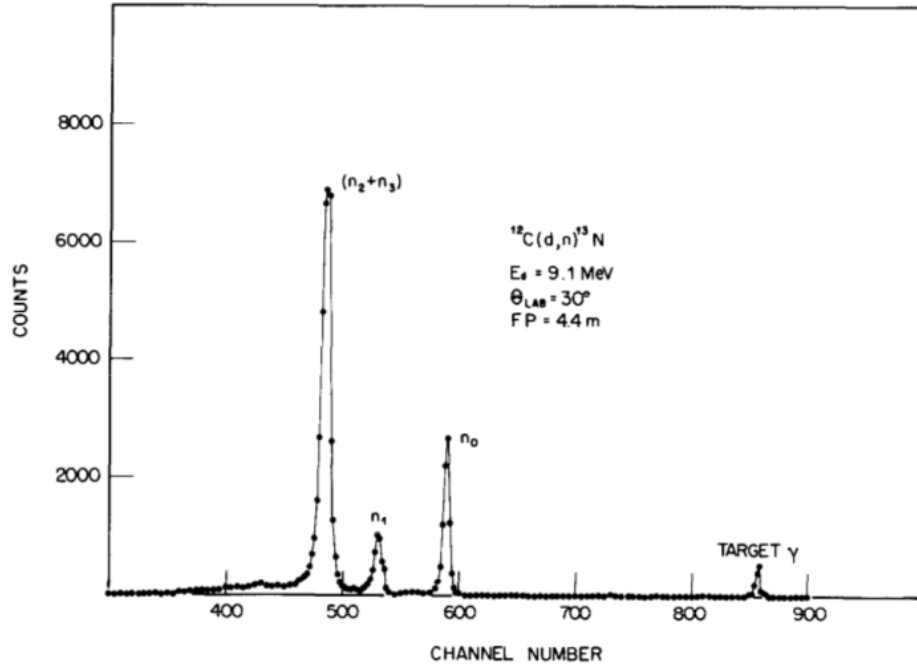


Figure 1.9: Typical neutron time-of-flight spectrum for the $^{12}\text{C}(d,n)^{13}\text{N}$ reaction at $\theta_{\text{lab}} = 30^\circ$ and $E_d = 9.1 \text{ MeV}$ adapted from H.R. Schelin et al. [6].

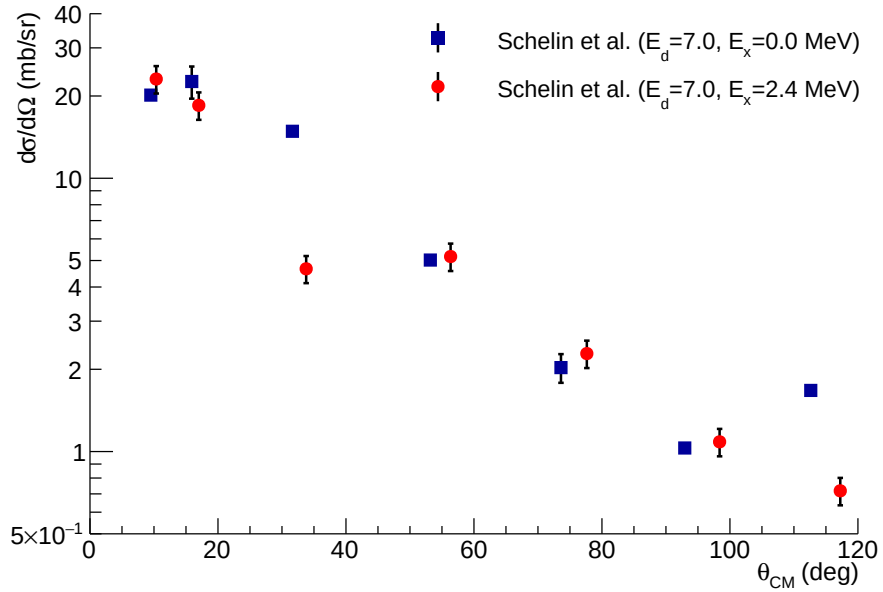


Figure 1.10: Reaction cross sections for the single proton transfer reaction $^{12}\text{C}(d,n)$ with a deuteron energy of 7 MeV for population of the ground state (blue) and first excited state (red) of ^{13}N as measured by H.R. Schelin et al. [6].

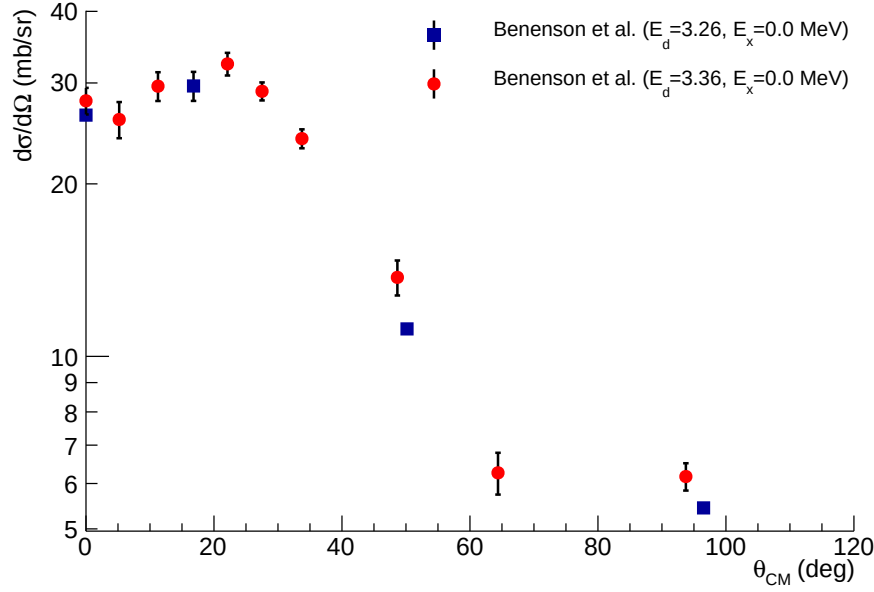


Figure 1.11: Reaction cross sections for the single proton transfer reaction $^{12}\text{C}(d, n)$ with deuteron energies of 3.26 MeV (blue) and 3.36 MeV (red) for population of the ground state of ^{13}N as measured by R.E. Benenson et al. [7]. Points for deuteron energy 3.36 MeV are normalized to those of deuteron energy 3.26 MeV.

A measurement detailed in R.E. Benenson et al. [7] was performed at the University of Wisconsin for deuteron energies of 2.68 MeV and 3.26 MeV. Figure 1.11 shows proton transfer cross-sections, at a deuteron beam energy of 3.26 and 3.36 MeV, for population of the ground state of ^{13}N . Note that in Figure 1.11, the points for deuteron energy 3.36 MeV are normalized to those of deuteron energy 3.26 MeV.

Chapter 2

Theory

2.1 Distorted Wave Born Approximation

The Distorted Wave Born Approximation (DWBA) is an approximate solution of the Schrödinger Equation for scattering by a potential. The scattering potential used in DWBA has the form $U = U_1 + U_2$. The scattering amplitude corresponding to such a potential is given by

$$f_{DWBA}(\theta, \phi) = f_1(\theta, \phi) - \frac{1}{4\pi} \int \chi_1^{(-)}(\vec{k}\prime, \vec{r}\prime)^* U_2(\vec{r}\prime) \chi_1^{(+)}(\vec{k}\prime, \vec{r}\prime) d\vec{r}\prime, \quad (2.1)$$

where an optical model potential is often used as the potential $U_2(r)$. Optical models attempt to replace complicated many-body interactions (such as transfer reactions) with a simple two-body system of particles having no structure and interacting via a simple potential. One of the most common forms of optical model potentials is

$$U(r) = -Vf(r, R, a) - iWf(r, R, a) - i(4a)W_D \left(\frac{d}{dr} \right) f(r, R, a), \quad (2.2)$$

where f is the Woods-Saxon form factor

$$f(r, R, a) = \frac{1}{e^{(r-R)/a} + 1} \quad (2.3)$$

The real part of the central optical model potential shown in Equation 2.2 represents elastic scattering while the imaginary part represents an absorptive term for non-elastic processes. The complex part of the scattering potential essentially causes a decrease in the flux of the elastic scattering channel without handling the non-elastic contributions explicitly.

Optical models may be thought of simply as an effective interaction to describe scattering. So the accuracy of DWBA ultimately depends upon the choice of potentials in the ingoing and outgoing channels.

2.1.1 Global Optical Models

There are several so called global optical models which provide smooth neutron and proton scattering potential parametrizations as a function of A , Z , nucleon type, and bombarding energy. These parametrizations are based upon large collections of nucleon scattering data on various nuclei and with a large range of energies. They are intended to allow predictions for scattering on nuclei which have little to no scattering data. This is especially useful for unstable nuclei where scattering data may be scarce.

One widely used global optical model is Koning-Delaroche (KD) [8]. This optical model is intended to be used for proton and neutron bombarding energies from 1 *keV* up to 200 *MeV* for scattering on “near-spherical” nuclides with masses between $A = 24$ and $A = 209$. The global parametrization used nucleon scattering data on nuclei ranging from ^{24}Mg up to ^{209}Bi .

Figure 2.1 shows total neutron scattering cross-sections for several light isotopes from ^{24}Mg to ^{40}Ca calculated using KD global optical model parameters. Calculations are compared to experimental data for energies between 10 *keV* and 250 *MeV*. For energies below a few MeV, large amplitude resonances appear and, according to Koning and Delaroche, “the optical model is only expected to provide smooth average results in this region”. It was observed that, at low incident energies, coupled-channels effects play an important role and decrease with increasing incident energy.

The lightest isotopes shown in Figure 2.1, ^{24}Mg , ^{27}Al , and ^{28}Si are all deformed. Koning and Delaroche hypothesize that this could be the cause of the discrepancies in the differential cross-sections between 5 *MeV* and 10 *MeV*. They also state that the effective mean field

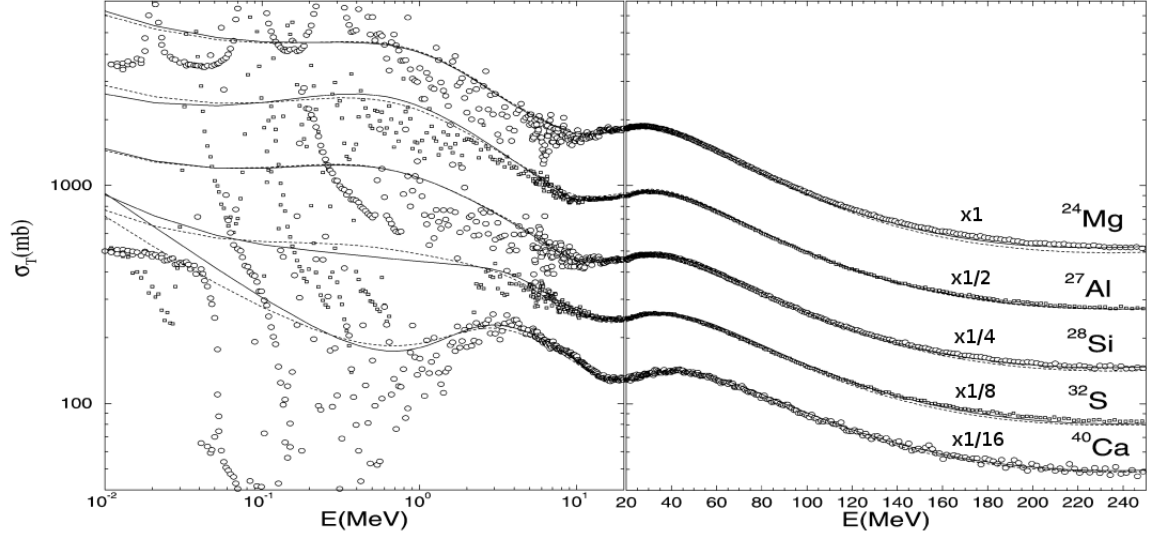


Figure 2.1: Comparison between total neutron scattering cross-sections calculated using Koning-Delaroche (KD) global optical model parameters and experimental data. Adapted from Koning and Delaroche [8].

may not be an adequate description of the nucleon-nucleus many body problem for such light nuclei.

The KD global optical model will be used in this study to compare to parameters obtained from W. Fitz et al. [9], see Section 2.4. Both ^{12}C and ^{16}O are considerably lighter than the lowest mass isotope in the evaluation by Koning and Delaroche, but reasonable agreement with experiment is still possible as will be shown in Chapter 5.

2.2 Adiabatic Distorted Wave Approximation

It has been stipulated that some of the reasons that the DWBA, and many other approximative methods, may not agree with experimental data in certain situations may be attributed to their inadequate treatment of three-body effects [38]. In the case of reactions involving a deuteron (e.g. (d, n) or (d, p)), the weak binding energy of the deuteron in the field of the nucleus A may lead to a non-negligible contribution from deuteron breakup in the incoming channel.

The ADiabatic Wave Approximation (ADWA) leads to a calculation which is similar to that of DWBA. The difference is that the incoming deuteron wave-function is replaced with

a three-body wave-function, which is a solution of a coupled system of two-body Schrödinger equations [39]. So, unlike DWBA, a deuteron optical potential plays no role in the incoming channel for ADWA. The $n - p$ potential is handled in an approximate manner, while the nucleon-nucleus potentials are described by effective potentials and are typically taken to be optical models. Calculations assume that the effective interaction between the two nucleons and the nucleus is the sum of the individual nucleon optical potentials typically evaluated at half the incident deuteron bombardment energy [38].

The ADWA method is generally used for processes which are dominated by direct reactions, such as transfer. The two major adiabatic potentials which may be used to account for breakup of the deuteron are zero-range Johnson-Soper (J-S) [38] and finite-range Johnson-Tandy (J-T) [39]. For this study, the J-S potential will be used to compare to experimental results.

2.3 Faddeev Three-Body Scattering Formalism

While theoretically more complex and computationally intensive than traditional three-body approximations, use of Faddeev scattering formalism [40] ensures that, once numerical convergence is achieved, discrepancies between experimental results and computation may be attributed to inadequacies in the nuclear potentials or to the inability of the three-body model to describe the system. Faddeev-type calculations will be used later for comparison to experimental data. These calculations, as performed by A. Deltuva [10], are beyond the scope of this work but are introduced below.

2.3.1 Exact Faddeev Alt-Grassberger-Sandhas (Faddeev-AGS)

The Alt-Grassberger-Sandhas (AGS) formalism [41] is built on the framework of the exact Faddeev formulations. Numerical calculations performed using AGS formalism use integral equations for transition operators instead of wave-functions. The transition operators contain the full physical information about the considered process.

The following discussion on the Faddeev-AGS formalism details work performed by A. Deltuva [10]. Unlike ADWA, which approximates the interaction between the neutron and

proton in the incoming channel, calculations performed under the Faddeev-AGS scattering framework, treat the incoming and outgoing channels using an exact three-body method. The AGS integral equations are solved numerically in the momentum-space basis. The AGS framework assumes short range potentials between the three particles. This requirement is included in the nuclear interactions ν_A , ν_p , and ν_n representing the neutron-proton, neutron-core, and proton-core potentials respectively. The Coulomb interaction between the proton and the core is included via the screening and re-normalization method. Since there is no Coulomb interaction between the neutron and the nucleus-proton pair, the final state $(n + Ap)$ is not distorted by the Coulomb force.

In partial waves with core-nucleon bound states, ν_n and ν_p must be real and energy independent. In coordinate space, the potentials have the form

$$\nu_\alpha(r) = -V_c f(r, R, a) + \vec{\sigma} \cdot \vec{L} V_{SO} \frac{2}{r} \frac{d}{dr} f(r, R, a), \quad (2.4)$$

where f is the Woods-Saxon form factor given in Equation 2.3. Standard values are taken for $R = r_0 A^{1/3}$, $r_0 = 1.25 \text{ fm}$, $a = 0.65 \text{ fm}$, and $V_{SO} = 6.0 \text{ MeV fm}^2$. The central potential depth V_c is adjusted to reproduce the binding energy of the final state nucleus. Excitations of the core A are not considered in the calculations for (d, n) [10]. They were, however, considered previously for elastic, inelastic, and neutron transfer reactions on ^{10}Be and ^{24}Mg cores [42].

The realistic nucleon-nucleon charge dependent (CD) Bonn potential [43] is used for the p-n potential (ν_A). Results show little sensitivity to the choice of ν_A as long as a realistic high-precision potential is used. Results are sensitive, however, to the nucleon-core optical potentials (ν_n and ν_p). Various parametrizations may be used such as Chapel Hill 89 [44], and Koning-Delaroche [8]. Local energy-dependent potentials are taken at half energy of the deuteron as proposed by Johnson and Soper [38].

Weakly bound systems, such as the first excited state of ^{17}F , are more sensitive to the Coulomb screening radius (R) than more strongly bound nuclei. Compared to (d, p) , calculation of (d, n) reactions is more demanding in terms of Coulomb screening radius but well-converged results are still obtainable [10].

Table 2.1: Optical model parameters used for incoming or outgoing channels for DWBA scattering calculations. Potentials V , W , and V_{SO} are in units of MeV and geometric parameters r and a are in units of fm . The parameter for the imaginary part of the potentials (W) is a surface term. Small imaginary volume components of the KD potentials are neglected for easier comparison to literature.

Set	E_p	V	r_0	a	W	r'_0	a'	V_{SO}	r_{SO}	a_{SO}
$^{12}C+d$ [9]	11.8	118	0.887	0.928	6.11	1.52	0.790	5.0	0.887	0.928
$^{12}C+p$ (KD)	1.55	56.2	1.127	0.676	5.433	1.306	0.525	5.729	0.903	0.59
$^{12}C+n$ (KD)	1.55	53.9	1.127	0.676	6.604	1.306	0.543	5.667	0.903	0.59
$^{13}N+n$ (KD)	2.56	54.9	1.131	0.676	7.44	1.305	0.542	5.648	0.910	0.590

2.4 DWBA Calculations

DWBA calculations which were part of this work were performed exclusively using the code TWOFNR [45]. The form of the scattering potential used by TWOFNR is

$$U(r) = V_C(r, R_C) - Vf(r, r_0, a) - iW(1 - C_{sd})f(r, r'_0, a') - iW4a'C_{sd}\frac{d}{dr}f(r, r'_0, a') + 2\left(\frac{\hbar}{m_\pi c}\right)\bar{l} \cdot \bar{s}\frac{1}{r}\frac{d}{dr}V_{SO}f(r, r_{SO}, a_{SO}), \quad (2.5)$$

where V_C is the Coulomb potential due to a uniformly charged sphere of radius R_C and f is the Woods-Saxon form factor given by Equation 2.3. The coefficient C_{sd} is the mixing factor for the volume and surface imaginary well W .

2.4.1 Comparison to Faddeev-AGS

The optical model parameters of Fitz [9] are based upon deuteron scattering measurements at an energy of 11.8 MeV . The KD global optical model is based upon nucleon scattering at various energies. This means that the model parameters must be scaled for the specific scattering nucleus and bombarding energy being used. Table 2.1 shows the parameters used for the comparison between KD and Fitz. Since ^{13}N is short-lived, it is difficult to measure neutron scattering for the outgoing channel $^{13}N+n$. So for this study, KD is used in the

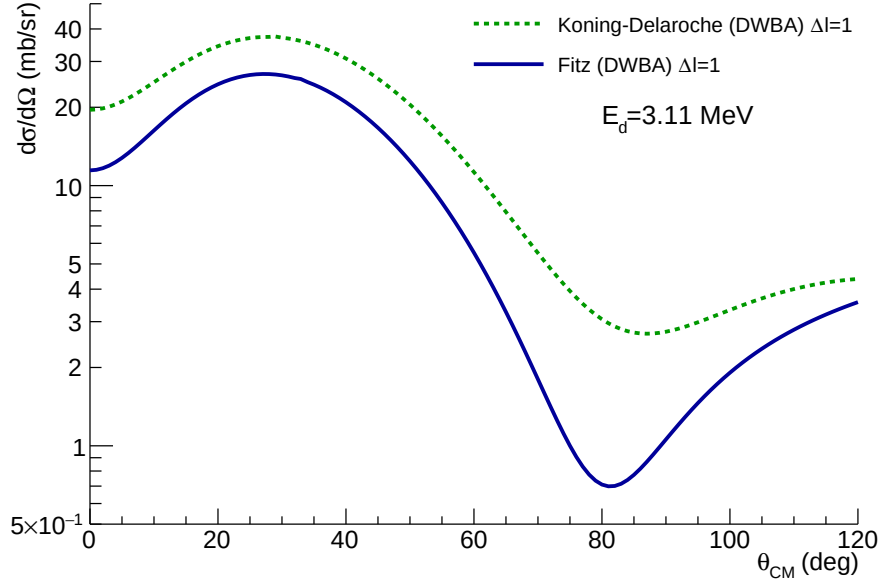


Figure 2.2: Comparison between an ADWA calculation (Johnson-Soper) using Koning-Delaroche (blue) and a DWBA calculation using optical model parameters of Fitz [9] (green) for the incoming potential for a bombarding energy of 3.11 *MeV*. Both calculations use Koning-Delaroche for the output channel ($^{13}\text{N}+n$).

outgoing channel for both calculations. Additionally, a Coulomb radius of 1.3 *fm* is used for both calculations.

Figure 2.2 shows comparison between JS+KD and Fitz on the incoming channel for a deuteron bombardment energy of 3.11 *MeV*. Since most of the macroscopic features are determined by the angular momentum transfer, $\Delta l = 1$ in this case, the maxima and minima of both calculations are in approximately the same location. The amplitude of each are significantly different however, especially around the first minimum at approximately 85°.

Figure 2.3 shows comparison between JS+KD, Fitz, and a Faddeev-AGS calculation by Deltuva for a deuteron bombardment energy of 7.00 *MeV*. Once again, the macroscopic features are all in approximately the same location for all three calculations, but the overall normalizations are significantly different. Comparison with proton transfer measurements will help to determine which distribution agrees best with data.

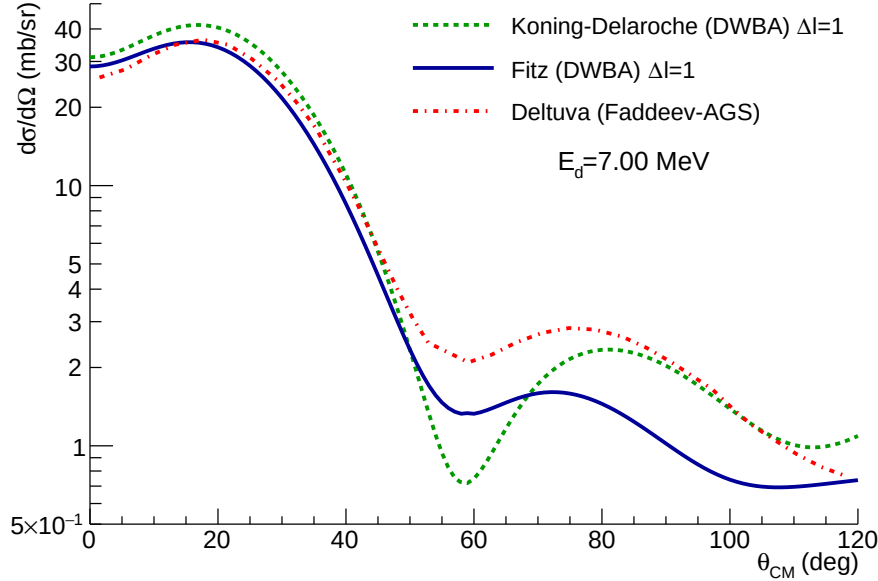


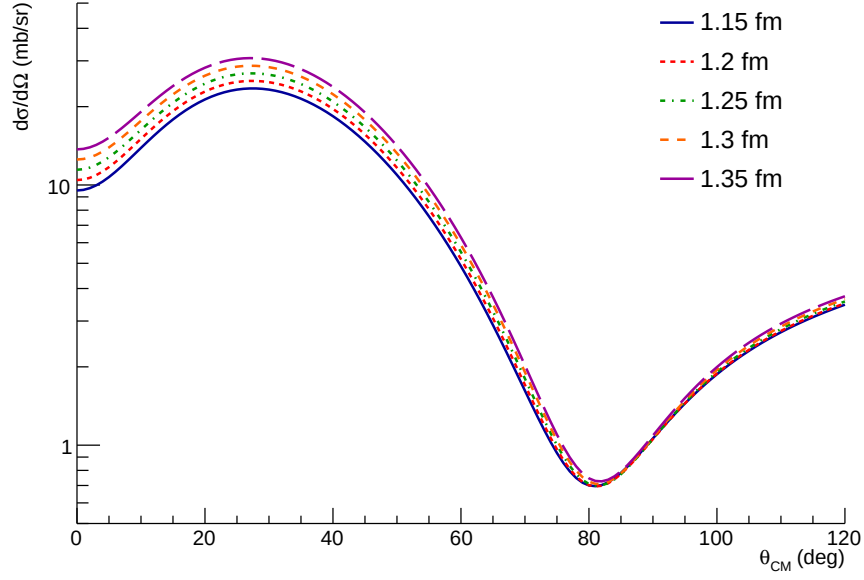
Figure 2.3: Comparison between calculations of $^{12}\text{C}(d,n)$ at $E_d = 7.0 \text{ MeV}$ using exact three-body Faddeev-AGS scattering formalism [10] (red), DWBA calculation using optical model parameters from Fitz [9] (blue), and that of Koning-Delaroche [8] (green).

2.4.2 Proton Binding Potential

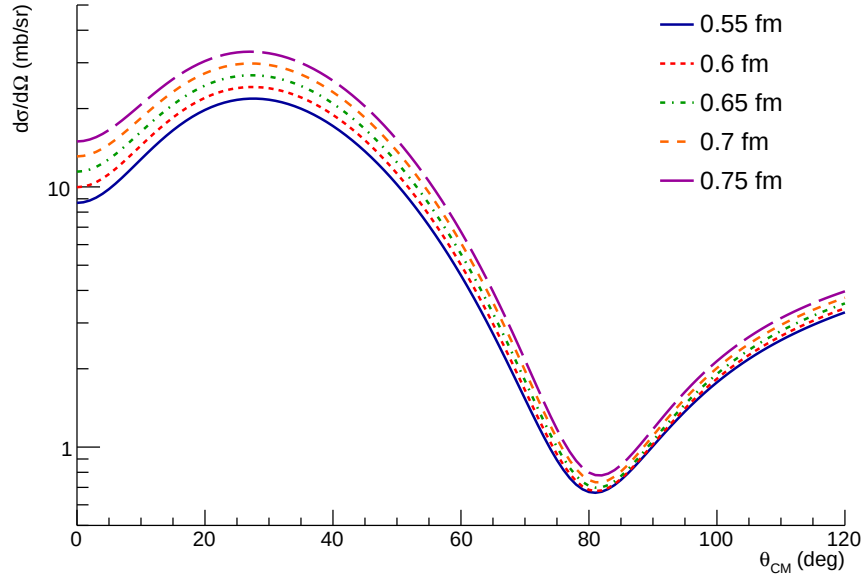
For both calculations presented in Figure 2.2, a proton binding potential of radius 1.25 fm and diffuseness 0.65 fm was used. Figure 2.4 shows that increasing (decreasing) the radius of the proton binding potential by 0.1 fm increases (decreases) the amplitude of the distribution by approximately 25% at 0° . Similarly, increasing the diffuseness of the proton binding potential by 0.1 fm increases the amplitude by approximately 30% at 0° . At angles larger than about 60° , modifying the radius has negligible effect on the amplitude while modification of the diffuseness has only a small effect.

2.4.3 Zero-Range Approximation

In a transfer reaction, the nucleon-nucleon interaction potentials have a finite non-zero range. If the wave functions are all in an s-state, and the nucleon interaction may be approximated by a point-like potential, then the interaction is described as being approximately zero-range. This greatly simplifies the calculation and is useful for transfer to or from deuterons and other s-wave particles [46]. If the interaction has a small, but non-zero, range then the local energy



(a) Radius of proton binding potential varied.



(b) Diffuseness of proton binding potential varied.

Figure 2.4: DWBA calculations for $^{12}\text{C}(d, n)$ at $E_d = 3.11 \text{ MeV}$ performed using optical potential of Fitz [9] for the input channel and Koning-Delaroche for the output channel. The radius and diffuseness of the proton binding potential for $^{12}\text{C}+p$ is varied to show the sensitivity of the distribution.

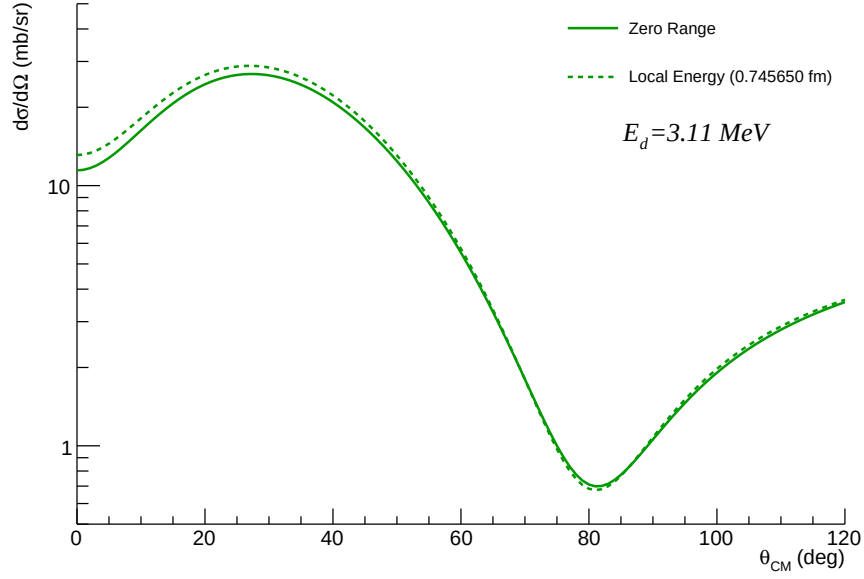


Figure 2.5: Comparison between zero-range and local energy approximation (finite range correction of 0.745650 fm) DWBA calculation using optical model parameters of Fitz [9] (green) for a bombarding energy of 3.11 MeV .

approximation (LEA) may be used. LEA provides a first-order correction to the zero-range approximation and may considerably improve its accuracy in some cases.

Figure 2.5 shows that using the Reid Soft-Core (SC) nucleon-nucleon potential finite range correction has very little effect on the amplitude or the shape of the resulting angular distribution. Because of its negligible effect, LEA finite range corrections will be neglected for this work.

Chapter 3

Experimental Setup

Proton transfer reaction measurements using stable beams of ^{16}O and ^{12}C and deuterated polyethylene (C_2D_4) targets [47] were performed at the Nuclear Structure Laboratory (NSL) of the University of Notre Dame in the summer of 2016. These measurements were intended to be used as proof-of-concept proton transfer measurements in inverse kinematics using VANDLE. The two measurements mimicked those using RIBs except at much higher intensities. Both stable beams were developed using the FN tandem and delivered to the experimental setup area.

3.1 The VANDLE Array

The Versatile Array of Neutron Detectors at Low Energy (VANDLE) [20, 16] is an array of Eljen Technology [13] EJ-200 (BC-408 equivalent) plastic scintillator bars instrumented with one inch diameter Hamamatsu [48] model R580 photomultiplier tubes (PMTs) on each end. The bars are wrapped with layers of reflective paper to help block outside light from entering the detector. Three sizes of VANDLE bars have been used for neutron detection experiments: small ($3 \times 3 \times 60 \text{ cm}^3$), medium ($3 \times 6 \times 120 \text{ cm}^3$), and large ($5 \times 5 \times 200 \text{ cm}^3$). The experiment detailed here used only small VANDLE bars.

Neutrons from the $d(^{16}\text{O}, n)^{17}\text{F}$ and $d(^{12}\text{C}, n)^{13}\text{N}$ reactions were detected using 21 small VANDLE bars, 5 liquid scintillator bars from the SABRE array (see Section 3.2), and 10

Notre Dame Experimental Setup: 16O(d,n) April 18-24 2016

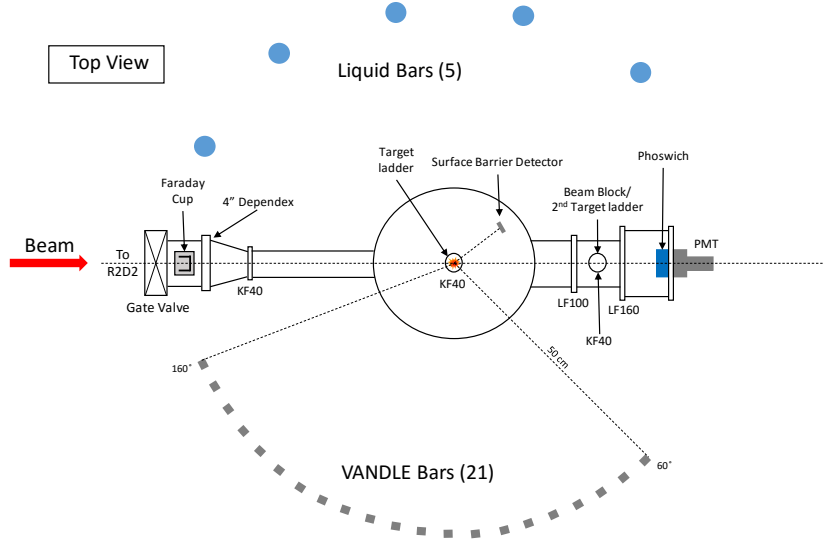


Figure 3.1: Top down view of proposed experimental setup on the R2D2 beam line at the University of Notre Dame in 2016.

$\text{LaBr}_3(\text{Ce})$ γ -ray detectors from the HAGRiD array [18]. The VANDLE, HAGRiD, and SABRE arrays are labelled A, F, and G in Figure 3.2 respectively.

The front surface of VANDLE and the liquid bar detectors were placed 50 *cm* radially from the target at laboratory angles ranging from $\theta_{LAB} = 60^\circ$ to $\theta_{LAB} = 160^\circ$, corresponding to approximately $\theta_{CM} = 5^\circ$ to $\theta_{CM} = 80^\circ$ in the center-of-mass (CM) frame for both reactions. Neutron detectors were not used at forward angles in the laboratory frame, as the outgoing neutron energy rapidly increases with decreasing angle while the detection efficiency of VANDLE decreases and the energy resolution worsens. The intrinsic neutron detection efficiency and neutron energy resolution are discussed in more detail in sections 4.2.6 and 4.1 respectively.

The SABRE array mirrored certain angles covered by VANDLE on the opposite side of the beam line. The HAGRiD detectors were mounted as close as physically possible to the target, below the target chamber, in order to reduce neutron scattering into the neutron detectors while optimizing their overall geometric efficiency.

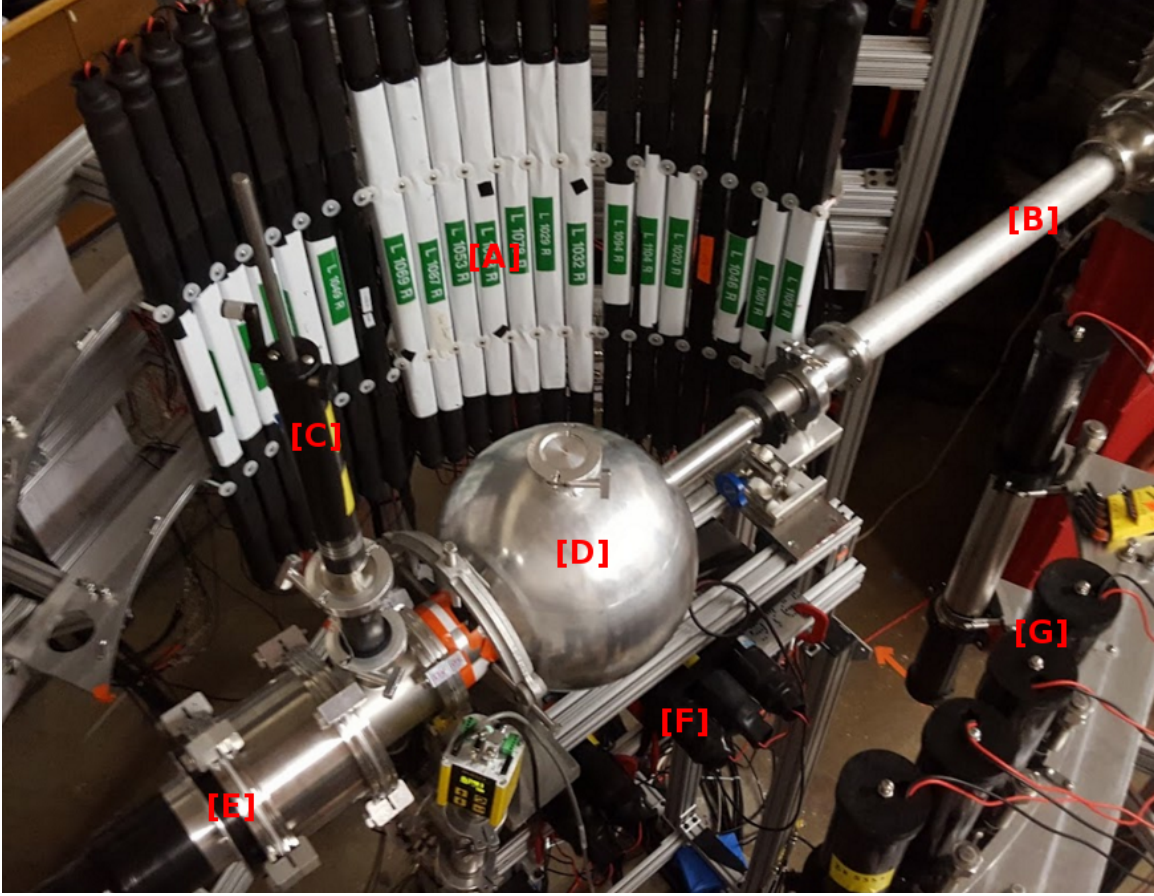


Figure 3.2: Actual view of the experimental setup on the R2D2 beam line at the University of Notre Dame in 2016. [A] 21 small VANDLE bars, [B] R2D2 beamline, [C] Beam-blocker ladder, [D] 12 inch diameter aluminum target chamber, [E] Recoil chamber and plastic phoswich, [F] 10 HAGRID detectors, and [G] 5 SABRE detectors.

3.1.1 Detector Thresholds

Below about 80 *keV*, γ -rays entering a VANDLE bar may be fully absorbed by the material [16]. This leads to a photopeak in the detector light yield spectrum whose mean in keVee (keV electron equivalent) is equal to that of the energy of the γ -ray in keV. The unit eVee represents the amount of light produced by an electron with a given kinetic energy coming to rest inside the scintillator material.

For higher energies, γ -rays entering VANDLE do not exhibit full energy absorption. They may still Compton scatter from electrons in the plastic. The energy of the scattered γ -ray is related to the energy of the incoming γ -ray by the Compton scattering formula

$$E' = \left[\frac{(1 - \cos(\theta))}{m_e c^2} + \frac{1}{E} \right]^{-1}, \quad (3.1)$$

where E is the incident γ -ray energy, m_e is the electron mass, and θ is the scattering angle. Those γ -rays which fully back-scatter ($\theta = 180^\circ$) will impart the most energy to the recoiling electron. Using Equation 3.1, the expression

$$E'_{max} = \frac{E}{(2E/m_e c^2) + 1}, \quad (3.2)$$

is the maximum energy which may be imparted to an electron and produces what is known as the Compton edge. Those γ -rays scattering with $\theta < 180^\circ$ lead to a continuous distribution of light yield, referred to as the Compton plateau. Figure 3.3 shows a light yield spectrum obtained from a VANDLE bar for a ^{137}Cs γ -ray source. The Compton plateau and Compton edge for the 662 *keV* γ -ray are labelled. By Equation 3.2, the energy of the Compton edge for the scattered electrons is 478 *keV* in this case. So in the example spectrum shown in Figure 3.3, the edge at a light yield of ≈ 2750 is equal to the light yield of an electron with a kinetic energy of 478 *keV*. Thus, this edge corresponds to a light yield of 478 *keVee*. For VANDLE, the “total” light yield is obtained by taking the square root of the product of the light yield from the left and right PMTs. From this point, references to the light yield of a VANDLE bar will refer to the total light yield.

For this analysis, the 30.8 *keV* γ -ray from a ^{133}Ba source was used to calibrate the software light yield threshold for all VANDLE detectors. This threshold must be set on a

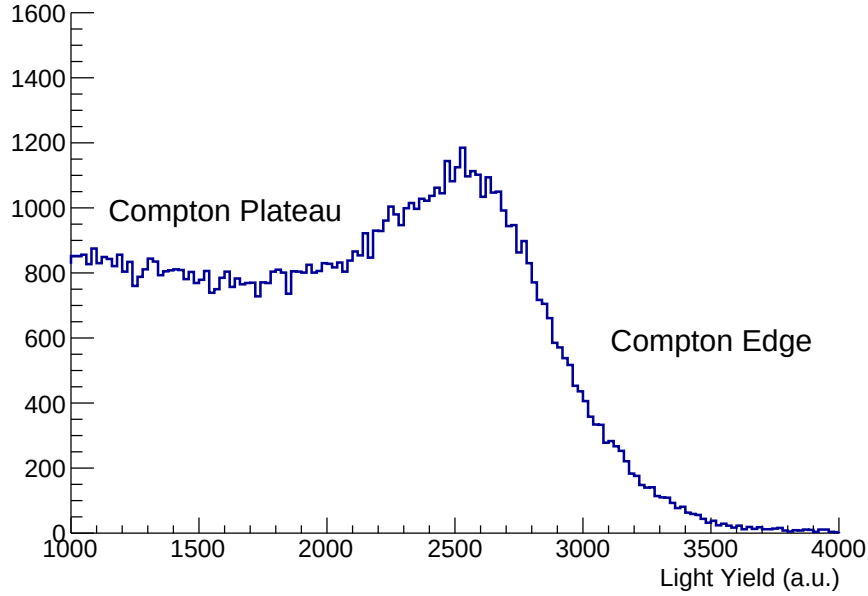


Figure 3.3: VANDLE total light yield ($\sqrt{L \times R}$) spectrum for a ^{137}Cs γ -ray source. The Compton edge and Compton plateau resulting from the Compton scatter of the 662 keV γ -ray from ^{137}Cs are shown.

detector-by-detector basis since the gain of each detector is slightly different. Figure 3.5 shows a typical VANDLE light yield spectrum for ^{133}Ba . The light yield spectrum was fit using a Gaussian peak on an exponential background for each detector as shown by the solid red line. The mean of the 30.8 keV photopeak, and thus the software light yield threshold, for this particular detector is marked by the vertical dashed line. The hardware threshold is visible to the left of the photopeak.

This process establishes the light yield threshold of all neutron detectors at 30.8 keVee . Since the light yield software threshold is set to that of ^{133}Ba , the 30 keVee efficiency curve may be used for calculating angular distributions (this is described in more detail in Section 4.2.6).

3.1.2 Array Geometric Efficiency

Conceptually, the geometric efficiency of a single detector is relatively straight forward to calculate. However, for many detectors at various positions and rotations, it may be simpler to use a Monte Carlo program to compute the total percentage of all generated particles that

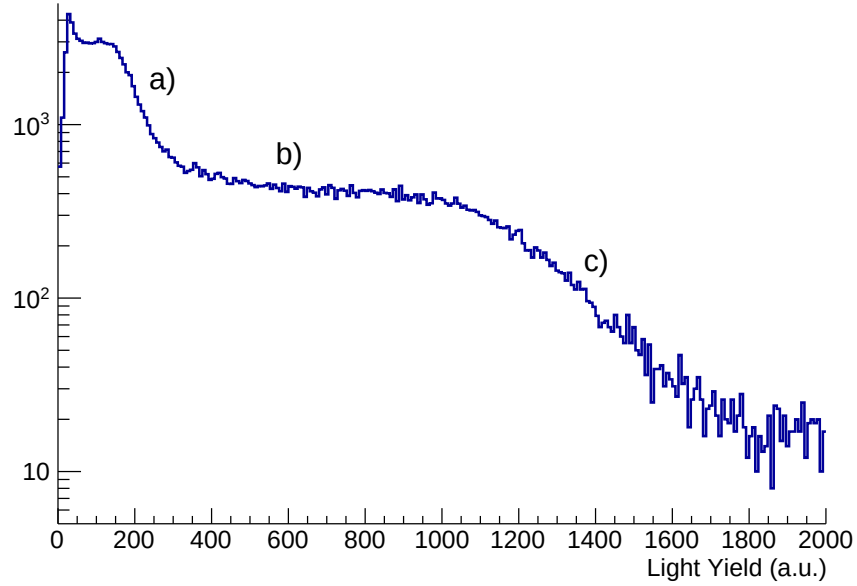


Figure 3.4: VANDLE total light yield ($\sqrt{L \times R}$) spectrum for a ^{133}Ba γ -ray source showing (a) Full energy absorption photopeak for the 30.8 keV γ -ray, (b) The Compton plateau from the 356 keV γ -ray, and (c) The Compton edge resulting from detection of fully backscattered 356 keV γ -rays at 207 keV.

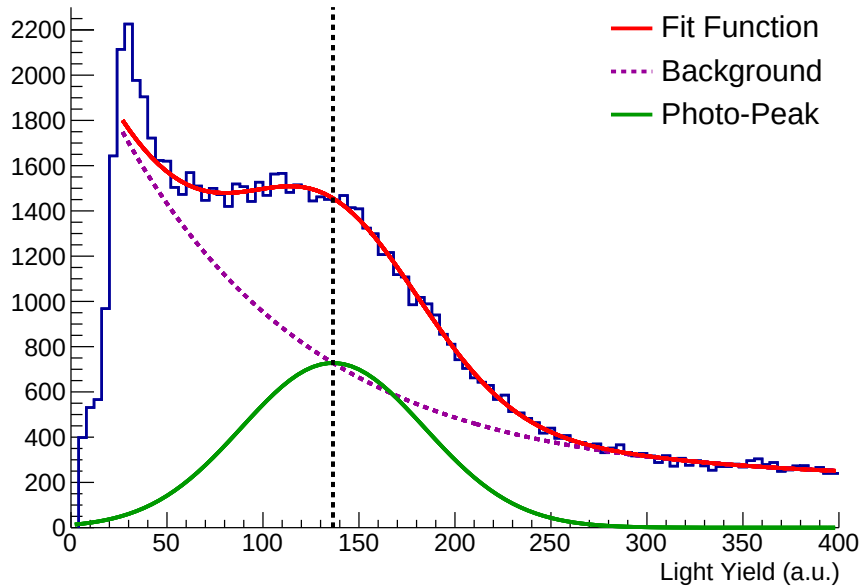


Figure 3.5: Typical VANDLE light yield spectrum showing the 30.8 keV γ -ray full energy absorption photopeak from a ^{133}Ba sealed source. The photopeak (solid green curve) is fit using a Gaussian on an exponential background (dashed magenta curve). The mean of the photopeak is marked by the dashed vertical line.

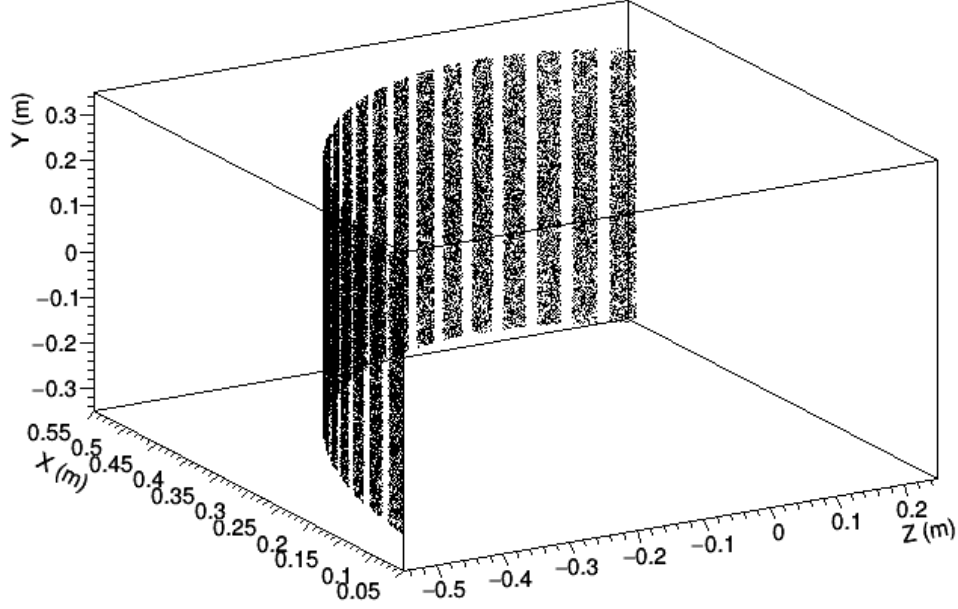


Figure 3.6: Monte Carlo simulation of an isotropic point source at the origin. The points in the plot represent locations where rays from the origin intercept the surface of a detector. This simulation shows the solid angle coverage of 21 small VANDLE bars located 0.5 m from the source.

will intercept a given detector. Figure 3.6 shows this process for an isotropic source of rays at the origin. The black points represent the intersection of those rays with the front surface of a VANDLE bar in the setup. The simulation determines how many of the rays from the origin intercept a given detector. Dividing the number of intercepts by the number of total generated events gives the fractional geometric efficiency (ϵ_{geom}) for an isotropic source at the origin.

When calculating the geometric efficiency of the setup for a reaction measurement, this procedure is not valid because the reaction does not produce neutrons isometrically in the laboratory frame. For this case, ϵ_{geom} is calculated by generating events using an isotropic source in the CM frame and then converting to the laboratory frame. Figure 3.7 shows the process for $d(^{12}\text{C}, n)$ with a beam energy of $E_{^{12}\text{C}} = 41.7 \text{ MeV}$. This must be done for each beam nucleus and bombardment energy.

As shown in Figure 3.7, the ratio of the number of detected events to the total number of generated events gives the fractional solid angle coverage of the total array for each 5° CM bin. It does not represent the solid angle in steradians (sr) which is what is needed to

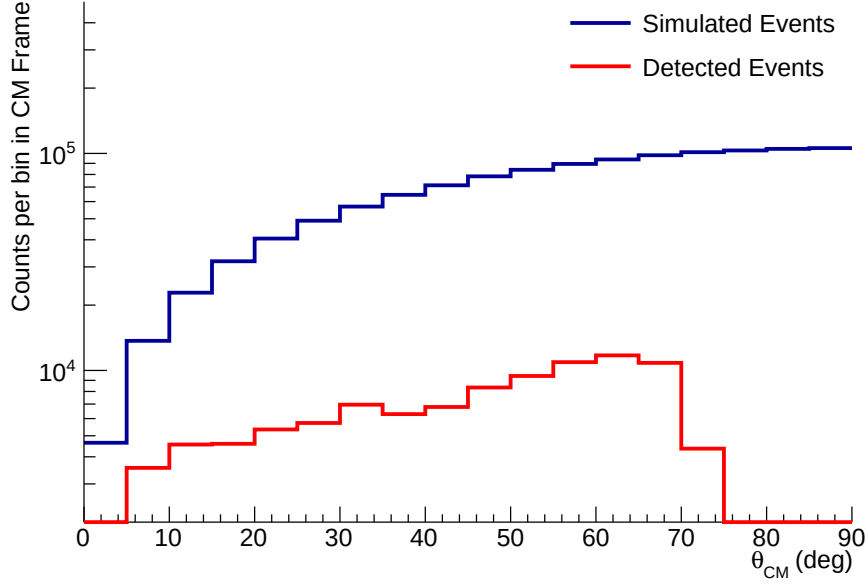


Figure 3.7: Total number of simulated Monte Carlo reaction events shown with the number of events which intersect the VANDLE setup for a source which is isotropic in the CM frame.

calculate angular distributions. In order to calculate the solid angle coverage of each bin in steradians (in the CM frame), one must integrate the differential $d\Omega = \sin(\theta)d\theta d\phi$ as

$$\Omega_{CM} = \int_0^{2\pi} \int_{\theta_i}^{\theta_f} \sin(\theta) d\theta d\phi = 2\pi [\cos(\theta_i) - \cos(\theta_f)], \quad (3.3)$$

where θ_i and θ_f are the lower and upper limit of the CM bin respectively. So the total geometric efficiency of the array in steradians is given by

$$\Omega_{CM} = 2\pi \sum_l \frac{N_{det,l}}{N_{sim,l}} [\cos(\theta_i) - \cos(\theta_f)], \quad (3.4)$$

where l is the current CM bin and N_{det} and N_{sim} are the number of detected events and the number of total simulated events respectively. For the example shown in Figure 3.7, the geometric efficiency for each bin is displayed in Figure 3.8. The total geometric efficiency for this case is simply a sum over all of the bins and is equal to 0.518 sr or 4.12% of 4π . The solid angle coverage in the CM frame changes for different beam energies as shown in table 3.1.

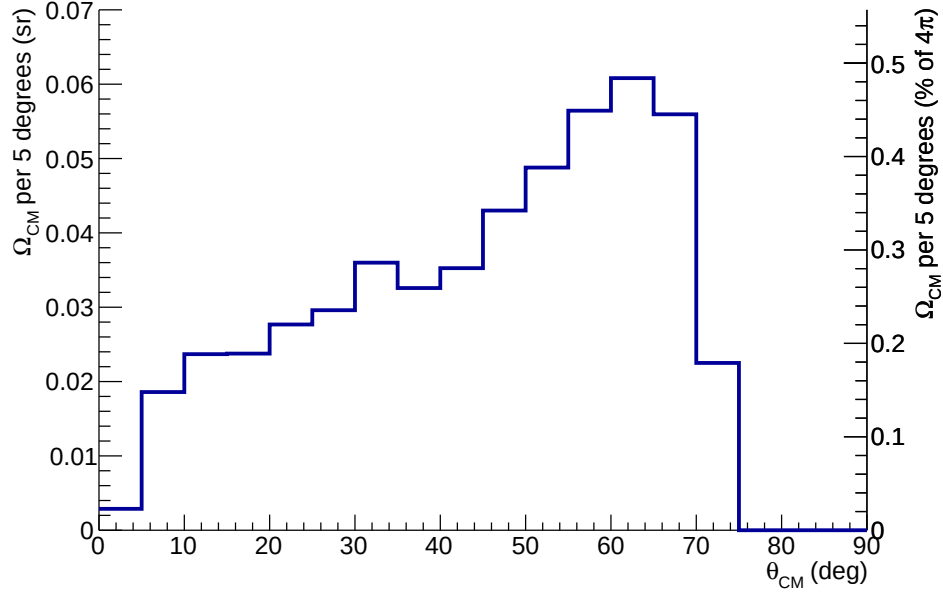


Figure 3.8: Solid angle coverage of the 2016 VANDLE setup for the reaction $d(^{12}\text{C}, n)$ with a beam energy of $E_{^{12}\text{C}} = 41.7 \text{ MeV}$ as a function of CM angle. The total solid angle coverage for this case is 0.518 sr or 4.12% of 4π .

Table 3.1: Total geometric efficiency (as a percentage of 4π) for the array of 21 small VANDLE bars for various energies of two inverse kinematics proton transfer reactions using stable beams of ^{12}C and ^{16}O .

Reaction	E_{beam} (MeV)	Ω_{CM} (% of 4π)
$d(^{12}\text{C}, n)$	41.70	4.12
	39.42	4.11
	37.14	4.11
	34.86	4.10
	32.58	4.09
	28.02	4.06
	23.46	4.01
	18.50	3.94
$d(^{16}\text{O}, n)$	64.00	3.44

3.2 The SABRE Array

The Scintillating Array of Bars for Reaction Experiments (SABRE) [49] is an array of cylindrical aluminum bars 5.08 *cm* in diameter and 27.9 *cm* in length with quartz windows epoxied to each end. The bars, developed at Oak Ridge National Laboratory (ORNL) with parts machined at the University of Tennessee, are filled with a liquid scintillator developed by researchers at ORNL. The scintillator is composed of p-xylene (C_8H_{10}), diphenyloxazole (POP, $C_{15}H_{11}NO$), 1,4-bis(5-phenyloxazol-2-yl) benzene (POPOP, $C_{24}H_{16}N_2O_2$), and naphthalene ($C_{10}H_8$). The bars were designed to be portable and refillable as better liquid scintillator mixtures are produced. For this measurement, 2 inch Hamamatsu [48] PMTs were optically coupled to both ends of the bar using silicone optical grease (Saint Gobain BC-630).

The neutron detection performance of the liquid scintillator is similar to that of VANDLE except that the liquid scintillator also exhibits $\nu - \gamma$ discrimination through the use of pulse shape discrimination (PSD). This measurement was intended to be used to commission the SABRE array for proton transfer. The $\nu - \gamma$ discrimination performance is shown in figures 5.16 and 5.17 during the measurement of the proton transfer reaction $d(^{12}\text{C}, n)^{13}\text{N}$ for a ^{12}C energy of 23.46 *MeV* ($E_d = 3.9$ *MeV*).

3.3 Primary Beam Production

Since the main limiting factor in many RIB measurements is the lack of beam current, reactions involving stable isotopes may be used to vastly increase the on-target intensity. In addition, stable beams are isotopically pure, as opposed to RIBs, and generally exhibit better beam optics.

Whereas a measurement with a RIB reaction may take a week or more of beam-on-target to collect enough statistics to be significant, a stable measurement will collect the same amount of statistics in minutes. This makes stable beam measurements a very valuable tool for testing neutron detector performance and allows researchers to quickly diagnose and

remedy problems with the experimental setup that may have otherwise not been discovered until months or years later during analysis.

The layout of the nuclear structure laboratory (NSL) at the University of Notre Dame is shown in Figure 3.9. This measurement used primary beams of ^{16}O and ^{12}C produced using the Multi-Cathode Source of Negative Ions Via Cesium Sputtering (MC-SNICS) ion-source. The MC-SNICS source produces high intensity beams of stable isotopes with a net charge of $-1e$ (where e is the charge of the electron) and with a kinetic energy of around 100 keV . The beam of negatively-charged ions is focused, collimated, and injected into the low energy (LE) column of the FN Tandem accelerator (FN) as shown on the left side of Figure 3.10.

The FN is a double-ended Vandegraff accelerator originally designed for a maximum terminal voltage of 10 megavolts (MV) but typically run at terminal voltages of 8 MV or less to maximize stability. When entering the LE column of the FN, the low energy ions are accelerated toward the positively charged terminal. Inside the terminal, the accelerated ions now have an energy of $E_{beam} = E_{SNICS} + V_T$, where E_{SNICS} is the energy of the ions after leaving the ion-source in MeV and V_T is the FN terminal voltage in MV .

Before leaving the terminal, the ions pass through a carbon stripper foil to remove atomic electrons. The charge-state distribution of the ions after stripping is dependent upon the mass and their kinetic energy at this point (i.e. the terminal voltage of the FN). As an example, the charge-state distributions for ^{16}O as produced by the FN with different terminal voltages is shown in Table 3.2. The energy lost in the stripper foil is negligible and is typically ignored.

Table 3.2 shows that the majority of the ^{16}O ions produced by the stripper foil in the FN terminal are not fully stripped. Upon exiting the stripper foil and the terminal, the partially stripped ions are accelerated away from the terminal by the positive potential and into the high energy (HE) column as shown on the right side of Figure 3.10. The energy of the beam particles upon leaving the HE side of the FN is given by

$$E_{beam} = E_{SNICS} + V_T(1 + Q_{beam}), \quad (3.5)$$

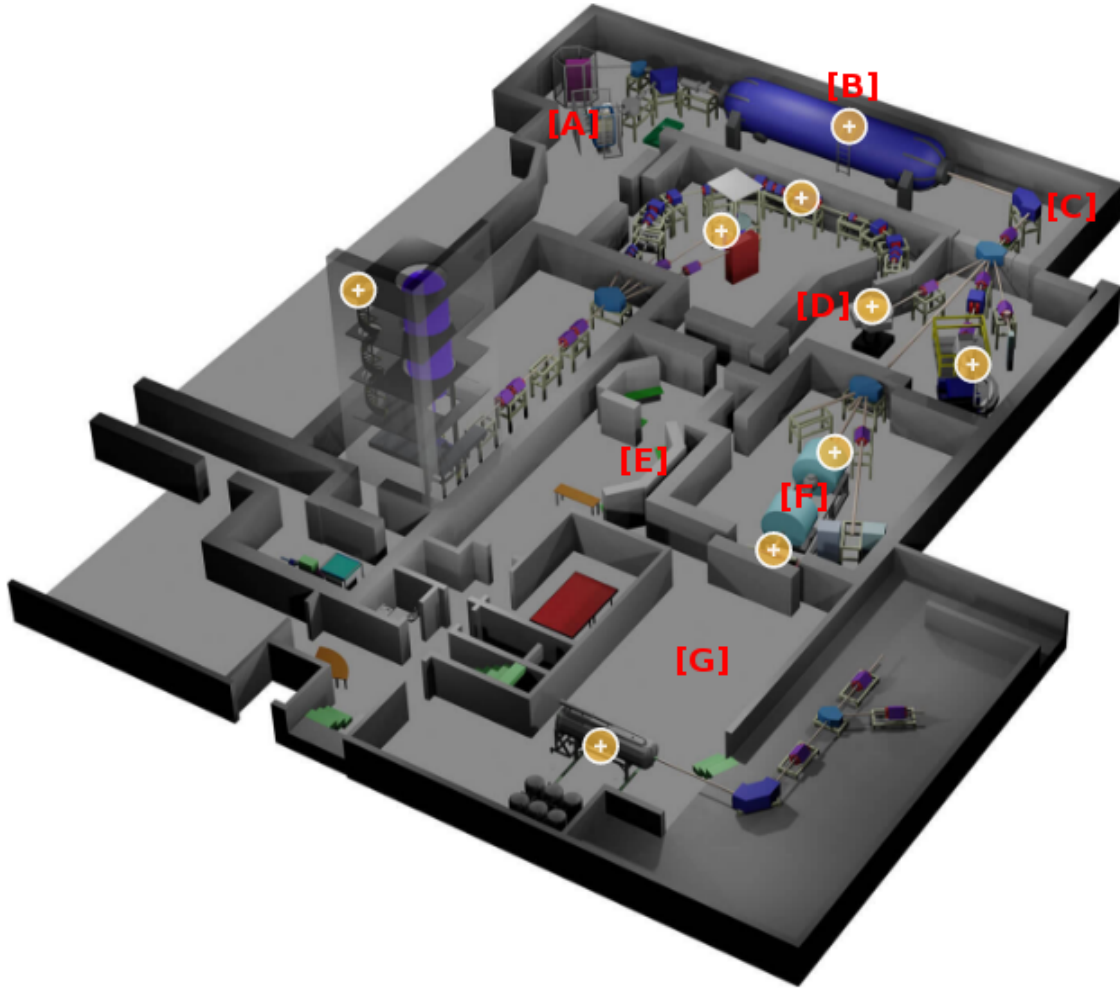


Figure 3.9: Isometric view of the Nuclear Structure Laboratory at the University of Notre Dame. [A] The Multi Cathode Source of Negative Ions Via Cesium Sputtering (MC-SNICS) ion source, [B] The 10 megavolt FN Tandem pelletron accelerator, [C] RF analyzing magnet, [D] R2D2 beam-line, [E] FN control console, [F] Twin-Sol, [G] Previously an experimental setup area.

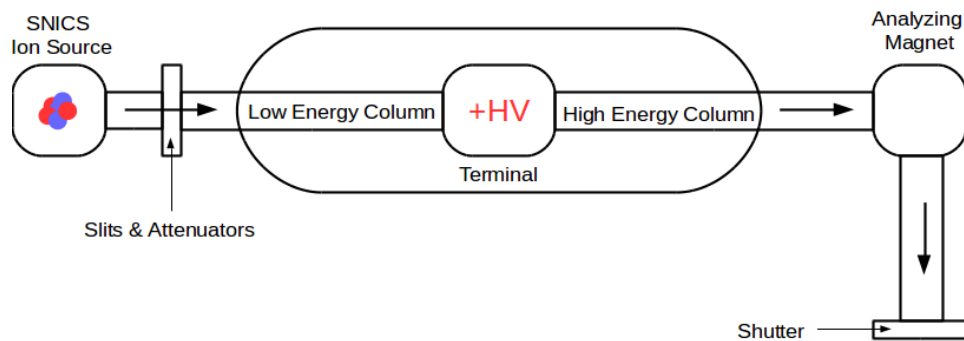


Figure 3.10: Simplified block diagram of the FN tandem accelerator. Not to scale.

Table 3.2: Normalized single-stripped charge-state distribution percentages for ^{16}O produced by the FN calculated using the qdist3 program from the NSL for a given FN terminal voltage.

^{16}O	7.0 MV	7.5 MV	8.0 MV	8.5 MV
0^+	0.0004	0.0003	0.0002	0.0001
1^+	0.0129	0.0090	0.0063	0.0046
2^+	0.2593	0.1901	0.1407	0.1058
3^+	3.1076	2.4398	1.9247	1.5322
4^+	18.963	16.287	13.9599	11.9849
5^+	46.024	44.507	42.5663	40.3847
6^+	29.363	33.334	36.9760	40.1618
7^+	2.2661	3.2257	4.4118	5.8012
8^+	0.0037	0.0075	0.0141	0.0248

where Q_{beam} is the charge state of the beam particle. Using Equation 3.5 and the charge-state distributions for ^{16}O listed in Table 3.2, the ^{16}O beam particle energy distributions may be computed. These distributions are shown in Figure 3.11.

Figure 3.11 shows that the energy of the accelerated beam particle is heavily dependent upon the electronic charge-state of the beam after stripping as well as the terminal voltage. Because of this, some beam energies are not physically accessible using the FN. Primarily due to prohibitively low beam intensities.

Selection of the charge-state, and thus the final energy of the beam particle is often a compromise between available intensity and desired energy. For this experiment, the 7^+ charge-state of ^{16}O was selected and accelerated with a terminal voltage of 8.08 MV (see Table 3.3). The charge state of the resulting continuous current beam was selected using the 90° analyzing magnet (shown on the right side of Figure 3.10). An RF sweeper was used to bunch the beam and a logic signal from the RF was used for neutron timing.

3.3.1 Beam Current Normalization

The number of expected neutrons from a reaction is dependent upon the reaction that is occurring as well as the physical properties of the experiment such as the beam intensity

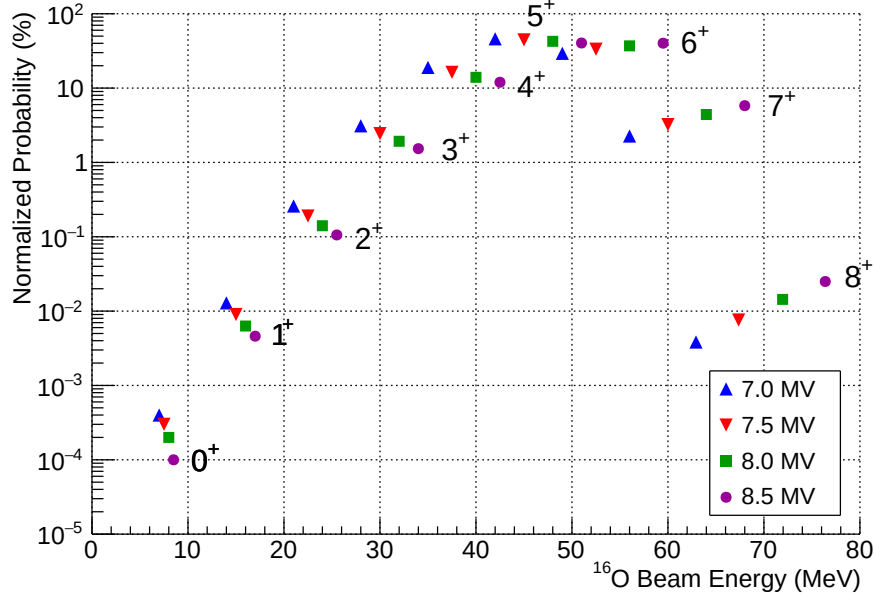


Figure 3.11: Normalized singly stripped charge-state distribution of ^{16}O beam energies produced by the FN using various terminal voltages. Distributions created using the qdist3 program from the NSL.

Table 3.3: Beam energies and FN terminal voltages with corresponding center-of-mass energies and equivalent deuteron energies for each run of this experiment.

Isotope	State	V_T	Beam Energy	CM Energy	E_d
^{16}O	7^+	8.08	64.00	7.158	8.059
^{12}C	5^+	6.95	41.70	5.993	6.999
^{12}C	5^+	6.57	39.42	5.665	6.616
^{12}C	5^+	6.19	37.14	5.338	6.234
^{12}C	5^+	5.81	34.86	5.010	5.851
^{12}C	5^+	5.43	32.58	4.682	5.468
^{12}C	5^+	4.67	28.02	4.027	4.703
^{12}C	4^+	4.69	23.46	3.372	3.938
^{12}C	4^+	3.84	18.50	2.659	3.105

and the target material and thickness. One may write the number of expected neutrons explicitly as a function of the differential proton transfer cross-section, $\sigma_{d,n}$,

$$N_{exp} = \sigma_{d,n} I_{beam} \rho_{targ} T \epsilon, \quad (3.6)$$

where $\sigma_{d,n}$ is in units of mb/sr ($1\text{ mb} = 10^{-27}\text{ cm}^2$) and is used to represent the probability that a (d,n) reaction will occur at a given CM angle and energy. I_{beam} is the intensity of the incoming beam in Hz or particles-per-second (pps), ρ_{targ} is the density of reacting particles in the target in $1/cm^3$, T is the length of elapsed time in s , and ϵ is the particle detection efficiency of the detector.

The total neutron detection efficiency of any neutron detector (ϵ) is equal to the ratio of the number of detected neutrons to the total number of neutrons.

$$\epsilon = \epsilon_{geom} \epsilon_{int} = \frac{N_{det}}{N_{tot}}, \quad (3.7)$$

where ϵ_{geom} is the fractional solid angle coverage of the detector and ϵ_{int} is the intrinsic neutron detection efficiency of the detector. In practice, the number of detected neutrons is determined directly from the detectors themselves, while all other quantities must be known independently.

The density of the target, ρ_{targ} , is more conveniently expressed as a function of the thickness of the target as in $\rho_{targ} = N_A \tau_{targ} / M_{targ}$ where $N_A = 6.0221 \times 10^{23}\text{ mol}^{-1}$ is Avagadro's number, τ_{targ} is the areal thickness of the target in mg/cm^2 , and M_{targ} is the molar mass of the target in mg/mol . The number of neutrons is typically not a useful quantity on its own. More often, experimenters are interested in determining the differential cross-section instead. So Equation 3.6 may be re-written as

$$\left(\frac{d\sigma}{d\Omega} \right) = \frac{N_{det} M_{targ}}{\epsilon I_{beam} N_A \tau_{targ} T}, \quad (3.8)$$

where Equation 3.7 is used to eliminate N_{tot} . Equation 3.8 shows that in order to produce normalized angular distributions for proton transfer reaction measurements, the number of possible interaction opportunities between the beam and the target must be known. The number of interaction points in the target is a function of the thickness and density of the

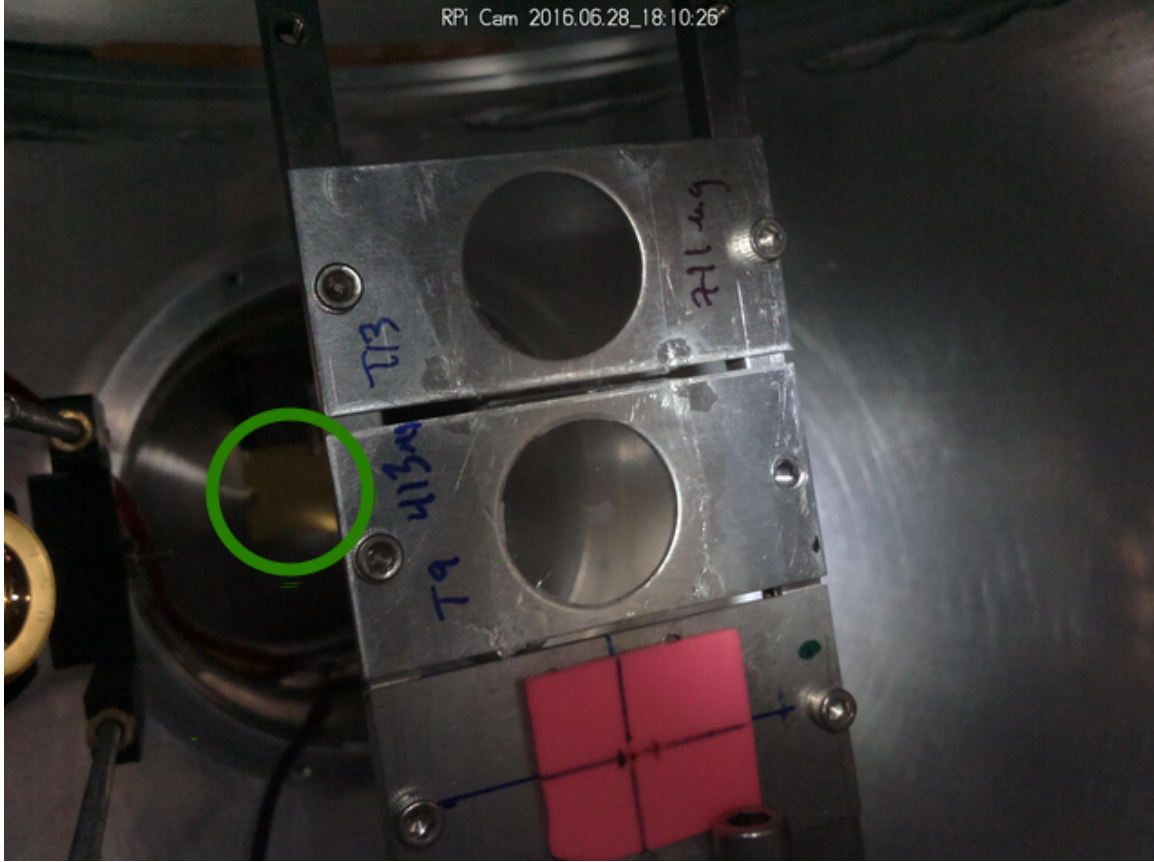


Figure 3.12: View along the downstream beam axis inside the target chamber during the (d, n) measurements. The $711 \mu\text{g}/\text{cm}^2$ and $413 \mu\text{g}/\text{cm}^2$ deuterated polyethylene (C_2D_4) targets are positioned in the foreground at the top of the target ladder. Beneath the targets is a phosphor used for beam tuning. Behind the target ladder, circled in green, is the electrically isolated brass beam blocker used for beam normalization. To the left of the image is an unused silicon detector.

material while the number of interacting beam particles is related to the intensity of the beam.

For this measurement, beam normalization was provided by a beam current integrator. The beam was incident upon an electrically isolated brass beam blocker installed approximately 10 cm downstream of the target as shown circled in green in Figure 3.12. The brass plate was wired to a current integrator which emits pulses whose frequency is dependent upon the total amount of incident charge on the plate.

Since the charge state of the beam was selected (as described in Section 3.3), the total integrated charge is only dependent upon the number of particles incident on the plate. Figure 3.13 shows the instantaneous beam blocker current for a typical (d, n) run during the

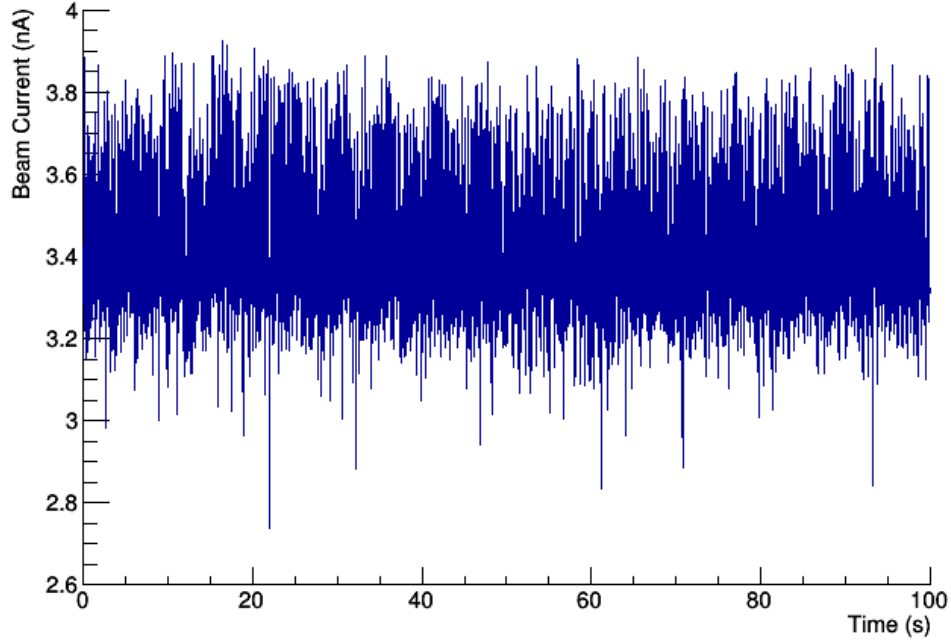


Figure 3.13: First 100 seconds of a (d, n) run showing the instantaneous beam current measured on the beam blocker as a function of time. The integral of this plot is equal to the total charge for the run.

Table 3.4: Table showing integrated beam currents for the inverse kinematics proton transfer reactions $d(^{12}\text{C}, n)$ and $d(^{16}\text{O}, n)$ for all beam energies studied in this measurement.

Isotope	E_{beam} (MeV)	Charge State	Run Time (s)	Total Q (nC)	Intensity (pps)
^{12}C	41.70	5^+	181.5	1461.75	1.0×10^{10}
	39.42	5^+	174.3	628.96	4.5×10^9
	37.14	5^+	195.4	823.12	5.3×10^9
	34.86	5^+	266.1	1238.36	5.8×10^9
	32.58	5^+	251.5	1306.13	6.5×10^9
	28.02	5^+	308.2	1285.98	5.2×10^9
	23.46	4^+	290.9	1201.50	6.4×10^9
	18.50	4^+	1058.0	3560.28	5.3×10^9
^{16}O	64.00	7^+	751.4	3702.58	4.4×10^9

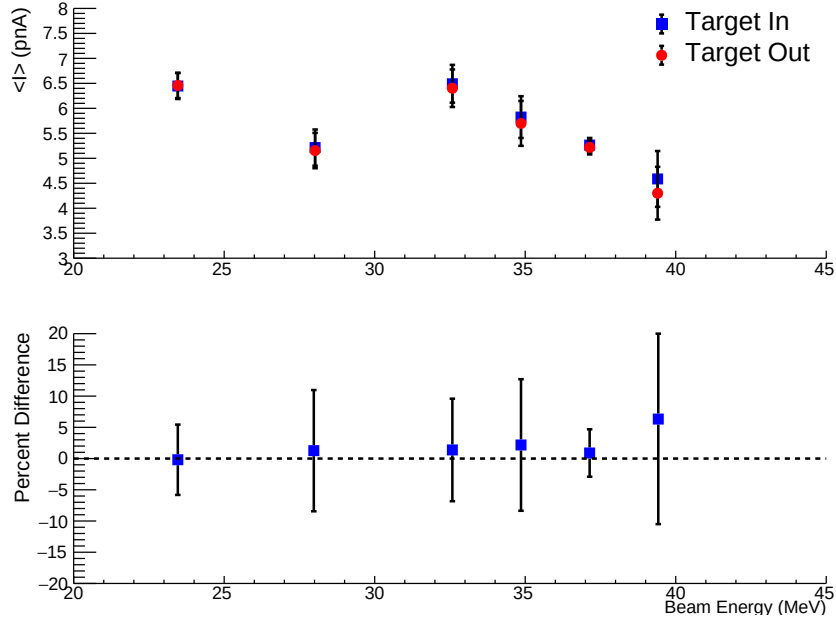


Figure 3.14: Incident ^{12}C beam currents measured on the beam blocker computed using the beam charge states listed in table 3.4. The top plot shows the incident beam current with the $711 \mu\text{g}/\text{cm}^2$ C_2D_4 target (blue) and with a blank target frame (red). The bottom plot shows the percent difference between the target-in and target-out beam currents.

campaign in 2016. The integral of the instantaneous current is equal to the total charge read from the beam blocker for the entire run. The total charge must be computed for each run in order to produce normalized angular distributions. The total charge for all beam energies from this campaign are shown in table 3.4.

Figure 3.14 shows the mean beam current (in pA) as measured on the beam blocker plate for six ^{12}C energies. The top plot compares the mean beam current for ^{12}C beam on a $711 \mu\text{g}/\text{cm}^2$ C_2D_4 target to beam on a blank target frame. The particle currents were computed using the beam charge states listed in table 3.4. The bottom plot shows the percent difference between the two. In all six cases, the difference between the target-in and target-out currents are consistent with zero. This plot shows that, at these energies, the target has a small effect on the final charge state of the beam hitting the plate.

3.4 Data Acquisition

3.4.1 XIA Digitizers

VANDLE utilizes a digital data acquisition system instead of traditional analog electronics. Digital systems have the ability to store a digitized version of the PMT output signal for later analysis. Despite increasing data throughput, this provides the benefit of allowing experimenters to re-analyze PMT traces as trace processing techniques and algorithms become more powerful.

A limitation of these systems is the finite sampling frequency of the analog to digital converters (ADCs) used to digitize the PMT signals. VANDLE uses 250 Megasamples per second (MSPS) 12-bit Pixie-16 digitizers from XIA LLC [50]. Each Pixie module contains 16 channels and each channel samples the input signal at 250 MSPS. The sampling frequency alone would normally establish the lower limit of particle timing with the VANDLE system at 4 ns. In order to obtain sub-sampling timing precision, VANDLE employs software trace processing algorithms (see Section 3.7). The parameters of these algorithms are set manually by the user and the high resolution times are extracted from the trace.

The raw VANDLE data that are written to disk contain three important parts. The first is a 48-bit timestamp, the second is a channel number identifier, and the third is an analog-to-digital converter (ADC) trace. These three pieces of information are the most important components of any digital TOF experiment. The structure of the output data stream that is written to disk changes with firmware revisions, but always contains the same basic elements. In this dissertation, the raw channel-by-channel events that are recorded to disk will be referred to simply as “events”. Every event contains exactly one timestamp, one channel number identifier, and one ADC trace (if enabled).

3.4.2 Event Timestamp

The 250 MSPS Pixie-16 digitizers have a system clock that runs at 8×10^{-9} seconds per tick, half the speed of the ADC clock, which runs at 4×10^{-9} seconds per tick. The 48-bit event

timestamp uses the system clock, while the ADC trace uses the ADC clock. This means that the inherent time resolution of the event timestamp is 8 ns.

3.4.3 ADC Trace

The Pixie-16 firmware allows the recording of PMT signals by writing an ADC trace to disk. Typical VANDLE PMT ADC traces are shown in Figures 3.16 and 3.17. 12-bit Pixie modules have a dynamic ADC range of 0 to 4095 ADC channels and 14-bit modules have a range of 0 to 16383 channels. It should be noted that there is a voltage offset that must be set for each individual channel. The voltage offset gives rise to the baseline of the trace shown later in this chapter in Figure 3.17 at around 410 ADC channels. This voltage offset must be adjusted for each channel to ensure that the largest dynamic range is available.

3.5 Raw-Event Building

Events written to disk have no inherent time structure, they are read from the onboard first-in-first-out (FIFO) buffer and written to disk in the order they were read from the modules. The events in the FIFO of each individual module are time ordered, but the modules are written to disk sequentially in increasing numeric order. This means that when events are read back from the binary data file, there is no information included on how those events should be ordered or grouped together. Therefore, data analysis codes must build a list of events that fall into a user-defined time window from the non-time-ordered events in the input data file. This list of events is referred to as a raw-event.

The first step to building a raw-event is to scan all of the events that fired and locate user-defined start events. A start is a special event that is used to open a raw-event time window. For this measurement, the RF logic signal from the beam buncher was used as the start signal for all particle detectors. The beam current integrator signal did not require coincidence with the buncher and was recorded whenever it was detected. This was done so that the measure of the total beam charge was not affected by the coincidence rate with the RF signal.

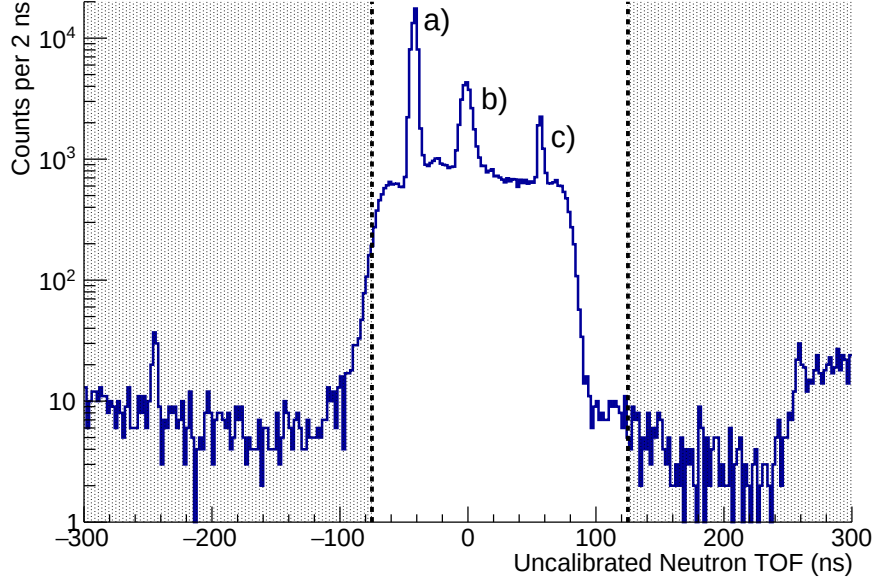


Figure 3.15: Uncorrected neutron TOF spectrum from a $^{12}\text{C}(d,n)$ run raw-event builder settings of $eventOffset = -500\text{ ns}$ and $eventWidth = 1000\text{ ns}$. a) Target γ -flash for de-excitation of nuclei in the target which are excited by the beam, b) Neutron peak from the (d,n) reaction, c) Target γ -flash for the following beam packet.

Once a start event is found, a new raw-event time window is opened. There are many ways to define a raw-event window. The simplest method is to look for events with a timestamp that is greater than or equal to that of the start event and is less than the time of the start event plus some user-defined raw-event width. This method, while simple, may miss signals that occur before the start event. So instead, it is better to define a raw-event offset in addition to the width.

Figure 3.15 shows an uncorrected neutron TOF spectrum for a $^{12}\text{C}(d,n)$ run with a raw-event offset of -500 ns and a width of $1\text{ }\mu\text{s}$. The majority of events fall within the analysis range of -75 ns to 125 ns . Events in the shaded regions should not be considered because they are correlated with different raw-events and are not physically realistic. Shortening the raw-event width prevents placing most of these events in the incorrect raw-event.

For this experiment, beam packets arrived from the RF buncher approximately every 100 ns . By necessity, the data acquisition recording time is set larger than 100 ns . This is done to avoid the risk of missing low energy neutrons that arrive outside the recording window. Since beam packets are arriving roughly every 100 ns and the recording time of the

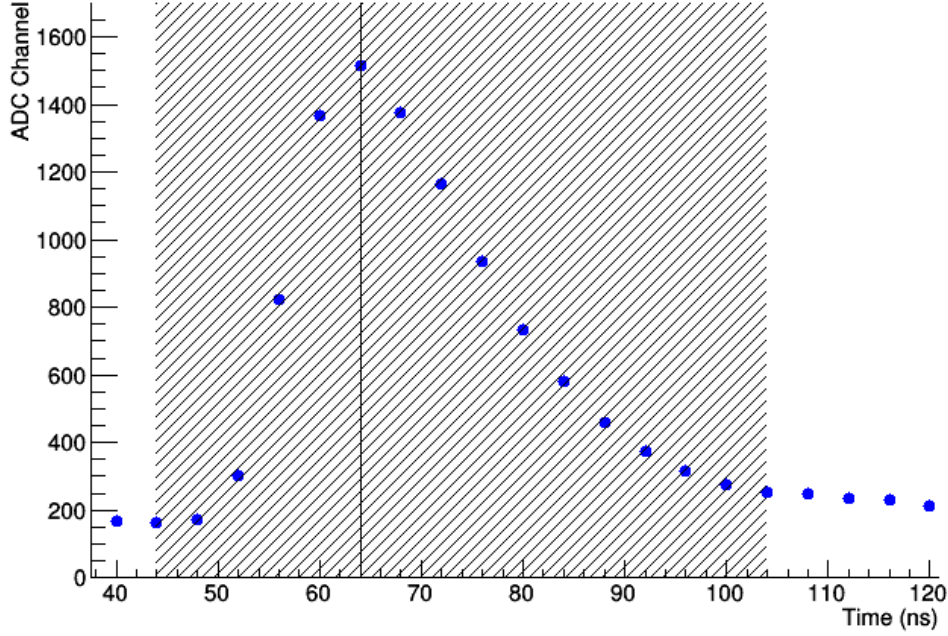


Figure 3.16: A typical VANDLE trace capture showing the TQDC integration region of $[T_{max} - 20, T_{max} + 40]$ ns.

data acquisition system is set to a value that is larger than 100 ns, multiple target γ -flashes are seen in the TOF spectra. This is demonstrated in Figure 3.15, where the target γ -flash and the flash from the following beam packet are visible. To avoid this, the raw-event may be started 75 ns before the start signal and the event width may be shortened to 200 ns (i.e. a range of -75 ns to 125 ns) to avoid events that fall before and after the events of interest.

3.6 Trace Integral (TQDC)

Photo multiplier tubes (PMTs) are commonly used with scintillator detectors. The Pixie-16 digitizers produce an ADC trace for each voltage signal from the PMT. In practice, the trace is of little use on its own. The trace amplitude as a function of time is dependent upon the material's optical properties and the PMT bias voltage and is typically not physically meaningful. Occasionally, the peak amplitude of the trace may be used to represent the amount of light which was emitted for a given scintillation event. More commonly, the integral of the trace is used to represent the entire amount of light which was produced.

For the VANDLE bars described in this study, the digitized ADC traces are integrated in the region $[T_{max} - 20, T_{max} + 40]$ using trapezoidal integration, where T_{max} is the index of the maximum ADC channel of the trace. The max ADC index is represented by a solid black line in Figure 3.16 and the integration region by a shaded box.

3.7 High Resolution Timing

For the vast majority of experiments which involve timing measurements, a time resolution of 8 ns is not precise enough. For VANDLE experiments, the recording of ADC traces is always enabled for TOF detectors. It should be expected that reading the arrival time of the trace should improve the time resolution to approximately 4 ns, since the ADC clock is twice as fast as the system clock.

Timing resolutions of significantly less than the sampling period of the digitizer (4 ns for 250 MSPS digitization as in this case) may be obtained by computing the time offset of the ADC trace, referred to here as the phase of the trace, ϕ . The phase may then be added to the event timestamp as shown in Equation 3.9 to obtain a time with a much higher resolution than the 48-bit timestamp offers.

$$T_{highres} = T_{timestamp}(8 \times 10^{-9} \text{ s/tick}) + \phi(4 \times 10^{-9} \text{ s/tick}) \quad (3.9)$$

There are several ways to compute the phase of the ADC trace. Commonly, a constant fraction discrimination algorithm (CFD) [17] or fitting function [51] may be used to perform this task.

3.7.1 Trace Fitting

One possible empirical formula for fitting VANDLE traces, such as the one shown in Figure 3.16, is detailed by S.V. Paulauskas et al. [51]. This piece-wise defined function is given by

$$f(t) = \begin{cases} 0 & \text{if } t \leq \phi \\ \alpha e^{-(t-\phi)/\beta} (1 - e^{-(t-\phi)^4/\gamma}) & \text{if } t > \phi \end{cases}, \quad (3.10)$$

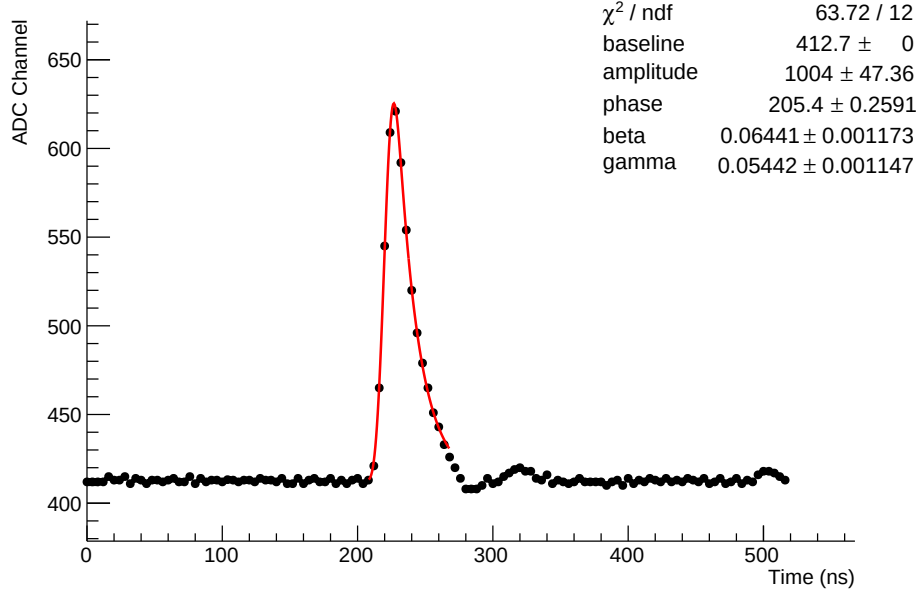


Figure 3.17: Typical VANDLE light trace fits using Equation 3.10 for a single trace and fitting in the range $T_{max} - 20 \text{ ns}$ to $T_{max} + 40 \text{ ns}$.

where α is related to the amplitude of the trace, β is the decay constant of the exponential term, γ is the width of the inverted-squared Gaussian, and ϕ is the offset phase of the trace. In practice, β and γ are obtained for each pulse shape using a timing analysis and are later fixed in the fit function for experimental data. Figure 3.17 shows a typical timing analysis for a single VANDLE PMT trace.

Typical β and γ values for VANDLE light pulse fits, as shown in Figure 3.17, are obtained by averaging many individual traces and fitting the resulting averaged distribution or by fitting many traces and averaging the fit parameters. The shape of the pulse changes slightly with varying pulse heights meaning that the fit parameters β and γ will also vary slightly as a function of trace amplitude.

3.7.2 Traditional Constant Fraction Discrimination (CFD)

An example of a traditional CFD algorithm [17] is given by

$$CFD[k] = \sum_{i=0}^{L-1} F \times \text{Trace}[k-i] - \text{Trace}[k-i-D], \quad (3.11)$$

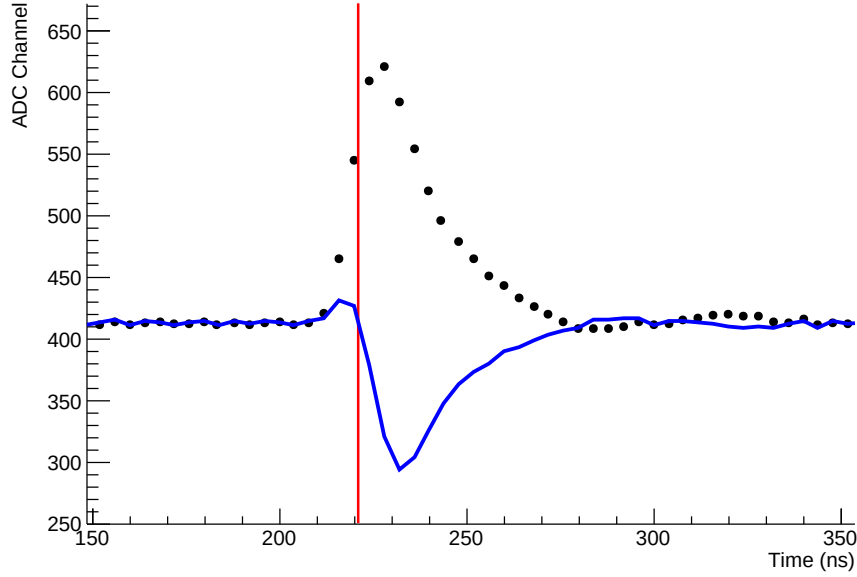


Figure 3.18: Typical VANDLE light trace with traditional CFD algorithm (Equation 3.11) output for $F = 0.5$ and $D = L = 2$ overlain. The blue line demonstrates the CFD waveform. The zero-crossing point, ϕ , is indicated by a vertical red line.

where D , F , and L are adjustable parameters and $Trace$ is the ADC trace array. CFD is a new array with the same length as $Trace$. This algorithm produces a completely new waveform that is the CFD processed version of the trace. The phase, in this case, is computed by calculating the zero-crossing point of the processed trace as shown in Figure 3.18. This algorithm is similar in operation to analog CFD electronics which are commonly used for discrimination and timing.

This algorithm has the benefit of being extremely fast, especially when compared to fitting algorithms which may take several orders of magnitude more time. It is designed to be fast enough to run in real time on digital hardware. The fact that there are three tunable parameters makes this algorithm somewhat cumbersome to use in practice. Knowledge of the pulse shape must be obtained beforehand and each of the three parameters must be optimized to maximize the time resolution.

The selection of different CFD parameters has a large effect on the zero-crossing point of the CFD waveform and, thus, the location of the phase of the trace. Unlike trace fitting in Section 3.7.1, CFD algorithms do not necessarily pick off the leading edge of the trace.

Table 3.5: Poly CFD algorithm pseudo-code

Step	Action
1	Identify the two highest points on the trace
2	Take one point on either side of the two maximum points
3	Fit all four points with a 3rd order polynomial (P3)
4	Use the maximum of P3 as the maximum of the trace
5	Compute the CFD threshold using $Threshold = F * P3(T_{max})$
6	Find the two points on the rise on either side of the threshold
7	Fit the two points along with the next highest point with a 2nd order poly (P2)
8	Find the phase of the trace by solving Equation 3.12 for ϕ

Instead, the phase is defined as wherever the zero-crossing of the CFD waveform happens to be. This means that if the CFD parameters are changed, the time offsets will need to be re-calculated.

3.7.3 Polynomial CFD

CFD algorithms, such as Equation 3.11, have the advantage of being very fast, relatively easy to implement, and robust. However, they typically have several parameters that must be optimized in order to obtain the best timing performance. This tuning of parameters must be done individually for different detectors. The parameter space for the CFD algorithm given by Equation 3.11 is very large. This work incorporates the use of a new CFD algorithm which is referred to as polynomial CFD (poly CFD). The idea behind poly CFD is to implement a high-resolution timing algorithm with a small parameter space that is largely independent of the shape of the pulse. The pseudo-code of this algorithm is shown in Table 3.5.

The phase of the pulse may be calculated by solving for the CFD threshold crossing point of the 2nd order polynomial, P2, shown below in Equation 3.12.

$$y(t) = Threshold = F * P3(T_{max}) = P2(\phi) = P_0 + P_1\phi + P_2\phi^2, \quad (3.12)$$

whose solution is

$$\phi = \frac{-P_1}{2P_2} \pm \frac{\sqrt{P_1^2 - 4P_2(P_0 - F * P3(T_{max}))}}{2P_2} \quad (3.13)$$

Equation 3.12 is double-valued for $P_1 \neq 2\sqrt{P_2(P_0 - F * P3(T_{max}))}$. Because the phase must always fall on the rise of the trace, the positive root of Equation 3.13 will always be used.

The parabola defined by Equation 3.12 opens upward for $P_2 > 0$ and downward for $P_2 < 0$. Because the phase must lie on the rise of the trace, the phase will lie on the right side of the minimum of P2 if the parabola opens upward, and on the left side of the maximum if the parabola opens downward. The minimum (or maximum) of P2 occurs at

$$t_{min/max} = \frac{-P_1}{2P_2}, \quad (3.14)$$

so Equation 3.13 may be rewritten as

$$\phi = t_{min/max} \pm A, \quad (3.15)$$

where the substitution $A = \frac{1}{2P_2} \sqrt{P_1^2 - 4P_2(P_0 - F * P3(T_{max}))}$ is used. When $P_2 > 0$, $\phi > t_{min}$ so

$$t_{min} \pm A > t_{min} \Rightarrow \pm A > 0 \quad (3.16)$$

Since $P_2 > 0$, A is always greater than zero. So the positive root of A must be used in this case. Similarly, when $P_2 < 0$, $\phi < t_{max}$ and

$$t_{min} \pm A < t_{min} \Rightarrow \pm A < 0 \quad (3.17)$$

In this case, $P_2 > 0$, so A is always less than zero. So the positive root of A must again be used.

An example of poly CFD in use is shown in Figure 3.19. The 3rd order polynomial, P3, which is fit to four points at the maximum of the pulse, is shown as a green line while the 2nd order polynomial, P2, which is fit to three points on the rise of the pulse, is shown as a magenta line. The calculated phase is shown as a vertical red line.

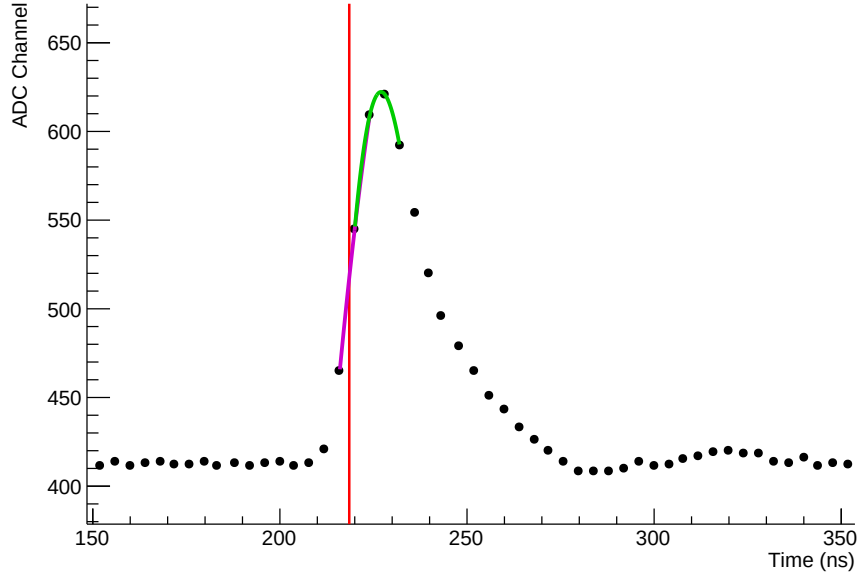


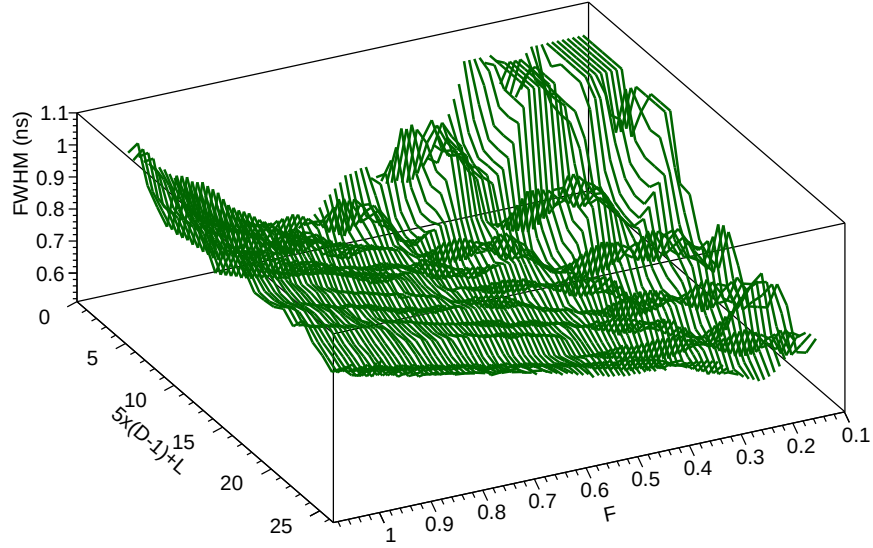
Figure 3.19: Typical VANDLE light trace with polynomial CFD algorithm output for $F = 0.5$ overlain. The second order polynomial used to find the threshold crossing point, ϕ (vertical red line), is shown in magenta while the third order polynomial used to find the peak maximum is shown in green.

3.7.4 Timing Algorithm Comparison

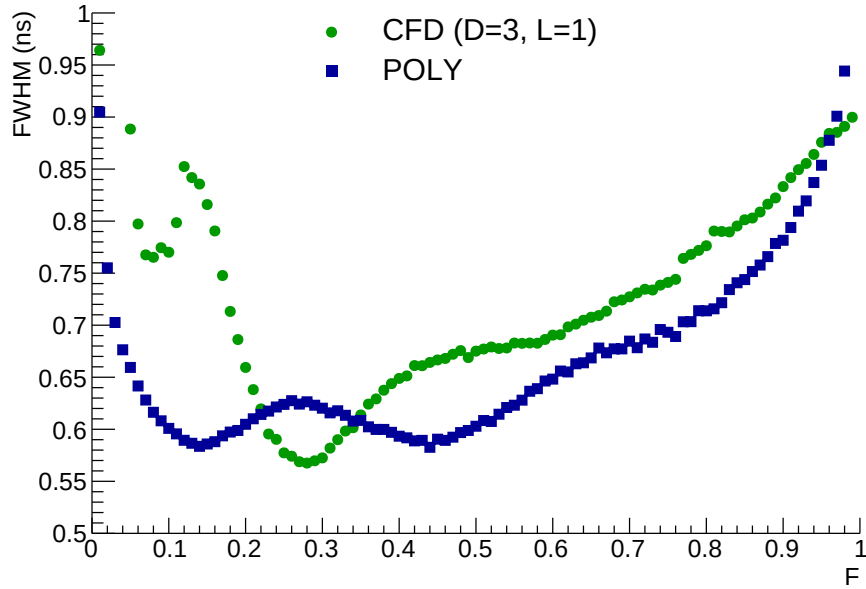
The following comparison between the two CFD algorithms listed in the previous sections uses five thousand left-right coincidence pairs from a VANDLE γ -ray source measurement. The uncollimated source was placed in the center of the bar equidistant from the left and right PMTs. A threshold of 2048 ADC channels, or 50% of the dynamic range of a 12-bit Pixie-16, was used for both the left and right PMTs. This ensures that the results will be largely unaffected by low amplitude timing walk.

The signal from the left PMT is used as the start signal while the right PMT is used as the stop. The CFD parameters of the start signal are iterated such that $F \in [0, 1]$ in steps of 0.01 (traditional and polynomial), $D, L \in [1, 5]$ in integer steps (traditional only). The parameters of the stop signal are held fixed at $F = 0.5$ and $D = L = 0.5$ as a control.

Figure 3.20a shows the complexity of the parameter space for the traditional CFD algorithm given by Equation 3.11. This is demonstrated by displaying the FWHM of the time difference as a function of the three CFD parameters F , D , and L . The time resolution is



(a) Parameter scan for $F \in (0, 1)$ in steps of 0.01, and $D, L \in (1, 5)$ in integer steps for CFD.



(b) Parameter scan for $F \in (0, 1)$ in steps of 0.01 for CFD and poly CFD.

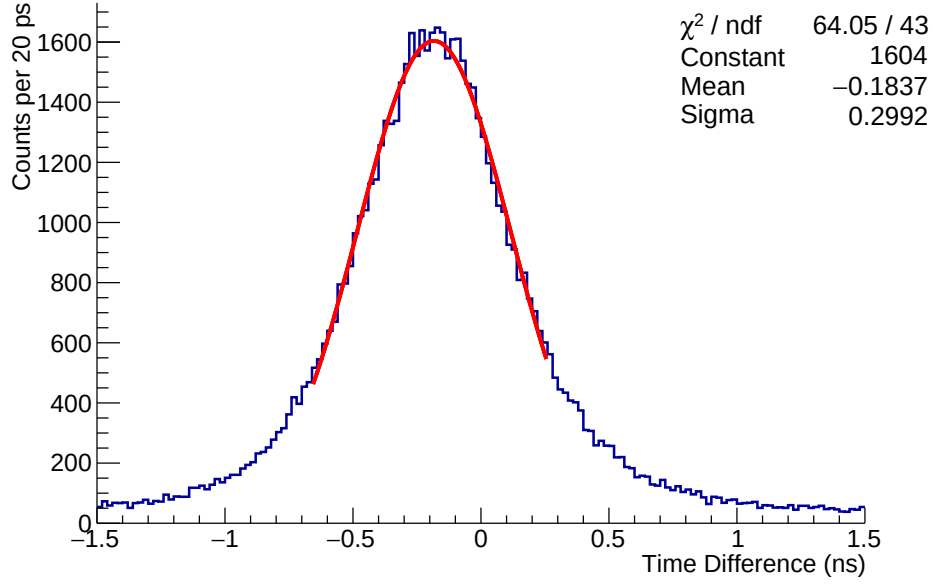
Figure 3.20: Scan over CFD parameters for a single VANDLE bar with a γ -ray source at the center. Five thousand left-right pairs are used for the analysis. An ADC threshold of 2048 channels is used (50% of a 12-bit ADC). Parameters are iterated for $F \in [0, 1]$ in steps of 0.01 (POLY and CFD), and $D, L \in [1, 5]$ in integer steps (CFD only).

minimized for parameters $F = 0.28$, $D = 3$, and $L = 1$ giving a FWHM resolution of 568 *ps*. The parameter space of polynomial CFD is, by comparison, much smaller. Figure 3.20b compares poly CFD to the traditional algorithm for $D = 3$ and $L = 1$. Poly CFD is optimized for $F = 0.44$ resulting in a FWHM resolution of 583 *ps*. Both values are comparable to the performance of the fitting function given in Equation 3.10 of approximately 500 *ps* [51].

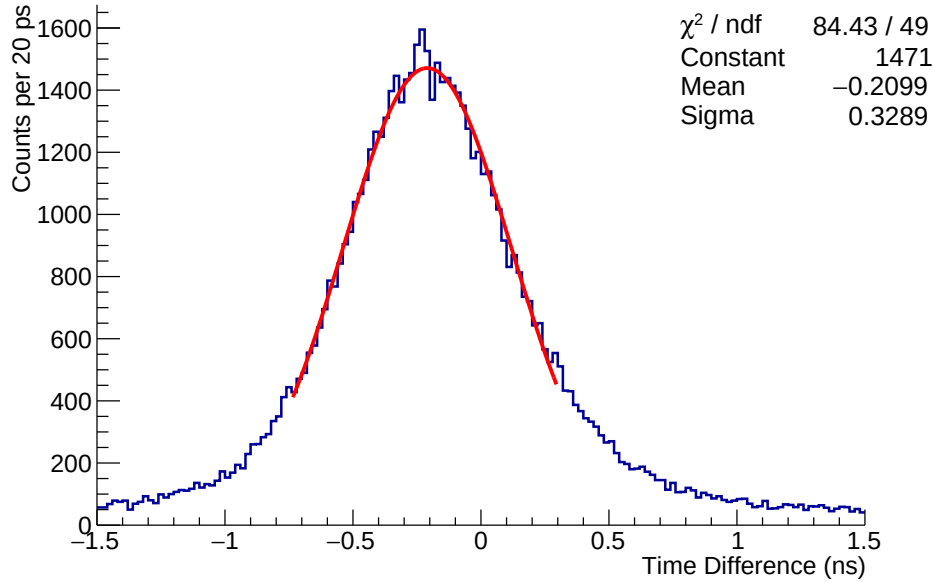
The optimized performance of poly CFD is comparable to that of the traditional algorithm with only a single parameter. Poly CFD also exhibits less sensitivity to the CFD parameter F over a larger range than the traditional CFD algorithm for $D = 3$ and $L = 1$, varying by only about 100 *ps* from $F = 0.1$ to $F = 0.65$. For both algorithms compared in Figure 3.20, sub-nanosecond timing resolution is achieved for nearly the entire range of parameter F .

For both CFD algorithms shown in Figure 3.20, optimized CFD parameters are used to compute time-differences between the two ends of a VANDLE bar for the same γ -ray measurement described earlier with no software ADC threshold imposed on the PMT traces. Results for the traditional CFD and polynomial CFD algorithms are shown in figures 3.21a and 3.21b respectively. The time difference between the left and right PMTs are fit with a Gaussian. The results of the fits are shown for each case. The FWHM resolution for traditional CFD is approximately 700 *ps* while poly CFD results in a resolution of 775 *ps*. When low amplitude traces near the hardware threshold are included, the performance of the two CFD algorithms is worse than that of fitting with Equation 3.10 which has been reported to achieve a FWHM resolution of approximately 600 *ps* [51] using a small $1 \times 1 \times 0.4$ inch³ piece of EJ-200 with a VANDLE PMT on each end. Further timing analysis is discussed in Appendix A.

In a typical reaction experiment, poor beam energy resolution, ion optics, target thickness, and the thickness of the detectors themselves will limit the time resolution of the measurement to several *ns*. So even though the CFD algorithms provide slightly worse time resolution than the quoted resolution of the fitting function, they still provide timing well below 1 *ns*. Poly CFD was used for the analysis of this measurement because of its speed and relative ease of use.



(a) Traditional CFD (Equation 3.11) for $F = 0.28$, $D = 3$, and $L = 1$



(b) Polynomial CFD (Section 3.7.3) for $F = 0.44$

Figure 3.21: Time difference spectra for optimized CFD algorithms. Data are taken from a measurement using a single VANDLE bar with a γ -ray source in the center. Spectra are fit using a Gaussian. Fit results are shown. No software threshold is used for ADC traces. The traditional CFD results in a FWHM time resolution of 704 ps. Polynomial CFD results in a resolution of 775 ps.

Chapter 4

Data Analysis

The overall objective of this measurement was to obtain angular distributions for the proton transfer reactions $^{12}\text{C}(d, n)$ and $^{16}\text{O}(d, n)$ in inverse kinematics. In order to produce angular distributions, the energy and position of the neutron must be measured. To do this accurately, the neutron detection system must be well characterized so that its detection efficiency, ϵ , does not distort the shape of the resultant distributions.

4.1 Neutron Energy Computation

For neutron detectors, scintillation light is created via the energy loss of particles in the scintillator material recoiling after scattering an incident neutron. The neutron typically only loses a portion of its energy in the material via scattering. Thus, the light response of the scintillator is not an accurate measure of the energy of the scattered neutron.

If the neutron detector is in a time-of-flight (TOF) configuration, the kinetic energy of the detected neutron may be computed using the relativistic equation

$$T_\nu = \left(\frac{1}{\sqrt{1 - \frac{d^2}{t^2 c^2}}} - 1 \right) M_\nu c^2, \quad (4.1)$$

where d is the flight-path of the neutron, t is the TOF, and M_ν is the mass of the neutron. For non-relativistic neutrons, the energy may be calculated from the neutron TOF using

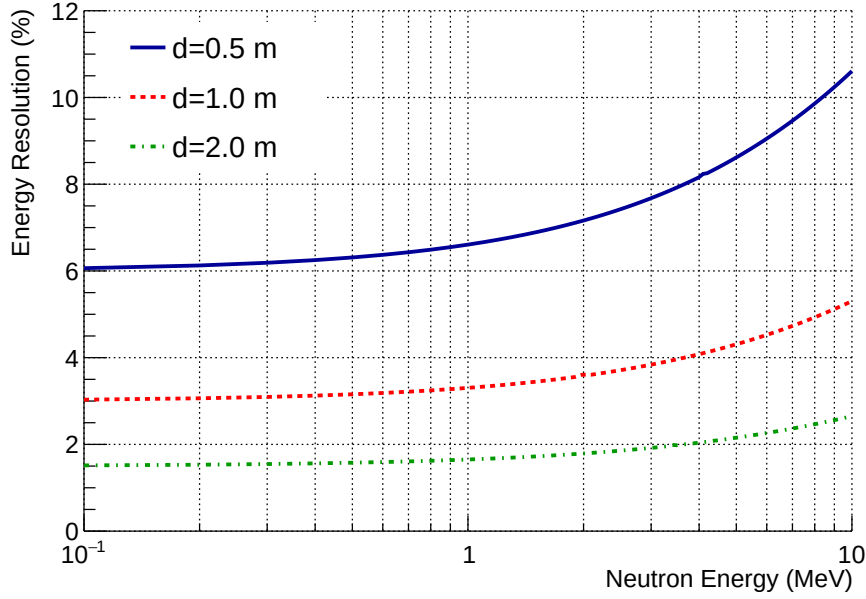


Figure 4.1: Expected energy resolution for a small VANDLE bar at a radius of 0.5 m (blue), 1.0 m (red), and 2.0 m (green) with a fixed time resolution of 1 ns.

$$T_\nu = \frac{1}{2} M_\nu \frac{d^2}{t^2}, \quad (4.2)$$

so the neutron energy resolution may be computed using

$$\frac{\delta T_\nu}{T_\nu} = \sqrt{\left[\frac{\delta d}{d} \right]^2 + \left[\frac{\delta t}{t} \right]^2}, \quad (4.3)$$

where it is assumed that the uncertainty in the mass of the neutron is negligible. In this formula, δd is the thickness of the detector, since the neutron does not necessarily interact at the surface, and δt is the inherent time resolution of the detection system. In this case, the resolution is approximately 1 ns (see Section 3.7 for more detailed discussion on the timing resolution for this measurement).

Since the thickness and time resolution are fixed, this formula shows that there are two ways in which to increase the energy resolution of a TOF detector. The first is to increase the flight-path of the neutron (d), the second is to increase the neutron TOF (t). As the TOF is directly dependent on the energy of the neutron, only the flight-path is modifiable.

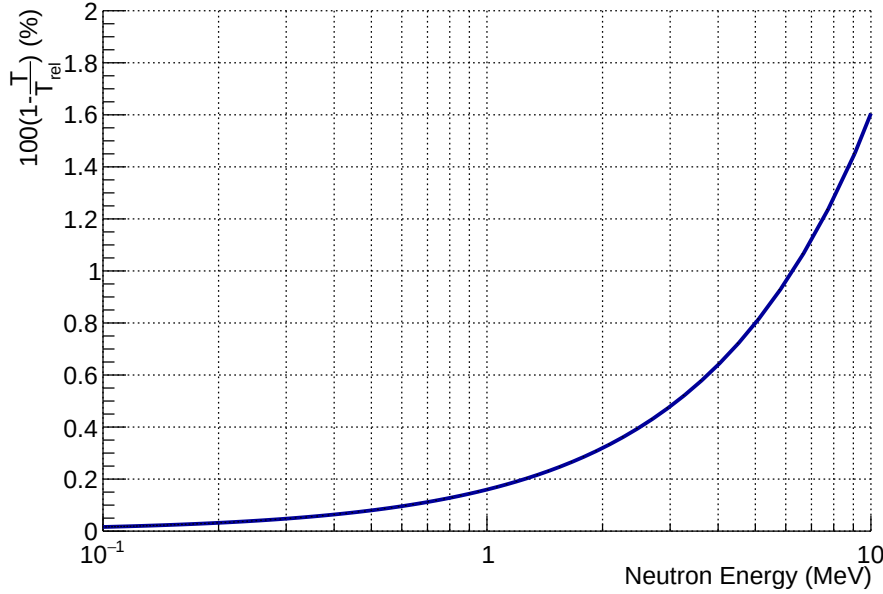


Figure 4.2: Relativistic correction percentage for neutron kinetic energy as a function of non-relativistic energy for a flight-path of 0.5 *m*.

Figure 4.1 shows the energy resolution for a VANDLE bar as a function of neutron energy for distances of 0.5, 1.0, and 2.0 *m* from the source. Clearly, doubling the distance from the source improves the energy resolution by a factor of two. This comes with the added cost of decreasing the geometric efficiency by a factor of four. There is a delicate balance between improving the energy resolution and decreasing the overall detection efficiency by moving TOF detectors further from the source.

The percent difference between the relativistic neutron kinetic energy (T_{rel}) given by Equation 4.1 and the non-relativistic energy given by Equation 4.2 is shown in Figure 4.2 for a neutron flight-path of 0.5 *m*. The percent difference between these two energies is below two percent up to neutron kinetic energies of 10 *MeV*, which is higher than the maximum neutron energy measured here. This correction factor is considerably less than the best energy resolution of $\approx 6\%$ for a flight-path of 0.5 *m* as shown in Figure 4.1. Therefore, neutrons detected by VANDLE in the range of 0 to 10 *MeV* may be considered non-relativistic and Equation 4.2 may be used to compute the energy of these neutrons.

4.1.1 Energy Compression

Neutrons at the maximum neutron energy which may be detected by VANDLE with any efficiency is approximately 10 *MeV*. In an actual VANDLE TOF measurement, the detectors are typically placed close to the source or reaction point in order to increase the angular coverage of the array. In these cases, these higher energy neutrons are not easily seen due to kinematic compression.

Equation 4.2 shows that the neutron energy is proportional to the inverse square of the neutron TOF and, conversely, the TOF is proportional to the inverse square root of the energy (i.e. $t \propto 1/\sqrt{E}$). High energy neutrons will be compressed toward TOFs of zero while low energy neutrons will be spread out to very large TOFs. In most measurements, neutrons from the source or target will be accompanied by what is known as the γ -ray-flash or simply the γ -flash (see Section 4.3.1). Depending upon the timing resolution of the measurement and the distance from the source or target interaction point to the detectors, higher energy neutrons may be buried beneath the γ -flash. This means that the detector setup itself will effectively limit the maximum detectable neutron energy.

4.1.2 Energy Binning

Figure 4.1 shows that the neutron energy resolution of VANDLE degrades with increasing energy. A fixed bin width in energy is not valid for detectors of this type. Instead, one may use Equation 4.3 to compute the appropriate energy bin width for a given detector setup. The bin width as a function of the energy at the center of the bin may be written

$$E_{width}(E_{mid}) = \frac{2E_{mid}}{d} \sqrt{\delta d^2 + \frac{2E_{mid}}{M_\nu} \delta t^2} \quad (4.4)$$

As expected, the width of the energy bin is inversely proportional to the distance to the source (d). If one requires finer energy resolution, Equation 4.4 shows that the detector must be moved further from the source. Figure 4.3 shows the energy bin width for a VANDLE bar at a distance of 0.5, 1.0, and 2.0 *m* from the target.

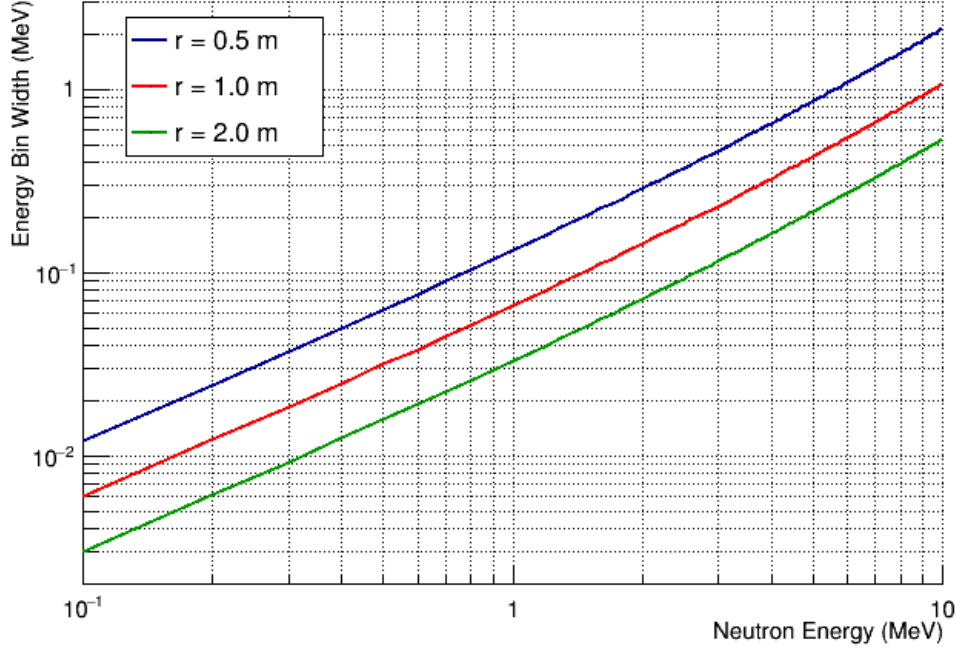


Figure 4.3: Energy spectrum bin width as a function of the centroid energy for a VANDLE bar at a distance of 0.5 (blue), 1.0 (red), and 2.0 m (green) from the origin and a fixed time resolution of 1 ns.

4.2 Neutron Detection Efficiency

Since neutrons carry no charge, they interact with material more weakly than their charged particle counterparts. Organic scintillator detectors use neutron scattering to detect neutrons. A portion of the neutrons incident on an organic scintillator may simply pass through the material without scattering. This contributes to a reduction of detection efficiency for a given material. This intrinsic efficiency is a function of the energy of the neutron, the chemical makeup of the material i.e. the neutron scattering length, as well as the apparent thickness of the material which the incoming neutron “sees”.

There are several different methods which may be used to measure the intrinsic neutron detection efficiency of a scintillator. One of the simplest methods is to use a calibrated ^{252}Cf neutron source with a known neutron flux. A neutron detector is placed a distance from the source and is used to detect neutrons from the spontaneous fission of the Cf in the source.

The spontaneous fission of ^{252}Cf has a branching ratio of 3.09% and has a half-life of 2.6 years [52]. If the neutron activity of the source is known, the expected neutron flux at the detector position may be calculated. More commonly, the exact activity of the source is not

known. In this case, a second detector with a well known detection efficiency may be used to normalize the neutron flux from the source.

In the fall of 2017, the efficiency of small and medium VANDLE bars was measured at Oak Ridge National Laboratory (ORNL) using the setup shown in Figure 4.4. An NE-213 liquid scintillator detector with a known efficiency was used to normalize the neutron flux for the two VANDLE bars. The small bar was placed at 2.089 *m* from the source, the medium bar at 2.088 *m*, and the liquid detector at 1.308 *m* (as measured from the source to the surface of the detectors). Longer flight-paths were used, in this case, to increase the energy resolution of the neutron detectors. A small plastic scintillator detector, placed against the source, was used as the start to the TOF while the neutron detectors themselves were used as the TOF stop signal.

4.2.1 Shadow Bar

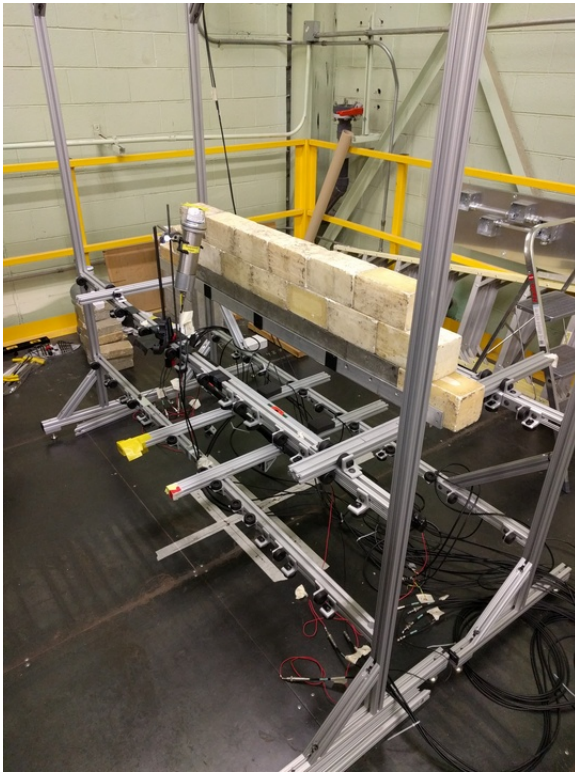
A significant source of background for such a measurement are γ -rays from room background as well as γ -rays and neutrons from the source, which are scattered from nearby materials. Room background γ -rays contribute a more-or-less constant background because they are uncorrelated with particles from the source. Scattered neutrons pose more of a problem because their time of arrival is not correlated with their energy because their flight-path is unknown. This effect tends to artificially boost the efficiency of the detector because neutrons which normally would not have been detected are now detected after scattering from a nearby surface.

To account for this effect, neutrons coming directly from the source were blocked using “shadow” material in order to obtain the TOF spectrum of just the scattered neutrons. Figure 4.5 shows the neutron detector shadowing material, a large stack of paraffin and tin bricks on a moveable rail. Paraffin is an excellent material for shielding neutrons and is used to shadow the detectors from neutrons from the source while blocks of tin are used to block the γ -rays.

Paraffin wax contains a high concentration of hydrogen atoms. Neutrons travelling through such a material will slow down due to repeatedly scattering from these light nuclei. Due to the scattering kinematics, neutrons may transfer anywhere between 0% and 100% of



Figure 4.4: Neutron detector intrinsic detection efficiency measurement setup at Oak Ridge National Laboratory.



(a) VANDLE bar shadow



(b) Liquid shadow

Figure 4.5: Neutron detector shadow material comprised of 10 *cm* of tin and 20 *cm* of paraffin wax.

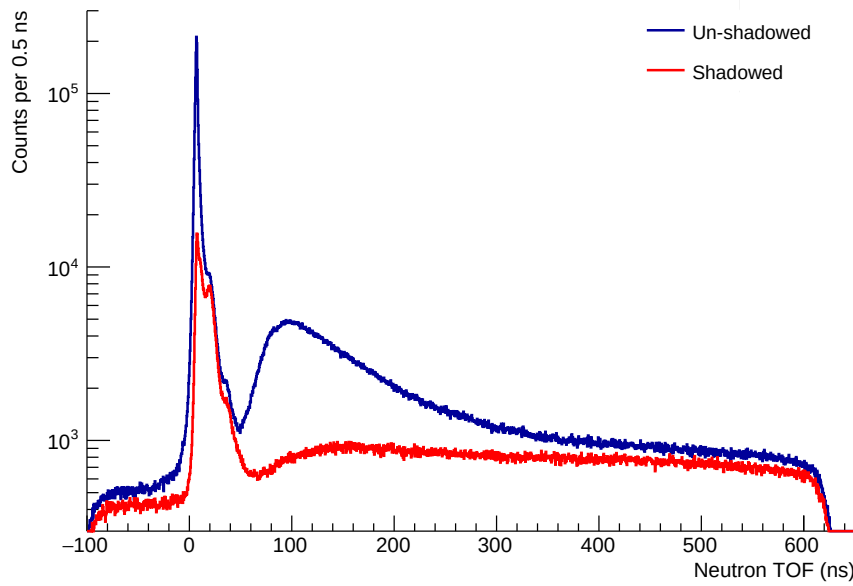


Figure 4.6: Small VANDLE bar TOF spectrum for ^{252}Cf source at radius of 2.08 m unshadowed (blue) and shadowed with 20 *cm* of paraffin wax and 10 *cm* of tin (red).

their kinetic energy to hydrogen atoms when elastic scattering. Depending on the volume of the material, neutrons may either scatter out of the material after losing some kinetic energy or will eventually lose enough energy to be absorbed by neutron capture. This makes light nuclei material, such as paraffin, excellent neutron moderators. This is not the case for heavier nuclei such as lead or iron which tend to scatter high energy neutrons without slowing them down.

The “shadow” spectrum allows the removal of unwanted scattered neutrons and room background. Figure 4.6 shows an unmoderated neutron spectrum from a ^{252}Cf source overlaid with a shadow spectrum for a small VANDLE bar. Both spectra are scaled for time. The γ -flash from the source is visible as an intense line near 0 *ns* as well as neutrons starting at around 50 *ns*. The shadowed spectrum exhibits reduced intensity in the γ -flash but maintains almost the exact same intensity in the γ -flash shoulder.

Subtracting the shadowed spectra from the non-shadowed removes the majority of the delayed γ -flash as shown in Figure 4.7. It also removes the majority of scattered neutrons from beneath the ^{252}Cf spectrum. The subtracted spectrum reflects the intrinsic efficiency

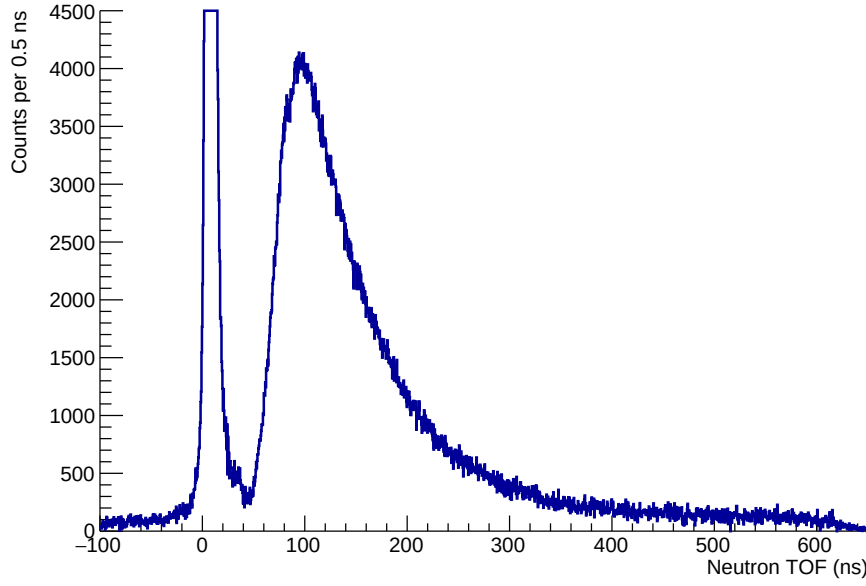


Figure 4.7: Shadow-subtracted Small VANDLE bar TOF spectrum for ^{252}Cf source at radius of 2.08 m.

of the detector folded with the geometric efficiency (or solid angle) and the neutron emission spectrum from the source.

4.2.2 Solid Angle Coverage

The procedure described in Section 3.1.2 was used to calculate the angular coverage of the small VANDLE bar for the efficiency measurement. For a single small VANDLE bar at 2.08 m from an isotropic source, the geometric efficiency is equal to 0.035% or 4.4 *msr*.

4.2.3 Neutron Emission Spectrum

Equation 3.7 may be used to calculate the intrinsic efficiency of the VANDLE bar, but the neutron emission spectrum from the source must be known. The neutron spectrum of ^{252}Cf is well studied and may be described by the normalized Watt equation

$$N(E) = \frac{2}{\sqrt{\pi b a^3}} e^{-ab/4} e^{-E/a} \sinh(\sqrt{bE}), \quad (4.5)$$

Table 4.1: Examples of γ -ray sources typically used for light response calibration.

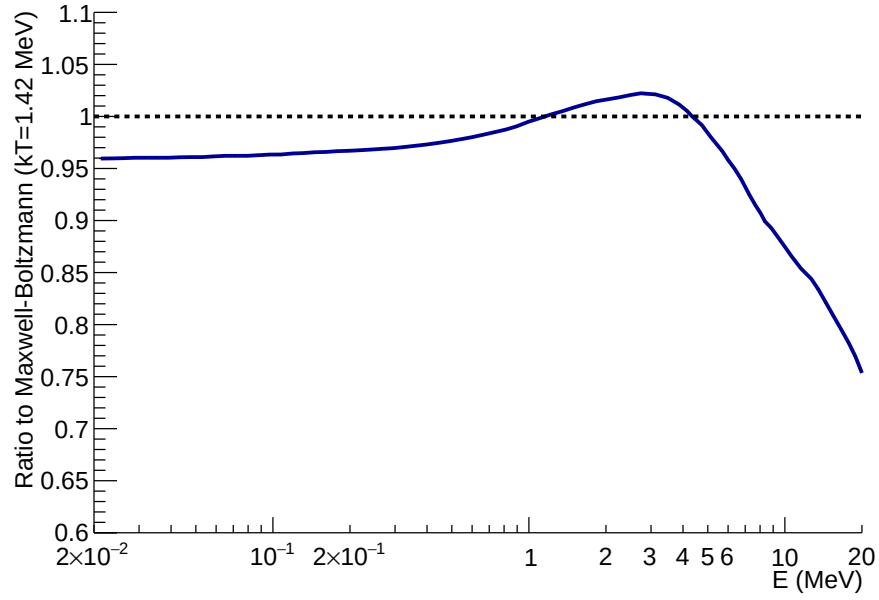
Isotope	γ -Ray Energy (keV)	Compton Edge (keV)
^{133}Ba	30.8	n/a
^{241}Am	59.54	n/a
^{207}Bi	74.97	n/a
^{133}Ba	356.01	207.27
^{207}Bi	569.7	393.3
^{137}Cs	661.7	477.4
^{207}Bi	1063.7	857.7
^{60}Co	1332.5	1118.1

where $a = 1.174 \pm 0.008$ MeV and $b = 1.043 \pm 0.056$ MeV $^{-1}$ for the neutron yield of ^{252}Cf as evaluated by W. Mannhart [11]. Figure 4.8b shows a comparison between the ^{252}Cf neutron yield as evaluated by Mannhart and the Watt Spectrum described in Equation 4.5. This empirical representation makes it much easier to fold into measurements of intrinsic neutron detection efficiency using Equation 3.7.

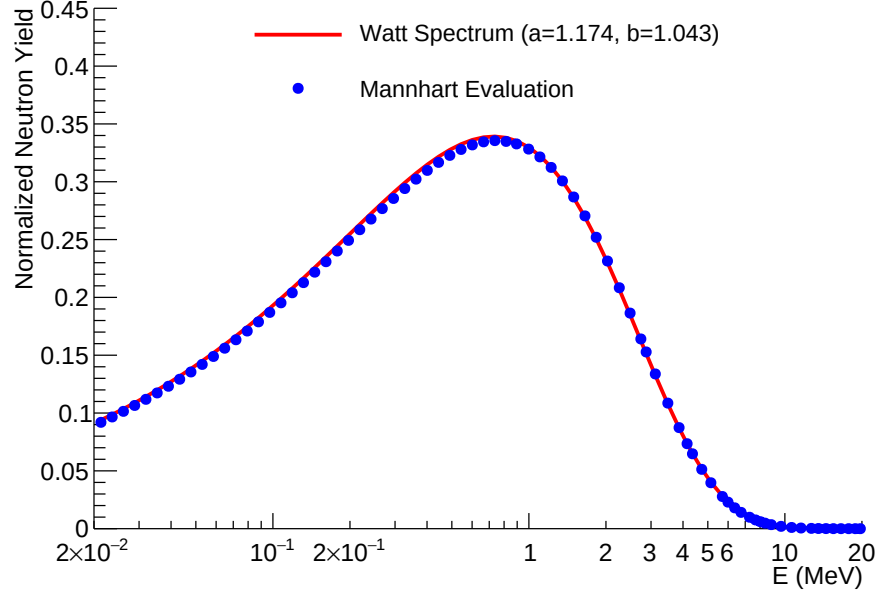
4.2.4 Detector Light Response

The total amount of light collected by the PMT for a detection event is dependent upon many factors in a measurement. These factors include the brightness of the scintillator being used, the energy of the neutron, and the model and bias voltage of the PMT. The integral of the PMT trace is proportional to the amount of light emitted by a scattering neutron and cannot be used to find the incident neutron energy as the its scattering angle is unknown. Typically, the light output of a neutron scintillation event is quoted in terms of the electron equivalent energy ($eVee$). The $eVee$ is a unit of light yield and is equivalent to the amount of scintillation light an electron with the same energy would produce in the material.

In order to calibrate the electron-equivalent light response of a detector, γ -ray sources may be used. The γ -rays emitted from a source Compton scatter from electrons in the material and the recoiling electrons produce scintillation light while slowing down. If the γ -ray energy is low enough, it may also be fully absorbed by the material. Compton scattering produces the broad “Compton plateau” as well as the “Compton edge”.

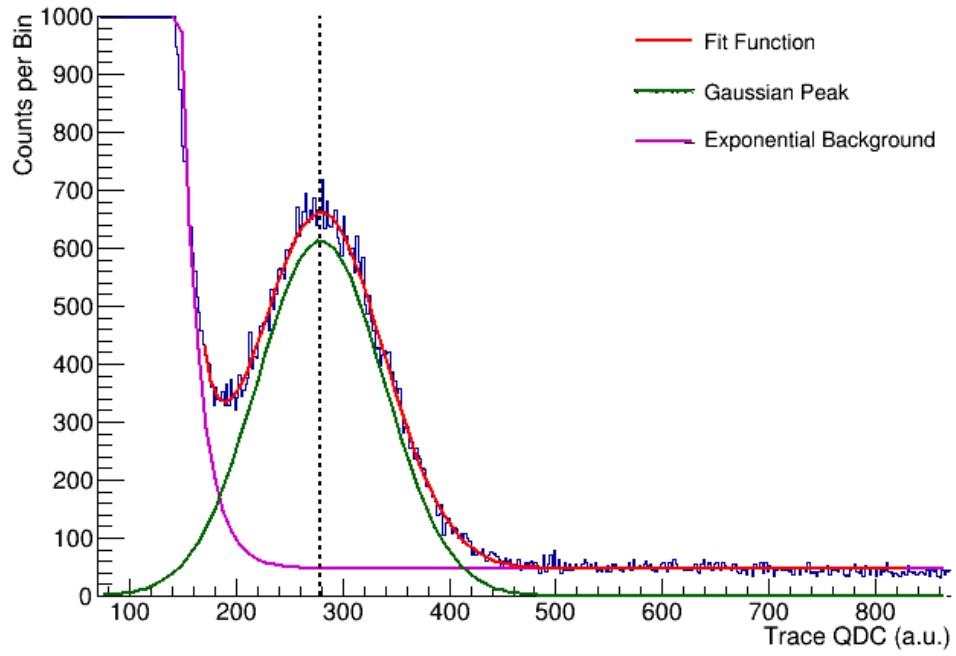


(a) Ratio to Maxwell-Boltzmann distribution with $kT = 1.42 \text{ MeV}$

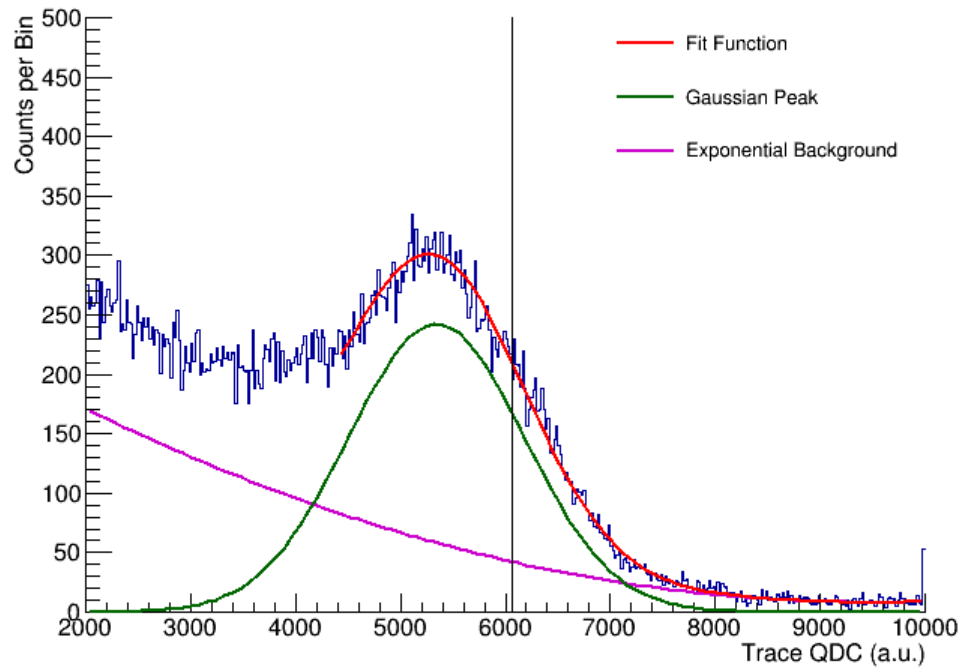


(b) Normalized ^{252}Cf neutron yield as a function of energy

Figure 4.8: Neutron yield of ^{252}Cf from IAEA evaluation by W. Mannhart [11]. (top) Ratio of neutron yield to the Maxwell-Boltzmann distribution for $kT = 1.42 \text{ MeV}$. (bottom) Normalized neutron yield as a function of energy.



(a) Photopeak fit spectrum for ^{241}Am



(b) Compton edge fit spectrum for ^{60}Co

Figure 4.9: Fitted light response spectra for the γ -ray sources ^{241}Am and ^{60}Co showing a total-absorption photopeak in the former and a Compton edge in the latter. The dashed black lines represent the center of the photopeak for ^{241}Am and 70% of the maximum amplitude for the Compton edge of ^{60}Co .

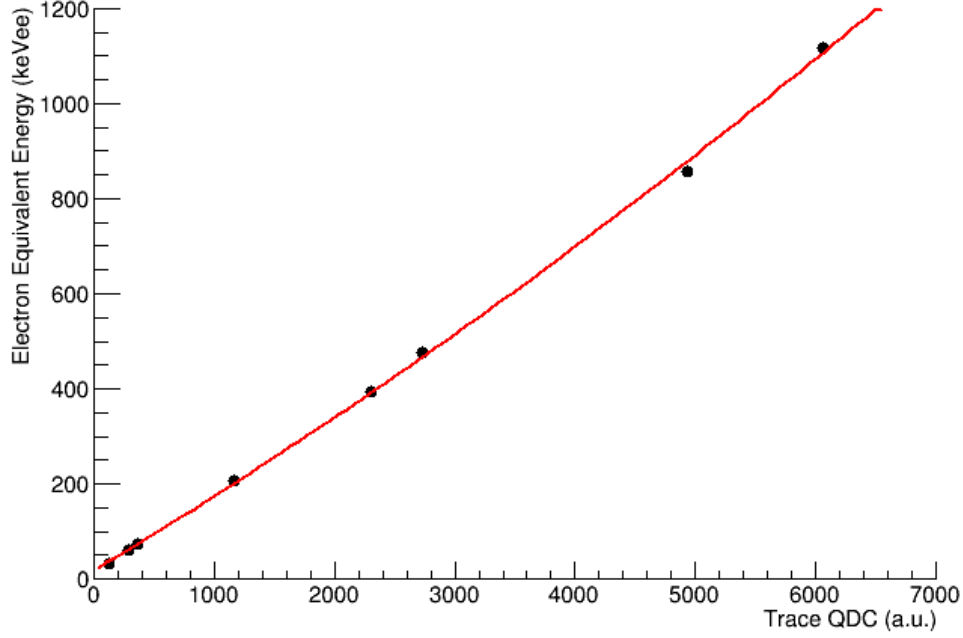
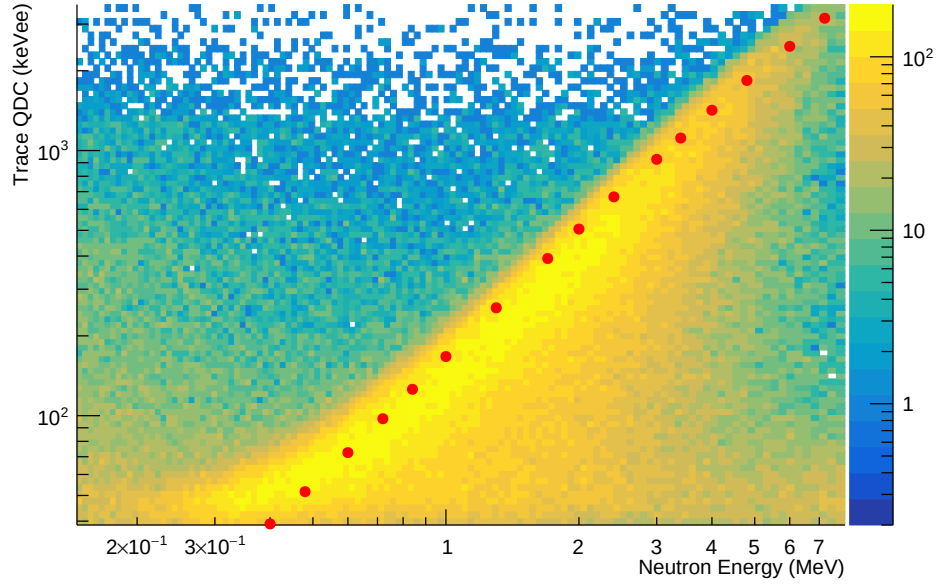


Figure 4.10: VANDLE bar calibration curve used for conversion from trace integral (trace QDC) to electron equivalent light response. Calibration uses γ -ray energies given in Table 4.1. Points are fit using a second order polynomial.

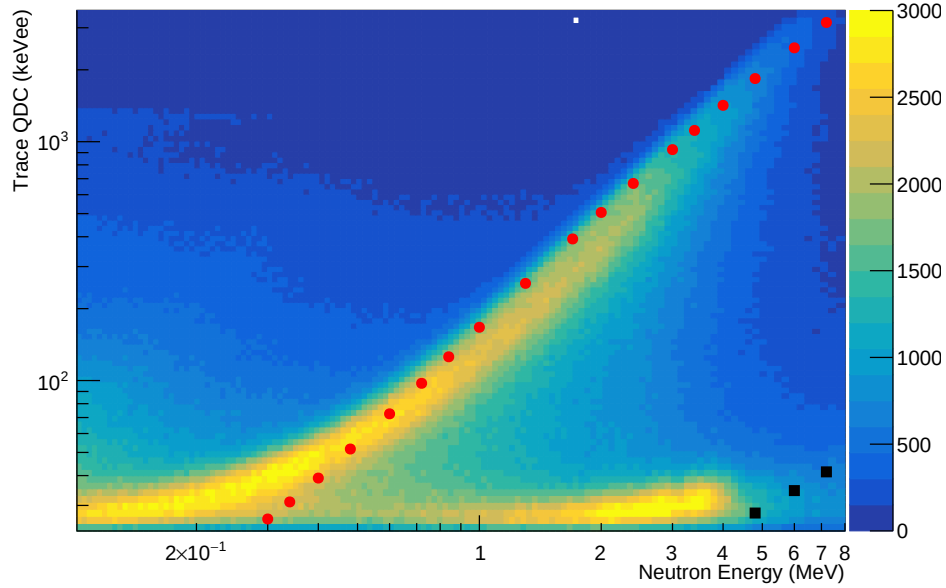
Table 4.1 lists the γ -ray energies and Compton edges for the various γ -ray sources which were used in this measurement to calibrate the light yield of the VANDLE bar. Note that for energies under ≈ 100 keV, the γ -rays are fully absorbed and no Compton edge is produced. Figure 4.9 demonstrates the difference between the full energy absorption photopeak produced by γ -rays with energies less than approximately 100 keV and the Compton edge (without a photopeak) which is produced by γ -rays with energies greater than 100 keV.

Figure 4.10 shows the calibration for the small VANDLE bar using the eight γ -rays listed in Table 4.1. The resulting distribution is fit using a second order polynomial and gives the electron equivalent light yield for the detector as a function of TQDC. Once the light response of a neutron detector is calibrated, it is possible to find the relationship between the light response and the incident neutron energy. This relationship is a characteristic of a given scintillator material and is shown in figures 4.11 and 4.12 for a small VANDLE bar.

The prominent edges shown in Figure 4.11 for the liquid detector (top) and for a small VANDLE bar (bottom) represent the maximum amount of light which is produced for a



(a) NE-213 liquid scintillator light yield versus incident neutron energy.



(b) Small VANDLE bar light yield versus incident neutron energy.

Figure 4.11: Calibrated light yields for NE-213 liquid scintillator (top) and a small VANDLE bar (bottom) as a function of incident neutron energy. The strong edges represent the light yields due to an incident neutron transferring all of its energy to a recoiling proton during a scattering event. Red points represent proton light yield of recoiling protons in NE-213 from V.V. Verbinski et al. [12]. The black points in the bottom plot are for the light yield of recoiling carbon atoms in NE-213 from Verbinski.

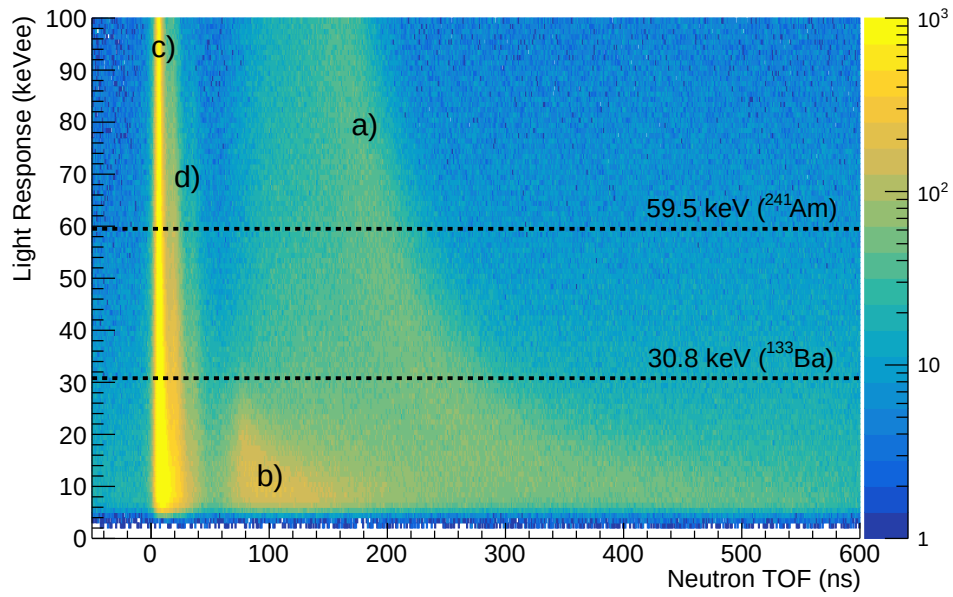


Figure 4.12: Calibrated light response for a small VANDLE bar as a function of neutron TOF for a ^{252}Cf source at a distance of 2.088 m. [A] Band caused by neutrons scattering from protons in the plastic. [B] Band caused by neutrons scattering from carbon in the plastic. [C] Prompt γ -ray flash from the source. [D] Delayed γ -ray flashes caused by nearby scattering surfaces and short-lived daughters of fission fragments.

neutron transferring all of its kinetic energy to a proton which it scatters from. All light responses below this edge are produced by neutrons transferring only a portion of their kinetic energy to the proton. Any events having a light response greater than this edge cannot possibly be neutrons and are likely γ -ray or muon background. This physical restraint on the light response allows for the removal of a portion of the events which are known to not be neutrons. Comparison between Figures 4.11a and 4.11b shows that the light yield of NE-213 is very similar to that of a small VANDLE bar (EJ-200).

4.2.5 Detector Thresholds

For a typical VANDLE measurement, sealed sources are used to establish the light response threshold of all individual detectors. ^{133}Ba and ^{241}Am are good candidates for this process because they emit high intensity γ -rays at 30.8 *keV* and 59.5 *keV* respectively. These low-lying γ -rays are useful for setting the threshold of the neutron detectors because they each produce a full energy absorption photopeak. The photopeak may be used to set a sharp cut-off in detector light response with very little ambiguity.

Figure 4.9a demonstrates how the software threshold is set for each detector. In this case, the ^{241}Am light response spectrum is fit using a Gaussian peak on an exponential background. The mean of the 59.5 *keV* photopeak and the threshold for this particular detector is marked by the vertical dashed line. The same method is used for the fully absorbed 30.8 *keV* γ -ray from ^{133}Ba .

4.2.6 Efficiency Results

For the case of an isotropic neutron source, such as ^{252}Cf , the expected number of neutrons, N_{exp} , becomes simply the Watt Equation (4.5). So, substituting Equation 4.5 into Equation 3.7 and solving for the intrinsic detection efficiency gives

$$\epsilon_{int}(E) = \frac{N_{det}(E)}{\epsilon_{geom} C \exp^{-E/a} \sinh(\sqrt{bE})}, \quad (4.6)$$

where the introduction of the normalization constant

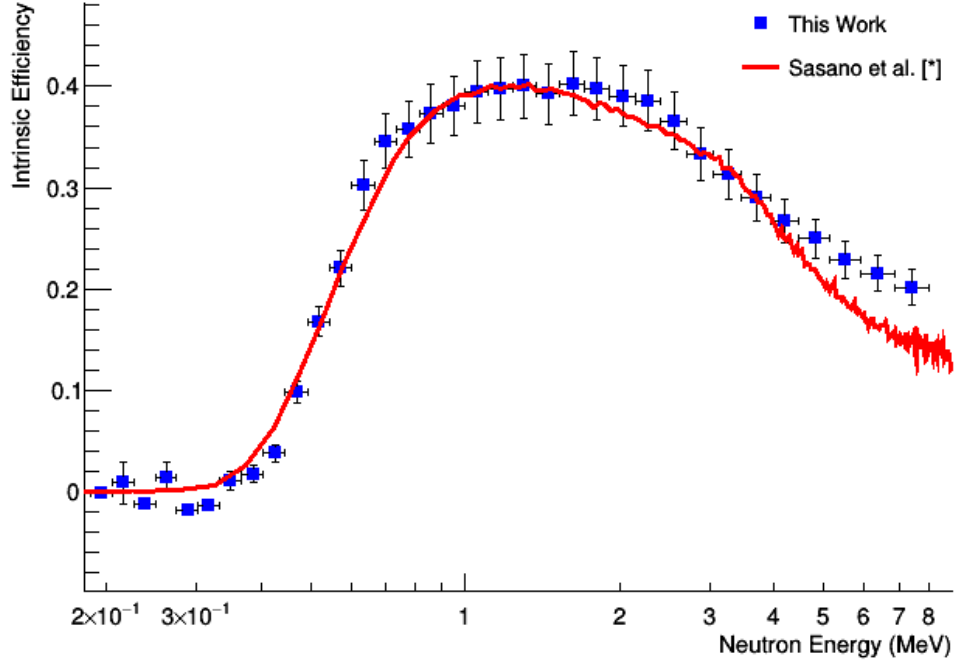


Figure 4.13: Intrinsic neutron detection efficiency of a NE-213 (Eljen [13] EJ-301) liquid scintillator detector with a light response threshold of 60 keVee . This measurement is compared to that of M. Sasano et al. [14, 15]. Data from this work are scaled by the factor $C = 4.1 \times 10^9$ where C is the normalization factor in Equation 4.6.

$$C = A \frac{2}{\sqrt{\pi b a^3}} e^{-ab/4}, \quad (4.7)$$

is used and A is related to the activity of the source. Only the normalization constant C is undetermined at this point. This normalization is computed by using a well-characterized reference detector. For this measurement a cylindrical metal can with diameter and height of 5.08 cm and filled with NE-213 (Eljen [13] EJ-301) liquid scintillator. This liquid scintillator was well characterized by M. Sasano et al. [14, 15]. The efficiency spectrum from that measurement is shown in Figure 4.13 and is compared to the current work.

The shape of the liquid scintillator efficiency with a light response threshold of 60 keVee is very similar to that of Sasano. The discrepancy at energies greater than approximately 4 MeV is due, primarily, to contamination from the γ -flash. Due to its small size, the liquid detector needs to be placed much closer to the source than the VANDLE bars in order to get a comparable number of statistics. The shorter flight-path compresses the higher energy neutrons closer to the γ -flash as discussed in Section 4.1.1. This makes the measurement for

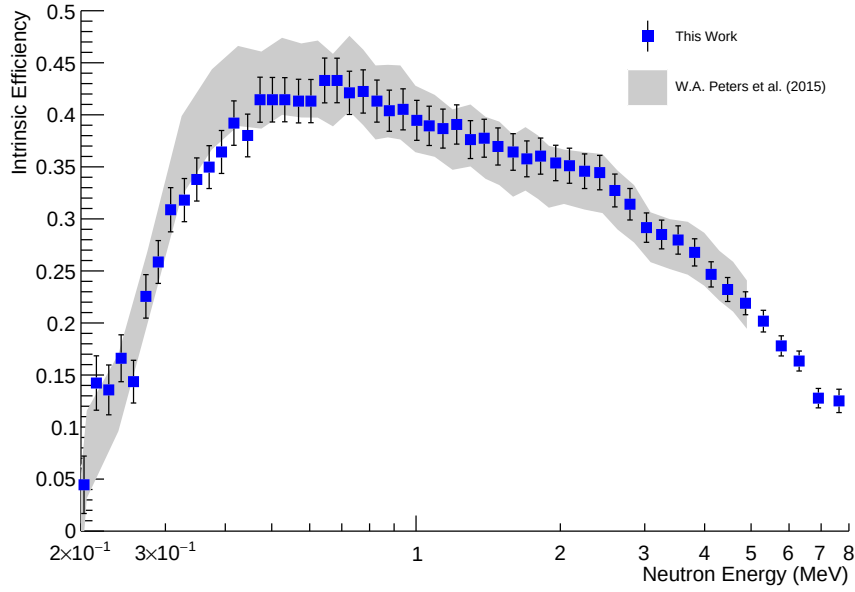


Figure 4.14: Intrinsic neutron detection efficiency of a small VANDLE bar with a light response threshold of 30 *keVee*. This measurement is compared to that of W.A. Peters et al. [16].

the liquid detector less reliable at higher neutron energies. The VANDLE bars exhibit less of this effect since they were approximately a factor of two further from the source.

In order to obtain the overall normalization, A is varied until the chi-squared differences between the data from literature and from the current measurement are minimized. For this measurement, a factor of $C = 4.1 \times 10^9$ was found to minimize the chi-squared differences. When this value of C is used for small VANDLE, the efficiency of the bar may be computed at various light response thresholds as shown in figures 4.14 and 4.15 for thresholds of 30 *keVee* and 60 *keVee* respectively.

As one might expect upon studying the relationship between VANDLE light response and neutron energy shown in Figure 4.11, increasing the light response threshold has a two-fold effect on the detector efficiency. The minimum neutron energy detection threshold is increased and the detection efficiency of neutrons at lower energies is decreased. The detection efficiency at higher energies remains largely unchanged for small changes in the light response threshold.

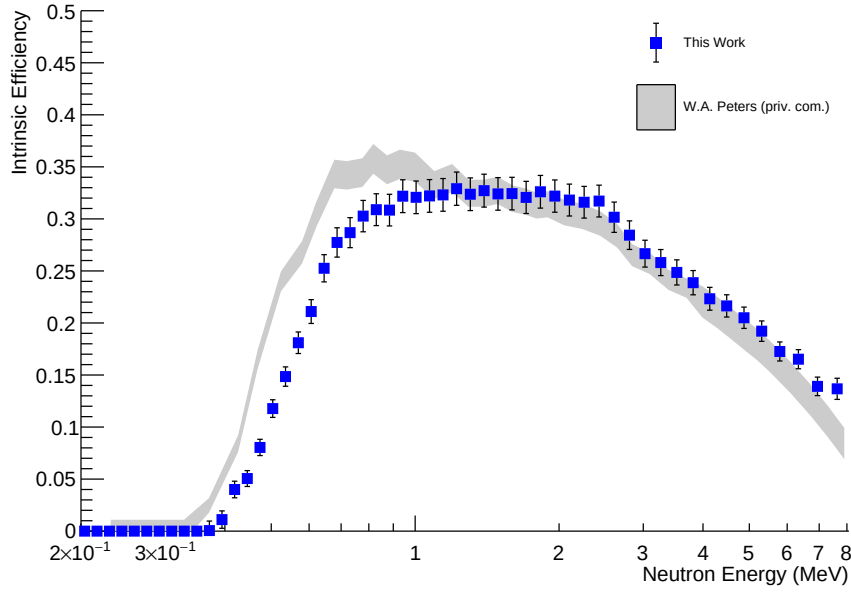


Figure 4.15: Intrinsic neutron detection efficiency of a small VANDLE bar with a light response threshold of 60 *keVee*. This measurement is compared to a previous measurement from a private communication from W.A. Peters.

In order to use the efficiency curves computed above, one must ensure that the same detector threshold is used. Since it is not practical to establish this limit using hardware thresholds for every detector before every measurement, the threshold is typically set using software later. During detector setup, the hardware threshold for each neutron detector is set slightly lower than this software cut-off.

4.3 Double-Ended Detectors

Single-ended detectors (i.e. those having only a single photo multiplier tube (PMT)) are fairly straight forward to analyze for a TOF experiment. If the thickness of the detector is small compared to the flight-path of the neutron, the TOF of the neutron is simply the arrival time of the neutron at the detector subtracted from the TOF start signal.

This is not the case for double-ended detectors (i.e. those having a PMT on both ends such as VANDLE). If the distance between the neutron detection point to each PMT is

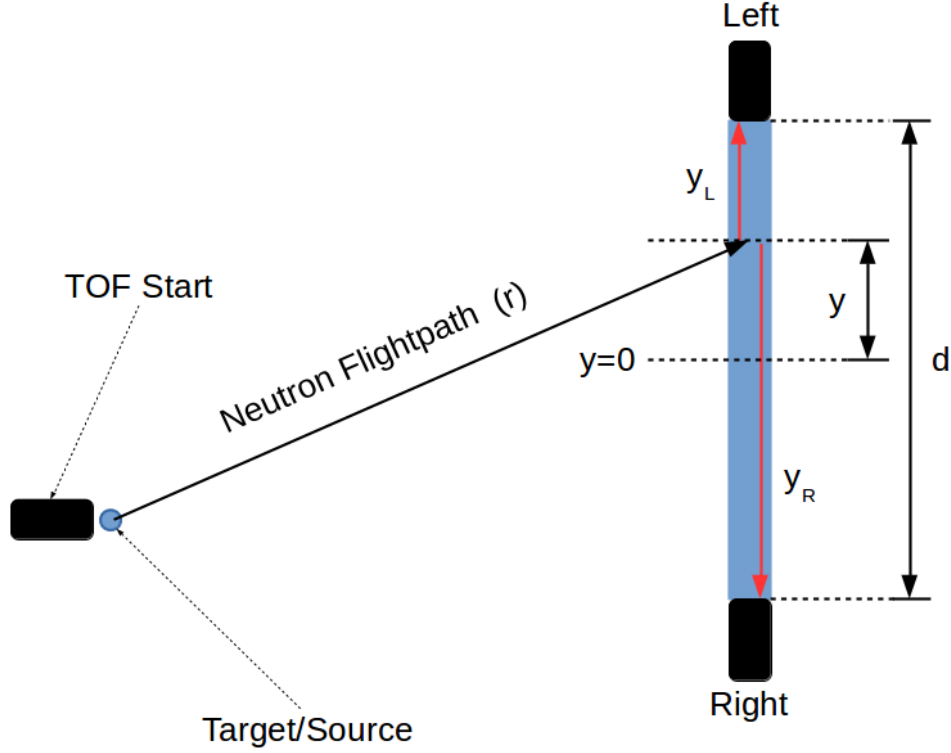


Figure 4.16: Typical TOF setup for a generic double-ended detector.

sufficiently far, the difference in the time of arrival of the scintillation light at both PMTs may be significant.

4.3.1 Detector Timing

Figure 4.16 shows a basic TOF setup with a double-ended detector of length d . Let r represent the neutron flight-path from the source or target to the scattering point inside the detector. By definition, the TOF is the time it takes the neutron to traverse distance r . The axial distance from the center of the detector to the scattering point is referred to here as the reconstructed position and is denoted y . The neutron source is assumed to be located at an arbitrary point in space and is not necessarily on the plane which bisects the center of the detector (shown here at $y = 0$). The distance from the scatter point to the left and right PMTs is denoted y_L and y_R respectively.

In terms of the variable y , the time taken between the neutron being emitted from the source and the scintillation light being detected at the left PMT is given by

$$t_L = TOF + \frac{(d/2) - y}{c_{det}} - T_{start}, \quad (4.8)$$

where TOF is the time-of-flight of the neutron to the scatter point, c_{det} is the speed of light inside the detector, and T_{start} is the high resolution time of the TOF start signal. Similarly, the time to the right PMT is given by

$$t_R = TOF + \frac{(d/2) + y}{c_{det}} - T_{start} \quad (4.9)$$

Taking the difference of these two equations gives

$$t_R - t_L = \Delta t = \frac{2y}{c_{det}}, \quad (4.10)$$

referred to here as the time-difference of the neutron detection event. Equation 4.10 shows the relationship between the position of the neutron event inside the detector and the speed-of-light in the detector. This Equation may also be used to compute the speed-of-light in the detector material. Taking the average of equations 4.8 and 4.9 gives the TOF of the neutron via the equation

$$TOF = \frac{t_R + t_L}{2} - \frac{d}{2c_{det}} - T_{start} \quad (4.11)$$

The TOF of the neutron computed using Equation 4.11 will have some inherent offset dependent upon the time offset of each individual channel of the digitizer. In order for the neutron energy to be computed from the TOF, this time offset must first be corrected.

Typically, the time offset is computed using what is known as the γ -ray flash (as shown in Figure 4.17). The γ -flash represents γ -rays that travel directly from the source, or target, into the detector. Because of this, the γ -flash represents the absolute fastest time which may be recorded by the detector for a given setup. Any time recorded before the flash is non-physical because it represents a particle moving faster than the speed of light, one that originated from a source closer to the detector, or one which was part of a previous event.

Correcting the neutron TOF spectrum requires aligning the γ -flash to the time taken for a particle moving at the speed-of-light to move from the source or target to the detector.

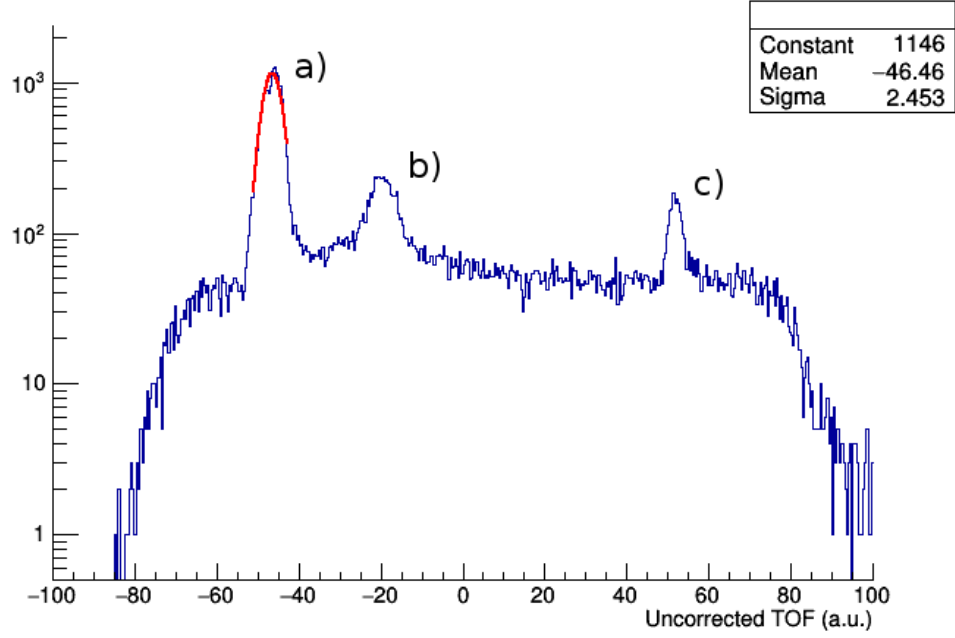
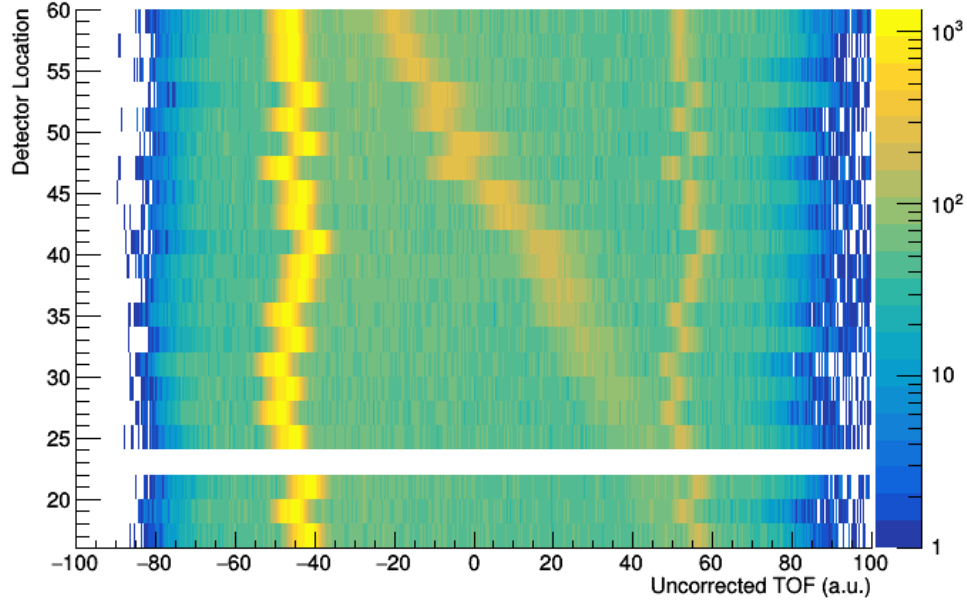


Figure 4.17: Uncorrected TOF spectrum for a small VANDLE bar showing a neutron spectrum from the reaction $d(^{12}\text{C}, n)$. a) The γ -flash from the deuterated target is fit using a Gaussian distribution, b) Neutrons from proton transfer into the ground state of ^{13}N , c) Following γ -flash from the next beam packet. A similar TOF spectrum is shown in Figure 3.15.

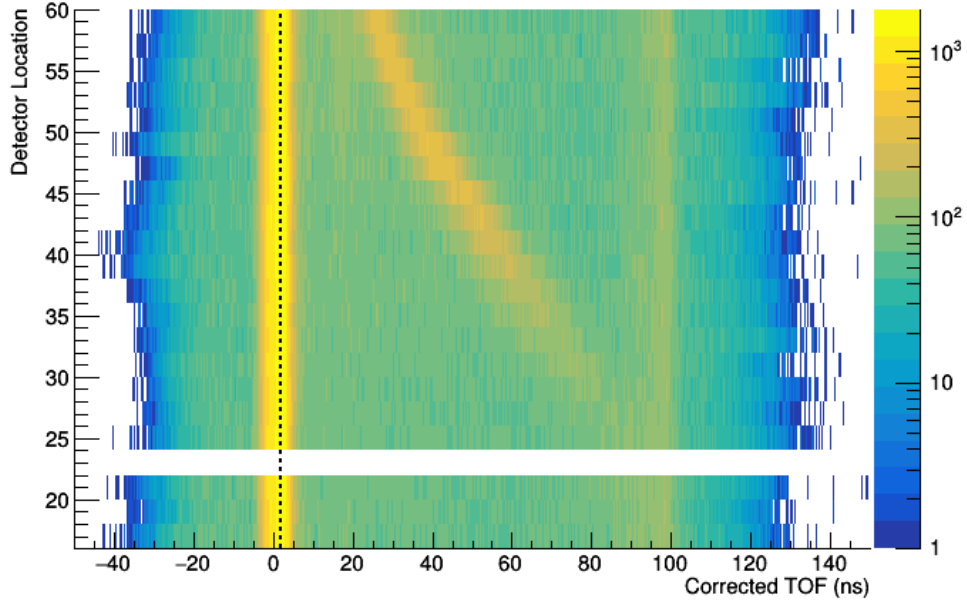
This process will be referred to as time-alignment. In Equation 4.11, the term $\frac{d}{2c_{det}}$ is a constant and may be ignored since a constant factor will not affect the time offset of the γ -flash in the TOF spectrum. So, one may rewrite the neutron TOF as

$$TOF = \frac{t_R + t_L}{2} - T_{start} - T_{flash}, \quad (4.12)$$

where T_{flash} is the γ -flash offset (in ns). This term may be computed by fitting the γ -flash peak with a Gaussian distribution as demonstrated in Figure 4.17. This correction must be performed for each detector in the setup because all will have slightly different time offsets as shown in Figure 4.18a. The result of this correction is shown in Figure 4.18b.



(a) Uncorrected neutron TOF spectrum



(b) Corrected neutron TOF spectrum

Figure 4.18: Uncorrected and corrected TOF spectra for a typical setup of 21 small VANDLE bars showing neutron spectra from the reaction $d(^{12}\text{C}, n)$ in inverse kinematics with a beam energy of 18.5 MeV .

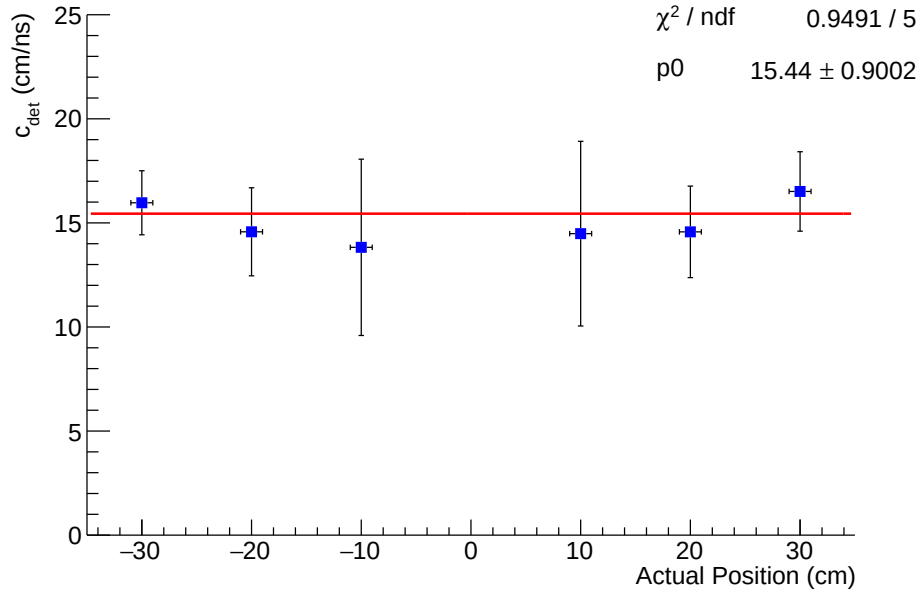


Figure 4.19: Speed of light for a small VANDLE bar calculated at various points along the surface of the detector. The TOF for a γ -ray travelling from the origin to the center of the detector is represented by the vertical dashed line in the corrected TOF spectrum. The average of the six points is shown by the horizontal red line.

4.3.2 Detector Speed of Light

Assuming that the interaction occurs along the axis of the detector and that the position inside the detector (y) is known, the speed-of-light inside the detector may be computed. Solving Equation 4.10 for the speed-of-light in the detector gives

$$c_{det} = \frac{2y}{\Delta t} \quad (4.13)$$

Figure 4.19 shows the calculated speed-of-light of a small VANDLE bar. For the position sensitivity test of that detector, a ^{90}Sr source was placed at various positions along the surface of the detector and the time differences between the two PMTs were recorded. Equation 4.13 was then used to compute the speed-of-light of the material at the different positions.

The average of the points in Figure 4.19 gives a speed-of-light of $c_{det} = 15.4 \pm 0.9 \text{ cm/ns}$ for the VANDLE bar used for the speed-of-light test. Once the speed-of-light for a given detector is known, Equation 4.10 may be used to calculate the reconstructed position of the

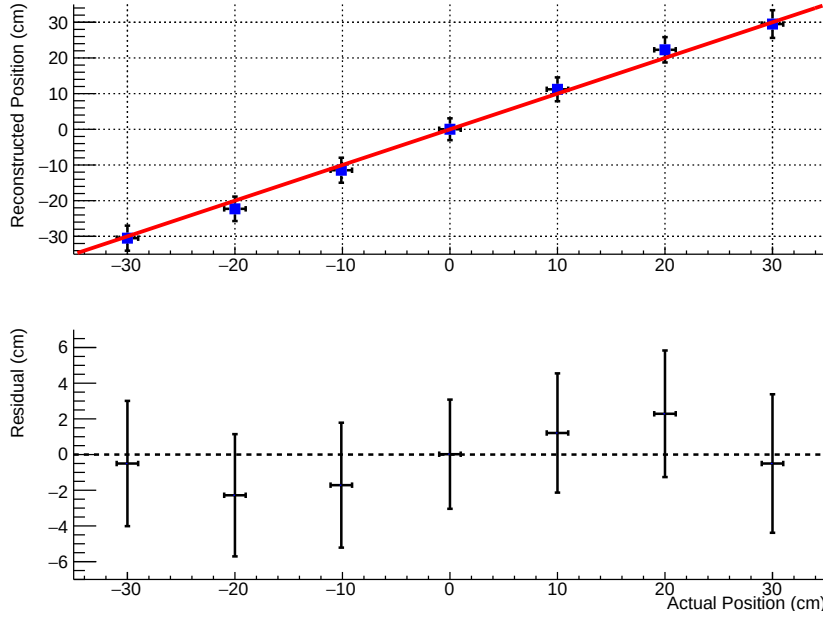


Figure 4.20: Position reconstruction using time difference of optical photon detection between both ends of a small VANDLE bar as a function of actual position. The solid red line has a slope equal to one. The residuals shown are the differences between the reconstructed position and the actual position.

interaction inside the detector on an event-by-event basis. Figure 4.20 shows the performance of the position reconstruction for a small VANDLE bar.

4.3.3 Time Difference Offset

Whenever pixie modules are booted or have their timing parameters changed, the ADC clock of each channel will have a random time offset. This means that the arrival time of each channel may be offset by as much as ± 8 ns from one another (for a 250 MSPS Pixie-16 module). So every time the system is rebooted, or the timing parameters are changed, the time offsets between the left and right PMTs of every double-sided detector will need to be recalculated.

Figure 4.21 shows the calibrated light response of a typical VANDLE bar as a function of the time differences between the left and right PMTs. Figure 4.22 shows the time difference spectrum for a threshold of 59.5 keVee.

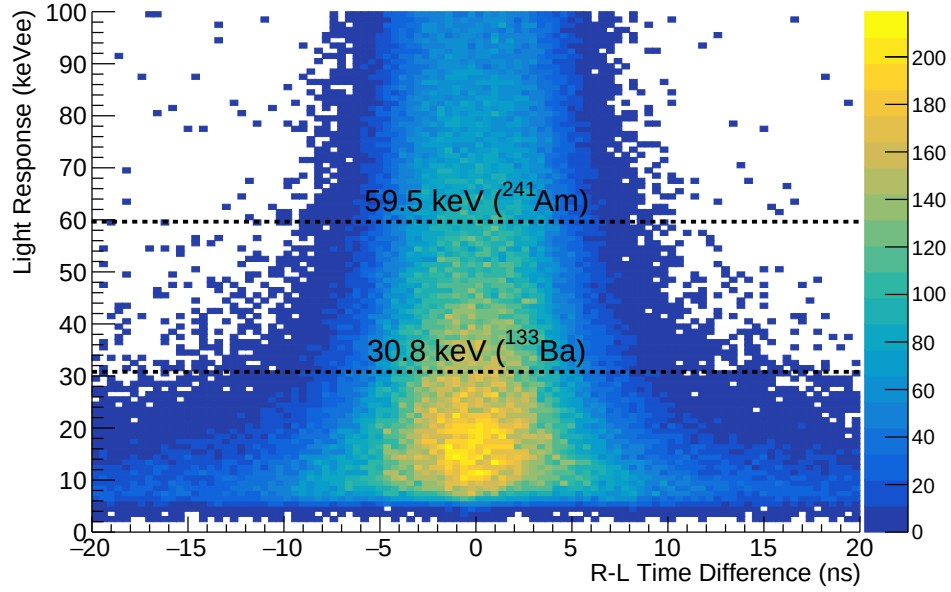


Figure 4.21: Calibrated VANDLE light response as a function of the time difference between the right and left PMTs. Horizontal dashed lines are included to indicate light response thresholds corresponding to 30.8 *keVee* (^{133}Ba) and 59.5 *keVee* (^{241}Am).

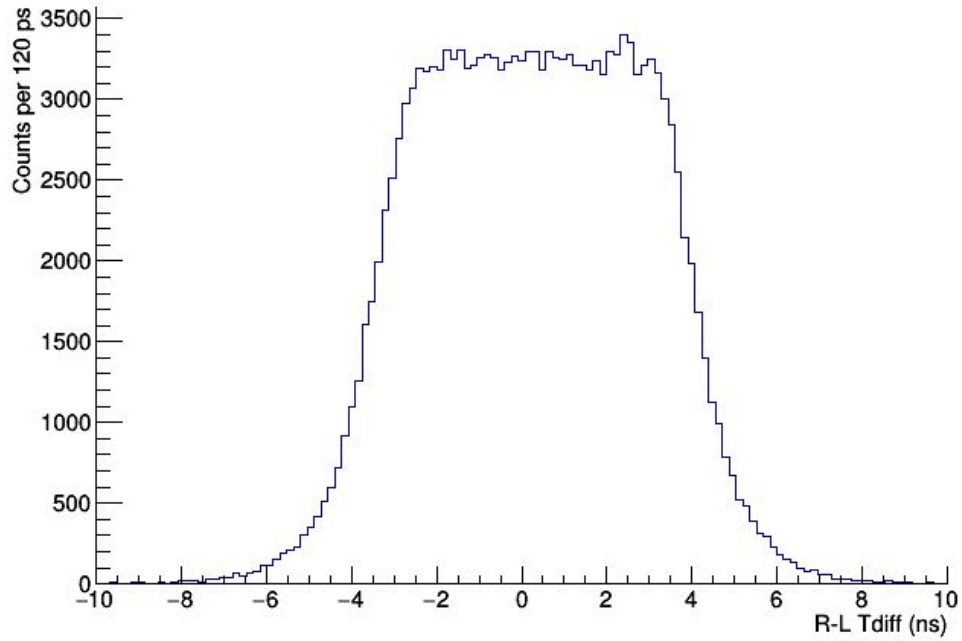


Figure 4.22: Typical time-difference spectrum for a small VANDLE bar with a threshold of 59.5 *keVee*.

Table 4.2: Double Woods-Saxon time-difference fit results.

Parameter	Value
V_0	1646
β	7.848 <i>ns</i>
T_0	0.2827 <i>ns</i>
a	0.494
b	0.427

The left and right sides of the time-difference distribution are described relatively well by the Woods-Saxon distribution

$$V(r) = -\frac{V_0}{1 + e^{(r-R)/a}}, \quad (4.14)$$

where V_0 is the depth, R is the radius, and a is the diffuseness. Rewriting in terms of the time-difference gives

$$V_{left}(\Delta t) = -V_0 \left[\frac{1}{1 + e^{\frac{\Delta t + \beta/2 - T_0}{a}}} - 1 \right], \quad (4.15)$$

for the left side (negative time) and

$$V_{right}(\Delta t) = \frac{V_0}{1 + e^{\frac{\Delta t - \beta/2 - T_0}{b}}}, \quad (4.16)$$

for the right side (positive time). In both Equation 4.15 and 4.16, V_0 is the height at the center of the time-difference spectrum, β is the FWHM of the spectrum, T_0 is the time offset at the center, and a and b modify the steepness of the left and right sides respectively. The full potential is given by

$$V(\Delta t) = \begin{cases} V_{left}(\Delta t) & \text{if } \Delta t < T_0 \\ V_{right}(\Delta t) & \text{if } \Delta t \geq T_0 \end{cases} \quad (4.17)$$

Figure 4.23 shows the results of fitting the time-difference spectrum from Figure 4.22 with Equation 4.17. The resulting fit parameters are summarized in Table 4.2. Solving Equation 4.10 for the axial detector position gives

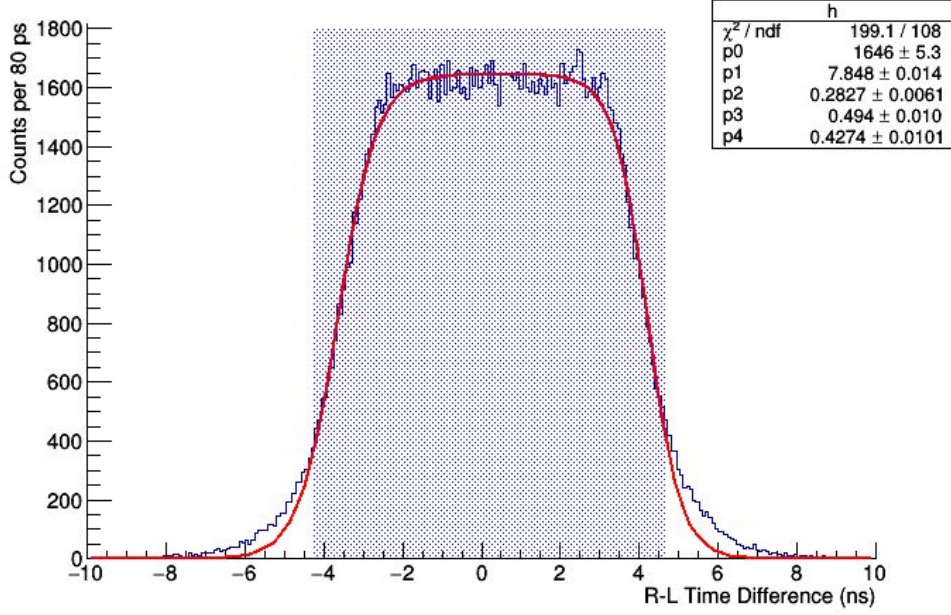


Figure 4.23: Typical PMT time-difference spectrum for a small VANDLE bar with a threshold of 59.5 keV overlaid with a fitted double Woods-Saxon distribution (shown in red). The shaded box represents the range used for the fit.

$$y(\Delta t) = \frac{1}{2} c_{det} \Delta t \quad (4.18)$$

So at the center of the detector, $y = 0$ and thus Δt must also equal zero. This time calibration must be done for each detector pair in the system before the axial position may be calculated. The time offset between the left and right channels in this case was $T_0 = 0.2827 \text{ ns}$. It turns out that the time-difference offset does not affect the calculation of the neutron TOF (Equation 4.11). To show this let $t_R \rightarrow t_R - T_0/2$ and $t_L \rightarrow t_L + T_0/2$ such that Equation 4.10 becomes

$$\Delta t = t_R - t_L \Rightarrow \Delta t' = t_R - t_L - T_0 \quad (4.19)$$

When averaging the time-differences of the left and right PMTs, the negative and positive $T_0/2$ terms cancel leaving only Equation 4.11. Similarly, Equation 4.18 becomes

$$y(\Delta t) = \frac{1}{2} c_{det} (t_R - t_L - T_0) \quad (4.20)$$

Using Equation 4.13, it is possible to compute the speed-of-light in the bar detector given the total width of the time-difference spectrum. There is some ambiguity in what the width of the spectrum should be defined as. If, for simplicity, the FWHM is used as the width of the distribution, then the physical length of the detector should correspond with this time width. Table 4.2 shows that the FWHM of the distribution is 7.848 ns . Using this value in Equation 4.13 gives a value for the speed-of-light of $c_{det} = 15.3\text{ cm/ns}$ for this particular VANDLE bar with a length of 60 cm .

The top plot of Figure 4.24 shows the detector speed-of-light for VANDLE bar ID number 12, calculated using Equation 4.20, as a function of experimental run while the bottom shows the speed-of-light for each VANDLE bar averaged over all experimental runs. The error bars in the bottom plot are equal to the maximum deviation from the mean speed-of-light for each detector. With the exception of detector number 22, the speed-of-light of each VANDLE bar calculated using Equation 4.20 is very consistent over all experimental runs. Possible causes for the large discrepancy between the first twenty detectors and detector number 22 are slight differences in the plastic manufacturing (i.e. different production runs) as well as differences in detector construction.

Once c_{det} has been calculated for each detector, Equation 4.20 may be used to compute the axial position in the bar detector. The result of this calculation using the time-difference spectrum in Figure 4.22 is shown in Figure 4.25.

4.3.4 Bar Position Resolution

Equation 4.20 may be used to compute the axial position of a neutron on an event by event basis. However, since the system has a non-zero time resolution, the reconstructed position will also exhibit a finite resolution. To demonstrate this, one may position a γ -ray source at various positions along the surface of the bar detector and measure the time difference between the two PMTs.

Figure 4.26 was created using this process. The PMT time difference ($t_R - t_L$) of a small VANDLE bar is shown along the x-axis. A source of ^{90}Sr was used for this test and was placed at distances of 0 cm to 60 cm from the PMT designated as the “left” in increments of

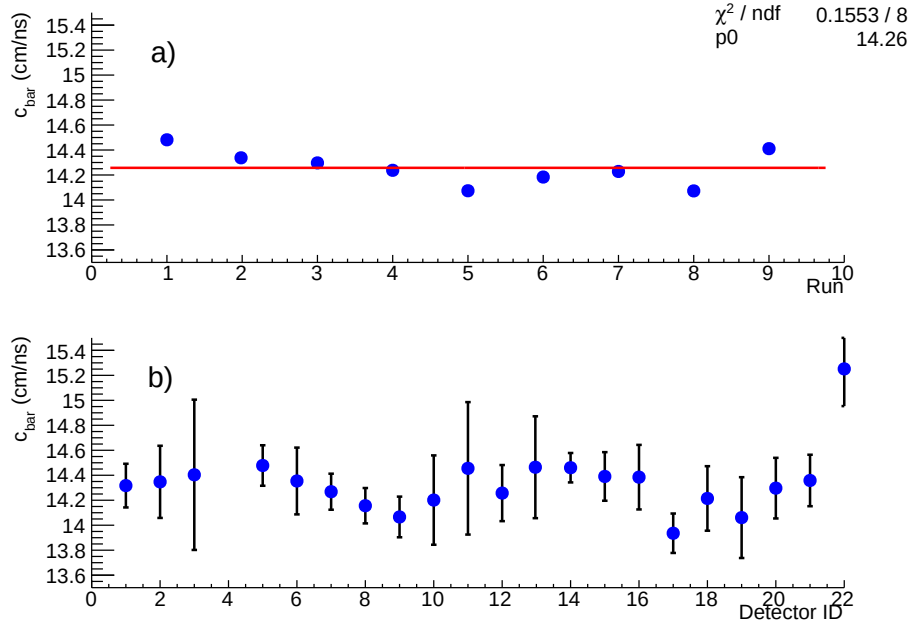


Figure 4.24: (a) VANDLE detector speed-of-light for a typical bar, ID number 12 in this case, calculated using Equation 4.20. (b) speed-of-light for each VANDLE bar averaged over all runs. The error bars are equal to the maximum deviation from the mean speed-of-light for each detector.

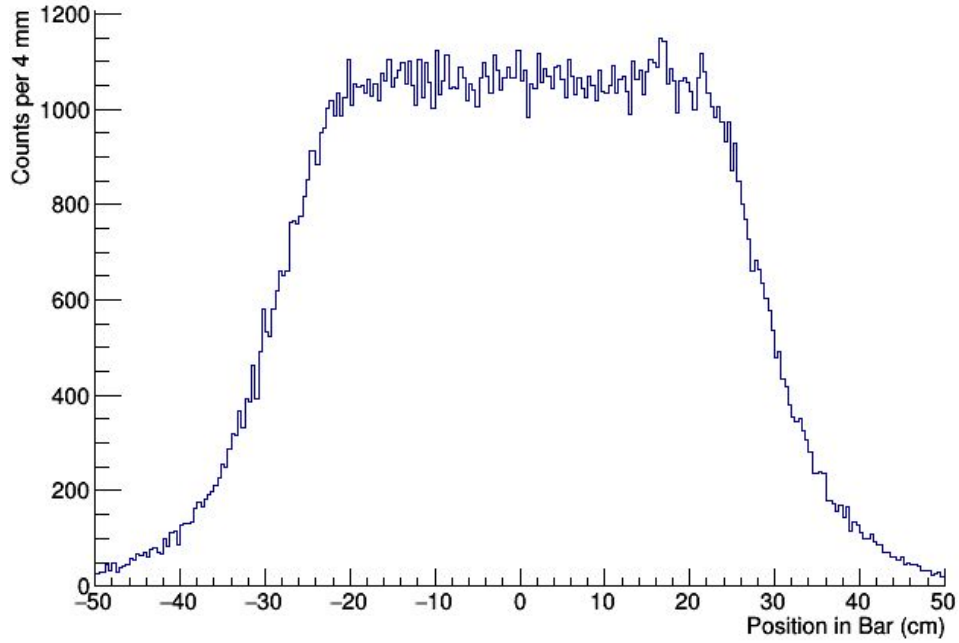


Figure 4.25: Typical position spectrum for a small VANDLE bar with a light response threshold of 60 keVee.

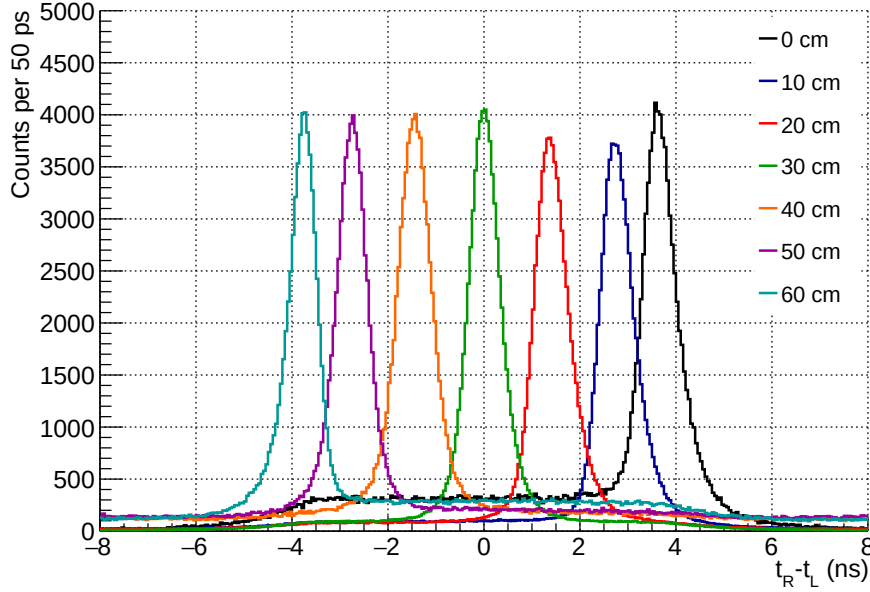


Figure 4.26: PMT time difference ($t_R - t_L$) of a small VANDLE bar for a ^{90}Sr source placed at distances of 0 *cm* to 60 *cm* from the “left” PMT in 10 *cm* steps.

10 *cm*. Note that $t_R - t_L$ is negative when the source is closer to the right PMT and positive when closer to the left.

The results of fitting all seven time difference spectra in Figure 4.26 with a Gaussian on a constant background is shown in Figure 4.27. The slope of the line taken from the fit is $7.8 \pm 0.5 \text{ cm/ns}$. By Equation 4.18, two times the slope of the line is equal to the speed-of-light in the detector and, in this case, is $15.6 \pm 1.0 \text{ cm/ns}$. This value agrees within error with the value of 15.3 cm/ns computed in Section 4.3.3, using an independent measurement, detector, and method.

The sigma of the Gaussian fits may be used to compute the position resolution of the small VANDLE bar. For the seven time difference peaks shown in Figure 4.26, the average FWHM position resolution is approximately 7 *cm*, or just over 11% of the length of the bar. The position resolution is directly related to the time resolution. Improving the time resolution of the detector system will also improve the position resolution proportionally.

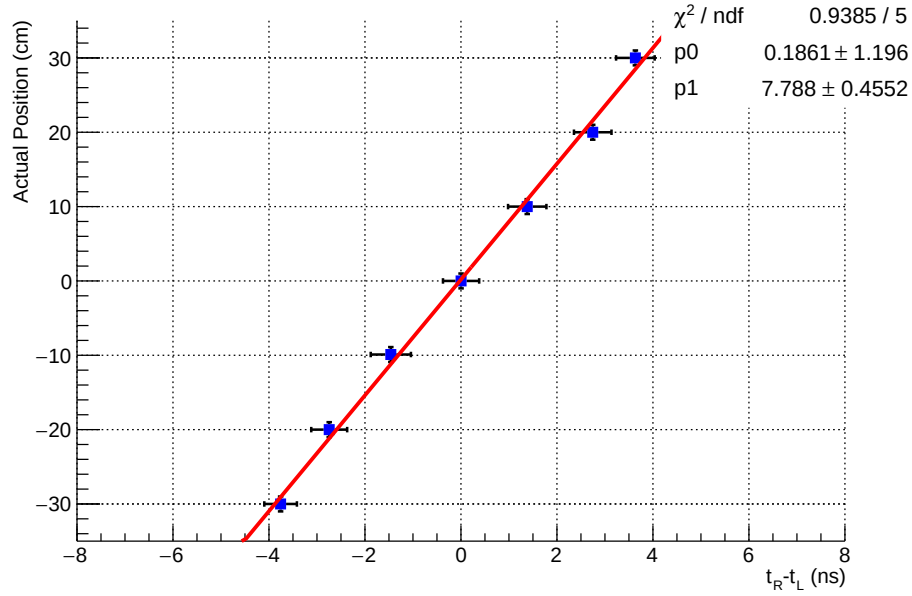


Figure 4.27: Position of a ^{90}Sr source placed along the surface of a small VANDLE bar versus PMT time difference ($t_R - t_L$). A fit to a first-order polynomial is shown. A constant uncertainty of $\pm 1 \text{ cm}$ is used for the x-axis errors and the FWHM position resolution is used for the y-axis errors.

4.3.5 Changing Coordinate Systems

Due to their construction, VANDLE bars are naturally suited to the cylindrical coordinate system and are usually implemented in a barrel configuration. If the position of the center of the bar is known, the time difference between the left and right PMTs may be used to compute the three cylindrical coordinates r , ϕ , and y and the neutron TOF, t . The angle about the vertical axis is denoted ϕ and y is the distance from the origin along the vertical axis. This coordinate system is fine for cases where the polar angle of a neutron detection event in three-dimensional space is not required (e.g. neutron counting experiments).

For experiments where the polar angle of an event is needed, such as experiments where angular distributions will be measured, the cylindrical coordinates need to be converted to spherical coordinates. This is shown in Figure 4.28 where the axial position along vertical VANDLE bars is plotted as a function of polar angle in the laboratory frame. As detectors approach 180° , each detector covers a larger range of polar angles along its length. Detectors nearer to 90° exhibit less of this effect.

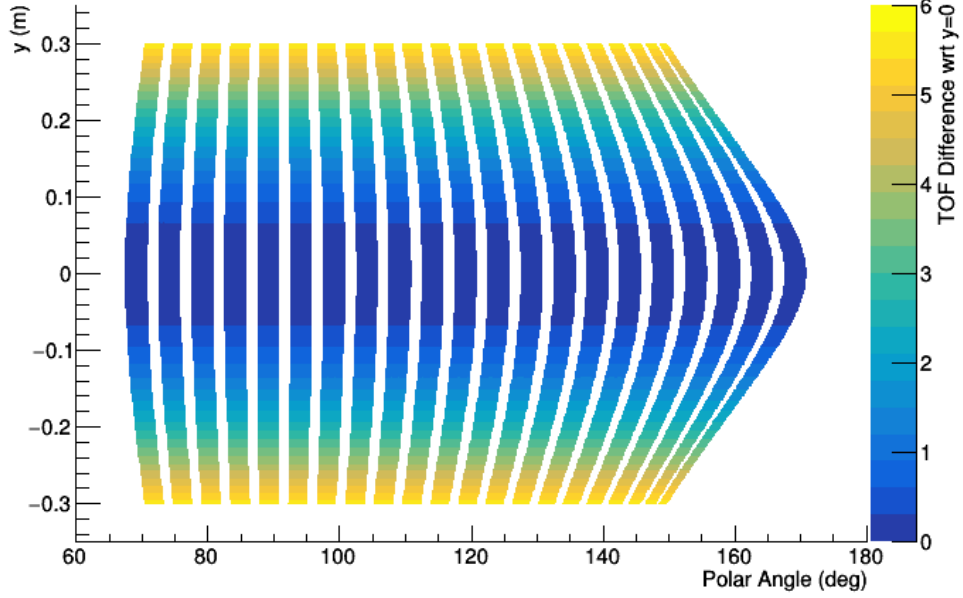


Figure 4.28: Plot of VANDLE axial position y vs. polar angle in the laboratory frame. The color scale shows the difference in neutron TOF (in ns) from the center of the detector at $y = 0\text{ m}$ assuming an isotropic source of 1 MeV neutrons and small VANDLE bars located at a distance of 0.5 m .

In terms of the known cylindrical coordinates t , r , ϕ , and y , the spherical coordinates of the event may be computed using the formulae

$$\begin{aligned}
 t' &= t \\
 r' &= r \\
 \theta' &= \tan^{-1} \left(\frac{r^2 + y^2}{y} \right) \\
 \phi' &= \phi
 \end{aligned} \tag{4.21}$$

Typically, researchers are interested in the angular distribution of a reaction as a function of the polar angle θ . In those cases, it is assumed that the reaction cross-section does not vary as a function of the azimuthal angle ϕ . This assumption greatly reduces the complexity of the (d, n) cross-section given by Equation 3.8, making it easier to evaluate experimentally.

Additionally, it is convenient to take advantage of the conversion to spherical coordinates to remove the dependence upon the radius of the event from the neutron TOF. This

dependence is shown for a Monte Carlo simulation in Figure 4.28 wherein the difference in TOFs between the center of the bar and the ends is shown as a function of axial position and polar angle. For 60 *cm* long small VANDLE bars placed vertically at a distance of 0.5 *m* from an isotropic source of 1 *MeV* of neutrons, the TOF varies by as much as 6 *ns* along the full length of the bars.

The process of transforming a neutron event from the cylindrical to the spherical frame essentially scales the TOF such that the event lies on a sphere of radius r_0 i.e. the distance from the origin to the center of the detector. Since the cross-section depends upon center-of-mass energy and polar angle, the energy of the neutron must remain fixed. So

$$E' = E \Rightarrow \frac{M_\nu r^2}{2t^2} = \frac{M_\nu r_0^2}{2t'^2} \Rightarrow t' = \frac{r_0}{r}t, \quad (4.22)$$

where, generally, the distance from the neutron source to the center of the bar is used for r_0 such that at the center of the bar, the TOF correction is equal to one. So for the special case of a neutron detection sphere of radius r_0 with azimuthal symmetry, equations 4.21 become

$$\begin{aligned} t' &= \frac{r_0}{r}t \\ r' &= r_0 \\ \theta' &= \tan^{-1} \left(\frac{r^2 + y^2}{y} \right) \end{aligned}, \quad (4.23)$$

where the azimuthal angle ϕ is not needed and is ignored. Performing these operations on an event-by-event basis is the equivalent of mapping a cylinder onto a sphere of radius r_0 . This frame conversion is shown in Figure 4.29 for a Monte Carlo simulation of 21 small VANDLE bars. The black points represent the intersection point of rays from the origin intersecting the front face of the bars. The red points show the intersection of those same rays with a sphere of radius 0.5 *m*.

The coordinate system transformation given in Equation 4.23 converts neutron events detected by an array of detector bars arranged in a cylindrical configuration to spherical

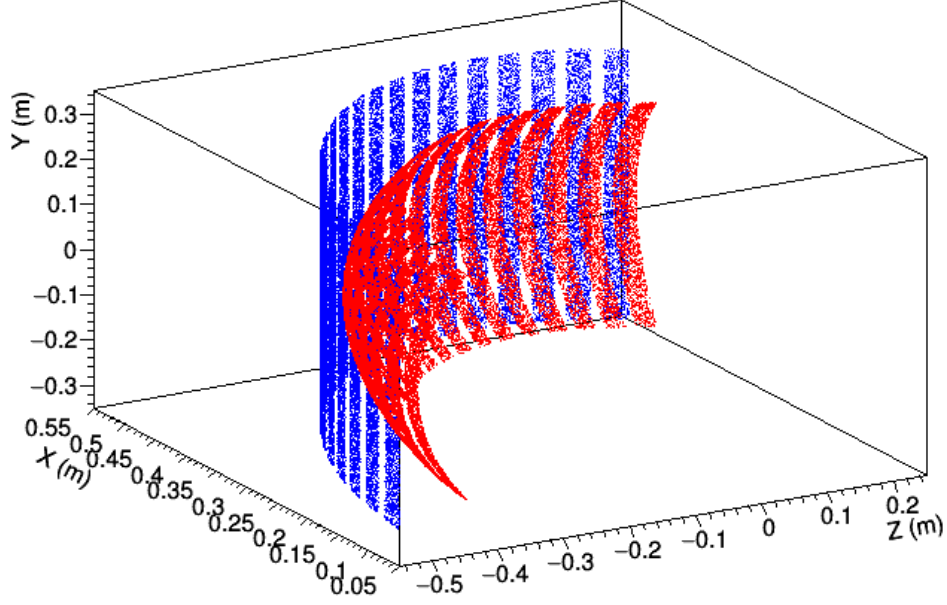


Figure 4.29: Monte Carlo points on the surface of 21 vertical small VANDLE bars located 0.5 m from an isotropic source (shown in blue) and the same points mapped to a sphere with radius 0.5 m (shown in red).

polar coordinates. Other more general coordinate transformations are possible but will not be discussed here.

Using the transformation given in Equation 4.23 and the axial position in Equation 4.18, the neutron TOF for a double-ended bar detector becomes

$$t' = r_0 \left[(t_R - t_L - T_0)^2 + r_0^2 \right]^{-1/2} t \quad (4.24)$$

In this notation, t is the neutron TOF given by Equation 4.11 so Equation 4.24 may be rewritten as the “corrected TOF”

$$TOF_{cor} = r_0 \left[(t_R - t_L - T_0)^2 + r_0^2 \right]^{-1/2} \left[\frac{t_R + t_L}{2} - T_{start} \right] + C, \quad (4.25)$$

where the constant term $\frac{d}{2c_{det}}$ is absorbed into the constant term C that may be used to set the detector time offset. This is typically done by aligning a known reference peak in the TOF spectrum (such as a γ -flash) with its actual value. This process must be done for each detector and is referred to as the detector time calibration or time alignment. Future

references to the neutron TOF will be synonymous with the corrected neutron TOF given by Equation 4.25.

4.4 Center-of-Mass Frame

The polar angle of a neutron detection event in the laboratory frame is heavily dependent upon the reaction kinematics. Because of this, differential cross-sections in literature are typically presented as a function of the center-of-mass (CM) angle instead of the laboratory angle.

In normal kinematics (i.e. light beam and heavy target), the polar angle of the neutron with respect to the beam axis is approximately equal to the center-of-mass (CM) angle of the reaction. When lighter beams and heavier targets are used, the laboratory angle of the neutron approaches the CM angle of the reaction. In inverse kinematics, this is no longer true. The conversion of the neutron polar angle between the laboratory frame and the CM frame is non-linear for that case.

Once the neutron detection event is in the spherical coordinate system, one may compute the CM angle on an event-by-event basis using the following equation [46],

$$\theta_{CM} = \tan^{-1} \left(\frac{\sin(\theta_{lab})}{\cos(\theta_{lab}) - V_{CM}/V} \right), \quad (4.26)$$

where θ_{lab} is the laboratory polar angle, V_{CM} is the velocity of the CM frame, and V is the velocity of the neutron in the laboratory frame. Each neutron CM angle may then be binned to eliminate the problem of single VANDLE detectors covering a large range of polar angles. This angular binning also allows the comparison between different angular distributions for different reactions and different beam energies as well as allowing direct comparison between those distributions measured in both inverse and normal kinematics.

4.5 TOF Spectrum Fitting

All that remains to compute the angular distribution for the (d, n) reaction is to calculate the number of reaction neutrons which are detected by VANDLE and inserting that value

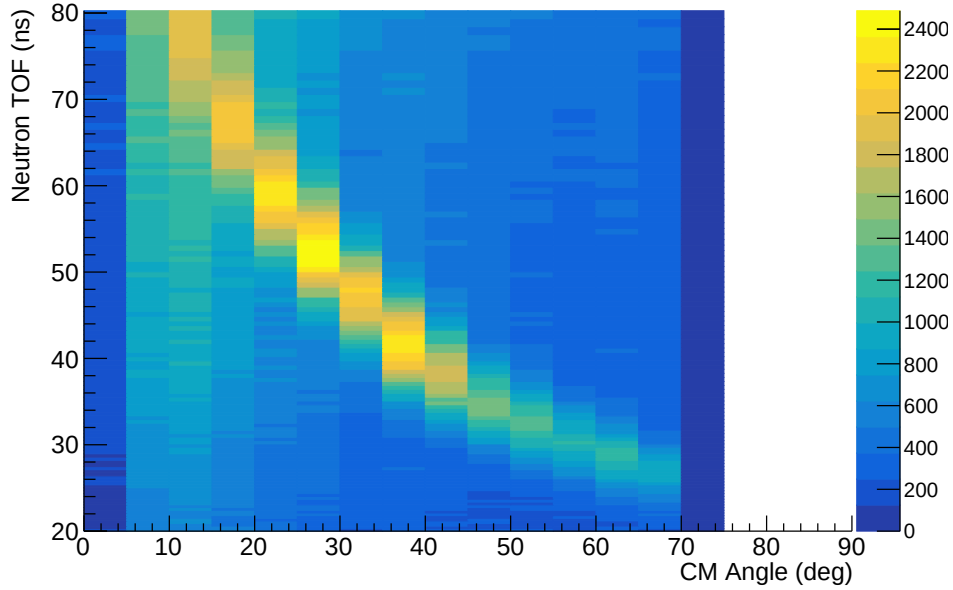


Figure 4.30: Neutron TOF versus CM angle for a $d(^{12}\text{C}, n)^{13}\text{N}$ measurement with a beam energy of $E_{^{12}\text{C}} = 18.5 \text{ MeV}$ ($E_d = 3.1 \text{ MeV}$). Events are placed into angle bins with a width of 5° in the CM frame.

(N_{det}) into Equation 3.8. Figure 4.30 shows the result of binning neutron TOF events, for a $d(^{12}\text{C}, n)$ measurement with a beam energy of $E_{^{12}\text{C}} = 18.5 \text{ MeV}$, by CM angle using Equation 4.26. Neutrons from the (d, n) reaction are placed into angular bins with a width of 5° in the CM frame. The neutron TOFs are placed into variable width bins based on the energy resolution of VANDLE at that energy. A strong neutron kinematic line is visible representing the population of the ground state of ^{13}N . The first excited state is not visible in this case because its kinematic curve only extends to about 5.8° in the laboratory frame at this energy.

If the width of the angular bins are selected carefully, the resulting projections will exhibit neutron peaks that are approximately Gaussian in shape. Figure 4.31 shows a projection in neutron TOF for CM angles of 30° to 35° or approximately 100° to 106.5° in the laboratory frame. The neutron peak is fit by a Gaussian distribution on a second order polynomial background shown by the green and magenta lines in Figure 4.31.

The number of detected neutrons (N_{det}) for this angular bin is computed by summing the number of counts under the Gaussian peak from the fit. This is not simply equal to the

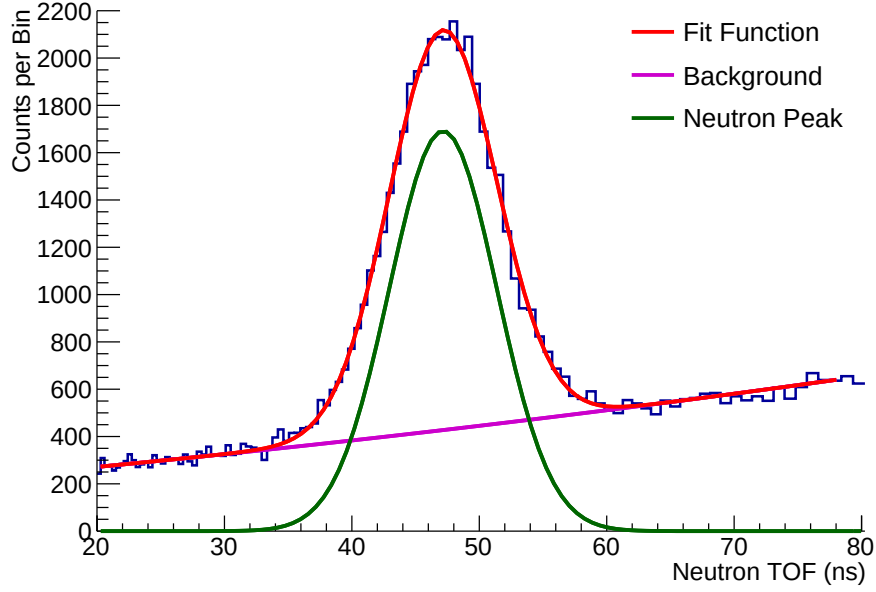


Figure 4.31: Neutron TOF spectrum for a $d(^{12}\text{C}, n)^{13}\text{N}$ measurement with a beam energy of $E_{^{12}\text{C}} = 18.5 \text{ MeV}$ ($E_d = 3.1 \text{ MeV}$) between CM angles of 30° and 35° or approximately 100° and 106.5° in the laboratory frame.

integral of the fit function which gives the area under the peak. The width of the variable bins in neutron TOF will change the shape of the fit function and, in turn, its integral. It should not, however, change the total number of neutron counts under the peak. So the number of counts under the curve is calculated by summing the average of the fit function, $f(t)$, over each TOF interval using

$$N_{det} = \sum_i \frac{1}{(b_i - a_i)} \int_{a_i}^{b_i} f(t) dt \quad (4.27)$$

where i is over all bins in the spectrum and a_i and b_i are the lower and upper limits of TOF bin i respectively. This ensures that the resultant N_{det} is independent of the shape of the fit function and will not change if the TOF binning is changed.

Chapter 5

Experimental Results

Angular distributions of neutrons following (d, n) reactions performed in inverse kinematics using stable beams of ^{12}C at eight beam energies and a single energy beam of ^{16}O will be presented in this chapter. Results will be compared to previous experimental measurements, where available, as well as theoretical calculations. Additional discussion will be given on the possible improvements for performing (d, n) measurements in inverse kinematics with radioactive ion beams (RIBs) and on possibilities for future work.

These measurements were performed in inverse kinematics, so the beam energies would normally be quoted as the energy of the heavy projectile. Since the results are intended to be compared to previous measurements in normal kinematics, all energies will be listed here as “equivalent deuteron” energies (i.e. the energy of the deuteron in normal kinematics). The conversion from ^{12}C energy to the equivalent deuteron energy is given by

$$E_d = \frac{m_d}{m_{^{12}\text{C}}} E_{^{12}\text{C}}, \quad (5.1)$$

where m_d is the mass of the deuteron and $m_{^{12}\text{C}}$ and $E_{^{12}\text{C}}$ are the mass and energy of the ^{12}C projectile.

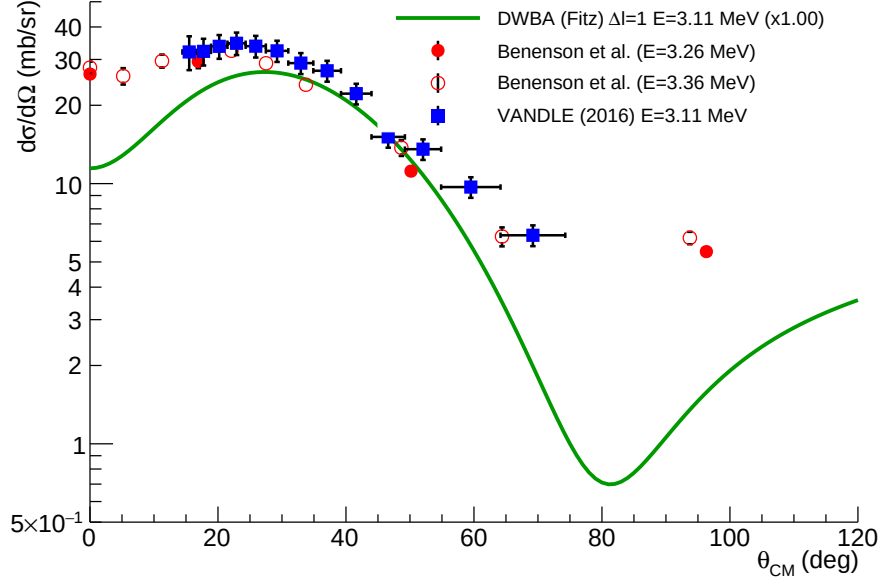


Figure 5.1: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 3.105 MeV ($E_{^{12}\text{C}} = 18.50 \text{ MeV}$). Current results are compared to previous results from R.E. Benenson et al. [7]

5.1 Transfer on Carbon-12

5.1.1 $E=3.1 \text{ MeV}$

Figure 5.1 shows the angular distribution for the population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ for an equivalent deuteron energy of 3.1 MeV . The current measurement (blue), agrees well with the measurement by R.E. Benenson et al. [7] at similar deuteron bombardment energies of 3.26 MeV (red, filled) and 3.36 MeV (red, open) at all angles measured.

The DWBA calculation presented in Figure 5.1 underpredicts the (d,n) angular distribution of both the current work and that of Benenson et al. [7] near 0° and 90° . These discrepancies between calculations of the direct reaction and experiment may be due to compound-nuclear (CN) contributions (^{14}N in this case) [53]. CN effects occur on time scales which are much longer than those of direct reactions. The time scales are of sufficient length that all nucleons have time to equilibrate. This effect is shown by relatively flat and featureless angular distributions which may smooth out the features of the direct component.

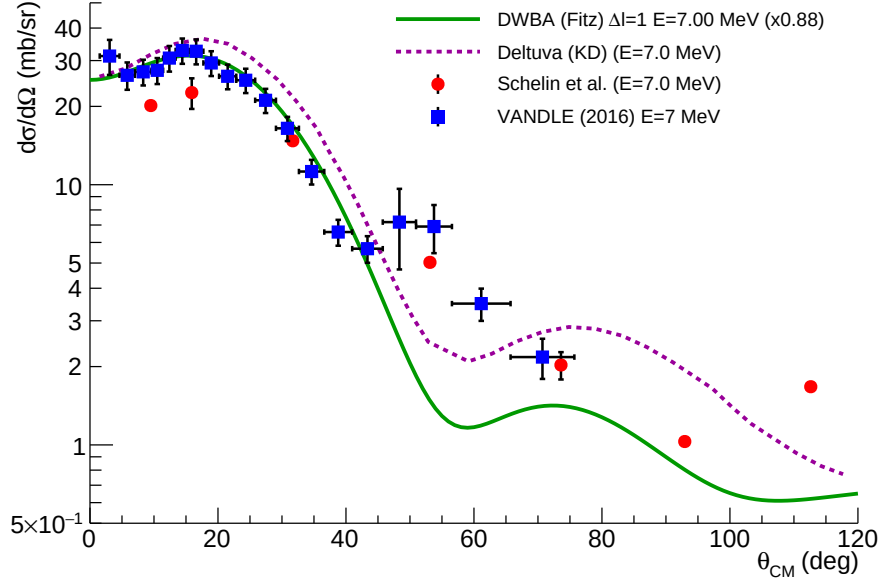
Figure 2.1 shows how calculations of the total neutron scattering cross-section on light nuclei disagree with experimental data when the bombardment energy is decreased to a few MeV. This is the region where large amplitude neutron resonances of the compound-nucleus start to dominate the scattering cross-section and CN effects play an important role. When using DWBA, where only one-step direct components are accounted for, calculations only provide the direct component of the cross-section and do not include resonant components which may be significant at these energies [8].

5.1.2 E=7.0 MeV

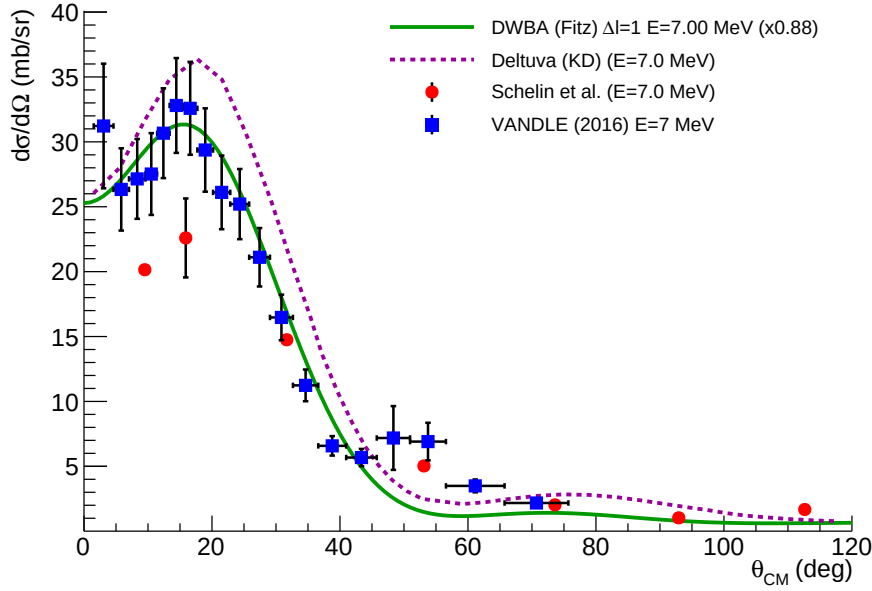
Figure 5.2 shows the population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ for an equivalent deuteron energy of 7.0 MeV. The current measurement (shown in blue), agrees very well with an exact Faddeev three-body calculation performed by A. Deltuva [10] (magenta, dotted) as well as a DWBA calculation (green, solid) at small CM angles. At larger CM angles, these data agree better with H.R. Schelin [6] than with the theory prediction. It is important to note that both measurements do not support the presence of a prominent minimum at around 55° that is predicted in the theoretical calculation.

DWBA calculations, as performed typically, assume that the full single-proton strength of an orbital is concentrated in a single state. In reality, the single-proton strength is shared between various states and so DWBA calculations typically need to be scaled down to compare with experimental data. The Faddeev-AGS distributions by Deltuva may include fragmentation of strength, but do not for these calculations. Deltuva states that since core excitations are not taken into account, all nuclei are in single component states with a spectroscopic factor of one [10]. The DWBA calculation was scaled by a factor of 0.88 to compare with data.

Data from this measurement at 7.0 MeV are in good agreement with the measurement by Davis and Din [5] as shown in Figure 5.3. The distribution of Schelin et al. at 7.0 MeV is systematically lower than both Davis and the current measurement by approximately 30%.



(a) Logarithmic Scale



(b) Linear Scale

Figure 5.2: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d,n)$ with an equivalent deuteron energy of 7.0 MeV ($E_{^{12}\text{C}} = 41.70\text{ MeV}$). Current results are compared to previous results from H.R. Schelin et al. [6] and exact three-body Faddeev calculations using Koning-Delaroche optical model potential [8] as performed by A. Deltuva [10].

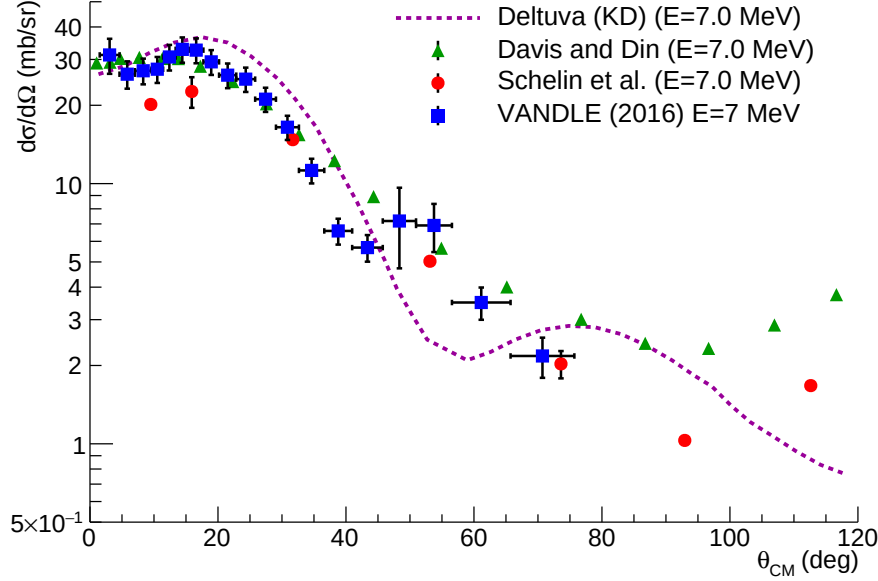


Figure 5.3: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d,n)$ with an equivalent deuteron energy of 7.0 MeV ($E_{^{12}\text{C}} = 41.70\text{ MeV}$). Current results (blue) are compared to previous results from H.R. Schelin et al. [6] (red) and J.R. Davis and G.U. Din [5] (green).

5.1.3 $E=3.9\text{ MeV}$ to 6.6 MeV

Proton transfer cross-sections corresponding to the population of the ground state of ^{13}N for deuteron bombardment energies between 3.9 MeV and 6.6 MeV are shown in Figures 5.4 to 5.9. The distributions start off relatively flat and featureless as does the distribution for $E_d = 3.1\text{ MeV}$ shown in Figure 5.1. As the deuteron energy is increased, the first minimum begins to become more pronounced as shown in Figures 5.6 through 5.9.

As no angular distributions from previous works exist at these energies, comparisons will be made to DWBA calculations using TWOFNR. The same optical model parameters from Fitz et al. [9] which are discussed in Section 2.4.1 are used for calculations at these energies. The calculations are displayed as the solid green line and are scaled by a scaling factor listed on the legend.

Figures 5.5 and 5.6 show the distributions for an equivalent deuteron energy of 4.7 MeV and 5.5 MeV respectively. Both have relatively good agreement with DWBA calculation and both have approximately the same shape and amplitude as is evident by their scaling

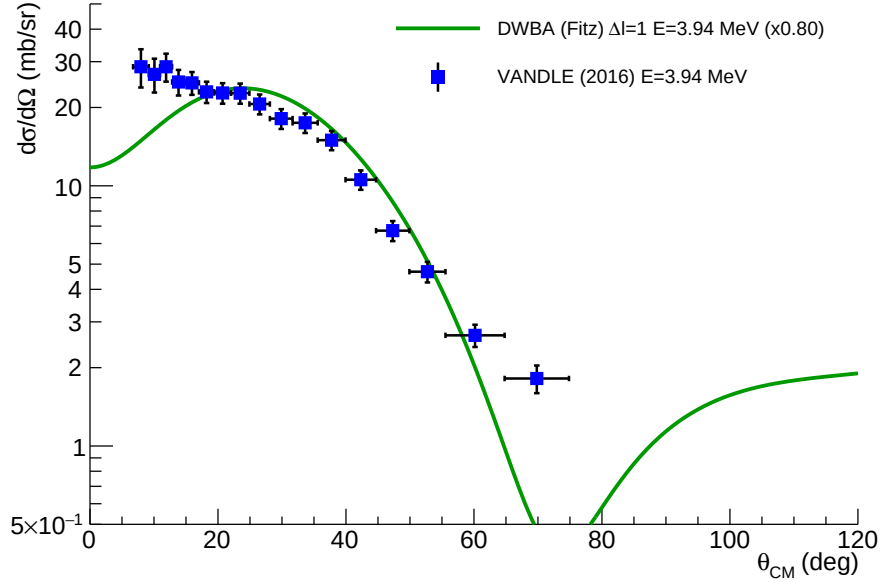


Figure 5.4: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 3.938 MeV ($E_{^{12}\text{C}} = 23.46 \text{ MeV}$).

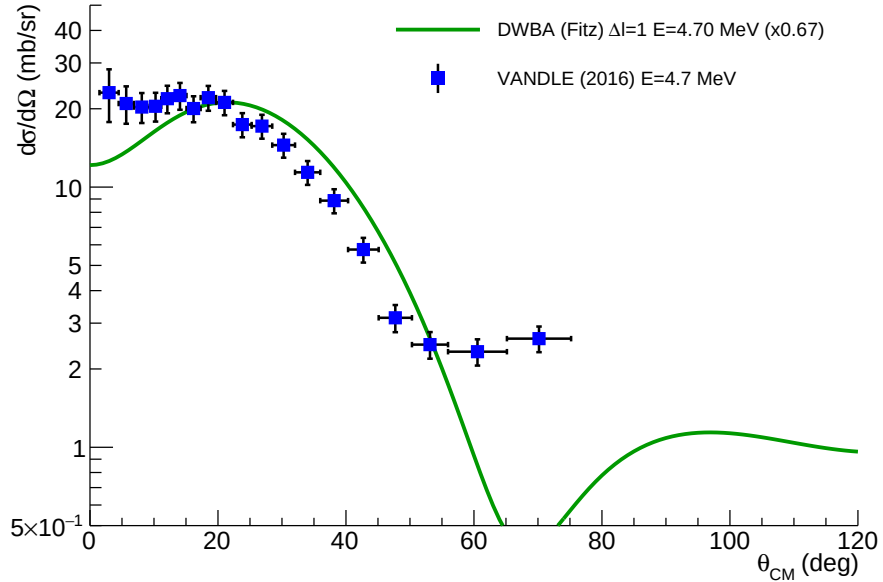


Figure 5.5: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 4.703 MeV ($E_{^{12}\text{C}} = 28.02 \text{ MeV}$).

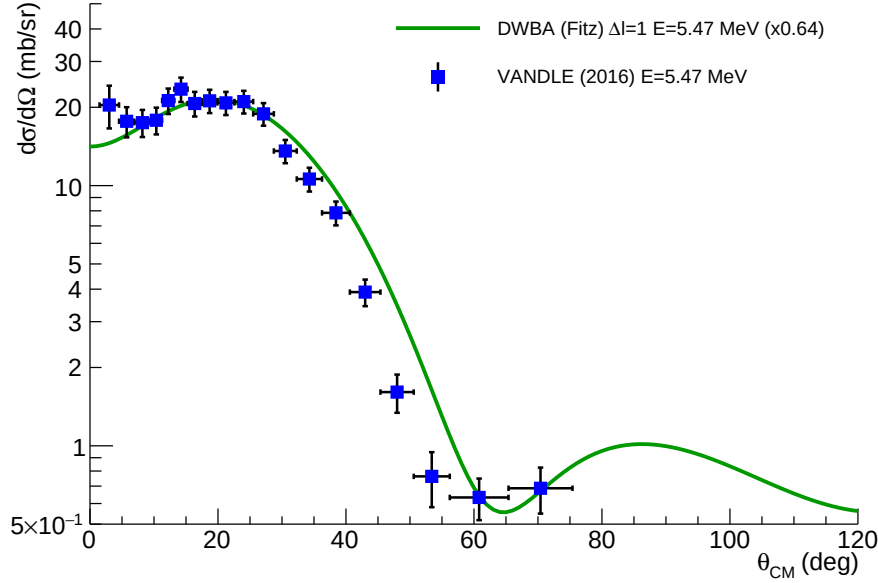


Figure 5.6: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 5.468 MeV ($E_{12C} = 32.58 \text{ MeV}$).

factors of 0.67 and 0.64. VANDLE data at 5.5 MeV agree well with calculation even up to the first maximum at approximately 65° . The distribution at 4.7 MeV flattens out where the calculation predicts the minimum. As stated previously, this is likely due to compound-nuclear effects washing out the relatively sharp features of the calculation.

Figures 5.7 and 5.8 show the distributions for an equivalent deuteron energy of 5.9 MeV and 6.2 MeV respectively. Both seem to suggest that the minimum occurs at a smaller angle than is predicted by the DWBA calculations. Both calculations place the minimum at just above 60° while the two measurements seem to suggest that the minimum occurs somewhere around 45° or 50° .

Figure 5.9 shows the distribution for an equivalent deuteron energy which is approximately 400 keV lower than that shown in Figure 5.2. The shape of the two are very similar, especially for the increase at around 60° . The overall amplitude at this energy is slightly larger at $E_d = 6.6 \text{ MeV}$ as demonstrated by the DWBA scaling factors used, 1.00 as compared to 0.88 at the higher beam energy.

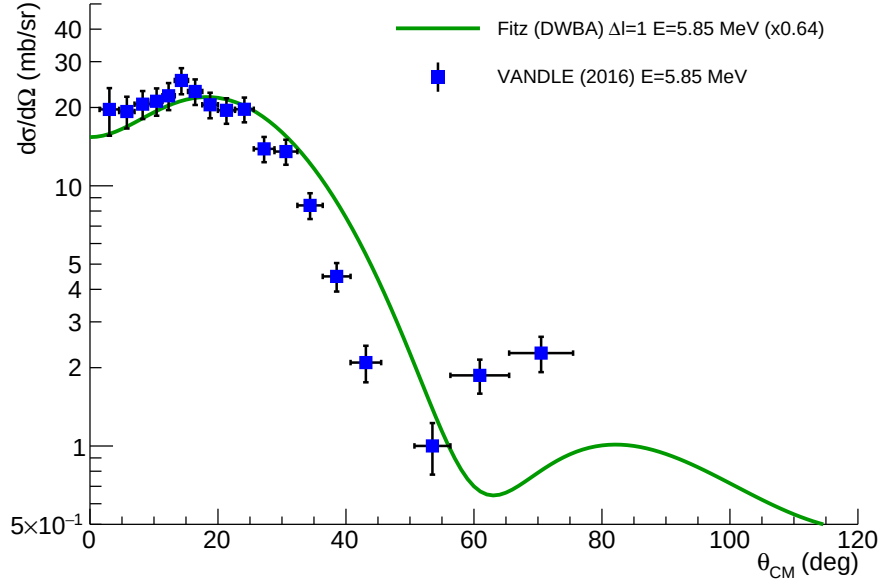


Figure 5.7: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 5.851 MeV ($E_{^{12}\text{C}} = 34.86 \text{ MeV}$).

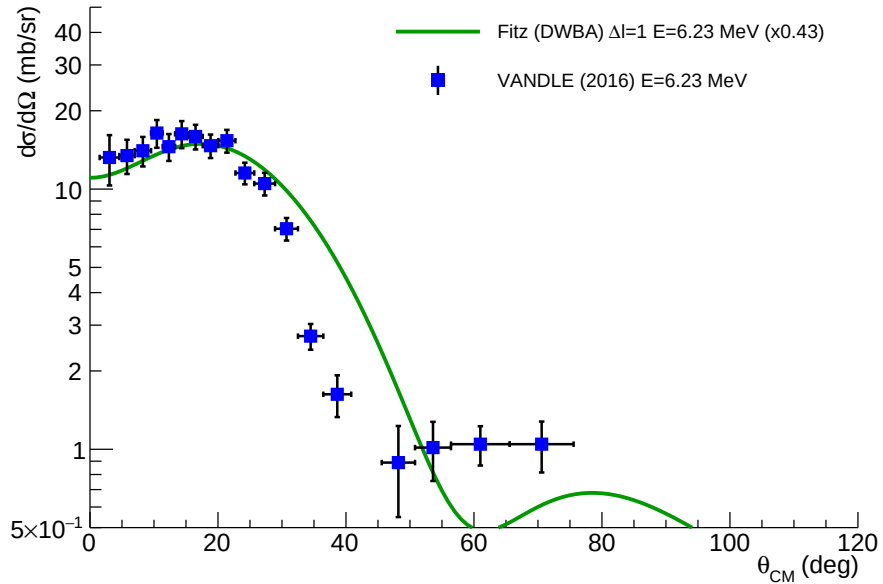


Figure 5.8: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 6.234 MeV ($E_{^{12}\text{C}} = 37.14 \text{ MeV}$).

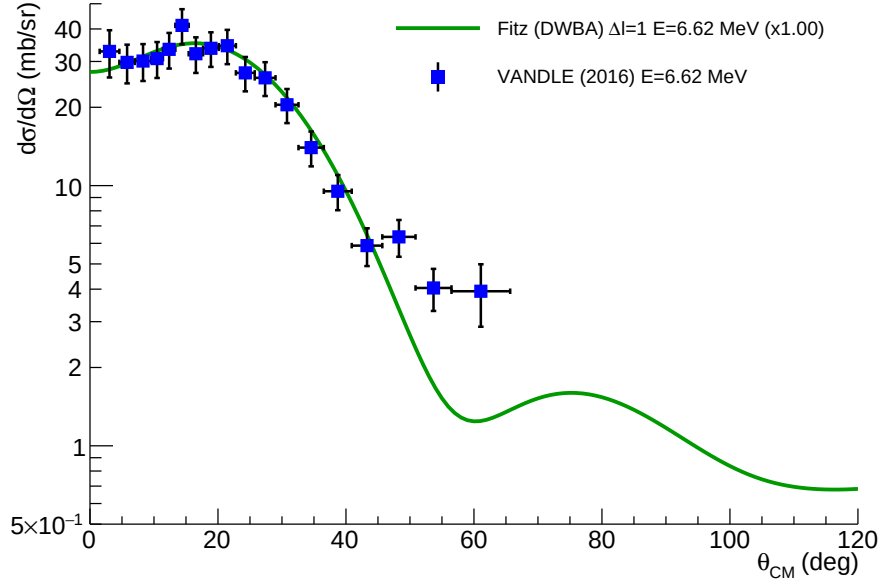


Figure 5.9: Reaction cross sections for population of the ground state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with an equivalent deuteron energy of 6.616 MeV ($E_{^{12}\text{C}} = 39.42 \text{ MeV}$).

All DWBA calculations are correctly reproducing the general features of the angular distributions, showing that there is significant contribution from direct components. The range of scaling factors, ranging from 0.4 and 1.0, which are used to compare to experimental measurements of the same reaction shows that the calculations are missing important physics needed to accurately describe the distributions.

5.1.4 2.3 MeV Excited State

Figure 5.10 shows the angular distribution for population of the unbound first excited state of ^{13}N at 2.36 MeV . Data from this measurement are shown in blue and are compared to a previous measurement by Schelin et al. [6]. Both data sets are in good agreement across the full angular range of this measurement, approximately 20° to 60° in the CM frame. Points at smaller angles are cut off by the 30 keVee software light yield threshold.

Figure 5.11 shows distributions for the population of the first excited state for deuteron bombardment energies of 5.9, 6.2, 6.6, and 7.0 MeV . Experimental data are compared to unscaled DWBA calculations performed using TWOFNR with optical model parameters of

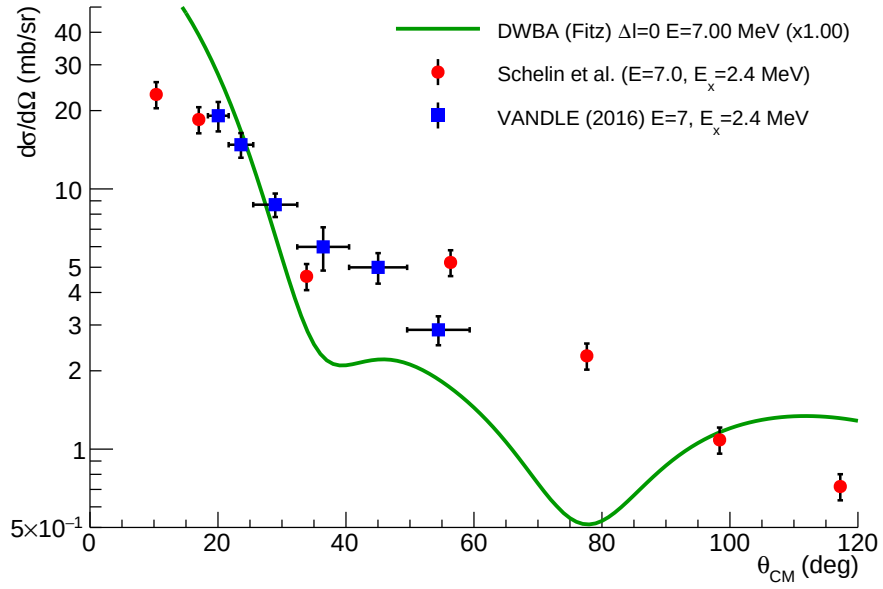


Figure 5.10: Reaction cross sections for population of the $(1/2^+)$ excited state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d,n)$ with an equivalent deuteron energy of 7.0 MeV ($E_{^{12}\text{C}} = 41.70\text{ MeV}$). Current results (blue) are compared to previous results from H.R. Schelin et al. [6] (red) and to a DWBA calculation using optical model parameters of Fitz et al. [9] on the incoming channel (green).

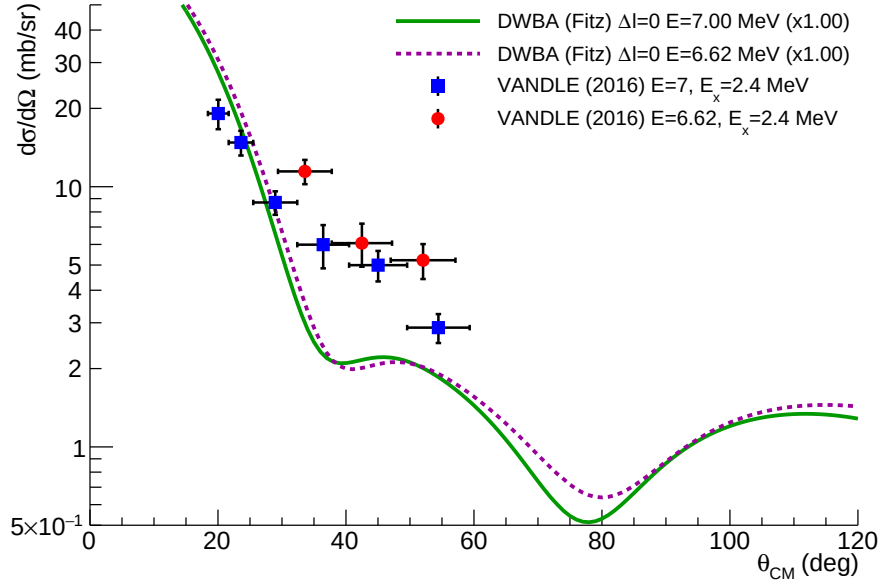
Fitz et al. on the incoming deuteron channel and Koning-Delaroche used for the outgoing neutron channel. The shapes of the distributions are not in agreement with experimental data. The amplitudes of the experimental points are significantly larger than the unscaled DWBA calculations for the case of $E_d = 6.6 \text{ MeV}$ and $E_d = 5.9 \text{ MeV}$. This means that more than the full single-proton strength is needed to explain the cross-section for population of this nuclear state, and indicates that physics is missing from the calculation.

For the distributions presented in Figure 5.11a the distribution for $E_d = 7 \text{ MeV}$ agrees reasonably well with the slope of the DWBA calculation. The data seem to support the location of the minimum at around 40° . The amplitude of the maximum of the calculation at 50° is too low as expected based upon previous discussion. For $E_d = 6.6 \text{ MeV}$, the present dataset has a small angular range due to low neutron energies. Therefore, a meaningful comparison with the DWBA calculation is not possible. The same is true for deuteron energies of $E_d = 5.9 \text{ MeV}$ and $E_d = 6.2 \text{ MeV}$ as shown in Figure 5.11b. Calculations are included in all cases for completeness, but not enough experimental points are available from the current measurement to make comparisons with DWBA.

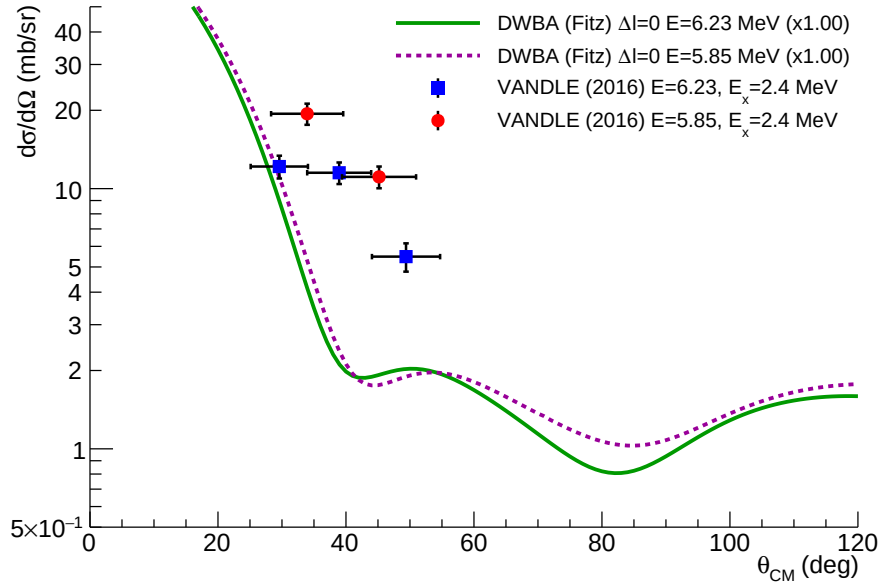
5.2 Excitation Functions

The excitation function for $^{12}\text{C}(d, n)$ near a CM angle of 0° is shown in Figure 5.12. Since the VANDLE measurement was in inverse kinematics, it is impossible to reach 0° in the CM frame without intersecting the incoming beam. So the zero degree excitation function is actually taken at an angle of $3 \pm 1^\circ$ for VANDLE. These data are compared to zero degree measurements from Benenson et al. [7] and Davis and Din [5] as well as at $\approx 9^\circ$ for Schelin et al. [6]. This measurement agrees well with the excitation function measured by Davis and Din as well the measurement at 3.26 MeV by Benenson.

The Schelin distribution was not measured at 0° due to the proximity of the deuteron beam-stop. This means that direct comparison between the zero-degree measurements of Davis and Din as well as that of Benenson are not optimal. It is possible however to extrapolate those data to zero and make a comparison using the extrapolated values. The data of Schelin seem to suggest an amplitude of just under 20 mb/sr if extrapolated to 0° .



(a) $E_d = 7.0 \text{ MeV}$ and $E_d = 6.6 \text{ MeV}$.



(b) $E_d = 5.9 \text{ MeV}$ and $E_d = 6.2 \text{ MeV}$.

Figure 5.11: Reaction cross sections for population of the $(1/2^+)$ excited state of ^{13}N via the proton transfer reaction $^{12}\text{C}(d, n)$ with deuteron energies between 5.9 MeV and 7.0 MeV (34.9 MeV to 41.7 MeV $E_{^{12}\text{C}}$ energy). VANDLE results (points) are compared to unscaled DWBA calculations using optical model parameters of Fitz et al. [9] on the incoming channel (lines).

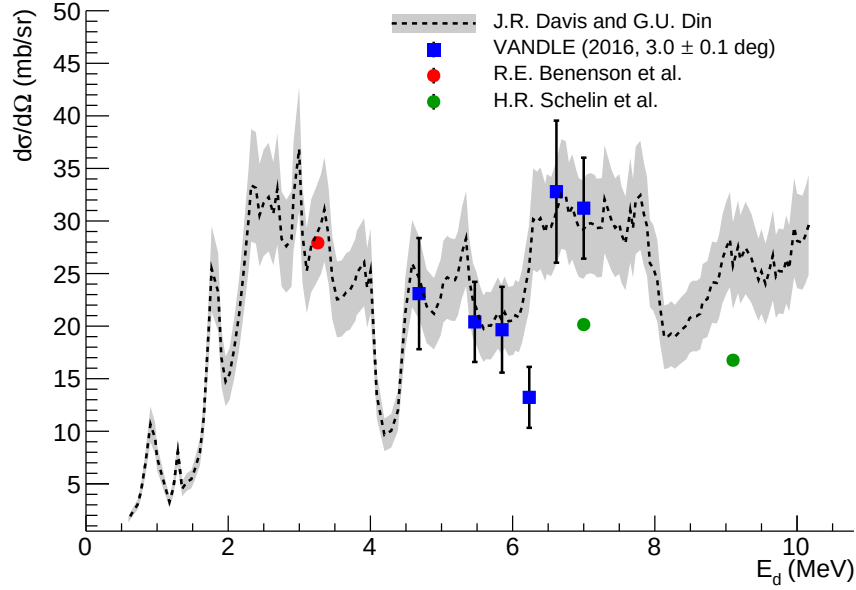


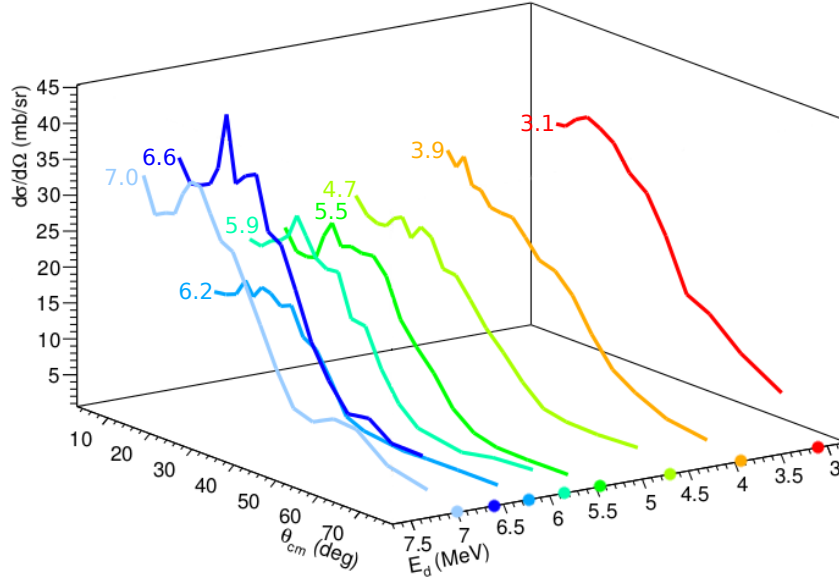
Figure 5.12: Near zero degree excitation function for $^{12}\text{C}(d, n)$. VANDLE data at $\approx 3^\circ$ (blue) are compared to those of Benenson et al. [7] at 0° (red), Schelin et al. [6] at $\approx 9^\circ$ (green), and Davis and Din [5] at 0° (grey shaded region).

This value is approximately 30% lower than that of Davis and Din as well this measurement. Schelin remark that their angular distributions for population of the ground state and first excited state of ^{13}N are also about 35% lower than a time-of-flight measurement by G.S. Mutchler et al. [54] at a similar bombardment energy of 11.8 MeV.

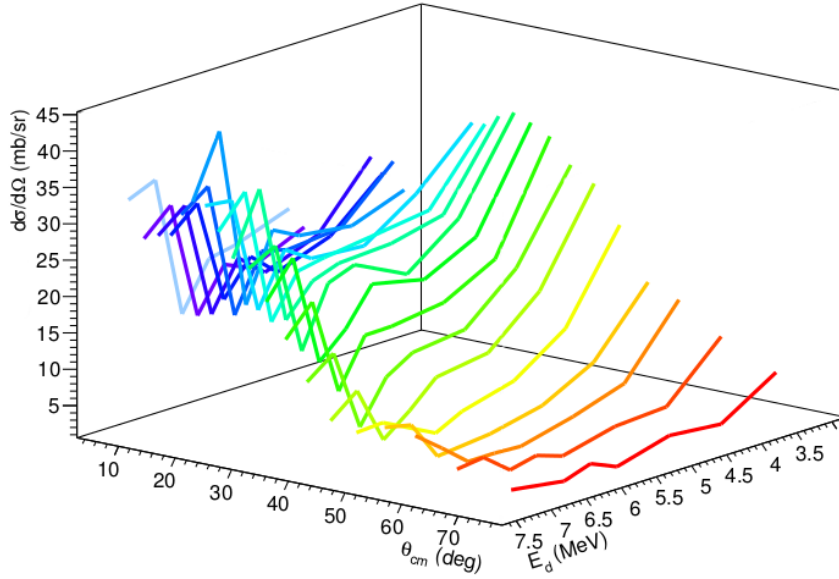
The top plot in Figure 5.13 shows all eight $^{12}\text{C}(d, n)$ angular distributions as a function of equivalent deuteron energy for population of the ground state of ^{13}N . The bottom plot shows nineteen excitation functions for $^{12}\text{C}(d, n)$ measured for equivalent deuteron energies between $E_d = 3.1 \text{ MeV}$ and $E_d = 7.0 \text{ MeV}$ and for CM angles between $\theta_{CM} = 3^\circ$ and $\theta_{CM} = 70^\circ$. The three dimensional plots make changes in the angular distribution more visible as the equivalent deuteron energy is varied.

5.3 Transfer on Oxygen-16

Figure 5.14 shows the population of the ground state of ^{16}O via the proton transfer reaction $^{16}\text{O}(d, n)$ for an equivalent deuteron energy of 8.0 MeV. the current measurement (shown

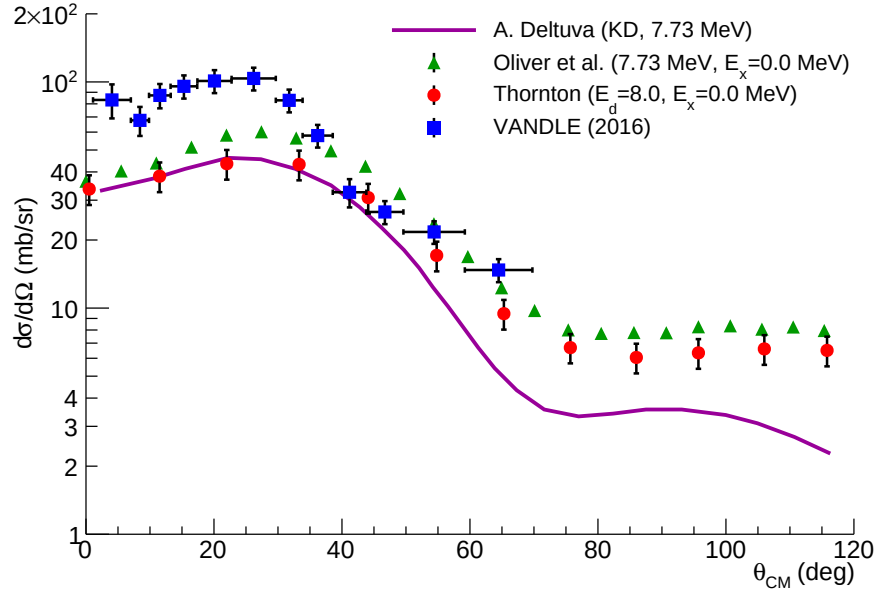


(a) Angular distributions as a function of equivalent deuteron energy.

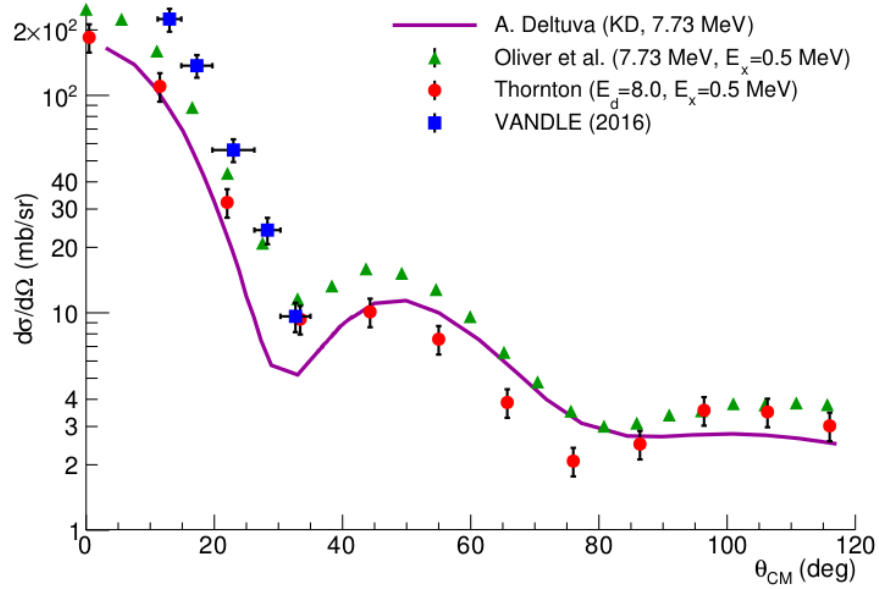


(b) Excitation functions as a function of equivalent deuteron energy.

Figure 5.13: Angular distributions and excitation functions for the proton transfer reaction $^{12}\text{C}(d,n)$ for population of the ground state of ^{13}N at various equivalent deuteron energies and angles.



(a) Ground state of ^{17}F ($5/2^+$)



(b) First excited state of ^{17}F ($1/2^+$) at 495 keV

Figure 5.14: Reaction cross sections for population of the ground state and first excited state of ^{17}F via the proton transfer reaction $^{16}\text{O}(d,n)$ with an equivalent deuteron energy near 8.0 MeV ($E_{^{16}\text{O}} = 64.00$ MeV). Current results are compared to previous results from S.T. Thornton et al. [4], C.J. Oliver et al. [3] and exact three-body Faddeev calculations using Koning-Delaroche optical model potential [8] as performed by A. Deltuva [10].

in blue) are more than a factor of two larger than previous measurements at 7.7 *MeV* by C.J. Oliver et al. [3] (green) and at 8.0 *MeV* by S.T. Thornton [4] (red). The same is true for population of the $(1/2^+)$ state of ^{17}F at 495 *keV*. It is possible that the solid angle correction is wrong, since small changes in the solid angle could easily account for a factor of two difference at certain angles. This is unlikely, however, since the same setup was used for both ^{12}C and ^{16}O and this effect is not apparent in the ^{12}C measurements.

The Faddeev-AGS calculations by Deltuva agree much better with previous experimental results for $^{16}\text{O}(d, n)$ than for $^{12}\text{O}(d, n)$. The overall shapes of the angular distributions for population of the ground and first excited states are well reproduced. But once again, the amplitude at forward angles is under-predicted for population of the ground state of ^{17}F . Deltuva states that this discrepancy is possibly due to compound-nuclear effects.

5.4 Uncertainty Quantification

The uncertainties in the $^{12}\text{C}(d, n)$ angular distribution for a deuteron bombardment energy of 7.0 *MeV* (Figure 5.2) are broken down by source in Figure 5.15. The total uncertainty for all points is just over 10% for this measurement. The other seven ^{12}C energies and ^{16}O distribution have similar uncertainties and are not shown here.

The accuracy of the resultant distribution is limited by systematic uncertainties, with the beam particle current having the largest contribution. It is possible to reduce the uncertainty in the particle current by using different beam normalization methods (e.g. measuring elastic scattering simultaneously) as well as the uncertainty in the target thickness. The uncertainty in the intrinsic efficiency, green line in Figure 5.15, would then dominate. Making a more precise measurement of the intrinsic efficiency using a neutron source is difficult. So, realistically, the most precise measurement of a reaction of this type using VANDLE would have an uncertainty of approximately 5%. For a RIB measurement, statistics will likely be the limiting factor and an uncertainty of 10% or more is not unlikely.

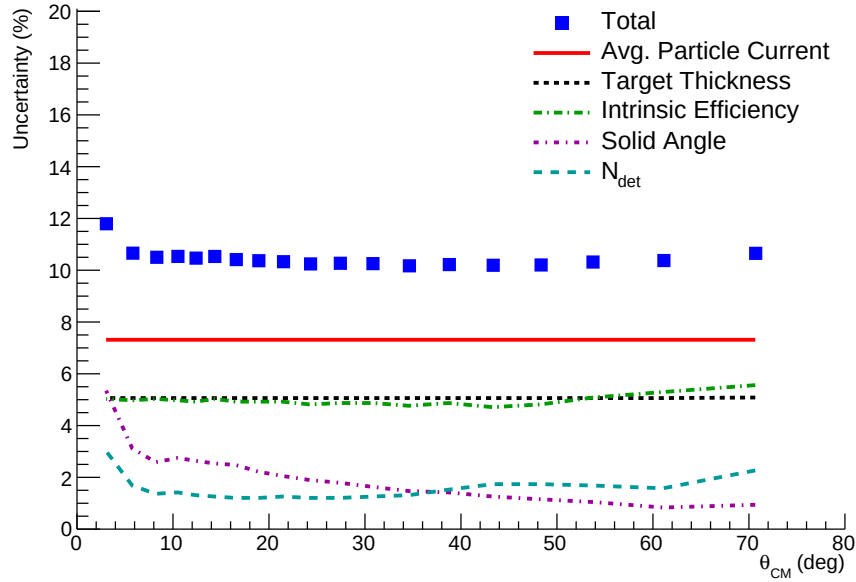


Figure 5.15: Uncertainties in the $^{12}\text{C}(d,n)$ angular distribution for a deuteron bombardment energy of 7.0 MeV ($E_{^{12}\text{C}} = 41.70\text{ MeV}$). The lines represent the contribution to the uncertainty from various sources. The blue points are equal to the total uncertainty as a function of CM angle.

5.5 SABRE Results

The pulse shape discrimination (PSD) performance of one of the detectors in the new liquid scintillator bar array (SABRE) [49] is presented in Figure 5.16. The neutron band (outlined in red and labelled ν in Figure 5.16) is comprised, primarily, of neutrons from the $^{12}\text{C}(d,n)$ transfer reaction. The remainder of events in the plot are γ -rays from room background as well as those from the target and beam-stop γ -flashes. Figure 5.17 shows a neutron TOF spectrum from the liquid bar both ungated (blue) and PSD-gated (red). The location of the neutron peak, in both the ungated and PSD-gated TOF spectra, is kinematically correlated with the proton transfer reaction $^{12}\text{C}(d,n)$ based on the expected energy of the neutron at that angle. This confirms that the events in the neutron band of the PSD spectrum are neutrons from the transfer reaction. The vast majority of events which were detected by the bar are γ -rays since they do not appear in the TOF spectrum when it is gated on PSD. Detectors that are capable of $\nu - \gamma$ discrimination would be invaluable for the effort of performing proton transfer reaction measurements using RIBs. However, the solid angle

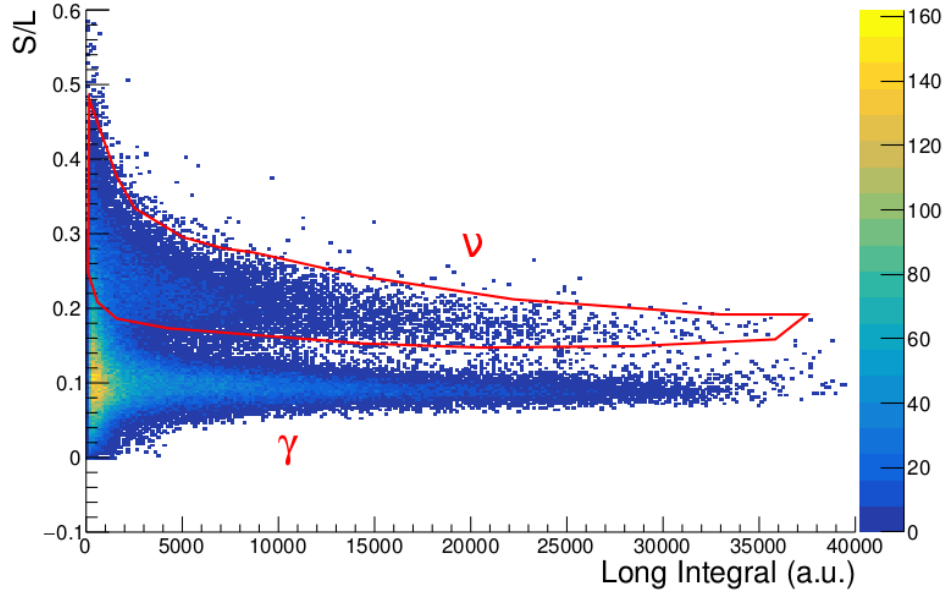


Figure 5.16: SABRE liquid scintillator bar pulse shape discrimination (PSD) performance showing $\nu - \gamma$ separation for the proton transfer reaction $d(^{12}\text{C}, n)$ with a beam energy of 23.46 MeV ($E_d = 3.9$ MeV).

coverage of the discriminating detectors needs to be large enough to have the geometric efficiency required for RIB measurements.

5.6 Improvements for (d,n) with RIBs

The simplest way to measure proton transfer reactions is through the use of high intensity deuteron beams in normal kinematics. Unfortunately, this method allows only for the study of long-lived isotopes. The only way to measure proton transfer on short-lived exotic nuclei is to use radioactive ion beams (RIBs) in inverse kinematics. RIBs, unlike stable beams, typically have many undesirable characteristics such as poor optical properties, significant contamination, and low rates. These characteristics make measuring (d,n) using non-discriminating scintillators very difficult, especially in an environment where large amounts of neutron and γ -ray background are present. There are several experimental methods and techniques which may be used to mitigate the issues related to using RIBs.

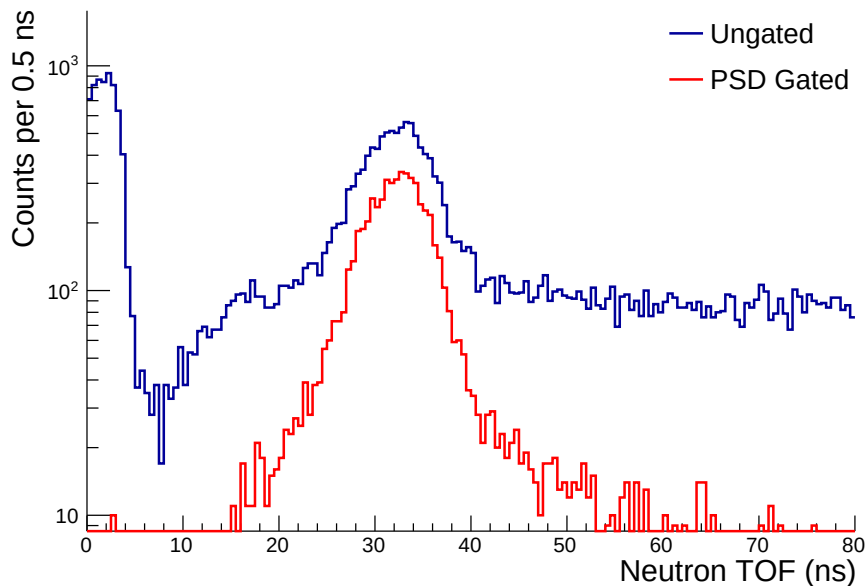


Figure 5.17: SABRE neutron TOF spectrum for the proton transfer reaction $d(^{12}\text{C}, n)$ ungated (blue) and gated on liquid PSD (red).

5.6.1 Pulse Shape Discriminating Scintillators

One of the most conceptually simple techniques to improve performance of a proton transfer measurement is to utilize liquid scintillators and $\nu - \gamma$ discriminating plastics instead of non-discriminating detectors. If many detectors are available, it is possible to simply swap non-discriminating plastic for liquid scintillator detectors in an experiment. Liquid scintillators have their own inherent drawbacks, such as typically being toxic or flammable, but have been used successfully in (d, n) experiments for decades. Discriminating plastics are still relatively new and expensive, but may provide a good alternative in cases where $\nu - \gamma$ discrimination is needed but liquid scintillators are undesirable.

5.7 Recoil Identification

In inverse kinematics, the heavy recoil particle is forward focused, sometimes in a cone with an opening angle of only a few degrees with respect to the beam axis. This effect is worsened as the mass of the beam is increased. There are some distinct drawbacks as well as advantages over normal kinematics, where the heavy recoil particle is not as forward focused.

Identification of the recoil particle is possible using devices such as recoil mass spectrometers (e.g. the S800 at the National Superconducting Cyclotron Laboratory or the St. George at the University of Notre Dame). These devices are typically very large instruments that remain fixed in one spot. So in order to utilize a recoil separator, experiments need to be planned around such a device. This sometimes limits flexibility since the availability of RIB species and energies varies greatly from facility to facility.

In inverse kinematics, the opening angle of the cone of recoil particles from the (d, n) reaction is typically only a few degrees (e.g. 4.9° in the laboratory frame for $d(^{12}\text{C}, n)$ with $E_{^{12}\text{C}} = 41.7 \text{ MeV}$). This makes the proximity of the unreacted beam at 0° an issue. Recoil separators designed for use with RIBs in inverse kinematics generally need to accept the full rate of the incident beam, which can range in intensities anywhere between tens to millions of particles per second.

5.7.1 Silicon Telescopes

While providing excellent energy resolution and recoil particle identification (PID), silicon telescopes are typically rate limited to only a few kHz of incident rate. Silicon detectors are normally ideal for measuring the charged reaction products from reactions (e.g. (d, p) , (d, d) , etc.) at angles away from the beam axis. But due to their low maximum incident rates silicon detectors are ill-suited for use as a recoil separator.

Silicon telescopes are made up of two layers of silicon. The top layer, referred to as the dE, is typically very thin (100s of microns) and the bottom layer, referred to as the E, is much thicker. Incident particles lose a fraction of their energy in the dE layer and then are stopped by the E layer. The total energy of the loci on a silicon PID plot is equal to $dE + E$.

Figure 5.18 shows a characteristic silicon telescope PID plot for a ^7Be RIB produced by TwinSol. The main constituent, ^7Be , is visible at an E of 17 MeV and dE of 6 MeV for a total beam energy of around 23 MeV for this particular beam tune. The main contaminant, un-reacted ^6Li primary beam, appears at $E = 11 \text{ MeV}$ and $dE = 4 \text{ MeV}$. Since TwinSol is a momentum separator, any particle from the production reaction $^6\text{Li} + ^3\text{He}$ that has the same magnetic rigidity as the ^7Be will make it to the secondary target.

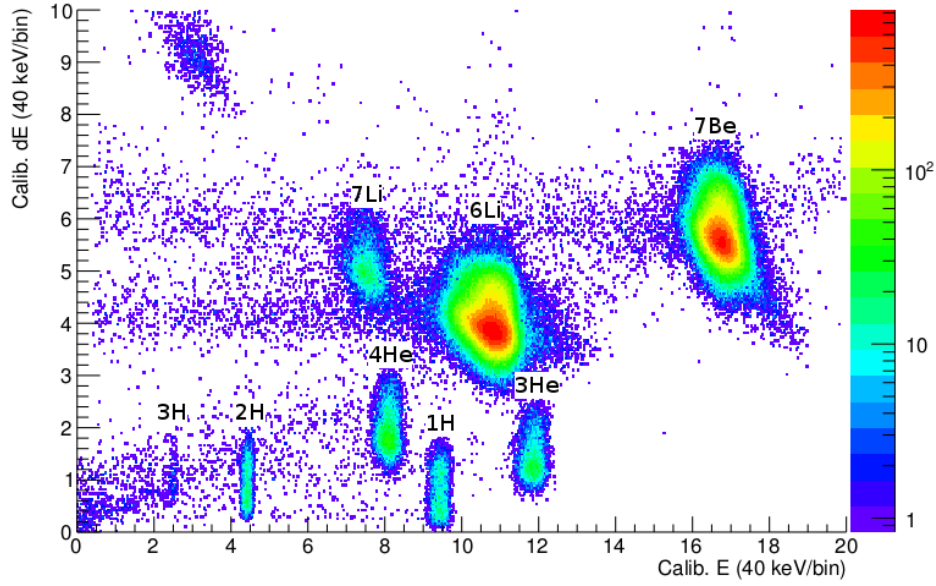


Figure 5.18: PID plot of a ^7Be RIB measured using an E-dE silicon telescope.

5.7.2 Ionization Chambers

Ion-chambers (ICs) are small, portable, and can easily be made to work with various experimental setups. These devices operate on the principle of charged particles ionizing particles in a gas (e.g. methane or similar) while losing kinetic energy in the gas. Wire grids are placed at uniform distances in the chamber to collect the electrons which are read out using pre-amplifiers or charge integrators. Depending on the experiment and the expected recoil nuclei, the gas, gas pressure, and grid spacing may be changed.

Since ICs rely on charge collection to measure the energy lost by the particle in the gas, they are inherently rate limited by the drift velocity of electrons in the gas. This is not really an issue at low incident rates, but as the incident rate is increased, events will start to pile-up. The fastest ICs are able to operate at incident rates up to around 5×10^5 pps [55].

5.7.3 Phoswich Detectors

Phoswich (short for phosphor-sandwich) detectors are devices which are comprised of two layers of scintillating material which are optically coupled together. The two layers are selected in such a way that the decay time of their light pulses are significantly different.



Figure 5.19: Plastic phoswich detector made by fusing a thin layer of plastic scintillator to a thick plastic scintillator disk in a vacuum oven. The top side of the thin layer is coated with a very thin layer of aluminium.

Typically, a thin layer of a “fast” scintillator is coupled to a thicker layer of a “slow” material having a decay time of several orders of magnitude longer than the fast. The scintillation light from the resulting detector is recorded by a single photo-multiplier tube (PMT) resulting in a single light pulse for each scintillation event. Since the two layers have differing decay times, the single light pulse contains a fast peak from the “fast” layer and a long tail from the “slow” layer. In this way, information about the amount of light from each layer may be extracted from the phoswich light pulse.

A particle incident on the phoswich will lose a certain amount of energy in the fast layer and then deposit the remainder in the slow layer. The amount of scintillation light produced by charged recoil particle traversing the two layers is characteristic of the mass, charge, and energy of the incident particle. The phoswich light pulse contains information about the amount of energy deposited in each layer. Pulse shape discrimination may be used on the phoswich light pulse in order to extract this information.

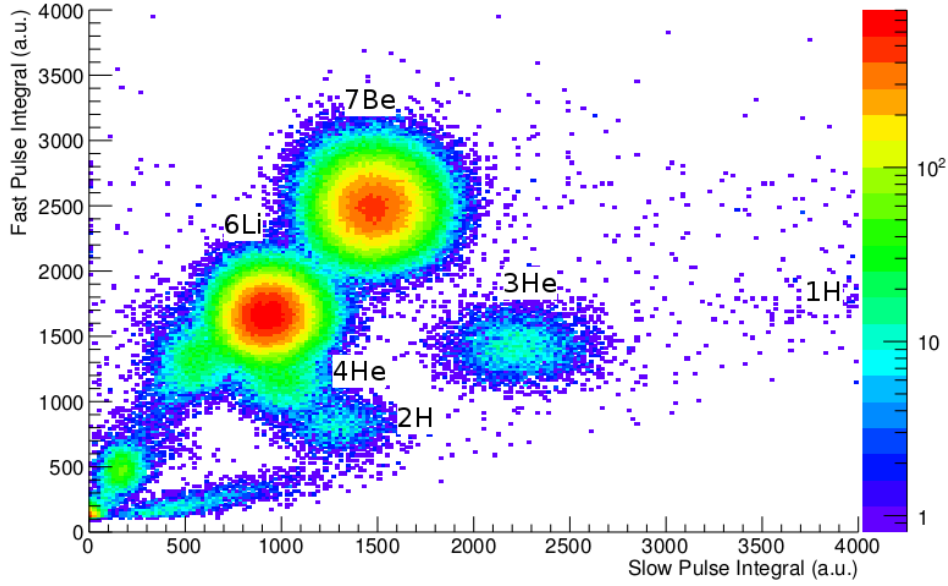


Figure 5.20: PID plot of a ^7Be RIB measured using a plastic phoswich detector.

Figure 5.19 shows a three inch diameter plastic phoswich which was made by fusing a $50\mu\text{m}$ layer of EJ-299 fast plastic scintillator to a thick layer of EJ-240-PS (polystyrene based) scintillator in a vacuum oven. Both plastics were purchased from Eljen [13]. The outer layer was coated with a very thin ($< 100\text{ nm}$) layer of aluminium using an evaporator at Oak Ridge National Laboratory. Figure 5.20 demonstrates the fast integral (dE) versus the slow integral (E) for a ^7Be RIB measurement at Notre Dame. This plot comes from the same RIB measured using a silicon telescope as shown in Figure 5.18. The primary beam constituents are still visible, albeit in different locations than in the silicon PID, and may be identified based on their relative locations and intensities. The PID in Figure 5.20 was produced using a beam of ^7Be with an incident rate of approximately 10 kHz. The rate of the phoswich is largely rate limited by the speed of the PMT. Faster phoswich PMTs will allow for high incident beam rates up to approximately 5×10^5 pps or higher, similar to fast ion chambers as discussed previously.

Figure 5.21 shows a phoswich PID for various RIBs of ^7Be and ^{14}O as well as stable beams of ^6Li , ^{10}B , and ^{12}C at various energies. This plot shows beam particle separation based on atomic charge from $Z = 1$ to $Z = 6$. For (d, n) measurements, the recoil particle has an increased atomic charge to that of the incident beam. This makes phoswich detectors

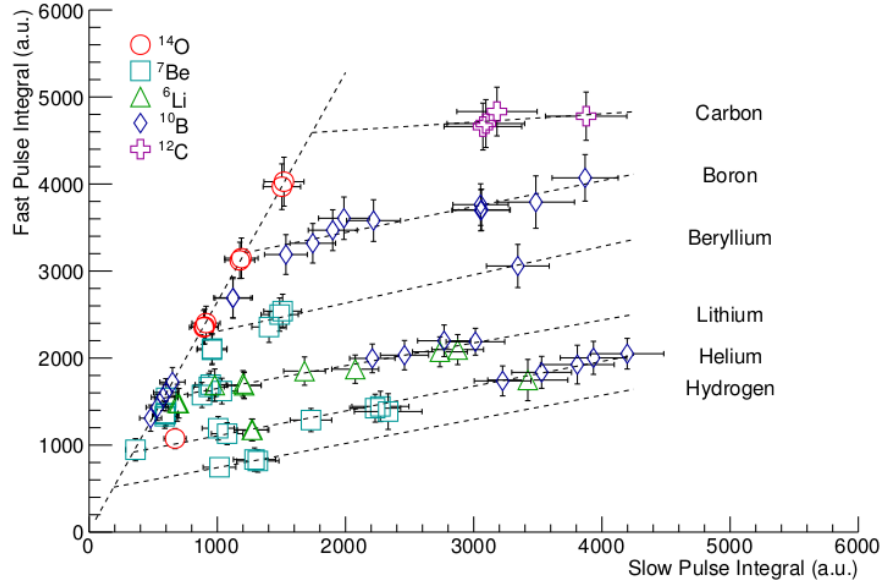


Figure 5.21: PID plot showing centroids of beam constituents for RIBs of ${}^7\text{Be}$ and ${}^{14}\text{O}$ as well as stable beams of ${}^6\text{Li}$, ${}^{10}\text{B}$, and ${}^{12}\text{C}$ at various bombardment energies. Atomic charge groups are labelled.

a good candidate for providing recoil separation for experiments at facilities where magnetic recoil separators are not available. More information will be available in [56].

Chapter 6

Conclusions

Several proton transfer reactions were measured in inverse kinematics using stable beams of ^{12}C and ^{16}O at the University of Notre Dame. Angular distributions obtained from VANDLE are in good agreement with previous ^{12}C transfer measurements performed by Benenson et al. [7] and Davis and Din [5] in normal kinematics with deuteron beams at 3.2 *MeV* and 7.0 *MeV* respectively. Resulting angular distributions for ^{16}O at $E_d = 8$ *MeV* were compared to previous measurements by C.J. Oliver et al. [3] at 7.7 *MeV* and S.T. Thornton [4] at 8.0 *MeV*. Results were also compared to relevant theoretical calculations performed by A. Deluva [10].

This experiment was the first successful measurement of (d, n) using VANDLE. Comparisons with previous proton transfer data show that VANDLE measurements in inverse kinematics can be competitive with those performed in normal kinematics. The resultant angular distributions can also be used to make meaningful comparisons to theoretical calculations, such as DWBA and Faddeev-AGS.

6.1 Carbon-12

The reaction $d(^{12}\text{C}, n)^{13}\text{N}$ was measured in inverse kinematics at eight equivalent deuteron energies ranging from 3.1 *MeV* to 7.0 *MeV*. Angular distributions were extracted below 80° for population of the ground state of ^{13}N for all energies measured and below about 60° for energies above 5.9 *MeV* for population of the unbound first excited state at 2.3 *MeV*.

At center-of-mass angles of less than about 40° , the VANDLE measurements were in good agreement with exact three-body calculations performed by Deltuva using the Faddeev-AGS three-body scattering framework. Forward of 40° , the calculation under-predicts both the current VANDLE measurement and that of Davis and Din. One possible source for this discrepancy comes from contributions from the compound-nucleus, ^{14}N , since it is expected to become more relevant as the deuteron bombardment energy is decreased. Figure 2.1 shows that calculated total neutron scattering cross-sections for light nuclei disagree with experimental data at energies of a few MeV or below. Broad neutron resonances of the compound nucleus are present in this energy region and they start to dominate the scattering cross-section.

The general shape of the distribution agrees well with a previous measurement by Schelin et al. [6] using a beam of 7.0 MeV deuterons. However, their absolute normalization is approximately 30% lower than that of this measurement and of Davis and Din. As noted by the authors, their measured cross-sections were also about 35% lower than those obtained by Mutchler et al. [54].

Results for all eight of the ^{12}C energies were compared to DWBA calculations made using the zero-range DWBA code TWOFNR [45]. The shapes of the calculations agree well with experimental results from VANDLE. As with the Faddeev calculations by Deltuva, one should not expect calculations of only the direct mechanism component to agree with experimental results where compound-nucleus effects may play a significant role.

Neutrons from the population of the first excited state of ^{13}N were not visible at all deuteron bombardment energies measured as the energy of the neutrons dropped below $\approx 200 \text{ keV}$. Angular distributions were extracted for the excited state at deuteron energies of 5.9 MeV and up. The distribution at a deuteron energy of 7 MeV was compared to previous measurement by Schelin et al. The shape and normalization are well reproduced by this measurement. Both datasets are in agreement about the location of the first minimum at approximately 35° .

6.2 Oxygen-16

The reaction $d(^{16}\text{O}, n)^{17}\text{F}$ was measured in inverse kinematics at an equivalent deuteron energy of 8 *MeV*. Angular distributions were extracted from 0° up to 60° for population of the ground state of ^{17}F and from 10° to 30° for the first excited state at 0.495 *MeV*.

At low angles, the VANDLE measurement is more than a factor of two larger than previous measurements by Thornton and by Oliver et al. as well as theoretical calculations by Deluva for population of both the ground state and first excited state of ^{17}F .

6.3 Future Work

A compact ionization chamber is currently being developed by researchers at the University of Tennessee. Figure 6.1 shows a mock-up design of the IC courtesy of S. Burcher and A.B. Carter. The chamber is intended to be small enough to easily move to various facilities and to attach to existing experimental setups. The dashed red line represents the beam axis while the green lines represent the size of the cone of heavy recoil reaction products from the target. The IC is intended to be used for reaction experiments in inverse kinematics where the cone of heavy recoil products only extends to a few degrees in the laboratory frame. The performance of the IC should enable the separation of reaction products from (d, n) at incident particle currents upward of 1×10^5 particles per second.

A three inch diameter plastic phoswich was designed and built for use with (d, n) measurements. The design of the phoswich was nearly identical to the one discussed in Section 5.7.3. The phoswich was not tested during the stable runs of $d(^{12}\text{C}, n)$ and $d(^{16}\text{O}, n)$ due to instabilities in the beam when restricted to RIB rates of approximately 1×10^6 *pps*. Phoswich detectors are RIB devices and should be used only with RIB measurements. Their recoil separation by atomic charge, as shown in Figure 5.20, is very promising for proton transfer measurements using RIBs.

The RIB measurement of $d(^7\text{Be}, n)$ is planned to be performed again at the University of Notre Dame in the near future using experimental and analysis techniques developed during this study. Recent improvements to TwinSol should provide RIB beams with increased purity

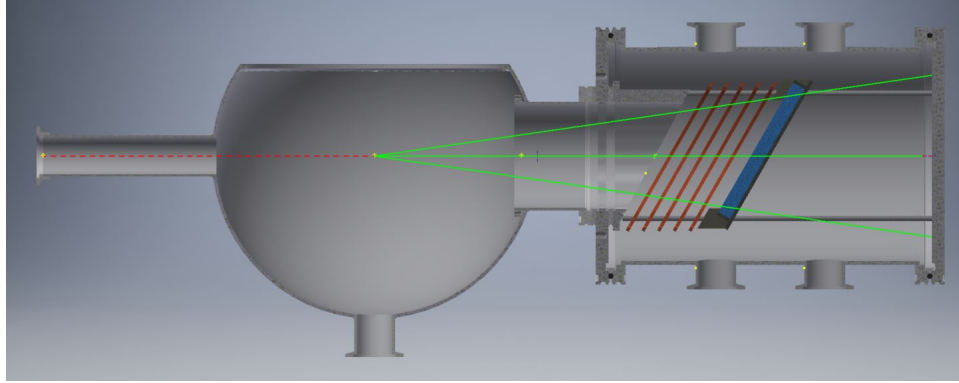


Figure 6.1: New design for a compact ionization chamber courtesy of S. Burcher and A.B. Carter. The chamber is positioned to the right of an existing thin-walled spherical aluminium scattering chamber used for (d, n) measurements. The dashed red line represents the beam axis while the three green lines represent the maximum extent of the heavy recoil reaction product cone from the target.

and better optics than were available previously. The use of the new ionization chamber will be used for recoil separation in order to gate the neutron spectra on the ^8B proton transfer reaction product. New recoil phoswich detectors will be tested at the same time for their use in proton transfer measurements.

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Appendix

Appendix A

Additional Timing Analysis

A Algorithm Comparisons

A detailed timing analysis was performed for a small VANDLE bar using data from a measurement with a ^{90}Sr source at the center of the bar. Only VANDLE traces with maximum amplitudes greater than 2048 ADC channels (50 % of a 12-bit ADC) were considered in this analysis. This restriction on pulse amplitude ensures that the results are largely unaffected by low amplitude timing walk.

For the example analysis shown in Figure A.1, pulse maxima are restricted to between 200 and 250 ADC channels above baseline and the resulting averaged pulse is fit in the range of $T_{max} - 20 \text{ ns}$ and $T_{max} + 40 \text{ ns}$. The resulting β and γ from the averaged distribution is $0.0712 \pm 0.0004 \text{ ns}$ and $0.0464 \pm 0.0002 \text{ ns}^4$ respectively. The three timing algorithms described in Section 3.7 are compared for VANDLE data in Figure A.2 using their respective parameters given in Table A.1.

The current results for the fitting function (eq. 3.10) are compared to those of Paulauskas et al. [51] for a time resolution measurement using a small $1 \times 1 \times 0.4 \text{ inch}^3$ piece of EJ-200 with a VANDLE PMT on each end. The time resolution of their setup for only high energy signals is quoted to be approximately 500 ps . This value is not reproducible given the current measurement using a small VANDLE bar and the fitting parameters given in Table A.1. A significantly degraded FWHM resolution of 736 ps is observed in this case, compared to 556 ps and 580 ps for the CFD and poly-CFD algorithms respectively.

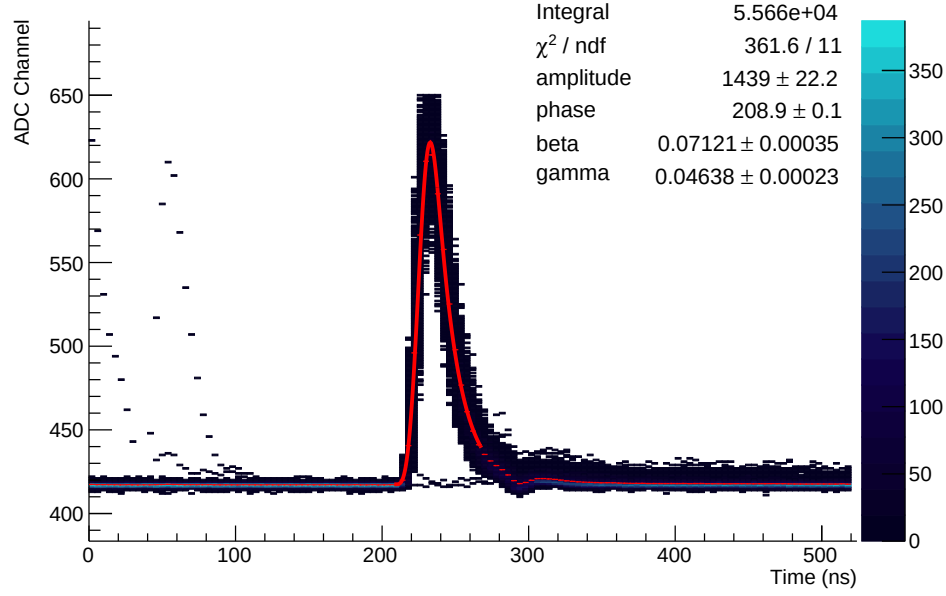


Figure A.1: Average of one thousand VANDLE PMT light traces fit using Equation 3.10 in the range $T_{max} - 20 \text{ ns}$ to $T_{max} + 40 \text{ ns}$.

Possible causes for this discrepancy may be differences in fitting parameters, fitting region, or differences in the setup. It should be noted that worse time resolution is expected for a longer detector (60 cm in this case versus a $\approx 1 \text{ cm}$ length detector). In addition, Paulauskas et al. use fitting algorithms from the Gnu Scientific Library compared to those built-in algorithms from the Cern ROOT package (MINUIT in this case).

Table A.1: FWHM time resolutions for various timing algorithms. Data are taken from a measurement using a single small VANDLE bar with a ^{90}Sr source placed at the center. An ADC software threshold of 2048 channels is used (50% of a 12-bit ADC). Fitting range of $T_{max} - 20 \text{ ns}$ to $T_{max} + 40 \text{ ns}$ used for fitting analysis.

Algorithm	Parameters	FWHM (ps)
CFD 3.7.2	$F = 0.28, D = 3, L = 1$	556
POLY 3.7.3	$F = 0.44$	580
Fitting 3.7.1	$\beta = 0.0712 \text{ ns}$ and $\gamma = 0.0464 \text{ ns}^4$ (fixed)	736

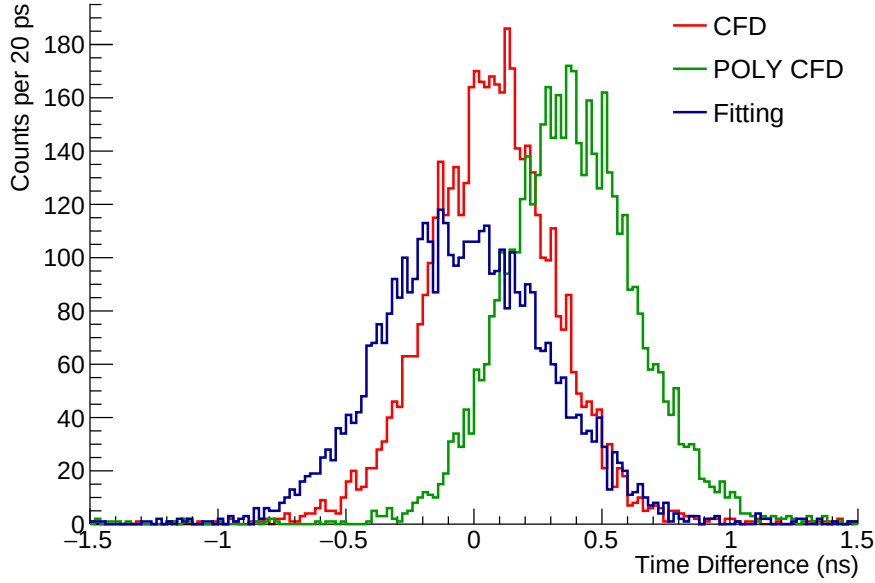
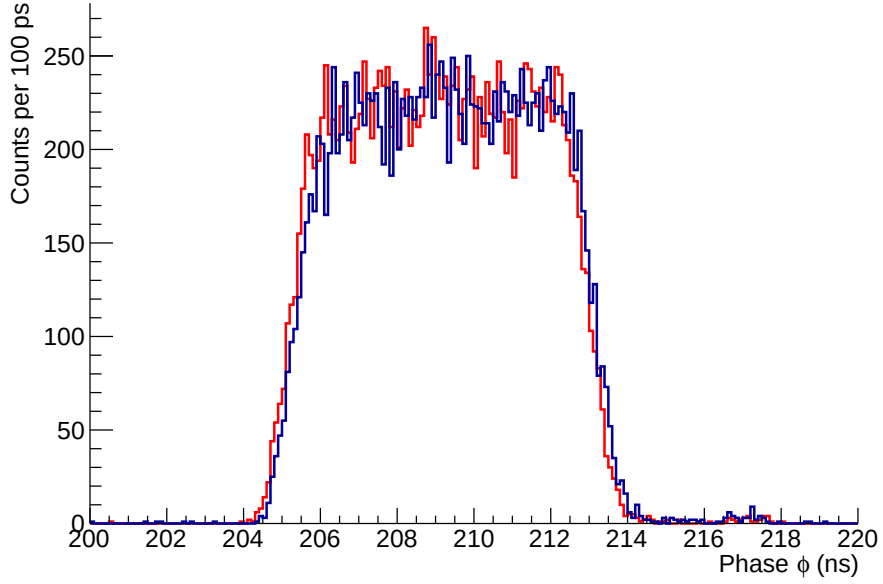


Figure A.2: Time difference spectra for fit function 3.10. Data are taken from a measurement using a single VANDLE bar with a ^{90}Sr source at the center. An ADC software threshold of 2048 channels is used (50% of a 12-bit ADC).

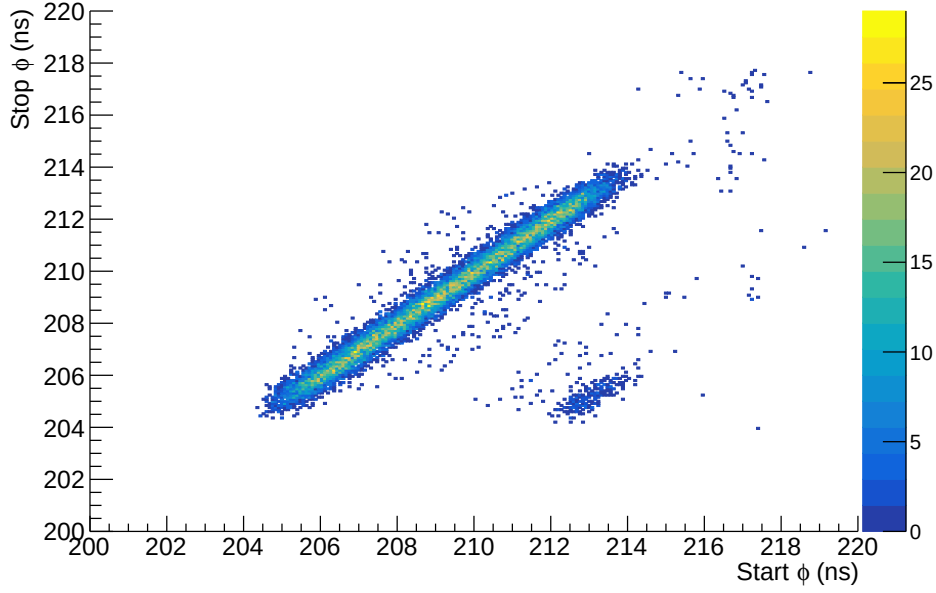
B Phase Analysis

CFD algorithms, despite being fast, typically have inherent bias which is usually a result of interpolation operations on the derivative of the trace in regions where the derivative is not necessarily linear. This bias manifests itself as a preferential determination of the phase of the trace (ϕ). Substantial bias is present for the traditional CFD algorithm as shown in Figure A.4. Phase bias is also present for the polynomial CFD algorithm, albeit much less severe than with CFD, as seen in Figure A.5. Paulauskas et al. state that fitting the traces results in no bias in the phase space. Figure A.3 shows that the phase-phase results of this measurement are in agreement with this statement.

Despite exhibiting considerable bias in the phase space of the traces, the two CFD algorithms tested do not result in double-peaking in the VANDLE time difference spectra as seen in Figure A.2. If any double-peaking is occurring, it is likely on a time scale which is less than the FWHM resolution of the algorithms. Very fast signals were not tested in this analysis and may exhibit more of an effect, but it does not seem to be an issue for VANDLE type pulses.

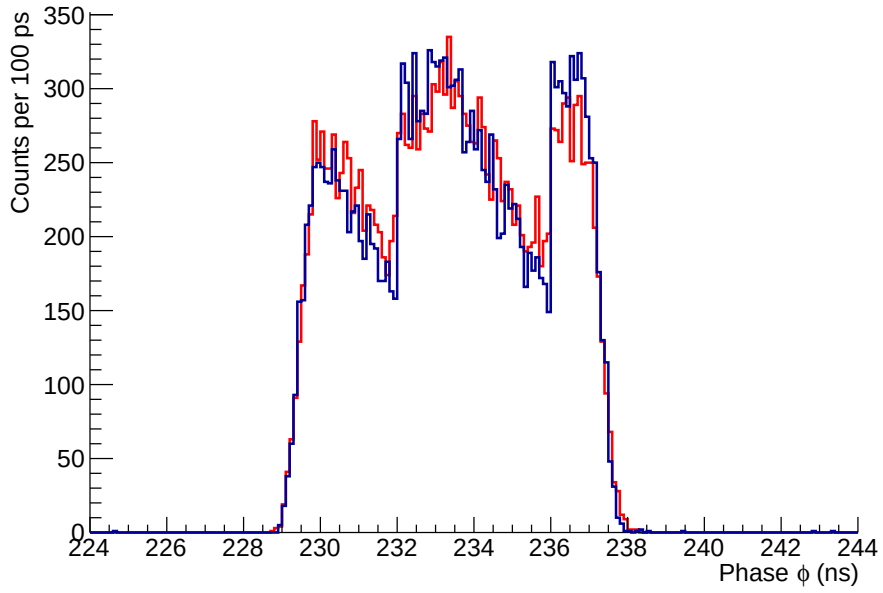


(a) Start (blue) and stop (red) phases for fitting function

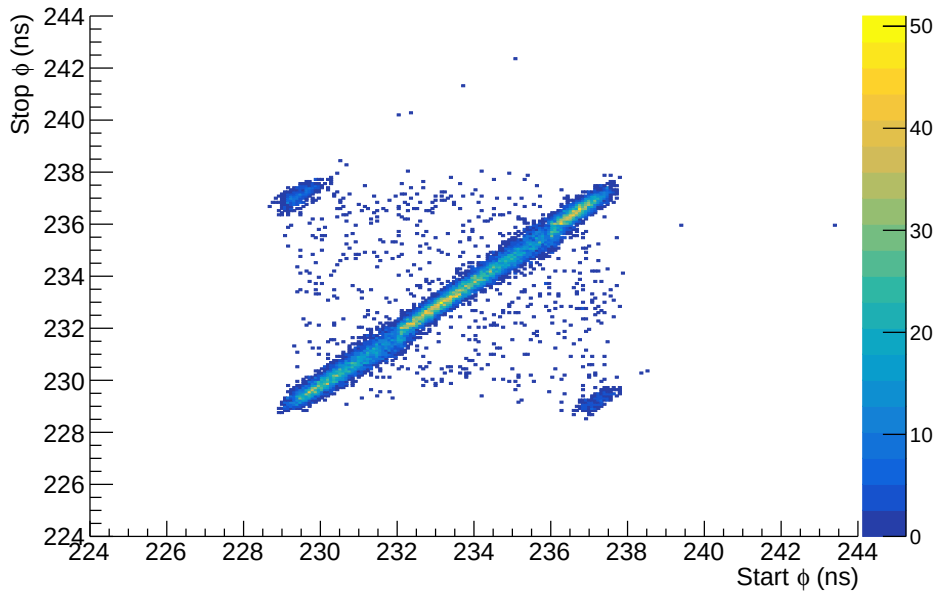


(b) Stop versus start phase for fitting function

Figure A.3: Start signal and stop signal phases (ϕ) for trace fitting using Equation 3.10 with $\beta = 0.0712$ and $\gamma = 0.0464$ fixed. Data are taken from a measurement using a small VANDLE bar with a ^{90}Sr source at the center and an ADC threshold of 2048 channels (50% of a 12-bit ADC).

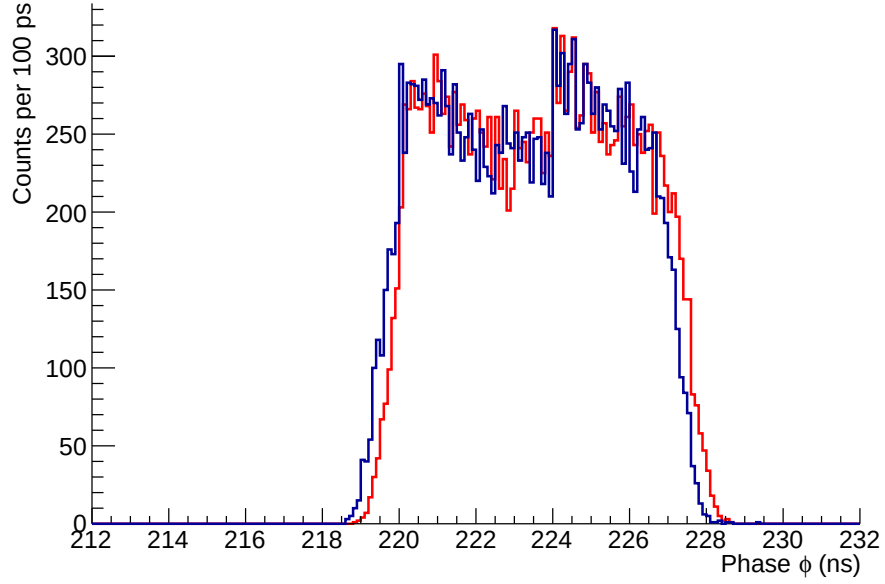


(a) Start (blue) and stop (red) phases for traditional CFD

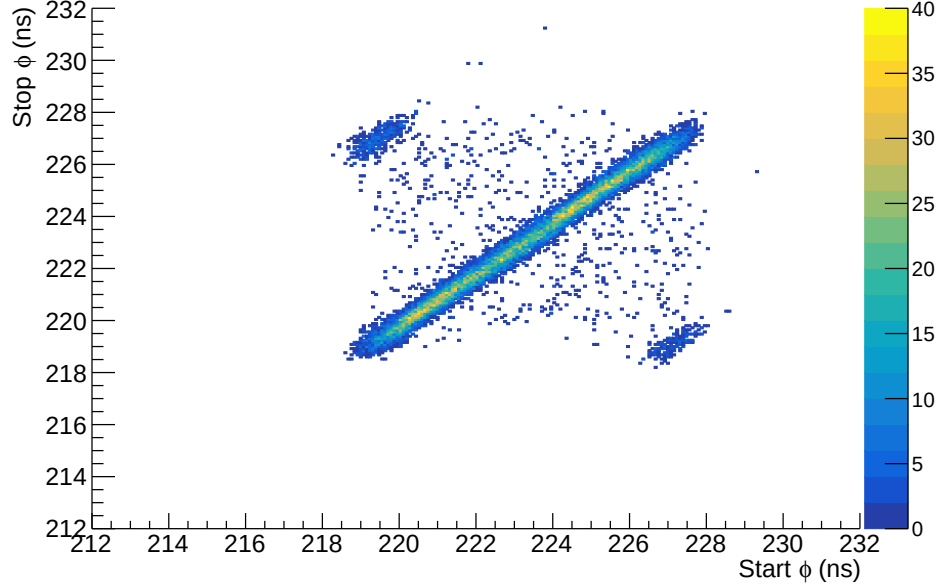


(b) Stop versus start phase for traditional CFD

Figure A.4: Start signal and stop signal phases (ϕ) for a traditional CFD algorithm [17] (see sec. 3.7.2) for $F = 0.44$. Data are taken from a measurement using a small VANDLE bar with a ^{90}Sr source at the center and an ADC threshold of 2048 channels (50% of a 12-bit ADC).



(a) Start (blue) and stop (red) phases for polynomial CFD



(b) Stop versus start phase for polynomial CFD

Figure A.5: Start signal and stop signal phases (ϕ) for polynomial CFD algorithm (see sec. 3.7.3) for $F = 0.44$. Data are taken from a measurement using a small VANDLE bar with a ^{90}Sr source at the center and an ADC threshold of 2048 channels (50% of a 12-bit ADC).

C HAGRiD Timing Analysis

A second timing analysis was performed for two 2-inch cylindrical LaBr(Ce) detectors from the HAGRiD array using only the polynomial CFD algorithm. Two HAGRiD detectors were placed back-to-back with a ^{60}Co source in the middle. The start signal is from 4386CA A9816 (-1103 V) and the stop signal is 4385CA A9818 (-1454 V) with 14-bit digitizers. Again, the minimum trace amplitude is restricted to 2048 ADC channels (12.5 % of a 14-bit ADC). A poly-CFD parameter scan for this setup is shown in Figure A.6. The FWHM resolution is minimized for $F = 0.77$ resulting in a time resolution of 631 ps . Figure A.7 shows the effect of removing the software threshold resulting in a FWHM resolution of approximately 800 ps over the full range of the ADC.

The left plot in Figure A.9 shows the maximum pulse amplitude for the stop detector versus the start detector. The red gate is drawn around the region where the 1173 keV and 1332 keV γ -rays being fully absorbed by the stop and start detectors respectively. This gate represents those events which correspond to a single decay of the ^{60}Co and provides a measure of the minimum time difference between the two detectors. The time difference using this gate is shown on the right of Figure A.9. The FWHM time resolution is 563 ps as shown by the fit using a Gaussian. This value is in agreement with the value of 576 ps obtained by Fallu-Labruyere et al. [17] at a γ -ray energy of 511 keV using the CFD algorithm given by Equation 3.11 with a similar setup.

If one assumes that the two HAGRiD detectors are identical, the total FWHM time resolution of 563 ps corresponds to a single-detector resolution of approximately 400 ps . This value is in line with other measurements of the time resolution of LaBr [18].

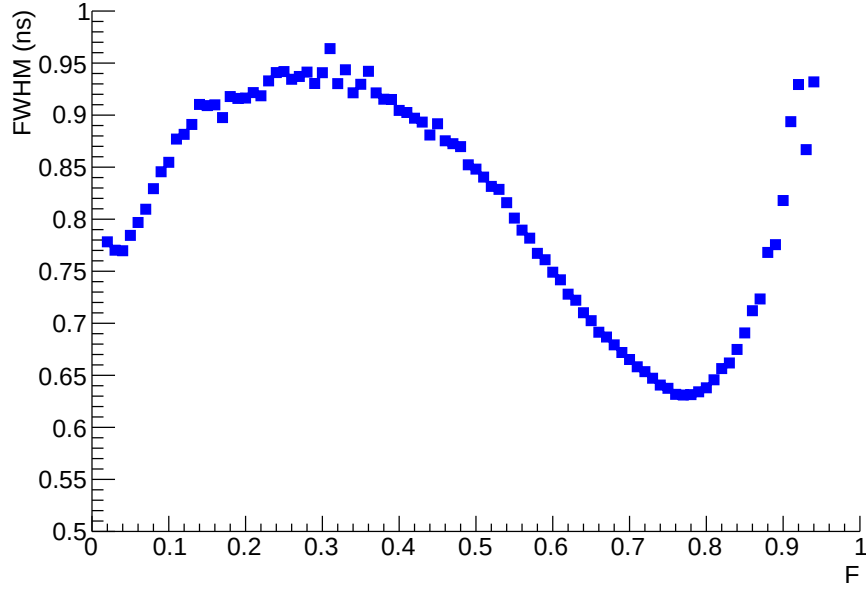


Figure A.6: Scan over CFD parameters for two back-to-back HAGRiD detectors [18] with a ^{60}Co γ -ray source between the two. Five thousand coincidence pairs are used for the analysis. An ADC threshold of 2048 channels is used (12.5% of a 14-bit ADC). Parameters are iterated for $F \in [0, 1]$ in steps of 0.01.

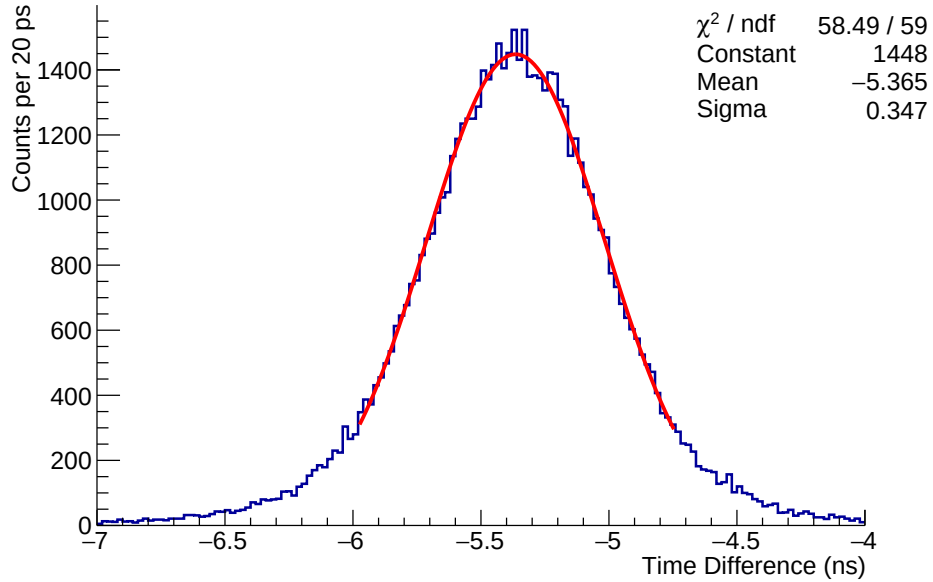


Figure A.7: Time difference spectra for optimized poly CFD algorithm. Data are taken from a measurement using two back-to-back HAGRiD detectors with a γ -ray source in the center. Time difference spectrum fit using a Gaussian. Fit results are shown. No software threshold is used for ADC traces. Polynomial CFD parameter of $F = 0.77$ is used resulting in a FWHM resolution of 817 ps.

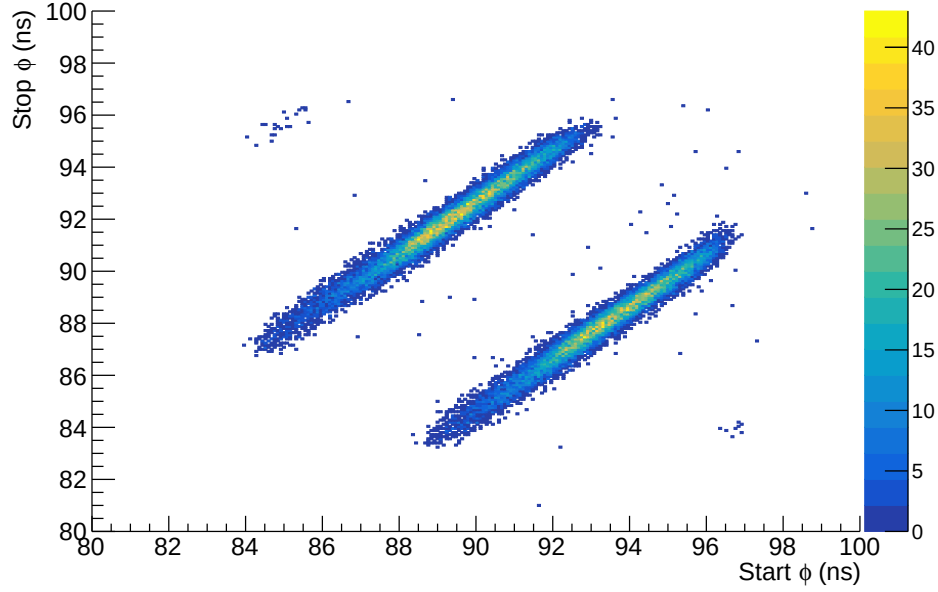


Figure A.8: Stop signal phase versus start signal phase plot for polynomial CFD algorithm (sec. 3.7.3) with $F = 0.77$. Data are taken from a measurement using two back-to-back HAGRiD detectors with a γ -ray source in the center. ADC threshold of 2048 channels (12.5% of a 14-bit ADC) is used.

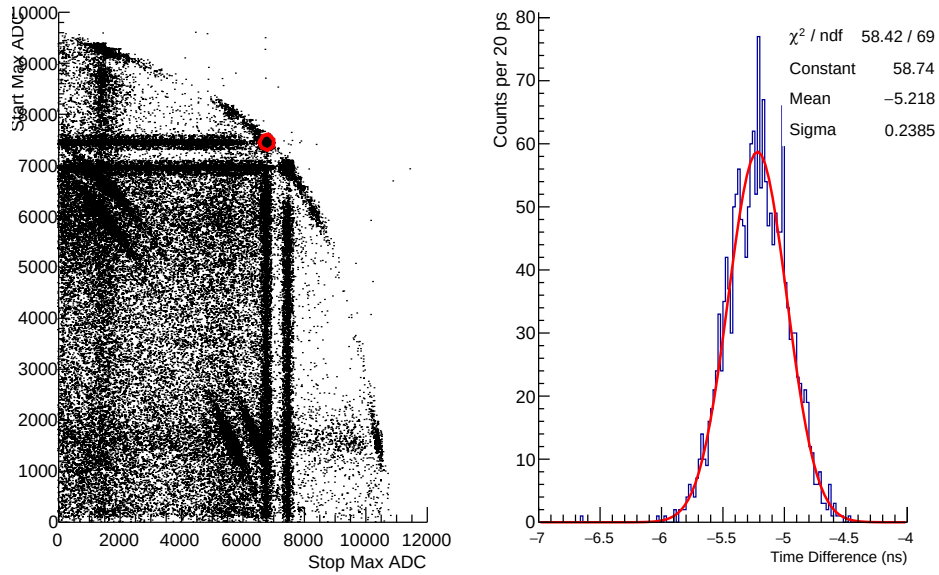


Figure A.9: (left) Start signal max ADC versus stop signal max ADC for two back-to-back HAGRiD detectors with a ^{60}Co source in the middle. A red gate is drawn around the structure corresponding to the 1173 keV and 1332 keV γ -rays being fully absorbed in the stop and start detectors respectively. (right) Time difference spectrum gated on the max-max plot shown in the left. The FWHM time resolution is 563 ps.

Vita

Cory was born in Morehead, KY in January of 1988. He attended high school at West Carter, taking courses in construction technology and participating in the Kentucky state construction competition in Louisville, KY in his senior year. Cory still does carpentry projects in his free time as well as performing unpaid carpentry, plumbing, and electrical work for friends and family. Cory attended college at Morehead State University where he had a dual major in physics and mathematics. Early in his undergraduate career, Cory taught himself to program simple games and programs in basic, eventually learning python, fortran, C++, and C#. He Received his bachelor degree from Morehead State in 2011. He was accepted to graduate school at the University of Tennessee department of Physics and Astronomy, majoring in low energy nuclear physics. The subject matter of his Ph.D. research is detailed in this dissertation.