



**DIFFERENTIAL (p, p') AND (p, d) CROSS
SECTIONS OF ^{89}Y AND ^{92}Zr**

THESIS

Molly A. Wakeling, 2d Lt, USAF
AFIT-ENP-MS-16-M-086

**DEPARTMENT OF THE AIR FORCE
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Abstract

Differential cross sections for the (p, p') and (p, d) reactions on ^{89}Y and ^{92}Zr were measured using a 28.25-MeV proton beam at the 88-inch cyclotron at Lawrence Berkeley National Laboratory. Angular distributions were obtained for the ground state and several excited states of each isotope using silicon detector telescopes over angles 10° to 140° in the reaction plane. These data were obtained by fitting a Gaussian function to each peak in the energy spectra and integrating the number of counts under each peak. These cross sections will be included in nuclear structure models so that neutron and other particle reaction cross sections can be predicted for other isotopes, including eventually those farther from stability and those whose half-lives are too short to measure experimentally.

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1. Introduction

Nuclear reaction cross section data have important applications throughout nuclear physics. Unfortunately, cross section data are difficult to obtain for some isotopes, particularly those that are difficult to synthesize or that have very short half-lives. Calculating these values is also prohibitively difficult because of the high level of knowledge of the nuclear structure of a given isotope that is required, as well as the interplay between different reaction mechanisms [1]. However, the surrogate reaction method allows cross section data to be obtained for difficult-to-produce targets. In order to utilize the surrogate method, accurate nuclear structure data from models such as the optical model are needed, and data from experiments, such as the experiment conducted in this research, are required.

Having accurate neutron capture cross section data is important for a variety of fields related to nuclear physics – particularly astrophysics, nuclear energy, and national security. In astrophysics, models of stellar nucleosynthesis rely on cross section data in order to predict the distribution of nuclei synthesized in a star, and the likelihood of a given nucleus to capture a neutron has a large impact on the eventual isotopic distribution. With regard to nuclear energy, accurate cross section data is important to inform reactor models to ensure greater safety, reliability, waste reduction, and proliferation resistance. In matters of national security, post-detonation analysis of fission product decay chain elements can provide information on performance, type, and sophistication of nuclear weapons.

This research focuses specifically on the (p, p') and (p, d) reactions for the ^{89}Y

and ^{92}Zr isotopes. To measure the reaction cross sections, these two isotopes were irradiated with a 28.25 MeV proton beam at the Lawrence Berkeley National Laboratory 88-inch cyclotron, and the reaction rates were measured at angles 10° - 140° in 10° increments in the reaction plane. The cross sections were calculated using these measured rates, along with the target thickness and integrated beam current, and the results are given as a function of angle. The objective of this research is to obtain the angular distributions of the cross sections for several nuclear states excited by the (p, p') and (p, d) reactions. These will then be compared to $(p, p'\gamma)$ and $(p, d\gamma)$ data taken in a different experiment, and optical model parameters will be fit to the two sets of data to improve nuclear structure models in the $A \sim 90$ region. The $(p, p'\gamma)$ and $(p, d\gamma)$ data were taken over a smaller angular distribution (30° - 60°) than in this work, which improves the angular distribution information by covering angles 10° - 140° .

Having more accurate differential cross sections for these isotopes will provide better information on their nuclear structure, such as excited state energy levels and angular momentum-parity (J^π) values. These data inform nuclear models that utilize structure information by strengthening them with experimental data. This allows for the parameters of the model to be adjusted to provide a good fit to the experimental data, and then the model can be applied to other isotopes and reactions that are more difficult to measure. This improved model will allow for greater accuracy in predicting the cross sections for neutron reactions with short-lived isotopes. Experimental measurements provide constraints for the theoretical model.

These experiments utilize an approach known as the surrogate method of determining cross sections for nuclear reactions for short-lived isotopes by using a different reaction on a nearby isotope to produce the same compound nucleus as for the reaction of interest. In this research, the ^{89}Y and $^{92}\text{Zr}(p, d)$ reactions are surrogates

for the ^{87}Y and $^{90}\text{Zr}(n, \gamma)$ reactions, respectively. The ^{87}Y reaction is of particular interest because of its short (79.8-hour) half-life, while the ^{90}Zr reaction serves as a benchmark, since it is a stable isotope and easily measured. The proton scattering (p, p') data provide additional nuclear structure information.

This research was conducted in collaboration with the Lawrence Livermore National Laboratory, specifically with Dr. Jason Burke and Ph.D. student Johnathon Koglin from Pennsylvania State University.

2. Theory and Background

2.1 Theory

Reaction Mechanisms.

There are two general types of reaction processes: direct and compound. In direct reactions, the incident particle interacts with the surface nucleons, and occurs on a rapid time scale, on the order of $\sim 10^{-22}$ seconds. In order for this to occur, the incident nucleons must have high enough energy, and hence short enough de Broglie wavelengths, to interact with the individual nucleons. For example, a 1 MeV nucleon will have a de Broglie wavelength of about 4 fm, which is on the order of the size of the nucleus, and thus will interact with the nucleus as a whole, and not the individual nucleons. However, a 20-MeV incident nucleon has a de Broglie wavelength closer to 1 fm, which is on the order of the size of individual nucleons, and thus is more likely to interact with individual nucleons in a direct reaction process.

Compound reactions occur on a much longer time scale than direct reactions, on the order of $\sim 10^{-15}$ - 10^{-18} seconds. The energy of the incident particle is “shared” among multiple nucleons in the target nucleus. The longer time scale for this type of reaction allows the nucleus to “forget” how it was formed. Because of the increased time scale for the compound reaction, the probability of the compound nucleus decaying by a given channel is independent of the method in which it was formed. It is because of these properties of compound nuclear reactions that the surrogate method is a valid approach for determining cross sections and other nuclear structure data for difficult-to-measure isotopes.

Surrogate Method.

The surrogate reaction technique is a way to create the same compound nucleus as the isotope of interest by using a nearby but different isotope that is easier to measure. The reaction of interest takes the form of $a + A \rightarrow B^* \rightarrow c + C$, where B^* is the compound nucleus, while the surrogate reaction takes the form of $d + D \rightarrow B^* + b \rightarrow c + C$ [2]. The subsequent decay of the compound nucleus B^* is the channel that is measured to extract the cross section. An illustration of this reaction is shown in Figure 1. The method assumes that the same compound nucleus is made by the

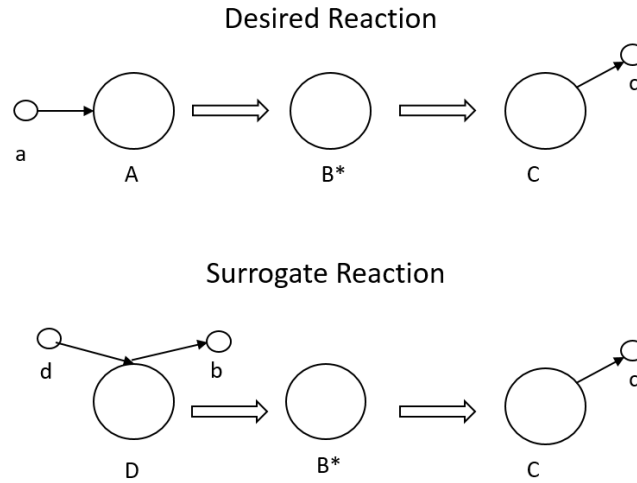


Figure 1. Schematic representation of the desired reaction and the surrogate reaction.

two different reactions. This is a valid assumption because the time for which the compound nucleus exists is several orders of magnitude longer, 10^{-18} to 10^{-16} seconds, than the characteristic absorption time of the incident particle, which is on the order of 10^{-22} seconds [3]. The surrogate method can be used to determine reaction cross sections on an isotope of interest because the same compound nucleus is made as would be made by the direct reaction, and it will decay by the same channels. For example, Burke et al. in [2] used the $^{238}\text{U}(\alpha, \alpha' f)$ reaction as a surrogate for the

$^{237}\text{U}(n, f)$ reaction to determine differential cross sections, since the half-life of ^{237}U is only 6.75 days. Here, the compound nucleus in common is the highly excited $^{238}\text{U}^*$ nucleus, the same compound nucleus from neutron absorption in ^{237}U , and the probability for that nucleus to decay by fission is hence measurable.

Hauser-Feshbach Theory.

Compound-nuclear reactions are described by the statistical Hauser-Feshbach theory [4]. Equation 1 gives the average cross section per unit energy in the outgoing channel χ' for reactions proceeding to an energy region in the final nucleus described by a level density.

$$\frac{d\sigma_{\alpha\chi}^{HF}(E_a)}{dE_\chi} = \pi\lambda_\alpha^2 \sum_{J\pi} \omega_\alpha^J \sum_{\ell s \ell' s' I'} \frac{T_{\alpha\ell s}^J T_{\chi\ell' s'}^J \rho_{I'}(U') W_{\alpha\chi}(J)}{\sum_{\chi'' \ell'' s''} T_{\chi'' \ell'' s''}^J + \sum_{\chi'' \ell'' I''} \int T_{\chi'' \ell'' s''}^J(E_{\chi''}) \rho_{I''}(U'') dE_{\chi''}} \quad (1)$$

The variable descriptions are summarized in Table 1.

Table 1. Description of variables used in Equation 1.

α	Entrance channel
χ	Exit channel
E_a	Kinetic energy of projectile
E_χ	Kinetic energy of ejectile
λ_α	Reduced wavelength of projectile
i, i'	Spin of incident, outgoing particle
I, I'	Spin of target, residual nucleus
s, s'	Channel spin for α, χ
$J\pi$	Compound nucleus angular momentum and parity
ω_α^J	Statistical weight factor
ℓ	Relative orbital angular momentum
$T_{\alpha\ell s}^J$	Transmission coefficient
$\rho_{I'}(U')$	Density of levels of spin I' at excitation energy U'
χ''	All energetically possible final channels
$W_{\alpha\chi}$	Width fluctuation function

Equation 1 can be simplified to a first-order approximation by integrating the cross section of interest over all final-state energies, as well as neglecting the width fluctuations. Integrating over the final-state energies is actually the value of interest for the cross section [5]. With these simplifications, the cross section can be expressed as in Equation 2.

$$\sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi) \quad (2)$$

Here, σ_{α}^{CN} is the cross section for forming the compound nucleus at excitation energy E_{ex} , which has J^{π} angular momentum and parity, and G_{χ}^{CN} is the branching ratio of decay into exit channel χ . When the surrogate method is used to perform an experiment, the measurements provide $P_{\delta\chi}(E_{ex})$, the probability of forming a compound nucleus through entrance channel δ and exit channel χ , as in Equation 3.

$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi) \quad (3)$$

Here, $F_{\delta}^{CN}(E_{ex}, J, \pi)$ is the probability of forming the compound nucleus B^* through a given entrance channel, δ . In the case of calculating the cross sections for $^{87}\text{Y}(n, \gamma)$, a reaction of interest, the $^{89}\text{Y}(p, d)$ reaction is measured instead, which results in ^{88}Y . The experimentally determined cross sections provide $P_{p,d}(E)$ for this reaction, the probability that the compound nucleus was formed with energy E by the (p, d) reaction, which is then used to develop an approximate model for G_{γ}^{CN} , the branching ratio for a given gamma ray energy. Then, uncertain parameters in the calculation of G_{γ}^{CN} are fit until the experimentally measured $P_{p,d}(E)$ is reproduced. Finally, these parameters can be used to calculate the (n, γ) cross section.

In general, in order to calculate accurate cross sections for various reactions, a precise description of the nuclear structure is required. Some of the necessary information

includes the gamma ray strength function, the level densities, and the energies, J^π , and branching ratios of the discrete low-lying nuclear states, as well as a good optical model fit. The optical model will be discussed briefly in Section 2.1. The gamma ray strength function is the distribution of the averaged width of level transitions for a particular multipole type (E (electric) or M (magnetic)) as a function of gamma ray energy. For higher-energy nuclear excited states, it is more appropriate to discuss transitions in terms of the gamma ray strength function as opposed to individual gamma energies. In a similar way, at higher energies, where the levels are more closely spaced, it is more useful to think in terms of level density as opposed to individual energy levels. For low-lying nuclear states, the branching ratio is the probability that a given level will decay by gamma ray emission to a specific lower level. The shapes of the cross section distributions as a function of angle, such as those determined in this research, provide information on the angular momentum and parity of the excited nuclear states.

Much of the work done with the surrogate method has used an approximation with the application of the Hauser-Feshbach theory, such as the Weisskopf-Ewing (WE) limit [5]. In work done in the 1960s and 1970s, it was assumed that the Weisskopf-Ewing approximation, as shown in Equation 4, was not dependent on angular momentum and parity.

$$\sigma_{\alpha\chi}^{WE}(E_a) = \sigma_{\alpha}^{CN}(E_{ex})\mathcal{G}_{\chi}(E_{ex}) \quad (4)$$

In Equation 4, $\sigma_{\alpha\chi}^{WE}(E_a)$ represents the formation cross section for the compound nucleus at energy E_{ex} , and the branching ratio $G_{\chi}^{CN}(E_{ex}, J, \pi)$ from Equation 2 becomes instead $\mathcal{G}_{\chi}(E_{ex})$. While this approximation proved valid for (n, f) reactions, the results it supplies for (n, γ) reactions do not agree with experimental results. The Hauser-Feshbach version of the approximation, which relies on angular momen-

tum and parity (Equation 2), is necessary in order to computationally estimate cross sections for (n, γ) reactions. The Weisskopf-Ewing approximation also fails for the low-energy (<1.5 MeV) region for (n, f) reactions [6]. Experiments such as in this work help to provide constraints on G_{χ}^{CN} .

The Optical Model.

The cross section data obtained from this research will be used to determine the optical model potential for the reactions studied. The optical model can be used to determine the formation cross sections of compound nuclei. This model is a simplified model that accounts for particle-nucleus interactions in the presence of absorptive effects, and is named such because of the resemblance of the calculations to that of light on a semi-opaque glass sphere [3]. Often, this potential takes the form of Equation 5.

$$V(r) = V_c(r) + V_0 f(r) + iWg(r) \quad (5)$$

The term $V_c(r)$ is the Coulomb potential, since the incident particles considered here are charged; $V_0 f(r)$ includes the Woods-Saxon part of the real potential [7] that represents the strong nuclear force, which is nearly constant within the nucleus and exponentially decreases beyond it; and the imaginary term, $iWg(r)$, accounts for absorption. The $g(r)$ part of that term represents the position of the absorption, either at the surface or within the volume. Additional terms can be included for spin-orbit potential, symmetry, and others.

In many cases, the optical model can be used to calculate the formation cross section of the compound nucleus, $\sigma_{\alpha}^{CN} = \sigma(a + A \rightarrow B^*)$, with reasonable accuracy [2]. However, the decay probabilities for the different outgoing channels χ , G_{χ}^{CN} , are usually uncertain. By using the surrogate method, these probabilities can be determined, or at least constrained, for the reaction of interest.

Level Schemes.

The nucleus of every isotope can be excited to discrete energy states. When a proton is incident on a target nucleus, it can transfer some of its kinetic energy to the target nucleus, resulting in a nucleus in one of these excited states. Many of these states were observed in this experiment by measuring the energy of the outgoing particle and subtracting that energy from the energy of the beam. The National Nuclear Data Center (NNDC) at Brookhaven National Laboratory maintains an on-line database that pulls information from a number of other databases, such as the Nuclear Data Sheets, and brings it together in a graphical format. Figures 2, 3, 4, and 5 show the levels for the first few bands up to 6 MeV for ^{89}Y , ^{88}Y , ^{92}Zr , and ^{91}Zr , with energies listed in keV. ^{88}Y and ^{91}Zr are shown because those are the resultant nuclei from the (p,d) reaction on ^{89}Y and ^{92}Zr , respectively. Angular momentum-parity values in parentheses are tentative, according to their respective publications. The blue arrows indicate gamma decay transitions between levels.

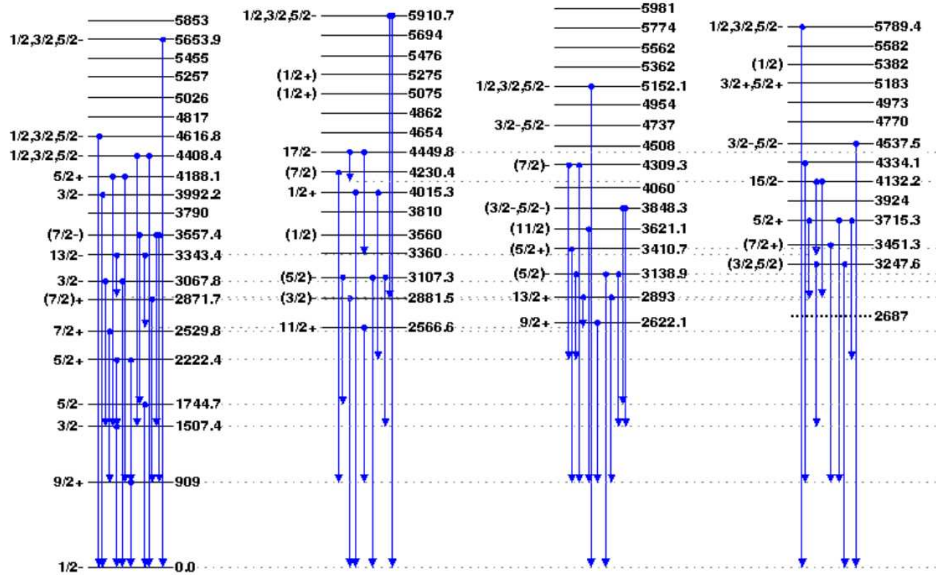


Figure 2. Partial level scheme for ^{89}Y , up to 6 MeV. Energies shown are in keV. [8]

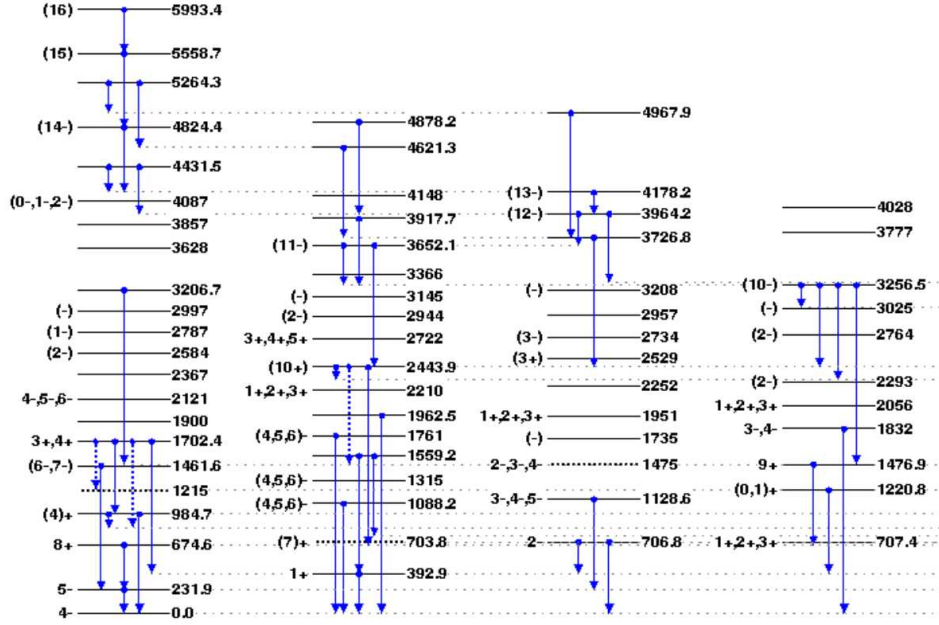


Figure 3. Partial level scheme for ^{88}Y , which is the result of the $^{89}\text{Y} (p, d)$ reaction, up to 6 MeV. Energies shown are in keV. [9]

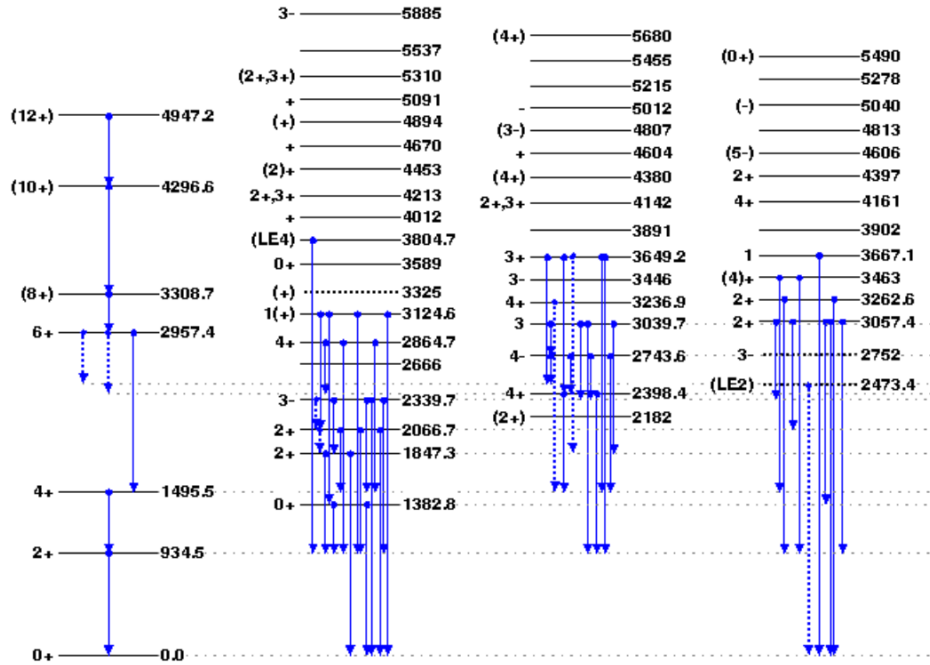


Figure 4. Partial level scheme for ^{92}Zr , up to 6 MeV. Energies shown are in keV. [10]

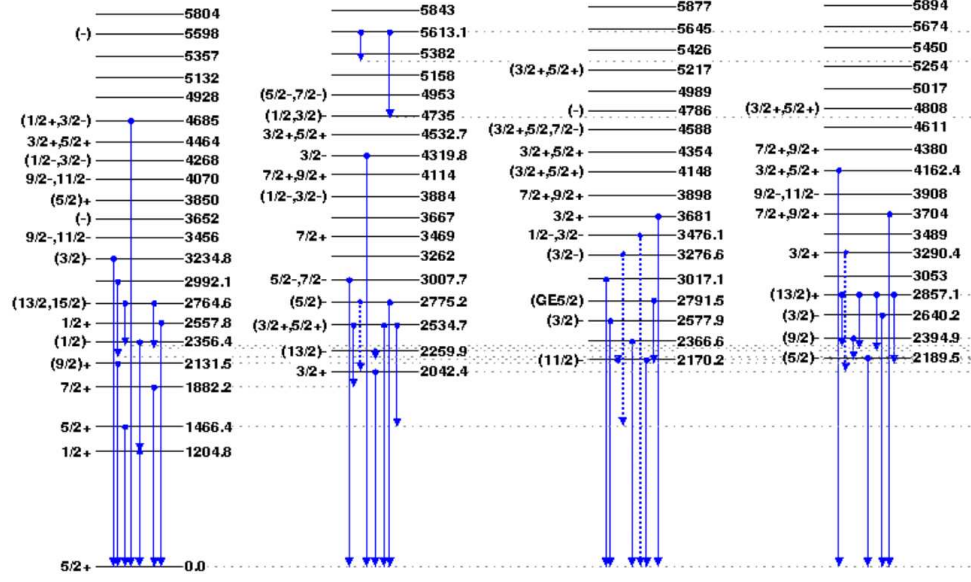


Figure 5. Partial level scheme for ^{91}Zr , which is a result of the $^{92}\text{Zr}(p,d)$ reaction, up to 6 MeV. Energies shown are in keV. [11]

Several of the low-lying states were observed in this experiment, and the levels listed in the NNDC database were used to identify the observed states.

2.2 Previous Work

The surrogate method was first used in the early 1970s by Cramer and Britt [12] to determine (n, f) cross sections for several actinides. They used the (t, pf) reaction on nearby nuclides, along with the calculation of the cross section of forming the compound nucleus from the optical model, to determine the (n, f) cross section data. They used the Weisskopf-Ewing approximation as well as Equation 2. Their results agreed with available direct measurements to within 10% – 20% for energies $\gtrsim 1$ MeV, but deviated more for lower energies. More recently, the surrogate method has received renewed interest, not only for determining (n, f) reactions for difficult-to-measure isotopes, such as some uranium isotopes in [13], [2], and [14], as well as

plutonium in [15] and other actinides, but also indirect (n, γ) measurements, such as in [16].

In the 1960s, it was shown in [17] that theoretical models could provide reasonably good fits between the optical model and experimental measurement of cross section data. Buck ([17]) created a model that works well for $A > 30$ isotopes that includes the effects of charged incident particles and spin-orbit coupling, and can be used with rotational and vibrational collective models. He compared this model to (p, n) cross section data taken for Ti, Cr, Fe, Ni, and Zn at energies 12-17 MeV, and concluded that the model fit the data quite well in most places.

Previous measurements of proton scattering cross sections were reported in [18] and [19], among others. In [18], (p, p') reaction cross sections were measured for ^{89}Y . One of their experiments used 24.5 MeV protons at the Michigan State University sector-focused cyclotron. Figure 6 shows the experimental data for the first two excited states of ^{89}Y fitted with the collective model, where they took the ground state of ^{89}Y to be a single proton in the $2p_{1/2}$ state outside a ^{88}Sr core. The authors concluded that a collective-model fit works reasonably well here.

In [20], the authors used the Oak Ridge National Laboratory 86-inch cyclotron to irradiate several zirconium isotopes with 22.5 MeV protons, covering outgoing angles 20° - 150° . Figure 7 shows the differential cross sections for elastic and inelastic scattering off of the ground state and two other low-lying states of ^{92}Zr .

These experiments and other similar measurements have been reported, but none of the existing literature has measurements at the right energy or cover enough angles to be used to determine detailed nuclear structure information for ^{89}Y and ^{92}Zr . Cross section measurements for the (p, p') and (p, d) reactions need to be obtained at a proton energy near 28.5 MeV in order to be compiled with the currently not-published $(p, p'\gamma)$ and $(p, d\gamma)$ taken during a recent experiment using a detector array

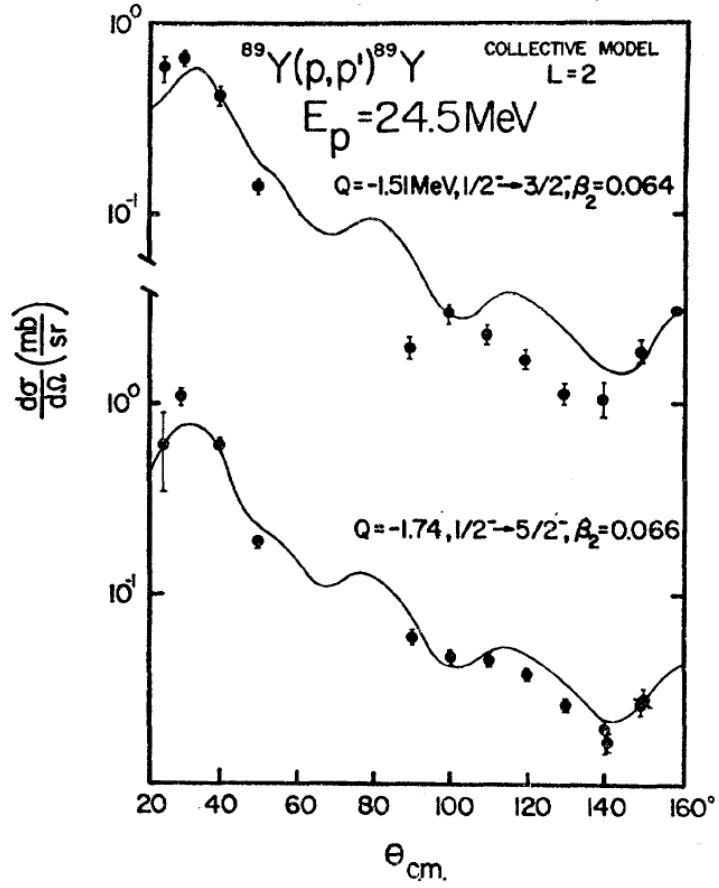


Figure 6. Collective-model fits for the (p, p') reaction of 24.5 MeV protons on ^{89}Y for the first two excited states. Reproduced with permission from [18].

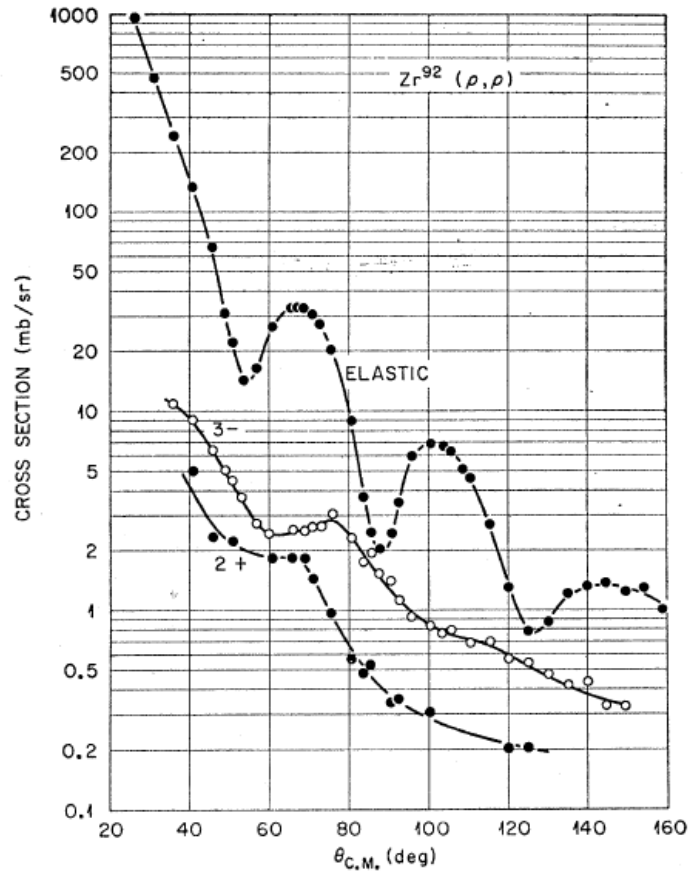


Figure 7. Differential cross sections for the the (p, p') reaction ground state and two low-lying excited states of ^{92}Zr . Reproduced from [20].

called STARLiTeR, which is described in [21] (for a different experiment) and was developed by the Lawrence Livermore National Laboratory. The experiment conducted in this work covers a wider angular distribution (10° - 140°) than the STARS/LIBERACE experiment did (30° - 60°), which will greatly improve the application of experimental results to the theoretical model. From this model, (n, γ) cross sections can be calculated for other rare earth isotopes (the lanthanides, as well as scandium and yttrium), including eventually isotopes farther from the valley of stability.

3. Experiment

3.1 Experiment Setup

The 88-inch cyclotron at the Lawrence Berkeley National Laboratory was used to bombard the Y and Zr targets with 28.25 MeV protons. The 12 silicon detectors, in a system named HYDRA that was developed by the Lawrence Livermore National Laboratory, are arranged in a circle in the reaction plane spanning 10° - 140° . The silicon detectors were in a $\Delta E - E$ configuration, using a $200\text{ }\mu\text{m}$ silicon detector just in front of a 5 mm lithium-drifted silicon detector in a telescope configuration. This setup allows for particles to be identified, as well as timing and energy information to be collected. Figure 8 shows a top-down view of the target chamber.

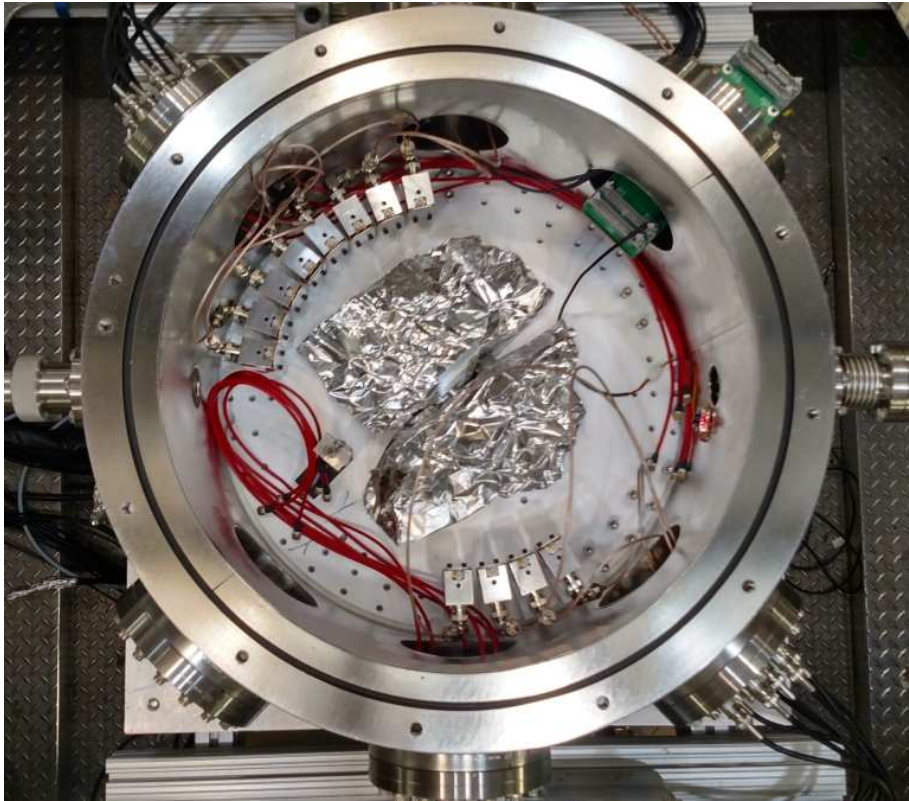


Figure 8. Top-down view of the HYDRA target chamber. The beam enters from the right and strikes the target in the center, and then exits to the left. At the time this photo was taken, not all of the detectors were connected.

To mount the $\Delta E - E$ detectors, custom brackets were made, which securely hold the ΔE detector to the front face of the E detector. These brackets mount to the floor of the chamber using optical mounts. Thin aluminum δ shields (16.26 μm thick) were attached in front of the ΔE detectors to block the δ electrons generated when the beam strikes the target from hitting the detectors. Only 12 detectors were available, so partway through the data collection, the 10° and 20° detector telescopes were moved to the 130° and 140° positions. Because of the high reaction rate at those most forward angles, a sufficient amount of data were collected at 10° and 20° after a shorter amount of time than the other angles. The detector telescopes had a 1σ energy resolution of 60 keV.

The targets were mounted on a remote-controlled target ladder inside of the chamber on aluminum frames. A phosphor target was also mounted on the ladder for beam tuning and alignment. Other targets included ^{90}Zr , ^{94}Zr , ^{208}Pb , and $^{\text{nat}}\text{C}$. The two zirconium targets were measured to help identify peaks from those isotopes in the ^{92}Zr data, since the ^{92}Zr target was enriched but was not isotopically pure, unlike the ^{89}Y target, which was isotopically pure. The ^{208}Pb target was measured because the relatively high mass of its nucleus means that it has less recoil when the proton beam strikes it, thus allowing a more accurate beam energy calculation. The $^{\text{nat}}\text{C}$ target was measured for contaminant subtraction. The carbon data also assisted with the determination of the beam energy, since the light carbon nuclei will have a much larger recoil energy, and will thus be more sensitive to the energy of the beam. A ^{226}Ra source was also placed in the target chamber before the experiment was performed to measure alpha energies for energy calibration of the detectors. It was removed before the start of the experiment.

Cross sections are reported per unit solid angle. To calculate the solid angle covered by the silicon detectors, Equation 6 was used from Knoll [22].

$$\Omega = 2\pi \left(1 - \frac{d}{\sqrt{d^2 + a^2}} \right) \quad (6)$$

Here, d is the distance between the source and the detector, and a is the diameter of a circular detector face. This equation assumes a point source. The spot size of the beam was approximately 3 mm, and the detectors were 15.716 cm away from the target, so this assumption is valid. Since only the particles that go through the ΔE detector first will be counted, the diameter of the ΔE detector was used for a . Using Equation 6, the solid angle subtended by each detector is 0.024083 sr.

3.2 Detector Efficiency Model

In order to determine whether these detectors were able to fully stop the protons and deuterons, simulations were run using the Geant4 toolkit [23]. The first simulation modeled one lithium-drifted silicon detector (Si(Li)), which has a 5 mm depletion depth and a radius of 8 mm. The specifications were based on the Ortec L-045-200-5 Si(Li) detector sheet, which are listed in Table 2, and schematics for both the L-series (E) and B-series (ΔE) detectors are shown in Figure 9.

Table 2. Specifications for the Ortec silicon detectors.

Manufacturer	Ortec	Ortec
Model	B-018-150-200	L-045-200-5
Function	Transmission	Full Energy
X (mm)	26.1	23.5
Y (mm)	7.9	15.2
Z (mm)	9.9	15.9
W (mm)	13.8	16
Area (mm ²)	150	200
Depletion depth	200 μ m	5 mm
α Resolution (keV)	18	45

In order to see the depths at which protons and deuterons deposit their energy on average for incident energies of 5-30 MeV, the detector model of just the E detector

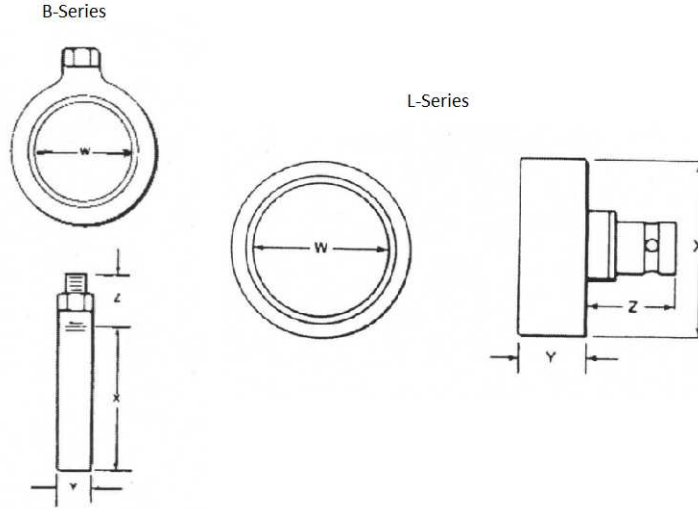


Figure 9. Design of the Ortec silicon detectors. The L-series is the lithium-drifted silicon detector, and the B-series is the totally depleted silicon surface barrier transmission detector.

was created consisting of 10 slices sandwiched together and surrounded by vacuum. Each slice was 0.5 mm thick. Figures 10 and 11 show a visualization of the detector model for one hundred 20 MeV protons from a point source.

As the protons and deuterons move through the detector, they will deposit energy in multiple steps along the way until they either stop or escape from the detector. Higher-energy particles will penetrate farther into the detector. One of the pieces of information collected from the simulations was the average energy deposited in each slice of the detector for each particle energy. Figure 12 shows the average energy deposited in each slice for protons of energy 5-30 MeV. Geant4 also provided the root-mean-square of the energies deposited, which make the error bars in the figure. Table 3 summarizes the data for two hundred thousand 25 MeV protons.

As the protons pass through the detector, they deposit increasingly larger amounts of energy in each slice up until they deposit the last of their energy and come to a full stop, which for the 25 MeV case is in the 8th slice, between 3.5-4.0 mm depth in the detector. This matches well with the specifications that Ortec reports for their 5 mm

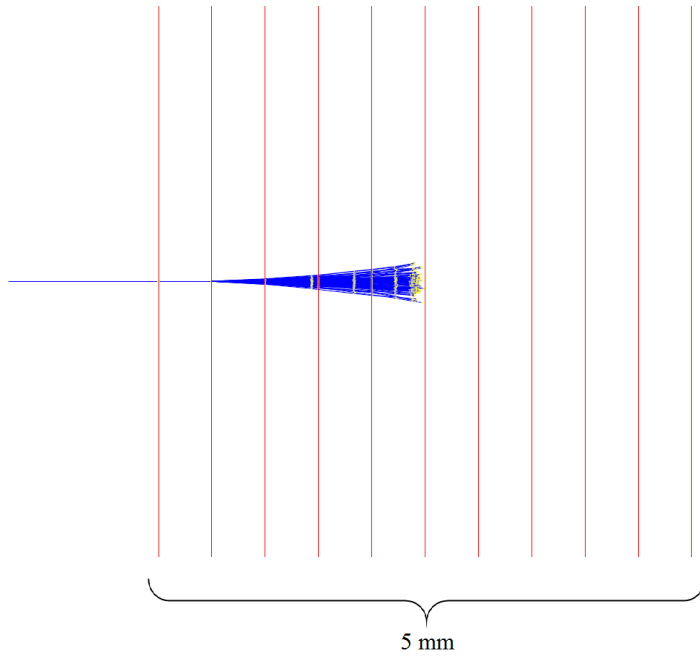


Figure 10. Side view of simulated Si(Li) detector with incident 20 MeV protons in vacuum (blue). The red lines indicate the slices of the detector made for the simulation.

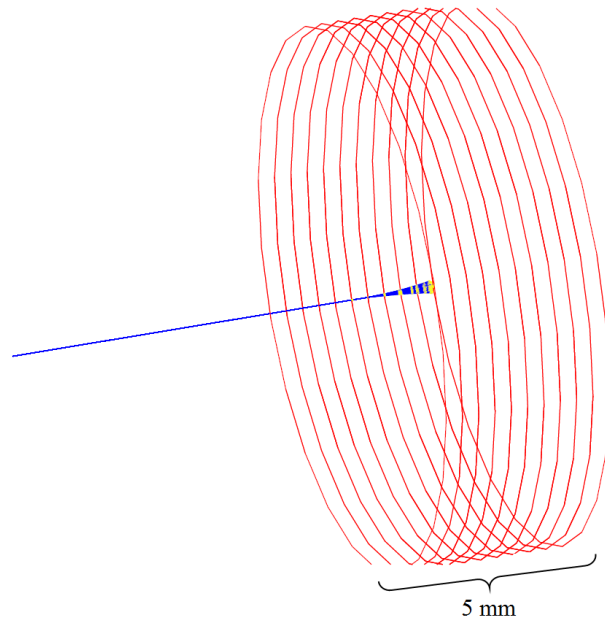


Figure 11. Rotated view of simulated Si(Li) detector.

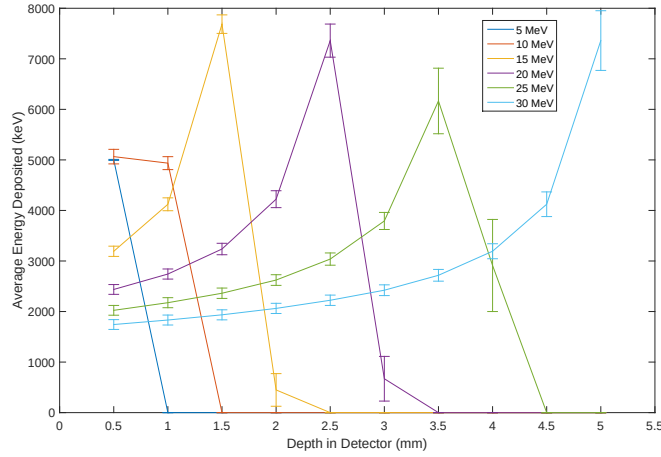


Figure 12. Average energy deposited by 5-30 MeV protons as a function of penetration depth into the detector.

Si(Li) detectors, which is that they can stop 25 MeV protons. At 30 MeV, some of the protons make it all the way through and exit the back of the detector.

In order to determine the efficiency of the silicon detectors, it is also necessary to know the probability that the incident particle will scatter out of the detector, either through the sides or the back. A second simulation was developed to model this using the Geant4 toolkit. The same detector model was used as described above, but instead of a single starting point, the particles were allowed to start anywhere within an area the size of the detector face, so that all particles generated could enter the detector at any point on the front face. Figure 13 shows a visualization of 100 protons interacting with the detector.

One million protons and deuterons were simulated with energies from 5-30 MeV in steps of 5 MeV (in separate runs), and the number of those that scattered out of the detector were counted. The results are shown in Table 4 and Figure 14.

For all of the configurations except for the 30 MeV protons, very few escape the detector either through the sides or the back. The majority of the 30 MeV protons escape through the back, as shown in the first simulation, which agrees with Ortec's

Table 3. Average energy deposited by 25 MeV protons as a function of penetration depth into the detector.

Slice	Mean energy deposited (keV)	RMS (keV)	Num. protons that passed through layer
1	2024	96.68	200000
2	2175	99.33	200000
3	2362	102.5	200000
4	2623	105.5	200000
5	3038	121.2	199989
6	3792	168.7	199972
7	6166	648.5	199941
8	2911	911	193829
9	0	0	0
10	0	0	0

Table 4. Probability of protons and deuterons 5-30 MeV to escape the Si(Li) detector.

Protons		
MeV	Num. Escape	Chance of Escape
5	612	0.061%
10	2801	0.28%
15	5895	0.59%
20	9622	0.96%
25	14350	1.44%
30	246646	24.66%
Deuterons		
MeV	Num. Escape	Chance of Escape
5	56	0.0056%
10	731	0.073%
15	1786	0.18%
20	3138	0.31%
25	4791	0.48%
30	6669	0.67%

detector specifications. The 30 MeV point was deleted from Figure 14 in order to make the other points more visible. This is a promising outcome, since it means that the vast majority of the particles that deposit energy in the detector will deposit their full energy and thus provide a very high efficiency for the detection of high-energy protons.

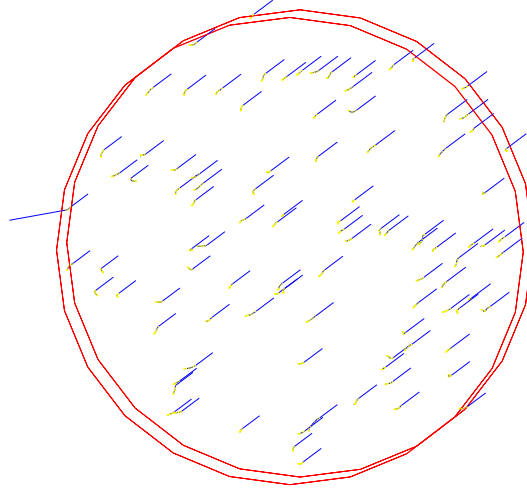


Figure 13. Visualization of a Si(Li) detector modeled in Geant4 with protons incident all over the surface.

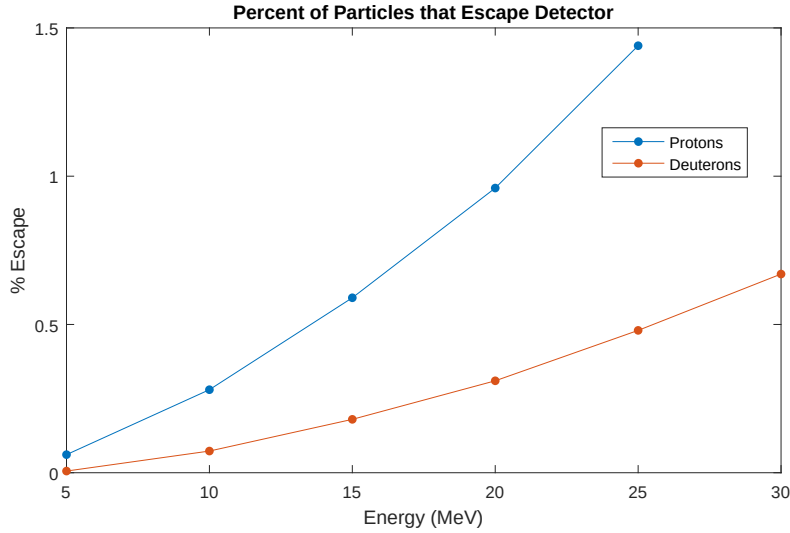


Figure 14. Probability that the protons and deuterons will escape the Si(Li) detector as a function of energy.

A third simulation was created that added the ΔE detector, a totally depleted silicon surface barrier detector, specifically the Ortec B-018-150-200, which has a radius of 6.9 mm and a depletion depth of 200 μm . As in the experimental setup, the 200 μm ΔE detector is situated directly on in front of the 5 mm E detector in the simulation. Figure 15 shows a visualization of this configuration with 20 MeV protons shown. Again, 1 million protons and deuterons of energies 5-30 MeV in increments

of 5 MeV were run. The results are provided in Table 5 and Figure 16.

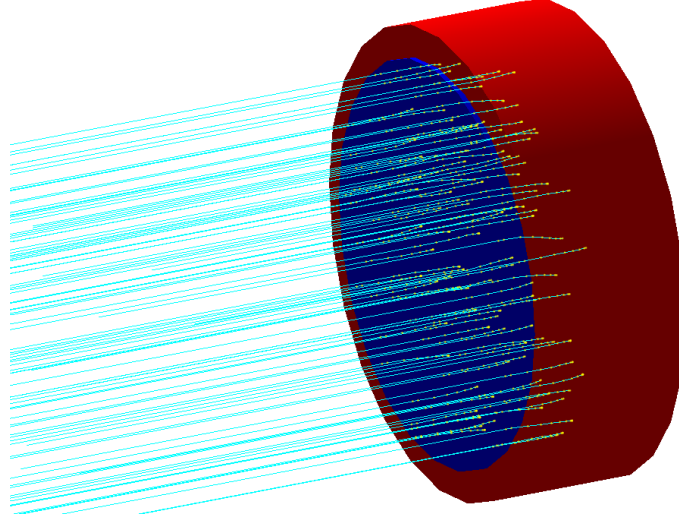


Figure 15. Side view of $\Delta E - E$ silicon telescope detector configuration in Geant4. The blue cylinder is the ΔE detector, and the red is the E detector. Shown here with 20 MeV protons.

Table 5. Probability of protons and deuterons 5-30 MeV to escape the $\Delta E - E$ detector configuration.

Protons		
MeV	Num. Escape	Chance of Escape
5	18	0.0018%
10	2	0.002%
15	5	0.005%
20	6	0.006%
25	23	0.0023%
30	118	0.0118%
Deuterons		
MeV	Num. Escape	Chance of Escape
5	0	0%
10	6	0.0006%
15	35	0.0035%
20	40	0.0040%
25	35	0.0035%
30	25	0.0025%

By adding the ΔE silicon detector, the probability of particles escaping the detector is even lower, nearly negligible. This is primarily because the ΔE detector has a

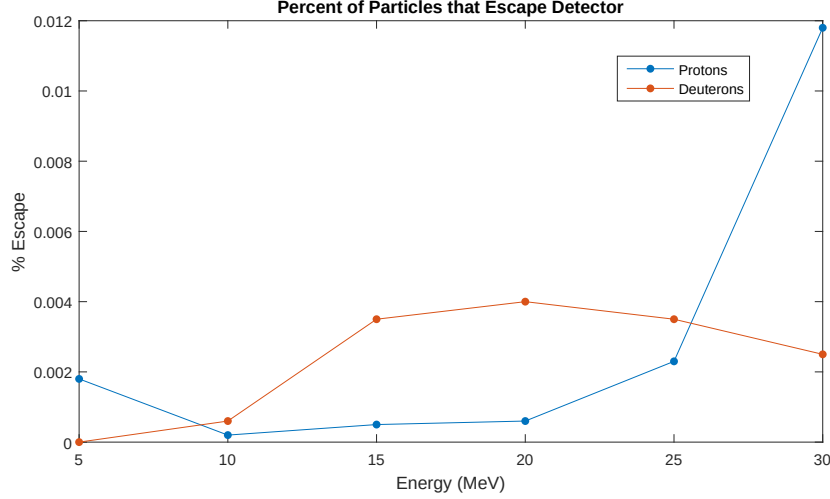


Figure 16. Probability of protons and deuterons 5-30 MeV escaping the $\Delta E - E$ detector configuration.

smaller diameter than the E detector, which means that no particles of interest that enter the E detector near its edge will be counted, since the two detectors were used in coincidence. Only particles that go through both detectors will be counted (as described in the next section), thus eliminating the ones that enter near the edges of the E detector and scatter out. Also, the additional detector depth from the ΔE detector that the particles must travel through greatly reduces the number of >25 MeV protons that escape the rear of the detector, allowing more of those to be counted.

3.3 Data Analysis

Data Acquisition System.

For each $\Delta E - E$ telescope, the ΔE and E signals go into a coincidence module. When the two signals are in coincidence, a trigger signal is sent to the analog-to-digital converters (ADCs). A gate and delay generator aligns the two signals in time. Each of those signals for all 12 detectors go into two pulse shapers, one for ΔE and one for E , and then the shaped pulses go into 13-bit ADCs. A master oscillator clock

set at 40 MHz, with precision to the millionth decimal place, sets the timing for the ADCs and TDCs (time-to-digital converters). Each ADC records which detector fired and the energy of the incident particle, and the TDC records the time of the signal arrival. This information was then written to a hard drive to be processed offline. A diagram of this setup is shown in Figure 17.

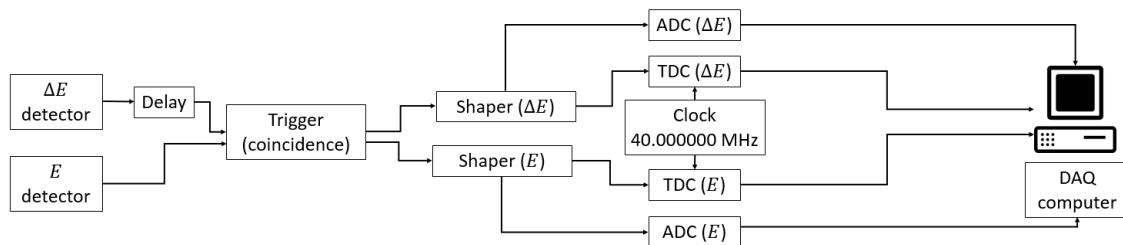


Figure 17. Diagram of the data acquisition system.

Besides energy data, timing data were also collected. When the trigger from the coincidence module fired, the TDC looked back into its buffer $10 \mu\text{s}$ and recorded the time difference between the current time from the master oscillator and the time that each signal within the window arrived, and output that time difference as a pulse measured in channel number in the same manner as the ADCs. The TDC data was used to discriminate between prompt and random events during the data processing stage.

Post-Processing.

When the data from the ADCs and TDCs were collected, it was saved as a custom-written file format as part of a data acquisition software suite called MIDAS, which was developed at LLNL. The information from each run is saved in a separate file, and contains the energy and timing pulse heights and which detector fired. These files are then converted to a binary format to reduce their size, and then they are time-ordered using a quick sort routine from *Numerical Recipes in C* [24]. Next, the data were extracted from the binary file, and a particle identification (PID) plot was

made by plotting the ΔE and E energies against each other. An example is shown in Figure 18.

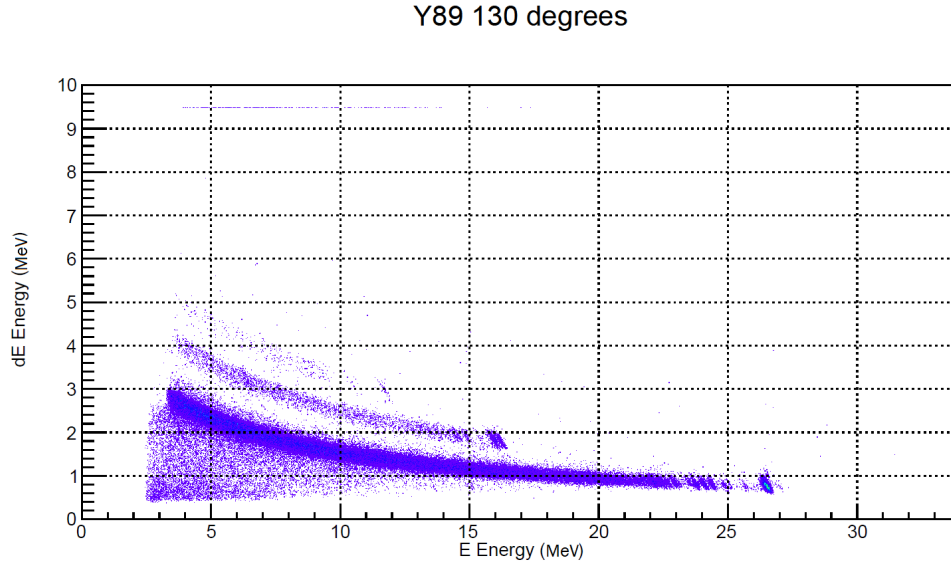


Figure 18. Example of a particle ID plot from a $\Delta E - E$ detector configuration. Data shown is from the ^{89}Y target, from the detector telescope at 130° . The bottom curve contains protons, the middle deuterons, and the top tritons. This example plot displays the data before the proper calibration and recoil corrections were applied.

The ΔE detector records the energy loss of the particles (protons, deuterons, or tritons) that pass through it, and discrimination between particles is possible because of differential energy loss. Plotting the energy deposited in the ΔE detector versus the energy deposited in the E detector results in different curves for different particles. In the PID plots such as the example shown, protons, deuterons, and tritons are all visible. The “hot spot” near 26.5 MeV in the proton curve is the large number of protons that scatter off the ground state of the nuclei. In order to apply a timing gate to discriminate random events from prompt events, the energy channels that this peak corresponds to were matched to their corresponding TDC values for the events that fill that peak, and the maximum and minimum times at which they occurred were recorded, which served as the timing gate criteria for all particles in each detector. Figure 19 shows an example of a timing spectrum for one of the E detectors. This

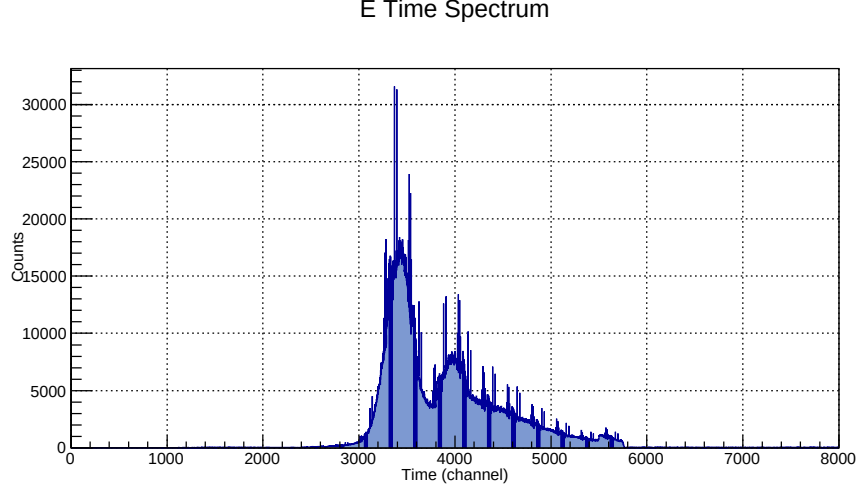


Figure 19. Example of a timing spectrum for the E detector at 30° , from one of the ^{89}Y datasets. The leftmost peak contains the prompt events, while the rightmost contains mostly random events, since they occur later in time after an event was triggered in the coincidence module. The time, shown here in terms of channel number, is recorded as the difference between the time from the master oscillator and the time at which the signal arrived, so lower channels correspond with shorter times between the triggering of the TDC and the occurrence of the event.

eliminated many of the random events, particularly within the cluster of points below the proton curve.

After the timing gate was applied, a calibration was applied to convert channel number to energy for both the ΔE and E detectors. The calibration was done using a ^{226}Ra source which, along with its daughters, emits four primary alphas: 4784 keV, 5489 keV, 6002 keV, and 7687 keV. The calibration measurements were collected with the δ shields removed. To get the calibration for the E detectors, the ΔE detectors were removed. A fifth point, the energy at which the protons scattering off the ground state of ^{208}Pb occurs in each detector array, was added to the E detector calibration, since higher-energy protons penetrate deeper into the detector and more fully deplete it than the alphas. The energy of the fifth point was determined by subtracting the recoil energy of the lead nucleus for each angle as well as the energy lost in the ΔE detector from the beam energy. The recoil energy of the lead nucleus was calculated by using Equation 7 from [3], and the energy lost in the ΔE detector was determined

by using an energy loss toolkit called ELAST (Energy Loss and Straggle Tool [25]) to calculate the energy lost by a 28.25 MeV proton traversing a 170-200 μm -thick silicon detector. A quadratic fit was done for each detector between the calibration points.

$$T_b^{1/2} = \frac{(m_a m_b T_a)^{1/2} \cos(\theta) \pm m_a m_b T_a \cos^2(\theta) + (m_T m_b)[m_T Q + (m_T - m_a)T_a]^{1/2}}{m_T + m_b} \quad (7)$$

T_b = Calculated energy of outgoing particle

T_a = Energy of the incident particle (beam energy)

m_a = Mass of incident particle (proton)

m_b = Mass out outgoing particle (proton or deuteron)

m_T = Mass of target nucleus

Q = Q-value of reaction

θ = Angle of outgoing particle with respect to the beam

Next, the recoil of the target nucleus was calculated for each angle, and that energy was added back to the measured energy of the outgoing particles. This provides the energy that the outgoing particle “should” have at a given angle, and then the recoil energy of the nucleus is determined by subtracting this value from the beam energy (in addition to adding the Q value for the reaction, if the outgoing particle is a deuteron). The Q value for the $^{89}\text{Y}(p, d)$ reaction is -9.25715 MeV, and for the $^{92}\text{Zr}(p, d)$ reaction it is -6.410224 MeV. The recoil energy (specific to the angle) is then added back to the measured energy of the particles.

Equation 8 was used to determine the energy of the states excited by the incident protons with all of the necessary corrections, including the recoil correction.

$$E_{ex} = E_{beam} - (E_{\Delta E} + E_E + E_{recoil} + E_{loss}) \quad (8)$$

Here, E_{beam} is the energy of the proton beam (28.25 MeV), $E_{\Delta E}$ is the energy deposited in the 200 μm silicon detector, E_E is the energy deposited in the 5 mm silicon detector, E_{recoil} is the calculated recoil energy for a given angle, and E_{loss} is the energy lost in the aluminum δ shield. SRIM (Stopping and Range of Ions in Matter) [26] was used to calculate the energy lost in the δ shield. The energy lost was minimal, only 20-25 keV for protons of energy 10-28 MeV, and 23-32 keV for deuterons of energy 10-28 MeV.

Next, the range was calculated in order to linearize the PID curves. This was necessary in order to easily gate on either protons or deuterons to measure the rate for that reaction. This was done by first using Equation 9 with the exponents shown in order to get the approximate cutoff between protons and deuterons, and then again after the recoil correction was applied with different exponents to get the curves to be as straight as possible. E_{tot} is the energy deposited in both the ΔE and E detectors added together, and E_E is just the energy deposited in the 5 mm E detector. Figure 20 shows an example of a range PID plot.

$$R = E_{tot}^{1.75} - E_E^{1.75} \quad (9)$$

After the range PID plots were produced for each input file, they were summed together into a total plot, which was saved to a text file. In another program, the range PID plot data were imported, and then the data were projected onto the range axis so that the cutoff between the protons and deuterons could be clearly determined. An example of the range projection plot is shown in Figure 21.

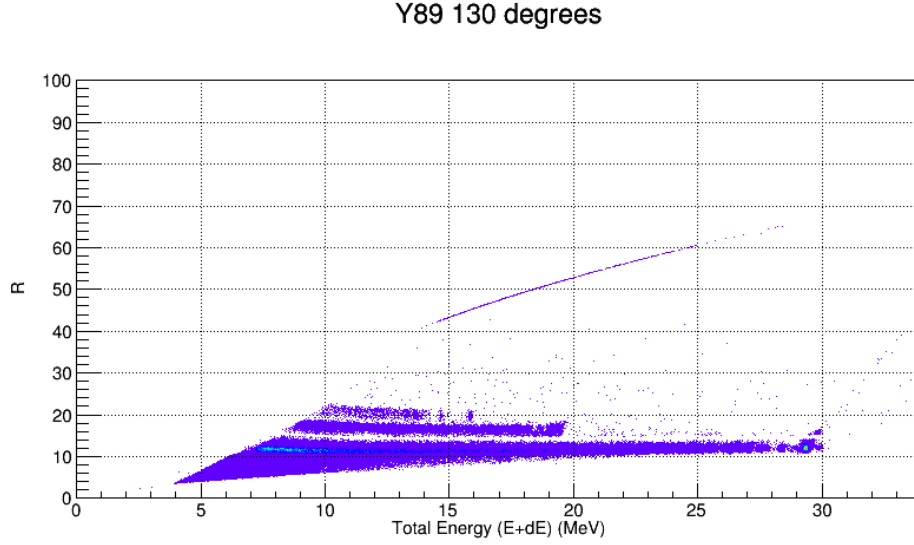


Figure 20. Example of a linearized particle ID plot for the $^{89}\text{Y}(p, p')$ reaction, from the 130° detector. The thin curved line near the top are data placed into the overflow bin at the top of the original (non-linearized) PID plot.

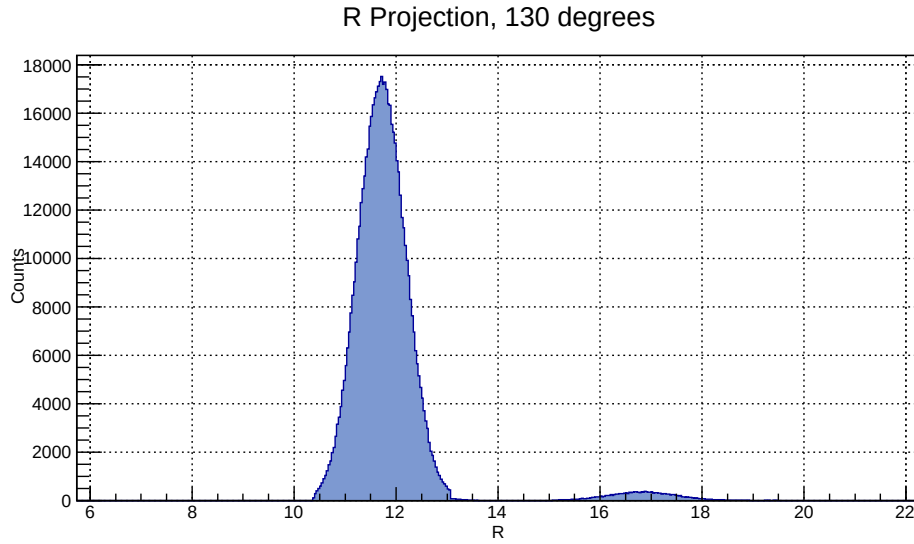


Figure 21. An example of the range PID plot projected onto the range axis in order to differentiate between protons and deuterons. This plot is for the ^{89}Y target from the 130° detector telescope. The value of the X-axis, the range, is calculated using Equation 9. The Y-axis is the number of counts. The leftmost peak contains protons, with the deuteron peak to the right.

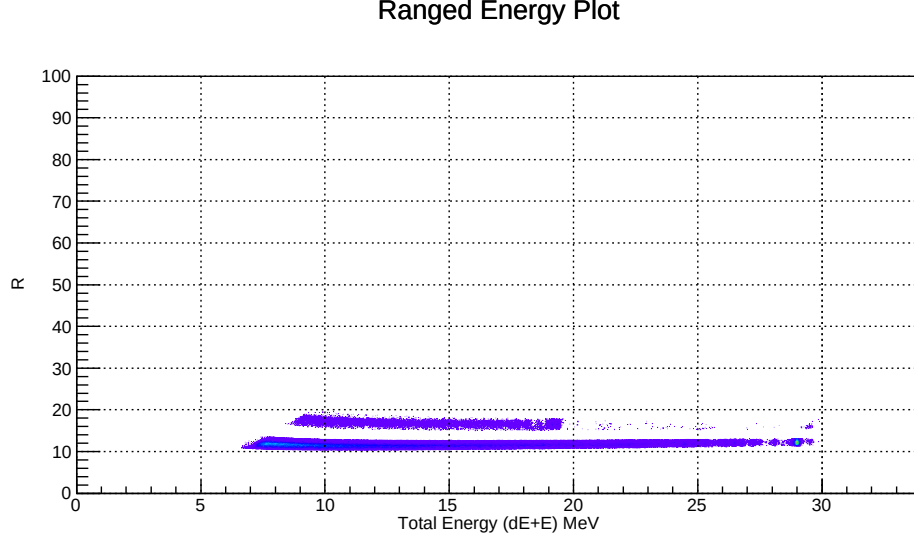


Figure 22. The range PID re-plotted without the points that fall outside of 3σ away from the mean of the proton and deuteron peaks in the range projection plot.

For each angle, the bounds of the range values for each peak were recorded, and then used for the next step of getting the energy spectra. These were determined by fitting a Gaussian function to the peak, and then using the mean $\mu + 3\sigma$ and $\mu - 3\sigma$ as the bounds. The range PID plot was then re-made without the points that fall outside of 3σ of the proton and deuteron peaks, an example of which is shown in Figure 22. This eliminates additional “random” particles (mostly protons) that were not eliminated with the timing gate alone in previous steps. These “random” protons are likely those that scatter off of other surfaces in the target chamber and lose some of their energy, such as the detector frame and the δ shield. The range projection shown in Figure 21 was generated after this cut was applied.

Next, a projection onto the particle energy axis is done for particles within the range bounds for either protons or deuterons, and this is the particle energy spectrum. An example is shown in Figures 23 and 24. In the energy spectra, the peaks indicate discrete nuclear states that were excited by the incident protons. Moving from right to left is the direction of increasing energy of the excited nuclear states. This is

because the incident protons lose some of their energy to promoting the nucleus to an excited state before they deposit their remaining energy in the detector. Exciting the nucleus to a higher-energy state leaves the proton with less energy. In the case of deuterons incident on the detector, they are less not only the energy of the excited state, but also the Q-value of the (p, d) reaction.

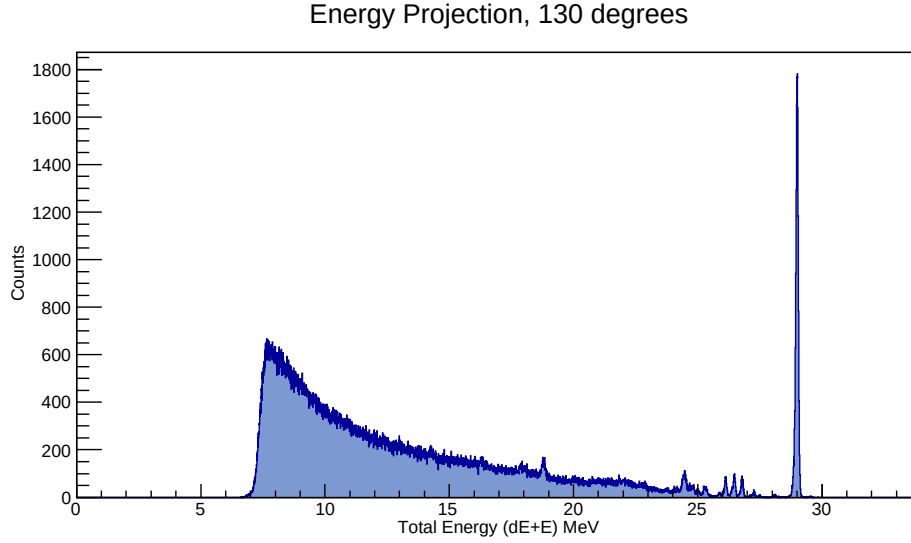


Figure 23. An example of the energy spectrum for the (p, p') reaction for ^{89}Y from the 130° detector telescope. The peak at the far right is the proton elastic scatter peak, and energy of the state excited by the incident protons increases to the left.

The peaks were then fit to Gaussian distributions using the ROOT peak fitting algorithm in its Minuit library. Once the parameters for the Gaussian fit were determined, the integral under the curve from -5σ to 5σ was calculated in order to determine the number of counts in that peak, as shown in Equation 10.

$$C = \left(\frac{1}{w} \right) \int_{\mu-5\sigma}^{\mu+5\sigma} A e^{-\frac{1}{2} \left(\frac{E-\mu}{\sigma} \right)^2} dE \quad (10)$$

Here, μ is the mean of the energy peak, σ is the standard deviation, A is the amplitude of the peak (counts), w is the bin width of the energy spectrum histogram (6 keV), and C is the total number of counts under the Gaussian-fitted peak. In order to

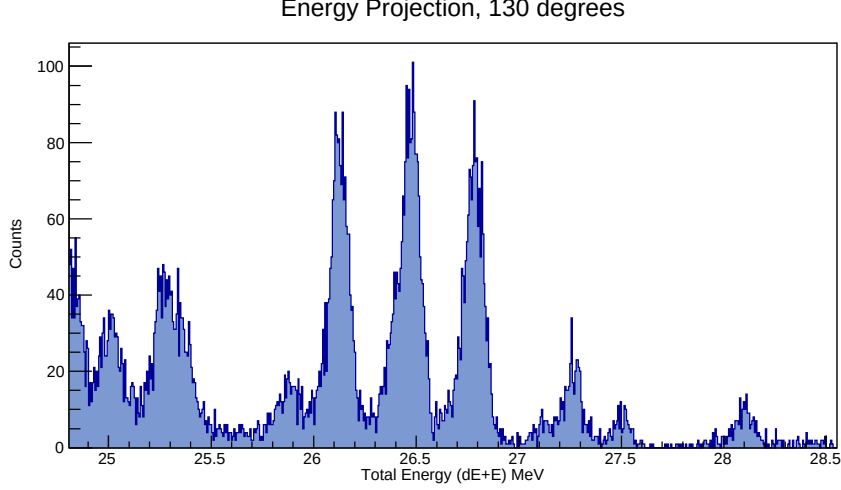


Figure 24. Figure 23, zoomed in to show detail.

determine which state corresponds with the peak, the mean energy for each peak was subtracted from the mean energy of the ground state peak, which is the largest and the furthest to the right in Figure 23. This allows a relative determination of the excitation energy of the nucleus. Figure 25 shows an example energy spectrum with labeled peaks, from the $^{89}\text{Y}(p, p')$ reaction at the 100° detector. Values in parentheses are the difference in keV between the mean of the Gaussian fits for that peak and the mean of the elastic peak at that angle, which is not shown in order to be able to see the excited state peaks more easily. Many of the higher-energy peaks show only the values in parentheses; this is because the known nuclear states become too close together to be able to identify with certainty, since the 1σ energy resolution was approximately 60 keV.

Once the number of counts under the Gaussian-fitted peak was calculated, the cross section for each nuclear state was calculated using Equation 11.

$$\frac{d\sigma}{d\Omega} = \frac{R/\ell}{I(1-c)(N/\cos(45^\circ))\Omega} \quad (11)$$

Here, R is the measured reaction rate for a single nuclear state at a single angle, ℓ

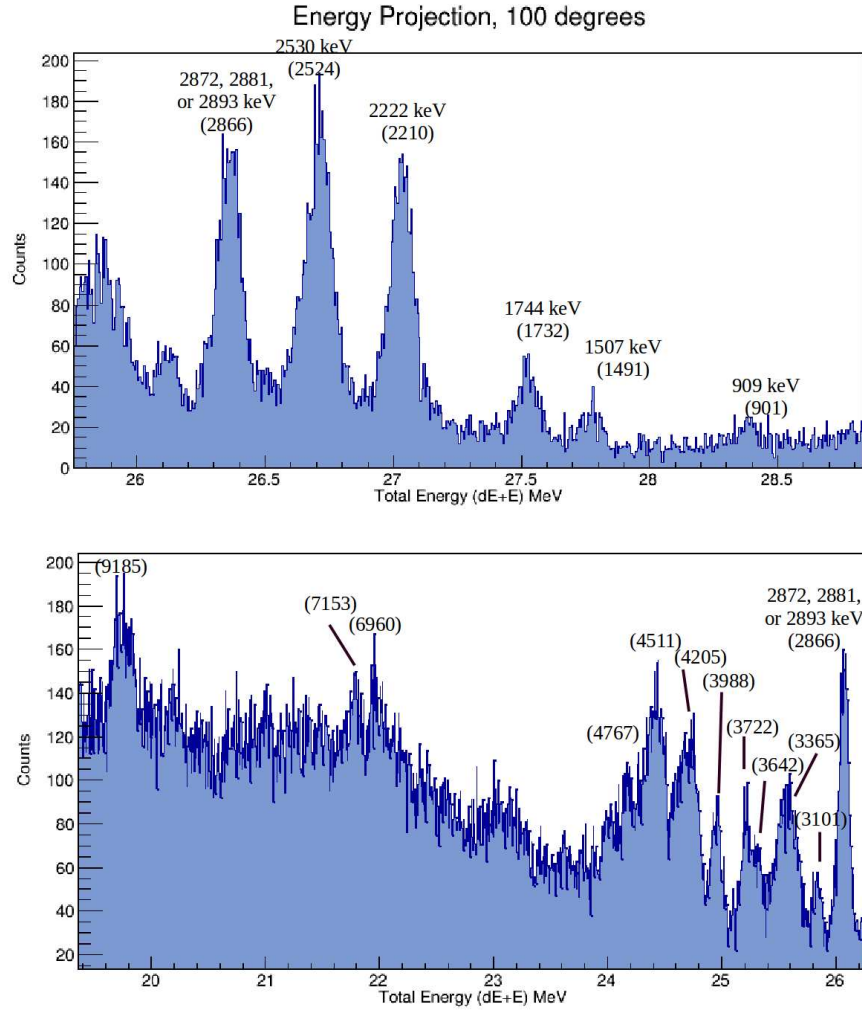


Figure 25. Labeled energy spectra for all discernible nuclear states for the $^{89}\text{Y}(p, p')$ reaction at the 100° detector. The top image are the lower-lying states, and the bottom image includes several of the higher-energy peaks. The elastic peak is not shown in order to more easily see the excited state peaks. Values in parentheses are the means of each peak subtracted from the mean of the elastic peak.

is the live time (as a percentage), I is the integrated beam current in Coulombs, c is a correction factor for the measurement of the beam current, N is the number of atoms in the target, and Ω is the solid angle subtended by a single detector. The live time was 87-94%, averaged for each angle over the course of the data collection time for each isotope. It was determined after the experiment that the beam current measured by the current integrator was slightly offset from the actual current, by 0.073 nA per unit nA, so this correction factor was taken into account as c . Since the target was mounted at a 45° angle with respect to the beam, the areal density of the target was divided by $\cos(45^\circ)$ to account for the additional thickness that the beam “sees.” The areal densities of the targets were 0.76 mg/cm^2 for the ^{89}Y target and 1.01 mg/cm^2 for the ^{92}Zr target, and were converted to number of atoms using Equation 12. The cross section is reported as mb/sr (millibarns per steradian) as a function of angle for each nuclear state.

$$N = \frac{\rho}{m_A} N_A \quad (12)$$

Here, ρ is the areal density of the target (converted to g/cm^2), m_A is the atomic mass in amu, and N_A is Avagadro’s number.

The codes that perform the post-processing were written in C/C++.

Error Analysis.

Alongside the calculation of the cross section, the uncertainty in that value was also calculated. There were three main sources of uncertainty: in the Gaussian fit, as reported by ROOT, and the uncertainty in the beam current and thickness of the target. The uncertainty associated with the live time is less than one percent, and thus does not contribute significantly to the total uncertainty of the cross section measurements. When ROOT performs its fitting routine, it provides an estimate of

the error of its fit for each parameter (the amplitude, the mean and the standard deviation). These were typically an order of magnitude or more smaller than the value of the parameter. The uncertainty in the beam current is given as 3-5%; 3% was used for the calculation. The uncertainty in the thickness of the target was taken to be 10%. To determine the uncertainty in the number of counts under each peak, the errors for each parameter of the Gaussian fitted to that peak were added or subtracted from the given value of the parameter, and then the integral under the Gaussian curve was calculated for each of these. To determine the low and high values of the cross section, the low and high values for the number of counts under the Gaussian curve, respectively, were used, as well as the beam current minus or plus the uncertainty.

The overall contribution to the total uncertainty in the cross section from the Gaussian fit uncertainty depended on the number of counts in the peak; for large peaks, the uncertainty in the fit was small, and for small peaks, the uncertainty was large. For example, the elastic peak at 10° for $^{89}\text{Y}(p, p')$ contained over two million counts, and the associated uncertainty in the Gaussian fit was only 0.4%. The two other sources of uncertainty, target thickness and beam current, made up the rest of the total uncertainty in the cross section for that angle at that energy, for a total of approximately 12%. On the other hand, the 1507 keV peak from the same reaction at 140° had only 71 counts, so the fit uncertainty was 70%, and the total uncertainty was 94%. Many of the cross sections did not have uncertainties quite this large, however; the majority are less than 30%, with many less than 20%.

4. Results and Analysis

4.1 Results

The final step of the data analysis was creating the angular distribution plots of the cross section data. Once the cross section and its associated uncertainty were determined for each angle for a particular nuclear state, the results were plotted as a function of angle, such as in Figure 26, which shows the cross sections for the 909 keV state excited by the (p, p') reaction on ^{89}Y .

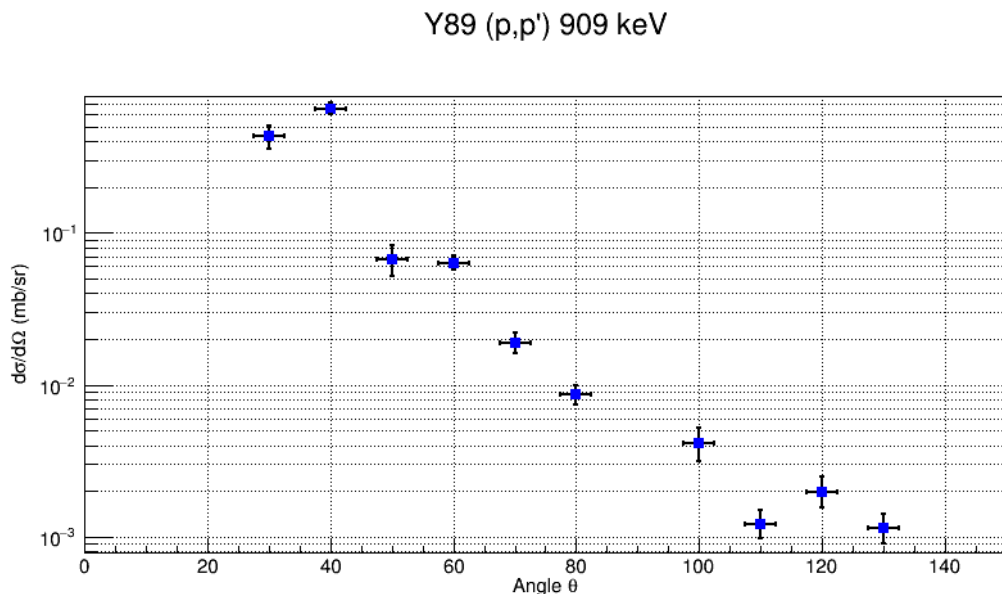


Figure 26. Cross section as a function of angle for the 909 keV state of ^{89}Y excited by the (p, p') reaction.

The horizontal error bars shown represent the width of the detector, which is 5° ($\pm 2.5^\circ$ on each side of the point). The shape of the plot that the cross sections provide gives information on the J^π of the nuclear state that was populated. That analysis is outside the scope of this work, but it is an important outcome of the data analysis in the near future.

Cross sections could not be determined for some of the angles. The 10° detector,

which spans approximately 7.5° to 12.5° , was forward enough in angle that most of the incident particles were directly from the beam without interacting with the target. Because of this, very few deuterons were present at that angle, and none of the excited states were visible either. At 20° , there was not much data available, since the 10° and 20° detectors were moved to the 130° and 140° positions after a short time. They were moved early on because of the high rate on the 10° detector due to its proximity to the beam. Data from the 90° detector showed fewer peaks than the other angles; this appears to be because the gain for the ΔE detector became approximately twice as high as the others, which spread out the data in the PID plots. Because the data were more spread out, only the tallest peaks are visible above the background in the energy spectra. Angular distribution plots for all other observed states are provided in Appendix A.

4.2 Comparison to Previous Work

To check these results against previous work, a comparison was made for a few of the states with experiments from the 1960s and 1970s done at similar proton beam energies. First, the ^{92}Zr elastic scatter peak was compared with the data from Ball, Fulmer and Bassel in 1964 [20]. They used a 22.5-MeV proton beam and irradiated several zirconium targets at the Oak Ridge National Laboratory 86-inch cyclotron, and measured the ejected protons and deuterons with a NaI(Tl) detector that was rotated between 20° - 150° . Figure 27 and Table 6 show data from this work and from [20] plotted together for comparison. Because of the large difference in beam energy, a difference in the measured cross sections is expected. However, the shape of the distribution between [20] and this work is quite similar, at least up to 110° .

In 1968, Benenson, Austin and Paddock [18] performed cross section measurements for ^{89}Y with a beam energy of 24.5 MeV, which is closer to the beam energy

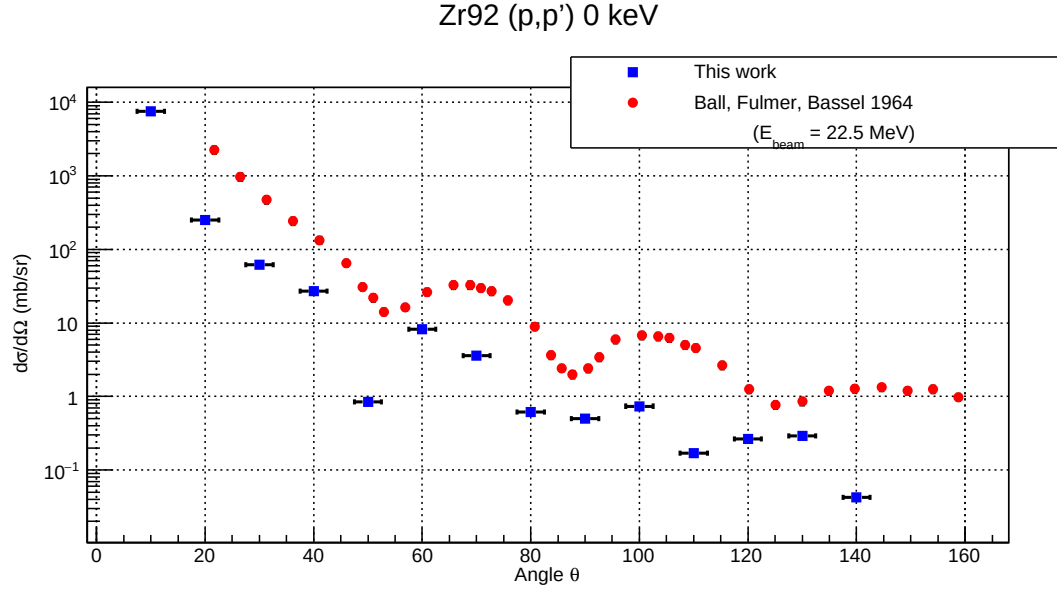


Figure 27. Cross section distributions for the elastic peak from $^{92}\text{Zr}(p,p')$ from both this work and [20]. The vertical error bars exist in both sets of data, but they are smaller than the points.

Table 6. Comparison between selected cross section values from [20] and this work. Note that the in [20], the beam energy is 22.5 MeV, and in this work it is 28.25 MeV.

Angle	Cross Section (mb/sr) from [20]	Cross Section (mb/sr) from this work
20	2250.0	252.3
40	133.0	27.0
60	26.4	8.16
80	8.93	0.62
100	6.76	0.74
120	1.25	0.27
140	1.28	0.043

used here. They also used a $\Delta E - E$ silicon detector telescope with an energy resolution of 100 keV, which was rotated around the target chamber to cover angles of 20°-150°. Figure 28 shows the cross section distribution for the lowest nuclear excited state of ^{89}Y populated by the (p, p') reaction compared to [18]. The values for these points are given in Table 7. Again, here, the energy of the incident protons in [18] was 24.5 MeV, so different values for the cross section are expected. The shapes of the angular distribution are similar, again until about 110°; after that, the slope of the distribution in [18] is less steep than that of this work.

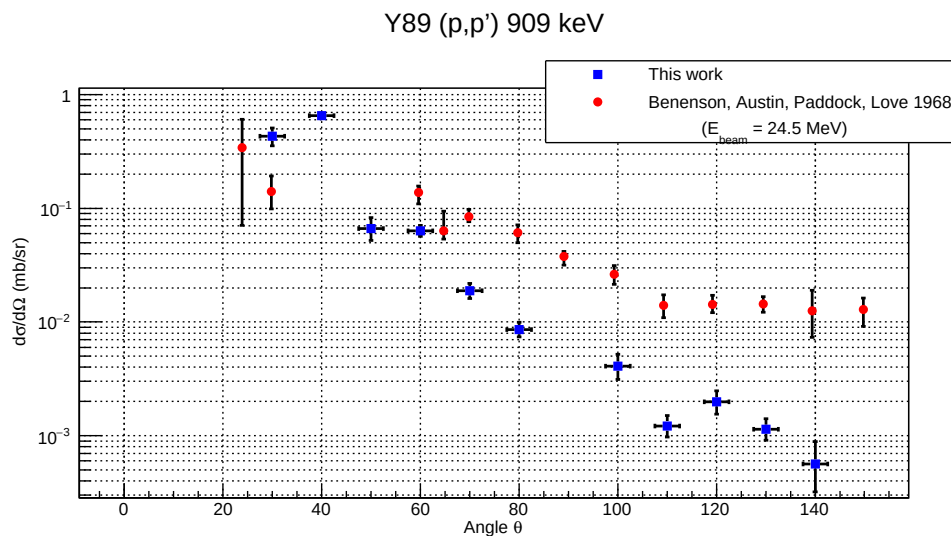


Figure 28. Cross section distributions for the 909 keV state of ^{89}Y from the (p, p') reaction, from both this work and [18].

For the (p, d) reaction, a comparison was made with Comfort, Nathan, Braithwaite and Duray [27], who used a 27.8 MeV proton beam, and detected the ejected protons and deuterons also using a $\Delta E - E$ silicon detector telescope that was rotated over angles 9°-50° in 3-4° intervals. Figure 29 and Table 8 compares the cross section distribution for the 766 keV nuclear state of ^{88}Y from the (p, d) reaction. Unfortunately, there is not much to compare with for this dataset, since the distribution from [27] covers the more forward angles, while the data collected here had poor results in the most forward angles (10° and 20°), especially for deuterons.

Table 7. Comparison between selected cross section values from [18] and this work. Note that the in [18], the beam energy is 24.5 MeV, and in this work it is 28.25 MeV.

Angle	Cross Section (mb/sr) from [18]	Cross Section (mb/sr) from this work
30	0.142	0.429
60	0.139	0.0636
70	0.0825	0.0188
80	0.0631	0.00861
110	0.0140	0.00122
120	0.0143	0.00198
130	0.0143	0.00114
140	0.0124	0.000564

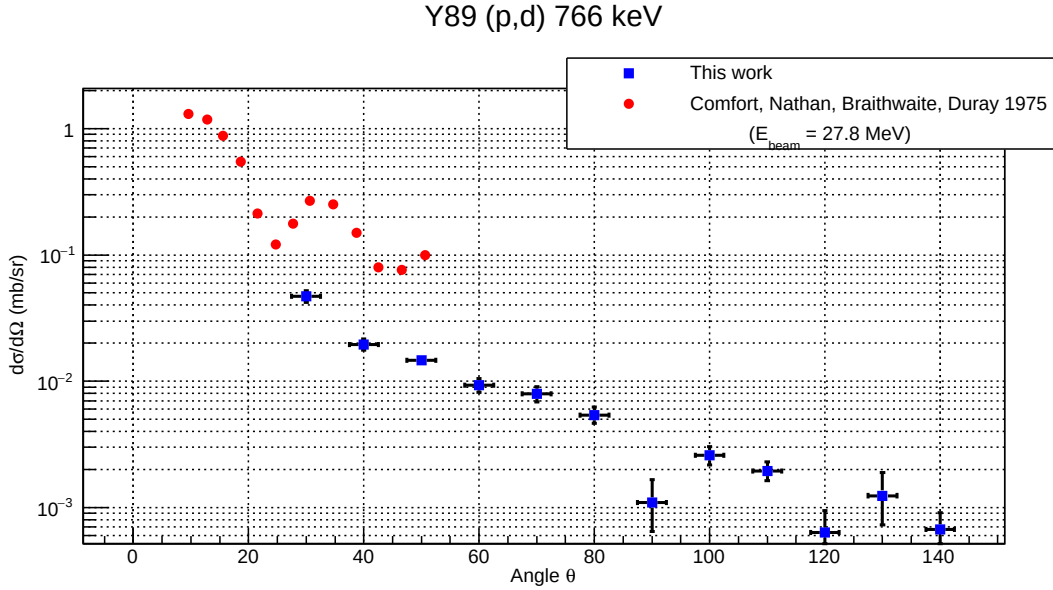


Figure 29. Cross section distributions for the 766 keV state of ^{88}Y from the (p, d) reaction, from both this work and [27].

4.3 Comparison to TALYS

TALYS-1.8 is a toolkit developed by European medical isotope producer NRG Petten and the French Alternative Energies and Atomic Energy Commission (CEA) that

Table 8. Comparison between selected cross section values from [27] and this work.

Angle	Cross Section (mb/sr) from [27]	Cross Section (mb/sr) from this work
30	0.269244	0.04699
40	0.149413	0.019544
50	0.099295	0.014616

simulates nuclear reactions [28]. It is capable of simulating reactions with incident energies of 1 keV - 200 MeV for protons, neutrons, gammas, tritons, helium-3, and alpha particles, and can be used for targets with mass number 12-339. It utilizes the optical model to calculate total and partial cross sections, energy spectrum angular distributions, double-differential spectra, and more. The TALYS-based Evaluated Nuclear Data Library (TENDL) was created using output from TALYS. TALYS draws nuclear structure parameters for its calculations from the IAEA Reference Input Parameter Library.

In order to compare this model to the experimental data obtained in this research, the output from TALYS was plotted alongside data from this work. The default optical model parameters were not changed for this comparison. Figure 30 shows one such plot, for the 935 keV state populated by the $^{92}\text{Zr}(p, p')$ reaction. While the values for the cross sections are not very close in many cases, the general shape of the angular distribution follows the experimental data quite closely. It is clear that in this case, the optical model settings used by TALYS fit reasonably well to what is experimentally observed.

Another example of reasonable agreement between model and experiment is shown in Figure 31, which shows a comparison for the 2222 keV state populated by the $^{89}\text{Y}(p, p')$ reaction. The agreement here in the shape of the angular distribution is not as good as in Figure 30, but the shapes of the distributions are relatively similar.

It was not always the case that the cross sections from this research were lower

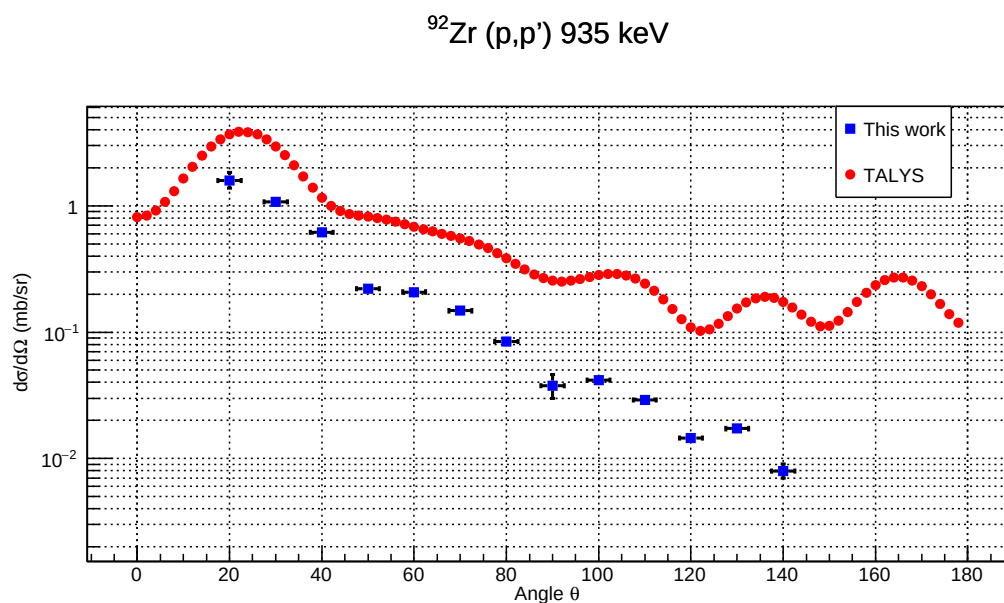


Figure 30. A comparison with output from TALYS for the 935 keV state populated by the $^{92}\text{Zr}(p,p')$ reaction.

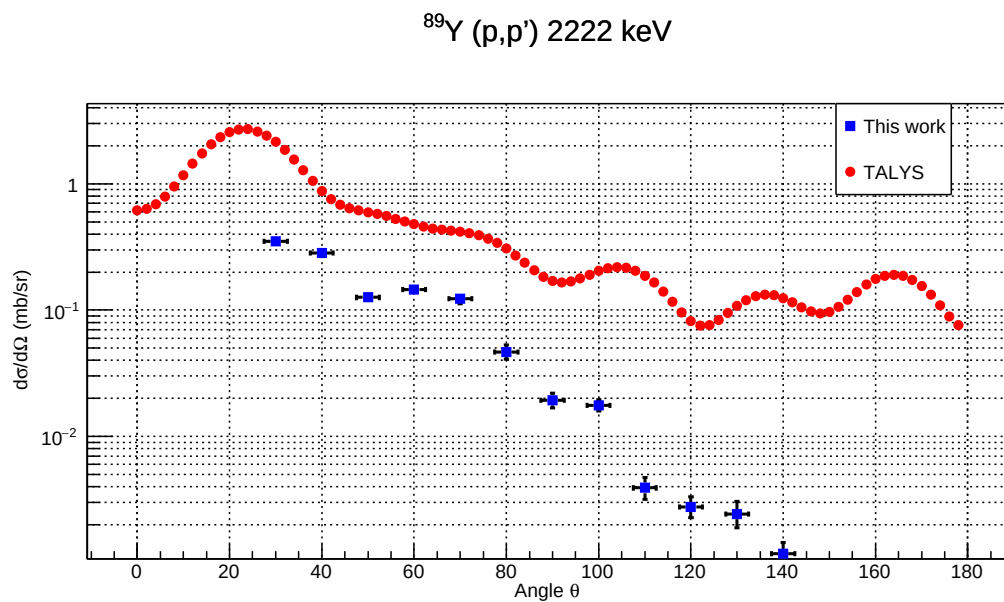


Figure 31. A comparison with output from TALYS for the 2222 keV state populated by the $^{89}\text{Y}(p,p')$ reaction.

than the output from TALYS. Figure 32 shows an example where the results from TALYS were closer in magnitude but lower than the experimental results. Again, here, the shapes of the angular distributions are quite similar.

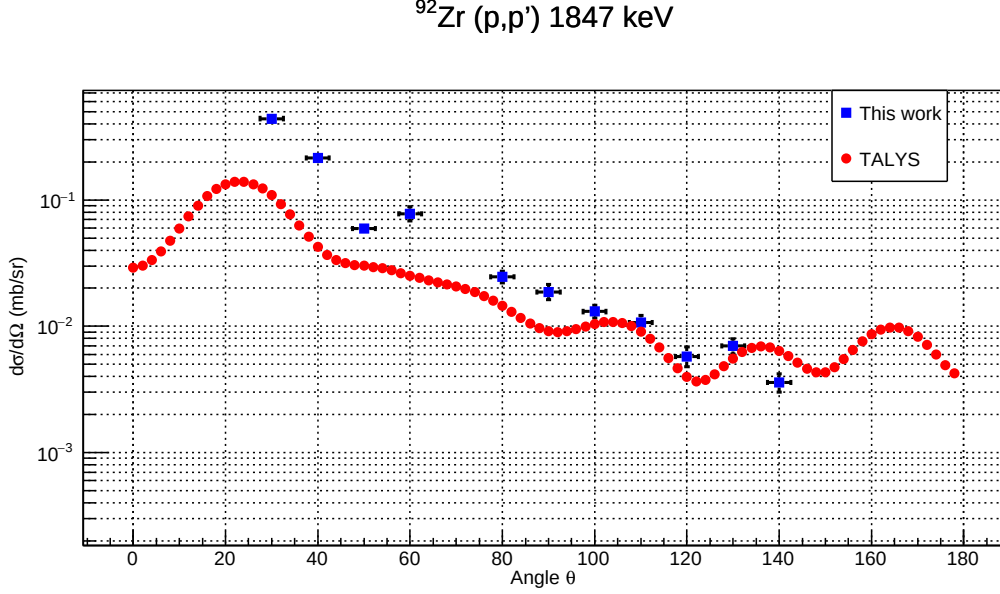


Figure 32. A comparison with output from TALYS for the 1847 keV state populated by the $^{92}\text{Zr}(p,p')$ reaction.

However, there were also many shortfalls with the output from TALYS. In the case of the $^{89}\text{Y}(p,p')$ reaction, there are several low-lying nuclear states that were observed in this research and in previous work that were absent from the TALYS output; for example, the 909, 1507, 1744, and 2530 keV states. Another problem appeared with the output for the (p,d) reactions for both isotopes studied. When compared to both the results from this research and those in the literature, the angular distributions produced for this reaction by TALYS appeared quite different. Figure 33 provides an example. It is obvious that the shape of the modeled distribution does not at all match experiment.

Despite the similarities in the shapes of the angular distributions for the (p,p') reaction, it is clear that there are more effects at work than are taken into account with current theoretical models such as TALYS. It is suspected that there may be an

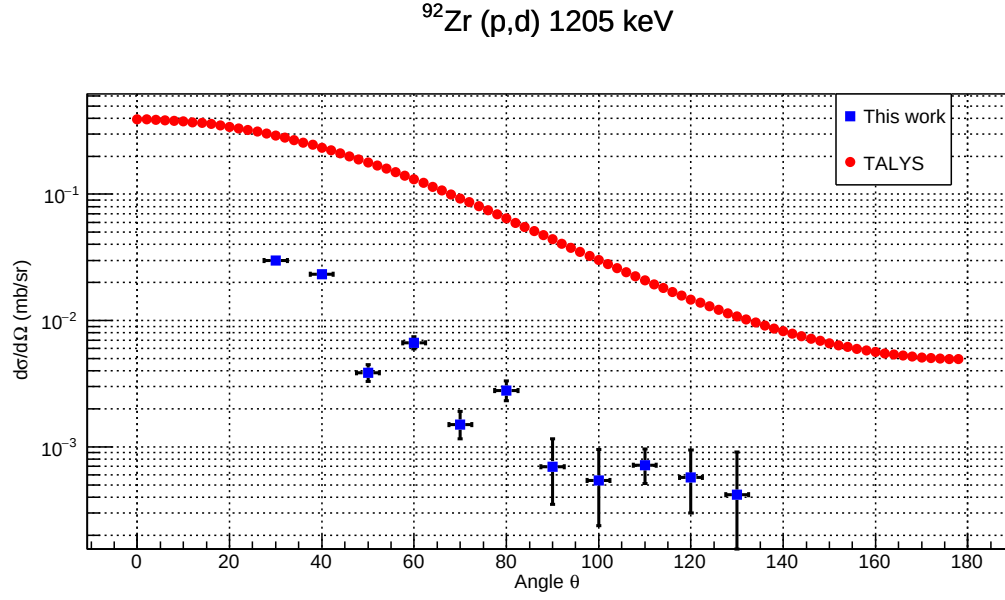


Figure 33. A comparison with output from TALYS for the 1205 keV state populated by the $^{92}\text{Zr}(p,d)$ reaction.

intermediate state before the formation of the compound nucleus, which introduces more complex configurations than previously considered. Experimental data for nuclear reactions on nearby neighbors to the isotopes of interest help to constrain the theoretical models and provide deeper insight to the nuclear structure, especially J^π values, of the isotopes of interest.

5. Conclusion

This research provided differential cross section and nuclear structure data for the $^{89}\text{Y}(p, p')$, $^{89}\text{Y}(p, d)$, $^{92}\text{Zr}(p, p')$, and $^{92}\text{Zr}(p, d)$ reactions to aid theoretical models that predict reaction cross sections for these and other isotopes. The differential cross sections measured in this research will be combined with data from $(p, p'\gamma)$ and $(p, d\gamma)$ reactions on these same isotopes from another experiment to discern detailed nuclear structure information, such as excited state energy levels and angular momentum-parity (J^π) states. Results from this and other experiments will be used to constrain theoretical models of compound nuclear reactions in order to predict cross sections for neutron reactions for nearby isotopes.

Once improved models are validated by experiment, cross sections for other isotopes can be determined, including short-lived rare earth isotopes, by using the surrogate method. Having a sound theory of nuclear reaction mechanisms and the ability to indirectly determine cross sections for short-lived isotopes has applications for nuclear forensics as well as astrophysics, national security, nuclear energy, and other fields. Knowledge of neutron cross sections, validated experimentally using the surrogate method, is key to understanding a number of nuclear and astrophysical processes.

In previous experiments done in the 1960s and 1970s, it was assumed that the theoretical determination of cross sections was not dependent on the angular momentum and parity of the nucleus that results from a given reaction, but in recent years this assumption has been shown to be invalid, particularly for (n, γ) reactions and low-energy (n, f) reactions (below 1.5 MeV). Knowledge of angular momentum and parity values of the possible excited nuclear states is an important component for a robust reaction theory, and the shapes of the angular distributions of the cross sections, such as those determined in this research, allow for those J^π values to be obtained. The ^{89}Y cross section distributions will provide an experimental constraint for calculating

cross sections for the $^{87}\text{Y}(n, \gamma)$ reaction by using $^{89}\text{Y}(p, d)$ as a surrogate reaction. An experiment done previously that has not yet been published made this measurement, but only for angles 30° - 60° ; this work covers a larger angular distribution, 10° - 140° , which improves the determination of J^π values. The $^{92}\text{Zr}(p, d)$ reaction is a surrogate for $^{90}\text{Zr}(n, \gamma)$ in the same way, but since ^{90}Zr is a stable isotope and thus more easily measurable, it serves as a benchmark in the application of the improved theoretical model.

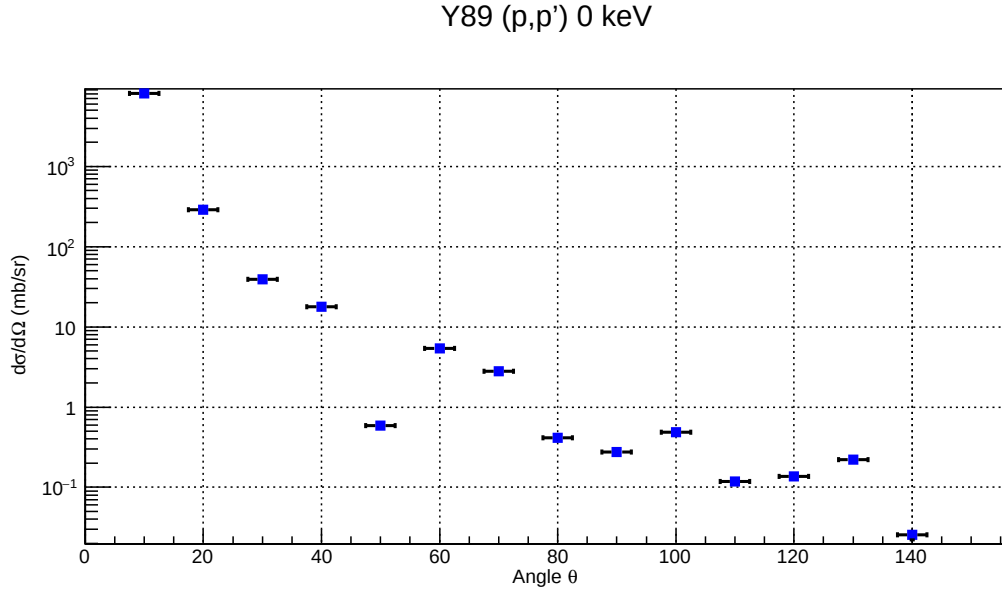
A new apparatus, HYDRA, was used for the measurement, employing twelve silicon detector telescopes to detect protons, deuterons, tritons, and alpha particles ejected from the target nuclei after irradiation from a proton beam. This system proved to be an effective method for measuring differential cross sections for discrete nuclear states. ^{89}Y and ^{92}Zr were the first such measurements done with this apparatus, and future experiments are in the planning stages with the addition of an array of solar cells for fission fragment detection. An upcoming experiment will use the $^{239}\text{Pu}(d, pf)$ reaction as a benchmark for use of the solar cells, since neutron-induced fission cross sections are well-known for ^{239}Pu , and eventually this apparatus will be used to measure neutron reaction cross sections for other actinides.

Appendix A.

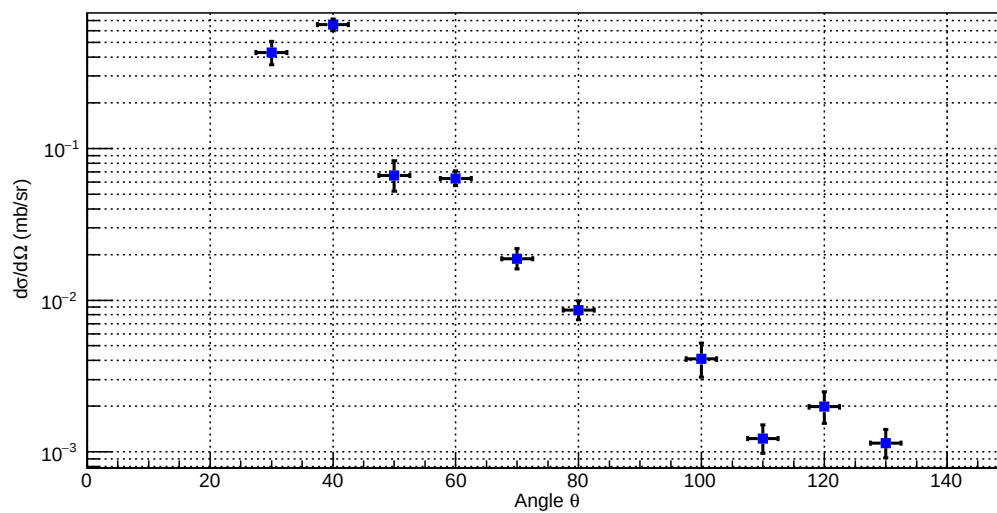
A.1 Cross Section Distributions

$^{89}\text{Y} (p, p')$.

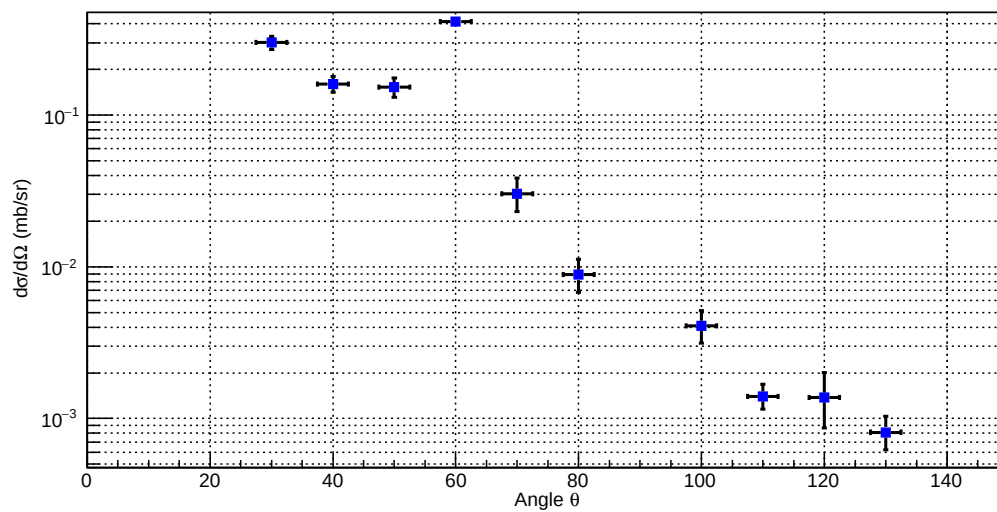
The plots shown here are the cross section distributions for each discernible nuclear state for the $^{89}\text{Y} (p, p')$ reaction. Absent points indicate that the nuclear state at that energy was not discernible at that angle, due either to an insufficient amount of counts under the peak or its proximity to another peak, which made fitting a correct Gaussian to that peak impossible.



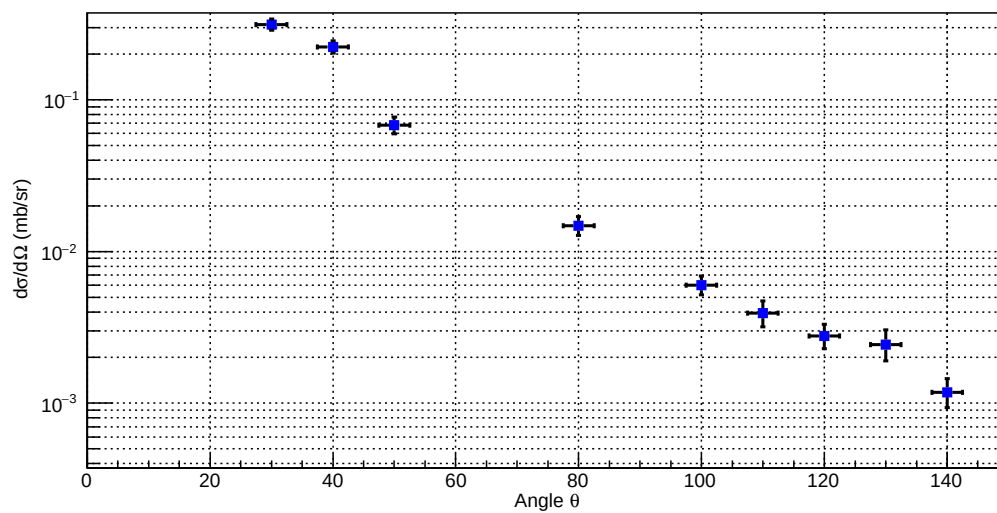
Y89 (p,p') 909 keV



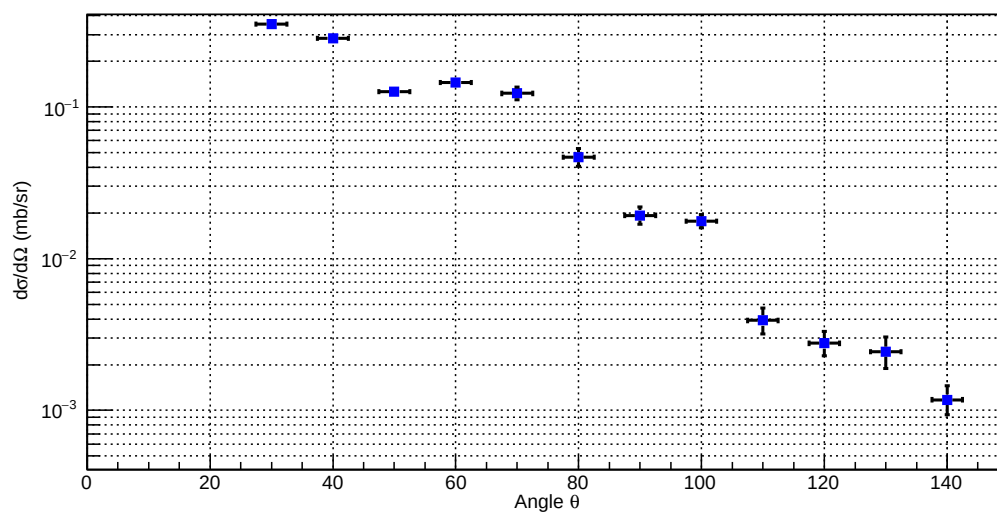
Y89 (p,p') 1507 keV



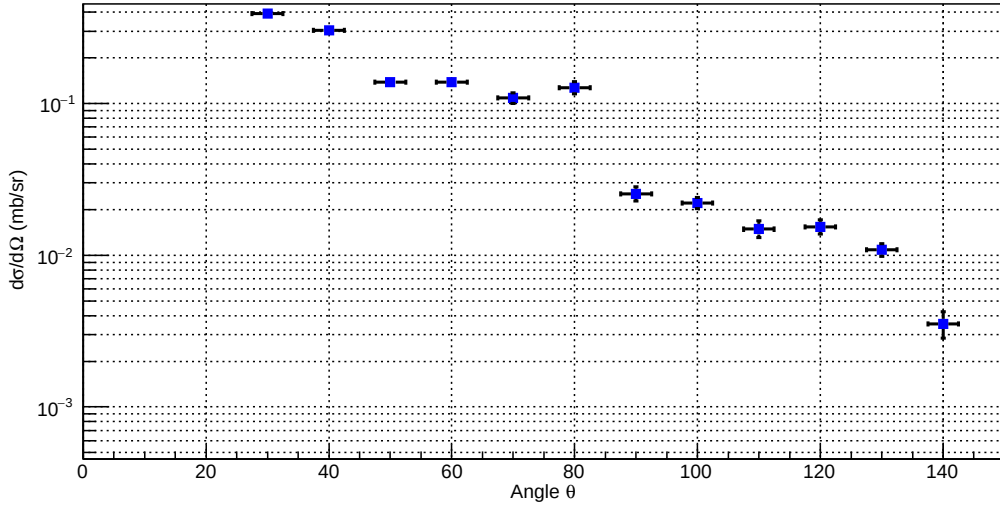
Y89 (p,p') 1744 keV



Y89 (p,p') 2222 keV

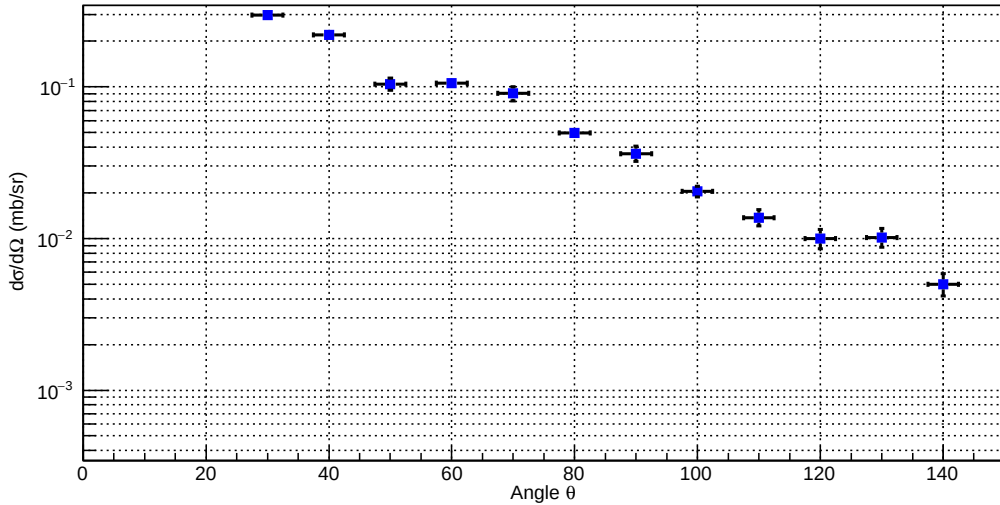


Y89 (p,p') 2530 keV

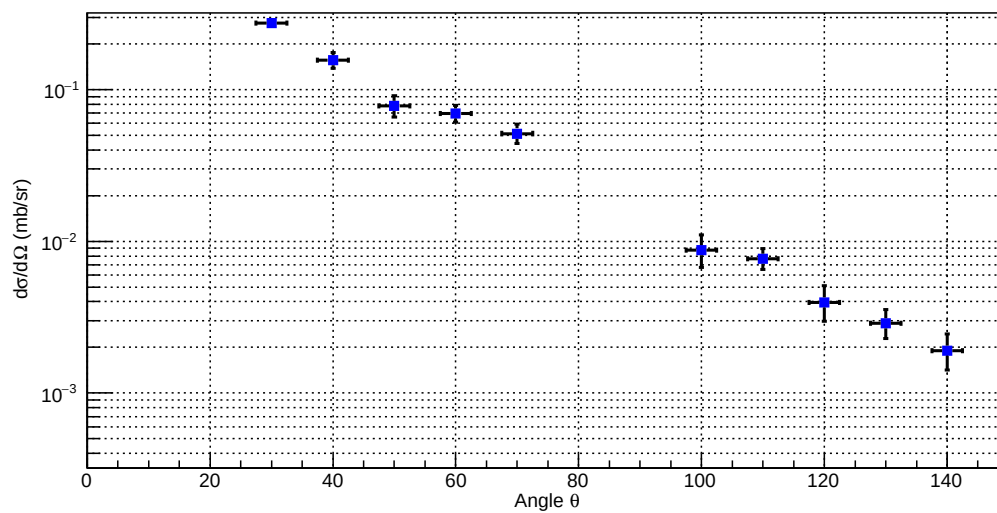


In the following plots, there is more than one known state in the vicinity of the energy of the peak in the energy spectra. The peaks are well-resolved, but which state they belong to is difficult to discern because of the 60 keV detector resolution. The plots are labeled here as groups of 100 keV that the peak may be located within. For example, there are three possible known states in the 2800 keV range (2872 keV, 2882 keV, and 2893 keV [8]), so the plot is labeled 2800 keV.

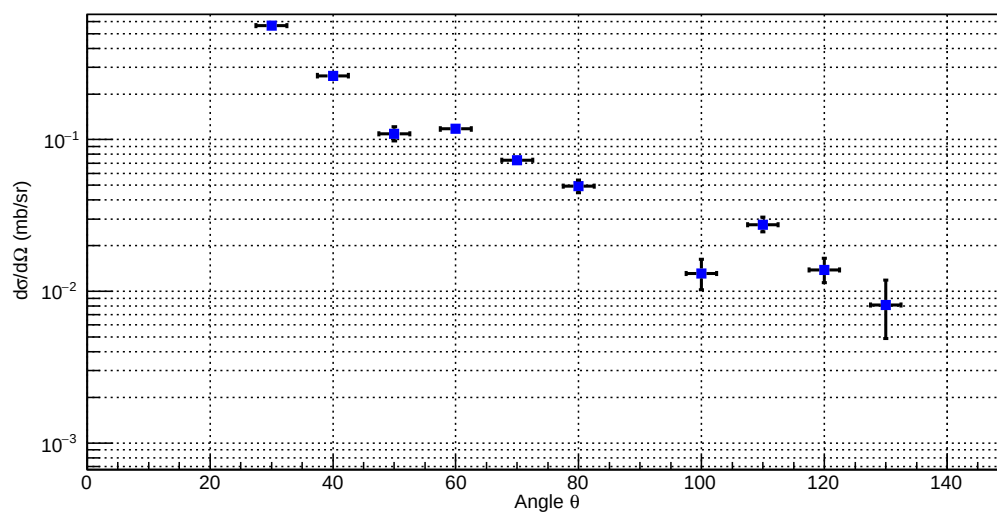
Y89 (p,p') 2800 keV



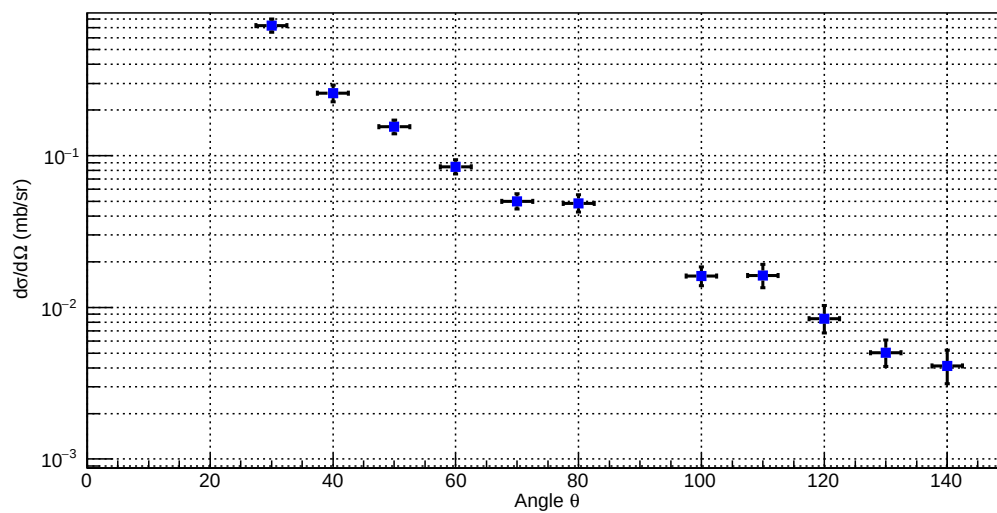
Y89 (p,p') 3100 keV



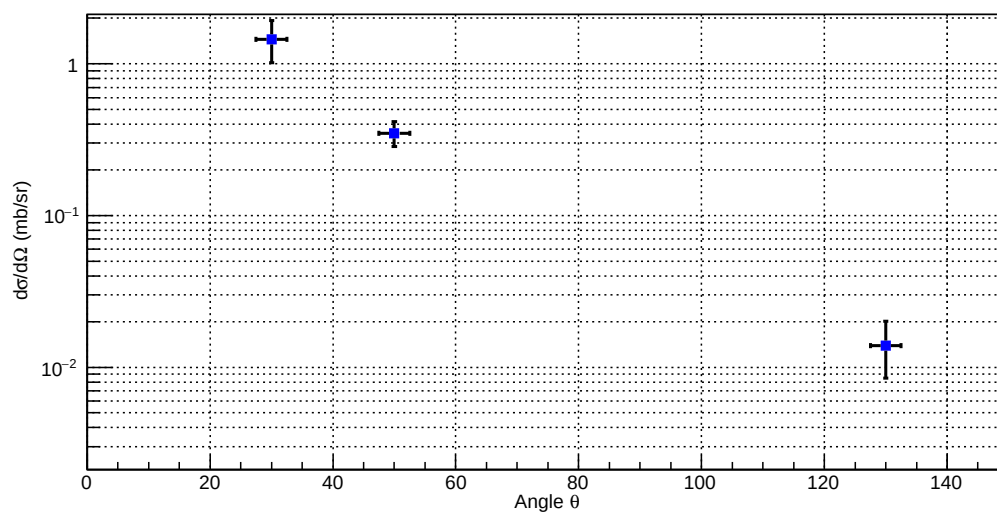
Y89 (p,p') 3700 keV



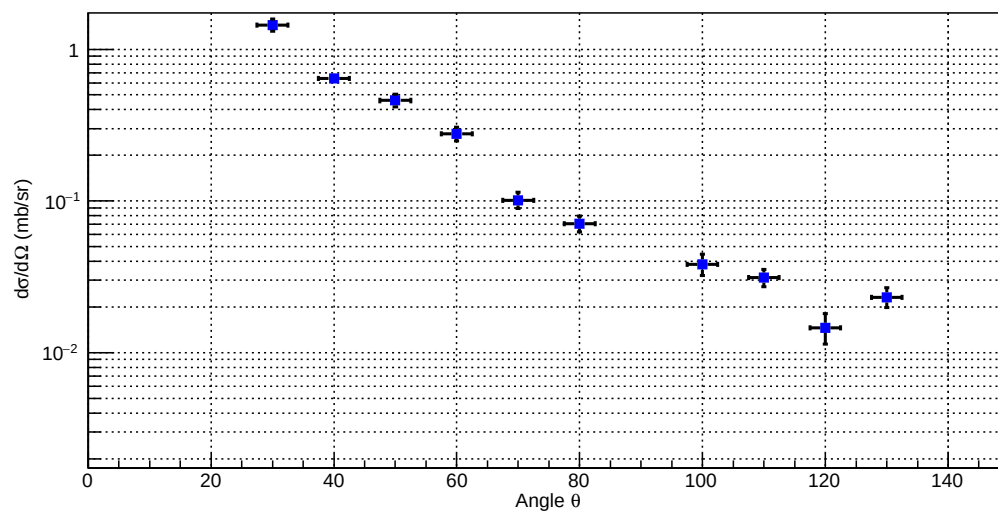
Y89 (p,p') 4000 keV



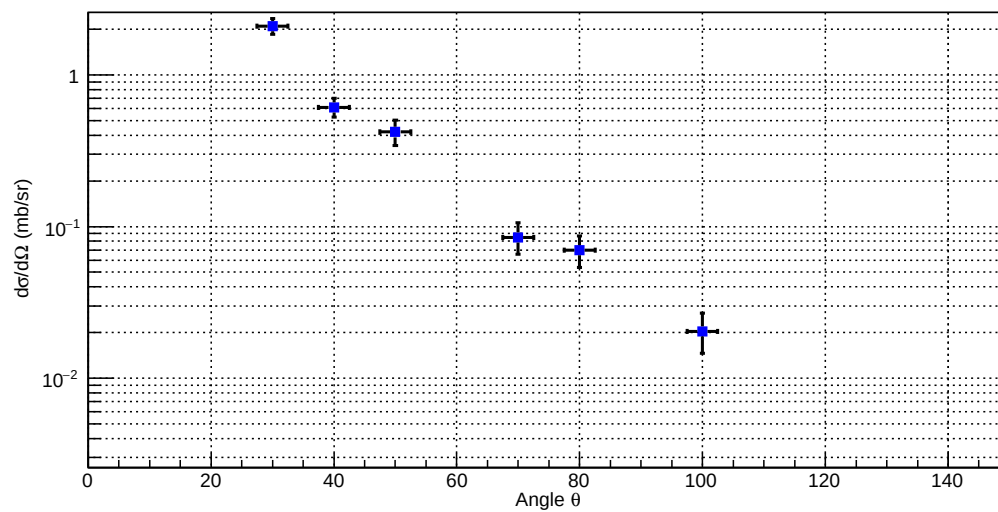
Y89 (p,p') 4300 keV



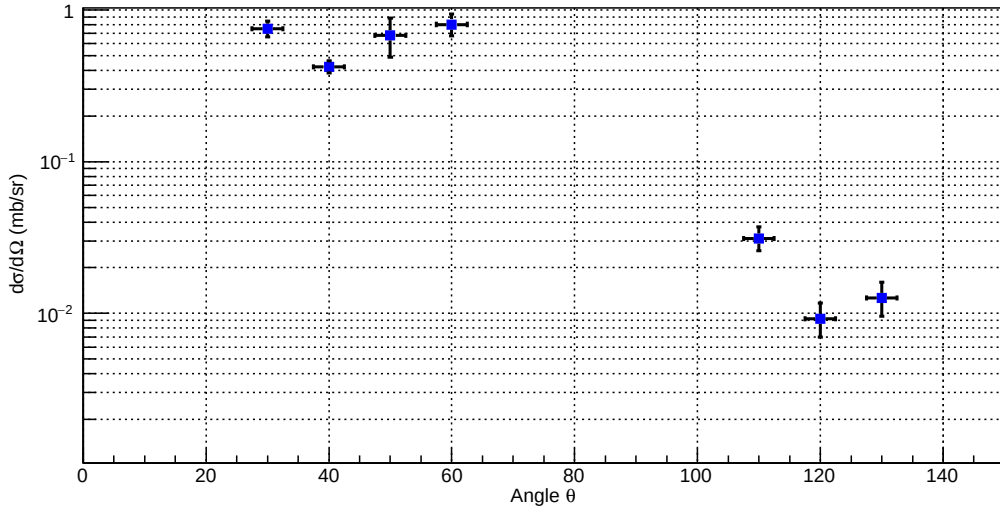
Y89 (p,p') 4500 keV



Y89 (p,p') 4800 keV



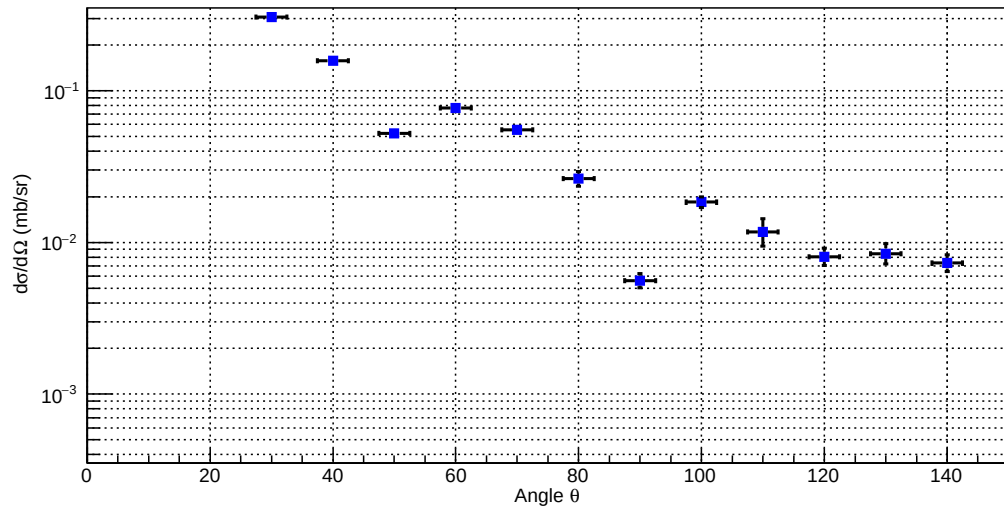
Y89 (p,p') 5200 keV



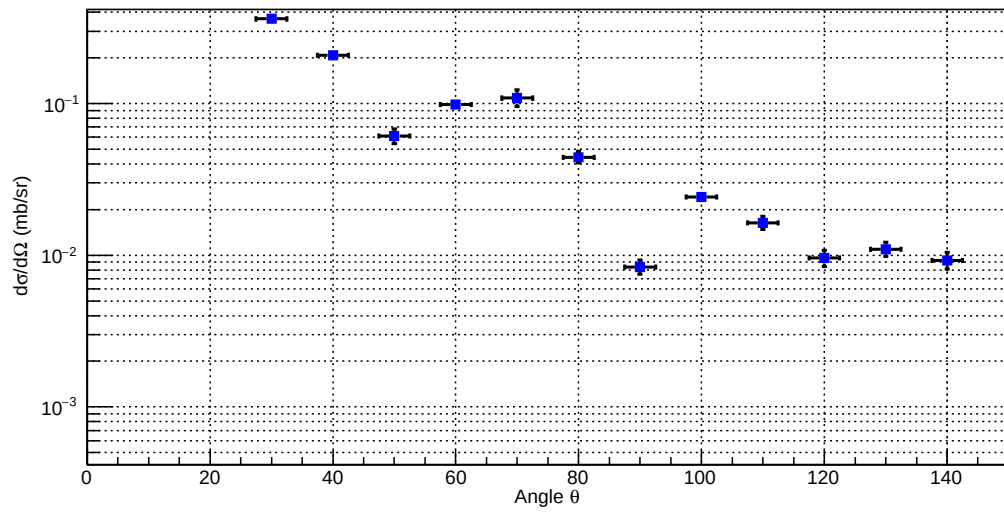
$^{89}\text{Y} (p, d)$.

The plots shown here are the cross section distributions for each discernible nuclear state for the $^{89}\text{Y} (p, d)$ reaction. Absent points indicate that the nuclear state at that energy was not discernible at that angle, due either to an insufficient amount of counts under the peak or its proximity to another peak, which made fitting a correct Gaussian to that peak impossible.

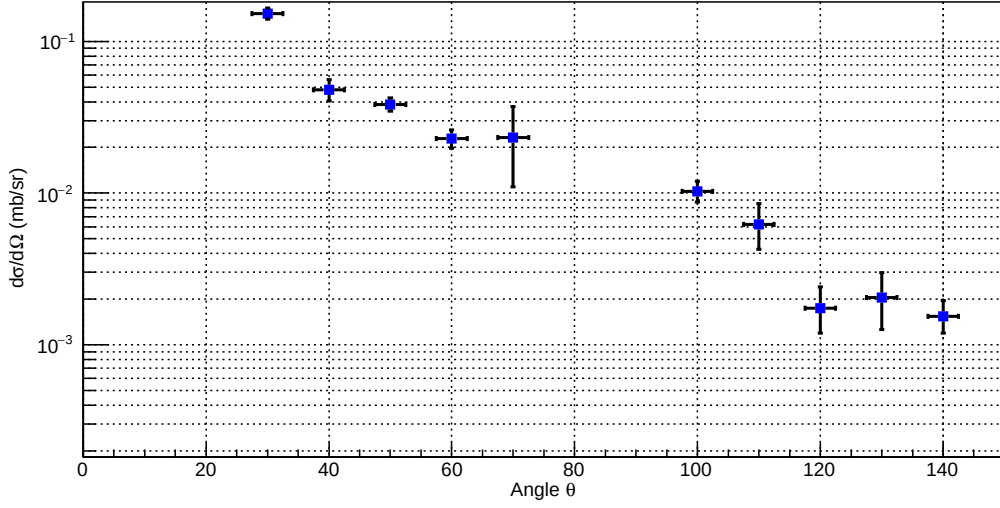
Y89 (p,d) 0 keV



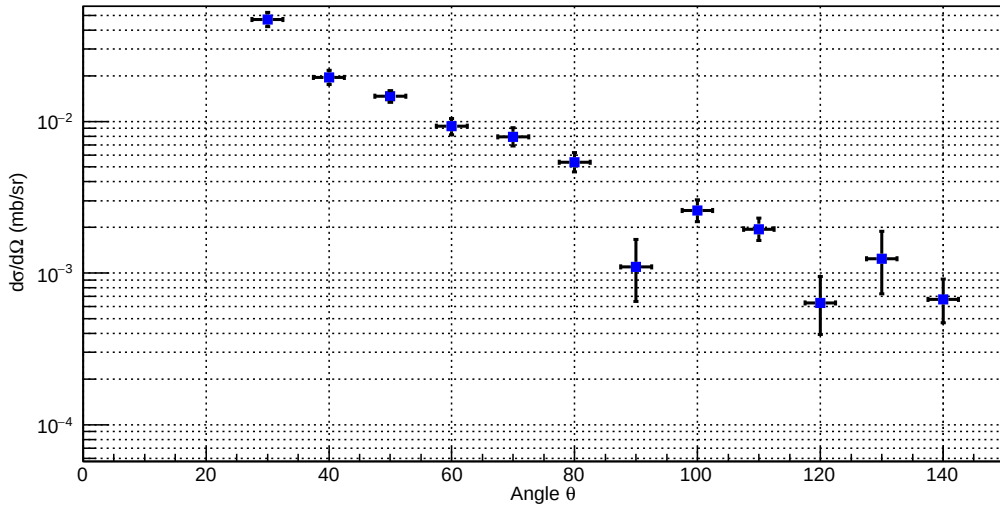
Y89 (p,d) 232 keV



Y89 (p,d) 393 keV

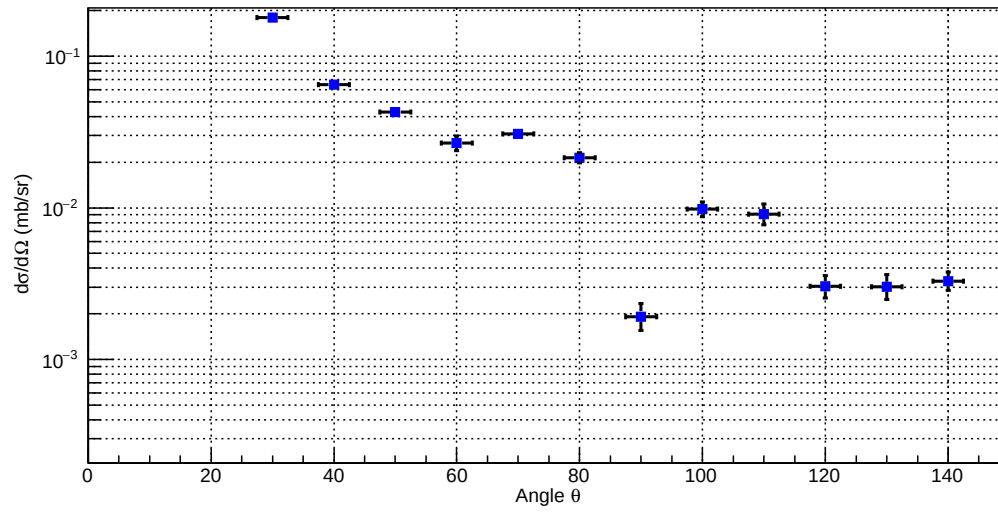


Y89 (p,d) 766 keV

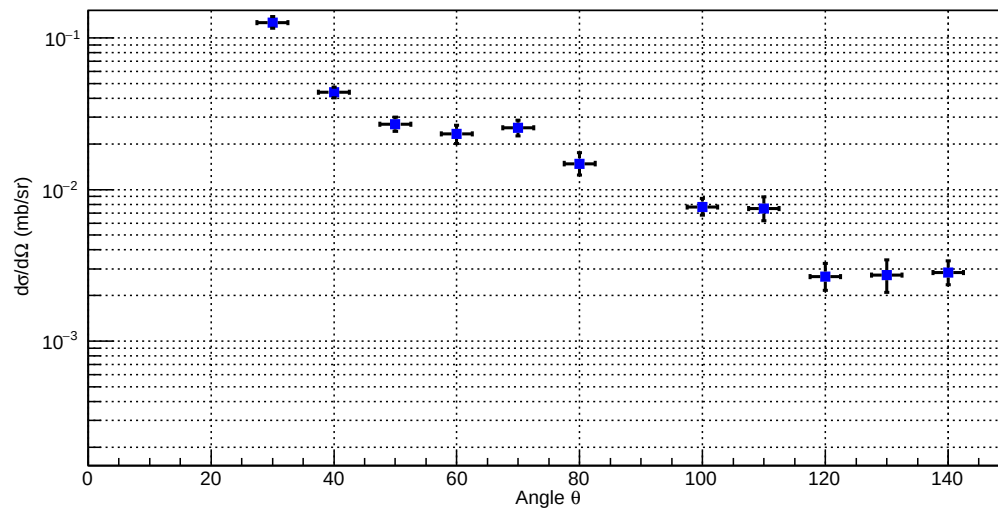


In the following plots, there is more than one known state in the vicinity of the energy of the peak in the energy spectra. The peaks are well-resolved, but which state they belong to is difficult to discern because of the 60 keV detector resolution. The plots are labeled here as groups of 100 keV that the peak may be located within. For example, there are six possible known states in the 1200 keV range [9], so the plot is labeled 1200 keV.

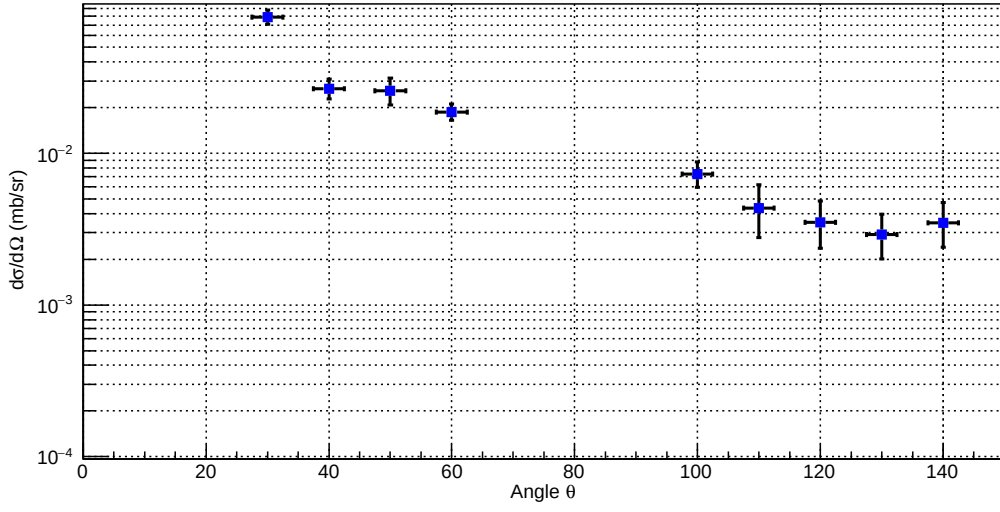
Y89 (p,d) 1200 keV



Y89 (p,d) 1500 keV



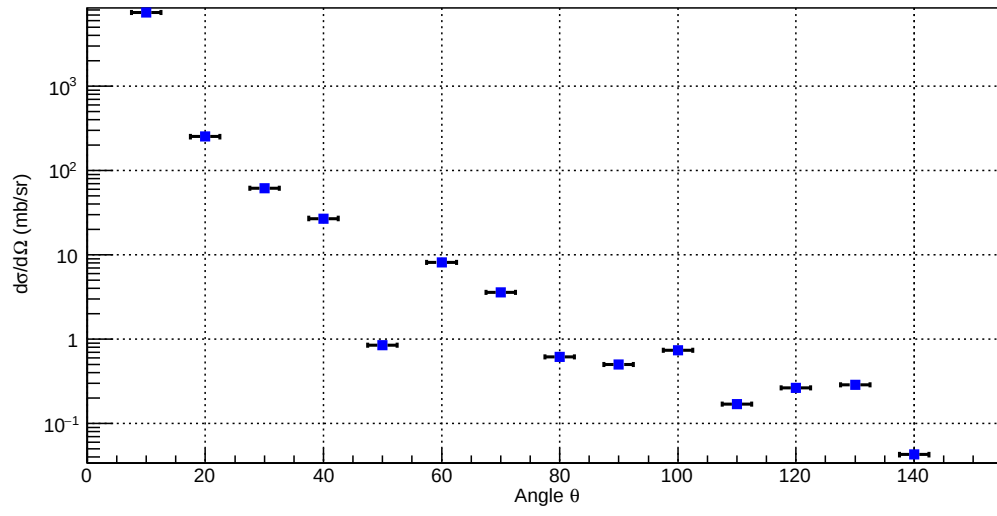
Y89 (p,d) 1700 keV



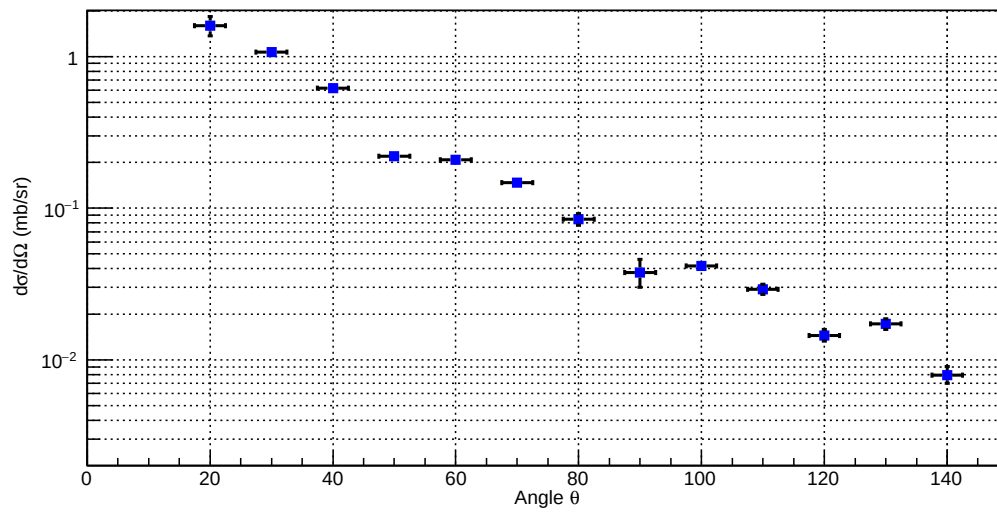
$^{92}\text{Zr} (p, p')$.

The plots shown here are the cross section distributions for each discernible nuclear state for the $^{92}\text{Zr} (p, p')$ reaction. Absent points indicate that the nuclear state at that energy was not discernible at that angle, due either to an insufficient amount of counts under the peak or its proximity to another peak, which made fitting a correct Gaussian to that peak impossible.

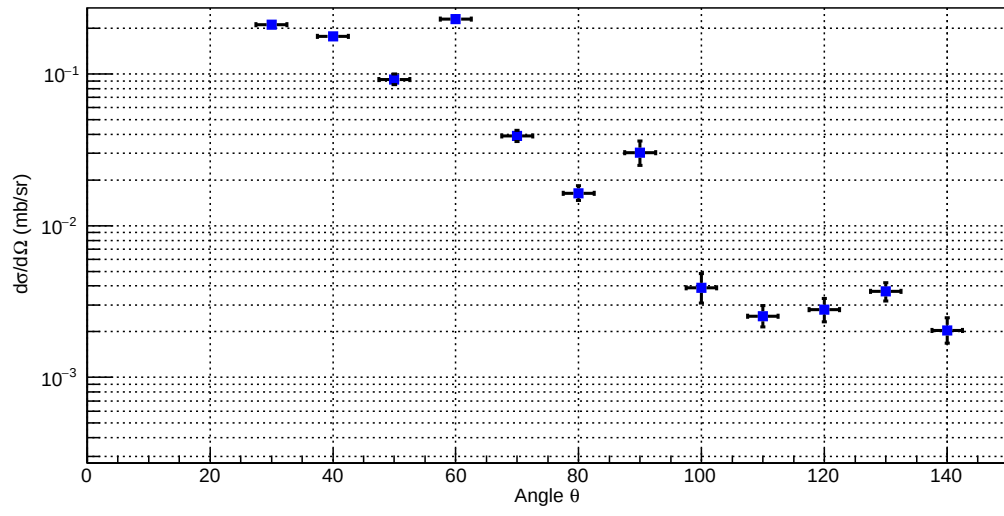
Zr92 (p,p') 0 keV



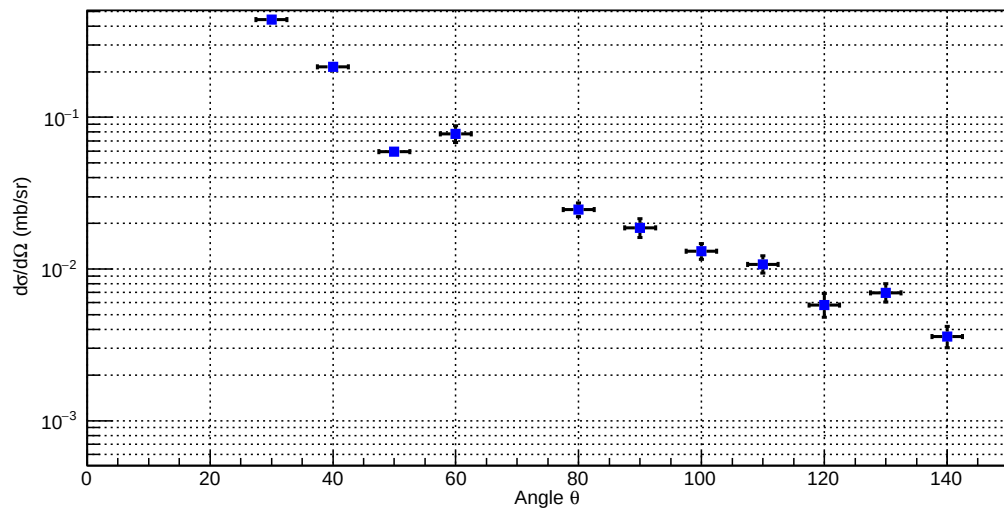
Zr92 (p,p') 935 keV



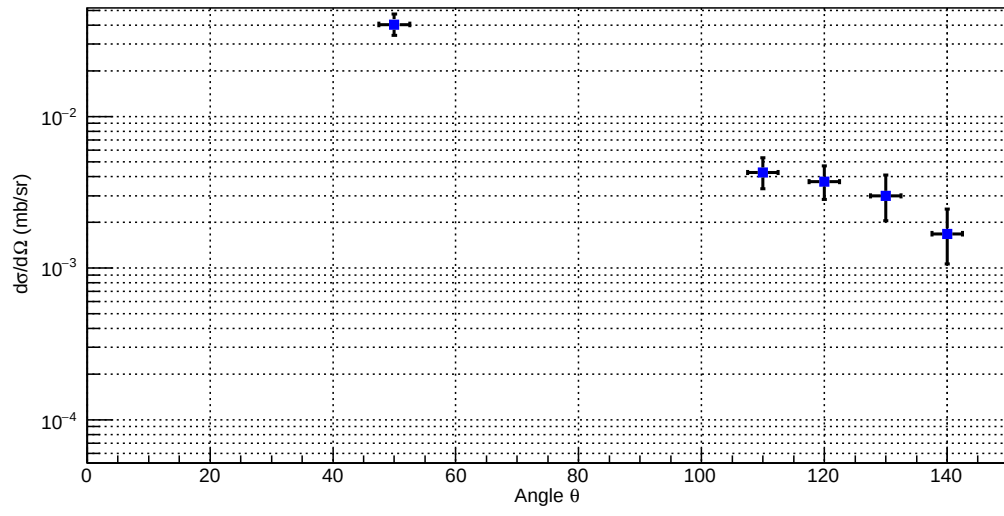
Zr92 (p,p') 1496 keV



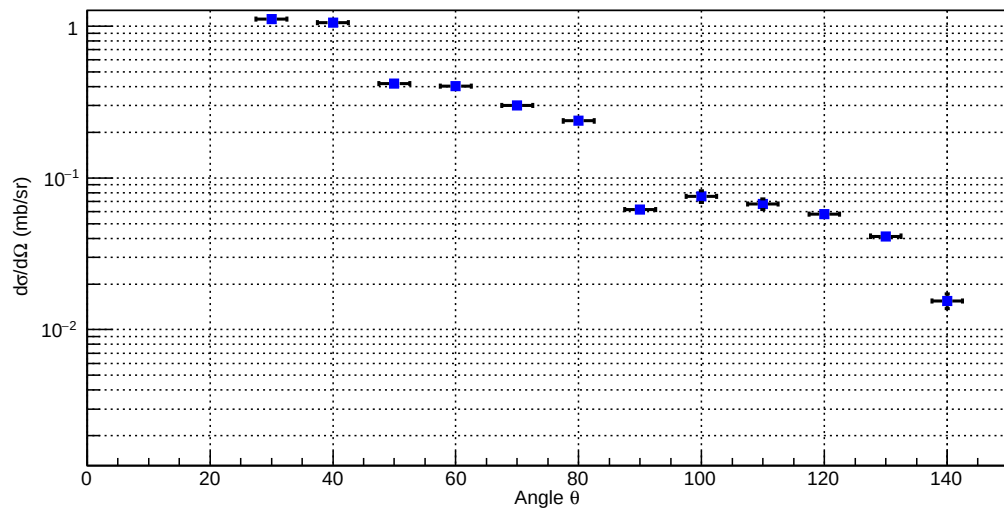
Zr92 (p,p') 1847 keV



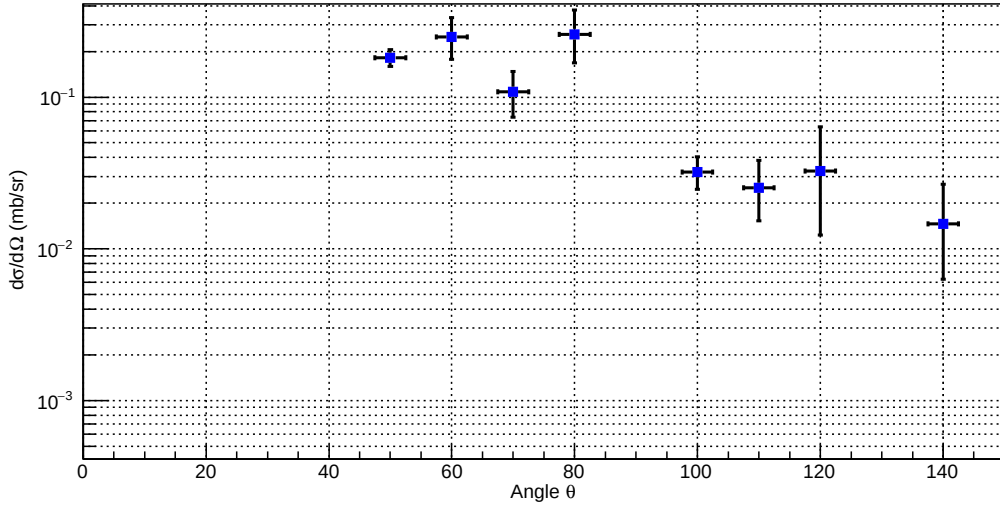
Zr92 (p,p') 2067 keV



Zr92 (p,p') 2340 keV

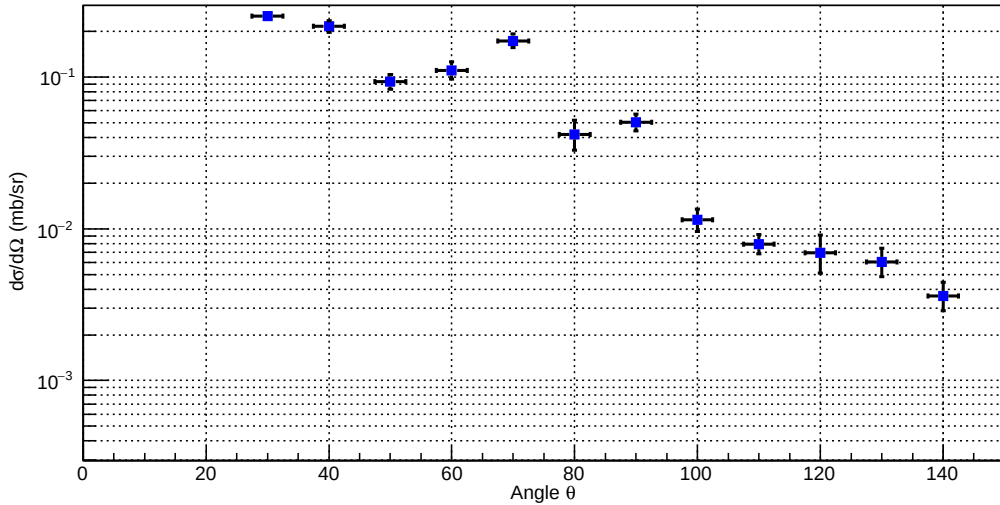


Zr92 (p,p') 2398 keV

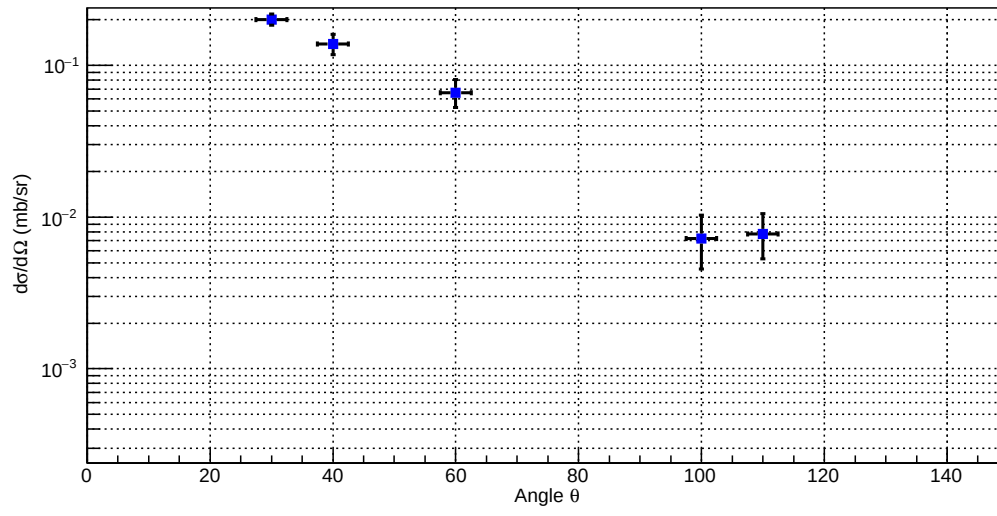


In the following plots (except for 3057 keV), there is more than one known state in the vicinity of the energy of the peak in the energy spectra. The peaks are well-resolved, but which state they belong to is difficult to discern because of the 60 keV detector resolution. The plots are labeled here as groups of 100 keV that the peak may be located within. For example, there are two possible known states in the 2800 keV range (2820 keV and 2865 keV [10]), so the plot is labeled 2800 keV.

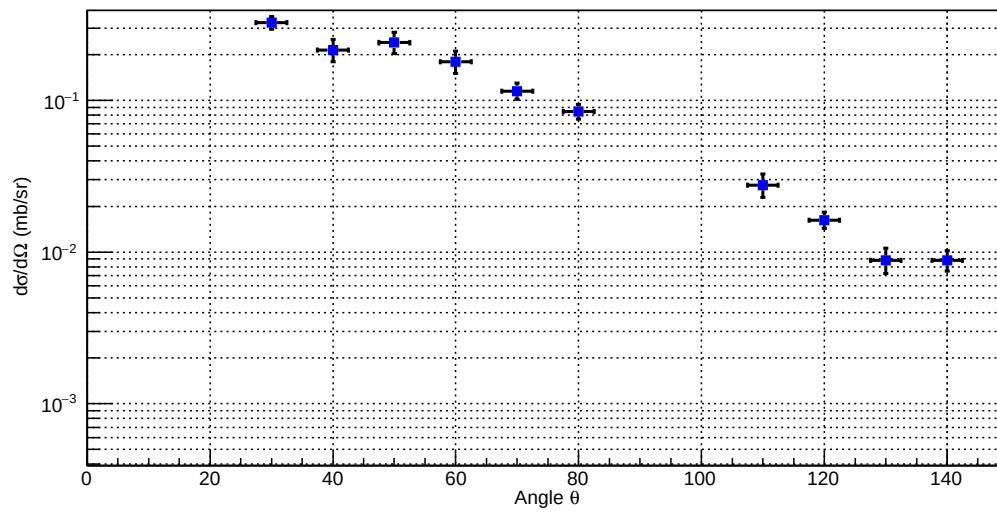
Zr92 (p,p') 2800 keV



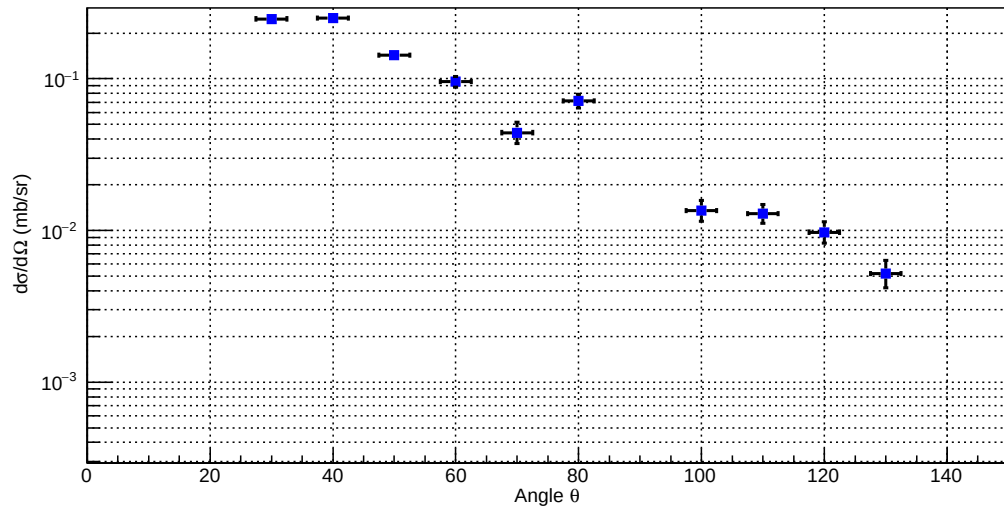
Zr92 (p,p') 3057 keV



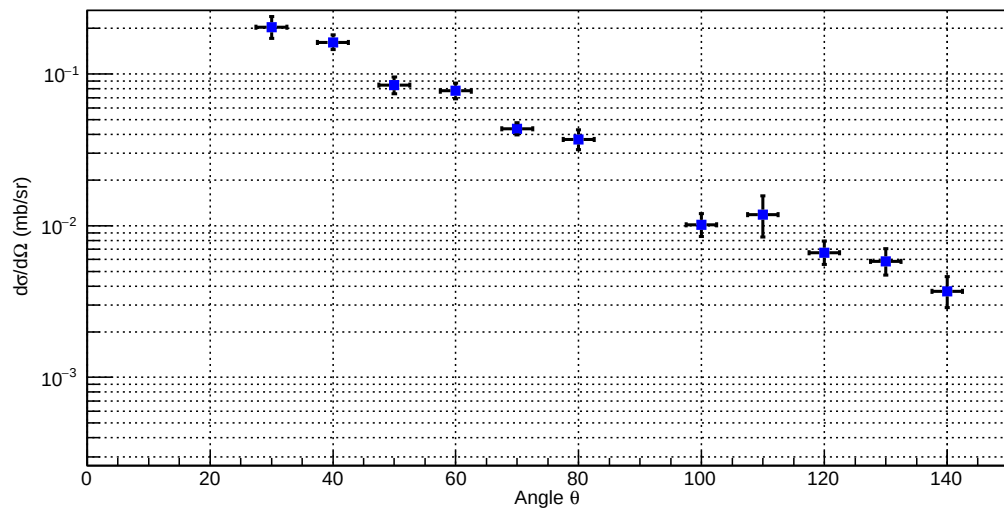
Zr92 (p,p') 3300 keV



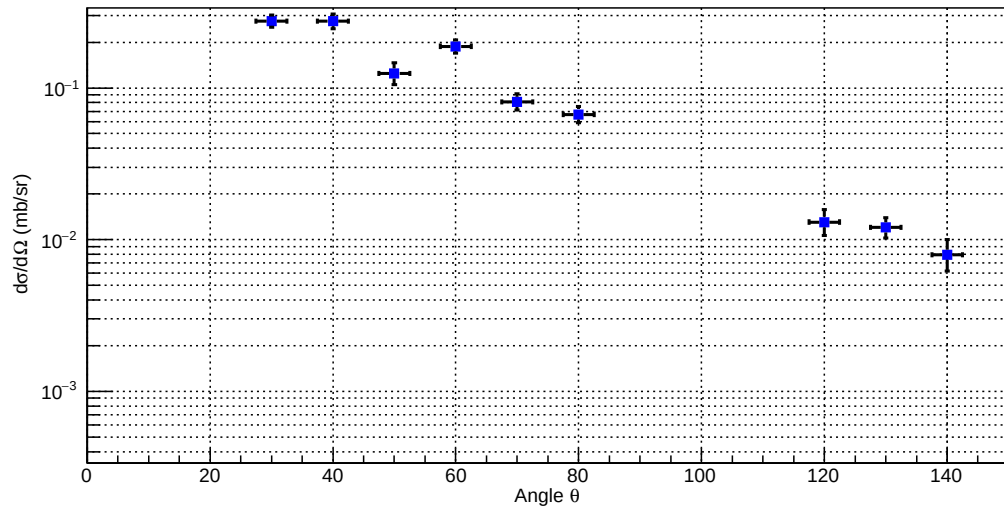
Zr92 (p,p') 3400 keV



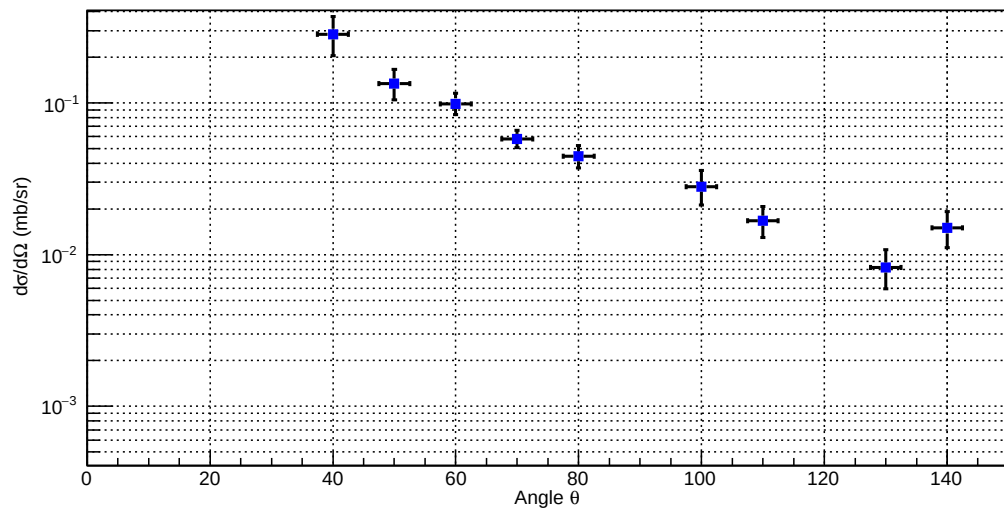
Zr92 (p,p') 3600 keV



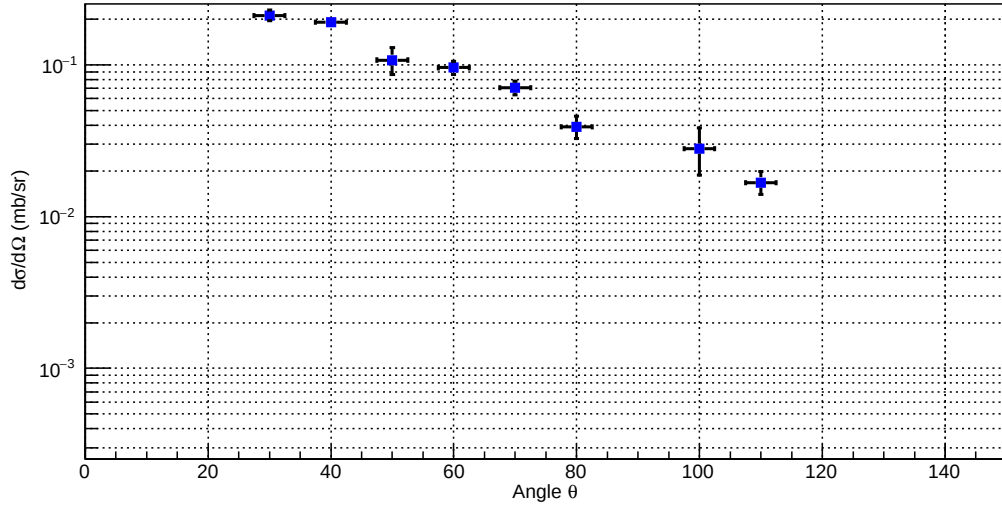
Zr92 (p,p') 4000 keV



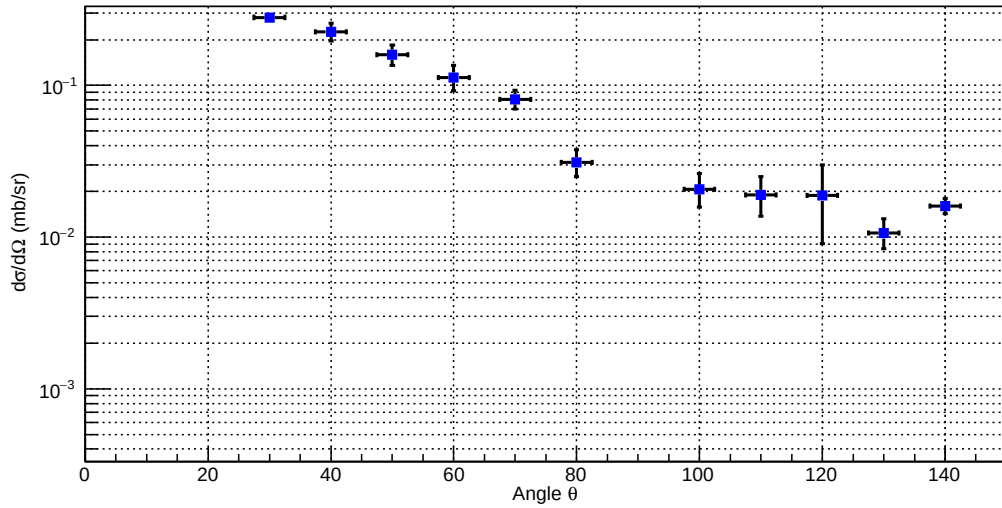
Zr92 (p,p') 4300 keV



Zr92 (p,p') 4400 keV



Zr92 (p,p') 4800 keV

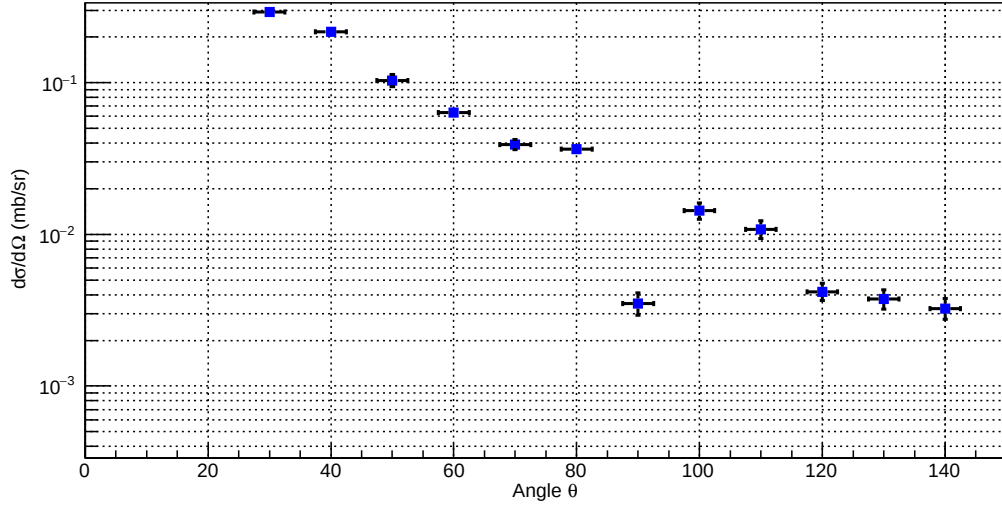


$^{92}\text{Zr} (p, d)$.

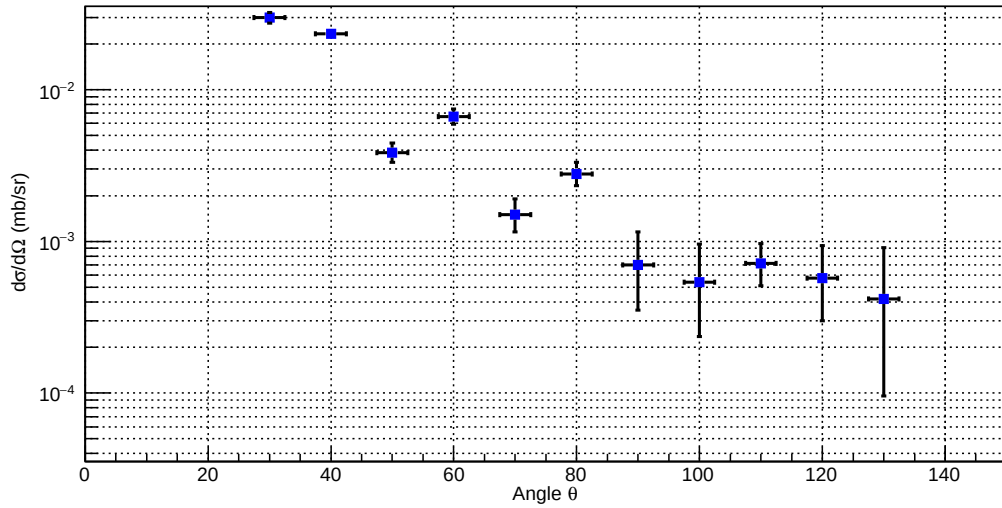
The plots shown here are the cross section distributions for each discernible nuclear state for the $^{92}\text{Zr} (p, d)$ reaction. Absent points indicate that the nuclear state at that energy was not discernible at that angle, due either to an insufficient amount of counts under the peak or its proximity to another peak, which made fitting a correct

Gaussian to that peak impossible.

Zr92 (p,d) 0 keV



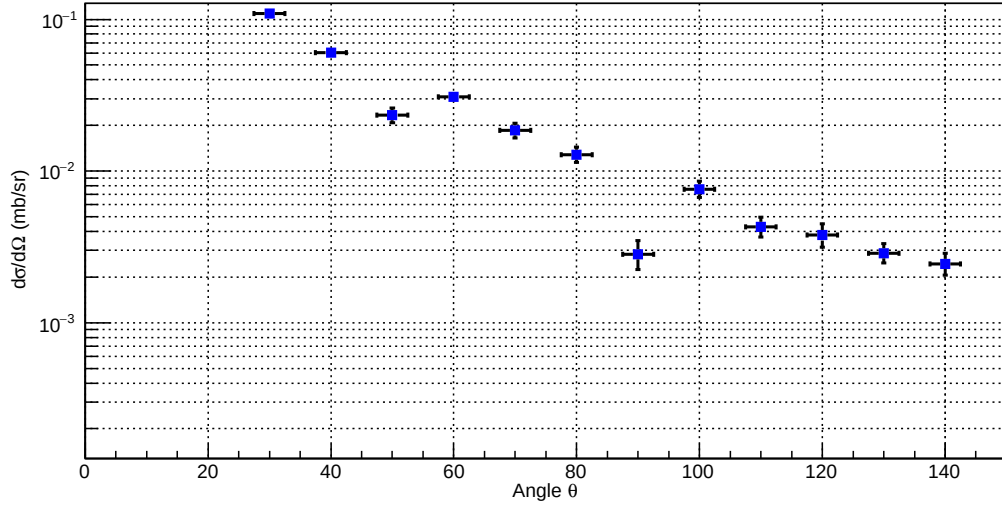
Zr92 (p,d) 1205 keV



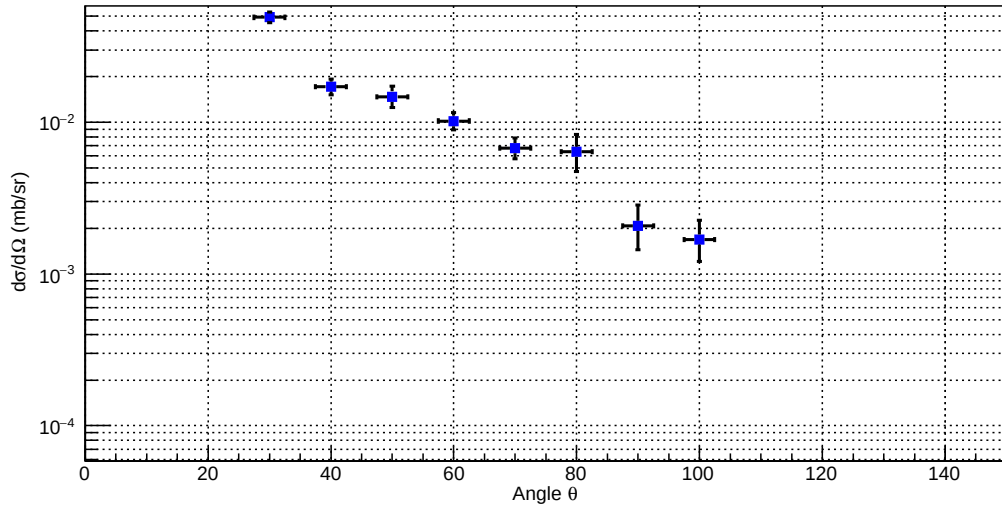
In the following plots, there is more than one known state in the vicinity of the energy of the peak in the energy spectra. The peaks are well-resolved, but which state they belong to is difficult to discern because of the 60 keV detector resolution. The plots are labeled here as groups of 100 keV that the peak may be located within.

For example, there are three possible known states in the 2100 keV range (2131 keV, 2170 keV, and 2189 keV [11]), so the plot is labeled 2100 keV.

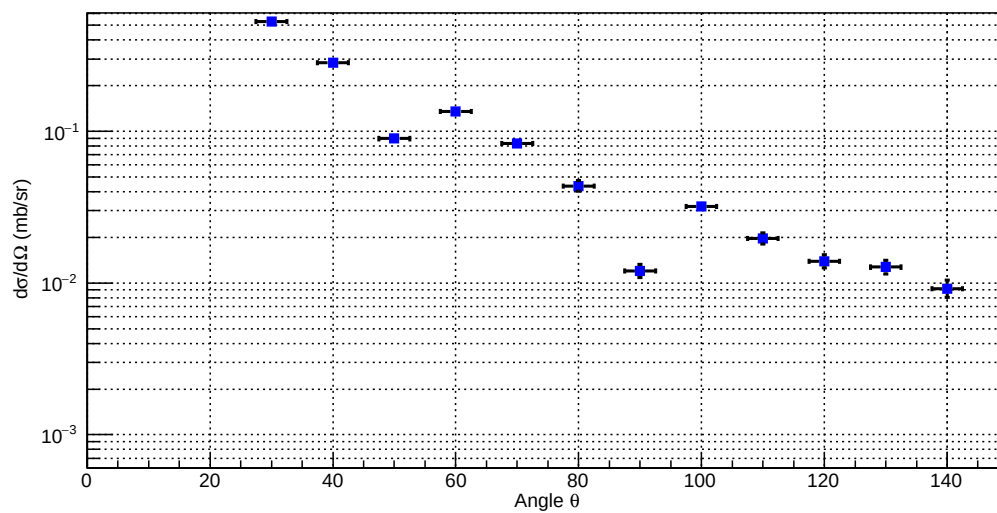
Zr92 (p,d) 2100 keV



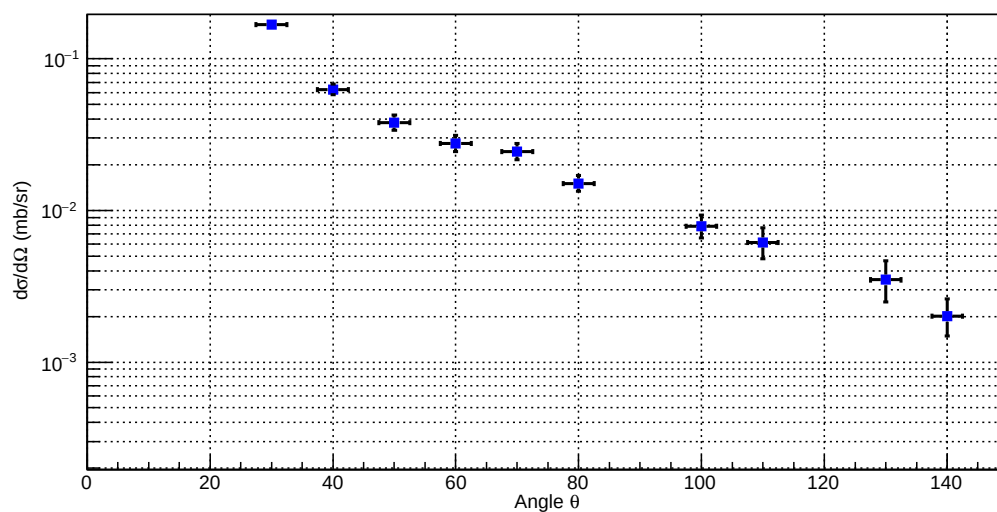
Zr92 (p,d) 2300 keV



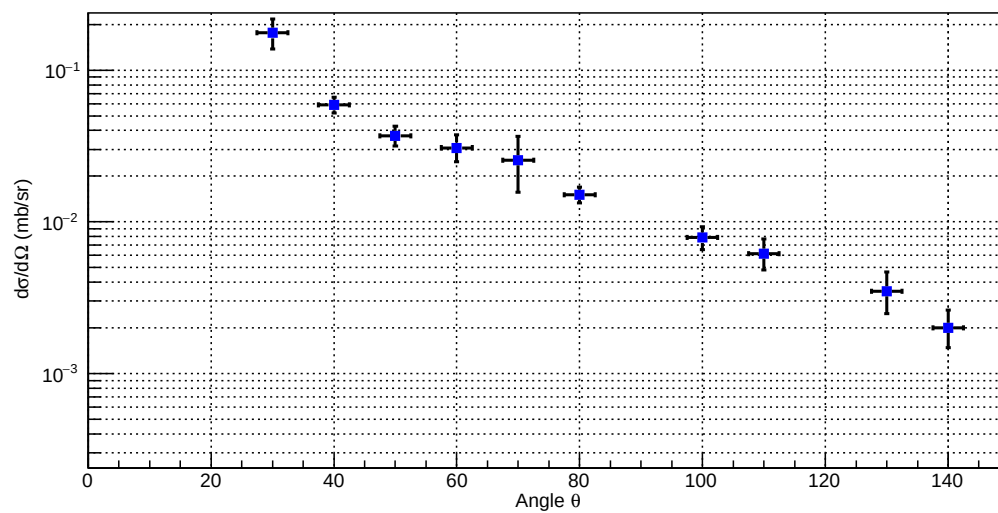
Zr92 (p,d) 2900 keV



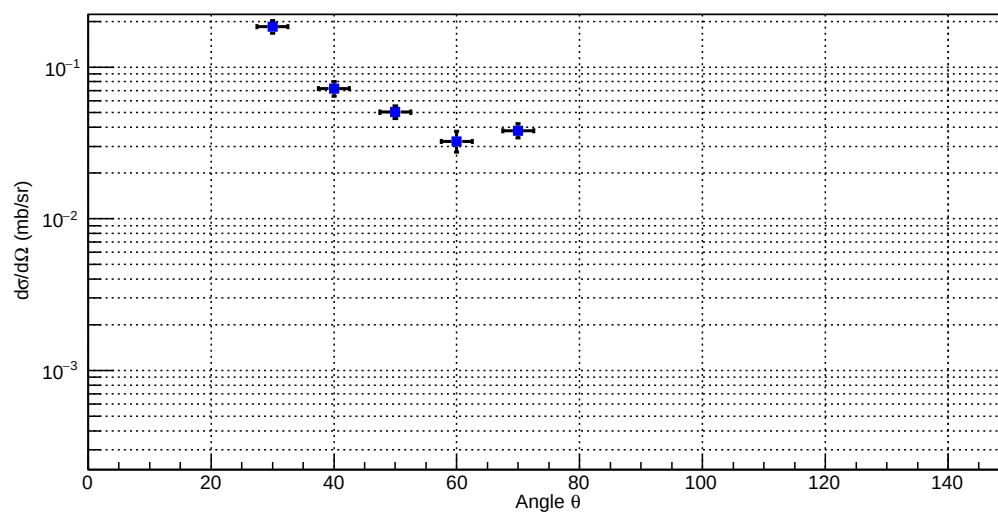
Zr92 (p,d) 3300 keV



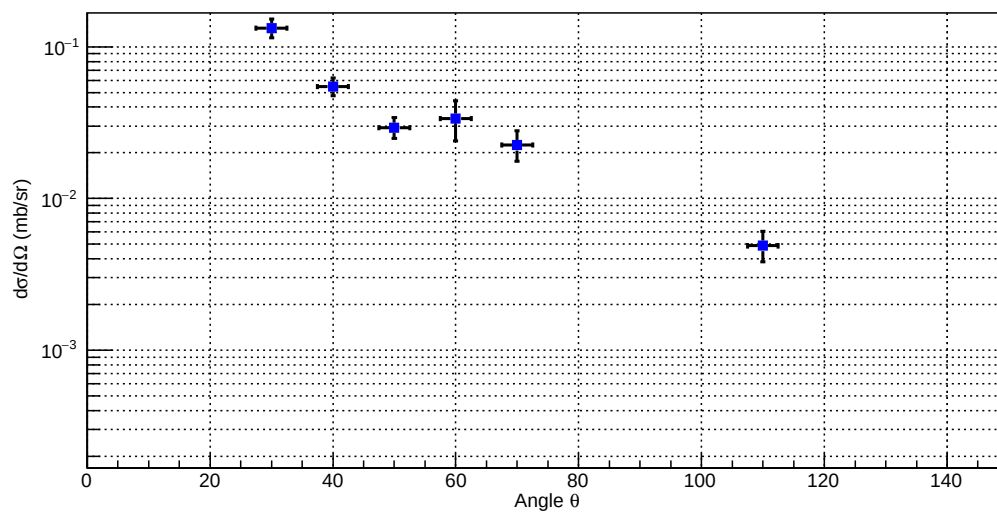
Zr92 (p,d) 3500 keV



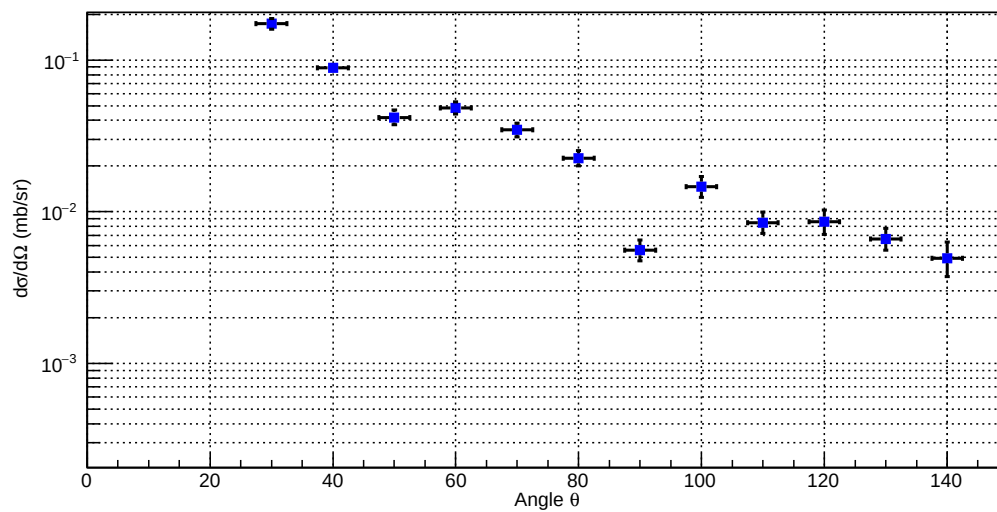
Zr92 (p,d) 3600 keV



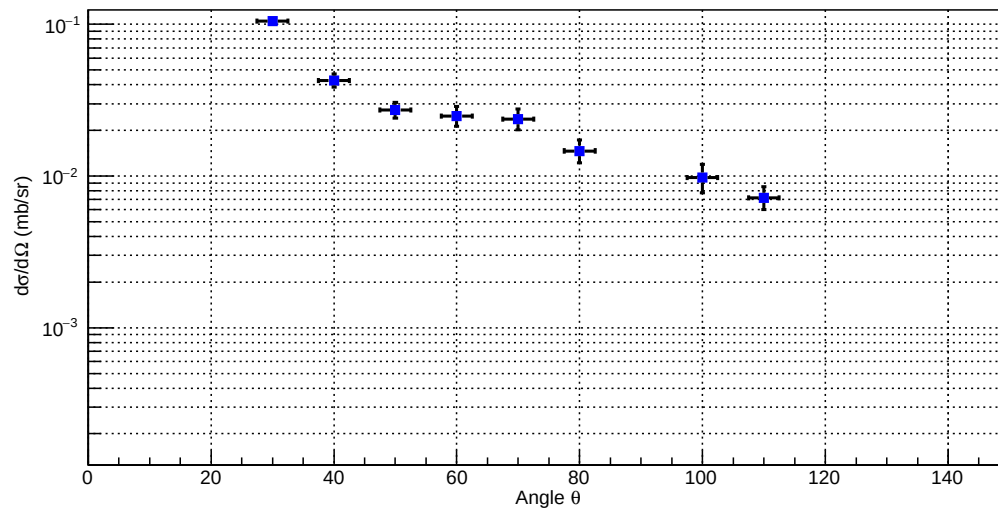
Zr92 (p,d) 3700 keV



Zr92 (p,d) 3900 keV



Zr92 (p,d) 4800 keV



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