Preparation for a Precision Measurement of the ^{3}He$(\alpha, \gamma)^7$Be Cross Section

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Abstract

This paper discusses my research during the ten weeks of the University of Washington summer REU program. I worked under Kurt Snover and Derek Storm on a project to make a precision measurement of the cross section of the ^{3}He$(\alpha, \gamma)^7$Be reaction. I participated in making detector efficiency calculations and in measuring test material contaminants. A precise value of the ^{3}He$(\alpha, \gamma)^7$Be cross section is very important for understanding new experiments on solar neutrino flux, and a more precise value than is currently known is necessary to check the predictions of the Standard Solar Model against experimental data.

1 Introduction

For many years physicists have been investigating neutrinos produced in solar fusion reactions, and their findings have consistently disagreed with theoretical predictions from the Standard Solar Model (SSM). Every solar neutrino experiment reported detecting significantly fewer neutrinos than expected from the SSM [2]. After checking and rechecking both the theoretical calculations and the experimental equipment and techniques, the question was raised as to whether physicists really understood how neutrinos behave over long distances.

All of the earlier solar neutrino experiments detected only electron neutrinos. Recently however, an experiment was conducted at the Sudbury Neutrino Observatory (SNO) that detected all three neutrinos. It is now understood that while all neutrinos begin in the sun as electron neutrinos, they can "oscillate," meaning that some of them become muon or tau neutrinos by the time they reach Earth. In fact, only approximately one third of neutrinos that reach Earth are electron neutrinos; the other two thirds are a combination of muon and tau neutrinos. This means that neutrinos, previously assumed to be massless, must have a small mass. But in order to learn more about neutrino masses, we need to know more about the cross sections for the reactions that create these neutrinos.

The ^{3}He$(\alpha,\gamma)^7$Be reaction is the branching point of the PPII and PPIII branches of the proton-proton chain, one of the main processes by which the sun produces its energy (Figure 1). Therefore, this reaction is of particular interest for solar neutrino research. Specifically, a precise value for the cross section of this reaction is crucial to understanding high-energy solar neutrinos produced by the ^{7}Be(p,γ)^{8}B reaction, neutrinos produced by the decay of ^{7}Be in the sun, and to verify the SSM [1, 4, 5].

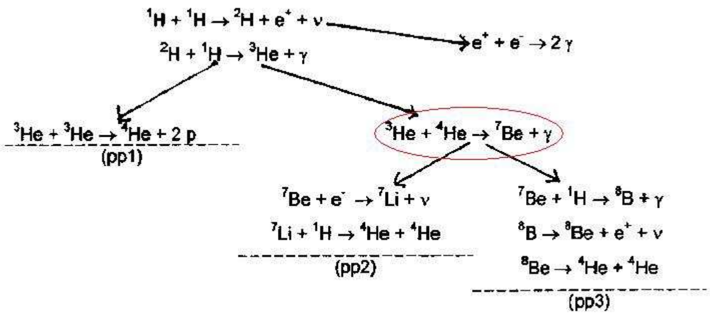

Figure 1: The proton-proton chain

2 Experiment Background

In the fusion of ^{3}He and ^{4}He there are three prompt γ-rays produced (Figure 2). In this reaction ^{7}Be can be formed in either the ground state or the first excited

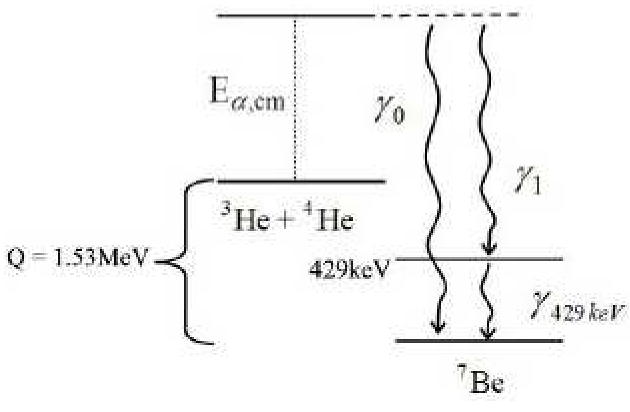

Figure 2: The ^{3}He ^{4}He fusion reaction

state. When it is formed in the ground state, it emits the γ-ray labeled as γ_0.

When it is formed in the first excited state it emits the γ-ray labeled as γ_1. The γ_{429} is emitted in the transition from the first excited state to the ground state. ^{7}Be decays by electron capture to ^{7}Li. It can decay to an excited state with a branching ratio of 10.4%, which then emits a γ-ray with an energy of 478 keV in the transition to ground state, denoted as γ_{478} in Figure 3.

There are two ways of measuring the cross section of the ^{3}He$(\alpha,\gamma)^7$Be reaction;

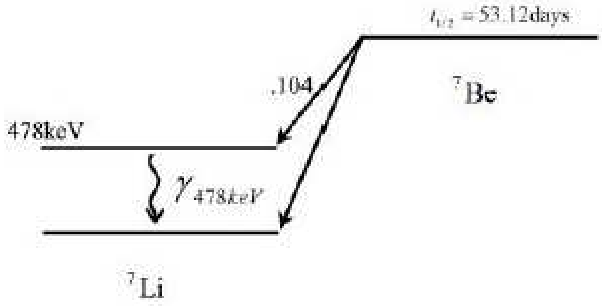

Figure 3: The decay of ^{7}Be

the first method is to measure the prompt γ-rays produced in the reaction, the second to measure the γ-ray produced by the decay of ^{7}Be. This has been done several times, but the two different methods lead to values which differ on average by about 10%, resulting in a low precision value for the astrophysical S-factor, $S_{34}(0)$. The purpose of this experiment is to make a precise measurement of the cross section for ^{3}He$(\alpha,\gamma)^7$Be, in order to determine $S_{34}(0)$ with an accuracy of 5% or better.

3 Experimental Set-up and Test Run

In 2004 the group did a test run of the experiment to ensure that it was possible to produce and detect ^{7}Be. Using the Van de Graaf accelerator at the University of Washington, they sent a beam of ^{4}He into a gas cell containing ^{3}He. This led to the fusion of ^{3}He and ^{4}He, and the ^{7}Be produced was then collected on a Cu target behind the gas cell. A diagram of the set-up from the test run is shown in Figure 4 [3].

The test run of the experiment showed that it was indeed possible to produce ^{7}Be in large enough amounts to be detected [3]. Since the test run was so successful the basic set-up for the experiment will remain unchanged.

4 Detector Efficiency Testing

It is very important to know the efficiency of the detectors being used in an experiment of this nature. In order to obtain a high precision measurement of the number of ^{7}Be atoms produced, then it must be known exactly how good the

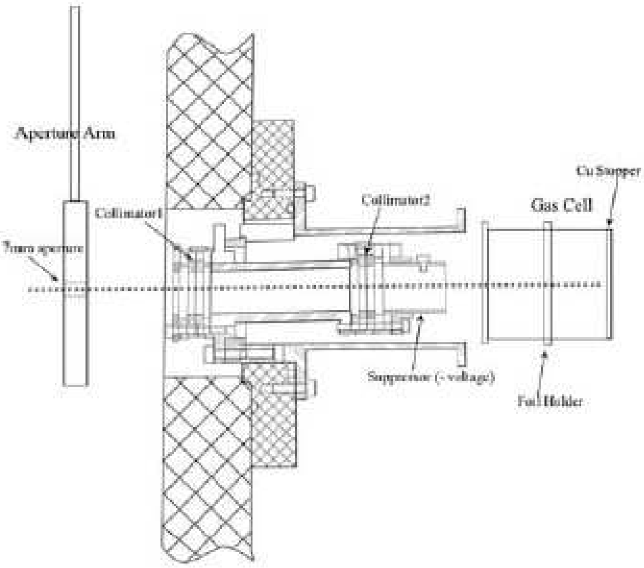

Figure 4: Diagram of test run experiment set-up

detectors are at detecting the emitted γ-rays. The major source of error in the preliminary run of the experiment was the uncertainty in the detector efficiency, approximately 24% [3]. The manufacturer provides a relative efficiency for the detectors, but in order to find an accurate value for the absolute efficiency it must be measured and calculated. Until this summer, an efficiency measurement had not been made with the two Ge detectors used in the Majorana room, which are called Canberra 1 and Canberra 2. An efficiency measurement was made using three well known γ sources at a specific distance from the Canberra 2 detector. The detector arrangement is shown in Figure 5

^{60}Co, ^{137}Cs, and ^{133}Ba were used in the efficiency measurements. ^{137}Cs emits one γ-ray, at 661.657 keV. ^{60}Co and ^{133}Ba each emit two γ-rays, ^{60}Co at 1173.24 keV and 1332.5 keV, and ^{133}Ba at 302.853 keV and 356.017 keV. The absolute activity of these sources is specified by the company to $\tilde{+}$/-1%. For each source a measurement was made at 25 cm and at 10 cm. Several background measurements were also made, since the efficiency measurements were sometimes a week apart. However, even with multiple background measurements, a slight gain shift in the detector was still noticeable when the background subtractions were made.

In order to calculate the efficiency of the detector from the γ spectra, the decay of the source since its creation must be considered. The branching ratio of the decay and the dead time of the detector must also be considered. In this

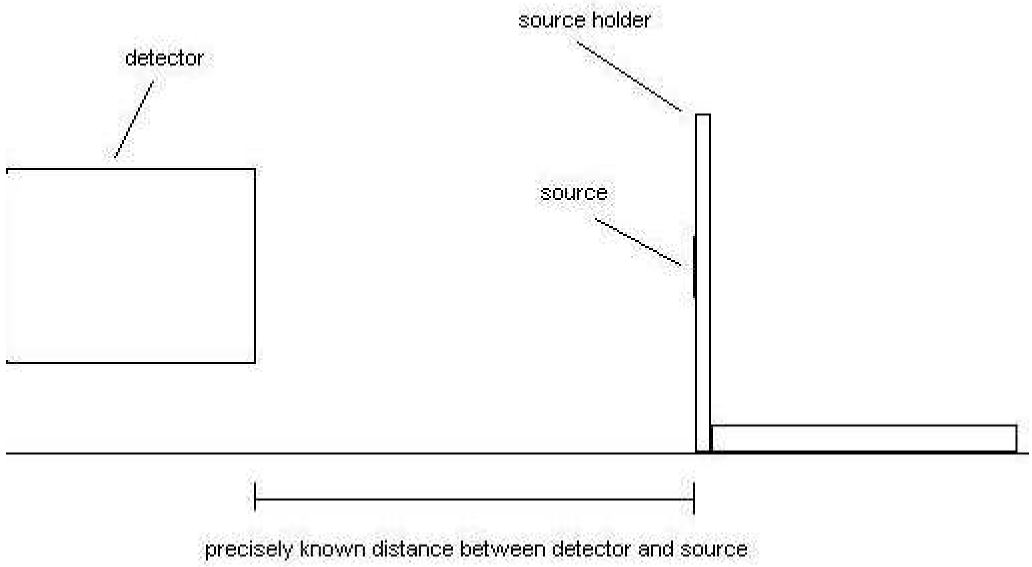

Figure 5: The set-up for the detector efficiency measurements

case the rates were low enough to not cause a significant amount of dead time.

The efficiency of the detectors is energy dependent. It is imperative to know the efficiency of the detector at 478 keV, since this is the energy of the γ-ray emitted by ^{7}Be. In order to do this, the efficiency at the energy of each of the five γ-rays mentioned above was calculated, which provided data points both above and below the desired energy. Microsoft Excel was used to fit a curve to these points, from which the efficiency at 478 keV can be extrapolated. The calculated efficiencies at 25 cm are listed in Figure 7, and the plot of these efficiencies with the fitted curve is shown in Figure 8. The other efficiency tables and curves can be found at the end of this paper.

This gives the efficiency of the Canberra 2 detector, but the ^{7}Be produced is measured with the Canberra 1 detector. The efficiency of the Canberra 1 detector can be found using the relative efficiencies provided by the manufacturer. They list the efficiency of the Canberra 2 detector as 100% and the efficiency of the Canberra 1 detector as 109%. Therefore by multiplying the efficiency of the Canberra 2 detector by 1.09 the efficiency of the Canberra 1 detector is obtained. This is necessary to calculate the number of ^{7}Be atoms produced.

5 Contamination Testing

There are two main possible sources of the difference between the two methods of measuring the cross section. To find the cross section in the first method, the ^{7}Be is measured by the detection of the prompt γ-rays emitted as the ^{7}Be is

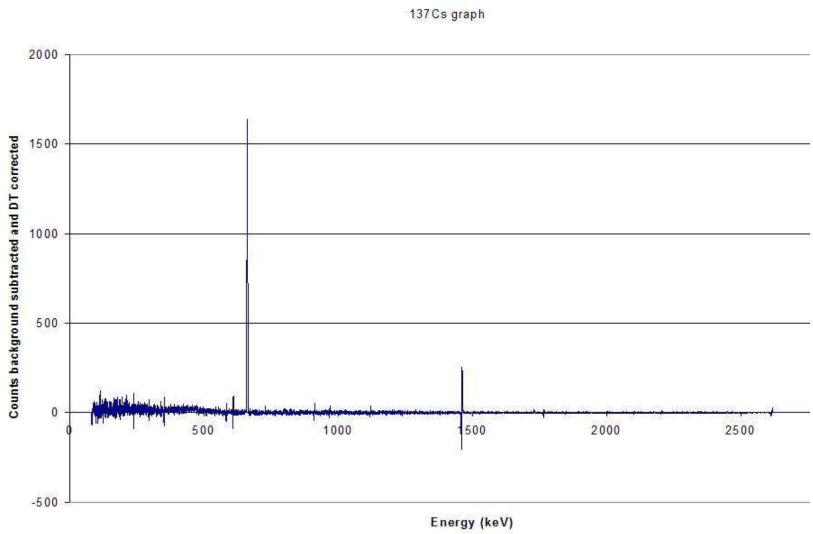

Figure 6: The ^{137}Cs spectrum with the background subtracted. The gain shift is evident by the matching lines above and below the zero line.

formed by the reaction ^{3}He(α, γ)^{7}Be. In the second method, it is measured by detecting the γ-ray emitted in the decay of ^{7}Be, presumably formed by the same reaction. The first possible source of the discrepancy is that ^{7}Be can occasionally be produced without the emission of the prompt γ-ray. This has been shown to be negligible[6]. But the second possibility is that there is ^{7}Be present which was not formed by this reaction. This may occur if there is a small amount of proton or deuteron contaminant in the beam and some specific test material contamination as well. There are two reactions other than ^{3}He(α, γ)^{7}Be which may create ^{7}Be[4, 5]:

$$^6\text{Li(d,n)}^7\text{Be} \quad \sigma(\text{E}_d = 1.25\text{MeV}) \cong 100\text{mb}$$
$$^{10}\text{B(p,}\alpha)^7\text{Be} \quad \sigma(\text{E}_p = 0.75\text{MeV}) \cong 150\text{mb}$$

Since the ^{3}He(α, γ)^{7}Be cross section is much smaller than these values[1], only a small amount of contaminant would result in enough ^{7}Be to cause the discrepancy between the two methods. Therefore it is very important to measure the amount of beam and test material contaminants in order to determine the amount of ^{7}Be actually produced by the ^{3}He(α, γ)^{7}Be reaction. A wide variety of materials were tested in 2004, and the results of those tests can be found in Ref. [5].

The first run this summer was in June. In this first run, Cu and Ta were tested for contamination. The Cu was chosen for its low γ background in the

[1] ^{3}He(α, γ)^{7}Be $\quad \sigma(\text{E}_{cm} = 3.5\text{MeV}) \cong 2.5\mu$b[5]

25cm-no absorber			
γ-source	Energy (keV)	Efficiency	Efficiency Error
133Ba	302.9	0.003129	8.34E-05
133Ba	356	0.002736	3.04E-05
137Cs	661.657	0.001858	1.94E-05
60Co	1173.24	0.001319	1.29E-05
60Co	1332.5	0.001199	1.2E-05

Figure 7: The efficiency with the source 25cm from the detector

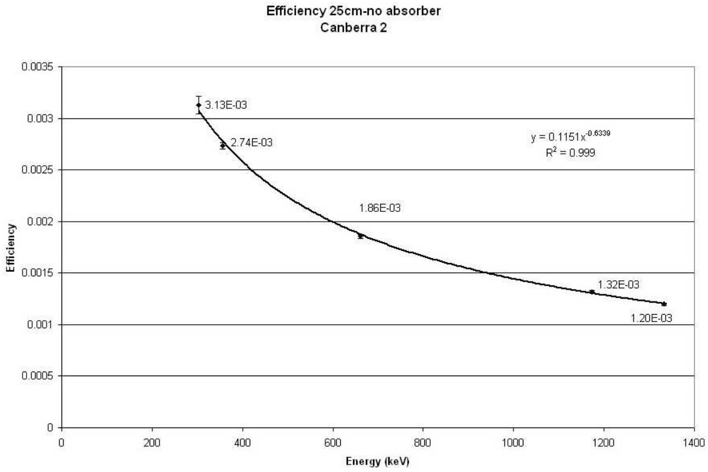

Figure 8: The efficiency curve with the source 25cm from the detector

region of interest, namely 478 keV. This particular Cu was not tested in 2004, so the Ta was tested in order to have a comparison with the results obtained a year ago. Another difference between the run in June 2005 and the run in 2004 was that the accelerator was run in tandem at 2.6 MeV in 2005, where as it was run as a terminal ion source at 1.5 MeV in 2004. The target ladder, described in Section 3, holds two samples each of Cu and Ta. One sample of each material was bombarded with protons and the other with deuterons to imitate beam contamination that could lead to one of the reactions mentioned above. Since the targets were bombarded with only the possible beam contaminant and the reaction can only take place if both contaminants are present, then if any ^{7}Be is found it was produced by one of the reactions above, and thus the test material is contaminated with either ^{6}Li or ^{10}B. This would reveal how much contamination is in the targets.

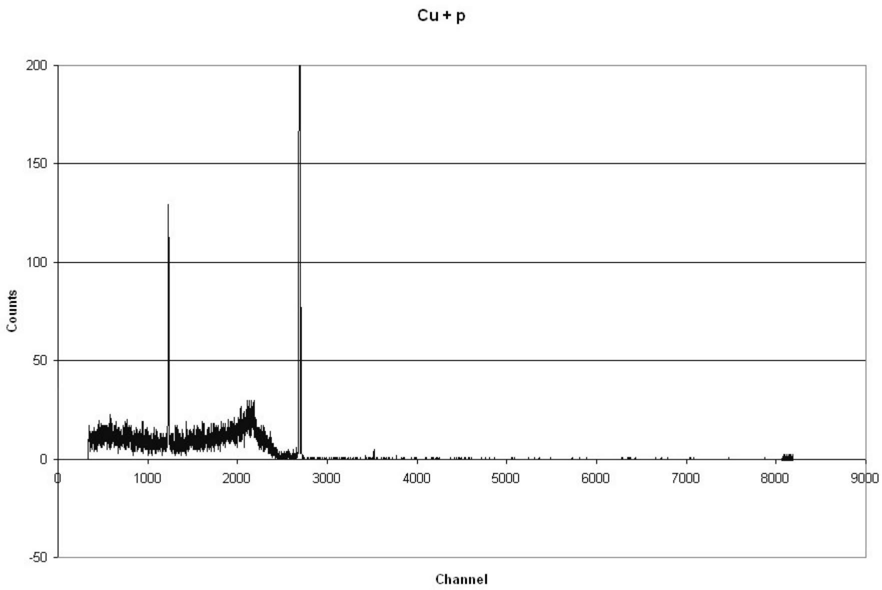

Figure 9: The spectrum of Cu bombarded with protons

After bombardment the targets were too hot[2] to be removed and measured immediately, so they were left to cool for about a week. They were then taken to the Majorana room where the two Ge detectors are located. Each sample was placed inside the lead shielding around the Canberra 1 detector to measure the 478 keV γ-ray produced by the decaying ^{7}Be. However, the resulting spectra of the targets in the lead shielding had approximately four times the background as the spectra with the sample removed. In addition to the added background, several new peaks were evident which were not in the background measurements with the sample removed. The Cu+p spectrum is shown in Figure 9 with the background subtracted. The rest can be found at the end of this paper. The ^{7}Be peak would be found in channels 1049-1199.

The decision to run the accelerator at 2.6 MeV instead of 1.5 MeV as before was made to be able to produce the ^{7}Be in a shorter amount of time. The cross sections for the two contamination reactions is approximately three times higher at 2.6 MeV than at 1.5 MeV. Since the current must remain constant, running at an energy where the cross section is three times higher enables the production of the same amount of ^{7}Be in one third of the time.

The energy of the Coulomb barrier of an element is proportional to the Z of the element, so the Coulomb barrier is larger for elements with larger Z values. The contaminants under consideration, ^{6}Li and ^{10}B, are low Z elements, so at 1.5 MeV the protons and deuterons have enough energy to overcome the Coulomb barriers. Cu and Ta are high Z elements, so the beam will not react

[2]"hot" refers to the radioactivity of the targets, not the temperature

with the targets at these energies.

At 2.6 MeV, the beam has just enough energy to overcome the Coulomb barrier for the Cu. In fact, it is believed that ^{65}Zn was created by the reaction below:

$$^{65}\text{Cu} + \text{p} \longrightarrow {}^{65}\text{Zn} + \text{n}$$

The ^{65}Zn decays by one of two process; it can decay by electron capture or by β^+ emission. These give a large peak at 511 keV due to the annihilation of the β^+ and a γ-ray at 1115 keV. These are the two peaks shown in Figure 9.

This was not anticipated when the decision to run at 2.6 MeV was made. As a consequence of the high energy, new channels of reaction were opened, and the beam reacted with the Cu target as well as with any contaminant contained in it. Since the target is primarily Cu and the contamination is small, it was not possible to see the ^{7}Be created by reaction with the contaminant.

Ta has a much higher Z, so even 2.6 MeV is not enough to overcome the Coulomb barrier. This prevented the protons and deuterons from reacting with the Ta, so most likely what was seen was just other light contaminants reacting with the protons and deuterons.

Despite the fact that it did not appear that anything would be found, a net area calculation was done to try to find the number of ^{7}Be atoms per proton that were produced. These results are shown in Figure 10.

Source	N(7Be)/p	Err. N(7Be)/p
Cu + p	1.58E-11	8.03E-11
Cu + d	-1.8E-12	1.94E-11
Ta + p	9.18E-13	6.7E-13
Ta + p	9.26E-13	2.89E-13
Ta + d	-5.3E-13	1.49E-12
Cu + p	-9E-11	9.27E-11
Cu + d	-4.4E-13	1.54E-12
Cu + d	8.11E-14	5.88E-13
Cu + p	-2.6E-11	3.47E-11

Figure 10: The number of ^{7}Be atoms produced per proton or deuteron for the June run

It was decided to do a second run of the contamination testing, this time with the accelerator as a terminal ion source at 1.5 MeV again. This time two Cu targets and one Ni target were used. The procedure was the same as the first time, except that the Ni was only bombarded with protons. Also, in addition to using the net area found in JAM[3] like the first time, a curve fitting program will be used to give more reliable numbers for the area under the peak.

[3]JAM is the data acquisition system used in the Majorana room

Source	N(7Be)/p	Err. N(7Be)/p
Cu + p	1.56E-12	7.86E-13
Cu + d	-4.40E-13	7.07E-13
Ni + p	2.91E-11	8.37E-13

Figure 11: The number of ^{7}Be atoms produced per proton or deuteron for August run

The data from the second run was analyzed using the net area calculations as before. There were no extra peaks in the spectra this time. Small amounts of ^{7}Be were found, and the amount of ^{7}Be formed per proton or deuteron was comparable to the amounts found in 2004. The results are listed in Figure 11

6 Conclusions

This summer has been spent working toward the precision measurement of the ^{3}He$(\alpha, \gamma)^7$Be cross section. One of the most important things that has been done this summer is the detector efficiency measurement and calculation. In the preliminary run, the efficiency of the detector was estimated based on efficiencies of similar detectors. However, this introduced a huge uncertainty into the calculations of the cross section. By making a precise calculation of this efficiency it will be possible to eliminate a significant amount of that uncertainty, which is the only way to obtain a precise measurement of the cross section.

This experiment is far from over. In the near future the precision run of the experiment will take place. The procedure will be very similar to that of the preliminary run, as they found that they obtained good results with that set-up and procedure. The measurements of the prompt γ-rays and the ^{7}Be decays will be used to calculate the ^{3}He$(\alpha, \gamma)^7$Be cross section. The detector efficiency will also be measured and calculated again, using more data points, including some at higher energies, to obtain a more accurate curve for the efficiency. This will in turn be used to find the astrophysical S-factor $S_{34}(0)$. Only by having a precise measurement for this value can the Standard Solar Model be verified.

7 Acknowledgements

My work this summer was made possible by the National Science Foundation, the University of Washington, and the Center for Experimental Nuclear Physics and Astrophysics. I would like to thank my advisors Dr. Kurt Snover and Dr. Derek Storm for their patience and eagerness to help me learn about all parts of this project. I would also like to thank Dr. Cristina Bordeanu and Towfiq Ahmed for their invaluable help this summer.

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10cm-no absorber			
γ-source	Energy (keV)	Efficiency	Efficiency Error
133Ba	302.9	0.014208	0.000113
133Ba	356	0.01254	4.82E-05
137Cs	661.657	0.008857	8.19E-05
60Co	1173.24	0.005765	5.52E-05
60Co	1332.5	0.005273	5.24E-05

Figure 12: The efficiency with the source 10cm from the detector

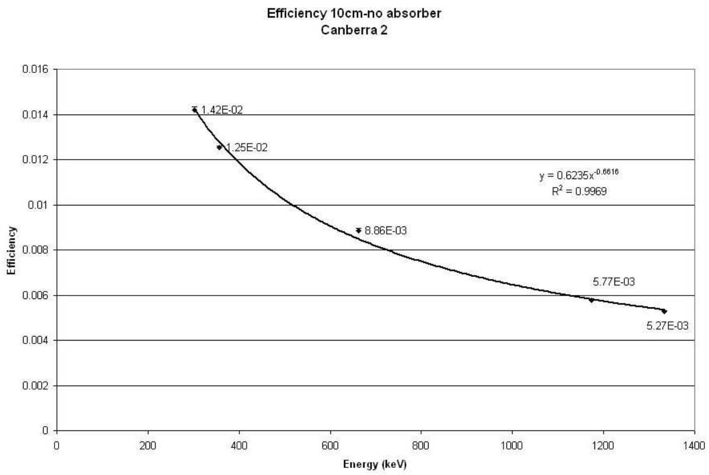

Figure 13: The efficiency curve with the source 10cm from the detector

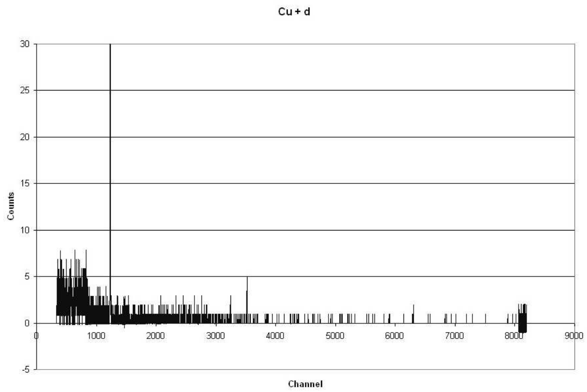

Figure 14: The spectrum of Cu bombarded with deuterons

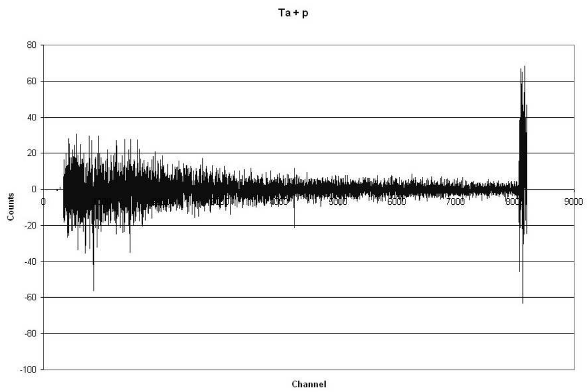

Figure 15: The spectrum of Ta bombarded with protons

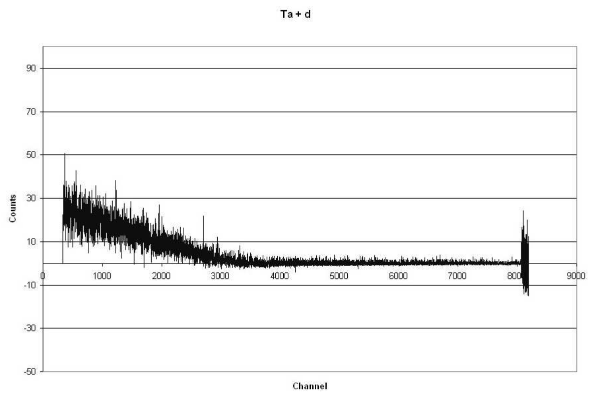

Figure 16: The spectrum of Ta bombarded with deuterons