Preliminary measurement of the $^3He(\alpha,\gamma)^7Be$ cross section

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Abstract

The current uncertainty of the $^3He(\alpha,\gamma)^7Be$ cross section greatly hinders the understanding of the high-energy solar neutrino flux from the $^7Be(p,\gamma)^8B$ reaction and, thus, is significantly important in the verification of the Standard Solar Model. I present the results of my efforts this summer in assisting the group lead by Kurt Snover to prepare for a high-precision measurement of the $^3He(\alpha,\gamma)^7Be$ cross section. This includes a successful test run of the experiment and a verification of our ability to see both the prompt γ-rays and the subsequent ^7Be activation.

1. Introduction

What is perhaps currently the hottest topic in astrophysics, solar neutrino flux measurements and predictions based on the Standard Solar Model are continuously being challenged and compared. The current uncertainty of the $^3He(\alpha,\gamma)^7Be$ cross section greatly hinders the understanding of the high-energy solar neutrino flux from the $^7Be(p,\gamma)^8B$ reaction [1] and, thus, is significantly important in the verification of the Standard Solar Model. Furthermore, precise knowledge of the cross section would facilitate the understanding of the primordial abundance of ^7Li [2].

The $^3He(\alpha,\gamma)^7Be$ reaction plays a major role in the proton-proton chain – the major nuclear burning stage in the (main sequence) stellar fusion of hydrogen into helium. The reaction is crucial in PPII and PPIII:

$$^1H + {}^1H \rightarrow {}^2D + e^+ + \nu$$

$$^2D + {}^1H \rightarrow {}^3He + \gamma$$

$$\mathbf{^3He + {}^4He \rightarrow {}^7Be + \gamma}$$

$$\swarrow \qquad \searrow$$

PPII	PPIII
$^7Be + e^- \rightarrow {}^7Li + \nu$	$^7Be + {}^1H \rightarrow {}^8B + \gamma$
$^7Li + {}^1H \rightarrow {}^4He + {}^4He$	$^8B \rightarrow {}^8Be + e^+ + \nu$
	$^8Be \rightarrow {}^4He + {}^4He$

The current data available on the $^3He(\alpha,\gamma)^7Be$ cross section were obtained by two different methods. The first method is through the detection of the prompt γ-rays resulting from the fusion of ^3He and ^4He [3,4]. The second method measures the resulting γ-activity of the produced ^7Be [3,4,5]. Table-1 summarizes the current data for $S_{34}(0)$. This S-factor is obtained from measurements of the reaction cross section (see Section-4 below).

Table - 1

$S_{34}(0)$ (keV b)	Reference
by prompt γ-rays:	
0.47±0.05	*Parker and Kavanagh (1963)*
0.58±0.07	*Nagatani et al. (1969)*
0.45±0.06	*Kräwinkel et al. (1982)*
0.52±0.03	*Osborne et al. (1982, 1984)*
0.47±0.04	*Alexander et al. (1984)*
0.53±0.03	*Hilgemeier et al. (1988)*
Weighted Mean=	0.507±0.016
by ^7Be activity:	
0.535±0.04	*Osborne et al. (1982, 1984)*
0.63±0.04	*Robertson et al. (1983)*
0.56±0.03	*Volk et al. (1983)*
Weighted Mean=	0.572±0.026

The values obtained from the two methods are consistently different. Resolving this discrepancy has been deemed one of the more important goals of nuclear physics [6] and the commonly accepted low-precision values for the S-factor are around 0.53keVb [6,7]. Clearly a more accurate measurement is needed.

My work this summer was focused on assisting the group led by Kurt Snover at CENPA in preparing for a high-precision measurement of the $^3He(\alpha,\gamma)^7Be$ cross section using both of the above methods simultaneously. The work completed as of the time of this paper has culminated in a rough test run of the $^3He(\alpha,\gamma)^7Be$ experiment.

2. $^3He(\alpha,\gamma)^7Be$

The first method in determining the $^3He(\alpha,\gamma)^7Be$ cross section is to count the number of prompt γ-rays resulting from the reaction and use that to determine how much ^7Be was produced.

We ran an alpha beam, so are therefore bombarding ^{3}He with the alpha particles. The γ-rays resulting from the fusion are "prompt" in the sense that their appearance is on the order of 10^{-16}s following the bombardment.

The energies of the resulting γ-rays depend on the center of mass energy of the alpha particle, $E_{\alpha,cm}$, given by

$$E_{\alpha,\mathrm{cm}} = \frac{m_2}{m_1+m_2} E_{\alpha,\mathrm{lab}} = \frac{3}{7} E_{\alpha,\mathrm{lab}} \quad (1)$$

The difference between the rest masses of the reactants and the products is the Q-value of the reaction. For the reaction ^{3}He(α,γ)^{7}Be, Q = +1.53MeV, and thus the resulting prompt γ-ray's energy is increased by this value.

Gamma rays of three different energies are produced in the reaction, as diagrammed in Figure-1.

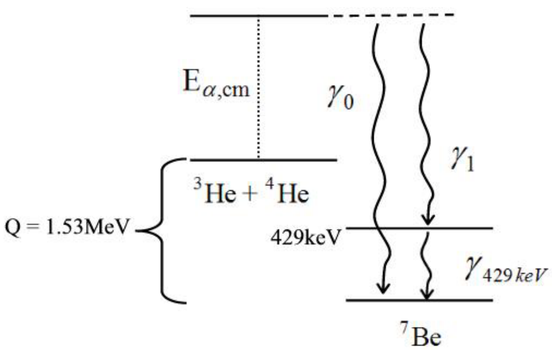

Figure-1 Energy level diagram of resulting gammas

As is evident from Figure-1, we can calculate the predicted γ-ray energies resulting from the reaction by:

$$\mathrm{E}_{\gamma_0} = \mathrm{Q} + E_{\alpha,\mathrm{cm}} \quad (2)$$

$$\mathrm{E}_{\gamma_1} = \mathrm{E}_{\gamma_0} - 429\mathrm{keV} \quad (3)$$

γ_{429keV} results from the transition from the first excited state to the ground state of ^{7}Be.

This is not the full story though. We have also to take into account that the reactions will not all take place precisely at the same place in the gas cell (as well as the fact that the beam will be attenuated through our Ni entrance foil in the gas cell). This requires other considerations and measurements, and these will not be discussed here.

3. ^{7}Be(e$^-$,ν)^{7}Li

The second method in determining the ^{3}He(α,γ)^{7}Be cross section is to count the γ-ray activity resulting from the subsequent decay of ^{7}Be to ^{7}Li.

After being produced, ^{7}Be decays with a half-life of 53.12 days[1] [8]. As illustrated in Figure-2, the decay will result in an excited state of ^{7}Li with a branching ratio of 10.4%.

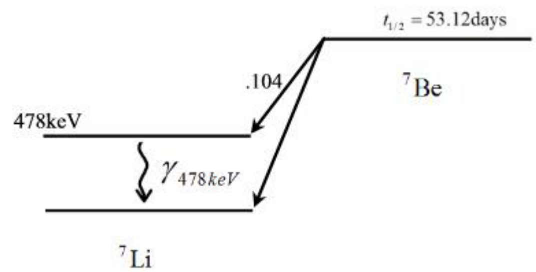

Figure-2 Energy level diagram for ^{7}Be decay

The decay is written

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu$$
$$\searrow$$
$$^7\mathrm{Li}^*(478\mathrm{keV}) + \nu$$
$$\downarrow$$
$$^7\mathrm{Li} + \gamma_{478}$$

Once the experiment is run, the ^{7}Be activity is counted over a long period of time and this is used to extrapolate how much ^{7}Be was produced during the bombardment.

4. σ*(E)* and the S-factor, $S_{34}(0)$

The astrophysical *S(E)* factor is given by:

$$S(E) = E\sigma(E)\exp(2\pi\eta) \quad (4)$$

where $2\pi\eta = 164.12/E^{1/2}$ with *E* in keV.

Calculation of $S_{34}(0)$, which is, of course *S(E)* with a center of mass energy of zero[2], cannot be measured directly, but instead must be extrapolated from values taken at higher energies.

Determination of the S-factor from the measurement of the prompt γ-rays (method 1 above) is significantly more difficult than by measurement of the subsequent ^{7}Be activation (method 2).

[1] The most widely accepted value is $t_{1/2}$=53.3days, but we will use a recent value of 53.12days (see ref.)

[2] The '34' subscript on $S_{34}(0)$ merely indicates that it's referring to the reaction ^{3}He + ^{4}He

If N_p is the number of incident particles (related to the beam current), n_t the number of target atoms per volume, l_{eff} the target length as seen by the detector ($N_t = n_t l_{eff}$), ε the absolute γ-ray efficiency of the detector and ω(θ,E) the angular distribution of the prompt gammas, then the γ-ray yield, *Y(E)*, is given by [3]

$$Y(E) = N_p n_t l_{eff} \varepsilon \omega(\theta, E)\sigma(E) \qquad (5)$$

The counted γ-rays are the yield, and Equation (5) is trivially solved to give the cross section if all of the other constants are precisely known. The difficulty is in accurately measuring these constants!

Calculation of the cross section from the measurement of the 478keV γ-ray of ^7Be decay requires the activity of the target backing (this is the material which has captured the produced ^7Be) to be counted for a long period of time. Obviously the longer the counting time the better the statistical strength of the measurement will be.

As ^7Be is produced, it subsequently begins to decay and so the expression for the rate of ^7Be production can be written [4]:

$$\frac{dN_{Be}}{dt} = \int \sigma(E_{cm}) I_\alpha n_t dx - \lambda N_{Be} \qquad (6)$$

where I_α is the alpha beam current in particles per second, n_t is the number density of the ^3He gas, and λ such that $t_{1/2}$=ln2/λ.

Since the experiment was really conducted over several discrete subperiods, it makes sense to calculate the amount of ^7Be produced during each individual subperiod and then correct for the length of time of decay that passes from the end of the subperiod until the time that counting begins. This requires a factor exp(-λΔ*t*) for each subperiod of ^7Be production. Summing over all of the subperiods, it can be shown that the expression for the total number of ^7Be nuclei at the beginning of the counting period is:

$$N_{Be} = \left(\frac{\sigma}{\lambda}\right) \sum_i \left[\left(N_t I_\alpha\right)_i \left(1 - e^{-\lambda t_i}\right) e^{-\lambda \Delta t_i} \right] \qquad (7)$$

where $N_t = n_t x$ and t_i is time of production for each subperiod. Equation (7) also allows us to compensate for a fluctuating beam current and ^3He gas pressure between runs.

Now we have to express the number of ^7Be nuclei at the beginning of the counting period in terms of the actual decay yield, Y_{478}, that is counted. If ΔN is the number of ^7Be decays counted during the counting period of length Δt_c, then the number of 478keV γ-rays detected should be

$$\Delta N = \frac{Y_{478}}{0.104\varepsilon} = N_{Be}\left(1 - e^{-\lambda \Delta t_c}\right) \qquad (8)$$

where .104 is the branching fraction of ^7Be decays that go to the excited state of ^7Li, and ε is the absolute efficiency of the Ge detector for the given position of the source.

Combining Equations (7) and (8), we get for the total cross section

$$\sigma = \frac{\lambda Y_{478}}{0.104\varepsilon \sum_i \left[\left(N_t I_\alpha\right)_i \left(1 - e^{-\lambda t_i}\right) e^{-\lambda \Delta t_i} \left(1 - e^{-\lambda t_c}\right) \right]} \qquad (9)$$

5. Experimental Setup

A ^4He beam was used, produced from the Model FN Tandem Van der Graff accelerator located at CENPA. The accelerator has been modified by the addition of a Terminal Ion Source (TIS), allowing it to function as a single ended machine (as opposed to in tandem).

Figure-3 is a rough schematic of the setup. The size of the alpha particle beam is determined by a swinging aperture arm, in which are located precisely drilled holes of diameter 3mm, 4mm, and 7mm. The position of the arm can be changed during an experiment, allowing beams of different sizes to be utilized without disturbing the setup.

Past the aperture arm, the beam continues through a series of collimators, and the current on the individual collimators can be monitored to facilitate focusing of the beam. Furthermore, knowing the current on the collimators is essential in accounting for the total current delivered to the gas cell. An electron suppressor (of negative voltage) helps force any stray electrons into the gas cell, which acts as a Faraday cup.

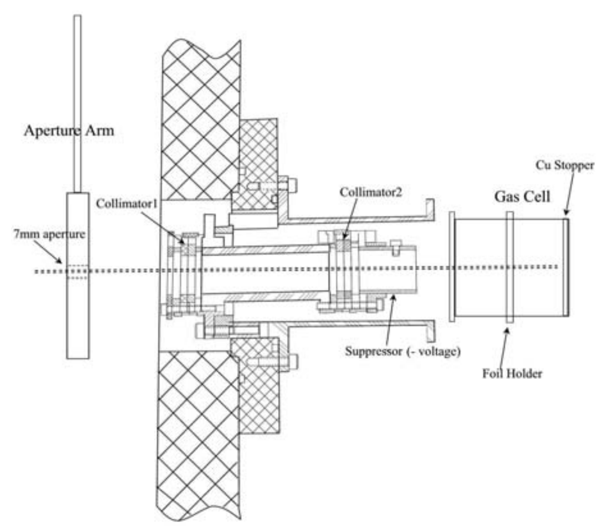

Figure-3 Schematic of the experimental setup

The gas cell is filled through an attached hose, which is connected to a network of valves and gauges through which we can carefully monitor and control the amount of gas contained within the cell. A Ni foil maintains the gas pressure in the cell and is mounted to the foil holder.

The Ni foil itself complicates the experiment. Great care was taken to choose Ni foils that were "pinhole free" so as to minimize the leakage of gas from the cell out into the chamber. A foil of approximately 1μm thickness was used so that the energy loss of the beam through the foil was small while keeping the foil strong enough to withstand a reasonable amount of beam current.

The beam was raster-scanned to avoid localized heating of the Ni foil. The area of the scan depended on the energy of the beam. At 3.5MeV, the beam was rastered over an area of $4.8 \times 4.8\text{mm}$. At 2.4MeV, $3.8 \times 3.8\text{mm}$. After several test runs of the beam on the Ni foil, it was determined that a current of below 1μA was sufficient to prevent significant foil degradation over several hours.

The inside walls of the gas cell were lined with a thin sheet of Ta foil, intended to catch backscattered ^{7}Be produced in the experiment. The Cu-OFHC (oxygen-free high conductivity) catcher was soldered to the Cu endplate using indium. The catcher material was chosen based on measurements of its background activity.

The Cu endplate (stopper) heats up while the beam is on, and so the heating of the backing must be controlled or the indium solder that holds the Cu-OFHC catcher will melt during the experiment. One way to cool the Cu endplate is to simply blow air on it from the outside.

We found that a high-pressure air hose worked well, keeping the temperature of the Cu backing under 150°F. However, we discovered later that the Ge detector is so sensitive to mechanical vibrations that the sound from the air hose was loud enough that it was creating significant noise in the spectra. This noise was reduced by reducing the airflow, but not so much as to undermine our ability to cool the Cu backing.

A GMX EG&G Ortec germanium detector was placed next to the gas cell, situated at 90° with respect to the beamline. The detector was electrically insulated from the gas cell and the table on which it sat. At least two inches of lead shielding surrounded each side of the Ge crystal. Care was taken to choose bricks of low contamination, specifically in the energy ranges relevant for measuring the production of ^{7}Be.

Activity measurements other than the detection of the prompt γ-rays were conducted in a low background room where a Pb shielding house has been built. The Pb house provides at least 8 inches of shielding on all sides of the Ge detector.

Background measurements were conducted in the counting room with and without Pb shielding. A comparison is shown in Figure-4 between the measured background rates for these two cases. Taken over the entire spectrum, the reduction of background by the Pb shielding is by a factor of 13!

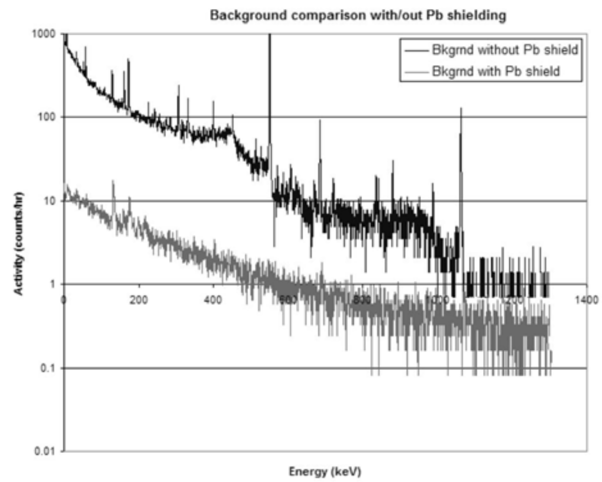

Figure-4. Actual rate comparison of background with and without lead shielding.

6. Results

In this section the results are given of the actual ^{3}He(α,γ)^{7}Be run that was carried out during the first week of August 2004, which was done just in time for this paper.

We ran a beam energy of 3.5MeV on the first day and then 2.4MeV on the second day. The same Cu-OFHC target was used at both energies, and therefore it would be useless to try to make an actual estimate of a cross section using Equation (9) since the cross section varies with different center-of-mass energies. However, we were still able to follow the procedure outlined in Section-4 to estimate the amount of ^{7}Be produced through the measurement of the subsequent ^{7}Be activity.

The experiment was run for approximately 7 hours at 3.5MeV and then 6 hours at 2.4MeV the following day.

The pressure in the gas cell was kept nearly constant at 200torr, which corresponds to an energy thickness of about 188keV. The beam was run at a current of around 200nA, well below the threshold for burning up the Ni entrance foil.

Using that ΔE_{foil}=492keV and ΔE_{gas}=188.16keV, we can estimate where the three gamma peaks for ^{3}He(α,γ)^{7}Be should be in the spectrum. The 429keV peak should be sharp, while the two higher energy peaks will be spread over an energy range corresponding to the energy thickness of the gas[3]. For the

[3] The width of the peaks are also affected to a much smaller extent by Doppler effects

3.5MeV beam energy we can calculate the two high-energy gammas, $E_{\gamma 0}$ and $E_{\gamma 1}$.

With no gas:

$$E_{\alpha,lab} = 3500\text{keV} - 492\text{keV} = 3008\text{keV}$$

$$E_{\alpha,cm} = \frac{3}{7} E_{\alpha,lab} = 1289\text{keV}$$

From Equations (2) and (3): $E_{\gamma_0} = 2876.14\text{keV}$ and $E_{\gamma_1} = 2447.14\text{keV}$.

With 200torr of gas:

$$E_{\alpha,lab} = 3500\text{keV} - 492\text{keV} - 188.16\text{kev} = 2819.84\text{keV}$$

$$E_{\alpha,cm} = \frac{3}{7} E_{\alpha,lab} = 1209\text{keV}$$

$E_{\gamma_0} = 2795.50\text{keV}$ and $E_{\gamma_1} = 2366.50\text{keV}$.

For a beam energy of 3.5MeV, we expect three resulting gamma peaks, the first a sharp one at 429keV, the second between 2367-2447keV, and the third between 2796-2876keV.

Figure-5 shows a spectrum from the ^{3}He(α,γ)^{7}Be experiment.

A major question that we wanted to answer with this test run was whether or not the two higher energy peaks would be visible in the spectrum. The worry was that the peaks would be broadened so much that they would essentially blend in to the background. This question is answered by Figure-5 – the peaks are visible and where we expect them to be with the thickness of the Ni foil and gas.

Following alpha bombardment, which we will refer to as the production period, the Cu-OFHC target backing (catcher) was placed inside the Pb housing in the counting room. The backing was placed inside a plastic ziplock bag (to prevent contamination of the detector) and was taped so that the irradiated area of the target was flush up against the front face of the Ge detector. Figure-6 illustrates this geometry.

The activity of the target backing was measured for 130.83 hours, and the measurement began 86.98 hours following the end of the production period. Figure-7 shows the 478keV peak measured. The total yield during this time contained within the peak is 2387.8±103.1 counts, calculated by finding the net area of the peak versus the overall slope of the spectrum.

Rewriting Equation (8), we get the following expression for the number of ^{7}Be atoms at the beginning of the counting period:

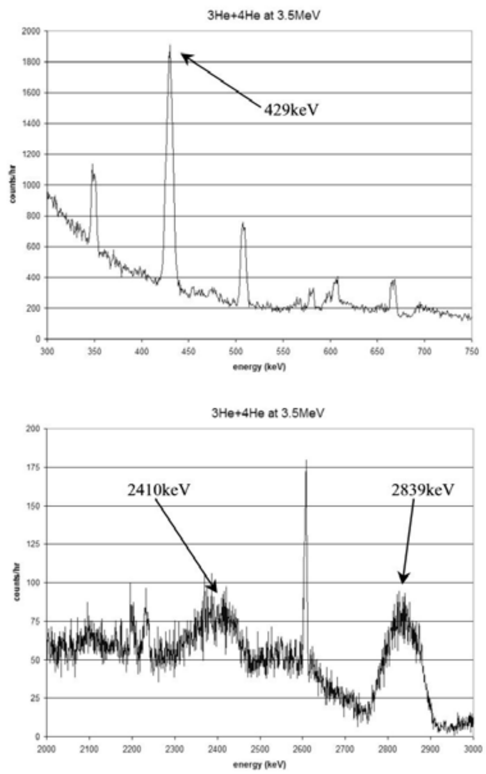

Figure-5. ^{3}He(α,γ)^{7}Be spectra showing the three gammas

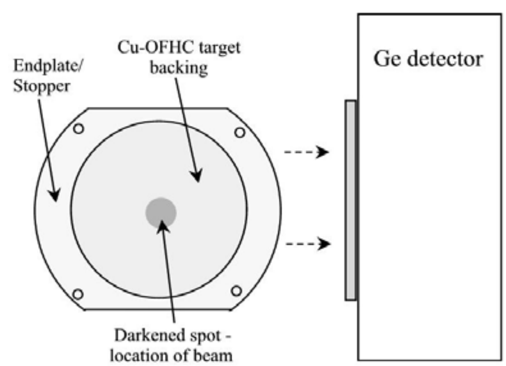

Figure-6. Diagram of the target backing (after irradiation) and detector geometry.

$$N_{Be} = \frac{Y_{478}}{0.104\varepsilon\left(1 - e^{-\lambda \Delta t_c}\right)} \qquad (10)$$

We have measured Y_{478}=2387.8±103.1. The decay constant is given by

$$\lambda = \frac{\ln 2}{t_{1/2}} = 5.4358 \times 10^{-4}\text{hr}^{-1}$$

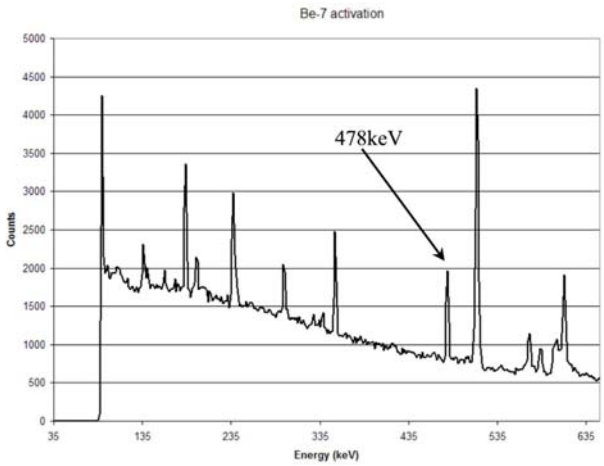

Figure-7. The Be-7 decay line after 130.8 hours of counting.

and the efficiency of the Ge detector has been estimated to be 0.0605±.0149 for the used geometry[4].

These values along with the counting time, t_c=130.83hr, in Equation (10) gives an estimate of the number of ^{7}Be atoms present at the beginning of the counting period $N_{Be} = 5.5281\times10^6$.

Taking into account the time between the production period and the counting period, Δt=86.98hr, we can extrapolate from the above estimate the number of ^{7}Be atoms present at the end of the production period:

$$N_{Be} = 5.7958\times10^6 \pm 1.38\times10^6 \ {}^7\text{Be atoms}$$

where the uncertainty was calculated using propagation of error of the efficiency and yield estimate.

7. Conclusions

We have learned a lot of things from this summer's work, and yet we have a lot of improvements to make.

It should be stressed that the test run of the ^{3}He(α,γ)^{7}Be experiment described in the last section was just that – a test. The information we really needed to obtain from the test run was whether or not the thickness of the foil and gas would cause the prompt gamma ray peaks to be spread too far out to be seen above the background. We have shown that we *can* see the peaks with the current experimental setup.

The second major piece of information to come from this same experiment was whether or not we were actually creating enough ^{7}Be to be effectively measured. The beam current must be kept low enough not to break the Ni entrance foil, and therefore it was important to see if the low current would cause a low ^{7}Be production rate. Well, Figure-7 clearly indicates that we are able to produce ^{7}Be in significant enough amounts to be measured.

The estimation of the ^{7}Be production given at the end of the last section has an error of about 24% based upon the errors of the detector efficiency and gamma counts! This enormous uncertainty is due almost entirely to the 25% uncertainty in the detector efficiency. In the near future an accurate measurement of the detector efficiency should bring the error associated with the efficiency down to 5% or so. A 5% uncertainty in the detector efficiency would reduce the uncertainty in the ^{7}Be estimation to around 6%. This efficiency measurement and a longer ^{7}Be decay counting time would be simple steps to improving the estimation.

8. Acknowledgements

The work I have done this summer would not have been possible without the support of the National Science Foundation and the University of Washington.

This summer I have had the extreme pleasure of working alongside a wonderful, and very professional, group of people – Kurt Snover and Derek Storm were endlessly patient with me and the respect I have gained for them both over the summer is inexpressible. My summer here would have been nowhere near as productive without the effort of Cristina Bordeanu, she was always there to answer my questions to the fullest. I have to also thank Kamil Michnicki, Doug Will and Greg Harper for all their help this summer, and, perhaps more so, for their senses of humor.

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