Analyzing Sources of Uncertainty in a Precision Measurement of $^{3}He(\alpha,\gamma)^{7}Be$

Amy Crisp
Center for Experimental Nuclear Physics and Astrophysics, University of Washington
Department of Physics, Florida State University

Abstract

The $^{3}He(\alpha,\gamma)^{7}Be$ reaction plays an important role in the solar p-p chain. The uncertainty in this reaction rate is currently the largest nuclear physics uncertainty in solar model calculations of the neutrino flux from the decay of both ^{7}Be and ^{8}B in the sun. At CENPA we are measuring the low energy cross section for this reaction at center-of-mass energies of 1.2 MeV and lower, using a ^{3}He gas cell with a thin nickel entrance window. The goal of this experiment is to determine the astrophysical S-factor to ±5% or better, from measurements of both the prompt γ's and the ^{7}Be activity produced in the same irradiation. In order to reach this goal one must measure and minimize the important systematic errors. We will discuss beam heating of the target gas, sources of background radiation, and detector efficiency, as well as other important aspects of the experimental technique.

Introduction

During my ten weeks at the University of Washington I worked with Dr. Kurt Snover, Dr. Derek Storm, and Dr. Tom Brown on the experiment to measure the $^{3}He(\alpha,\gamma)^{7}Be$ reaction with high precision. This reaction is an important piece of the solar proton-proton chain, shown in figure 1. The uncertainty in this reaction rate is currently the largest nuclear physics uncertainty in solar model calculations of the neutrino flux from the decay of both ^{7}Be and ^{8}B in the sun.

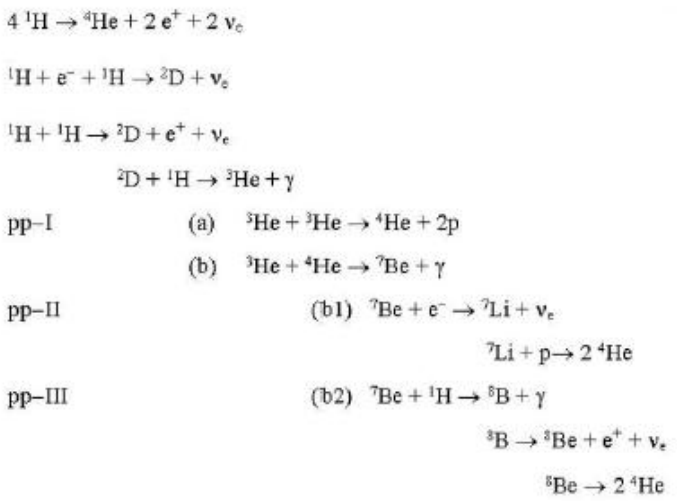

Figure 1: The solar proton-proton chain. [1]

It is difficult to measure this reaction in the lab at the low energies at which it takes place in the sun. Therefore, the cross section is measured at higher energies and used to calculate the astrophysical S-factor, which is related to the cross section as follows:

$$\sigma(E) = [S(E)/E]*\exp(-2*\pi*\eta(E)).$$

The S-factor can be extrapolated to lower energies, and then used to determine the cross section at the energies in the sun.

The goal of the experiment is to determine the S-factor to ±5% or better. Therefore, it is important to identify, understand, and minimize the important sources of systematic uncertainty. During the summer I worked on three of these uncertainties: background radiation, beam heating, and detector efficiency.

Experimental Setup

The reaction was measured using the Model FN Tandem van de Graaff accelerator at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) at the University of Washington. It was run at alpha beam energies of 2.1 and 2.35 MeV during the ten weeks that I

participated in the experiment. There was also previous data at 2.6 and 3.5 MeV. The beam passed through a nickel foil and interacted with ^{3}He and ^{4}He gases separately, which were contained in the gas cell shown in Figure 2.

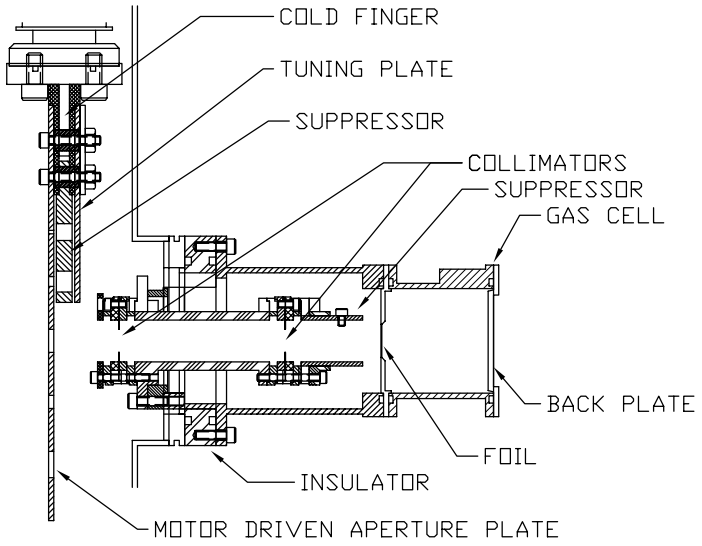

Figure 2: The experimental setup.

A germanium detector with a diameter of 8cm and depth of 8cm, referred to as Canberra 2, is used to detect the prompt gamma rays from the reaction. In the back of the gas cell is a Cu stopper plate and a tantalum liner, which absorb the ^{7}Be nuclei created in the $^{3}He(\alpha,\gamma)^{7}Be$ reaction. The stopper and liner are placed in front of another Ge detector at a later time after the experiment, and the ^{7}Be activity is detected as it decays with a lifetime of 53.28 days. The combination of prompt gamma ray detection and ^{7}Be activity detection is what makes this experiment unique.

Background Radiation

Since the γ_0 and γ_1 gamma rays (figure 3) are not stationary in the spectra, but rather depend on the beam energy, the background radiation interfering with these peaks also varies.

At certain energies we were able to position the γ_0 peak between background peaks, but this is not always possible. Therefore, it is helpful to understand what sources produce the individual background peaks.

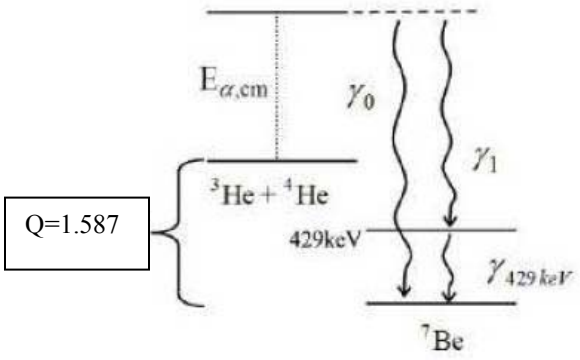

Figure 3: Decay of ^{3}He + ^{4}He.

To measure the room background, the detector was run to collect data while the beam was off. Figure 4 shows a spectrum from one of these measurements, which were typically run overnight or over the weekend to maximize statistics. The main sources of room background include ^{228}Ac, ^{214}Pb, ^{214}Bi, ^{208}Tl, ^{137}Cs, ^{60}Co, and ^{40}K.

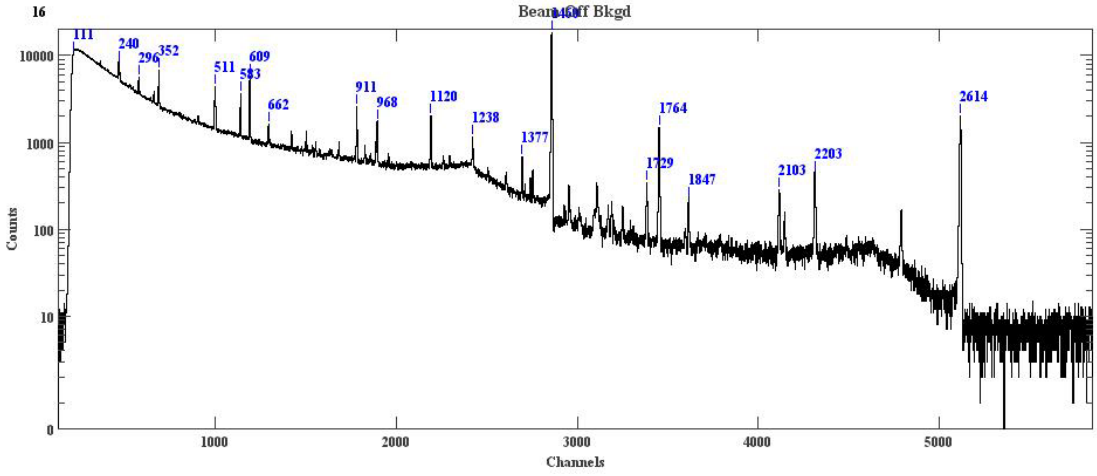

Figure 4: A spectrum from the beam-off room background measurement. The large 1461 keV and 2614 keV peaks come from ^{40}K and ^{208}Tl, respectively.

To determine the background radiation produced from the alpha beam reacting with various elements of the experimental setup, the gas chamber was filled with ^{4}He and the $^{4}He(\alpha,\gamma)^{8}Be$ reaction was measured. Figure 5 shows a spectrum from this reaction with the beam-off room background normalized and subtracted out. I was able to identify various gamma rays from ^{63}Cu at 585, 670, 899, 962, 1327, 1547, and 1861 keV. Identification of peaks involved searching through a database [2] to find nuclei that produce gamma rays at that particular energy, and then looking for evidence of other gammas that would be produced by that nucleus, especially from the same decay level.

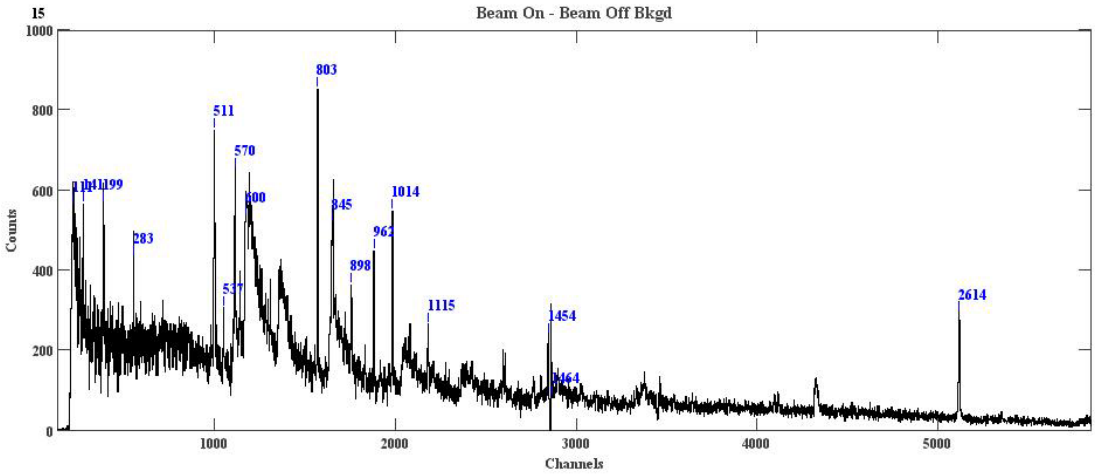

Figure 5: $^{4}He(\alpha,\gamma)^{8}Be$ spectrum with the room background subtracted. The broader peaks at 563, 596, 691, 835, and 1040 keV are produced by the excitation of germanium isotopes in the detector.

This beam-on background measurement is based on the assumption that $^{4}He+^{4}He$ produces the same background as $^{3}He+^{4}He$. We can have confidence in this assumption based on the lack of background remaining when both background spectra (beam-off and beam-on) are normalized and subtracted from the $^{3}He+^{4}He$ spectrum, as shown in figure 6. The only prominent peaks remaining are the γ_0, γ_1 and γ_{429}.

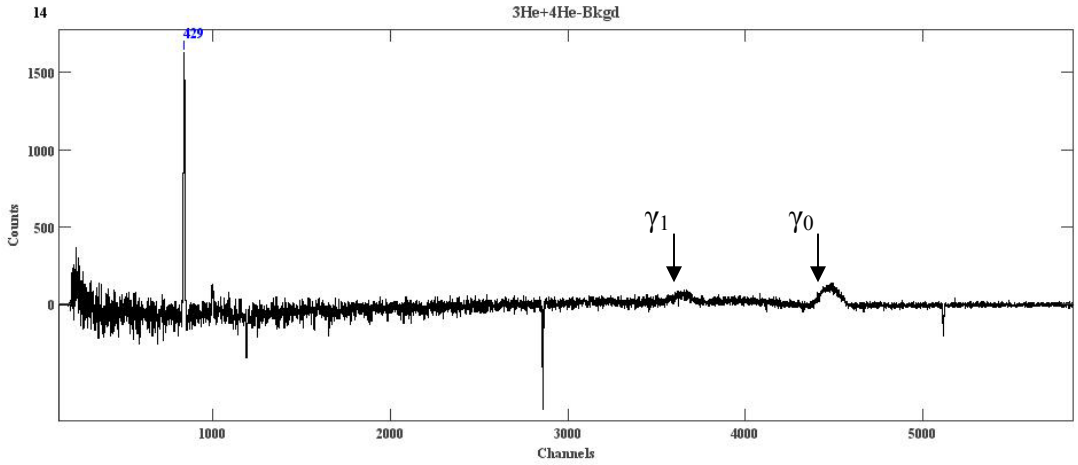

Figure 6: $^{3}He(\alpha,\gamma)^{7}Be$ spectrum with the room background and beam-on background subtracted.

Beam Heating

To determine the cross section of a reaction, one must know the number of atoms per unit area in the target. Since this experiment uses a gas target, we need to know the density of the gas in the cell where the reaction takes place. This density depends on the pressure of the gas, which is known, along with the temperature of the gas along the beam. The beam does not illuminate the entire gas cell, but rather a small section of the gas cell in the direct path of the beam, creating a variation of temperature within the gas cell. While we can and do measure the overall temperature of the gas cell, it would be highly impractical to place a temperature sensor in the direct line of the beam. Therefore, measurements must be made to determine how much the beam heats the gas in the cell.

In order to do this, the $^{10}B(\alpha,p)^{13}C$ reaction was measured under three different circumstances, exciting a resonance that makes a 3860 keV gamma ray. The first time, there was no gas in the cell and no nickel foil in place. The beam energy was varied between 1.4 and 1.575 MeV. The yield of the 3860 keV gamma ray was measured, giving the dark blue points in figure 7.

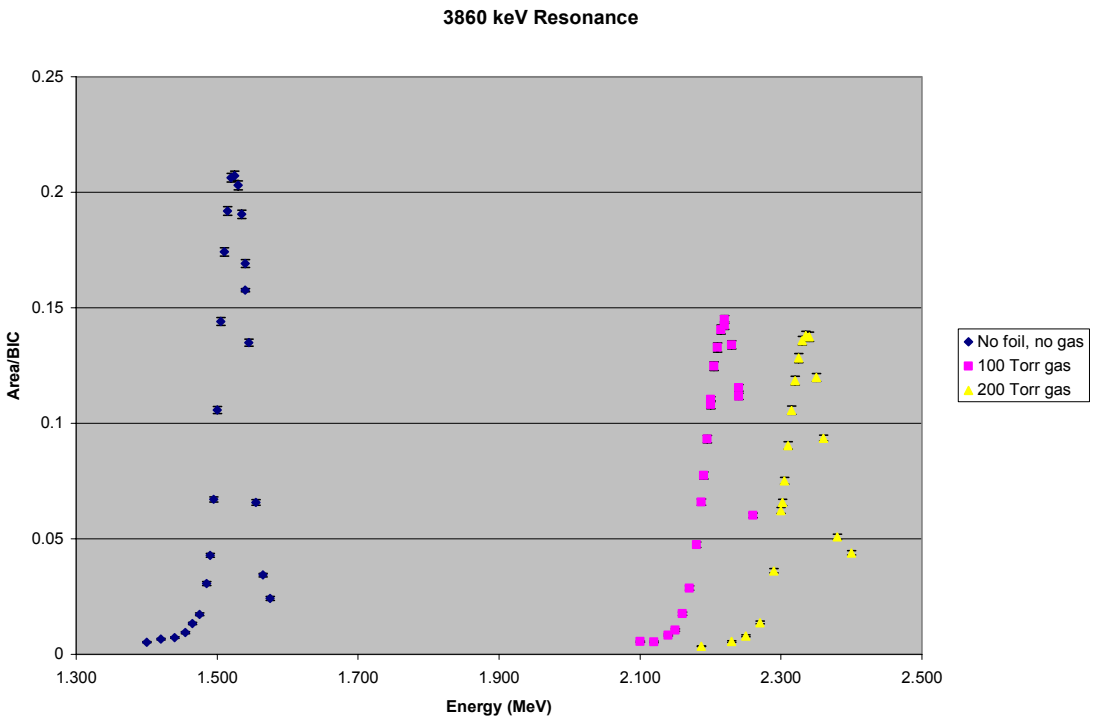

Figure 7: The resonance curves for the $^{10}B(\alpha,p)^{13}C$ reaction.

Then the nickel foil was put into place and the cell was filled with 100 Torr of ^{3}He gas. This was run at beam energies between 2.1 and 2.26 MeV, producing the pink points in figure 7. Then the beam energy was kept at 2.187 MeV, which is near the center of the rise of the curve in figure 7 (near the resonance energy), while the beam current (I) was varied between approximately 50 and 500nA, as shown in figure 8.

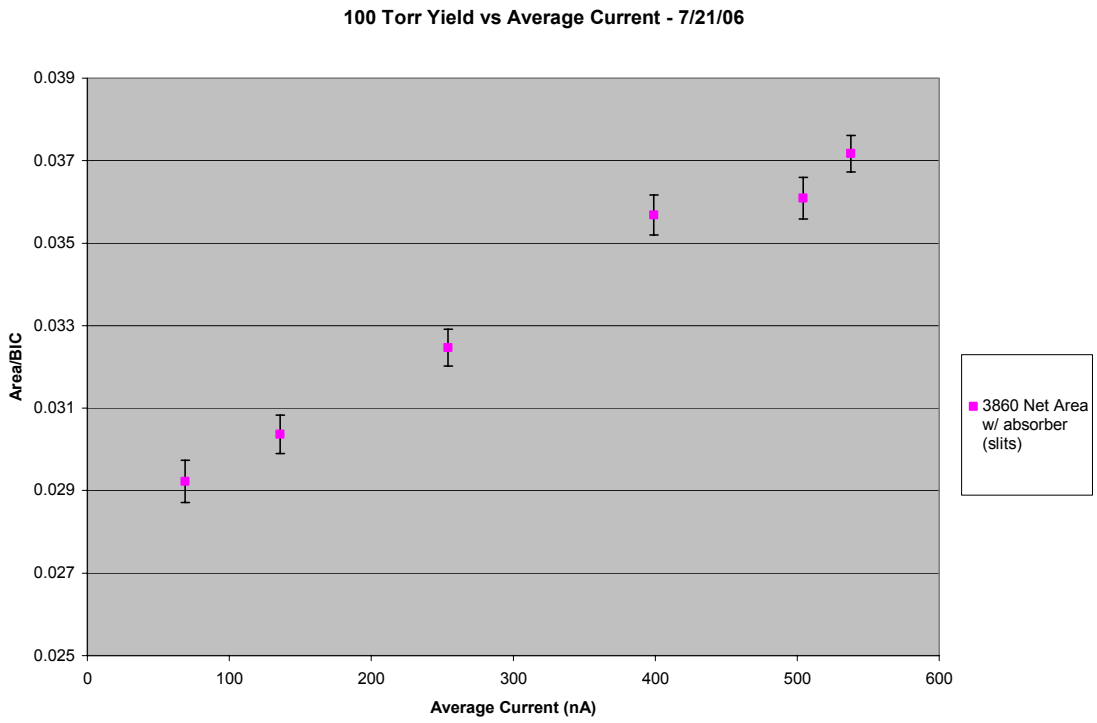

Figure 8: Yield of the 3860 keV peak vs. beam current at 100 Torr.

This process was repeated with the gas cell filled with 200 Torr of ^{3}He gas. The beam energy was varied between 2.23 and 2.4 MeV, and then the current was varied between 50 and 500nA while the beam energy was kept at 2.302 MeV.

A linear fit of the yield vs. current data was used to find the yields at 100 and 500nA. Then a fit of the energy resonance curve was used to find what energy would give those same yields. Using these values, dE/dI was calculated and divided by the total loss in energy of the beam going through the gas at 100 and 200 Torr as needed. This value is equal to $(d\rho/dI)/\rho_0$. Therefore, the corrected density would be

$$\rho = \rho_0[1 + (1/\rho_0)*(d\rho/dI)*I]$$

For 100 Torr, $(d\rho/dI)/\rho_0$ was found to be $-0.089 \pm 0.015\mu A^{-1}$, and for 200 Torr it is $-0.130 \pm 0.020\mu A^{-1}$.

Detector Efficiency

The efficiency of the germanium detector can vary if the detector is moved or otherwise changed. Therefore, periodic measurements must be made of the detector efficiency. To do this, a radioactive source is placed in front of the detector, and a measurement is taken. A special apparatus has been built to ensure that the sources are placed in exactly the same place every time. The sources used were ^{60}Co, ^{137}Cs, ^{203}Hg, ^{54}Mn, ^{113}Sn, ^{88}Y, and ^{7}Be. For each of these sources, the yield of one of the characteristic gamma rays was measured, and a ratio was made of this yield to the one found during the last efficiency measurement. Between the last efficiency measurement done in May, 2006 and the one done in July, 2006, the efficiency changed approximately 1%. Upon inspection, it was apparent that the table on which the detector stands had been moved a small distance from the gas cell.

Conclusion

During my ten weeks at the University of Washington, I worked on the high precision measurement of the ^{3}He$(\alpha,\gamma)^{7}$Be reaction. My focus was on the analysis of three particular sources of uncertainty in the measurement. A search for possible sources of background radiation, both beam-on and beam-off, found various gamma rays from ^{228}Ac, ^{214}Pb, ^{214}Bi, ^{208}Tl, ^{137}Cs, ^{60}Co, ^{40}K, and ^{63}Cu. The larger peaks in the beam-off background have mostly been identified now, as well as many of the larger beam-on peaks. Measurements were made of beam heating effects on the gas, which gave values for the fractional changes in density of $-0.089 \pm 0.015\mu A^{-1}$ for 100 Torr, and $-0.130 \pm 0.020\mu A^{-1}$ for 200 Torr. The efficiency of the germanium detector was measured, and analysis showed that the efficiency had changed by approximately 1%. More measurements will be made of this reaction at lower beam energies, in order to

extrapolate the S-factor to very low energies. Currently, reaching the goal of determining this value within 5% is probable.

Acknowledgements

[1] W.C. Haxton, P.D. Parker, C.E. Rolfs, nucl-th/0501020, 10 Jan 2005

[2] www.nndc.bnl.gov/nudat2/