The (n,2p) Reaction as a Probe for the Pre-existing Nuclear Δ^{++} Component

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1. Abstract

The ^{3}He(n,2p)2n and ^{4}He(n,2p)3n cross-sections are being measured as a means to explore the Δ^{++} component of the nuclear wave function. The incident neutron beam ranges between 250 and 800 MeV. Scattered protons on beam right pass through magnetic spectrometers which measure the momentum of the proton. The spectrometer consists of a thin ΔE scintillator, two drift chambers, two permanent magnets and finally two thin scintillators. On beam left, a horizontal ΔE scintillator array in front of a vertical proton scintillator array also detects scattered protons.

2. Motivation

Traditional models of the nucleus, which treat it as a non-relativistic system of nucleons, do not completely explain the binding energies and the electromagnetic properties of nuclei. By the 1960s, theorists suggested the presence of a pre-existing Δ particle in the ground-state nuclear wave function and that this Δ resonance might be important in nuclear structure. The Δ^{++} has a mass of about 1232 MeV, spin and isospin of 3/2, and a +2e charge. To investigate the Δ^{++} component of the nucleus, the ^{3}He(n,2p)2n and the ^{4}He(n,2p)3n cross-sections are being measured at the Weapons Nuclear Research (WNR) facility, a division of the Los Alamos Nuclear Science Center (LANSCE) in Los Alamos, New Mexico.

There are two primary ways that the ^{3}He(n,2p)2n and the ^{4}He(n,2p)3n reactions may proceed. For a two proton nucleus, the reaction may proceed in two steps, as shown below.
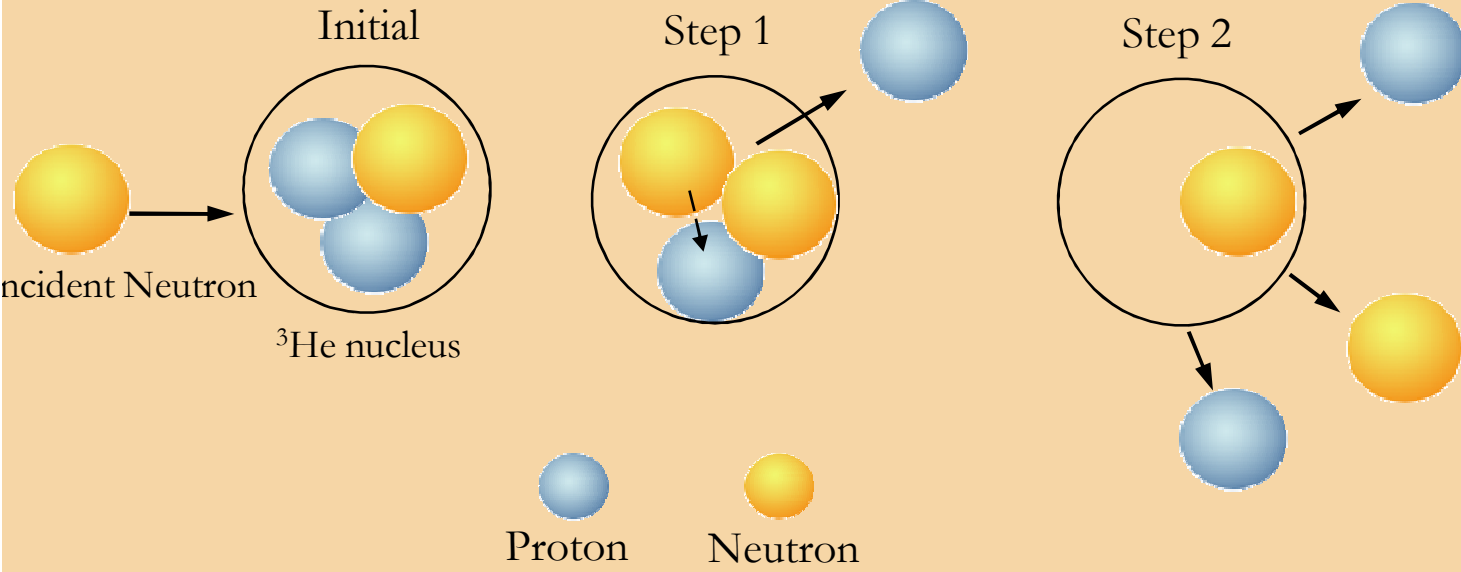
However, this reaction may proceed in one step if a Δ^{++} is involved as shown in the Feynman diagram below. In this diagram, time progresses from left to right across the diagram and pions are mechanisms for exchanging charge and energy among nuclei. A positive pion is exchanged between the two protons, causing one of the protons to become a Δ^{++} particle and the other a neutron. In this exchange, charge is conserved. Once there is a Δ^{++} particle, a neutron interacts with it and a pion is exchanged during the collision such that the neutron and Δ^{++} are replaced by two protons. This is a single step since the neutron interacted with only one other particle.
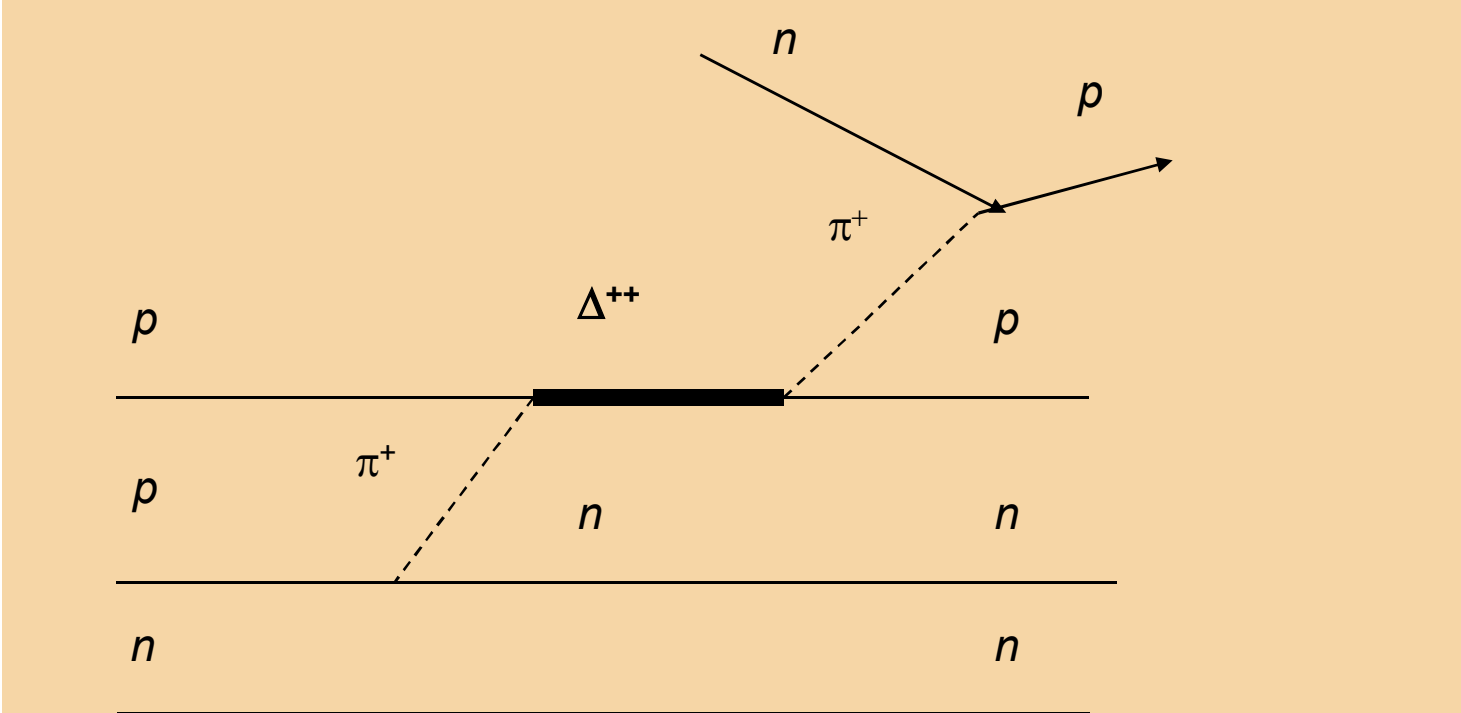
This single step reaction has a distinguishable kinematic signature which allows the approximate Δ^{++} (n,2p) contribution to be determined. A kinematic diagram of what this reaction may look like is shown below.
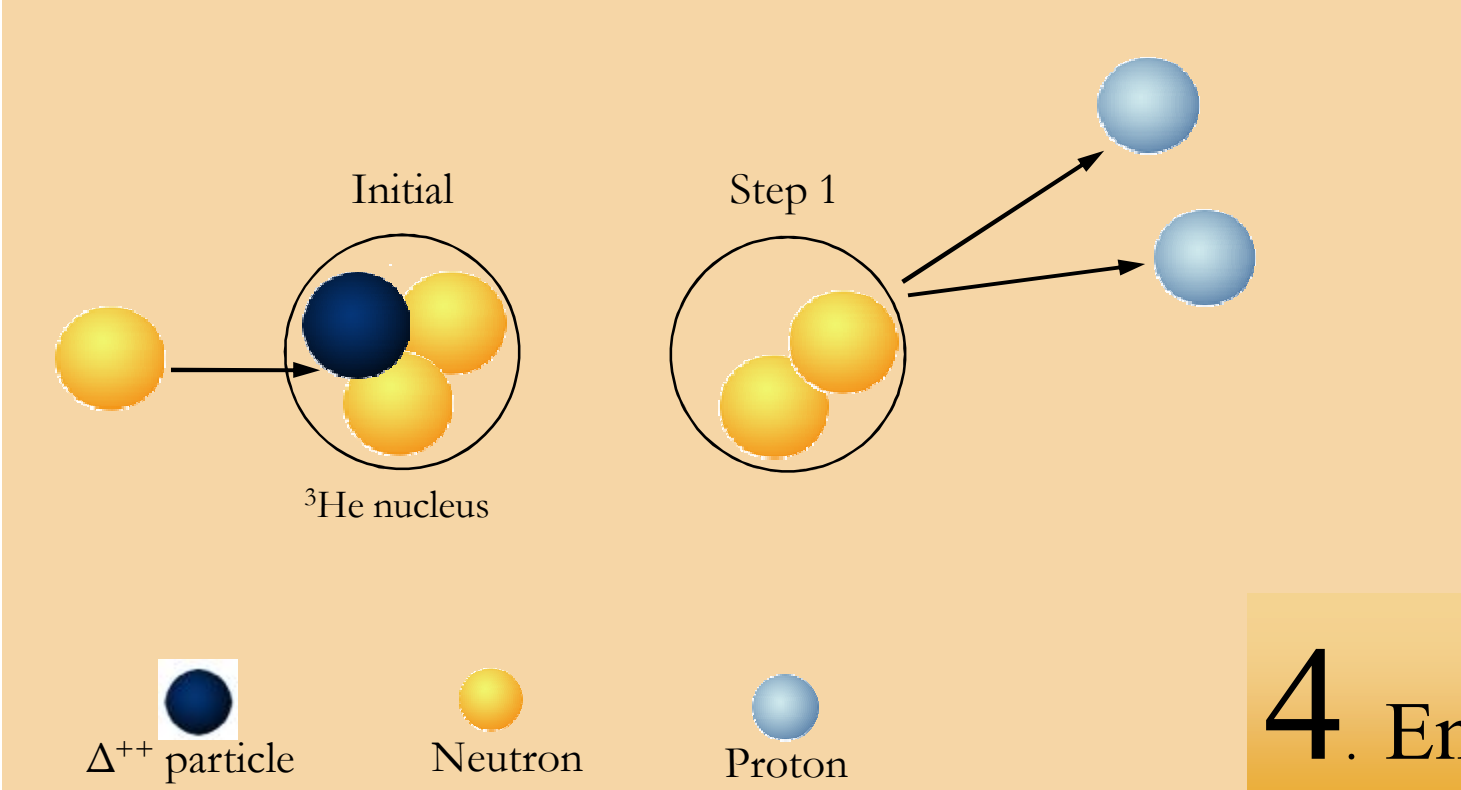
There have been previous investigations of Δ particles in various nuclei. Measurements such as those performed by Morris et al. (C.L. Morris et al., Phys. Lett. B419, 25 (1998)) have looked at the Δ^- component in ^{3}H, ^{3}He, ^{6}Li, ^{7}Li, ^{12}C, ^{13}C, ^{90}Zr, and ^{208}Pb nuclei using the (π^+,π^-p) reaction. Like the (n,2p) reaction, the (π^+,π^-p) reaction will generally proceed in two steps, but with a pre-existing Δ^- particle in the nucleus it may proceed in one step. These measurements indicate a 1-3% Δ^- component of the nuclear wave function. In 1996 and 1997 the ^{3}He(n,2p)2n and the ^{4}He(n,2p)3n reactions were studied by our group of collaborators from MIT and Los Alamos National Laboratory using the WNR facility. Unfortunately, not enough events were detected to determine a statistically meaningful value for a Δ^{++} component. However, this (n,2p) data, together with the (π^+,π^-p) data, encouraged the further exploration of pre-existing Δ^{++} components of the nuclear wave function. For this reason, the ^{3}He(n,2p)2n and ^{4}He(n,2p)3n reactions are again being studied in an attempt to collect sufficient data to determine the Δ^{++} component of the nuclear wave function.

3. Experimental Apparatus

The experimental apparatus is shown below. The neutron beam passes through the fission chamber and is incident on the helium target. Left and right detector arms are designed to detect the two scattered protons in coincidence.
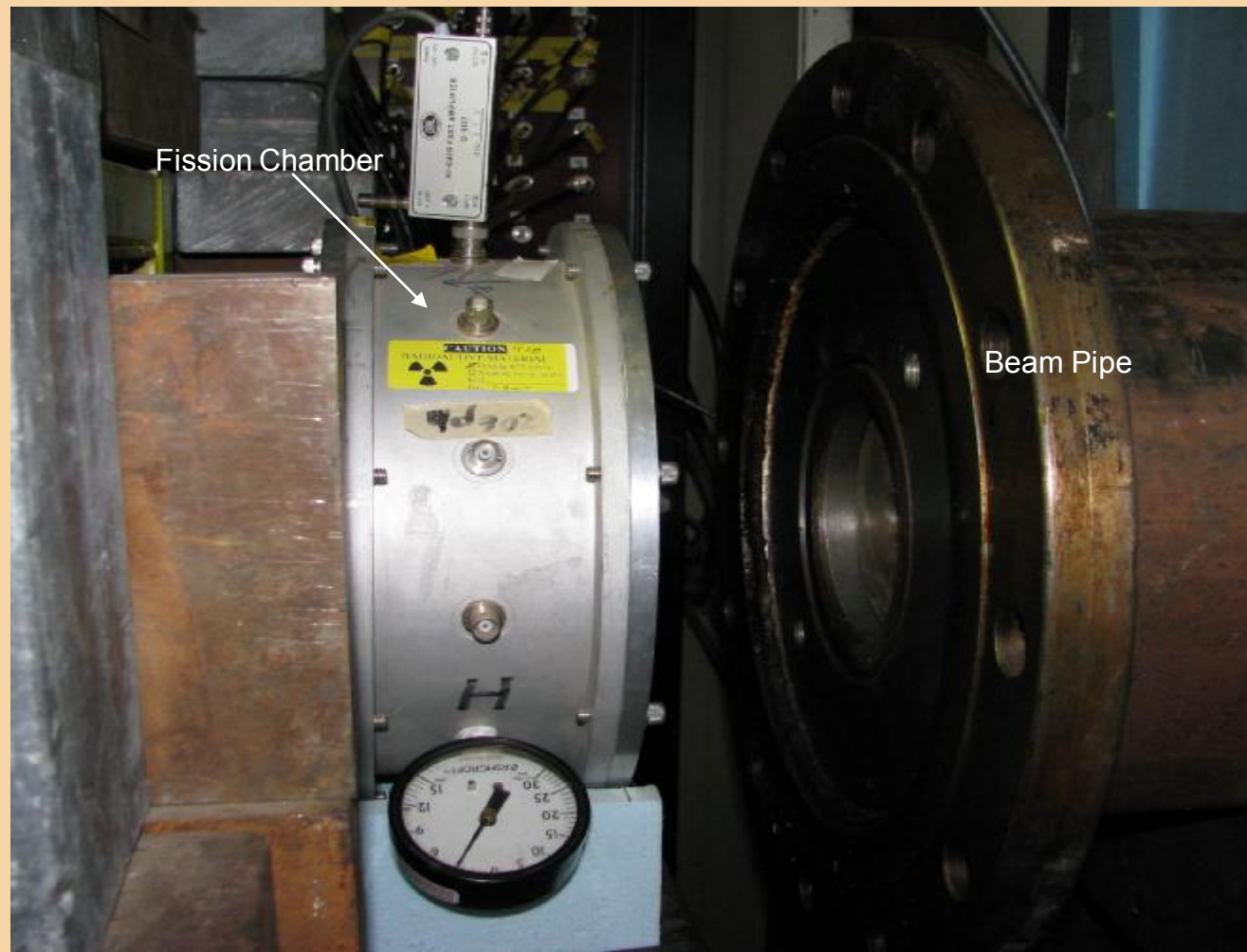

3.a. Neutron Beam

The neutron beam used in this experiment is produced by spallation using the half-mile long Clinton P. Anderson proton accelerator at LANSCE. Proton beam production begins when hydrogen ions (H$^+$ or H$^-$) are accelerated through the linear accelerator, which consists of drift tubes that accelerate protons in stages. Each stage sets up an accelerating potential across a region of space, giving the proton energy. Inside each of the conductive tubes the particle is shielded from the electric field. Thus, inside the tubes protons drift freely until reaching the next potential difference. In order to ensure that the proton always accelerates between drift tubes, the polarity between the tubes switches at fixed intervals when the proton is shielded from the electric field. Furthermore, the lengths of the drift tubes increases such that each proton spends an equal amount of time inside each drift tube. In this manner, the protons are accelerated to about 800 MeV. This high energy proton beam is incident upon a Tungsten spallation target. Neutrons scatter off the target and travel towards various experimental areas.

3.b. Fission Chamber

The flux of incident neutrons on the target must be monitored so that any changes in the beam can be detected. Measured cross sections from the ^{3}He(n,2p)n and ^{4}He(n,2p)2n reactions are compared to the neutron flux to determine a ratio between the total number of neutrons striking the target and the number of particles detected. Neutron flux is measured by the fission chamber.

The fission chamber is a cylinder (29.2 cm in diameter) and contains ^{238}U deposits which lie in the beam's path. Neutrons pass through the fission chamber, some of which are absorbed by the ^{238}U. The newly formed, unstable ^{239}U nucleus splits into two isotopes which ionize the gas mixture. The resulting free electrons are collected by an anode and the resulting signal is processed. Neutron flux can be measured in this way since the fission rate is proportional to the number of neutrons passing through the chamber.
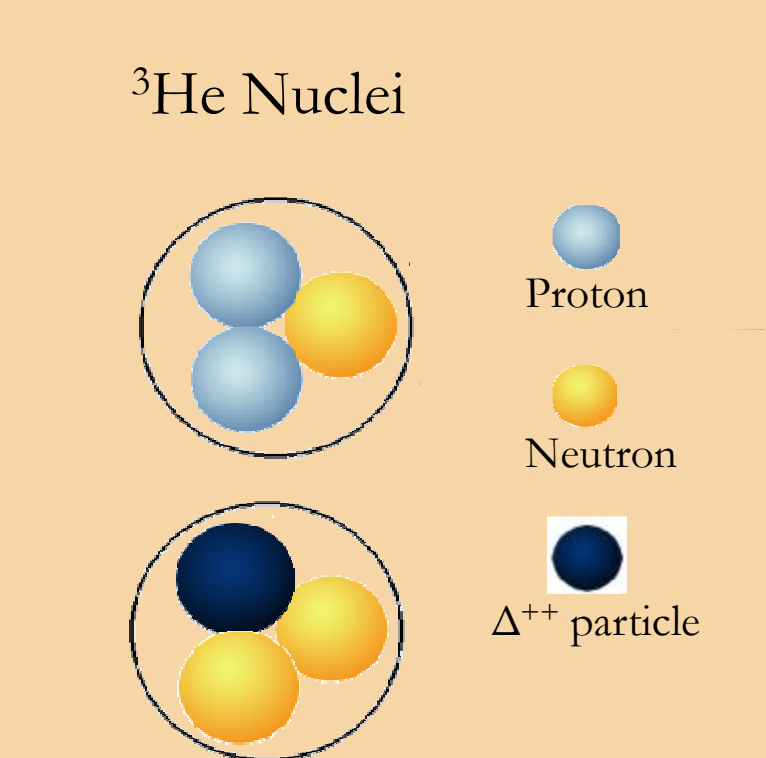

Shown above is a photograph of the fission chamber. The neutron beam passes through the fission chamber after traveling along the beam pipe. Terminals located along the outer wall of the chamber allow the electronic signals to be sent to computers for data analysis.
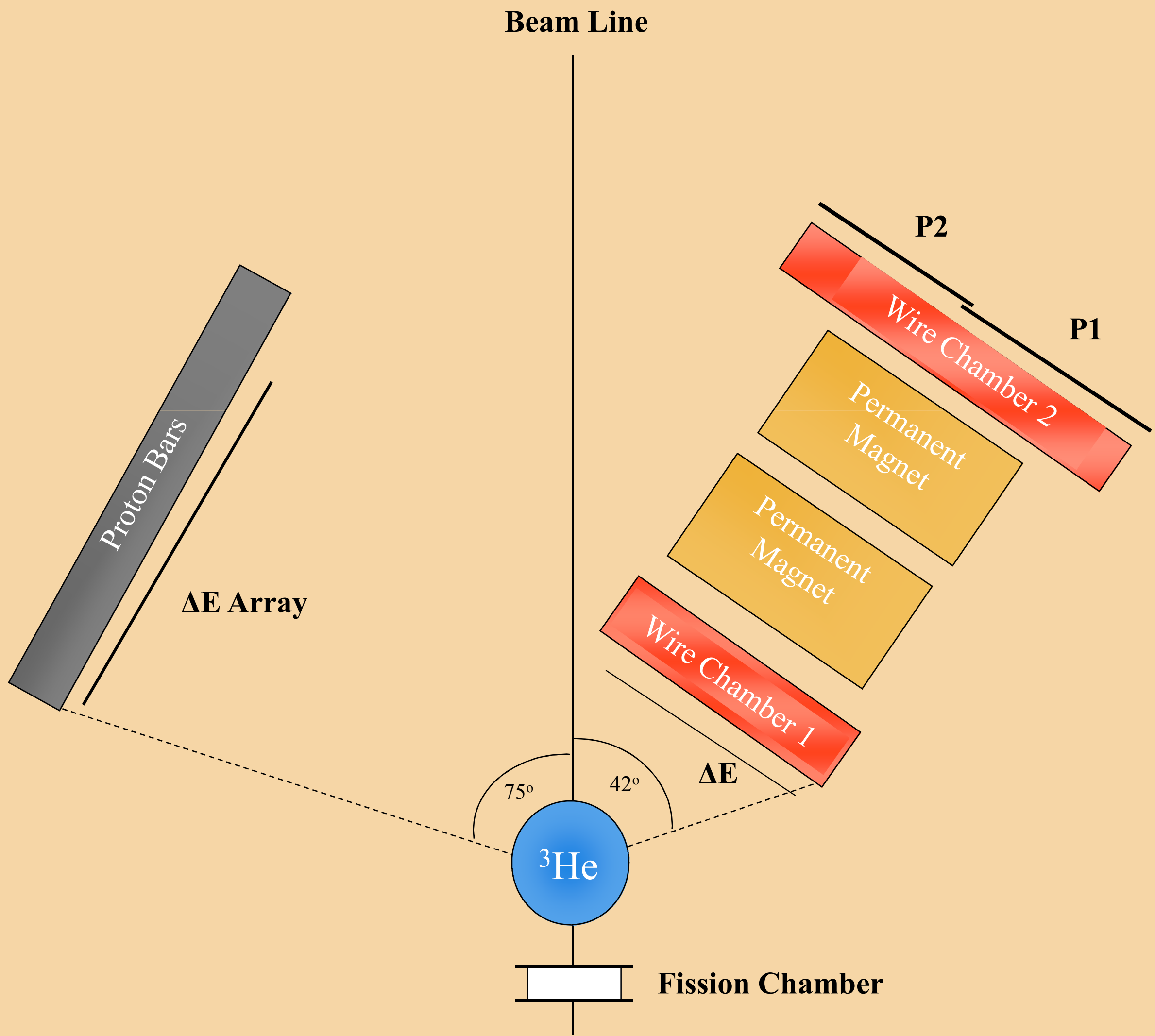
3.c. Target

Both ^{3}He and ^{4}He targets are used for this experiment. Generally, there are two protons in a ^{3}He or ^{4}He nucleus. However, Δ particles can also exist in the nucleus, and the Δ^{++} is predicted to be the most probable of all the Δ charge states found in the ^{3}He and ^{4}He nuclei.

In this experiment, neutrons are the incident particles. A neutron can interact with two protons in the ^{3}He nucleus, causing them to scatter. However, an incident neutron can also interact with a Δ^{++} in the nucleus. When a Δ^{++} particle is scattered from the nucleus, it decays into two protons. These two protons have a different kinematic relationship than two protons that are scattered individually from the ^{3}He nucleus. When detected in coincidence, whether the protons came from a single Δ^{++} particle or from two protons in the ^{3}He nucleus can be determined by looking at the position and energy of the two protons. The fact that Helium has only two protons and that it is a relatively small atom makes ^{3}He and ^{4}He ideal for detecting the Δ^{++} component of the nuclear wave function.

Shown above are two possible configurations for ^{3}He nuclei. In one scenario, the nucleus contains two protons and a neutron. The other possible configuration has a Δ^{++} particle and two neutrons.
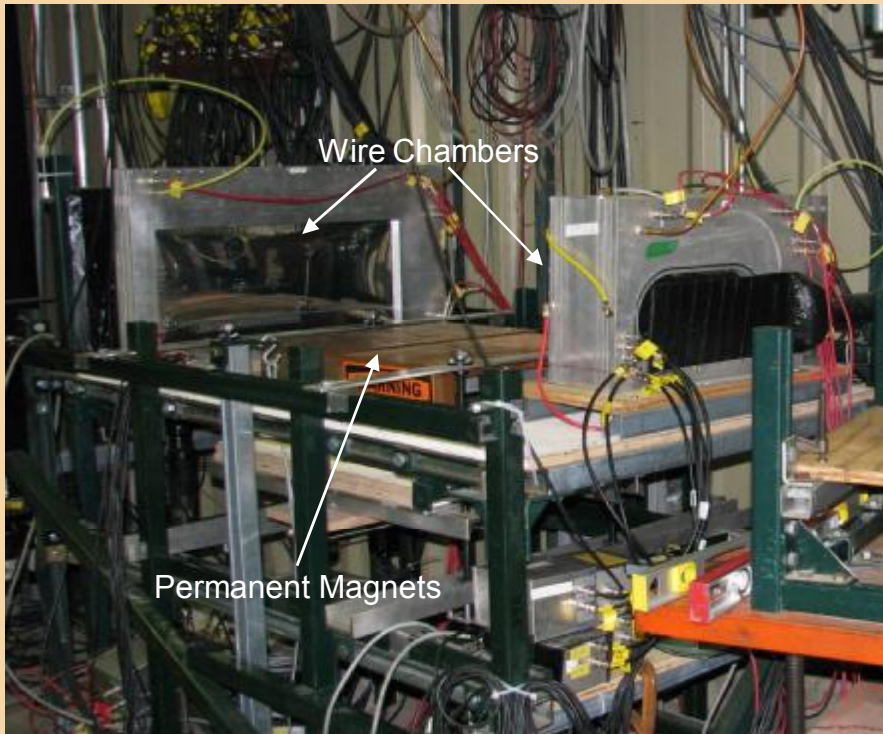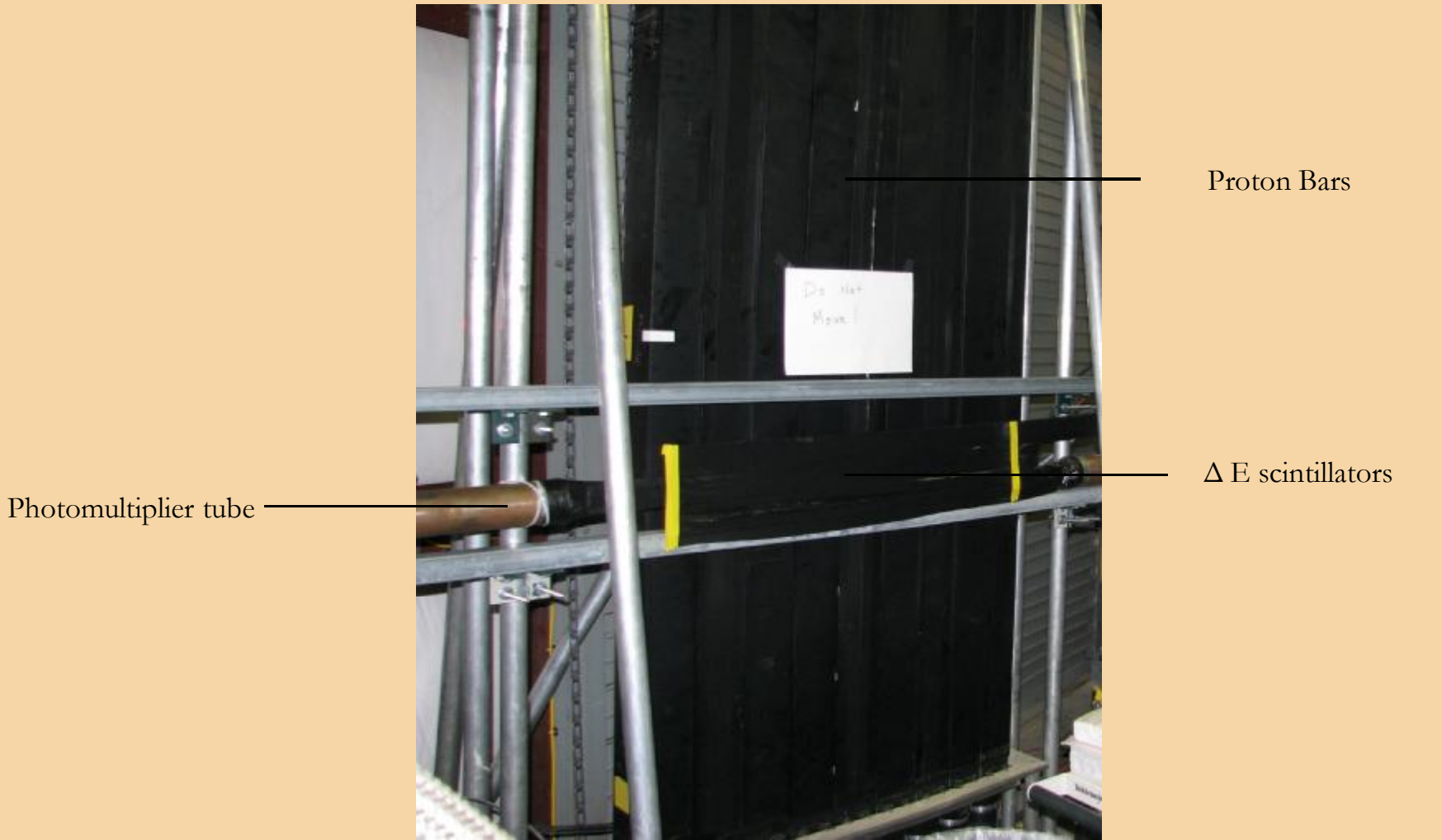

Shown above is a photograph of the spectrometer featuring two wire chambers and permanent magnets. Protons will pass through the first wire chamber before its trajectory is bent by the two SmCo permanent magnets. The particle will then pass through the second wire chamber from which the particle's final trajectory can be determined. Information obtained from the two wire chambers can be used to determine the particle's momentum.

3.d. Spectrometer

The permanent magnet spectrometer, pictured at left, is used for tracking protons, giving measurements of their momentum and position. It is made up of two permanent magnets with a drift chamber and scintillators on either side. Drift chambers have horizontal and vertical planes of alternating cathode and anode wires and are filled with gas. As charged particles pass through the chamber, the gas is ionized. Electrons drift toward the nearest anode wire and create a current in that wire, allowing the wire which was nearest the path of the proton to be identified.

A delay line connects the anode wires together. When charged particles drift to the anode wires, pulses are formed that travel to each end of the delay line. The time difference between when the pulses arrive at each end indicates which wire the proton was nearest. The sum of the delay line times allows the drift time to be calculated. Using this information from the vertical and the horizontal wires, the position of the proton can be found.

Cathode wires detect positively charged ions after a proton excites the gas in the chamber. Cathode wires are organized such that every other cathode wire is considered 'even', while the rest of the cathode wires are considered 'odd'. By looking at the cathode wire to which the ions drifted, which side of an anode wire an event took place can be determined.

3.e. Scintillators

Scintillation is the flash of light that occurs in certain organic materials as a result of molecular transitions caused by ionizing radiation passing through the scintillator. This radiation causes the scintillator's molecules to excite from a ground state to a higher energy state. Once in this higher energy state, the molecule will lose some of the gained energy through lattice vibrations and end up in a slightly lower excited state. Most of this energy loss is dissipated in the form of heat. At this lower energy excited state, the molecule will de-excite back down to its ground state, losing energy in the process by emitting a photon.

The light emitted by de-excitation is weak and must be amplified. This is done by a photomultiplier tube which is attached to the plastic scintillator. Photons emitted by the scintillator strike a photocathode in the tube. The low work function of the photocathode causes it to emit electrons when given the photons' energy. These electrons are then accelerated to subsequent dynodes which are at increasingly lower voltages. When electrons strike a dynode, secondary electrons are emitted from the dynode resulting in more electrons. Thus, the number of electrons increases as they travel down the tube. By the time the electrons reach the anode, there are far more electrons than originally emitted by the photocathode and the current is amplified. The anode then collects the electrons, outputting a signal in the process.

Shown above are ΔE scintillators in front of the larger scintillator 'wall'. These are used to detect scattered protons on beam left.

4. Energy Calculations

The energies of the detected particles must be known to obtain meaningful data about the (n, 2p) reaction. This experiment is set up to maximize the difference in expected cross-section between the two ways the experiment can proceed, in one step or two. These cross-sections, however, can only be determined if the energies of the scattered protons are known. Thus, a system to find scattered proton energies must be implemented.

On beam right, a permanent magnet spectrometer is used. When a proton passes through a magnetic field its trajectory changes. How much the proton's trajectory is changed depends on its energy. Outside the magnetic field the proton's trajectory is constant. Thus, by measuring the proton's trajectory before and after the magnetic field, the energy of the proton can be found.

On beam left, the energies of the protons detected are calculated using time of flight. The time the neutron is incident upon the target can be found, and the time that the proton is detected on beam left is known. Since energy is proportional to velocity, the energy of the proton can then be found using the time it took to reach the scintillator after scattering from the target.

5. Wire Chamber Analysis

First, the data from the odd and even cathode wires are examined. To remove events that are just noise, for each event the pulses in the odd wires are summed with those in the even wires and events which are below a given threshold are removed. In the histogram below, the events below channel 200 would be ignored.
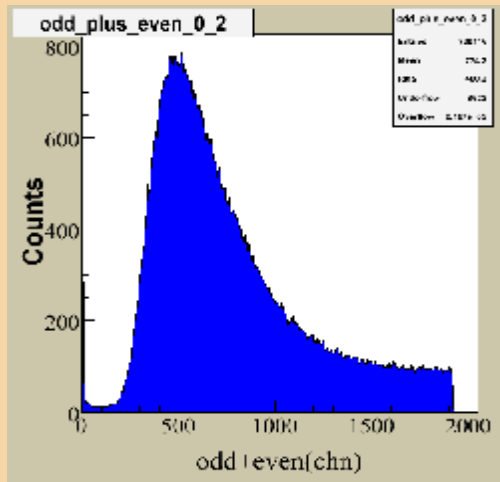

A histogram is then made which subtracts the even pulses from the odd pulses for each individual event that passes the first test. Below, events where the even pulses are greater than the odd pulses are represented in the leftmost peak and the events where the odd pulses are greater are shown on the right.
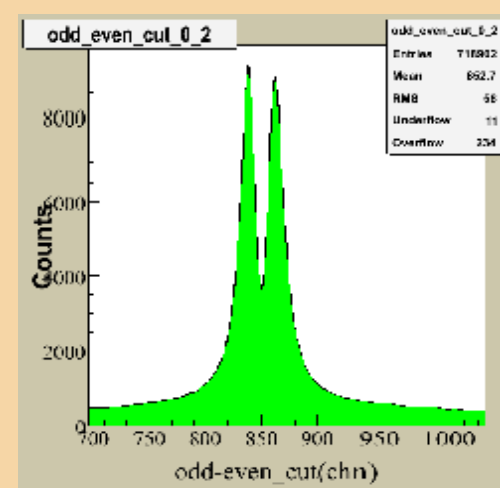
From this histogram it can be determined which events drifted toward odd and which drifted toward even anode wires. This is then used to determine the actual path of the proton as it traveled through the chamber.

6. Electronics

The electronics read in and process the signals coming from the various detectors and send them to the computer. There are multiple triggers in this experiment, most importantly the one which determines when two charged particles on opposite sides of the beam line have been detected. In order for a trigger to occur, a signal in the beam right ΔE detector and proton detector as well as a signal in the beam left ΔE detectors and proton bars must be set off in coincidence. This ensures that two charged particles were detected in all detectors, and suggests that the particles detected scattered from the target.
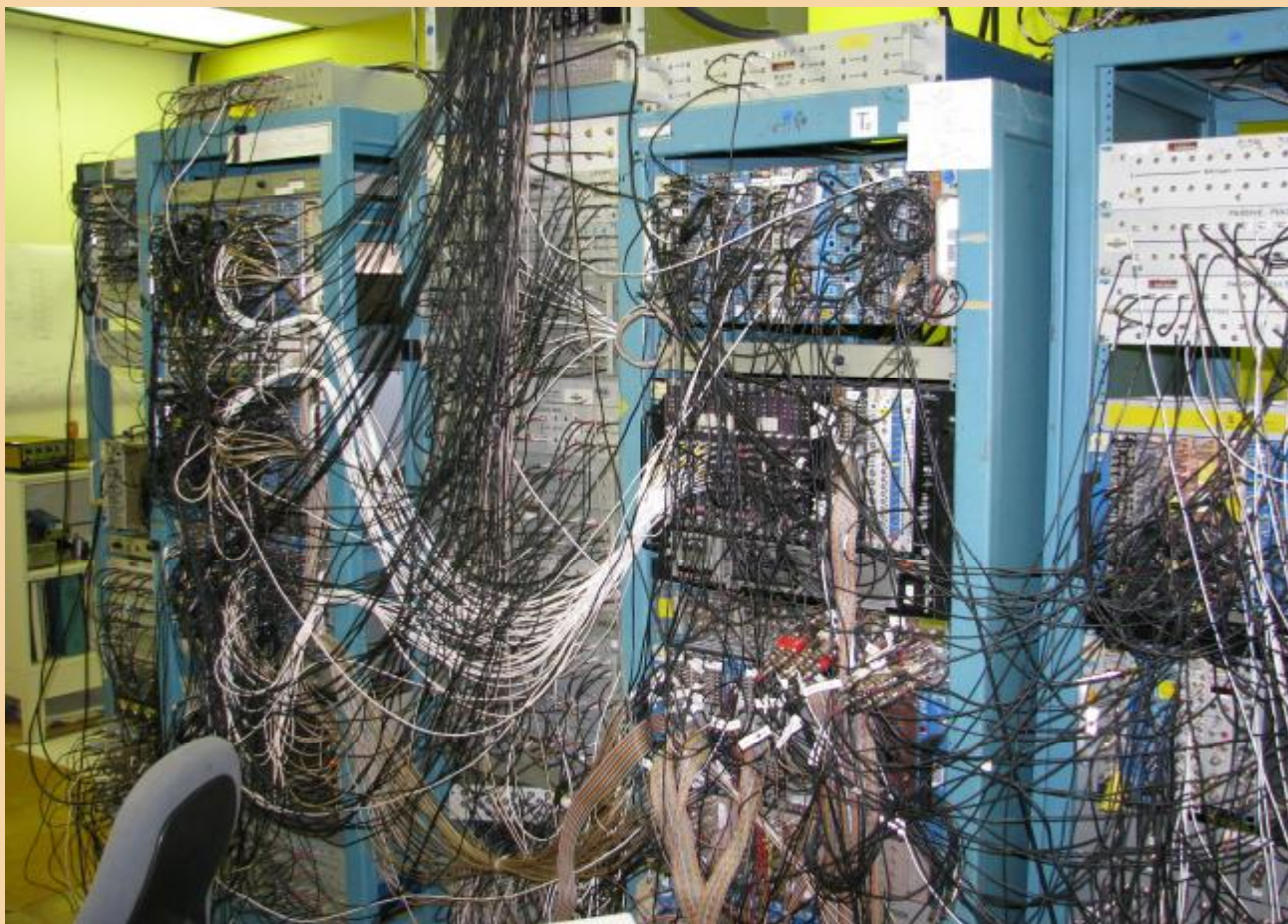
The outputs for all the detectors are read into the computer using FERA modules.

7. Conclusion

A feasibility study of the ^{3}He(n,2p)2n experiment is currently underway. When complete, the analysis will be focused on interpreting the drift chamber information to calculate the trajectories and thereby momenta of the protons in coincidence with a proton detected on beam left. Results from this experiment are expected to lead to a full-scale experiment during the summer of 2009. Ultimately, theoretical predictions will be compared to the analysis of these experiments and a measurement of the nuclear Δ^{++} component hopefully made.