Light-Weighting in Cerenkov Detectors

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Abstract

The Q-weak experiment, conducted at Jefferson Laboratory, aims to make the first measurement of the weak charge of the proton as it tests the Standard Model of particle physics. To achieve this, electrons are scattered from a hydrogen target and then detected by a magnetic spectrometer. These electrons are bent by a magnetic field, travel through vertical drift chambers that aid in the track reconstruction process and then hit the trigger scintillator, creating a time signal for the track and verifying that a charged particle has passed through it. From here, the electrons travel through a lead sheet that stimulates more scattering processes, producing positrons, photons, and more electrons, and this shower of charged particles hits the Cherenkov light detectors (main detectors) yielding a greater amount of Cherekov light for the photomultiplier tubes. The main job of these detectors are to capture and record the amount of Cherenkov light emitted by scattered electrons. One important aspect of the data analysis procedure for this experiment is the light-weighting process. To make a precise measurment of the weak charge of the proton, weights must be applied to the light collected by the main detectors. As such, the main detectors need to yield consistent data (both over time and between each other) or else many different weights must be applied. To determine this consistency, an analysis tool has been developed in the form of a ROOT macro. In this tool, plots are generated that show the distribution of tracks that hit the main detectors. After analyzing these graphs, it is clear that main detector 2 developed an issue with its glue joint throughout the experiment. Also, there is no evidence that main detector optical performance degraded over time.

1 Introduction

The Standard Model of Particle Physics (SM) lays out precise predictions of the natural world. It has been rigorously tested over the past 30 years, and it has yet to be experimentally proven incorrect. As such, it is the leading theory that decribes both the strong and weak nuclear forces as well as the electromagnetic force. However, The SM is still believed to be incomplete since it fails to include gravity, among other things, though it is quite clear that gravity is present in our universe.

Testing the Standard Model comes in two forms: energy, and precision. The energy form of testing occurs at extremely high energy accelerators like the Large Hadron Collider at CERN. Energy levels in these experiments can reach levels like $1\text{x}10^8$, or even $1\text{x}10^9$ eV. At these high energy levels, new particles can be directly seen, thus adding to, or disproving, the SM. Precision experiments use much lower energy levels, and they aim to test precise predictions laid forth in the SM. If an experiement shows a SM prediction to be incorrect, it will have indirect proof of new physics beyond the Standard Model. This is the Q-weak experiment's goal.[1]

Q-weak aims to measure parity-violating asymmetry by looking at elastic electron scattering. It is parity violating since right-handed electrons scatter at a different rate than left-handed electrons. The asymmetry in this experiment is measured by taking the difference between left and right handed electrons and normalizing that number by the total amount of electrons [2]:

$$A = \frac{N^R - N^L}{N^R + N^L}$$

This parity violating asymmetry is also directly related to the weak charge of the proton [2]:

$$A = KQ^2[Q_W^P + B(\Theta, Q^2)Q^2]$$

Since K is a compilation of constants of nature, and B is a well determined property of the proton, the last unknown to determine is Q^2, the four-momentum transfer.

Four-momentum (Q^2) is a frame-independent term; it is a relativistic invariant. In the Q-weak experiments, four-momentum transfer occurs when an electron collides with a proton, and the scattering angle is heavily dependent on the amount of momentum that is transferred. To ensure the quality measurement of an average Q^2 term, weights must be applied to many individual values, and this process is called light-weighting.[1]

The main goal of this project is to determine the consistency of data collected by the eight Cherenkov light detectors (main detectors). These detectors are an essential part of this experiment and will be discussed at length later. If the detectors collected similar results between each other and over the duration of the Q-weak experiment, then only one weight will need to be applied. However, if inconsistencies occur, different weights will need to applied to different Q^2 values to ensure a precise average Q^2 term.

2 Q-weak Experiment

In the process of electron-proton scattering, electrons are accelerated at a stationary liquid hydrogen target and a collision can occur. This collision facilitates the exchange of either a photon or a Z-boson. The exchange of a photon is well understood, and it is governed by the electromagnetic charge. The exchange of a Z-boson, however, is governed by the weak charge of the proton: a value that has yet to be precisely measured. The Q-weak experiment, that was conducted at Thomas Jefferson National Accelerator Faciity (Jefferson Lab), aims to make the first precise measurement of the weak charge of the proton[1].

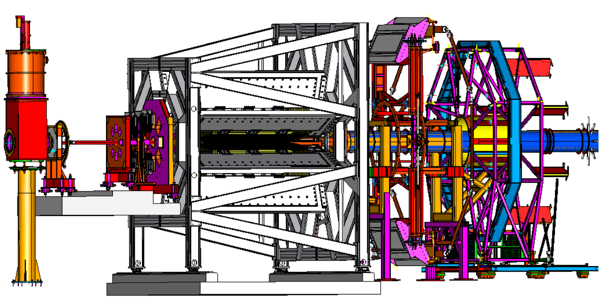

Figure 1: A schematic drawing of the Q-weak apparatus.

To accomplish this, an electron beam is directed at a liquid hydrogen target. The accelerated electrons can then scatter off of a proton, and these scattered electrons are detected by a magnetic spectrometer. A magnetic field bends the electrons to a trajectory that takes them through the vertical drift chambers.

These chambers prove to be very important in the track reconstruction process and will be discussed later[3].

From the VDCs, these scattered electrons hit a pre-radiator positioned in front of the Cherenkov detectors. This is made of lead, and when accelerated particles move through this medium, bemsstrahlug can occur. Bremsstrahlung occurs when charged particles are decelerated, and it results in the electromagnetic radiation of the charged particle. In this case, the electrons are decelerated, and they eject electromagnetic particles in the process: electrons, positrons, and photons. Most of these particles exit the pre-radiator, and a shower of electromagnetic particles strike a main detector. Once inside the main detector, the electrons are moving faster than the speed of light in that medium, causing the emission of Cherenkov photons. These blue photons are emitted in a connical shape, and this process is entitled Cherenkov radiation. Electromagnetic particles that achieve maximum internal reflection bounce to either side of the main detector and eventually into a photomultiplier tube (PMT). The PMT converts these photons into an electrical impulse, and this becomes the stored data used for analysis purposes. This information was discussed in reference [1]

2.1 Vertical Drift Chambers

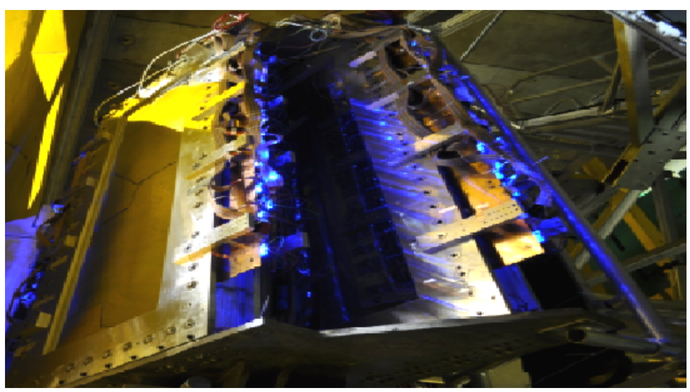

Figure 2: One of the vertical drift chambers used in the Q-weak experiment.

Vertical drift chambers serve as the main mechanism for electron track reconstruction. 558 wires are contained within each chamber as well as Argon gas, and these wires are held at a 0V potential.[4] When a charged particle travels through a VDC, an electron is ejected from the Argon gas, in a process called ionization, and it drifts to one of the wires[4].

After the electron passes through a vertical drift chamber, it strikes a trigger scintillator, creating a precise time measurment. When ejected electrons collide with wires in a VDC, more time outputs are recorded along with wire location. All of this data is sent to a program that reconstructs the electron's trajectory.

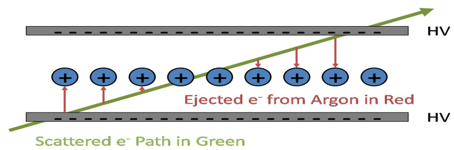

Figure 3: Diagram of an electron passing through a vertical drift chamber.

2.2 Cherenkov Light Detectors

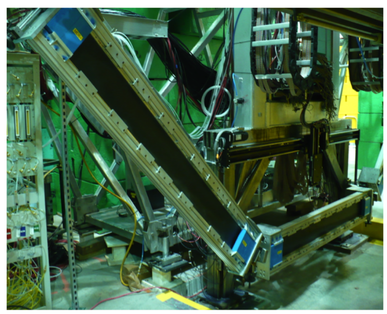

Figure 4: A close up of a main detector in the Q-weak experiment without a pre-radiator.

Cherenkov light detectors' (main detectors) main purpose is to capture and record Cherenkov photons emitted by electromagnetic particles. These detectors are two meters long, and they are made of a synthetic quartz material in hopes of mitigating radiation damage. Due to cost concerns, 16 one meter long synthetic quartz bars were ordered and each pair glued together, yielding eight main detectors in total[5].

Figure 5 illustrates the main detectors' setup during the experiment. Since there were eight detectors, an octagonal shape was chosen to ensure the collection of the most data.

On each end of a main detector rests a photomultiplier tube. These serve to convert the influx of Cherenkov photons into an electrical signal that can be recorded for later analysis.[5] A pre-radiator also sits in front of each main detector. This is made of 2cm thick lead, and its purpose is to faciliate the bremsstrahlung process so the PMTs can more easily detect electrons that hit the main detectors.[5]

Since the location of each electron track on the main detector is determined by the scattering angle, which is closely related to Q^2 and the weak charge, main detector consistency is an essential part of the data analysis portion of the Q-weak experiment. This is the main reason why this project, testing data consistency, focuses so heavily on the main detectors.

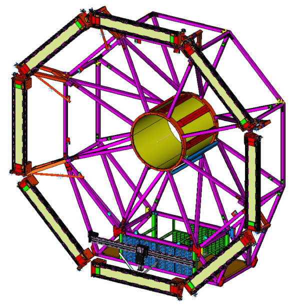

Figure 5: The "ferris wheel" set up of the main detectors. This was used to capture as many electrons as possible.

3 Experimental Methodologies

This project focuses solely on data collected by the main detectors. To be able to analyze such a large amount of data, a ROOT macro was coded to construct plots and write out important bits of data. The initial file aimed to only make plots of analog-digital converter (ADC) and time-digital converter (TDC) data. ADC data represents the electrical signal sent by a PMT, while TDC data comes from the triger scintillator. The first generated graphs included all of the ADC data for one main detector. These graphs contained a large spike near zero, which were pedestal values, thus a TDC cut was applied. The TDC graphs contained two spikes: a pedestal spike at zero, and a peak around -200ns (relative to the electron hitting the trigger scintillator) which represented the actual data. Any ADC value that did not have an accompanying TDC value in the true data peak was cut from the dataset.

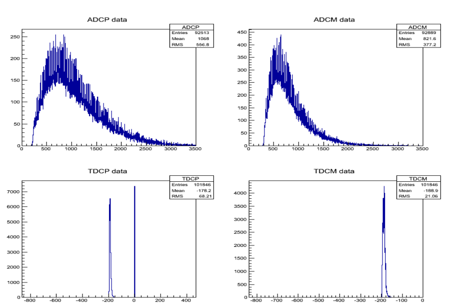

Figure 6: ADC graphs (after TDC cuts) and accompanying TDC graphs.

Next in the graph generating process was to create profile plots for each main detector. These plots illustrate ADC values as seen from each PMT as related to where the shower of electromagnetic particles hit the main detector. Also, to make sure that the vertical drift chambers are performing correctly, graphs of showers hitting the main detectors were generated. A distribution, called the "moustache" shape, was expected and predicted in the simulation.

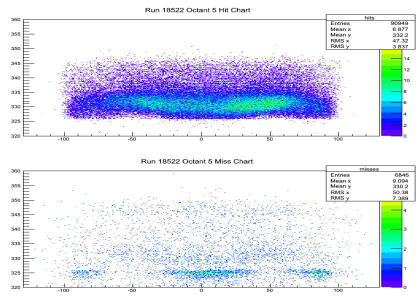

Figure 7: The moustache distribution.

After qualitatively analyzing the data by successfully creating profile plots and distribution graphs, it was time to quantitatively analyze the data. To do this, the profile plot data was fit with both exponential and linear piece-wise functions. Through chi-squared per degree of freedom analysis, it was determined that the linear fits generally gave better results (with less uncertaint) than the exponential fits. Thus, linear piece-wise functions were used to fit data used in the main detector profile plots.

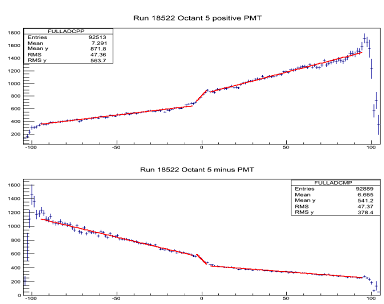

Figure 8: Profile plots of ADC values from a typical main detector with linear piece-wise fits.

From these fits, two types of data were extrapolated: glue joint factors and normalized slopes. Glue joint factors are unitless numbers that represent the loss of light as photons travel across the glue joint, and it is calculated by taking the ratio of intercepts at $x = 0cm$ of the linear functions. A perfect glue joint is 1.00. The normalized slopes are in units of inverse centimeters, and they represent the percentage of light lost per unit centimeter. They are calculated by taking the slope of each line and dividing it by the highest point on each corresponding linear fit. All of these data points were written out to a file for future analysis purposes.

The last type of plot created was an efficiency plot, and this type of graph showed the relative efficiency of the main detectors. It calculated the efficiency by taking the number of hits seen by both photomultiplier tubes and divided it by the number of electrons projected to actually hit the main detector. The mean location of each main detector was collected and written out to a file for later analysis.

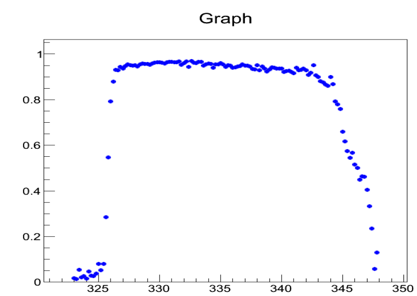

Figure 9: Typical efficieny plot.

After the completion of code to make every plot and gather all information needed to quantitatively analyze the main detector data, a total of about 40 runs were analyzed. Using the data collected and stored in various output files, graphs were generated illustrating the consistency of main detector performance both against time and against other detectors.

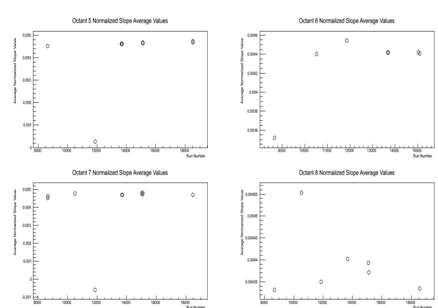

Figure 10: Graphs of tpical average normalized slope values.

These plots embodied results from this project as well as facilitated the initial drawing of conclusions.

4 Results and Conclusions

The main results that this project aimed to find were related to main detector consistency, and as determined by graphs and quantitative information gathered from the main detector data, there seemed to be very little inconsistency in main detector performance. Main detectors three, four, five, six, seven, and eight all had normalized slope values that agreed to within seven percent. Octants one and two were the inconsistent detectors, and they both had poor glue joints which could be a contributing factor. Octant two began the experiment with an ideal glue joint [glue joint factor aroun 1.15], but worsened gradually over time. After a six month break at Jeffereson Lab, octant two's glue joint factor was around 2.30, almost identical to that of octant one. The main cause for this worsening glue joint is most likely radiation damage, but since its glue joint factor continued to worsen during the experiment's break, it is possible that main detector two could have been bumped by workers as well. The slopes in octant one and octant two (after the six month break at Jefferson Lab) agree to around 21 percent with the other detectors.

As the experiment progressed, there is no evidence of degradation of optical performance by the main detectors over time. Although the normalized slopes did decrease, it was gradual and consistent over each main detector. This can be explained by the large volume of electrons hitting the PMTs and their decreased sensitivity to charged particles. This means that, if this assertion remains true with high statistics, no time-dependent weights will need to be applied to Q^2 terms. Any weights to four-momentum transfer terms will most likely need to be main detector-specific. At the moment, more statistics are needed to verify the results of main detector consistency, and then the correct weights will need to be applied to be able to obtain the first precise measurement of the weak charge of the proton.

References

[1] R.D. Carlini, et al. *The Qweak Experiment: A Search for New Physics at the TeV Scale via a Measurement of the Proton's Weak Charge.* 2012: http://arxiv.org/abs/1202.1255

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