

SCIENCE FROM THE SOURCE

FIRST DETERMINATION OF THE PROTON'S WEAK CHARGE

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The weak charge of the proton has been determined for the first time via a high precision electron-proton scattering experiment, Qweak, carried out at Jefferson Laboratory (JLab) in Newport News, USA. The weak charge is a basic property in subatomic physics, analogous to electric charge. The Standard Model makes a prediction for the weak charges of protons and other particles. First results described here are based on an initial 4% of the data set reported in 2013¹, with the ultimate goal of the experiment being a high precision Standard Model test conducted with the full Qweak data set. These initial results are consistent with the Standard Model prediction; they serve as an important first determination of the proton's weak charge and a proof of principle that the ultimate goals are within reach.

INTRODUCTION

Nuclear and particle physics focus on the detailed structure of atomic nuclei and their constituents – protons and neutrons. The last 100 years have seen remarkable progress, culminating in a microscopic theory of fundamental particles and their interactions called the Standard Model. The Standard Model describes the electromagnetic, weak and strong interactions in a rigorous mathematical framework based on the exchange of force carriers², or field particles, between fundamental particles.

The Standard Model explains, for example, how the proton and neutron are composite particles, consisting of 3 pointlike quarks³, held together by the strong interaction. They exist in the sub-nuclear realm on size scales of 10^{-15} m and below – roughly 100,000 times smaller than the size of an atom. The proton and neutron have a finite size and shape, which have been mapped out in a variety of experiments. Their composite nature, combined with the mathematical complexities of the strong interaction, makes it

very difficult to calculate the proton and neutron properties from first principles. This is why precision measurements such as Qweak are so important to help advance our understanding.

From the highly successful Standard Model we have a prediction of the proton's weak charge, but prior to the Qweak experiment, it had never been measured. This prediction is based on state of the art theoretical physics techniques and input data from other experiments. The ultimate goal of Qweak is to perform a high precision measurement that can be directly compared to the Standard Model prediction. If a statistically significant disagreement were found, this could indicate 'new physics', e.g., it could suggest the presence of hitherto unobserved force carriers in nature.

ACCESSING THE WEAK CHARGE

The weak charge of the proton sets the scale (or strength) of weak interactions of the proton with other particles, and can be probed in scattering experiments. A high-energy electron beam is an excellent probe for this purpose, as the electron is point like, and only the weak and electromagnetic interactions play a significant role in the electron-proton scattering process. As its name implies, the weak force makes a relatively small contribution when an electron and a proton interact with each other, yet it is this small contribution that we need to identify and measure.

Fortunately, the weak interaction has a unique signature that can be used to identify its contribution: it depends on the 'handedness' of the interacting particles. A right-handed (RH) electron has a different probability of scattering from a proton than a left-handed (LH) one does. This property is known as 'parity violation'.

A simple exercise can be used to illustrate this phenomenon. Make a fist with your right hand but

“The Standard Model makes a prediction for the weak charges of protons and other particles.”

exclude the thumb so that it points forward. Hold out your arm this way and face a mirror with your right thumb pointing toward the glass. The image you see in the mirror is of your “mirror twin”, holding out his/her left hand in a similar fashion and pointing back at you, as shown in Figure 1.

Now to relate this to the Qweak experiment, you can think of each electron as a tiny sphere of electric charge, mass and energy spinning around an axis through its center. The fingers of your fist are pointing in the direction that the electron is spinning, and the thumb points in its direction of motion. With this setup your right hand is a model of a ‘right handed’ electron. The mirror

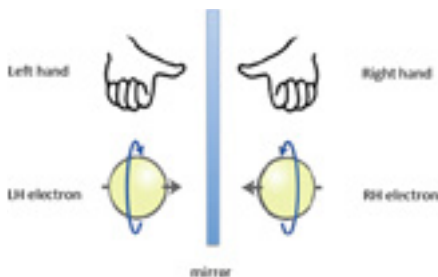


Figure 1:

Large-scale model of a spinning electron. The electron moves in the direction of the thumb (straight arrow), while spinning in the direction indicated by the fingers (curved arrow).

image represents an electron spinning in the same direction but moving in the opposite direction: a ‘left-handed’ electron. To change the ‘handedness’ of the electron, simply reverse the direction of motion relative to the direction of spin, or vice versa.

Another word for ‘handedness’ for particles is ‘helicity’; by convention, a right handed particle has positive helicity, and a left handed one has negative helicity (this allows a convenient labelling convention: + or -). In these terms, the key observable measured in the Qweak experiment is the parity-violating asymmetry in elastic electron-proton scattering, A_{ep} , which is proportional to the proton’s weak charge:

$$A_{ep} = (\sigma_+ - \sigma_-) / (\sigma_+ + \sigma_-)$$

Equation 1: The parity violating asymmetry A_{ep} in elastic electron-proton scattering. The symbols +/- refer to the beam helicity, and σ is the scattering cross-section, representing the probability of a scattering event taking place.

EXPERIMENTAL STRATEGY

The Qweak experiment required an electron beam that could be prepared either RH or LH, which we refer to as ‘polarization’. Fortunately, the beam polarization

was easily controlled by manipulation of lasers at the input to the Jefferson Lab electron beam accelerator. We also needed a proton target, an apparatus to isolate and detect the scattered electrons, and various diagnostic elements to monitor the incoming beam properties as well as quantify backgrounds and other sources of systematic error. For Qweak, the beam energy and scattering angle were optimized to minimize the dependence on the proton’s internal structure, which simplifies the interpretation of the data⁴ -- this led to the choice of a relatively low ~ 1 GeV beam energy and small scattering angle (~ 8°).

To set the context of the Qweak experiment, the Standard Model prediction $A_{ep} \sim -3 \times 10^{-7}$ was used to establish the design parameters. This represents the smallest asymmetry ever measured in a parity violating electron scattering experiment. The ultimate goal of Qweak is to reach an uncertainty of $\pm 2\%$ in A_{ep} . Reducing the statistical error to this level requires averaging the results of many scattered electrons. With a year of continuous beam time allocated for the measurements and an ambitious uncertainty goal, Qweak had to push the envelope in many areas, including beam intensity,

¹ First Determination of the Weak Charge of the Proton, D. Androic et al., *Physical Review Letters* 111, 141803 (2013).

² The force carriers for the electromagnetic, weak and strong interactions are the photon, weak vector boson, and gluon, respectively; gravity is not yet included in the Standard Model.

³ The proton consists of 2 ‘up’ quarks and 1 ‘down’ quark: uud; the neutron is udd.

⁴ The weak charge is a point like or structure-independent feature of a particle; to emphasize this feature, the experiment was done using only glancing collisions, at a low momentum transfer of 0.025 (GeV/c)².

⁵ For example, a helicity-correlated beam motion would produce a measured asymmetry, even if A_{ep} were zero, unless all detector units were absolutely identical. The approach taken in Qweak was to purposely modulate the beam position interspersed with data taking, and thereby to measure the sensitivity to this type of false effect. During data taking, beam monitors measured the helicity-correlated beam motion, and appropriate corrections were made to the data

target volume and cooling capacity, low noise electronics, and precision beam diagnostics.

Major achievements included Jefferson Lab's development of the world's highest power liquid hydrogen (proton) target, capable of withstanding over 2 kW of beam power at a temperature of 20K with minimal density fluctuations. The laboratory also developed a very high intensity polarized electron beam (up to 180 μA at 89% polarization) and implemented a fast (1 kHz) helicity reversal capability. Experimenters from 22 institutions in the US and Canada developed high precision custom built detectors and electronics over the ~10 year preparation period for Qweak. The Canadian team, from the Universities of Manitoba, Northern B.C., Winnipeg, and from the TRIUMF Laboratory in Vancouver, played a major role in Qweak from its

inception. Installation and running of the experiment took place at JLab from 2010 to 2012.

APPARATUS

The basic design of the main apparatus is indicated in Figure 2. A 3-stage collimator system selected electrons scattered at small angles from the 35 cm liquid hydrogen target; the scattered electron beam was deflected radially from the primary beamline by a toroidal magnetic spectrometer, and was focused onto a set of 8 quartz detector bars located in a heavily shielded instrumentation bunker. An auxiliary tracking system consisting of trigger scintillators and two sets of drift chambers was inserted for dedicated measurements at lower beam intensity; this system was used to map the angle, energy acceptance and response of the main detectors, all crucial ingredients for interpreting the data.

A key feature of the Qweak apparatus was the very open geometry to maximize the number of scattered electrons that could be detected. The choice of a toroidal magnetic spectrometer (magnetic field lines are circles in the plane perpendicular to the coils) was ideal for this purpose. The only portion of the forward-scattered acceptance that was excluded from the measurements was that which was blocked by the large copper conducting coils of the magnet, shown in the figure – these regions were blocked by the collimation system. The 8 identical, 2-m long quartz detector bars located behind the shield wall provided independent measurements of the scattered electron rate. The main detector segmentation provided a very useful diagnostic capability, and the symmetry of the detector array provided a high degree of suppression of geometrically-dependent systematic errors.

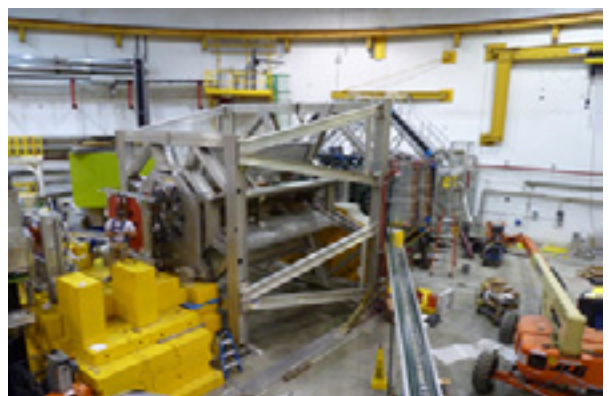
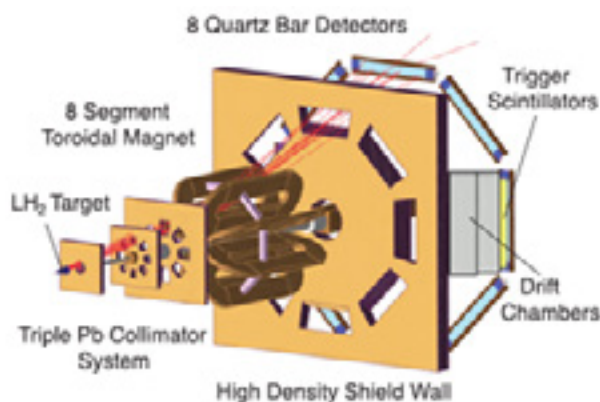


Figure 2:

Left panel: layout of the main Qweak apparatus¹. Right panel: photo of the apparatus during installation in Hall C at Jefferson Lab; the large aluminum structure supports the magnet coils with several of the main detector bars (black) visible behind the magnet structure.

Canadian contributions included the large water-cooled copper coils of the Qweak magnetic spectrometer, a set of novel diamond detectors used to measure the polarization of the electron beam, custom built low noise readout electronics, and a major focus on the main detector array as well as systematic error control.

MAIN DETECTOR ASYMMETRY SIGNAL

To acquire Qweak's data set, the main detectors were read out in "current mode". This is an unusual and particularly challenging method of data acquisition that is required when the rate of detected particles vastly exceeds the rate at which they can be individually distinguished in the electronics. Current mode detection was an absolutely crucial element of the Qweak strategy. Each scattered electron produced a burst of visible light via the Cerenkov effect when it traversed a main detector element. This light propagated to the ends of the detector bar where it was converted to an electrical

signal by a photomultiplier tube (PMT) – one at each end. The high scattered electron rate meant that the detector bars emitted a continuous glow of blue Cerenkov light. This steady light level was converted to a current by the PMT, and the current was then converted to a voltage by custom-built low noise electronics.

The time sequence of a typical measurement cycle is illustrated in Figure 3. The PMT voltage levels, which were proportional to the rate of scattered electrons and hence to the cross-section σ introduced in equation 1, were sampled, digitized, and averaged over each helicity state of the beam. A parity-violating asymmetry is manifest as a small helicity-correlated change in the detector signal levels, which can be seen in the figure. The detector signals were normalized to precision beam intensity monitors located upstream of the hydrogen target, and from these values, the helicity-dependent asymmetry was calculated for each quartet

of spin states (approximately 4 ms of data) according to equation 1. The helicity of the first state of each quartet was selected pseudo-randomly; this pattern cancels false effects due to gain and DC (direct current) offset drifts in the electronics that occur on a timescale comparable to the switching frequency.

DATA COLLECTION AND QUALITY CHECKS

A histogram of quartet asymmetries accumulated over several days' data collection is shown in Figure 4. The shape of the asymmetry histogram is consistent with a random Gaussian distribution, with a width that is only slightly larger than the theoretical minimum given by counting statistics. This is a great achievement, which is vitally important to the success of the experiment. The mean value, averaged over many 4 ms data samples, is proportional to the proton's weak charge.

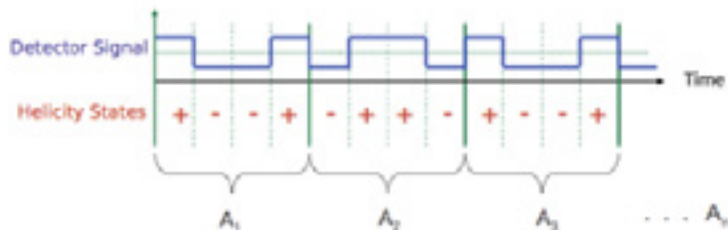


Figure 3: Schematic of the helicity reversal and detector readout time sequence. Each helicity state lasts for 1 ms. An asymmetry (A_1, A_2, \dots etc.) is calculated for each helicity quartet, according to equation 1. The helicity average signal is indicated by the dashed green line.

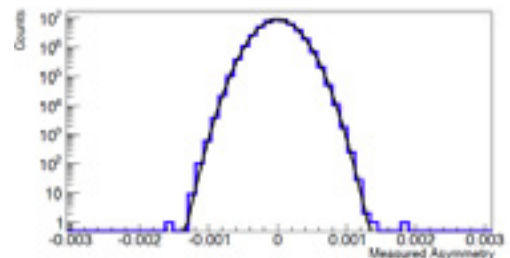


Figure 4: Histogram of asymmetry values calculated per helicity quartet (4 ms of data) accumulated over a several day measurement period; the smooth curve is a Gaussian fit, with an RMS width of 230 parts per million (blue curve). The mean is consistent with zero on this scale.

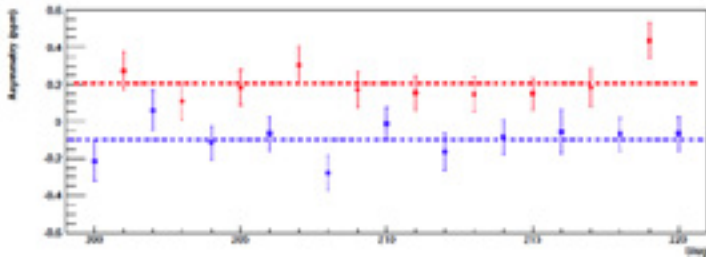


Figure 5:

Time sequence plot of uncorrected average asymmetries (parts per million) measured in ~8 hour counting intervals ('slugs') with alternating slow helicity reversal. The average of the red data points is shown by the red line; the points shown in blue average (within errors) to a similar magnitude but opposite sign. This is as expected for an overall helicity reversal between the two data sets. The data shown are 'blinded' by an arbitrary numerical factor to avoid bias until the analysis is complete.

For N such 4-ms measuring intervals, the statistical error on the average is reduced by a factor $1/\sqrt{N}$. Thus, to obtain a statistical error of 0.03 ppm, as reported in our first paper, we needed about 59 million measuring intervals, corresponding to several days of nonstop data acquisition.

In order to interpret the experimental asymmetries, many auxiliary measurements were required for systematic error control and background studies. These included independent measurements of helicity-correlated beam motion and intensity, which could mimic the weak charge effect that we set out to measure⁵. Careful calibrations of the apparatus sensitivity, together with the suppression factors achieved by a geometrically symmetric detector and target system, were used to quantify systematic uncertainties. A separate set of detectors measured backgrounds. We also took data with 'dummy targets' in order to measure and correct for the parity-violating asymmetry that arises from the aluminum target windows. The Qweak tracking

system was used to calibrate the kinematic acceptance and sensitivity of the detectors. High precision polarimetry was used to measure the helicity of the beam.

Independent methods of slow helicity reversal were used to check the consistency of the results over time. The latter is shown in Figure 5, where we plot the average asymmetry in parts per million measured in ~ 8 hour data 'slugs' with opposite overall helicity achieved by inserting / removing an additional optical element in the path of the laser beam at the polarized source. As seen in the figure, the asymmetry clearly reverses sign with slow helicity reversal, as it should.

RESULTS

A careful analysis of the first 4% of the Qweak asymmetry data has yielded a value of $A_{ep} = -279 \pm 35$ (stat) ± 31 (sys) parts per billion (ppb) for the helicity dependence of electron-proton scattering at a momentum transfer of 0.025 (GeV/c)². All systematic error corrections to the measured asymmetry are comparable to the experimental uncertainty at

this level. Using the results of previous experiments to evaluate the small contribution from the proton's internal structure, we obtained the first experimental value of the proton's weak charge: $Q_w^p = 0.064 \pm 0.012$, which is in good agreement with the Standard Model prediction of $Q_w^p = 0.0710 \pm 0.0007$. Also in combination with other measurements, the Qweak data allow significant constraints to be extracted for the weak charges of the constituent up and down quarks. These in turn allow us to also evaluate the weak charge of the neutron as $Q_w^n = 0.975 \pm 0.010$ in agreement with the Standard Model prediction.

OUTLOOK

The Qweak experiment acquired a much larger data set in total than has been reported here. This includes many more independent checks on the data, as well as auxiliary experiments to understand asymmetry contributions from other processes that will provide interesting physics results in their own right. An intensive data analysis effort is currently

underway and we anticipate releasing a final result with ~5 smaller error bar (25× more data) sometime during the next year. This ultimate high precision measurement will provide a stringent test of the Standard Model prediction; a significant discrepancy, if one is found, could be a signature of ‘new physics’, hinting at additional particles and fundamental interactions that have not yet been observed.

RESOURCES

1. **Androic, D.** et al., First Determination of the Weak Charge of the Proton. *Phys. Rev. Lett.* 2013, 111, 141803.
2. **Kane, G.** The Dawn of Physics beyond the Standard Model. *Sci. Am.* 2006, 15, 4-11.
3. **Lincoln, D.** The Inner Life of Quarks. *Sci. Am.* 2012, 307, 36-43.
4. **The Standard Model:** <http://www.particleadventure.org/standard-model.html>
5. **The Qweak web page:** <http://www.jlab.org/qweak>
6. **Jefferson Laboratory:** <http://www.jlab.org>
7. **TRIUMF:** <http://www.triumf.ca>

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Q&A WITH DR. SHELLEY PAGE

WHAT IS YOUR DAY-TO-DAY WORK LIFE LIKE AS A RESEARCHER IN PHYSICS?

I am a Professor at the University of Manitoba, so my time is shared between teaching, research and service – nominally 40% each for the first two and 20% for service. My day-to-day work varies seasonally, with a heavy emphasis on undergraduate teaching from September through May, and more time for research in the summer months. That being said, research consumes a part of every day, even if it is only time spent keeping up with progress made by graduate students and other researchers in the collaborations that I work in; that plus general advances in the field of course!

Since I came to Manitoba in 1985, my experimental work has always been based at an off-site

facility – a national or international research laboratory. Initially, our group carried out a program of experiments using polarized proton and neutron beams at the TRIUMF laboratory in Vancouver, and I have maintained a close connection with TRIUMF since I began my career in nuclear and particle physics. More recently, our program has been centered at Jefferson Laboratory in Newport News, VA, USA, where the Qweak experiment was carried out. I work in teams of up to 100 scientists, including faculty from universities all over North America and some from Europe and Japan, as well as laboratory research scientists, postdoctoral fellows, graduate and undergraduate research students.

A typical experiment in my field takes at least a decade from the initial idea and planning stages, through a campaign for funding support, then the actual R&D to develop the required instrumentation, and so on. The Qweak experiment certainly followed this pattern. In the early days, a lot of time is spent writing and defending research proposals, planning how to do the measurements, doing numerical simulations to predict the equipment performance, and building prototype apparatus. At this stage, the collaboration gets together several times per year for a 2-3 day meeting to review progress on all aspects of the project. We use an electronic log book to post day to day progress on the internet, and there are frequent conference calls to discuss technical aspects of the

various subsystems that we are working on. With so many active researchers all working towards a common goal, there is a great deal of information to be shared and kept up to date on – just keeping up takes a fair bit of time each day.

Then we move to the stage of constructing, installing and debugging the apparatus at the accelerator laboratory, followed by actual running of the experiment to collect data. This stage requires considerably more travel. Our graduate students usually relocate to the laboratory at this stage, and faculty apply for research study leaves to spend up to a year working at the experimental site. In my case, I was fortunate to have two such study leaves at Jefferson Lab during the course of the Qweak experiment. In 2001, I visited JLab when the initial proposal for Qweak was being put together, and I was invited to serve as a co-spokesperson. There was a tremendous effort at that time to put together a fairly detailed initial design of the experiment that was reviewed by JLab's Program Advisory Committee (PAC) and was subsequently recommended for beam time. Having received an "A" scientific rating for the proposal, we then turned to the funding agencies – the US Department of Energy and the US National Science Foundation, and the Natural Sciences and Engineering Research Council of Canada (NSERC) for support. Every 3 years, the scientific and technical merit of the Qweak

experiment had to be re-defended to the JLab PAC, and our group had to re-apply for operating funds from NSERC.

All of this required a sustained effort over many years. We had a number of very talented undergraduate and graduate students working on the experiment, and it has been a real inspiration to work with them. I went back to Jefferson Lab in 2010-11 for a full year sabbatical when the experiment was commissioned and the first Qweak data were acquired. Data taking continued through May, 2012 – for the later running period, I functioned in "suitcase mode", travelling to the lab whenever I could to fulfil my share of shift duty (supervising the acquisition of data). This was an equally exciting and exhausting experience, as the beam was delivered continuously for weeks on end, with only a pause to fix items that failed (either in the experiment or the accelerator systems). We were scheduled right up until the very last minute when the accelerator was to be shut down for a higher energy upgrade. We knew that there would be no chance for extra time, so there was tremendous pressure to do the best possible job we could in the time available.

Since we finished data taking in 2012, the collaboration has focused on analyzing our very large and multi-faceted data set. The Qweak collaboration includes 23 graduate students and an equal number of postdoctoral fellows who have played a major role in the data acquisition and

analysis. A number of students have already graduated; others are primed to report on the final Qweak result when we agree that the data analysis has been fully completed. There are actually a great many additional measurements that were made to understand the various background and systematic error contributions, and those will all yield important physics results in their own right, so there is no lack of PhD thesis topics for our students!

Coming back to the day-to-day activities, I am on sabbatical this term and am enjoying the break from teaching in order to focus on research. This has been a great opportunity to take some time and write up our work for CYSJ. Before the end of term I will also spend time helping to prepare a manuscript to be ready for submission when the full Qweak data analysis has been completed. This afternoon, I participated in a 2-hour conference call to rehearse 3 Qweak graduate student talks for the upcoming American Physical Society meeting in Hawaii. One of our Canadian PhD students, Scott MacEwan will be presenting our first results at that meeting, so it is an exciting time for him in particular. Earlier today I met with one of our postdoctoral fellows, Dr. Mitra Shabestari, who joined our group at the University of Manitoba in August. She is planning a trip to Jefferson Lab in October with another of our graduate students, Ryan Spies, who will be visiting JLab for the first time and preparing for shift

duty on a new experiment that is starting up this fall with the newly-commissioned higher energy JLab beam. I am coordinating a technical planning document for another new experiment that is planned to measure the neutron electric dipole moment using a new ultra-cold neutron (UCN) facility under construction at TRIUMF, and my next job is to incorporate some submissions received this week from colleagues at UBC

and the University of Winnipeg; tomorrow I will visit the University of Winnipeg in the afternoon to discuss plans for a UCN collaboration meeting.

To sum this all up, the day to day experience involves interactions with students, postdocs and collaboration scientists all over the world, via email, telephone, collaboration meetings and conferences. Over the course of a large scale experiment like Qweak,

there are activities ranging from scientific and technical proposal writing, to giving talks, coaching students, designing and building equipment, travel to the lab to carry out the measurements, analysis of data, and finally preparing manuscripts for research journals to disseminate the results. There is never a dull moment, and sometimes the pace of progress is so fast that it is hard to keep up!