Searches for Physics beyond the Standard Model

Willem T H van Oers
Department of Physics and Astronomy, University of Manitoba
Winnipeg, MB R3T 2N2, Canada
and
TRIUMF, 4004 Wesbrook Mall
Vancouver, BC V6T 2A3, Canada
E-mail: vanoers@triumf.ca

Abstract. The Thomas Jefferson National Accelerator Laboratory has the demonstrated ability to test the fundamental symmetries of nature to very great precision and thereby probe for new physics beyond the Standard Model (SM). In the following objectives and descriptions will be given of three Jefferson Laboratory (JLab) experiments: Qweak, MOLLER, and PVDIS. The Qweak experiment is to measure the weak charge of the proton (via the vector coupling of the \(Z^0\) boson to the proton). The MOLLER experiment is to measure the weak charge of the electron. The PV-DIS experiment will measure combinations of vector couplings and axial-vector couplings to the quarks of the nucleons. These three experiments follow from the advances made in precision parity-violating electron scattering measurements at the CEBAF of JLab. The Standard Model makes accurate predictions of the 'running' of the electroweak mixing angle or \(\sin^2(\theta_W)\) from the \(Z^0\) pole down to low energies and therefore of the weak charges of the proton and electron. The Qweak experiment will make the first precision determination of the weak charge of the proton, \(Q_p^{\text{W}} = 1 - 4 \sin^2(\theta_W)\), from a measurement of the parity-violating asymmetry in the elastic scattering of longitudinally polarized electrons from the protons in a liquid hydrogen target at very low momentum transfer. The projected result will determine the proton's weak charge with a 4.1% total error and consequently \(\sin^2(\theta_W)\) with a 0.3% error. The Qweak experiment is at present three months into its commissioning run. The MOLLER experiment is to measure the parity-violating asymmetry in the scattering of 11 GeV longitudinally polarized electrons from the atomic electrons in a liquid hydrogen target. The longitudinal analyzing power \(A_Z\) is predicted to be 35.6 ppb at the kinematics of the experiment and is to be determined with a precision of 0.73 ppb, which would make the MOLLER experiment the most precise parity-violation experiment ever undertaken. The result would yield a measurement of the weak charge of the electron to 2.3% at an average \(Q^2\) value of 0.0056 (GeV/c)^2 and in turn a determination of the electroweak mixing angle \(\sin^2(\theta_W)\) with an uncertainty of \(\pm 0.00026\) (stat) \(\pm 0.00013\) (syst), comparable to the accuracy of the two best determinations at the \(Z^0\) pole. The PV-DIS experiment is to measure the parity-violating asymmetry in deep inelastic scattering of longitudinally polarized electrons from an unpolarized deuterium target. The longitudinal analyzing power can be expressed in terms of the quark distribution functions of the deuterium target and the couplings \(C_{1q}\) (axial electron x vector quark) and \(C_{2q}\) (vector electron x axial quark), which in the Standard Model can be expressed in terms of \(\sin^2(\theta_W)\).

1. Introduction
The theory of electroweak interactions in the Standard Model has survived stringent experimental tests over more than three decades. Consistency has been achieved at the 0.1%
level, where electroweak radiative corrections involving the top quark, the massive vector bosons ($Z^0$ and $W^{±}$), and the Higgs boson become manifest. All experimental data to date, with direct access to a center of mass energy of 200 GeV in $e^+ - e^-$ collisions, and approaching 1 TeV in the hard scattering of partons in $p - \bar{p}$ collisions are in agreement with theoretical predictions. Nevertheless, there are compelling theoretical arguments, input from cosmological observations (about the existence of dark matter and dark energy), and the discovery of the neutrino mass with its inherent neutrino oscillations, that strongly motivate the exploration of the multi-TeV mass scale via direct searches at high-energy colliders as well as via ultra-precise electroweak measurements at low energy.

The Standard Model provides a firm prediction of the weak charge of the electron as well as of the proton, based on the ‘running’ of the weak mixing angle or $\sin^2(\theta_W)$, from the $Z^0$ pole down to low energies as shown in Fig. 1. The average of the precise measurements at the $Z^0$ pole (from LEP [leptonic] and from SLD [semi-leptonic]) makes it possible to calibrate the curve at one particular energy. However, it should be noted that these most precise leptonic and semi-leptonic measurements made at the $Z^0$ pole differ by 3σ, a difference so far without definitive explanation. The two measurements result in boundaries of the Higgs mass outside the allowed range from all other measurements as shown in Fig. 2. The shape of the curve for $\sin^2(\theta_W)$, shown in Fig. 1, away from the $Z^0$ pole is the prediction based on the Standard Model (in the modified minimal subtraction scheme). The theoretical uncertainty is given by the thickness of the curve. Measurements away from the $Z^0$ pole are importantly and urgently required.

At the present there exist several low $Q^2$ determinations of $\sin^2(\theta_W)$: from an atomic parity violation measurement on $^{133}$Cs [2,3], and from the parity-violating electron-electron, Moller, scattering experiment [4] (E158 at SLAC), the predecessor of the MOLLER experiment at NUANCE.

Figure 1. Calculated ‘running’ of the weak mixing angle in the Standard Model, as defined in the modified minimal subtraction scheme [1]. The uncertainty in the predicted ‘running’ is given by the thickness of the curve. The black points with error bars show the existing data, while the pink points with error bars (with arbitrarily chosen ordinates) refer to the projected Jefferson Laboratory Qweak and MOLLER experiments’ results. The existing measurements are from atomic parity violation [2,3], SLAC E158 Moller scattering [4], NuTeV deep inelastic neutrino/antineutrino scattering [5,6], and LEP and SLC $Z^0$ pole asymmetries [7].
Figure 2. Higgs mass versus top quark mass. Shown are 1σ bands from various precision measurements. The red filled-in ellipse is a 90% C.L. contour of all precision electroweak data. The shaded yellow regions are excluded via direct searches at colliders - including the latest exclusion band from the Tevatron. The strongest constraint on the width of the purple dotted contour from current low-energy measurements is already now obtained from the SLAC E158 Moller scattering experiment, while its shape and its location in the figure is mostly due to the NuTeV result (without the corrections mentioned in the text). As shown it favors large values for the Higgs mass. Note also the discrepancy of the LEP leptonic and SLC semi-leptonic measurements at the $Z^0$ pole for the Higgs mass. The MOLLER experiment with projected precision will provide a constraint of similar slope and precision as both the $Z^0$ pole measurements and the potential to resolve their discrepancy.

Jefferson Laboratory. The result from the NuTeV experiment [5] becomes also in agreement with the Standard Model if corrections for nuclear effects, charge symmetry breaking, and strange quark asymmetry effects are applied [6].

A rather general and model-independent way to quantify the effects of new high energy dynamics in low-energy processes is to express the resulting new amplitudes in terms of four-Fermi contact interactions among leptons and quarks. For vector and axial-vector interactions between electrons, the MOLLER experiment with an anticipated 2.3% overall uncertainty, leads to a sensitivity of $\Lambda/\sqrt{|g_{RR}^2 - g_{LL}^2|} = 7.5$ TeV, where $\Lambda$ represents the energy scale and $g$ the coupling strengths. This compares favorably to current limits from LEP-2. At the level of the anticipated sensitivity the MOLLER experimental result could be influenced by radiative loop effects of new particles predicted by the Minimal Supersymmetric Standard Model (MSSM). For electron-proton scattering the isospin dependence of a new interaction can be parameterized in terms of an angle $\theta_h$ with $h_V^L = \cos \theta_h$ and $h_V^T = \sin \theta_h$. The constraints on new physics beyond the Standard Model in terms of the mass scale versus the isospin dependence from previous electron scattering parity-violation experiments and the Qweak experiment with projected uncertainty is presented in Fig. 3. The impact of the deviations of the weak charges of the electron $Q^e_W$ and the proton $Q^p_W$ have been analyzed in detail [8] as shown in Fig. 4. The dots on the right hand side of the figure show the results of a random scan over a set of MSSM parameters whose values are consistent with current precision measurements and search limits.
Figure 3. Constraints on new physics beyond the Standard Model in terms of the mass scale versus isospin dependence. New physics is ruled out at the 95% CL below the curves. The red curve shows the limits based on the earlier measurements, while the blue curve shows the new limits based on the SAMPLE, PVA4, HAPPEX, and G0 measurements. The dashed curve displays the reach of the Qweak experiment at Jefferson Laboratory, assuming agreement with the Standard Model. The solid purple region shows the possible discovery potential of Qweak (also at 95% CL), assuming central value agrees with current measurements.

The allowed loop contributions to $Q_{eW}$ can be as large as $+8\%$, which with the anticipated error of the MOLLER experiment, would constitute a deviation of $3.5\sigma$. If the assumption of R-parity conservation is relaxed (RPV), tree-level interactions could generate even larger deviations in $Q_{eW}$ and $Q_{pW}$. The left hand side of the figure shows the allowed region in the parameters $Q_{eW}$ and $Q_{pW}$ after constraints from low-energy precision data have been taken into account. Many theories of new TeV-scale dynamics predict the existence of new, super-massive $Z'$ bosons with masses in the TeV range. Low-energy measurements would help decipher any indication of extra $Z'$ bosons obtained at the LHC in its first phase of operation. Only with a luminosity upgraded LHC, if a new boson is in the 1 to 2 TeV mass range, will LHC measurements of couplings become possible.

2. Qweak Experiment

The Qweak experiment is to carry out the first precision measurement of the weak charge of the proton, $Q_{pW} = 1 - 4\sin^2(\theta_W)$, at JLab, building on the technical advances that have been made in the laboratory’s world-leading parity-violation electron scattering research program and using the results of earlier such measurements to constrain hadronic corrections. The experiment is a high-precision measurement of the longitudinal analyzing power (after dividing the measured asymmetry by the electron beam’s polarization) in electron-proton elastic scattering at $Q^2 = 0.026(\text{GeV}/c)^2$ employing up to 180 $\mu$A of 85% polarized beam on a 0.35 m long liquid hydrogen target. The experiment will determine the weak charge of the proton with a projected 4.1% combined statistical and systematic error.

In the absence of physics beyond the Standard Model, the experiment will provide an approximately 0.3% measurement of $\sin^2(\theta_W)$, which will make it the most precise stand alone
Figure 4. Relative shifts in the electron and proton weak charges due to SUSY effects. Dots indicate the range of allowed MSSM-loop corrections. The interior of the truncated elliptical regions give possible shifts due to R-parity violating (RPV) SUSY interactions, with (a) and (b) corresponding to different assumptions on limits derived from first row CKM unitarity constraints.

measurement of the weak mixing angle at low $Q^2$, and in combination with other parity violation measurements, a high precision determination of the weak couplings, $C_{1q}$, to the ‘up’ and ‘down’ quarks, improving on the present knowledge, see Fig. 5. The measurement of $Q_{W}^p$ will be performed with statistical and systematic errors considerably smaller than of the existing low $Q^2$ data for $\sin^2(\theta_W)$. Any significant deviation from the Standard Model prediction for $\sin^2(\theta_W)$ at low $Q^2$ would be a signal of new physics, whereas agreement would place new and significant constraints on possible extensions of the Standard Model.

It is to be noted that electroweak corrections affect the proton and electron weak charges differently. In addition to the effect of the ‘running’ of $\sin^2(\theta_W)$, there is a relatively large WW box graph contribution to the weak charge of the proton that does not appear in the case of the electron. This contribution compensates numerically for a large part the effect of the ‘running’ of $\sin^2(\theta_W)$ for the proton, which is not the case for the electron. In addition there are $\gamma$ and $Z^0$ two boson exchange contribution corrections [9] with intermediate states described by nucleons and $\Delta$ baryons. However, cancellations make their effect on the weak charge of the proton rather modest. The $\gamma$ Z box diagram may cause a somewhat larger correction, but still a marginal shift in the total precision of the nominal 4.1% measurement of Qweak. For a discussion see Ref. [10].

The Qweak experiment has been installed on the beam line in Hall C of JLab (for a layout of the Qweak experiment see Fig. 6). Commissioning of the Qweak experiment commenced in July 2010 with data taking in September 2010. The experiment is scheduled to be taking data till the middle of May 2012 with an interruption of six months in 2011.

3. MOLLER Experiment
The MOLLER experiment [11] will measure the parity-violating analyzing power in the scattering of longitudinally polarized electrons off the electrons of a liquid hydrogen target, using an 11 GeV beam in Hall A of the upgraded CEBAF of Jefferson Laboratory. The measurement
Figure 5. Experimental constraints on the effective neutral weak couplings. The grey contour displays the experimental limits (68% CL) from all earlier sources, dominated by the precision experiment on Cesium. The green filled ellipse denotes the additional constraint (at 68% CL) provided by recent high precision parity-violating electron elastic scattering measurements (SAMPLE, PVA4, G0, and HAPPEX). The total constraint (68% CL) from combining all measurements is displayed by the red contour. The projected precision of the $Q_{\text{weak}}$ measurement is shown by the solid blue band, assuming agreement with the Standard Model is obtained.

is to improve on the existing result of the same quantity from the E158 experiment at SLAC by more than a factor five in fractional precision (see Fig. 1). The quantity to be measured is $A_z = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$ where $\sigma^+$ and $\sigma^-$ refer to the cross sections for electrons of right handed and left handed helicity, respectively. Scattered electrons will be detected corresponding to the center of mass angular range from 46° to 127°. It is expected that $A_z \simeq 35.6$ ppb for the kinematics of the experiment. It is intended to measure this with a precision of 0.73 ppb in 30 weeks of beam time. The resulting precision in $\sin^2 \theta_W$ of about ±0.00025 is comparable to the precision reached in the two better measurements at the $Z^0$ pole. To arrive at this precision requires an electron beam of 85 $\mu$A with a polarization of 85% incident on a 1.5 m long liquid hydrogen target, resulting in a Moller rate of 153 GHz in the 7 open sectors of the 14 sector magnetic spectrometer. To avoid the complications of double counting (since Moller scattering involves two identical particles) the spectrometer contains seven open sectors with the diametrically opposite sectors blocked to the scattered electrons. The Lorentz boost causes all scattered electrons to be confined to a narrow forward cone. To separate spatially the scattered electrons from the through going electron beam in a sufficient manner a set of two sequential toroidal magnets will be used.

As in the $Q_{\text{weak}}$ experiment, the counting rate is too high for conventional pulse counting techniques. Consequently, the experiment will operate in current mode with ersatz quartz
Figure 6. Schematic layout of the Qweak experiment. The polarized electron beam is incident from the left and scattered electrons exit the target and pass through the first collimator, the region-1 GEM detectors, the two stage second precision collimator which surrounds the region-2 horizontal drift chambers, the eight-fold symmetric toroidal spectrometer magnet, the region-3 vertical drift chambers, the trigger scintillators, and finally the ersatz quartz Cherenkov main detectors. The tracking system chambers and the trigger scintillators, mounted on rotatable wheels, will be extracted outwards during high current data taking to measure $A_z$. Luminosity monitors, which will be used to monitor target density fluctuations and to provide sensitive null tests, are located downstream of the main apparatus very close to the through going beam. Further luminosity monitors are placed just downstream of the $LH_2$ target at large angles.

detectors for both the main detector system and for the luminosity monitors. The latter detectors at extreme forward angles will be used for null measurements of the analyzing power and for normalization purposes. Many of the experimental details are taken over from the Qweak experiment. The main detector system is divided radially to observe electron-proton scattering and Moller scattering. It will also observe pions produced in inelastic processes. A schematic layout of the experiment is shown in Fig. 7. One of the more challenging technical aspects of the experiment is the liquid hydrogen target with its $5 \text{kW}$ heat load. Fluctuations in the target density as a result of boiling need to be suppressed by rapid turbulent flow of the liquid hydrogen and by rastering of the incident electron beam (over a $5 \text{ mm} \times 5 \text{ mm}$ area). As for the Qweak target, the MOLLER liquid hydrogen target cell has been modeled using computer assisted fluid dynamics calculations. To further limit the effects of density fluctuations of the liquid hydrogen target fast helicity changes (at $1 \text{ kHz}$) will be adopted. False asymmetries resulting from helicity correlated modulations in the incident electron beam parameters (position, direction, size, intensity, polarization, and energy) have to be strictly controlled by a largely azimuthally symmetric detection system with minimal sensitivity to helicity correlated modulations, by minimizing the unwanted helicity correlated modulations in the beam parameters, and by measuring these concurrent with the data taking to make corrections knowing the sensitivities of the detection system from a series of control measurements. Active feedback systems are only introduced as a last resort (e.g. to suppress helicity correlated intensity modulations) because of the possibility of coupling to other unwanted beam parameter modulations. To a very large extent the unwanted helicity correlated modulations of the incident polarized electron beam originate at the polarized electron source. With the precision required (significantly more precise than any other polarized hadron or electron parity-violation experiment) many improvements to the operation of the polarized electron source have to be introduced. To obtain the analyzing power, the incident electron beam polarization needs to be divided out. Both very precise Moller and Compton polarimetry will be used. The former in particular, which is destructive to the
incident electron beam in general, needs to be adopted to allow operation at the high beam currents of the experiment. A series of control measurements will determine the average $Q^2$ acceptance of the main detector system for which a set of retractable event recording auxiliary detectors will be employed. The experiment is currently in a conceptual engineering stage.

4. PVDIS Experiment

The upgrade of the CEBAF beam energy to 12 GeV will expand the range of kinematics in which parity-violation measurements can be made. In particular it will include significantly more of the deep inelastic scattering (DIS) region, where new information can be obtained on charge symmetry breaking in the quark distributions, higher twist contributions to nucleon structure, and the electroweak coupling constants. To differentiate between these effects, measurements of parity violation in deep inelastic scattering (PVDIS) need to be made over a large kinematic range in both Bjorken $x$ and $Q^2$. The asymmetry in polarized electron scattering on unpolarized deuterium in DIS kinematics was first measured by Prescott et al. at SLAC as a confirmation of the Standard Model of the electroweak interaction [12]. This asymmetry can be expressed in terms of quark distributions of the target, and the couplings $C_{1q}$ (axial-vector electron x vector quark) and $C_{2q}$ (vector electron x axial-vector quark), which in the Standard Model can be expressed in terms of $\sin^2 \theta_W$:

\[
C_{1u} = - \frac{1}{2} + \frac{4}{3} \sin^2 \theta_W, \quad C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \\
C_{2u} = - \frac{1}{2} + 2 \sin^2 \theta_W, \quad C_{2d} = \frac{1}{2} - 2 \sin^2 \theta_W
\]

Considering only the three lightest quark contributions, the longitudinal analyzing power for polarized electron scattering from an isoscalar target as deuteron can be expressed as,

\[
A^{D}_{DIS} = - [3G_F Q^2/(2\sqrt{2}\pi\alpha)](2C_{1u} - C_{1d})(1 + R_s(x)) + Y(2C_{2u} - C_{2d})R_{\nu}/[5 + R_{\nu}(x)],
\]

where the kinematical factor $Y$ is a function of the incident and scattered electron energy, and $R_s$ and $R_{\nu}$ are functions of the quark distributions. Whereas the Qweak and MOLLER experiments will determine the $C_{1q}$ coefficients, the PVDIS experiment [13] will provide unique information on the $C_{2q}$ coefficients. The projected determination of the $C_{2q}$ coefficients is given in Fig. 8. The 11 GeV PVDIS experiment will be mounted in Hall A of Jefferson Laboratory following the currently ongoing upgrade of CEBAF.

5. Conclusion

The brief description of the three precision electron parity violation experiments (Qweak, MOLLER, and PVDIS) indicate the unique role, fully complementary to the LHC, that Jefferson Laboratory is able to fullfil in its 6 GeV current research program and in its future 12 GeV research program.
Figure 8. Projected knowledge of the coupling constants $C_{2q}$. The green diagonal band shows the expected uncertainty from the PVDIS experiment. The red colored square represents the uncertainty as given in the PDG handbook, prior to the PVDIS experiment, which is much larger than the entire graph.

6. References

[1] Erler, J and Ramsey-Musolf, M J Phys. Rev. D 72, 073003 (2005).
[2] Bennett, S C and Wieman, C E Phys. Rev. Lett. 82, 2484 (1999).
[3] Porsev, S G, Beloy, K, and Derevianko, A Phys. Rev. Lett. 102, 181601 (2009).
[4] Anthony, P L et al. (SLAC E158), Phys. Rev. Lett. 88, 091802 (2005).
[5] Zeller, G P et al. (NuTeV Collaboration), Phys. Rev. Lett. 88, 091802 (2002).
[6] Cloet, I C, Bentz, W, and Thomas, A W Phys. Rev. Lett. 102, 252301 (2009).
[7] Schael, S et al. (ALEPH, DELPHI, L3, OPAL, SLD, LEP), Phys. Rep. 427, 257 (2006).
[8] Kurylov, A, Ramsey-Musolf, M J and Su, S Phys. Rev. D 68, 035008 (2003).
[9] Tjon, J A, Blunden, P G and Melnitchouk, W Phys. Rev. C 79, 055201 (2009).
[10] Roche, J, van Oers, W T H and Young, R D (to be published).
[11] Jefferson Laboratory Proposal PR-09-005, Kumar, K (contact person).
[12] Prescott C Y et al., Phys. Lett. B77, 347 (1978); Prescott, C Y et al., Phys. Lett. B84, 524 (1979).
[13] Jefferson Laboratory Proposal PR12-09-012, Souder, P (contact person).