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Frontiers of polarized electron scattering experiments

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Abstract. Parity-violating electron scattering has developed into a precise and sensitive tool to probe the structure of weak neutral current interactions at $Q^2 \ll M_Z^2$. Steady improvements in experimental techniques have made feasible asymmetry measurements with precision approaching 10 parts per billion and fractional accuracy of a few percent. In the future, upgrades of new facilities, new laboratories and further refinements of experimental techniques should allow us to explore new aspects of the strong and electroweak interactions. We describe some of these ideas in this article.

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1 Introduction

The past couple of decades have seen the emergence of parity-violating electron scattering (PVES) experiments to the forefront of probing electroweak and strong interactions at low energy. Major experimental innovations have been made [1], such as the development of highly polarized electron beams, dense cryogenic targets, radiation-hard integrating detectors that effectively count at GHz rates, counting detectors that can count at MHz rates, precision beam monitoring and precision measurements of beam polarization with fractional accuracy approaching 1%.

When the accuracy of PVES measurements is combined with new accelerator capabilities, the investigation of novel aspects of weak neutral current (WNC) interactions becomes feasible. Further, the high rate capabilities and the ability to measure small asymmetries opens the window into measurements of beam-normal asymmetries, where the incident beam polarization is transverse to the scattering plane. In the following, we introduce the observables of interest and discuss possible new measurements.

1.1 Parity-violating asymmetries A_{PV}

In PVES, one measures the fractional difference A_{PV} of the scattered flux from an unpolarized target for incident longitudinally polarized electrons whose spins are aligned along or against the momentum. For $Q^2 \ll M_Z^2$, the leading contribution to the asymmetry is the ratio of the WNC amplitude (mediated by the Z boson) to the electromagnetic amplitude and thus A_{PV} is small and proportional to the four-momentum transfer Q^2:

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|A_Z|}{|A_\gamma|} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}. \tag{1}$$

For typical Q^2 values of interest (between 0.01 and 1 GeV^2), A_{PV} ranges from 0.1 to 100 parts per million (ppm). The WNC amplitude is typically dominated by the piece of the low energy WNC interaction that arises from the product of the axial-vector electron coupling and the vector coupling of the target particle.

The discovery potential of PVES measurements arises in several different kinematic situations. In some cases, the weak vector coupling of the target provides access to a new linear combination of the underlying quark vector currents, leading to novel insights of nuclear and nucleon structure [2]. Experiments HAPPEX, SAMPLE, A4 and G0 (probing the strange structure of the nucleon) and the planned PREX experiment (probing the neutron skin of ^{208}Pb), fall under this category.

In special circumstances, if the vector coupling of the target is very well-known or if there are cancellations that make the ratio of weak and electromagnetic amplitudes insensitive to hadron structure, one can probe new particle physics at TeV scales [3]. The SLAC E122 (Deep Inelastic Scattering), SLAC E158 (Møller scattering) and Qweak (elastic electron-proton scattering) experiments fall under this category.

A third class of measurements access the small amplitudes that arise from the product of the electron vector coupling and the target axial-vector coupling. The A4, SAMPLE and G0 experiments probe the axial nucleon current in this manner.

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2 Beam-normal asymmetries A_T

If the incident beam is polarized transverse to the beam direction, one can construct an asymmetry:

$$A_T \equiv \frac{2\pi}{\sigma^\uparrow + \sigma^\downarrow} \frac{d(\sigma^\uparrow - \sigma^\downarrow)}{d\phi} \tag{2}$$

which is proportional to $\mathbf{S_e} \cdot (\mathbf{k_e} \times \mathbf{k'_e})$, where $\mathbf{S_e}$ is the incident electron spin vector and the incident and final electron 3-vectors $\mathbf{k_e}$ and $\mathbf{k'_e}$ define the scattering plane. The primary contribution to A_T comes from two photon-exchange. The transverse asymmetry is suppressed by the electron boost and thus an order of magnitude estimate is $A_T \sim \alpha m_e/\sqrt{s}$. However, even for elastic electron-proton scattering, the intermediate states between the two virtual photons have to be summed over the full virtuality kinematically available to each photon, resulting in enhancements that are quite sensitive to nucleon excited state structure [4,5,6].

Recently, analysis of data on proton elastic form factors have shown a disagreements between cross-section and asymmetry measurements. The real part of two-photon exchange amplitude is a good candidate to explain a signficant part of the discrepancy [7]. While A_T measurements are sensitive to the imaginary part of the same amplitude, detailed studies might be possible since the amplitude constitutes the leading contribution. Thus, A_T measurements have emerged as an important component of precision studies of nucleon structure.

3 PV deep inelastic scattering at high x

The upgrade of Jefferson Laboratory (Jlab) to 11 GeV incident energy will allow precision measurements in parity-violating deep inelastic scattering (PV DIS). For the first time, high statistics can be accumulated at high $x \sim 0.7$, where x is the fraction of the nucleon momentum carried by the struck quark. PV DIS provides access to novel aspects of nucleon structure, complementing and enhancing precision electromagnetic DIS studies.

A_{PV} in DIS can be written as

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha} \Big[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x) \Big], \tag{3}$$

$$a(x) \equiv \Sigma_i f_i(x) C_{1i} q_i / \Sigma_i f_i(x) q_i^2, \tag{4}$$

$$b(x) \equiv \Sigma_i f_i(x) C_{2i} q_i / \Sigma_i f_i(x) q_i^2. \tag{5}$$

Here, $C_{1i}(C_{2i})$ are the weak vector(axial-vector) weak charges for the ith quark flavor, $f_i(x)$ are parton distribution functions and q_i are the electromagnetic charges. The $a(x)$ term arises from the product of the electron axial-vector coupling and the quark vector coupling and is typically the dominant term. For an isoscalar target such as deuterium, the dependence on structure largely cancels out in the A_{PV} ratio of the weak and electromagnetic amplitudes:

$$a(x) = \frac{6}{5} \Big[(C_{1u} - \frac{1}{2} C_{1d}) + \text{corrections} \Big]; \tag{6}$$

$$b(x) = \frac{6}{5} \Big[(C_{2u} - \frac{1}{2} C_{2d}) \frac{q(x) - \bar{q}(x)}{q(x) + \bar{q}(x)} + \text{corrections} \Big], \tag{7}$$

where $q(x) = u(x) + d(x)$. For scattering off the proton,

$$a(x) = \Big[\frac{u(x) + 0.91 d(x)}{u(x) + 0.25 d(x)} \Big]. \tag{8}$$

3.1 Charge symmetry violation

As can be seen from 6, $a(x) \approx 1.15$ for an isoscalar target, independent of x. This results from the assumption of charge symmetry, where the u-quark distribution in the proton is the same as the d-quark distribution in the neutron, with a similar assumption for the proton d-quark distribution: $u^p = d^n$ and $d^p = u^n$. If $a(x)$ can be measured with high precision over a range of x values, one is thus quite sensitive to charge symmetry violation (CSV). If one defines CSV parameters:

$$\delta u(x) = u^p(x) - d^n(x); \quad \delta d(x) = d^p(x) - u^n(x), \tag{9}$$

then the dependence on the parity-violating asymmetry for an isoscalar target is [8]:

$$\frac{\delta A_{PV}}{A_{PV}} = 0.28 \frac{\delta u - \delta d}{u + d} \equiv 0.28 R_{CSV}. \tag{10}$$

While R_{CSV} is known to be less than 0.01 for $x < 0.4$ from neutrino DIS measurements [9], a bag model calculation suggests that $R_{CSV} \sim 0.01$ for $x \sim 0.4$ and rising to 0.02 for $x \sim 0.6$. At high x, knowledge of $u + d$ is limited. As $x \to 1$, if $u + d$ falls off more rapidly than $\delta u - \delta d$, then R_{CSV} might rise to 0.1 at $x \sim 0.7$, which would be observable with a 1% A_{PV} measurement. Further, R_{CSV} is quite unconstrained at large x. There is the tantalizing possiblity that R_{CSV} in the moderate and high x region is a factor of 3 bigger than above-mentioned values, which would be large enough to explain the 3σ discrepancy in the neutrino-nucleon DIS measurement (NuTeV anomaly) [9] and would be a very important discovery.

3.2 d/u at high x

As can be seen from 8 for PV DIS off the proton, $a(x)$ is quite sensitive to the ratio $d(x)/u(x)$. The value of d/u as $x \to 1$ is a very important parameter to pin down in DIS physics. It is required in order to properly constrain fits of parton distribution functions and impacts predictions for QCD processes at high energy colliders.

More importantly, d/u at high x provides new information on important pieces of the nucleon wave function. There is empirical evidence that the minority quark in the nucleon is suppressed at high x, an intuitive notion in terms of a hyperfine interaction. While the SU(6) wave function would predict $d/u \sim 0.5$, simple SU(6)-breaking arguments would predict $d/u \sim 0$. However, a perturbative QCD calculation predicts $d/u = 0.2$ as $x \to 1$ [10].

Currently, the best estimates of d/u comes from ^{2}H DIS structure function data, but uncertainties in the ^{2}H wave-function limits the ability to discriminate between various predictions for d/u [11]. There are plans to measure d/u via the ratio of ^{3}H and ^{3}He structure functions and also via measurements of deuteron structure functions with tagged slow recoiling protons.

A precise enough measurement of $a(x)$ for the proton at $x \sim 0.7$ would be able to distinguish between competing predictions for d/u as $x \to 1$. The advantage of A_{PV} measurements over other methods is that there are no nuclear corrections since the PV DIS measurement can be made on a proton target.

3.3 Higher twist effects

The topics discussed above can be accessed only if the physics of leading twist dominates the weak and electromagnetic amplitudes. However, it is well-known from unpolarized structure function studies that hadronic corrections from higher twist (HT) effects might add Q^2 dependence to the asymmetry:

$$A_{PV}(x, Q^2) = A_{PV}(x)(1 + C(x)/Q^2). \qquad (11)$$

It is not possible to calculate $C(x)$ from first principles, so ideally it must be extracted from data.

PV DIS has the potential to probe for interesting HT effects, since the A_{PV} weak-electromagnetic amplitude ratio would be sensitive to the amount of contributions from coherent quark combinations such as diquarks. For example, if spin-0 diquarks dominate, then the HT effects are expected to be small, with a $1/Q^4$ dependence [12]. Additionally, novel HT effects arising from the interference of HT effects involving γ exchange on one quark and Z exchange on a different quark might contribute [13].

Recently, an NNLO QCD analysis has shown that HT effects in the unpolarized structure functions are small for $x < 0.6$ but does not rule out 10 to 20% effects for $x \sim 0.7$ [14]. It would be interesting to search for HT effects in PV DIS. If they are large, they would point to dynamics specific to DIS processes involving $\gamma - Z$ interference. Determining whether HT effects are small or large is critical to ensure that the physics of CSV and the d/u ratio can be extracted cleanly. The size of HT effects can already be constrained or discovered with a 6 GeV beam; there is a proposal under consideration at Jlab to pursue this measurement [15].

3.4 Experimental equipment for PV DIS at high x

To comprehensively address the physics topics discussed above experimentally, a series of A_{PV} measurements in the range of 1 to 2% accuracy are required for the x range from 0.3 to 0.7, with a lever arm of a factor of 2 in Q^2 while keeping $W^2_{\mathrm{min}} > 4$ and $Q^2_{\mathrm{min}} > 1$. With the upgrade of Jlab, high luminosity with a beam energy of 11 GeV becomes possible for the first time. However, to achieve sufficient statistics at the highest possible Q^2, a spectrometer with at least 50% acceptance in the azimuth is required.

A conventional magnetic spectrometer with the requirements specified above would be prohibitively expensive. However, it might be possible to employ a calorimeter with the ability to identify and count clusters at rates of 10 to 20 MHz, such as the one employed by the Mainz A4 experiment. The scattered electron energies of interest would range from 2 to 4 GeV. A large acceptance toroid could serve as a sweeping magnet, to remove low energy pions, Møller electrons and to shield the calorimeter from line-of-sight photons. The conceptual design for such an apparatus is now under way, and might be potentially useful for other applications besides PV DIS.

3.5 Transverse asymmetries

As a bonus, the use of a device such as the one described in the previous section makes possible a precision study of an entirely new process. Beam-normal asymmetries in the DIS region would become measureable with high precision. While leading twist contributions to transverse asymmetries might be of the order of ppm, HT effects might be enhanced by one to two orders of magnitude [16] due to large logarithms in the sum over intermediate states in the 2-photon amplitude. Thus, HT effects could potentially be studied in detail.

4 Asymmetries at low Q^2 and forward angle

The unprecedented high luminosity available at Jlab as well as the upgrade of the energy provides new opportunities to measure asymmetries with sufficient precision at very forward angles, in a Q^2 range between 0.05 and 1 GeV^2, both in elastic scattering as well as in highly inelastic scattering ($W^2 > 4$ GeV^2).

4.1 Longitudinal asymmetries

The E158 experiment has carried out an auxiliary measurement of the PV asymmetry in electron-proton scattering at $Q^2 \sim 0.05$ GeV^2. The measurement is consistent with roughly $A_{PV} \approx -10^{-4} Q^2$ for the inelastic scattering component (mostly real and virtual photoproduction), which constituted about 30% of the flux. The remaining signal comes from elastic electron-proton scattering, with an asymmetry that is a factor of 5 smaller.

It would be interesting to measure A_{PV} in inelastic electron-proton scattering at forward angles, mapping out the asymmetry variation as function of the target recoiling mass W. This would provide new information on parity-violating real and virtual photoproduction, which is presumably related to electromagnetic photoproduction via an isospin rotation. Thus, prevailing parametrizations on leptoproduction, primarily from the HERA collider [17], would be tested in a new way.

4.2 Transverse asymmetries

As described in Sect. 2, A_T measurements have emerged as an important probe of nucleon structure. These asymmetries are enhanced as the incident beam energy is increased, since inelastic intermediate states with one quasi-real photon makes a significant contribution. At very low Q^2 (< 0.1 GeV^2) and forward angle, A_T can be predicted using the optical theorem [4,5]. At intermediate Q^2 ($0.1 < Q^2 < 1$ GeV^2), the inelastic amplitudes from single and multiple pion production are expected to dominate [4]. As Q^2 is increased, A_T receives increasing contributions from off-forward structure functions. At $Q^2 \sim 1$ GeV^2, A_T can be calculated in a perturbative QCD framework where it is related to Generalized Parton Distributions [18].

There are currently plans for A_T measurements at the G0 and A4 experiments. The kinematics are well-suited to test the regime of single pion production. On the other hand, it would interesting to measure A_T at forward angle at very low Q^2 (< 0.1 GeV^2) and at high $Q^2 \sim 1$ GeV^2 in order to connect to the optical theorem at one extreme and parton distributions at the other extreme.

4.3 Experimental program

The longitudinal and transverse asymmetry measurements discussed above require the ability to measure very high flux rates ($\sim$ 100 MHz) and small asymmetries ($\sim$ 1 ppm). A spectrometer/detector package that provides this along with azimuthal coverage to measure A_T with high efficiency would have to be similar in concept to the E158 design, where the entire primary and scattered beam were enclosed in a set of quadrupole doublets. This allows the separation of elastic and inelastic electron-proton scattering events from background while providing acceptance in the full range if the azimuth. A compact radiation-hard calorimeter would be placed downstream of the quadrupole spectrometer to integrate the scattered flux.

Alternatively, a more conventional forward angle spectrometer setup perhaps enhanced with septum magnets could be contemplated, although the solid angle would be significantly smaller. Indeed, these studies can be launched already with a 6 GeV beam and a proposal is under consideration at Jlab to pursue this measurement [19].

5 Electroweak physics

As mentioned in the introductory paragraphs, with judicious choice of target and kinematics, it is possible to probe the structure of the WNC interaction itself, with little uncertainty from hadron structure. High precision measurements of such amplitudes at $Q^2 \ll M_Z^2$ continue to be important and complementary to measurements at high energy colliders [20]. The latter are typically sensitive to parity-conserving observables that probe contact interaction scales better than 10 TeV. They are typically less sensitive to PV contact interaction scales by an order of magnitude.

There are only a select few reactions that can probe the 10 TeV scale in fixed target WNC interactions [3]. Successful measurements have been reported in atomic parity violation [21], neutrino DIS (NuTeV) [22] and fixed target Møller scattering (E158) [23]. One legacy of such precision measurements is that they are sensitive enough to observe electroweak radiative corrections (higher-diagrams that involve W and Z bosons in quantum loops). A convenient manifestation of this sensitivity is the "running", as a function of momentum transfer Q^2, of the weak-mixing angle $\sin^2 \hat{\theta}_{\mathrm{W}}(Q^2)_{\overline{\mathrm{MS}}}$ [24].

It is important to measure $\sin^2 \theta_W$ with sufficient precision to observe the running in as many different reactions as possible in order to comprehensively probe for physics beyond the standard model at the TeV scale. The E158 measurement has established the running of $\sin^2 \theta_W$ at the 7σ level. The NuTeV measurement has a 3σ descrepency with the standard model prediction, the origin of which is a subject of active theoretical and experimental debate. In the following, we describe plans and new ideas to make more precision measurements of $\sin^2 \theta_W$ at low Q^2.

5.1 Elastic electron-proton scattering

At sufficiently forward angles and low Q^2, the hadronic structure undertainty in the WNC elastic electron-proton amplitude becomes small enough such that one can measure the underlying coherent $2u + d$ e-q amplitude combination to high precision. This combination is proportional to $1 - 4\sin^2 \theta_W$, so that a 4% measurement of A_{PV} would achieve a precision of $\delta(\sin^2 \theta_W) = 0.0007$

The experiment would use a 1 GeV 180μA electron beam incident on a 35 cm liquid hydrogen target. Scattered electrons would be focused by a toroidal field in the full range of the azimuth on to Čerencov detectors. The predicted asymmetry is 0.3 ppm. The experiment, named Qweak [25], has been approved for initial construction at Jlab and the first data collection is projected for 2008.

It turns out to be quite complementary to compare A_{PV} measurements from elastic electron-proton scattering and Møller scattering. Various models for new physics at the TeV scale can induce constructive or destructive interferences in one or both reactions. In particular, one might be able to distinguish between conventional and R-Parity breaking SUSY models, which is relevant to the viability of a SUSY dark matter candidate [26].

5.2 Deep inelastic scattering

If the PV DIS asymmetry can be measured to an accuracy of 1% at $Q^2 \sim 5$ GeV^2 and $x \sim 0.35$ for an isoscalar target such as deuterium, then the parameter $a(x)$ can be measured with high precision, free from hadron structure uncertainties [27]. This measurement would be robust only if the program described in Sect. 3 is carried out. Indeed, as can be seen from 6, $a(x)$ is independent of x and simply a function of $\sin^2\theta_W$ under the assumption of charge symmetry and assuming that HT effects are either directly measured or constrained.

The measurement is interesting for several reasons. Firstly, it would test the WNC amplitude in the lepton-quark sector, where there is currently a 3 σ discrepancy in the NuTeV result. Secondly, combined with other measurements in elastic electron-proton scattering, precise constraints would be possible on the lesser known axial-vector quark couplings C_{2i}. This would, among other things, provide complementary constraints on various models with new heavy Z' bosons [3].

5.3 Møller scattering

The PV asymmetry in fixed target Møller scattering is unique among WNC processes at $Q^2 \ll M_Z^2$ in being able to probe for new physics at the 10 TeV scale in a purely leptonic reaction. The recently completed E158 experiment has provided the most precise measurement of $\sin^2\theta_W$ at low energy [23]. Nevertheless, it is useful to consider future ideas to measure the asymmetry with higher precision.

One way to achieve higher precision is to consider a high luminosity measurement with the 12 GeV beam at the upgraded Jlab [27]. If the 40 ppb asymmetry can be measured with a precision of 3%, then the weak mixing angle could be measured with a precision of 0.0004. At this level, the asymmetry is sensitive to SUSY loops in the radiative corrections. In particular, the higher precision facilitates further stringent constraints on R-parity violating terms, with important implications for SUSY dark matter candidates [26].

The figure of merit for Møller scattering (the precision with which the asymmetry can be measured for a given luminosity) rises linearly with incident beam energy. Thus, at a future linear collider operating at 250 to 500 GeV, Møller scattering offers a way to measure the weak mixing angle to a precision of 0.00007 [28]. At this level, the asymmetry becomes sensitive to radiative corrections involving fundamental scalars such as the Higgs boson, providing an important crosscheck of the symmetry breaking sector of the electroweak theory. Such a measurement would be competitive with precision electroweak measurements such as the W boson mass and left-right asymmetries at future lepton and hadron colliders.

6 Outlook

Parity-violating electron scattering will continue to remain in the forefront of studies of low energy electroweak interactions in the future. Over the next few years, there are exciting possibilities for novel experimental programs as new facilities are developed, addressing physics topics from nucleon structure to physics beyond the standard model at the TeV scale.

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