Measurement of Electron-Deuteron PVDIS Asymmetry at Jefferson Lab 6 GeV

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Summary. — Parity violation in deep inelastic scattering (PVDIS) of 6.0674 GeV polarized electrons from a unpolarized detuerium target has been measured at four-momentum transfer squared of $Q^2 = 1.121$ and 1.925 (GeV/c)^2 at Jefferson Lab. The asymmetry result at $Q^2 = 1.121$ (GeV/c)^2 can be used to explore hadronic effects in this observable, while the asymmetry at $Q^2 = 1.925$ (GeV/c)^2 can be used to extract the neutral weak coupling combination $2C_{2u} - C_{2d} \equiv 2g_V^e g_A^u - g_V^e g_A^d$, providing a factor of five to six improvement over the current world data. Analysis update of this experiment is presented here.

The parity violating asymmetry of $\vec{e}$–^{2}H deep inelastic scattering (PVDIS) was measured more than thirty years ago at SLAC [1, 2], and was the first experiment that established the value of the Standard Model weak mixing angle $\sin^2\theta_W$. The experiment reported here (JLab E08011) [3] was conducted from October to December 2009 in experimental Hall A of Jefferson Lab (JLab) in Newport News, Virginia, USA. The goal of the experiment is to provide an up-to-date measurement on the $\vec{e}$–^{2}H PVDIS asymmetry. This will not only improve the world knowledge on the electron and quark neutral weak couplings, but also serve as an exploratory step for the future PVDIS program at the JLab 12 GeV Upgrade [4].

The PV asymmetry of electron deep inelastic scattering (DIS) off a nuclear target is

$$A_{PV}^{DIS} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[2g_A^e Y_1(y)\frac{F_1^{\gamma Z}}{F_1^Z} + g_V^e Y_3(y)\frac{F_3^{\gamma Z}}{F_1^Z}\right] \tag{1a}$$

$$= -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x)Y_1(y) + a_3(x)Y_3(y)\right] \ . \tag{1b}$$

With $r^2 = 1 + \frac{Q^2}{\nu^2}$ and $R^{\gamma,\gamma Z}$ the ratio of the longitudinal and transverse virtual photon electromagnetic absorption and the $\gamma - Z^0$ interference cross sections, respectively:

$$Y_1 = \left[\frac{1+R^{\gamma Z}}{1+R^\gamma}\right]\frac{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma Z}}\right] - xy\frac{M}{E}}{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma}}\right] - xy\frac{M}{E}} \ , \quad \text{and} \tag{2a}$$

$$(2b)\qquad Y_3 = \left[\frac{r^2}{1+R^\gamma}\right]\frac{1+(1-y)^2}{1+(1-y)^2-y^2\left[1-\frac{r^2}{1+R^\gamma}\right]-xy\frac{M}{E}}\ .$$

In the quark parton model,

$$(3a)\qquad a_1(x) = 2g_A^e\frac{F_1^{\gamma Z}}{F_1^Z} = 2\frac{\sum C_{1i}Q_i q_i^+(x)}{\sum Q_i^2 q_i^+(x)}\quad\text{and}$$

$$(3b)\qquad a_3(x) = g_V^e\frac{F_3^{\gamma Z}}{F_1^Z} = 2\frac{\sum C_{2i}Q_i q_i^-(x)}{\sum Q_i^2 q_i^+(x)}\ ,$$

where the summation is over the quark flavor $i = u, d, s\cdots$, Q_i is the corresponding quark electric charge, $q_i^\pm(x)$ are defined from the PDF $q_i(x)$ and $\bar{q}_i(x)$ as $q_i^+(x) \equiv q_i(x) + \bar{q}_i(x)$ and $q_i^-(x) \equiv q_{i,V}(x) = q_i(x) + \bar{q}_i(x)$. For an isoscalar target such as the deuteron,

$$(4a)\quad a_1(x) = \frac{6\left[2C_{1u}(1+R_c) - C_{1d}(1+R_s)\right]}{5+R_s+4R_c}\quad\text{and}\quad a_3(x) = \frac{6\left(2C_{2u}-C_{2d}\right)R_v}{5+R_s+4R_c}\ .$$

Neglecting effects from heavier quark flavors and assuming that $u^p = d^n$, $d^p = u^n$ [$u, d^{p(n)}$ are the up and down quark PDF in the proton (neutron)], $s = \bar{s}$, and $c = \bar{c}$, one has

$$(5a)\qquad R_c \equiv \frac{2(c+\bar{c})}{u+\bar{u}+d+\bar{d}},\ R_s \equiv \frac{2(s+\bar{s})}{u+\bar{u}+d+\bar{d}}\ \text{and}\ R_V \equiv \frac{u-\bar{u}+d-\bar{d}}{u+\bar{u}+d+\bar{d}}.$$

For E08-011 the Hall A High Resolution Spectrometer (HRS) pair [7] was used to detect the scattered electrons in the inclusive mode. The central settings of the spectrometer were $Q^2 = 1.121$ and 1.925 (GeV/c)^2, comparable to the SLAC experiment. Because the expected asymmetries as well as their statistical uncertainties are larger by 1-2 orders of magnitude than other JLab parity experiments of the same period (HAPPEX-III [5] and PREX [6]), control of beam-related systematic uncertainties which was the major challenge to these parity experiments, is less of a concern for PVDIS. In contrast, because of the high pion background typical to DIS measurements, the "tradiational" integration method could not be used. Instead a specially-designed, fast counting DAQ was used and a major part of the analysis effort in the past two years was devoted to understanding the DAQ performance. Design and tests of the DAQ were reported at the last PAVI meeting in 2009, about four months before the start of the experiment.

The polarization of the electron beam was measured by the Møller polarimetry intermittently during the experiment, with an average value of $P_b = [88.47 \pm 0.047(stat.) \pm 1.8(syst.)]\%$. The uncertainty was dominated by the knowledge of the Møller target polarization. The Compton polarimeter monitored the polarization throughout the experiment and found $P_b = [90.18 \pm 1.8(syst.)]\%$. The uncertainty of the Compton measurement came primarily from the limit in understanding the shielding used to reduce the background events. The beam polarization contributes as the largest systematic uncertainty of this experiment.

The target was a 20-cm long liquid deuterium cell with two 5 mil aluminum windows. The helicity-correlated density fluctuation was monitored by the luminosity monitor. Assuming a $\pm 10\%$ difference in the PVDIS asymmetry between aluminum and deuterium, the correction to the measured deuteron asymmetry is 0.2% for both Q^2 results.

Dedicated measurements on a carbon multi-foil target were performed to determine the uncertainty of the scattering angle and the spectrometer momentum reconstruction. The uncertainties on the Q^2 were determined from the method of the optical calibration and the instrumentation limit, and were found to be 0.725% for $Q^2 = 1.121$ and $(0.58 - 0.64)$% for $Q^2 = 1.925$ (GeV/c^2), respectively.

As mentioned earlier, a trigger and DAQ system was specially designed for this experiment. In each HRS, the CO_2 gas Čerenkov detector and the double-layered lead-glass shower counter were used for particle identification at the hardware level and both electron and pion triggers were formed and counted by scalers. Low rate data were taken daily during the experiment in order to compare the performance of the new DAQ with the traditional one. Some of the detector signals were sampled by flash-ADCs for further understanding the DAQ performance. For electron triggers, the overall electron efficiency is found to be $\approx 95\%$ with a $> 1000:1$ pion rejection. The pion contamination are found to 'decrease ("dilute") the absolute value of the measured electron asymmetry by 10^{-4}.

The deadtime correction from the DAQ contributes as a major systematic uncertainty for this experiment. The deadtime of the DAQ consists of three parts: the "path" deadtime caused by summing and discriminating the preshower and shower signals to form preliminary electron and pion triggers; the "veto" deadtime caused by combining the preshower/shower triggers with the HRS T1 trigger and cherenkov signals; and the "final or" deadtime caused by taking the logical OR of 6 (8) paths to form the final electron and pion triggers for the left (right) HRS. A full scale simulation package was developed to study specifically the timing performance of the DAQ: Measured T1 and detector rates were used as inputs to the simulation, as well as the preshower and the shower ADC amplitudes from the HRS DAQ. The software then simulate the performance of each electric module in real time. In addition, each component of the deadtime is confirmed by a second method: the "path" deadtime is confirmed by data from the pre-installed "tagger" system. The "veto" deadtime is checked by both first-order calculations and data from the flash-ADCs. The "or" deadtime is checked by first-order calculations. The final deadtime correction to the electron trigger is at the 1-2% level, with an error bar of 20% relative depending on how well the simulated results agree with the second, cross-checking method.

Two independent asymmetry analyzes are being carried out. To avoid bias in the analysis, the electron asymmetries from DIS kinematics are blinded. All pion asymmetries are not blinded, neither are electron asymmetries in the transverse, the resonance, and the positron measurements. The statistical uncertainties of the PVDIS asymmetry are 4% and 3% for $Q^2 = 1.121$ and 1.925 (GeV/c)^2, respectively. So far, blinded DIS electron asymmetries from the two analyzes agree within 0.2 ppm, about 1/20 of the statistical uncertainty. The statistical quality of the measured asymmetries is shown in fig. 1. The non-Gaussian tail for kinematics #1 ($Q^2 = 1.121$ (GeV/c)^2) taken on the left HRS and for #2 ($Q^2 = 1.925$ (GeV/c)^2) taken on the right HRS were due to variations in the beam current (85-105 μA) used at the beginning of the experiment. This non-Gaussian tail is not present in later data taking where a consistent 105 μA current was used, as can be seen from data on kinematics #2 collected from the left HRS.

The transverse asymmetry were found to be 26.9 ± 15.66 ppm for $Q^2 = 1.121$ and 11.84 ± 49.89 ppm for $Q^2 = 1.925$ (GeV/c)^2, respectively, and would cause a 10^{-4} uncertainty to the measured PVDIS asymmetries. Effects from the pair production background were studied by reversing the polarity of the spectrometer magnet settings and were found to be at the 10^{-4} level for $Q^2 = 1.121$ GeV/c^2. The asymmetry of the pair production at this Q^2 was found to be 723.2 ± 1154.7 ppm, consistent with zero.

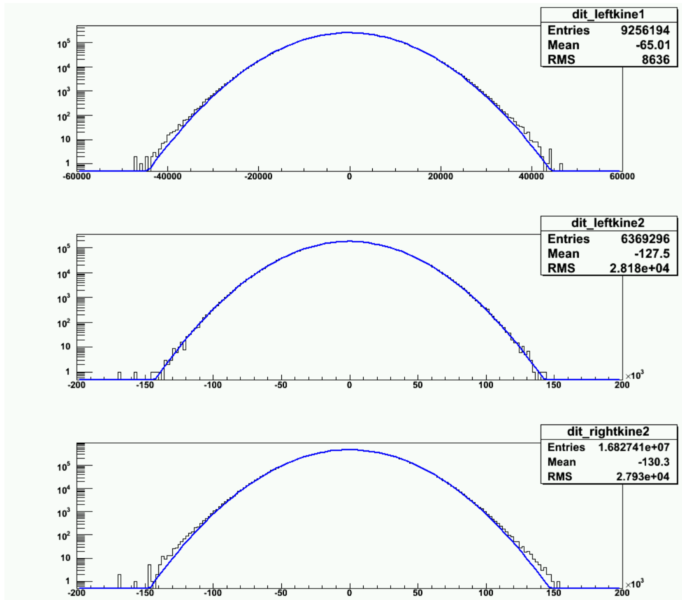

Fig. 1. – Overall statistical quality of the data after dithering correction. From top to bottom: kinematics #1 taken on the left HRS, kinematics #2 taken on the left HRS, and kinematics #2 taken on the right HRS. All asymmetries shown are blinded.

False asymmetries were found to be consistent with zero from measurements of polarized beam scattering off unpolarized ^{12}C targets. Asymmetries of pion triggers are being extracted. Because the pion triggers of our DAQ used only the gas cherenkov (not the lead glass detector) to reject electrons, a high electron contamination is expected for the pion trigger and must be understood before we interpret the pion results.

Radiative corrections were performed for both the internal and the external radiation effects. External radiative corrections were performed based on the procedure first described by Mo and Tsai [8]. Apart from elastic and quasi-elastic $e-^2$H scattering asymmetries, parity violation asymmetries of the nucleon resonances calculated from two models [9, 10] [with [9] for the $\Delta(1232)$ only] have been used, while a third set of calculation is underway [11]. Each calculation was provided to us in tabulated forms to cover the full range of E, E' and θ needed by our simulation. For kinematics that these tables do not cover but are within the resonance region ($W < 2$ GeV), we constructed "toy" models which scale the asymmetry calculated from the DIS formula and PDFs by the ratio of the resonance cross section to the cross section calculated from the DIS formula. The toy model thus has the quark-hadron duality "built-in" but may not work for the Δ region. Measurements of the resonance PV asymmetries were performed with a beam energy of 4.8674 GeV and provide a $\pm(10-15)\%$ precision each for the $\Delta(1232)$, the 2^{nd} and the 3^{rd} resonances. These are being used to check the validity of the resonance calculations and thus provide an estimate on how reliable these inputs to the radiative correction are.

In comparing with the asymmetry from the Standard Model, we used CTEQ6 and CTEQ10 [12, 13], MRST2008 [14] and MSTW2010 [15] as PDF inputs to Eq.($4a$). The uncertainty was estimated using the difference between these parameterizations. For R^{γ} we used Ref. [16]. For the higher twist effects on the a_3 term, we used neutrino data [18] and found it would shift the asymmetry by +0.70 ppm and +1.2 ppm for the lower and the higher Q^2. The higher twist effects on R^{γ} were estimated in Ref. [18] and the effect on the asymmetry is < 0.2 ppm for $Q^2 = 1.121$ but is as large as 0.5 ppm for $Q^2 = 1.925$ (GeV/c^2). Effect of possible difference between $R^{\gamma Z}$ and R^{γ} [17] is found to be small.

Our result at $Q^2 = 1.121$ (GeV/c^2) will set an upper limit on the Q^2-dependence of the hadronic correction. Assuming the Standard Model value for C_{1q} and no corrections from hadronic effects, we will extract the value of $2C_{2u} - C_{2d}$ from the $Q^2 = 1.925$ (GeV/c^2) asymmetry results. The current statistical uncertainty of the asymmetry indicates that we will improve this coupling combination by a factor of five to six compared to the current PDG value [19]. We expect to finalize the analysis and publish these results within the next year.

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