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## Measurement of the Parity-Violating Asymmetry in Inclusive Electroproduction of $\pi^-$ near the $\Delta^0$ Resonance

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The parity-violating (PV) asymmetry of inclusive  $\pi^-$  production in electron scattering from a liquid deuterium target was measured at backward angles. The measurement was conducted as a part of the G0 experiment, at a beam energy of 360 MeV. The physics process dominating pion production for these kinematics is quasifree photoproduction off the neutron via the  $\Delta^0$  resonance. In the context of heavy-baryon chiral perturbation theory, this asymmetry is related to a low-energy constant  $d_{\Delta}^-$  that characterizes the parity-violating  $\gamma N\Delta$  coupling. Zhu *et al.* calculated  $d_{\Delta}^-$  in a model benchmarked by the large asymmetries seen in hyperon weak radiative decays, and predicted potentially large asymmetries for this process, ranging from  $A_{\gamma}^- = -5.2$  to  $+5.2$  ppm. The measurement performed in this work leads to  $A_{\gamma}^- = -0.36 \pm 1.06 \pm 0.37 \pm 0.03$  ppm (where sources of statistical, systematic and theoretical uncertainties are included), which would disfavor enhancements considered by Zhu *et al.* proportional to  $V_{ud}/V_{us}$ . The measurement is part of a program of inelastic scattering measurements that were conducted by the G0 experiment, seeking to determine the  $N - \Delta$  axial transition form factors using PV electron scattering.

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In electron scattering, the size of parity-violating asymmetries is usually related to an interference between  $Z$  and  $\gamma$  exchange amplitudes. Therefore, in the photoproduction

limit ( $Q^2 = 0$ , where  $Q^2$  is the negative four-momentum transfer squared) virtual  $Z$  bosons cannot be exchanged, and the asymmetry is expected to tend to zero. But, in the

case of scattering from nucleons, parity violation also occurs in weak interactions among quarks, generically referred to as the hadronic weak interaction; this form of an electroweak radiative correction can lead to nonzero asymmetries in the photoproduction limit.

Zhu *et al.* [1,2] studied electroweak radiative corrections in the photoproduction limit theoretically for PV inelastic scattering of electrons from nucleons. The variation of the PV asymmetry with  $Q^2$  in this case is particularly of interest because of the desire to extract  $N - \Delta$  axial transition form factors, and to compare to and improve the determinations made by neutrino scattering experiments.

In Ref. [1], the PV asymmetry  $A_{\gamma}^{-}$  was calculated for the process  $\vec{\gamma} + d \rightarrow \Delta^0 + p \rightarrow \pi^{-} + p + p$  using heavy-baryon chiral perturbation theory (HB $\chi$ PT). The PV asymmetry was found to be related to a new low-energy constant in the effective weak Lagrangian  $d_{\Delta}^{-}$  characterizing the PV  $\gamma N \Delta$  coupling:

$$A_{\gamma}^{-} \equiv \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{2d_{\Delta}^{-}}{C_3^V} \frac{M_N}{\Lambda_{\chi}}, \quad (1)$$

where  $d\sigma_{R,L}$  are the differential cross sections for right- ( $R$ ) or left- ( $L$ ) circular-polarized incident photons,  $C_3^V$  is the dominant  $N - \Delta$  vector transition form factor,  $M_N$  is the mass of the nucleon, and  $\Lambda_{\chi}$  is the scale of chiral symmetry breaking. Nonresonant, higher order chiral, and  $1/M_N$  corrections are neglected here, as in Ref. [1].

By naive dimensional analysis, it would be expected that  $d_{\Delta}^{\pm} \sim g_{\pi}$ , where  $g_{\pi} \sim G_F F_{\pi}^2 / 2\sqrt{2} \sim 5 \times 10^{-8}$  is the scale of the weak charged-current hadronic process. (Here, the quantity  $d_{\Delta}^{\pm}$  refers specifically to the process  $\vec{\gamma} + p \rightarrow \Delta^+ \rightarrow \pi^+ + n$ .) Zhu *et al.* considered possible enhancements to  $d_{\Delta}^{\pm}$  via the inclusion of intermediate  $J^{\pi} = \frac{1}{2}^{-}$  and  $\frac{3}{2}^{-}$  resonances which would mix with the nucleon or  $\Delta$  respectively via the hadronic weak interaction. A similar treatment yielded excellent agreement with observables in hyperon decay, simultaneously describing weak radiative and weak hadronic decay in the  $\Delta S = 1$  sector of the hadronic weak interaction [3]. In the  $\Delta S = 0$  sector, less information about the amplitudes was known, and so their scale was taken to be of order the  $\Delta S = 1$  amplitudes. Because of unknown possible phase factors between the amplitudes, this resulted in a range of predictions of  $|d_{\Delta}^{\pm}| \sim (10-25)g_{\pi}$ . Since the amplitudes could be related to the hadronic charged-current interaction, the  $\Delta S = 0$  amplitudes might be further enhanced over their  $\Delta S = 1$  counterparts by a factor  $V_{ud}/V_{us}$  where  $V_{ij}$  are elements of the CKM matrix.

Zhu *et al.* concluded that a reasonable range of predictions is  $|d_{\Delta}^{\pm}| = (1-100)g_{\pi}$ , citing a “best value” of  $|d_{\Delta}^{\pm}| = 25g_{\pi}$  [1]. Through Eq. (1), this corresponds to a range  $|A_{\gamma}^{\pm}| = (0.052-5.2)$  ppm, with a best value of 1.3 ppm. We sought to test these predictions experimentally via

inclusive electroproduction of  $\pi^{-}$  off the deuteron. The detailed analysis is presented in Ref. [4].

Data were acquired during the backward angle phase of the G0 experiment, performed in Hall C at Jefferson Laboratory [5]. Data were acquired during our low-energy liquid deuterium ( $LD_2$ ) target measurements, collected simultaneously with inclusive quasielastic and inelastic electron scattering data, over a two-week period.

The G0 experimental apparatus was described in Ref. [6]. A polarized electron beam of current  $35 \mu A$  and energy 360 MeV impinged on a 20 cm liquid deuterium target [7]. The average beam polarization, measured with Møller [8] and Mott polarimeters [9], was  $85.8 \pm 2.1\%$  (combined statistical and systematic uncertainty). Helicity-correlated current changes were corrected with an active feedback system.

A superconducting toroidal spectrometer, consisting of an eight-coil magnet, collimators, and eight detector sets, detected  $\pi^{-}$  scattered at an average angle of  $100^{\circ}$ . Each detector set included two arrays of scintillators, one near the exit of the magnet (“CED”), and the second along its focal surface (“FPD”). For each detector set, an aerogel Čerenkov detector with a pion threshold of 570 MeV was used in concert with the scintillators, allowing separation of  $\pi^{-}$  from electrons.

The pion rate was signified by a coincidence between particular pairs of CEDs and FPDs, and an absence of a signal above threshold in the Čerenkov detector. Rates were corrected for deadtime and random coincidences in a manner analogous to our electron data [5]. The overall deadtime for this data set was 15%. The rate sensed within the selected locus of CED-FPD pairs is displayed graphically in Fig. 1.

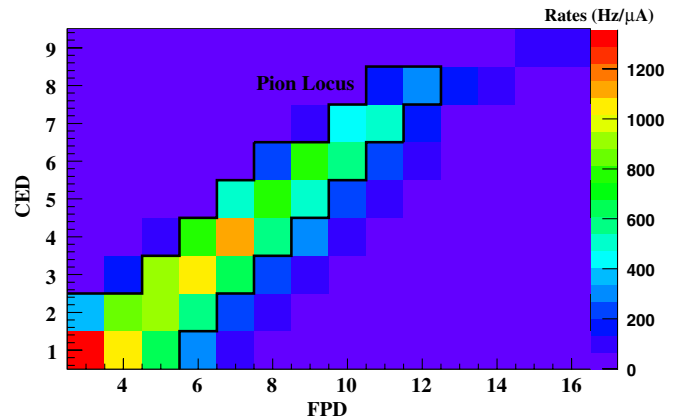


FIG. 1 (color online). Pion counting rates for various CED-FPD combinations (FPDs 1 and 2 not used). Pion tracks occur mainly in the lower left corner of the matrix. Rates in the far upper right corner are due to misidentification of electrons via Čerenkov inefficiency for electron detection. The locus of combinations analyzed for inclusive pion production is outlined in black.

Helicity-correlated beam properties were characterized using beam-current and beam-position monitors. Sensitivities of the detector to changes in beam-current, position, angle, and energy were also measured. Instead of correcting for helicity-correlated beam properties, a conservative error of 0.21 ppm was assigned, determined by multiplying the largest observed helicity-correlated property times the largest sensitivity, averaged separately over the run period. Averaging the product of the two appropriately would have resulted in negligible overall corrections.

Possible electronic leakage of the helicity signal into the data-acquisition system was studied by periodically inserting a half-wave plate into the laser beam path in the polarized source, which would act to reverse the direction of the polarization of incident electrons. Upon insertion, all asymmetries measured by the experiment should reverse sign, and averaging the results for different half-wave plate states should result in zero. In the case of these data, the average determined in this way showed some lack of consistency across octants. Averaging in turn over octants gave  $(1.7 \pm 0.8)$  ppm (prior to correction for beam polarization), in reasonable agreement with zero. No evidence of an unknown systematic effect could be found subdividing the data in different ways and, in particular, studying known octant-dependent corrections. Furthermore, the data, when the correct half-wave plate setting was taken into account, were statistically consistent. Therefore, no additional systematic uncertainty was assigned.

The data were then corrected for backgrounds. In these data, backgrounds were mainly due to misidentified electrons which did not create a signal above threshold in the Čerenkov detector. The backgrounds were characterized in special data-taking runs where the electron beam was pulsed at 31 MHz. In these runs, time-of-flight (TOF) spectra for particles (their flight path being from the target to the FPD's) were used as an alternate method to determine the particles' identities. By defining hard cuts on TOF, pure samples of pions and electrons could be defined, which would then be used to characterize Čerenkov performance (see Fig. 2). Particle fluxes could be estimated from two-Gaussian fits to the TOF spectrum. The combination of techniques allowed determination of the pion efficiency and electron contamination for the pion sample.

The CED-FPD pairs in the pion locus were selected by requiring the electron contamination of the pion sample, in a given pair, before background correction, to be below 10%. The resultant average contamination by electrons for the pion locus was 2.6%. This was corrected by appropriately subtracting the measured electron asymmetry in each of the same CED-FPD pairs. (Without the veto provided by the Čerenkov counter, the electron contamination would have been 20%.) The average efficiency for pion identification was  $>99\%$  for pions satisfying the CED-FPD coincidence condition.

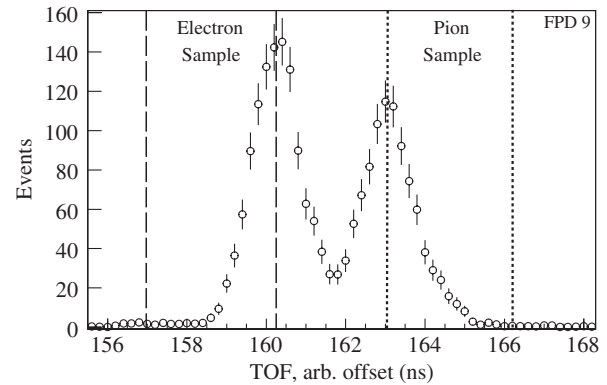


FIG. 2. Sample time-of-flight spectrum (for particles sensed by detector FPD09) during a data-taking run using a pulsed beam. Electrons correspond to the left peak and pions to the right peak. Analysis of the time spectrum in concert with the Čerenkov counter enabled a measurement of the particle identification properties of the Čerenkov counter.

The polarization axis of the electron beam was controlled by a Wien filter in the 5 MeV section of the accelerator. The Wien filter setting was adjusted to optimize the longitudinal polarization in dedicated measurements with the Møller polarimeter in Hall C [8]. The resultant beam, while dominantly polarized in the longitudinal direction, possessed a slight degree of polarization transverse to the direction of propagation, in the bend plane of the accelerator. This in turn resulted in a parity-conserving azimuthal dependence to the asymmetries measured by the experiment, which can be sensed because of the azimuthal segmentation of the detectors into octants.

By adjusting the Wien filter setting, dedicated runs were conducted with the degree of transverse polarization arranged to be as large as possible, so that the sensitivity of the detector to this azimuthal asymmetry could be deduced. The azimuthal asymmetry measured by this technique was sinusoidal in its dependence over octants, with an amplitude of  $\sim 170$  ppm. It is believed that this rather strong azimuthal dependence ultimately results from a sensitivity to the LT interference term seen in parity-conserving pion electroproduction [10], and we intend to study this process in a separate publication.

The luminosity monitors for the experiment [6] were also segmented azimuthally. By comparing the luminosity monitor asymmetry under the transverse and longitudinal Wien filter settings, the degree of transverse polarization in the nominally longitudinal beam was deduced to be  $4.3 \pm 0.2\%$ . Using the azimuthal pion asymmetries determined for transversely polarized beam, and the degree of transverse polarization measured using the luminosity monitors, the pion longitudinal asymmetries could be corrected as a function of octant. The success of this correction in removing the residual azimuthal dependence in the nominally longitudinally polarized electron beam data is displayed graphically in Fig. 3.



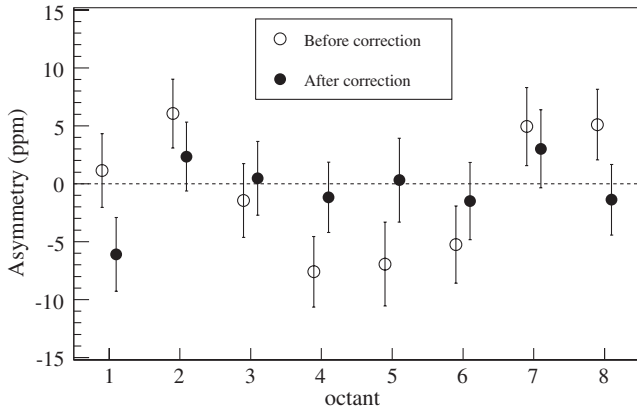


FIG. 3. Measured pion asymmetries before and after correction for the residual transverse polarization in the electron beam. The correction successfully diminishes the sinusoidal variation with octant number from the data, with little impact on the octant-averaged result for the asymmetry, and reduces  $\chi^2/\text{DOF}$  for a fit to a flat line from 3.5 to 1.2.

Backgrounds due to the thin aluminum target windows were 2%. These were not corrected because quasifree production of  $\pi^-$  off neutrons is expected to dominate the asymmetry, and therefore this process should carry the same asymmetry as the deuterium data to well within the precision of the data. Correcting finally for beam polarization results in the measured raw PV asymmetry attributable to inclusive production of  $\pi^-$  off the LD<sub>2</sub> target. The inclusive pion asymmetry including all experimental corrections was  $A_{\text{meas}} = -0.55 \pm 1.03 \pm 0.37$  ppm, where the first uncertainty is statistical, and the second systematic. A list of the systematic uncertainties is presented in Table I.

The measured asymmetry,  $A_{\text{meas}}$ , includes pion fluxes induced by both photoproduction and electroproduction of pions. We desire to extract the photoproduction asymmetry  $A_{\gamma}^-$  that would be induced by incident real photons. The two are related by

$$A_{\text{meas}} = f_{\text{brems}} \langle D(y) \rangle A_{\gamma}^- + f_{\text{virt}} \langle A_e^-(Q^2) \rangle. \quad (2)$$

Here,  $f_{\text{brems}}$  and  $f_{\text{virt}}$  are the fractional fluxes of pions initiated by bremsstrahlung photons and virtual photons (i.e., electroproduction), respectively, ( $f_{\text{brems}} + f_{\text{virt}} = 1$ ). The factor  $D(y)$  is the degree of circular polarization

TABLE I. Systematic uncertainties assigned for the corrections described in the text.

Source	Uncertainty (ppm)
Rate corrections	0.26
Helicity-correlated corrections	0.21
Backgrounds, particle identification	0.12
Residual transverse polarization	0.08
Beam Polarization	0.01

carried by the bremsstrahlung beam [11], relative to the electron beam ( $y$  being the fractional energy carried by the photon). The factor  $A_e^-(Q^2)$  is the asymmetry for electroproduction of pions. According to theoretical expectation [2],  $A_e^-(Q^2)$  is approximately linear in  $Q^2$  for the range of  $Q^2$  dominating this experiment, with the intercept at  $Q^2 = 0$  being equal to  $A_{\gamma}^-$ . We therefore characterized the average  $Q^2$  for the electroproduction events and extrapolate to the photon point. Since the scattered electrons were not detected in coincidence with the scattered pions, for this measurement, we employed simulation techniques to calculate the factors  $f_{\text{virt}}$ ,  $\langle D(y) \rangle$ , and  $\langle Q^2 \rangle$ . Theoretical input was used to constrain the slope of the electroproduction asymmetry with  $Q^2$ .

The simulation was benchmarked by comparing with our measured pion rates, and their distribution in the acceptance of the experiment. The simulation of the detector acceptance was based on the GEANT3 toolkit [12]. Pion absorption in the apparatus was estimated to affect the rate at the percent level, and would not affect the PV asymmetry determination. Physics generators for both bremsstrahlung and virtual-photon induced reactions were developed. The cross sections used in the generators were based on the MAID model of pion production [13], applied to a neutron target. These were further tested by comparing with published extractions of the  $n(\gamma, \pi^-)pp_s$  [14], and found to be in good agreement. Nuclear corrections to the cross section were based on the same reference. Additionally, corrections for Fermi motion were computed by generating a random initial-state neutron momentum according to a parametrization of the nucleon momentum distribution in the deuteron, and were found to smear the pion rates in the detector acceptance. (Possible nuclear corrections to the PV asymmetry were argued to be small in Ref. [1], and therefore we made no correction for such effects.) Particular care was taken in the generation of electroproduction events, where virtual-photon flux formulae valid down to  $Q^2 \sim m_e^2$  were used. This part of the cross section was also compared with analytical formulas [15] over a broad range of kinematics.

The simulation of the pion rate was found to agree with the data to within 15%, generally reproducing trends seen in CED-FPD space. The fraction of events induced by virtual photons was found to be  $f_{\text{virt}} = 0.45 \pm 0.07$ , in good agreement with simple estimates based on the target's radiation length and the effective radiation length for virtual-photon induced reactions. The uncertainty was assigned based on the level of agreement of the simulation with data, and with the simple estimates.

The average  $\langle D(y) \rangle$  was  $0.95 \pm 0.05$ , where the stated uncertainty is systematic. The quantity  $D(y)$  becomes unity as  $y \rightarrow 1$  and for 90% of the simulated events,  $y > 0.7$  corresponding to  $D(y) > 0.9$  [11]. We therefore think the assigned systematic uncertainty is conservative. The

average accepted photon energy was 320 MeV ( $y = 0.89$ ); the average invariant mass of the final-state hadronic system was  $W = 1220$  MeV.

The average  $\langle Q^2 \rangle$  for electroproduction events was determined to be  $0.0032$  (GeV/c) $^2$ . A systematic uncertainty of 10% on  $\langle Q^2 \rangle$  was assigned based on shifts observed in the simulation varying the magnetic field, beam energy, and target position within reasonable ranges. This agreed to the same level of precision with a simple estimate based on the virtual-photon flux factor varying approximately as  $1/Q^2$  and averaging over the permitted electron kinematics. The simulated electroproduction events were heavily weighted towards low  $Q^2$  with 90% of them falling below  $Q^2 = 0.01$  (GeV/c) $^2$ .

The slope of  $A_e^-(Q^2)$  with  $Q^2$  was estimated based on Ref. [2]. The dominant term in the slope is a constant related linearly to  $\sin^2\theta_W$ . The slope was assigned a 14% theoretical uncertainty, which is the full size of the non-resonant and structure-dependent terms in the asymmetry, including the electroweak radiative corrections, calculated in the same reference.

Solving Eq. (2) then yields  $A_\gamma^- = -0.36 \pm 1.06 \pm 0.37 \pm 0.03$  ppm where the third uncertainty is the theory uncertainty explained above. Using Eq. (1) with the values  $C_3^V = 1.6$  and  $\Lambda_\chi = 1$  GeV (from Ref. [2]) then yields  $d_\Delta^- = (8.1 \pm 23.7 \pm 8.3 \pm 0.7)g_\pi$  where  $g_\pi = 3.8 \times 10^{-8}$ . No additional uncertainty was assigned for the interpretation in this particular model.

Our new result means that possible enhancements considered in Ref. [1], proportional to  $V_{ud}/V_{us}$ , are disfavored. The possibility of an unexpectedly large PV asymmetry in pion photoproduction on the  $\Delta$  resonance has been limited to the ppm level.

Results on related parameters in PV inclusive inelastic electron scattering are forthcoming from the G0 experiment [16] and will be related in a separate publication [17]. Measurements being conducted by the  $Q_{\text{weak}}$  experiment [18] will shed light on the inclusive parameter  $d_\Delta$  via PV inclusive inelastic electron scattering at low  $Q^2 \sim 0.027$  (GeV/c) $^2$ .

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