

Measurement of the vector analyzing power in elastic electron-proton scattering as a probe of double photon exchange amplitudes

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We report the first measurement of the vector analyzing power in inclusive transversely polarized elastic electron-proton scattering at $Q^2 = 0.1$ (GeV/c)² and large scattering angles. This quantity should vanish in the single virtual photon exchange, plane wave impulse approximation for this reaction, and can therefore provide information on double photon exchange amplitudes for electromagnetic interactions with hadronic systems. We find a non-zero value of $A = -15.4 \pm 5.4$ ppm. No calculations of this observable for nuclei other than spin 0 have been carried out in these kinematics, and the calculation using the spin orbit interaction from a charged point nucleus of spin 0 cannot describe these data.

13.88.+e, 13.60.Fz, 13.40.-f, 14.20.Dh

The recent development and refinement of experimental methods for measurements of small (few parts per million, or ppm) parity violating effects in polarized electron scattering [1–3] provides a new technique for further studies of the electromagnetic structure of hadrons and nuclei. We have exploited these methods for the first time to measure the small vector analyzing power in elastic electron-proton scattering at large scattering angles ($130^\circ \leq \theta_{lab}^e \leq 170^\circ$), corresponding to $Q^2 = 0.1$ (GeV/c)². This parity conserving quantity is associated with transverse electron polarization, in contrast to the parity violating longitudinal (i.e. helicity dependent) asymmetry. It has been previously noted [4] that transverse polarization effects will be suppressed by the relativistic boost factor $1/\gamma$. Nevertheless, as demonstrated in this Letter, the development of the technology to measure small parity violating asymmetries, along with the ability to produce transversely polarized electron beams

at high energies, now renders these transverse polarization effects amenable to measurement.

The vector analyzing power is a time reversal odd observable which must vanish in first order perturbation theory, and can only arise in leading order from the interference of double photon exchange (second order) and single photon exchange amplitudes. Our observation of this quantity therefore demonstrates the viability of a new technique to access physics associated with the absorption of two virtual photons by a hadronic system. Thus, the study of vector analyzing powers provides another method to study double photon exchange processes that is complementary to virtual compton scattering (VCS). VCS involves the coupling of one virtual and one real photon to a hadronic system, but in practice includes problematic Bethe-Heitler amplitudes associated with radiation of a real photon from the electron. Nonetheless, there is presently a great deal of interest in

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the exploitation of VCS [5] to further probe the electromagnetic structure of hadrons and nuclei, and the vector analyzing power described here potentially offers an attractive alternative to access double photon exchange amplitudes.

Using the apparatus for the SAMPLE experiment [1,6], a high statistics measurement of the parity violating asymmetry in inclusive elastic $p(\vec{e}, e')$ scattering at the MIT/Bates Linear Accelerator Center, we have made measurements of the asymmetry in the elastic scattering of 200 MeV transversely polarized electrons from the proton at backward scattering angles. This represents the first measurement of a vector analyzing power in polarized electron scattering from the proton at this high a momentum transfer.

The vector analyzing power in electron-nucleus scattering results in a spin-dependent asymmetry, which can, for example, be generated by the interaction of the electron spin with the magnetic field seen by the electron in its rest frame [7]. This spin-dependence in the scattering cross section $\sigma(\theta)$, can be written as [8,9]

$$\sigma(\theta) = \sigma_0(\theta)[1 + A(\theta)\mathbf{P} \cdot \hat{\mathbf{n}}], \quad (1)$$

where $\sigma_0(\theta)$ is the spin-averaged scattering cross section, $A(\theta)$ is the vector analyzing power for the reaction, and \mathbf{P} is the incident electron polarization vector (which is proportional to the spin vector operator \mathbf{S}). The unit vector $\hat{\mathbf{n}}$ is normal to the scattering plane, and is defined through $\hat{\mathbf{n}} \equiv (\mathbf{k} \times \mathbf{k}')/|\mathbf{k} \times \mathbf{k}'|$, where \mathbf{k} and \mathbf{k}' are wave vectors for the incident and scattered electrons, respectively. The scattering angle θ is found through $\cos \theta = (\mathbf{k} \cdot \mathbf{k}')/|\mathbf{k}||\mathbf{k}'|$, and, in the Madison convention, is positive for the electron scattering toward the same direction as the transverse component of \mathbf{k}' . The beam polarization \mathbf{P} can be expressed in terms of the number of beam electrons with spins parallel ($m_s=+1/2$) and antiparallel ($m_s=-1/2$) to $\hat{\mathbf{n}}$, so that the measured asymmetry at a given scattering angle $\epsilon(\theta)$, is defined through

$$\epsilon(\theta) = \frac{\sigma_{\uparrow}(\theta) - \sigma_{\downarrow}(\theta)}{\sigma_{\uparrow}(\theta) + \sigma_{\downarrow}(\theta)} = A(\theta)\langle P \rangle, \quad (2)$$

where $\sigma_{\uparrow, \downarrow}(\theta)$ is the differential cross section for $m_s = +1/2$ and $-1/2$, respectively. Thus, with knowledge of the magnitude of the incident beam polarization $\langle P \rangle$, measurement of $\epsilon(\theta)$ can yield a determination of the vector analyzing power $A(\theta)$, which contains the underlying physics of the electron-nucleus interaction.

The formalism and conventions reviewed here have been well established, and used extensively for ‘‘Mott’’ polarimeters which measure electron beam polarizations at low incident beam energies (~ 100 keV) [7], where it is valid to assume the nucleus is simply a point charge. The ‘‘Mott’’ asymmetry for transversely polarized electrons scattering from a point nucleus of charge Ze and spin 0 is calculated as [10],

$$A_{Mott} = -\frac{4Z\alpha\beta}{\gamma} \left(\frac{\csc \theta \ln(\csc \frac{\theta}{2})}{\csc^4 \frac{\theta}{2} - \beta^2 \csc^2 \frac{\theta}{2}} \right), \quad (3)$$

where α is the electromagnetic fine structure constant, β and γ are the usual relativistic kinematic quantities, and θ is the laboratory scattering angle defined above. The analyzing powers calculated via Eq. (3) for low energies using very high Z targets are much larger than the vector analyzing power for electron proton scattering reported here, and this is commonly exploited as a means to measure the polarization of low energy electron beams. Such measurements, however, are not sensitive to the internal structure or spin of the hadronic system. More recently, some level of nuclear structure has been taken into account in calculations of analyzing powers for high energy elastic scattering of transversely polarized electrons from heavy spin 0 nuclei at forward electron scattering angles, performed in the eikonal expansion and using finite charge densities for the nuclei [11]. In these calculations, the non-zero analyzing powers were generated through the distortion of the electron waves in the Coulomb potential of the nuclear targets, providing the needed extension beyond single photon exchange to the distorted wave impulse approximation. To date, however, no such calculation exists for the scattering of transversely polarized electrons from nuclear targets of any spin other than 0 at any energy. In the SAMPLE kinematics, the electron energy of 200 MeV is much larger than the energies used for Mott polarimetry, the proton target has the smallest possible Z so that Coulomb effects are at a minimum, and the electrons are scattered at large angles where magnetic effects are important. These facts, along with the spin 1/2 nature of the proton, imply that our measurement of the vector analyzing power will be sensitive to non-trivial electromagnetic structure of the proton not taken into account in previous theoretical treatments.

The data we report are the result of an experiment performed at the MIT/Bates Linear Accelerator Center with a 200 MeV polarized electron beam of average current $40 \mu\text{A}$ incident on a 40 cm liquid hydrogen target [12]. The scattered electrons were detected in a large solid angle (~ 1.5 sr), axially symmetric air Čerenkov detector consisting of 10 mirrors, each shaped to focus the Čerenkov light onto one of ten shielded photomultiplier tubes. This combination of large solid angle and high luminosity allow measurements of small asymmetries in a relatively short period of time. The data presented here were acquired in just two days of running under these conditions. Properties of the detector signals and beam have been described in detail in Ref.’s [1] and [6], along with the method of asymmetry extraction and correction. Thus, here we report only the differences between the experimental running conditions for longitudinally polarized beams as used for parity violation measurements, and the transversely polarized beam used for the vector

analyzing power measurements. The systematic errors associated with the asymmetries from each of the individual mirrors are the same for these measurements as for those in Ref.'s [1] and [6], totaling 0.7 ppm, and are negligible compared with the overall statistical error of 5.4 ppm obtained for these measurements.

The polarized laser light used on the bulk GaAs source crystal produces electron beams with longitudinal polarization, consequently significant spin manipulation was required to orient the beam polarization transversely. This was achieved with a Wien filter, which contains electric and magnetic fields oriented perpendicular to each other and to the beam direction, and a set of beam solenoids. The Wien filter was positioned immediately downstream of the source anode, and was used to precess the electron spin away from the beam direction ($\sim 90^\circ$ for these measurements). The beam solenoids were positioned near the first accelerating cavity in the beam line, and precessed the resulting transverse components of the beam polarization. The combination of these beam line elements allowed the polarization direction to be chosen arbitrarily, and each element was calibrated such that the polarization direction is determined to $\pm 2^\circ$ [13].

For the measurements reported here, two orthogonal transverse beam polarizations were used during two running periods: one with the polarization directed to beam right (which we denote $\Phi=0$), and one with the polarization pointing up ($\Phi=90$). The magnitude of the beam polarization was measured with a Moller apparatus positioned on the beam line, and averaged $36.3 \pm 1.8\%$ during these measurements. Finally, to minimize false asymmetries and test for systematic errors, the electron beam polarization was manually reversed relative to all electronic signals, for both $\Phi=0$ and $\Phi=90$ running, with the insertion of a $\lambda/2$ plate in the laser beam. Thus, four separate sets of measurements were made: $\Phi=0$, $\lambda/2$ IN and OUT, and $\Phi=90$, $\lambda/2$ IN and OUT.

The elastic scattering transverse asymmetry was determined for each of the 10 individual mirrors in each running configuration after correction for all effects, including beam polarization, background dilution, and radiative effects, as described in Ref.'s [1] and [6]. Although the geometry of this detector allowed for combining the asymmetries from individual mirrors positioned on opposite sides of the incident beam (via Eq. (2) and imposing the rotational invariance criterion $A(\theta) = -A(-\theta)$ [9]), we chose an alternative form of analysis wherein the full statistical information contained in the data set could be used to extract the vector analyzing power. Because the individual mirrors were positioned at varying azimuthal angles ϕ relative to the polarization direction, the asymmetries measured in the mirrors should follow a sinusoidal dependence in this angle. The sinusoidal dependence in the azimuthal angle ϕ is seen by rewriting Eq. (2) as

$$\epsilon(\theta, \phi) = A(\theta)P \sin(\phi + \delta), \quad (4)$$

where ϕ measures the angle of the polarization vector in the plane transverse to the beam direction, and the phase δ takes into account the direction of \mathbf{P} relative to $\hat{\mathbf{n}}$. Table 1 summarizes the polar (θ) and azimuthal (ϕ) angles at the center of each individual mirror within the SAMPLE detector. As seen in Table 1, mirrors 4 and 5 have the same azimuthal angle relative to the polarization direction, but different polar angles relative to the incident beam direction. A separate analysis, however, indicated that the polar angle dependence to the asymmetry was negligible, allowing us to combine the asymmetries from these two mirrors (similarly for mirrors 6 and 7) into one asymmetry at the same azimuthal angle ϕ .

The data set for each Φ and $\lambda/2$ running configuration therefore consists of eight data points at varying ϕ values, to which we perform a χ^2 minimization to a two parameter function via

$$\chi_{d.o.f.}^2 = \frac{1}{6} \sum_{i=1}^8 [A_i^{meas} - (a \sin \phi_i + b \cos \phi_i)]^2 / [\delta A_i^{meas}]^2, \quad (5)$$

which is linear in the coefficients a and b . Here A_i^{meas} is the measured asymmetry at each azimuthal angle ϕ_i , corrected for all effects [1,6] including beam polarization normalization (as suggested in Eq. (4)). The coefficients a and b can then be converted into an amplitude and phase, i.e.,

$$A_{fit} = A \sin(\phi + \delta) \quad (6)$$

as in Eq. (4), where the amplitude A gives the magnitude of the vector analyzing power, and the phase δ verifies the direction of the beam polarization and determines the overall sign of the analyzing power.

The sinusoidal dependence just discussed is illustrated in Fig. 1, where the combined data for $\Phi = 0$ and $\Phi = 90$ are shown as a function of azimuthal angle, along with the best fit to the data according to the procedure outlined above. Here we have defined $\phi = 0$ to be at beam left, and have taken into account the 90° phase difference between the $\Phi = 0$ and $\Phi = 90$ polarization directions. For these combined data, the overall χ^2 per degree of freedom for the best fit was found to be 0.9, providing a 50% confidence level that the data follow this dependence [14]. This should be compared, however, with the χ^2 per degree of freedom of 2.1 for a fit to $A = 0$, which has a corresponding confidence level of 4% that the data are consistent with $A = 0$. Even if we allow an overall offset to a constant dependence, we find an average of $A = 3.5 \pm 3.7$ ppm, with a χ^2 per degree of freedom of 1.9, and a corresponding confidence level of 7%.

In Table 2 we summarize our results using this analysis procedure for the four independent running condi-

tions. Note that the deduced magnitudes are all consistent within experimental errors, and the deduced phase changes by 180° upon the insertion or removal of the $\lambda/2$ plate as expected, and by 90° from one Φ running configuration to the other. Combining these four independent measurements, we quote our final result: a vector analyzing power for elastic electron-proton scattering of -15.4 ± 5.4 ppm at the average electron laboratory scattering angle of 146.1° , corresponding to $Q^2 = 0.1$ (GeV/c) 2 . To demonstrate the precision to which this quantity has been determined relative to the original derivation of Mott [10], we plot this data point in Fig. 2 along with the prediction of Eq. (3) for a point nucleus of charge $Z = 1$ and spin 0 as a function of electron laboratory scattering angle, covering the angular range accepted by the SAMPLE detector.

The data reported here represent the first measurement of a vector analyzing power in polarized electron scattering at this high a momentum transfer. Our observation of this quantity demonstrates the viability of a new technique to access physics associated with double photon exchange, which may address some of the same physics issues as virtual Compton scattering measurements. We have also made measurements of the vector analyzing power in inclusive quasielastic electron-deuteron scattering, the results of which will be reported in a future letter. Further parity violation measurements at higher Q^2 values are planned [15] from both hydrogen and deuterium targets, where high statistics transverse asymmetry data will also be taken. Thus, we hope that the results reported in this Letter will motivate theoretical calculations of vector analyzing powers in polarized electron scattering for hadronic systems with $S \neq 0$ and non-trivial electromagnetic structure, which will be necessary to interpret such measurements.

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larized Electron Scattering, B. Frois and M.-A. Bouchiat (ed.'s) World Scientific, Singapore, 423 (1999).

- [4] T.W. Donnelly and A.S. Raskin, *Ann. Phys.* **169**, 247 (1986).
- [5] P.A.M. Guichon and M. Vanderhaeghen, *Prog. Part. Nucl. Phys.* **41**, 125 (1998).
- [6] B. Mueller *et al.*, *Phys. Rev. Lett.* **78**, 3824 (1997).
- [7] T.J. Gay and F.B. Dunning, *Rev. Sci. Instrum.* **63**, 1635 (1992), and references therein.
- [8] J. Kessler, *Polarized Electrons*, 2nd ed. (Springer, Berlin, 1985).
- [9] G. G. Ohlsen, *Rep. Prog. Phys.*, **35**, 717 (1972).
- [10] N.F. Mott, *Proc. Roy. Soc. (London)* **A135**, 429 (1932).
- [11] E.L. Kronenberg, Ph.D. Thesis, MIT, 1989, unpublished.
- [12] E.J. Beise *et al.*, *Nucl. Inst. and Meth.* **A378**, 383 (1996).
- [13] M. Pitt *et al.*, *Proceedings of The 12th International Symposium on High-Energy Spin Physics (SPIN96)*, (World Scientific, 1996), ed. C.W. de Jager *et al.*, p. 813.
- [14] *Review of Particle Properties*, *Phys. Rev.* **D50**, 1173 (1994).
- [15] JLab Experiment E91-017, "G0", (D. Beck spokesperson).

Mirror	θ (deg.)	ϕ (deg.)
1	146	135
2	154	90
3	146	45
4	138	180
5	161	180
6	161	0
7	138	0
8	146	225
9	154	270
10	146	315

TABLE I. Polar (θ) and azimuthal (ϕ) angles of each individual mirror within the SAMPLE detector.

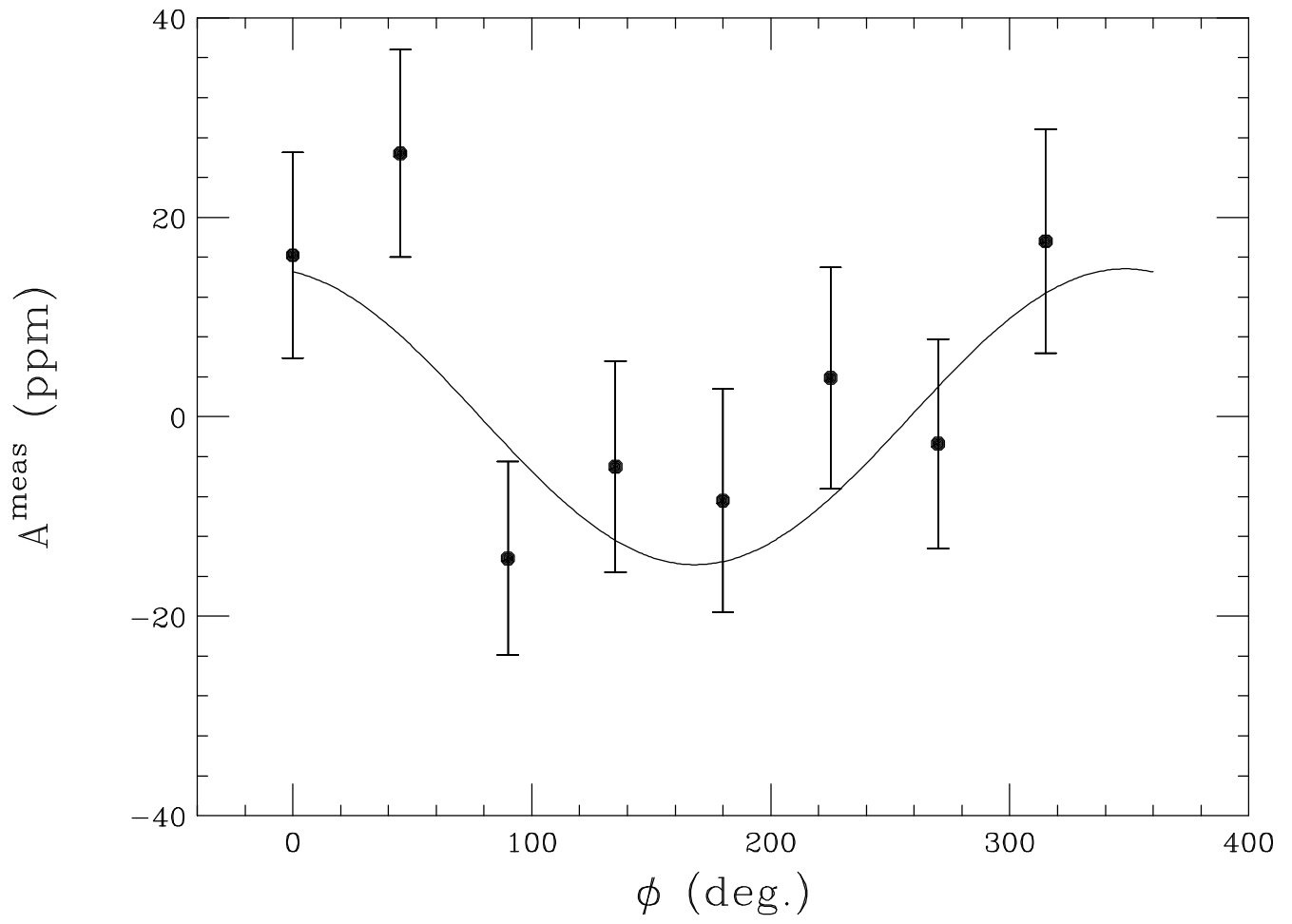
Φ	$\lambda/2$	A (ppm)	δ (deg.)	$\chi_{d.o.f.}^2$
0	IN	12.9 ± 9.8	173.8 ± 39.5	1.30
0	OUT	13.8 ± 9.9	16.9 ± 39.5	1.50
90	IN	18.4 ± 11.8	-84.1 ± 39.8	0.30
90	OUT	18.1 ± 11.7	127.2 ± 38.0	2.07

TABLE II. Results of the fitting procedure described in the text.

- [1] D.T. Spayde *et al.*, (SAMPLE Collaboration), *Phys. Rev. Lett.* **84**, 1106 (2000).
- [2] K.A. Aniol *et al.*, (HAPPEX Collaboration), *Phys. Rev. Lett.* **82**, 1096 (1999).
- [3] R.D. McKeown, in *Parity Violation in Atoms and Po-*

FIG. 1. Plot of the measured asymmetry, corrected for all effects including beam polarization, background dilution, and radiative effects, as a function of azimuthal scattering angle ϕ for the combined data of all four running configurations as described in the text. The curve represents the best fit to the data according to Eq. (5).

FIG. 2. Plot of the measured vector analyzing power in elastic electron-proton scattering in the SAMPLE kinematics, along with the prediction of the original Mott derivation [10], given in Eq. (3).



Vector Analyzing Power

