Measurement of the Transverse Beam Asymmetry for Elastic Scattering for Selected Nuclei


(HAPPEX Collaboration)

1Argonne National Laboratory, Argonne, Illinois 60439, USA
2California State University, Los Angeles, Los Angeles, California 90032, USA
3Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
4CEA Saclay, DAPNIA/SPbN, F-91191 Gif-sur-Yvette, France
5China Institute of Atomic Energy, Beijing 102413, China
6Clermont Université, Université Blaise Pascal, CNRS/IN2P3, Laboratoire de Physique Corpusculaire, FR-63000 Clermont-Ferrand, France
7College of William and Mary, Williamsburg, Virginia 23187, USA
8Christopher Newport University, Newport News, Virginia 23606, USA
9Duke University, TUNL, Durham, North Carolina, 27706, USA
10Florida International University, Miami, Florida 33199, USA
11Hampton University, Hampton, Virginia 23668, USA
12Harvard University, Cambridge, Massachusetts 02138, USA
13INFN, Sezione di Bari and University of Bari, I-70126 Bari, Italy
14INFN, Dip. di Fisica dell’Univ. di Catania, I-95123 Catania, Italy
15INFN, Sezione di Roma, I-00161 Rome, Italy
16INFN, Sezione di Roma, gruppo Sanità, I-00161 Rome, Italy
17Istituto Sperimentale di Sanità I-00161 Rome, Italy
18Indiana University, Bloomington, Indiana 47405, USA
19Institut Jozef Stefan, 3000 SI-1001 Ljubljana, Slovenia
20Institut Jozef Stefan Institute, 1000 Ljubljana, Slovenia
21Kent State University, Kent, Ohio 44242, USA
22Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine
23Laboratoire de Physique Corpusculaire, Clermont-Ferrand Campus des Cézeaux, 63171 Aubière Cedex, France
24Laboratoire de Physique Subatomique et de Cosmologie, 38026 Grenoble, France
25Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
26Longwood University, Farmville, Virginia 23909, USA
We have made measurements of the beam-normal single-spin asymmetry in the elastic scattering of transversely polarized electrons from $^4$He and for the first time on $^4$He, $^{12}$C, and $^{208}$Pb. The asymmetry is a probe of the imaginary part of the two photon exchange amplitude. For $^4$He and $^{12}$C, the results are in qualitative agreement with calculations including inelastic hadronic intermediate states. Surprisingly, for $^{208}$Pb, our result for the asymmetry is consistent with zero.


Traditionally, electron scattering has been analyzed in terms of the one boson (photon or Z) exchange approximation. For heavy nuclei, distorted plane waves, based on solutions to the Dirac equation in the strong electric field of the nucleus, are also required to describe the data. Recently, the inclusion of the exchange of one or more additional photons has been necessary for the interpretation of some precision data. The classic example is the discrepancy in the ratio of the elastic form factors for the proton, $G_E/G_M$, based on whether a Rosenbluth separation or spin transfer method is used [1]. Calculations including two-photon exchange provide a plausible explanation for the difference [2]. Another example is corrections to the parity-violating asymmetry $A_{PV}$ in $e - p$ elastic scattering, which provides a measurement of the weak charge of the proton and serves as a sensitive test of the Standard Model of electroweak interactions. For interpreting $A_{PV}$, $\gamma-Z$ box diagrams are important [3].

The effect of the extra boson is relatively small on the measured cross section or asymmetry for the above examples. (The effect on the ratio $G_E/G_M$ is quite large because the cross section depends weakly on $G_E$.) The beam-normal spin-asymmetry for elastic scattering, $A_n$, is dominated by two-$\gamma$ exchange at beam energies above about 1 GeV. Several measurements of $A_n$ for the proton have been reported [4–7] Several theoretical papers compute values of $A_n$ that are in qualitative agreement with the data when they include the effects of inelastic intermediate hadronic states [8–11].

Studying the transverse asymmetry $A_n$ is a good way to probe radiative corrections, because time reversal symmetry ensures that $A_n$ is zero in first Born approximation. Furthermore measuring $A_n$ from nuclei with a range of charge $Z$ should allow one to separate Coulomb distortion effects that depend strongly on $Z$ from dispersion contributions that may be less sensitive to $Z$. Afanasev et al. [2] and Gorchtein et al [12] have calculated $A_n$, in a two-photon exchange approximation, but including a full range of intermediate excited states. Gorchtein et al. predict that $A_n$ scales roughly as the ratio of mass number $A$ to $Z$ and is not strongly $Z$ dependent. In contrast Cooper et al. [13] calculate Coulomb distortion effects and work to all orders in photon exchanges by numerically solving the Dirac equation. However they only consider elastic intermediate states. Cooper et al. [13] also finds that elastic intermediate state contributions, while in general small, increase very strongly with increasing $Z$. To predict $A_n$ for nuclear targets, Afanasev used a unitary-based model [11] with total photoproduction cross section and the Compton t-slope as input; his results for $^4$He shown in ref [11] are the same order of magnitude as the value of $A_n$ reported in this paper.
Unfortunately, there is not yet a calculation of \( A_{PV} \) that includes both Coulomb distortion effects and a full range of excited intermediate states. In this case, measuring \( A_{PV} \) as a function of \( Z \) should reveal the role of Coulomb distortions and motivate more detailed calculations. To this end, in this Letter, we report data on the beam-normal spin-asymmetry \( A_n \) on the targets H, \(^3\)He, \(^{12}\)C, and \(^{208}\)Pb.

To observe the beam-normal single-spin asymmetry, the spin vector of the beam \( \vec{P}_e \) must have a component normal to the scattering plane defined by the vector \( k = \vec{k}_e \times \vec{k}_{out} \), where \( \vec{k}_e \) is the beam momentum vector and \( \vec{k}_{out} \) is the momentum of the scattered electron. The measured beam-normal single-spin asymmetry is then defined as \( A_n^m = (\sigma_\uparrow - \sigma_\downarrow) / (\sigma_\uparrow + \sigma_\downarrow) \) where \( \sigma_\uparrow(\downarrow) \) is the cross section for beam electron spin parallel(anti-parallel) to \( k \). The measured asymmetry \( A_n^m \) is related to \( A_n \) by

\[
A_n^m = A_n \cdot \vec{P}_e \cdot \hat{k} \quad (1)
\]

We define \( \phi \) to be the angle between \( \hat{k} \) and \( \vec{P}_e \), i.e. \( \cos \phi = P_e \cdot \hat{k} / |P_e| \).

The measurements were carried out in Hall A at the Thomas Jefferson National Accelerator Facility. The data were obtained as a part of a study of systematic errors for three experiments designed to measure the parity-violating longitudinal asymmetry \( A_{PV} \) in elastic electron scattering. The transverse asymmetry \( A_n \) can induce a false longitudinal asymmetry \( A_{PV} \) during the longitudinal measurement if the beam polarization has transverse components and the apparatus lacks perfect symmetry. The only experimental difference between the \( A_n \) and \( A_{PV} \) measurements is that the injector for the accelerator is set up to deliver vertical transverse or longitudinal spin direction at the target.

The data were obtained in 2004 for the H and \(^3\)He targets and in 2010 for the \(^{12}\)C and \(^{208}\)Pb targets. The first two targets were used to measure \( A_{PV} \) in order to determine the strange form factors in the nucleon [14, 15]. The 2010 run made a measurement of \( A_{PV} \) in \(^{208}\)Pb in order to determine the radius of the distribution of neutrons [16, 17]. For the latter experiment, test data were also obtained with a \(^{12}\)C target. The scattering angle for each experiment was on the order of 5°. The beam energy was about 3 GeV for the 2004 data and 1 GeV for the 2010 data. The exact kinematics for each target is given in Table I.

With the exception of the \(^{12}\)C target, heating from the \(^3\)He targets and in 2010 for the \(^{12}\)C and \(^{208}\)Pb targets. The high pressure \(^3\)He targets featured rapid vertical flow of the fluid. In addition, the beam was rastered over a 4 mm square for all targets. The 0.55 mm thick isotopically pure \(^{208}\)Pb target was sandwiched between two 150 \( \mu \)m diamond foils, and the edges were cooled with the cold helium.

Electrons elastically scattered from the targets were focused onto detectors in the focal plane of the Hall A High Resolution Spectrometers. The entrances to the two spectrometers are symmetric about a horizontal plane, and since the beam polarization was vertical transverse, the beam-normal asymmetry is at the maximum and minimum of the sine function and has opposite signs in the spectrometers. The resolution of the spectrometers was sufficient so that essentially only elastic events were accepted.

The detectors had to withstand the radiation damage caused by the high signal flux and also provide a uniform response to the electrons so that integrating the signals did not increase the noise. For the 1 GeV data, each spectrometer had two 3.5 cm by 14 cm quartz detectors oriented at 45° to the direction to the electrons in the spectrometer, one in front that was 5 mm thick and one behind that was 1 cm thick. This geometry was a compromise between maximizing light output and minimizing large signals due to electromagnetic showers in the detector. Light from each quartz bar was collected by air light guides and detected by 2-inch quartz photomultipliers. For the 3 GeV detector data, a five-layer sandwich of quartz and brass provided sufficient energy resolution.

The polarized electron beam originated from a GaAs photocathode illuminated by circularly polarized light [18]. The direction of the polarization could be controlled by a Wien filter and solenoidal lenses near the injector. The accelerated beam was directed into Hall A, where its intensity, energy and trajectory on target were inferred from the response of several monitoring devices. By reversing the sign of the laser circular polarization, the direction of the spin at the target could be reversed rapidly [19].

The beam monitors, target, detector components and the electronics were designed so that the fluctuations in the fractional difference in the PMT response between a pair of successive windows was dominated by scattered electron counting statistics for rates up to 1 GHz. This facilitated \( A_{PV} \) measurements with statistical uncertainty as small as 100 parts per billion (ppb) in a reasonable length of time. To keep spurious beam-induced asymmetries under control at this level, careful attention was given to the design and configuration of the laser optics leading to the photocathode.

The pattern of spin-reversal was selected pseudo-randomly at 30 Hz for the 3 GeV data and 240 Hz for the 1 GeV data. The dominant noise in \( A_{raw} \) at 240 Hz was pick-up from 60 Hz line noise. By combining quadruplets of windows with the pattern either \( + - - + \) or \( - + + - \), this source of noise was eliminated. The sequence of these patterns was chosen with a pseudo-random number generator.

Each period of constant spin direction is referred to
as a “window”. The integrated response of each detector PMT and beam monitor was digitized by an ADC and recorded for each window. Loose requirements were imposed on beam quality, removing periods of beam intensity, position, or energy instability. This left about 75% of the data sample for further analysis. No spin-direction-dependent cuts were applied.

The right-left spin-direction asymmetry in the integrated detector response, normalized to the beam intensity, was computed for each window pair to form the raw asymmetry $A_{\text{raw}}$ in each spectrometer arm.

The dominant source of noise due to the beam fluctuations arose from position fluctuations in the horizontal beam position monitors. The correction was asymmetry, was computed for each window pair to form the raw detector response, normalized to the beam intensity, position, or energy instability. This left about 5% of the beam quality, removing periods of beam instability.

Jitter in the beam energy or noise in the beam current monitors, which contribute to noise in $A_{PV}$, largely cancel. On the other hand, jitter in the beam energy or noise in the beam current monitors, which contribute to noise in $A_{PV}$, largely cancel. In a measurement of $A_n$.

As explained in detail in [14–16], noise from beam jitter was reduced by using the data $\Delta x_i$ from precision beam position monitors. The correction was $A_{\text{beam}} = \sum c_i \Delta x_i$. The $c_i$ were measured several times each hour from calibration data in which the beam was modulated by using steering coils and an accelerating cavity. The largest of these sensitivities $c_i$ was for $^{208}$Pb and was on the order of 50 ppb/nm. The noise in the resulting $A_{\text{beam}} - A_{\text{raw}}$ was small and dominated by counting statistics. For example, for $^{208}$Pb, which had the highest rate of our targets, this corresponding to a rate of about 1GHz at 75 $\mu$A.

A half-wave ($\lambda/2$) plate was periodically inserted into the laser optical path which passively reversed the sign of the electron beam polarization. Roughly equal statistics were thus accumulated with opposite signs for the measured asymmetry, which suppressed many systematic effects. About one day was spent on each target.

The values of $A_n^m$ were consistent from run to run as shown in Figure 1. The asymmetries in each arm of the HRS were opposite. Under the reversals, the absolute values of $A_n^m$ are consistent within statistical errors. The reduced $\chi^2$ for $A_n^m$ run averages is close to one in every case. The average corrections due to systematic spin-reversal-correlated differences in beam parameters were small.

The physics asymmetry $A_n$ is formed from $A_n^m$ by correcting for the beam polarization $P_b$, average value of $\cos \phi$ as given in table I, and subtractions from the Al windows in the cryotargets and the diamond surrounding the lead.

Nonlinearity in the PMT response was limited to 0.1% in bench-tests that mimicked running conditions. The total relative nonlinearity between the PMT response and those of the beam intensity monitors was limited to 1.5% by studies. The acceptance correction $K$ accounted for the non-linear dependence of the asymmetry with $Q^2$.

### Table I: Kinematic values for the various targets.

<table>
<thead>
<tr>
<th>Target</th>
<th>H</th>
<th>$^4$He</th>
<th>$^{12}$C</th>
<th>$^{208}$Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>6°</td>
<td>6°</td>
<td>5°</td>
<td>5°</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>0.099</td>
<td>0.077</td>
<td>0.099</td>
<td>0.009</td>
</tr>
<tr>
<td>$E_b$(GeV)</td>
<td>3.0</td>
<td>2.75</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\langle \cos \phi \rangle$</td>
<td>0.968</td>
<td>0.967</td>
<td>0.963</td>
<td>0.967</td>
</tr>
</tbody>
</table>

### Table II: Errors (in ppm) for the various targets.

<table>
<thead>
<tr>
<th>Target</th>
<th>H</th>
<th>$^4$He</th>
<th>$^{12}$C</th>
<th>$^{208}$Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>False asymmetry</td>
<td>0.14</td>
<td>0.11</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>0.17</td>
<td>0.30</td>
<td>0.08</td>
<td>0.003</td>
</tr>
<tr>
<td>Linearity</td>
<td>0.07</td>
<td>0.14</td>
<td>0.06</td>
<td>0.004</td>
</tr>
<tr>
<td>Target Windows</td>
<td>0.06</td>
<td>0.13</td>
<td>0.00</td>
<td>0.002</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>0.24</td>
<td>0.37</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
<td>Statistical</td>
<td>1.47</td>
<td>1.34</td>
<td>0.36</td>
<td>0.21</td>
</tr>
</tbody>
</table>

### Table III: Beam-normal single-spin asymmetry $A_n$ and the Invariant Asymmetry $A_n$ (eqn. 2) for the four nuclei. This is plotted in Fig. 2.
of this prediction. On the other hand, the small value
plot the quantity \( \hat{A} \) of \( \hat{A} \) for the
FIG. 2: The Invariant Asymmetry \( \hat{A} \) for H, He, C
and Pb.

\[ A_{n}^{Pb} = +0.28 \pm 0.21\, \text{stat} \pm 0.14\, \text{syst ppm}. \]

For H, our number is consistent with the measurement
given in reference [5] for the same \( Q^2 \) but at the lower
beam energy of 0.85 GeV.

In order to focus on the dependence of \( A_{n} \) on the
nucleus, we note that in our kinematic range, the calculations
in reference [12] scale approximately with \( Z, A, \) and
\( Q^2 \) as

\[ A_{n} = \hat{A}_{n} \frac{Q A}{Z} \]

(2)

w where \( \hat{A}_{n} \) is approximately constant. In Figure 2, we
plot the quantity \( \hat{A}_{n} \) extracted from our data. The values
of \( \hat{A}_{n} \) for H, \(^4\)He, and \(^{12}\)C are all in qualitative
agreement with this prediction. On the other hand, the small value
of \( A_{n} \) for \(^{208}\)Pb is quite surprising.

In conclusion, we find that \( A_{n} \) for H, \(^4\)He, and \(^{12}\)C
agree qualitatively with the calculations of reference [12].
These calculations include a dispersion integral over inter-
mediate excited states. However, they are only good
to order \( \alpha^2 \) (two-photon exchange) and neglect Coulomb
distortions. In contrast we find that \( A_{n} \) for \(^{208}\)Pb is very
small and disagrees completely with previous theoreti-
cal calculations. This result for \(^{208}\)Pb could be due to
the effects of Coulomb distortions. These were shown
in reference [13] to grow rapidly with \( Z \) and should be
important for the highly charged \(^{208}\)Pb nucleus. If so,
the large difference in \( A_{n} \) between \(^{208}\)Pb and \(^{12}\)C may
be a “three-photon exchange” observable. It is not pre-
dicted by two-photon exchange calculations and may re-
quire Coulomb distortions involving the third (or more)
photon. In future work, one should calculate \( A_{n} \) includ-
ing both Coulomb distortions and a range of excited in-
termediate states and measure \( A_{n} \) for a number of nuclei
with \( Z \) intermediate between \(^{12}\)C and \(^{208}\)Pb.

We wish to thank the entire staff of JLab for their
efforts to develop and maintain the polarized beam
and the experimental apparatus. This work was sup-
ported by DOE contract DE-AC05-84ER40150 Modification
No. M175, under which the Southeastern Universi-
ties Research Association (SURA) operates JLab, and by
the Department of Energy, the National Science Foun-
dation, the INFN (Italy), and the Commissariat à l’Énergie
Atomique (France).

---

\* now at Technische Universitaet Muenchen, Excellence
Cluster Universe, Garching b. Muenchen, Germany
\( \dagger \) Deceased
\dagger now at Thomas Jefferson National Accelerator Facility,
Newport News, Virginia 23606, USA
\( \ddagger \) now at Ohio University, Athens, Ohio 45701, USA
\* Electronic address: souder@physics.syr.edu

C. Chen, M. Vanderhaeghen, Phys. Rev. D72, 013008
(2005).
(2007).
(2004).
(2004).
(2008).


