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Parity Nonconservation in Proton Scattering at Higher Energies*

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Abstract

A parity-nonconservation experiment in the scattering of longitudinally-polarized protons at an incident proton momentum of 6 GeV/c is examined. This experiment indicates a sharp rise with energy of the total cross section correlated with proton helicity that was unexpected. This energy dependence is due to the strong part of the interaction and may indicate the role of a diquark component in the nucleon. New experiments at higher energies are needed to confirm such a model. Future experiments can benefit from an analysis of sources of systematic error that have been encountered in the experiment discussed here.

1 Introduction

The first experiments [1] to search for parity nonconservation in proton scattering at higher energies used double-scattering or triple-scattering geometries. This technique was limited to a precision of $\sim 10^{-3}$. A new generation of experiments began in 1972 with a proposal to measure the helicity dependence of the transmission of 1.5-GeV/c longitudinally-polarized protons through an unpolarized target [2]. An interference between the strong amplitude and the parity-nonconserving weak amplitude is expected to produce a longitudinal asymmetry $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ at the level of 10^{-7}, where $\sigma_+(\sigma_-)$ is the total cross section for positive (negative) helicity protons.

Each experiment in the current generation has taken several years to reach the required level of precision. When a 6-GeV/c polarized beam became available at the Argonne ZGS, an experiment was started in 1974 and ended when the ZGS was closed in 1979. This experiment, together with experiments at 13.6 MeV [3], 15 MeV [4], 45 MeV [5], and 800 MeV [6] sample the energy dependence of A_L. A common theme of all these experiments is the identification and suppression of sources of systematic error. This paper will discuss the ZGS experiment in detail. The lessons learned from previous experiments can be applied to future experiments at comparable or higher energies.

2 Theoretical and Experimental Background

When comparing experimental values of A_L with theoretical predictions, there is a contrast between the situation at low energies and at high energies. Measurements [3–5] of A_L at 13.6, 15, and 45 MeV on hydrogen yield results in reasonable agreement with theoretical predictions based on a meson-exchange model [7] and a hybrid quark model [8]. (See Fig. 1.)

On the other hand, the experiment [9] with 6-GeV/c protons on a H_2O target has reported a value of $A_L = (26.5 \pm 6.0) \times 10^{-7}$, which is much larger than expected from calculations made prior to the

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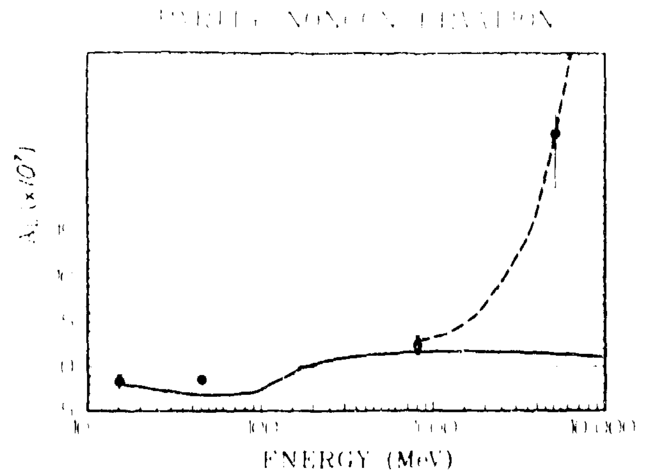

Figure 1: Measured values of A_L versus energy. The solid curve is a generic meson-exchange calculation and the dashed curve is the model of Ref. [14].

experiment [10]. Later calculations using meson exchange [11], the multi-peripheral model [12], or heavy boson exchange [13] have confirmed the prediction of $A_L \sim 1.0 \times 10^{-7}$.

Later a calculation was reported that considers the effects of parity nonconservation at the quark level. This calculation included both the scattering contribution and the wave-function part [14]. The interaction takes place in the nucleon between one quark and a vector diquark. The results are dominated by the wave function part with $A_L = +(0.7 - 2.7) \times 10^{-6}$. Although this model is expected to be valid only at high energy and the uncertainty is large, the result is very encouraging.

This and most other calculations have been for proton-proton scattering and have not considered nuclear effects and the role of the neutrons. A Glauber model calculation [15] predicts that the effect for p-p scattering should be a factor of 1.7 larger than that measured on water.

The experiments at 1.5 GeV/c (800 MeV) are at an energy intermediate to that of the previous measurements. The result for polarized protons on an LH_2 target [6] is $A_L = (2.4 \pm 1.1) \times 10^{-7}$. This result can be compared with a surprisingly large range of values among published predictions for the asymmetry at 1.5 GeV/c. [16] The variation is mainly due to the use of different parametrizations of the strong nucleon-nucleon interaction.

No theoretical approach describes the energy dependence of p-nucleon scattering at all energies. The meson-exchange approach can explain experimental results at energies up to 1.5 GeV/c, but underestimates the 6-GeV/c result. The QCD approach is consistent with the 1.5- and 6-GeV/c results, but is not applicable at low energies. These experiments were originally envisioned as a study of the weak interaction between nucleons, but the most difficult parts of the problem for theorists are the strong-interaction aspects. The indication that the diquark component of the nucleon is important is very intriguing. An experiment at higher energy can confirm the energy dependence of A_L predicted by this model.

3 Experimental Method

The usual technique to determine A_L at higher energies is to measure the beam intensity before and after the target in a transmission geometry. An alternative is to monitor the incident or transmitted beam and detect scattered protons. At high energy the fractional asymmetry could be large enough to compensate for the reduced statistics in this geometry.

The ZGS experiment utilized the transmission technique. Two independent detector systems measured the number of protons upstream and downstream of the target for each beam pulse. The detector currents were integrated, as the required beam intensities prohibited counting individual protons. For the scintillation counter system, the transmission for one pulse of protons from the ZGS was measured as $Z_1 = T/I$ where T and I are the signals from the downstream and upstream counters, respectively. The second system used three identical ionization chambers. For each pulse, the signal from the downstream chamber D was subtracted from the upstream chamber, U, and normalized to the monitor chamber, M (located upstream). Thus, $1 - Z_2 = (U - D)/M$.

Because each successive beam pulse had opposite helicity, the fractional change in transmission for each pair of pulses is

$$\zeta \equiv \Delta Z/2Z = (Z_+ - Z_-)/(Z_+ + Z_-) \quad (1)$$

where $Z_+(Z_-)$ is the transmission (from either detector system) for the positive (negative) helicity pulse.

Fluctuations in ΔZ resulted from statistical uncertainties in the measurements of Z and from changes in Z due, for example, to random fluctuations in beam properties. The dependence of Z on beam motion and intensity fluctuations was removed by defining a corrected transmission, Z', for each pulse given by

$$Z' = Z - a_1(x - x_0)^2 - a_2(y - y_0)^2 - a_3(\langle i^2 \rangle / I) \quad (2)$$

Here $(x - x_0)$ and $(y - y_0)$ are horizontal and vertical deviations of the beam from the symmetry axis of the experiment (given by x_0, y_0). A measure of the time structure of the beam within a beam pulse is given by the square of the instantaneous beam intensity, $\langle i^2 \rangle$, normalized to the beam intensity for the whole pulse, I. The coefficients a_i were determined from a linear regression analysis to minimize fluctuations in Z'.

An average $\langle \zeta' \rangle$ was calculated for each run. The uncertainty in $\langle \zeta' \rangle$ was determined from rms fluctuations in ζ' and is designated $\delta(\zeta')$. Corrections were applied to the $\langle \zeta' \rangle$ from each run for known background processes such as residual transverse polarization that could give a change of transmission correlated with helicity, yielding

$$\langle \zeta' \rangle' = \langle \zeta' \rangle - \sum_i \gamma_i d_i \langle \Delta H_i' \rangle \quad (3)$$

where γ (cm^{-1}) is the sensitivity constant for the term; d (cm) is the displacement of the beam from the symmetry axis; and $\langle \Delta H \rangle$ is the average change of a polarization-correlated quantity. The values of the H and d quantities were monitored each beam pulse and the γ values were measured in calibration runs.

An unanticipated source of asymmetry in the ZGS experiment was due to beam scattered by the small amount of material in those parts of the beam channel where the polarization was fully vertical. The scattered beam produced a signal in the I counter and U chamber that was correlated with beam helicity (to the extent that the beam was displaced from the effective center of the upstream detectors). In the runs measuring this so-called beam-matter interaction, the interaction probability was increased by adding a known amount of material in the channel and measuring the asymmetry.

After all runs were combined, a correction for the correlation between transverse polarization and position within the beam was applied to the weighted average. This last correction is given by $\gamma\epsilon$ where γ is the sensitivity to transverse polarization and ϵ is the spatial first moment of the beam polarization distribution. A transverse component of polarization that averages to zero can produce a spurious parity signal [4, 17].

After all corrections have been applied, the value of $\langle \zeta' \rangle'$ is converted to the corresponding value of A_L.

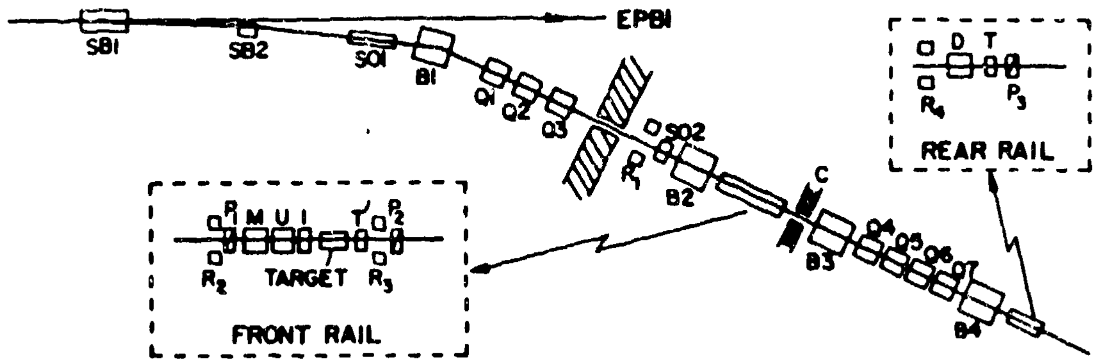

Figure 2: Schematic diagram of the beam line and apparatus. Detectors and beam line components are described in the text.

4 ZGS Experiment

4.1 Polarized proton beam and target

The 6 GeV/c beam from the ZGS had an average intensity of 3.2×10^8 protons/pulse, a spill width of roughly 700 ms, and a repetition rate of 0.3 Hz. The polarization direction was reversed at the source each ZGS pulse. The polarization was vertical during acceleration in the synchrotron and remained so in the external proton beam.

A plan view of the beam line and apparatus is shown in Fig. 2. Most of the beam line was evacuated but the beam encountered the vacuum windows and air in some regions. The magnet B2 deflected the beam upward through 7.75° to rotate the transverse polarization into the longitudinal direction. Solenoids in the beam line were used to control the transverse polarization of the beam at the target. A quadrupole triplet focused the beam on the aperture of a brass collimator, C, located after the target. The target was distilled water; the transmission coefficient of the target was $\mathcal{Z} = 0.18 \pm 0.01$.

4.2 Detector systems

Most of the detectors were mounted on two rigid rails. Three scintillation counters were used for the transmission measurement. Counter I was located upstream of the target, T' was just downstream of the target, and T was placed after the spectrometer. The beam position and polarization were measured every beam pulse by several sets of scintillation counters. The horizontal and vertical beam positions were measured by three sets of detectors with wedge-shaped scintillators, P_1, P_2, and P_3. The R_1 and R_2 polarimeters measured the scattering asymmetries at the entrance to the experimental area due to material in the beam line. The R_3 detector monitored residual transverse polarization by measuring the left-right and up-down scattering asymmetry of the beam scattered from the water target. The R_4 detector monitored scattering in the magnetic spectrometer. The beam centroid at position detector P_1 was stabilized pulse to pulse with the aid of a feedback loop.

4.3 Experimental procedure

The beam-line magnet currents were adjusted to maximize the transmission of the beam through the apparatus. Information from the calibration runs allowed the beam to be positioned on the null of symmetry axis of the experiment where contributions from beam-matter effects were minimized. The beam was focused at the collimator, the smallest aperture in the beam line, to minimize the noise due to beam motion. There were a total of $\sim 9 \times 10^{13}$ protons on target.

The polarimeters monitored scattering asymmetries throughout the experiment and the results are incorporated into the correction terms in Eq. (3). Three types of calibration runs were taken to measure the sensitivity coefficients γ, for the correction terms in Eq. (3). Added-absorber runs to measure the beam-matter interaction effects were taken with 1, 2, and 5 cm of Lucite placed about 2 m upstream from the center of B2, which increased $\langle \Delta R_{2y} \rangle$ by a factor of ten to $\sim 3.5 \times 10^{-2}$. Beam-partially-blocked runs to measure the polarization distribution in the beam were taken with either the top, bottom, left, or right half of the beam removed with a collimator.

4.4 Analysis and results

The signal from each phototube for each pulse was obtained by subtracting electronic offsets and dark current as measured in the appropriate gating intervals. The data selection procedure eliminated about 10% of the data from beam pulses with poor beam quality.

A regression analysis was employed to reduce the effects of beam properties on the measured transmission. The evaluation of the coefficients in Eq. (2) was based on an analysis using polarization independent combinations of the variables. The next stage of the analysis corrected for known helicity correlated quantities based on Eq. (3). For each run, including calibration runs, the values of $\langle \zeta' \rangle$, $\langle \Delta R_i' \rangle$, and $\langle P_i \Delta R_i' \rangle$ were found. The coefficients were determined with a χ^2 minimization procedure applied to these values. The 10% of the runs that contribute a $\chi^2 > 5$ to the fit were rejected. The result is $\langle \zeta' \rangle' = (-2.92 \pm 0.80) \times 10^{-6}$ for the scintillators and $\langle \zeta' \rangle' = (-4.96 \pm 0.99) \times 10^{-6}$ for the ion chambers. A weighted average gives

$$\langle \zeta' \rangle' = (-3.73 \pm 0.62) \times 10^{-6} \qquad (4)$$

For the final correction, the average helicity correlated components of polarization, $\langle \Delta R_y \rangle$ and $\langle \Delta R_x \rangle$, were measured with the beam partially blocked. Then $\epsilon = a(\langle \Delta R_x \rangle - \langle \Delta R_y \rangle)$, where the coefficient a depends on the beam shape and the distribution of polarization across the beam. The value of γ is that determined for transverse polarization, leading to a correction of $(-0.50 \pm 0.37) \times 10^{-6}$ to $\langle \zeta' \rangle'$.

The parity-nonconservation asymmetry A_L is related to the net $\langle \zeta' \rangle'$, in the limit of small ΔZ, by the expression $A_L = 1/(|P| \ln Z) \langle \zeta' \rangle'$. The result is

$$A_L = (2.65 \pm 0.60 \pm 0.36) \times 10^{-6} \qquad (5)$$

The first error is statistical; it is dominated by the uncertainties in the individual measurements of the transmission that have been propagated through the analysis but also includes contributions from the statistical uncertainties in the corrections. The second error is an estimate of systematic uncertainties. Because the largest correction to $\langle \zeta' \rangle$ comes from beam-matter interaction, several possible sources of error in the assumptions were studied carefully. From these considerations a plausible systematic uncertainty is 20% of the correction, or 0.3×10^{-6}. Another possible systematic error comes from uncertainties in the correction for the effect of polarization correlated with position within the beam. The total estimated uncertainty in the correction is 30%, leading to an estimated systematic uncertainty in the result of 0.2×10^{-6}. Other sources of systematic error, such as the treatment of residual transverse polarization and the effect of hyperon decay products, are negligible.

5 Discussion

Each version of the experiment benefited from the earlier ones. The experience gained from these experiments may also be applied to future experiments. Most immediately this applies to the experiment underway at 230 MeV at TRIUMF. Other possibilities for future experiments include Saclay at 3 GeV, BNL or KAON at energies up to 30 GeV, and Fermilab or RHIC at 200 GeV or higher.

The first measurement [18] at the ZGS found $A_L = (5.0 \pm 9.0) \times 10^{-6}$ using a Be target. It was found that the dominant contribution to the fluctuations in the measurements of Z was due to nonuniformities in the target coupled with random motion of the beam. This lead to the use of a water target with flat and parallel end windows in subsequent runs. In the second version of this experiment [19], A_L was found to be $(-15.0 \pm 2.4) \times 10^{-6}$. This value of A_L was attributed to the production of polarized hyperons in the target. The result of the final experiment [20] using the T' detector, which reproduces the geometry of the detectors without the spectrometer, does not confirm the large negative asymmetry for the value of A_L but finds $A_L(T') = (3.9 \pm 0.72) \times 10^{-6}$ after all corrections. The third experiment [21] included a collimator and spectrometer to eliminate hyperon decay products. A large transverse scattering asymmetry due to the beam-matter interaction was discovered (six times greater than the present experiment). The result was $(-26.3 \pm 7.5) \times 10^{-6}$. It is probable that beam-matter interaction was responsible for the large negative result in the second and third versions.

In the final version the contribution from beam-matter interaction was reduced by evacuating the beam line where possible, adding helium elsewhere, and enlarging the aperture at the entrance to the experimental area just upstream of B2. Even so, the largest systematic correction to A_L in this experiment comes from the beam-matter interaction. The correction to A_L, with the beam carefully positioned on the symmetry axis, is -1.2×10^{-6}. Transporting a longitudinally polarized beam to the experimental area would eliminate this contribution to A_L. Otherwise beam halo can be a very subtle and time-dependent source of systematic error.

An attractive feature of the ZGS experiment was the ability to make two simultaneous independent measurements of A_L. Two detector systems with different properties increase the confidence in the final result by aiding in the understanding of systematic and random backgrounds. This experiment measured A_L with an accuracy of better than 6×10^{-7} in about a six-week period of data taking. The error is roughly three times greater than expected from the statistical fluctuations of the beam absorption in the target.

With beam intensities above 5×10^{8} protons/pulse, the noise factor increased rapidly, precluding a more precise measurement of A_L in a reasonable amount of time with these detectors. The extra fluctuations in the transmission measurement in each detector system are uncorrelated and therefore did not originate from a common source. The dominant source of noise for the ion chambers was due to spallation in the plates [22]. Beam motion during the spill, 60 Hz and greater, contributed to the noise for the scintillation counters. To improve the noise factor, a regression analysis removing beam motion from the transmission and a data-selection procedure, during the spill, could be accomplished by electronically dividing the beam spill into small time segments. The gain drifts of both detector systems were random and negligible.

Ion chambers perform well in intense beams but scintillation counters do not because of radiation damage to the plastic scintillator. The use of liquid scintillator instead of plastic scintillator is a possible solution to this problem. Alternatively, an experiment that measures only the scattered beam from the target with scintillation counters and the transmitted beam with ion chambers could utilize high beam intensities.

The credibility of such experiments depends on the identification and study of all sources of systematic error greater than approximately half of the desired statistical accuracy. This is no easy task as there is no global test to determine the presence of a systematic contribution to A_L. Therefore, careful consideration should be given to detector systems that monitor beam properties and the models used to make corrections should be experimentally tested. Also, classes of systematics may be studied with unpolarized beam. The ZGS experiment had only a simple reversal of spin between pulses. A reversal pattern of $+--+$ can remove linear drifts. In addition, there should be a method of reversing the proton spin external to the source. This helps to separate spin related systematics from those due to other beam properties.

The method used in these experiments to measure residual transverse polarization contributions to A_L could be repeated in a more sensitive measurement of A_L. A position feedback loop controlling the current in an upstream bending magnet is necessary to minimize beam motion and maintain the beam position on the symmetry axis to minimize effects of residual transverse polarization. The correlation of polarization with phase space should be measured at apertures that intercept scattered beam and can be determined by passing a thin scatterer through the beam and measuring the resulting transverse scattering asymmetry [23].

Calibration runs should be repeated frequently during the experiment to compensate for changing conditions. In spite of the similarities of the sources of systematic error in the existing experiments, each accelerator is different and has its own potential for surprise.

6 Conclusions

The existing measurements of A_L indicate a strong energy dependence of the amplitude for the interference between the strong and non-leptonic weak interactions. New measurements at higher energies are needed to confirm this energy dependence and validate the quark-model predictions. These experiments are very difficult, but with adequate beam intensity and quality, the lessons of previous experiments should guide new efforts to a successful conclusion.

7 Acknowledgments

My colleagues on the ZGS experiment are listed as the authors of Ref. [9]. I am indebted to them and to the others listed in these references for the success of these experiments. This paper has been adapted from Ref. [16].

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