Precision Measurement of Parity Nonconservation in Proton-Proton Scattering at 45 MeV

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Parity nonconservation in *pp* scattering has been studied by measuring the helicity dependence of the cross section, $A_z=(\sigma^+-\sigma^-)/(\sigma^++\sigma^-)$, for longitudinally polarized incident protons of 45 MeV. We found $A_z=(-1.50\pm0.22)\times10^{-7}$ for the angular range 23° to 52° (laboratory frame). The uncertainty is the root square sum of the error of the measured asymmetry ($\pm0.19\times10^{-7}$), the error of the applied corrections ($\pm0.05\times10^{-7}$), and of various systematic errors ($\pm0.09\times10^{-7}$). This is the most accurate result ever obtained on parity nonconservation in the nucleon-nucleon interaction.

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This paper reports on a precision measurement of the parity-nonserving helicity dependence on the *pp* scattering cross section. The measured quantity is the longitudinal analyzing power $A_z=(\sigma^+-\sigma^-)/(\sigma^++\sigma^-)$ at 45 MeV, where $\sigma^\pm$ refers to the cross section for positive and negative helicity of the incident longitudinally polarized protons. A_z is predicted[1] to have a broad maximum near the present proton energy, and is essentially independent of scattering angle, since only $J=0$ partial waves contribute significantly.

Parity nonconservation in the nucleon-nucleon interaction is at present the only experimentally accessible signature of flavor-nonchanging purely hadronic weak interactions. Although the standard model of weak and electromagnetic interactions is generally accepted, its matrix elements are still poorly understood for systems where quark confinement is important.[2]

Measurements in the *np* system have not yet reached the accuracy needed to detect parity-nonconserving effects.[3,4] The most accurate low-energy[5] *pp* scattering results published so far yielded[6] $A_z(15\text{ MeV})=(-1.7\pm0.8)\times10^{-7}$ and[7] $A_z(45\text{ MeV})=-2.3\pm0.9)\times10^{-7}$. However, analysis showed[7,8] that reduced experimental uncertainty is needed in order to provide tighter constraints for theory. We therefore resumed these measurements after a similar study in *pα* scattering.[8]

In general, the layout and the methods are as described in Ref. 7 but with improvements in important details. We shall stress here mainly those points which were crucial to obtain the improved accuracy.

The experiment made use of the cyclotron at the Swiss Institute for Nuclear Research (SIN), which is equipped with an atomic-beam–type polarized-ion source. The polarization of the beam (typically $P=0.83\pm0.02$) was reversed in an irregular pattern[7] ~33 times a second by energizing two different rf transitions in the ion source. Longitudinal polarization (p_z) at the target was obtained by passing the 50.7-MeV proton beam, which is polarized in the vertical direction (p_y), through a 90° spin-precession solenoid and then deflecting the beam horizontally by 47.6°. The protons were scattered in a 100-bar H_2 gas target and detected in a cylindrical ionization chamber of 20-cm outer radius and 2-cm active thickness, coaxial with beam and target.[7] The transmitted beam was monitored in a Faraday cup. A_z is obtained from the ratio

$$R=\frac{(N_s/N_p)^+-(N_s/N_p)^-}{(N_s/N_p)^++(N_s/N_p)^-}$$
$$=|p_z|A_z+\text{systematic effects},$$

where N_s is the integrated ionization chamber current and N_p the integrated beam current in the Faraday cup. The basic integration time is 20 msec in order to suppress line-frequency (50 Hz) modulations. In between integrations there is a roughly 10-msec dead time during which beam intensity and polarization profiles are measured by special beam scanners[9] 10 and 95 cm before the target entrance.

With a beam current of 4 μA, the statistical accuracy achieved is 0.5×10^{-4} in 20 msec and 2.5×10^{-7} in a 20-min run. Obviously, the main problem is to reduce all systematic effects to a level well below 10^{-8}. The majority of beam time was devoted to this problem.

The new data have been accumulated in six series (beam times) numbered 3 to 8, containing a total of 350 20-min data runs and roughly 6000 individual test and calibration measurements. Between series 5 and 6 the atomic beam stage of the polarized ion source was replaced by a new one with a cooled dissociator nozzle.[10] This increased the beam current on target from typically 1.5 to 4 μA, but it also produced larger beam intensity modulation correlated with polarization reversal (5×10^{-4} instead of 5×10^{-5}).

Results, corrections, and systematic uncertainties are summarized in Table I. Compared to our previous measurements[7] (series 1 and 2), not only the statistical accuracy but the limits on most of the systematic effects were improved considerably. This resulted from improvements in the experimental arrangement, additional and more frequent test and calibration measurements, and refined data analysis.

The most important changes in the apparatus are the following. (i) A new Faraday cup further downstream, better shielded, and with a carbon instead of a tungsten beam stop[8] reduced the background current in the ionization chamber (measured with empty target) from 2.7% to 0.35%. (ii) Improvements of the current integrators and digitizing system and implementation of constant current subtraction for high beam currents. This reduced digitizing errors and improved the linearity of the system and thus the sensitivity to intensity modulation. (iii) A new data-acquisition system for the beam scanners permitted higher count rates (up to ~200 kHz, limited only by pileup within single cyclotron micropulses). (iv) Increased target gas circulation reduced thermal gradients in the target which contribute to the sensitivity to possible modulations in beam diameter, particularly at high beam currents. (v) Addition of a solenoid after the last beam deflection simplified procedures to obtain horizontal transverse polarization (p_x) at the target, and permitted more frequent calibrations and tests with p_x. (vi) Improved focus conditions (new beam line with additional quadrupoles) yielded some reduction in the corrections for transverse polarization moments. (vii) Implementation of computer control of the experiment including hardware parameters reduced the time needed for parameter changes and was crucial for frequent performance of tests and calibrations between parity measurements.

Data analysis and treatment of systematic effects have been explained in Refs. 7 and 8 and in the work of Nessi-Tedaldi[11] and Simonius *et al.*[12] In the following, we restrict ourselves to a short summary, emphasizing those points where improvements were made. Details are found in Ref. 11.

Instrumental effects which arise from *coherent modulations* of beam properties, i.e., modulations of beam properties correlated with polarization reversal at the ion

TABLE I. Summary of data, corrections, and limits on systematic effects for A_z in units of 10^{-7}.

Series / No. of 20-min. runs	3 / 51	4 / 84	5 / 48	6 / 58	7 / 50	8 / 59	Total 3–8 / 350
"Raw" asymmetries $R/\lvert p_z\rvert$	-1.79 ± 0.66	-1.31 ± 0.53	0.48 ± 0.73	1.78 ± 0.43	-2.44 ± 0.40	-4.94 ± 0.37	-1.98 ± 0.19
Runwise corrections (total contribution) with statistical errors							
Transverse polarization components	-1.38 ± 0.10	0.82 ± 0.07	1.18 ± 0.10	3.78 ± 0.07	-1.40 ± 0.09	-3.49 ± 0.07	-0.56 ± 0.04
Intensity modulations[a,b]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Position modulations[a]	0.07 ± 0.17	0.04 ± 0.15	0.65 ± 0.49	-0.01 ± 0.04	-0.04 ± 0.03	0.04 ± 0.03	0.05 ± 0.04
Limits on systematic effects (1σ)							
Transverse polarization components	±0.08	±0.12	±0.12	±0.11	±0.07	±0.07	±0.04
Emittance modulation[a]	±0.09	±0.04	±0.09	±0.08	±0.06	±0.04	±0.03
Energy modulation[b]	±0.21	±0.01	±0.05	±0.09	±0.02	±0.04	±0.03
Electronic crosstalk, etc.[b]	±0.00	±0.00	±0.00	±0.00	±0.00	±0.00	±0.00
Corrected asymmetries A_z	-0.50 ± 0.73	-2.15 ± 0.57	-1.35 ± 0.90	-1.99 ± 0.47	-0.99 ± 0.42	-1.47 ± 0.39	-1.46 ± 0.21
Beta-decay asymmetry[c]							±0.03
Double scattering[c]							±0.03
Empty target background							±0.05
Uncertainty of beam polarization ($\pm2\%$)							±0.03

[a]Sensitivities measured with artificially enhanced modulations, coherent modulations monitored during measurement.
[b] Suppressed by solenoid reversal.
[c]Depends on incoming helicity itself which cannot be kept small.

source, are in general treated by the following procedure: In separate calibration runs, R is measured with artificially enhanced modulation, e.g., transversely polarized beam, as a function of beam displacements from the axis, in order to determine *sensitivities* of our measurement to a given modulation. During parity measurements beam displacements and modulations are kept small and monitored continuously (beam intensity and polarization profiles, beam current) or in interspersed test runs. Combined, this yields quantitative corrections or upper limits. Important also is the suppression of some effects (intensity and energy modulation) by reversal of the field in the spin precession solenoid which reverses the phase between p_z at the target and the polarization after the cyclotron. This *solenoid reversal* was therefore performed after every second parity run.

Residual *transverse polarization components* in the longitudinally polarized beam give rise to the only significant correction. They are due mainly to inevitable nonuniformity of the polarization direction over the beam profile and are dominated by contributions of first moments of the transverse beam polarization with respect to the beam center of gravity.[7,12] The corrections are determined for each run from the intensity and polarization profiles of the beam provided by the beam scanners. Although we used a new target assembly, the corresponding sensitivities were similar to those in our earlier measurements.[7] They were determined usually 3 times for each series from measurements of R with transverse polarization for 10 to 20 different beam trajectories through the target. This permits also the determination of upper limits on sensitivities to second and third moments of the transverse polarization distribution across the beam which *a priori* are expected not to contribute significantly.[12] The limits on their contribution are estimated using the uncorrelated higher polarization moments in the parity runs provided by the beam scanners.[11,12] They are contained in the systematic errors in Table I.

The amplitude of coherent beam *intensity modulation* was obtained from the integrated Faraday cup currents ($N_p^{\pm}$). The sensitivity was determined every six runs by artificial modulations. Runwise corrections were typically 0.1×10^{-7} before and 1×10^{-7} after the modification of the source. As one would expect, these corrections perfectly cancel with solenoid reversal (see Table I).

Position modulations were monitored with the beam scanners. The sensitivities should be zero for a perfectly symmetric arrangement and centered beam. The unusually large contribution for series 5 (Table I) was due to an intrinsic misalignment within the scattering chamber which was subsequently corrected.

Effects due to *emittance modulation* can be expressed in terms of width modulations of the beam at *three* different locations along the beam. At two locations width modulations are measured during parity runs by the beam scanners. The third location is best chosen at the center of the target.[7] Here, width modulations were measured in regular tests between parity runs by intercepting the outer portions of the beam with a secondary-electron emission foil with a hole or a slit in the center and measuring the modulation of its current. The main part of the corresponding sensitivities, dominated by the one at the center of the target, are obtained from the dependence of R on beam trajectory through the target in measurements with artificially enhanced position modulations.[7] An additional part can be caused by temperature and thus density gradients in the target. It depends on the actual beam properties and was determined regularly between measurements by modulating a small quadrupole ca. 2 m in front of the target. With efficient target gas circulation it turned out not to be important.

Coherent *energy modulation* of the beam cannot be monitored directly. If it is stable its effect completely cancels with solenoid reversal. A potential effect would show up as a nonzero difference $\Delta A_z = \frac{1}{2}(A_z^+ - A_z^-)$ between A_z measured with positive (+) and negative (−) field in the solenoid.[7] Yet, within the same statistical error as for A_z, no such effect has been observed [$\Delta A_z = (0.23\pm0.20)\times10^{-7}$]. As a precaution, in order to guard also against possible drifts of a small energy modulation due to changing cyclotron conditions,[8] artificial energy modulations were induced at the ion source[8] before and after each of the 175 solenoid reversals. From this, *experimental suppression factors*[8] were obtained which, when multiplied by ΔA_z, give the limits quoted in Table I.

Above methods cannot be used for the last three effects to be discussed since they depend on the incoming helicity itself. They therefore had to be approached by separate investigations.

If nuclei activated in various parts of the apparatus inherit some of the beam polarization and retain it until they decay, the usual parity-violating *β-decay asymmetry* could lead to a false signal. The upper limit (Table I) was obtained from separate measurements of activation probabilities and decay asymmetries in the materials used,[11,13] together with detailed calculations of their effect in our apparatus.[11]

Double scattering can produce a false asymmetry if the beam-target-detector arrangement has no symmetry plane.[7] Upper limits were obtained from measurements with five different arrangements of deliberately introduced inhomogeneities of target wall and ionization chamber together with measured upper limits on inhomogeneities in the apparatus.[11]

The limit for the effect due to the 0.35% *empty-target background* is obtained from the asymmetry $A_z = (5\pm15)\times10^{-7}$ measured with evacuated target.

We emphasize that for only two of the effects listed, transverse polarization components and intensity modulations, a statistically significant nonzero contribution has ever been seen during these measurements.

The distribution around the mean of the 350 new 20-

min data runs, with runwide corrections mentioned in Table I applied, but no systematic errors included, yields $(\chi^2/N_D)^{1/2}=1.05$. This is consistent in view of the fact that some of the systematic effects for which no runwise correction can be made (in particular higher polarization moments, phase space, and energy modulations) could be fluctuating within the errors given in Table I.

The final result was computed as weighted mean of the corrected values of A_z for the 8 series with errors *including* the series-specific systematic uncertainties (root square sum) as listed in Table I. This yields $(\chi^2/N_D)^{1/2}=1.04$ (confidence level 33% for all eight series together). The common systematic errors were then added in quadrature.

The new result from the present measurements is $A_z=(-1.46\pm0.22)\times10^{-7}$. Including our previous measurements[7] (series 1 and 2) in the average, we obtain our *final result*

$$A_z=(-1.50+0.22)\times10^{-7}$$

at 45-MeV average beam energy in the target. The error is the root square sum of a purely statistical error (0.19×10^{-7}), a statistical error of corrections (0.05×10^{-7}) and a total of systematic uncertainties (0.09×10^{-7}).

This is the actually measured value of A_z averaged over the angular range 23° to 52° of our acceptance with the weight function given in Ref. 7. It differs by a (5 ± 5)% correction[7] for angular dependence from the usually cited but not well defined asymmetry in the "total cross section without Coulomb interaction" for which we obtain $A_z^{tot}=(-1.57\pm0.23)\times10^{-7}$.

In conclusion, we have presented here a new measurement of parity nonconservation in low-energy proton-proton scattering with an accuracy not reached heretofore in this field. It will provide tight constraints for theoretical analysis, be it in terms of parity-nonconserving meson-nucleon coupling constants or in a direct quark-model approach as tried by Kisslinger and Miller.[14]

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