Measurement of Parity Nonconservation in *pp* Scattering at 45 MeV

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Parity nonconservation in p-p scattering has been studied by comparing the cross sections σ^+, and σ^- for longitudinally polarized 45-MeV protons of positive and negative helicity. The longitudinal analyzing power is found to be $A_z = (-3.2 \pm 1.1) \times 10^{-7}$. The quoted uncertainty includes the statistical error, the uncertainties of corrections applied, and estimates of systematic effects.

It has been suggested[1] that a possible parity nonconservation in the nucleon-nucleon interaction can be studied by comparing the p-p cross sections σ^+ and σ^- for an incident beam of longitudinally polarized protons of positive and negative helicity. Since the scattering cross section is proportional to the ratio of the number of scattered protons, N_s, to the number of incident protons, N_p, the longitudinal analyzing power A_z can be written as

$$A_z = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{1}{|P_z|} \frac{(N_s^+/N_p^+) - (N_s^-/N_p^-)}{(N_s^+/N_p^+) + (N_s^-/N_p^-)},$$

where $|P_z|$ is the magnitude of the beam polarization. Calculations show that A_z has a broad maximum near 50 MeV, where A_z can be expected[2] to be at most a few times 10^{-7}. At 15 MeV, where previous measurements have been reported,[3] A_z is predicted to be about half as large as at 50 MeV.

The experiment described here made use of the 50-MeV polarized proton beam from the Schweizerisches Institut für Nuclearforschung injector cyclotron. The polarized protons (~1.2 μA on target) are produced in an atomic-beam–type polarized-ion source.[4] rf-transitions, which act on the neutral atomic beam, are used to switch the proton polarization P_z between ±0.83 every 30 msec.

The experimental arrangement is shown schematically in Fig. 1. A solenoid (S) precesses the vertical polarization (P_y) into the horizontal plane, and a 47.6° deflection magnet (M) produces a longitudinally polarized beam. Here, the solenoid field is called positive if $+P_y$ leads to $+P_z$ in the scattering chamber. Protons scattered in a 100-atm H_2 target (T) by 25°–55° enter a cylindrical ionization chamber (diameter 40 cm) filled with 1 atm H_2. To obtain $N_s^\pm$ and $N_p^\pm$, the currents from the ionization chamber and the Faraday cup are integrated over 20 msec. Individual 20-msec measurements are separated by 10 msec dead time, during which the polarization is reversed, the digitized integrated charges are stored in a computer and beam scanners move through the beam. To suppress periodic noise, the phase of the polarization-switching signal is reversed after 8 such 30-msec cycles. In addition, the initial sign of polarization for each group of 16 measurements is set by a random-number generator.

The principal problem of the experiment was the elimination of systematic errors caused by possible changes in the proton beam which are coherent (i.e., in step) with the reversal of P_z. In order to determine corrections (or upper lim-

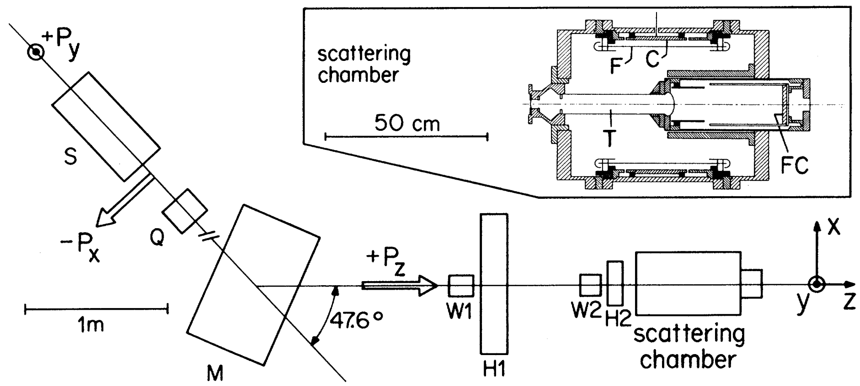

FIG. 1. Schematic diagram of the experimental arrangement. The figure shows the spin precession elements (solenoid S, deflection magnet M), the beam scanners H1 and H2, the beam modulation elements Q, W1, W2, and the scattering chamber. The inset shows the scattering chamber in more detail: the target vessel (T), the Faraday cup (FC), and the ionization chamber which consists of an aluminum foil (F) at 10 kV and the ion collector (C).

its) for such effects, we employed specially designed on-line digital beam monitors[5] which provide a continuous record of the intensity and the polarization distributions of the beam. Two scanners (H1 and H2, Fig. 1) were used to obtain information about position as well as direction of the beam. In the following, beam coordinates will be specified by the coordinates (x_1, y_1) and (x_2, y_2) at the two scanners.

The sensitivity of the apparatus to various beam modulations was measured by introducing artificial modulations of the intensity, position, emittance, and transverse polarization of the beam, combined with deliberate beam misalignments. The following instrumental effects were considered:

(1) Transverse polarization components. Different elements of the finite beam inevitably have different residual small components of transverse polarization which change coherently with the reversal of the longitudinal polarization. Thus, corrections to A_z arise from the regular (parity-conserving) analyzing power in proton scattering. Part of the correction arises from an average transverse polarization ($\langle P_x \rangle$, $\langle P_y \rangle$ $\approx 3\times10^{-3}$) combined with small beam misalignment ($\simeq$0.1 mm in H2), but by far the most important effect is the nonuniform distribution of $P_x(y), P_y(x)$ within the beam.[6]

The sensitivity of A_z to $P_{x,y}$ was measured repeatedly as a function of beam displacement (x_1, y_1) and (x_2, y_2) using transversely polarized beams. Typical values for the corrections, which are evaluated and applied individually for each 20-min run, are given in Table I.

(2) Intensity modulation. Information about the coherent intensity modulation is available from the digitized Faraday-cup signal $(N_p^{\pm})$. The sensitivity of A_z to intensity modulation was measured periodically. In Table I, the uncertainty in the sensitivity represents the variance in the test measurements during the parity runs.

(3) Beam position modulation. Within the accuracy of the measurements there is no evidence for coherent position modulation in either beam scanner (see Table I). Artificial position modulations in x and y were produced with magnets W1, W2 (Fig. 1). The sensitivity of A_z was mapped as a function of beam position and was checked periodically.

(4) Emittance modulation. To detect coherent modulation of the beam diameter, we inserted apertures in the beam and measured the modulation in the ratio of beam passing through the aperture to beam striking the aperture. The sensitivity of A_z to such modulations was deduced from the sensitivity to position modulation and checked by modulating the beam with a small quadrupole magnet Q (Fig. 1). The results showed that the effect depends on the modulation of the beam diameter (but not its divergence) at the center of the target. Table I lists the observed amplitude of this modulation.[7]

(5) Electronic effects. To test for spurious electronic coupling between the signal which determines the helicity of the proton beam and the signals from the scattering chamber, tests were made with constant-current sources added to the Faraday-cup and ion-chamber current integrators (see Table I).

TABLE I. Summary of systematic errors.

Instrumental effect	Value	Sensitivity of $\|P_z\| A_z$	Effect on $\|P_z\| A_z$ (in units 10^{-7})	Contribution to error in final result A_z (in units 10^{-7})
(1) Transverse polarization components[a,b]				
$\langle P_x(y_1)y_1\rangle$	(4.6 ± 1.1) μm	$(-50\pm1.3)\times10^{-10}$/μm	-0.23 ± 0.06	0.2
$\langle P_y(x_1)x_1\rangle$	(20.7 ± 1.1) μm	$(50\pm1.3)\times10^{-10}$/μm	1.04 ± 0.08	
$\langle P_x(y_2)y_2\rangle$	(2.1 ± 0.6) μm	$(590\pm7)\times10^{-10}$/μm	1.24 ± 0.37	
$\langle P_y(x_2)x_2\rangle$	(0.6 ± 0.6) μm	$(-590\pm7)\times10^{-10}$/μm	-0.35 ± 0.37	
(2) Coherent intensity modulation				
$(I_p^+-I_p^-)/(I_p^++I_p^-)$[a]	$-(80\pm5)\times10^{-6}$	$(1.35\pm0.23)\times10^{-3}$	-1.1 ± 0.3	0.2
(3) Coherent position modulation				
$\delta\langle x_1\rangle$[a]	(1 ± 1) μm	1.5×10^{-8}/μm	0.15 ± 0.15	0.1
$\delta\langle x_1\rangle$[d]	(0.2 ± 0.2) μm	$<1.5\times10^{-8}$/μm	0.01 ± 0.03	
$\delta\langle x_2\rangle$[a]	(0.3 ± 0.5) μm	5×10^{-8}/μm	0.15 ± 0.25	
$\delta\langle x_2\rangle$[d]	(0.1 ± 0.1) μm	$<5\times10^{-8}$/μm	0.02 ± 0.05	
(4) Coherent emittance modulation				
$\delta r^2=\delta\langle x^2\rangle+\delta\langle y^2\rangle$[e]	$(1\pm1)\times10^{-4}$ mm^2	10^{-4}/mm^2	<0.3	0.3
(5) Electronic pick up[e]	$(-0.21\pm0.16)\times10^{-7}$			0.2
(6) Asymmetry of β-decays[e]				0.2

[a]Typical value for a 20-min run.
[b]The sum of the two contributions mentioned in the text is given; cf. also Ref. 6.
[c]And similar terms for $\delta\langle y_1\rangle$ and $\delta\langle y_2\rangle$.
[d]Average over all measurements.
[e]Measured in separate runs and/or calculated; see text.

(6) Asymmetry from β decay. The incident protons produce short-lived (polarized) β-active nuclei in various parts of the scattering chamber. Because of the parity-nonconserving asymmetry in the β decay the electrons could produce a helicity-dependent contribution to the current in the Faraday cup and in the ionization chamber. The magnitude of this effect depends on the activation cross sections, the polarization transfers, the depolarizations during stopping, the β-decay asymmetries, geometric factors and, finally, a reduction factor R which depends on the time

TABLE II. Summary of experimental results for A_z (in units of 10^{-7}).

	Solenoid +	Solenoid −	Average
Raw data[a]	-3.2 ± 1.2	-2.0 ± 1.8	···
After correction for transverse polarization[a]	-4.6 ± 1.2	-1.3 ± 1.8	-3.0 ± 1.1[b]
After correction for intensity mod. and for transverse polarization[a]	-3.3 ± 1.2	-3.0 ± 1.8	-3.2 ± 1.0
Root square sum of all systematic uncertainties			±0.5
Final result for A_z			-3.2 ± 1.1

[a]The indicated error is the statistical error of the raw data and the statistical error in the measured corrections.
[b]The average of the measurements with solenoid + and solenoid − is taken rather than the weighted mean because the individual values contain a systematic effect from intensity modulation.

development of the longitudinal polarization prior to decay. In order to suppress a possible effect, our measurements were done with a transverse magnetic field of ±1 mT over target and Faraday cup which is reversed every minute. Since there are no static intrinsic fields in the metals used[8] (aluminum alloy and tungsten), the spin system precesses with the Larmor frequency $\omega = 4.8\times10^4 \times g\ \mathrm{sec}^{-1}$, where g is the gyromagnetic ratio. For a typical β-decay constant $\lambda = 1\ \mathrm{sec}^{-1}$ and $g = 1$, one finds a reduction factor $R \lesssim 10^{-5}$. A detailed calculation, taking into account the time structure of the parity measurements and possible effects from residual longitudinal components in the magnetic field, yields an upper limit of 2×10^{-8}.

The uncertainty which the above effects cause in the final value of A_z are given in the last column of Table I. Systematic errors in the determination of the corrections for effects (1) and (2) are included. The fact that the influence of effects (2), (4), and (5) is reduced by reversal of the solenoid current is taken into account.

Table II lists the average values of A_z for the 24 runs with positive sign of the solenoid field and the 10 runs with negative sign. Each of these runs has a statistical uncertainty of about $\pm5\times10^{-7}$, determined from the variance of the roughly 2500 individual measurements (each of which comprises 16 polarization reversals). The 34 corrected runs are statistically consistent ($\chi^2 = 1.11$).

Our final result for a mean proton energy of 45 MeV is

$$A_z = (-3.2 \pm 1.1)\times10^{-7}.$$

The uncertainty includes the statistical and systematic errors (root square sum).

The measurements are continuing in the hope of further reduction of the uncertainties.

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[6]For a detailed discussion of the theory on which these corrections are based, see M. Simonius, R. Henneck, Ch. Jacquemart, J. Lang, W. Haeberli, and Ch. Weddigen, to be published.

[7]A more detailed analysis shows that it is not sufficient to measure the variation of the beam diameter at two locations along the beam. In addition, *correlations* of the modulations in the beam intensity distributions at the two locations were considered.

[8]H. Alloul, in *Nuclear Magnetic Resonance in Solids*, edited by L. Van Gerven (Plenum, New York, 1974), p. 157.