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Study of Parity Nonconservation in $p\alpha$ Scattering

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Parity nonconservation in $p\alpha$ scattering has been studied by comparing the cross sections σ^+ and σ^- for longitudinally polarized 46-MeV protons of positive and negative helicity. The longitudinal analyzing power is found to be $A_z = (0.3 \pm 1.3)\times 10^{-7}$. This result, together with earlier measurements on parity nonconservation in pp scattering, gives new limits for the weak pion-nucleon coupling constant.

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According to present theory, the interaction between nucleons (*NN* interaction) contains a small contribution from weak interactions (hadronic weak currents) which can be described by weak-coupling constants associated with the exchange of various mesons (π, ρ, ω, etc.). Experimentally, the weak *NN* potential can be detected because it leads to a small parity nonconservation in nuclear interactions. The presence of such effects has been clearly demonstrated, e.g., through the detection of circular polarization P_γ in the γ decay of various nuclei, but there is insufficient information at present to determine the individual weak meson-nucleon coupling constants (see Haeberli[1] and Desplanques[2] for reviews).

The work reported here is the first measurement of parity nonconservation in $p\alpha$ scattering. The experiment consists of comparison of cross sections σ^+ and σ^- for logitudinally polarized proton beams of positive and negative helicity. Recent calculations[3,4] of the longitudinal analyzing power $A_z = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$ predict values of the order of a few times 10^{-7} and suggest that the contribution from the weak pion-nucleon coupling constant, f_π, should dominate A_z. The value of f_π is of particular interest because this coupling constant is strongly affected by the weak *neutral* currents in the theory of Weinberg and Salam. Study of the $p\alpha$ system is attractive because it is the simplest one available (apart from the pp and and np systems) and because its scattering states are relatively well known.

The experimental technique was essentially the same as in our earlier investigation on pp scattering.[5,6] The arrangement is shown schematically in Fig. 1. Protons are scattered in a 100-bar He target whose walls are sufficiently thick (2-mm Al alloy) that charged particles from breakup reactions are stopped. Protons scattered by 23°–97° are detected in a hydrogen-filled (1-bar) cylindrical ionization chamber which surrounds the target. The proton beam was provided by the Swiss Institute for Nuclear Research cyclotron which is equipped with an atomic-beam–type polarized-ion source. The arrangement in Fig. 1 is preceded by a spin-precession solenoid and a 47.6° deflection magnet, which, together, precess the vertical polarization of the beam from the cyclotron ($\pm P_y$) into a beam of longitudinal polarization $\pm P_z$ or $\mp P_z$, depending on the sign of the solenoid field. The helicity of the beam is reversed every 30 msec by switching rf transitions in the ion source. Every few hours the overall phase of P_z is reversed by reversal of

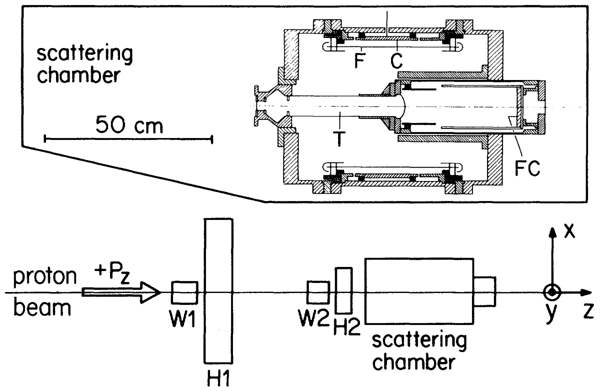

FIG. 1. Schematic diagram of the experimental arrangement. The figure shows the beam scanners H1 and H2, and deflectors W1 and W2 which are used to produce artificial modulations in beam direction and beam position. The top of the figure shows the scattering chamber in more detail: the He target (T), the Faraday cup (FC), and the ionization chamber consisting of an aluminum foil (F) at 10 kV and a collector electrode (C).

the current in the spin-precession solenoid.[5,6]

The longitudinal analyzing power is calculated from the expression

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

where $N_s^\pm$ is the integrated ionization chamber current (proportional to the number of scattered protons), and $N_p^\pm$ is the integrated beam current measured in the Faraday cup (proportional to the number of incident protons). The superscripts denote the helicity of the beam, and $|P_z| \simeq 0.83$ is the magnitude of the beam polarization. The integration of the currents in the ionization chamber and the Faraday cup extends 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.

The principal problem of the experiment is the elimination of systematic errors caused by possible changes in the proton beam which are coherent (i.e., in step) with the reversal of the helicity. In fact, the majority of beam time was devoted to these problems. The beam properties were sampled continuously during the parity runs with the aid of two pairs of beam scanners[7] (H1 and H2 in Fig. 1) which measure not only the intensity distribution but also the polarization profiles of the beam. To measure the sensitivity of the scattering chamber to various beam modulations, we introduced artificial modulations of the intensity, position, diameter, and transverse polarization of the beam, combined with deliberate misalignments.[5] The following instrumental effects, which are summarized in Table I, were considered:

(1) Transverse polarization components.—Corrections to A_z arise from the regular (parity-conserving) analyzing power in $p\alpha$ scattering coupled with small residual transverse polarization components in the beam.[8] The most important contribution is due to the nonuniform distribution of the polarizations $P_x(y)$ and $P_y(x)$ *within* the beam. In order to ascertain the stability of the corrections the sensitivities were remeasured repeatedly. The systematic errors quoted in Table I include small variations of the sensitivities with target gas pressure, systematic errors in the determination of the polarization distribution in the beam, as well as upper limits for the contribution of higher-order moments.

(2) Intensity modulations.—Information about the coherent intensity modulations is available from the integrated currents in the Faraday cup ($N_p^\pm$).

(3) Beam position modulations.—The coherent position modulations of the beam have been measured with the beam scanners. The amplitude of the largest modulation was $\langle \delta x_1 \rangle = 0.3 \pm 0.3$ μm (average value over all runs).

(4) Emittance modulations.—To detect coherent modulations of 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 was obtained from modulations of the beam with a small quadrupole magnet.

(5) Energy modulations.—If, for some reason, the beam energy changes slightly (δE) with reversal of the beam polarization at the ion source, a false contribution δA to A_z results. Since we have no means to measure δE to the required accuracy ($\delta E/E = 10^{-8}$ causes $\delta A = -5\times 10^{-8}$), we use the fact that this *error* in A *reverses sign* when the field in the spin precession solenoid is reversed. Thus δA would reveal itself as a difference in the corrected results for the two solenoid signs (Table II), but would cancel when the average is formed. The uncertainty for this effect in Table I includes the possibility that this cancellation is not complete because of possible changes of δE with time during the experiment. Rapid variations (within a run) are averaged out, but are included as part of the statistical error in

TABLE I. Summary of systematic errors.

Instrumental effect	Sensitivity	Typical values for a 20-min. run: Value	Correction to $\|p_z\|A_z$ (or upper limit) (10^{-7})	Contribution to $\|p_z\|A_z$ in final result (10^{-7})
1. Transverse polarization components:				
(a) $\langle p_y \rangle$	$(2.8 \pm 5.0)\times 10^{-6}$	$-(4.2\pm 0.3)\times 10^{-3}$	-0.12 ± 0.21	0.22 ± 0.12
$\langle p_x \rangle$	$-(15.7\pm 3.0)\times 10^{-6}$	$(5.8\pm 0.3)\times 10^{-3}$	-0.91 ± 0.18	
(b) $y_1\langle p_x \rangle$	$(8.1\pm 0.1)\times 10^{-8}\ \mu\text{m}^{-1}$	$-320\ \mu\text{m}\times 5.8\times 10^{-3}$	-1.50 ± 0.08	-0.37 ± 0.40
$\langle y_1 p_x(y_1)\rangle$	$(8.1\pm 0.1)\times 10^{-8}\ \mu\text{m}^{-1}$	$-(6.5\pm 0.9)\ \mu\text{m}$	-5.27 ± 0.73	
+6 similar terms				
Sum (including higher order terms)				-0.14 ± 0.49
2. Intensity modulation: $(N_p^+ - N_p^-)/(N_p^+ + N_p^-)$	$(1.3\pm 0.3)\times 10^{-3}$	$(4.6\pm 0.2)\times 10^{-5}$	0.60 ± 0.14	-0.01 ± 0.05
3. Beam position modulation:				
$\langle \delta x_1 \rangle$	(dependent on	$< 3.7\ \mu\text{m}$	(0.9)	
+3 similar terms	beam position)			-0.05 ± 0.19
4. Emittance modulation:				
$\langle \delta r^2 \rangle$	$2.5\times 10^{-10}\ \mu\text{m}^{-2}$	$< 200\ \mu\text{m}^2$	(0.5)	$<\pm 0.4$
5. Energy modulation				$<\pm 0.2$
6. β decay				$<\pm 0.1$
7. Double scattering				$<\pm 0.2$
8. Periodic beam modulation				$<\pm 0.1$
9. Electronic effects				$<\pm 0.1$
Total Correction				-0.20 ± 0.74

the final result. Substantial variations from run to run can be excluded because of the excellent internal consistency of the measurements ($\chi^2/N = 0.99$, where N is the number of degrees of freedom).

(6) β decay.—Proton-induced reactions can produce polarized β emitters whose parity-nonconserving decay contributes to the measured currents in the scattering chamber. The treatment of this effect in Ref. 5 was improved by direct measurements of the activation calculations for the short lifetimes. The uncertainty in A_z from this effect is well below 0.1×10^{-7}.

TABLE II. Summary of experimental results for A_z (in units of 10^{-7}). The errors given in this table include only the statistical errors of the measurements and statistical errors in the measured corrections.

	Raw data	Corrected values
Solenoid +	-16.64 ± 1.28	-0.40 ± 1.30
Solenoid −	16.08 ± 1.24	1.04 ± 1.28
Average A_z	0.10 ± 0.89	0.34 ± 0.92
$\frac{1}{2}$ difference	-16.35 ± 0.89	-0.72 ± 0.92

(7) Double scattering.—If the arrangement lacks perfect axial symmetry, double scattering of protons can lead to a systematic error, since the protons acquire a transverse polarization component after the first scattering. To enhance such an effect large deliberate asymmetries were introduced in the scattering chamber (enhancement factor $\gtrsim 100$), but no effect could be seen in these auxiliary measurements with an accuracy of a few times 10^{-7}.

(8) Periodic modulations of the beam.—The intensity of the beam shows a rather large (~5%) modulation synchronous to the line frequency (50 Hz). The influence of these modulations was reduced by integrating the currents in the ionization chamber and in the Faraday cup during exactly 20 msec, by a special polarization pattern (+ − + − + − + − − + − + − + − +), and by a pseudorandom change of the sign of the polarization after sixteen individual measurements.

(9) Electronic null test.—A test with constant current sources gave a null asymmetry: $(-0.10 \pm 0.11)\times 10^{-7}$. A possible effect would be further reduced by reversal of the solenoid field.

Table II lists the average values of A_z for the

27 runs (of 20 min duration) with positive sign of the spin precession solenoid and the 27 runs with negative sign. The 54 *corrected* runs are statistically consistent ($\chi^2/N = 0.99$) and the *corrected* values show no dependence on the sign of the solenoid field.

Our final result for a mean proton energy of 46 MeV is

$$A_z = (+0.3 \pm 1.3) \times 10^{-7}. \quad (2)$$

The uncertainty includes the statistical and systematic errors (root square sum). The measured A_z is an average over scattering angle. The relative acceptance of the scattering chamber as a function of $\theta_{\rm lab}$ was calculated numerically. It has a maximum at $\theta_{\rm lab} = 33°$ and falls to one tenth of the maximum at 24° and 58°.

Besides f_π, $A_z^{p\alpha}$ contains contributions from the weak ρNN and ωNN coupling constant ($h_{\rho,\omega}$). To a large extent, the contributions from $h_{\rho,\omega}$ can be subtracted out, since they enter in similar combination into A_z^{pp} for pp scattering at 45 MeV. We can write f_π as[9]

$$f_\pi = -1.92(A_z^{p\alpha} - 1.44 A_z^{pp}) - 0.25(\chi_{pn}^{+} - \chi_{pp}), \quad (3)$$

where χ_{pn}^{+} and χ_{pp} are certain linear combinations of $h_{\rho,\omega}$ defined in Ref. 2. In a recent paper[10] best estimates and extreme limits are given for all weak parity-nonconserving meson-nucleon coupling constants, based on a detailed quark-model analysis taking into account hyperon decay data. This leads to $0.25(\chi_{pn}^{+} - \chi_{pp}) = (-1.9 \pm 1.3) \times 10^{-7}$, where the uncertainty is the most pessimistic value compatible with the limits of Ref. 10. If we use the experimental value[1,11] A_z^{pp}(45 MeV) $= (-2.3 \pm 0.8) \times 10^{-7}$, we find $f_\pi = (-5.0 \pm 3.6) \times 10^{-7}$ which is at the low end of the range of values [(0 to 12) $\times 10^{-7}$ for the Weinberg-Salam theory] given in Ref. 10. By comparison, results on P_γ in heavy nuclei agree with the "best-guess" $f_\pi = 4.6 \times 10^{-7}$ (Ref. 1), while recent reanalyses of γ transitions in certain light nuclei yielded $f_\pi = 1.5 \times 10^{-7}$ (Haxton, Gibson, and Henley[12]) and $< 2.5 \times 10^{-7}$ (Brown, Richter, and Godwin[13]). Since the present error quoted for f_π is dominated by the experimental uncertainties of $A_z^{p\alpha}$ and A_z^{pp}, it is important that these measurements be improved.

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