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Test of Parity Conservation in p-p Scattering*

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We report a result of $(1\pm4)\times10^{-7}$ for the parity-nonconserving component in the p-p nuclear cross section at 15 MeV. Our experiment uses rapid spin reversal of a longitudinally polarized proton beam and an unpolarized H_2 target. Sources of systematic error are discussed and found to be $<10^{-7}$.

The presence of weak interactions between hadrons, which is implied by the current-current form of weak interaction theory,[1] has been established by observations of parity mixing in many nuclei.[2] However, no quantitative agreement exists between theory and experiment, either for heavy nuclei, where nuclear-structure effects complicate calculations, or for the lightest system with a reported effect, $np\to d\gamma$.[3,4] This lack of agreement emphasizes the necessity for studying the nucleon-nucleon system through p-p scattering is estimated to be a few parts in 10^7, the actual effect, which is sensitive to the details of the interaction including the possible presence of neutral currents, could be considerably different. The smallest previous experimental upper limit on the magnitude of the parity admixture in p-p scattering is 5×10^{-3} at 210 MeV.[7] Order-of-magnitude improvements are needed to test the various models of the weak interaction.

Our experiment is sensitive to the pseudoscalar term $\hat{\sigma}\cdot\hat{p}$ in the total nuclear cross section arising from the interference between the parity-conserving and parity-nonconserving parts of the scattering amplitude. ($\hat{\sigma}$ is the spin and $\hat{p}$ the momentum of the incident proton.) This interference is observed by scattering a longitudinally polarized proton beam on an unpolarized hydrogen target and detecting the change in the total nuclear cross section when the polarization is reversed.

A 200-nA beam of longitudinally polarized protons from a Lamb-shift ion source[8] is accelerated to 15 MeV at the Los Alamos tandem Van de Graaff accelerator and strikes an H_2 gas target (Fig. 1). A two-stage fast-steering system with feedback stabilizes the beam position and angle at our detector, reducing movement of the beam by a factor of ~50.

A measure of the total cross section is obtained by detecting the scattered beam over a solid angle of nearly 4π. To realize adequate statistical accuracy in a reasonable time, the scattered beam current (~3×10^9 protons/sec) is measured

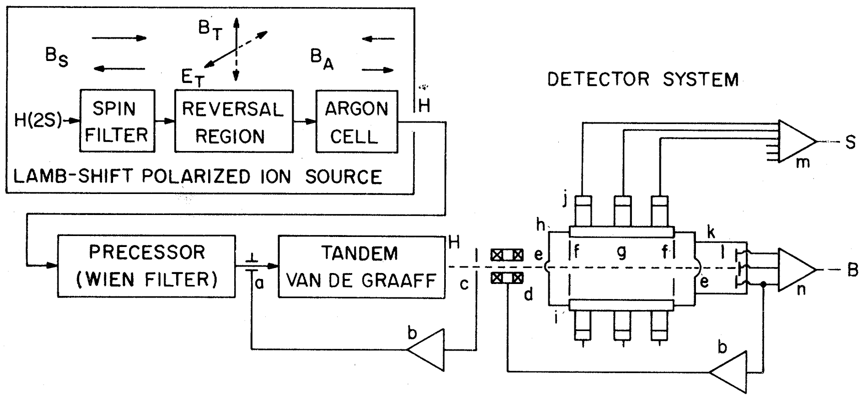

FIG. 1. System for p-p parity-conservation test. a, steering plates; b, steering amplifier; c, position detector; d, steering coil; e, window; f, aperture; g, H_2 gas; h, pressure vessel; i, scintillator; j, photomultiplier; k, vacuum chamber; l, beam stop and position detector; m, side-detector summing amplifier; and n, rear-detector summing amplifier.

instead of counting individual protons.[9] Low-noise amplification of the scattered proton current is achieved with a scintillator-photomultiplier combination followed by operational-amplifier current-to-voltage converters. Four liquid-scintillator cells, each viewed by three phototubes, are arranged to form a 76-mm-square cylinder 380 mm long centered on the beam axis in a vessel containing H_2 gas at 3 atm. The currents from the twelve phototubes are summed, with gains adjusted so that each tube contributes equally, to make the S (side-detector) signal. The beam enters and leaves the pressure chamber through Kapton foil windows. A gold aperture prevents the beam from scattering directly into the scintillators from the front window. The beam intensity is monitored by the current on a gold beam stop in an evacuated chamber behind the pressure vessel. The beam stop is divided into a central disk and outer quadrants that provide position signals for the downstream steering feedback system. The amplified signals from the five parts of the beam stop are summed to form the B (back-detector) signal.

An analog divider is used to form the ratio $Y = (S-B)/B$. Adjusting the amplifier gains to make $S-B \cong 0$ insures optimal divider performance and normalizes the signal. With this normalization the change in Y is equal to the relative change in cross section with polarization reversal. The polarization is reversed at 1 kHz, and the change in Y at 1 kHz, Y_f, is detected with a phase-locked amplifier (PLA) synchronized with the reversal. The output of the PLA is integrated for 1-sec intervals with an integrating digital voltmeter (DVM) and results from successive intervals are accumulated in a computer. Treatment of the data is discussed later.

The details of the polarization reversal technique are important to the discussion of systematic errors and control experiments. In the ion source a beam of hydrogen atoms in the metastable 2S state is formed by passing 500-eV H^+ ions through cesium vapor. A spin filter then quenches to the ground state all magnetic substates except the desired $m_J = +\frac{1}{2}$, $m_I = +\frac{1}{2}$ state.[8] The transmitted state is selected by tuning the longitudinal magnetic field B_S of the spin filter to 540 G. The beam then passes through an argon gas cell where the metastable atoms are preferentially ionized to form H^- for acceleration in the Van de Graaff. A 6-G longitudinal guide field B_A in the argon cell region keeps the metastable atoms aligned until the H^- ions are formed. In conventional operation B_A is parallel to B_S and the polarization is reversed by changing the sign of both fields. However, this method is impractical for fast polarization reversal because of the large inductance of the spin-filter coil. If B_A is antiparallel to B_S, the polarization can be reversed rapidly by turning on and off a 2-G transverse field B_T located at the zero in the longitudinal field. When B_T is zero, the metastable atoms are transmitted with their spin direction unchanged; when B_T is on, the spin is adiabatically guided around, reversing its direction. The antiparallel configurations of B_S and B_A, $+-$ and $-+$, are both used to measure the parity-noncon-

TABLE I. Experimental results for each ion-source field configuration.

Source fields B_S	B_A	Beam helicity B_T off	B_T on	Reversal	Ideal[a] form of data	Raw data $\bar{Y}_f \times 10^7$	Corrected[b] results $\times 10^7$
+	+	R	R	No	0	$+6.0 \pm 7.6$	$+4.7 \pm 6.0$
−	−	L	L	No	0	-10.6 ± 7.7	-8.4 ± 6.1
+	−	R	L	Yes	ϵ	$+4.5 \pm 7.7$	$+3.6 \pm 6.1$
−	+	L	R	Yes	$-\epsilon$	$+2.9 \pm 7.4$	$+2.3 \pm 5.9$

[a] ϵ is a hypothetical parity-nonconservation effect for purposes of illustration.
[b] Corrected for Coulomb scattering and net polarization change.

servation effect. The two parallel configurations, ++ and −−, are used to test for systematic errors, since here polarization reversal cannot occur even though B_T is being turned on and off. The left-hand columns of Table I illustrate the effect of the four field configurations on the polarization and the ideal form of the data. Any statistically significant deviation from this pattern of results indicates the presence of systematic errors.

The magnitude of the change in polarization is measured using a transversely polarized beam with a carbon foil scatterer and two opposing quadrants of the S detector as an analyzer. By shielding the reversal region from stray fields and by optimizing the shape of the longitudinal B field, we can reverse 95% of the metastable atoms in a 25-mm-diam beam, as determined by comparing fast reversal to the conventional method of reversal. On the basis of the measured polarization of the beam, 86%,[10] the net change in polarization with fast reversal is 1.64. The carbon-foil analyzer is also used to test the alignment of the longitudinally polarized beam. A Wien filter type of spin precessor adjusts the direction at the target.

Five possible sources of systematic errors have been considered: (1) current modulation, (2) phase-space modulation, (3) polarization misalignment, (4) ground loop currents, (5) offset and linearity errors in the PLA and DVM. The first three of these are properties of the beam to which the experiment is designed to be insensitive. We estimate their effect on the results by measuring separately each property and the sensitivity of the experiment to that property. Errors arising from sources (1), (2), (4), and (5) are distinguishable by failure of the data to fit the pattern listed under "ideal data" in Table I for the four configurations of the source fields.

(1) Current modulation arises from the quenching of the metastable atoms by the motional E field from B_T. This quenching is compensated by a transverse electric field that is turned on whenever B_T is on. The residual current modulation is $< 2 \times 10^{-4}$ of the beam current. The divider rejects any current modulation common to both S and B by a factor of 2×10^3. Therefore, the effect of current modulation is $< 10^{-7}$.

(2) Phase-space modulation arises because a few ions are formed in the reversal region and are steered by B_T. The number of steered ions in the beam has been reduced by increasing the pumping speed and applying a transverse electric sweeping field in the reversal region. The movement of the beam centroid at the target is estimated to be < 1 μm. Since we measure a signal of $< 10^{-4}$ with a deliberate position modulation of 1 mm impressed on the beam, this error term is less than 10^{-7}.

Because the polarization reversal is independent of the sign of B_T, we can reduce phase-space and current-modulation effects even further by changing the sign of B_T and E_T on alternate cycles. If the magnitudes of B_T and E_T are unchanged in this process, the phase-space and current-modulation error signals will be converted to 500 Hz and will not be detected by the PLA.

(3) The beam polarization is never exactly longitudinal. A small reversing transverse component of polarization is analyzed by the target gas. The resulting scattering asymmetry contributes to the divider output unless the target is exactly symmetrical. We have measured an effective analyzing power of 10^{-3} and an asymmetry of 10^{-2} for our detector. The transverse component of polarization was adjusted to be less than 10^{-2}. The error from polarization misalignment is therefore less than 10^{-7}.

(4) Ground-loop errors result when the signals from the reference oscillator are coupled into the input of the PLA or the amplifiers preceding it through a common ground impedance. Careful grounding techniques and the use of optical isolators for all of the reference outputs reduce this error to $\sim 10^{-8}$.

(5) Errors introduced by the dc offset and nonlinearity of the PLA and DVM have been measured to be below the 10^{-8} level.

Data were taken for 22 runs of 400 sec in each of the four ion-source field configurations. For each run the mean and variance of 400 Y_f values are calculated. The averages and statistical errors for each set of runs are listed in Table I. Two correction factors are applied to the data. The ratio of the signal from Coulomb-scattered events to nuclear scattering is estimated from the p-p cross section to be 0.3 for our target geometry. To correct for this dilution by Coulomb scattering, $\overline{Y}_f$ is multiplied by 1.3. The result is then divided by 1.64, the total change in polarization, to obtain the parity-nonconserving component of the nuclear cross section $F=(\sigma_R - \sigma_L)/(\sigma_R+\sigma_L)$; σ_R (σ_L) is the total nuclear cross section for right-handed (left-handed) helicity. No correction for the finite solid angle of the detector is necessary, assuming the same angular distribution (S wave) for the weak and strong parts of the scattering amplitude.

The data for the control runs ++ and −− are consistent with our estimate that systematic errors are $<10^{-7}$. The data for the +− and −+ configurations are combined to give $F=(1\pm 4)\times 10^{-7}$. This result already excludes any effect much larger than predicted by conventional theory.[11] We are encouraged that our data appear to be limited only by the statistics of the scattered protons and plan to extend these measurements.[12]

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