Charge-Symmetry Violation in Neutron-Proton Elastic Scattering at $E_n = 183$ MeV

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Measurements of the spin dependence of n-p elastic scattering at $E_n = 183$ MeV have been carried out with polarized neutrons and polarized protons. If charge symmetry holds, the two analyzing powers A_n and A_p must be equal. The measured value of $\Delta A \equiv A_n - A_p$, averaged over the angular range $82.2° \leq \theta_{\text{c.m.}} \leq 116.1°$, is $(33.1 \pm 5.9 \pm 4.3) \times 10^{-4}$. This result represents clear evidence of charge-symmetry violation in the strong interaction. The measurement agrees well with predictions from meson-exchange theory when these include the isospin mixing of the ρ^0 and ω^0 mesons.

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One of the most basic and long-standing questions in nuclear physics concerns the extent to which isospin symmetry is preserved by nuclear forces: Do the particles that make up a given isospin multiplet—for example, the neutron and proton–experience identical strong interactions? Isospin symmetry plays an important role in the study of nuclei, giving rise to simplifications in nuclear-structure calculations, selection rules for β and γ decay, conservation laws for nuclear reactions, and a natural explanation for regularities in the properties of nuclei. In quantum chromodynamics, isospin symmetry arises from the assumption that the basic quark-quark interactions are independent of quark flavor. In this context, violations of isospin invariance can arise either from the mass difference between the u and d quarks or from Coulomb interactions between the quarks.

It has been recognized for many years that nucleon-nucleon interactions do not obey isospin symmetry in its most general form.[1] Experiments show that in the $^1S_0$ state, the scattering length for the np system ($a_{np} = -23.75 \pm 0.01$ fm) is significantly more negative than either the nn scattering length[2,3] ($a_{nn} = -18.6 \pm 0.4$ fm) or the Coulomb-corrected pp scattering length[1] ($a_{pp} = -17.3 \pm 0.4$ fm). In meson-exchange calculations this effect is largely attributed[1] to the mass difference between the neutral and charged π mesons.

Charge symmetry (CS) is a less restrictive form of isospin symmetry, according to which interactions must be invariant under a specific rotation in isospin space that interchanges every particle with its isospin mirror—for example, $n \leftrightarrow p$. At the quark level this is equivalent to interchanging the u and d quarks. Since the π-meson masses are invariant under this transformation, experiments that test CS have the potential to probe smaller isospin violations that arise fundamentally at the quark level.

Applied to the NN system, CS requires that $V_{nn} = V_{pp}$ (neglecting Coulomb interactions). In addition, V_{np} must be invariant under interchange of the two interacting particles. In practice, this means that V_{np} must depend in a symmetric way on the spins of the neutron and proton.

In the present Letter we report new measurements for neutron-proton elastic scattering at $E_n = 183$ MeV which show clear evidence of CS violation in the np system. Basically, the experiment involves measuring the "analyzing powers" A_n and A_p. These quantities carry information on the sensitivity of the scattering cross section to the spin polarization of the neutron and proton, respectively. Thus, if A_n and A_p are measured at the same c.m. angle and energy, CS requires $A_n = A_p$. This experiment is similar in many respects to a recent measurement[4] at TRIUMF (at $E_n = 477$ MeV). However, because of the large energy difference the experiments are sensitive to different CS-breaking mechanisms. In addition, the new measurement is more accurate by a factor of 3, and provides information about the angular dependence of the CS violation.

One important feature of the experiment is that, in contrast to conventional tests of CS (such as the comparison of binding energies of mirror nuclei[5]), the corrections for electromagnetic (EM) effects are small. For example, in the $A = 3$ system about 90% of the observed binding-energy difference, $B(^3\text{H}) - B(^3\text{He}) = 764$ keV, is caused by EM effects with only 80 ± 20 keV attributed to CS violation in the strong interaction.[6] Similarly, in the comparison of the scattering lengths, the Coulomb correction to a_{pp} is large (nearly 10 fm) and has an uncertainty[1] which is significant on the scale of the nn-pp difference. For the np experiments there is also an EM contribution, but in this case the correction is smaller than the residual strong-interaction CS-violating signal.

The new measurements were carried out at the Indiana University Cyclotron Facility (IUCF). The polarized

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neutron beam was produced by bombarding a 20-cm-long liquid-deuterium target with 200-MeV polarized protons. Neutrons from the reaction $^2\mathrm{H}(\vec{p},\vec{n})2p$ at $\theta_{\mathrm{lab}}=10°$ were collimated into a beam 5 cm wide by 7 cm high which bombarded a polarized proton target (PPT) located 4 m downstream from the liquid-deuterium cell. The neutron energy distribution is dominated by a single peak approximately 15 MeV wide (FWHM). The average energy of the accepted events was 183 MeV. The vertical component of the neutron polarization (typically 0.56 in magnitude) was reversed at regular intervals (roughly 30 s) by switching rf units at the polarized ion source. The PPT is similar in many respects to the device described in Ref. 7. The target polarization was typically 0.42, and the magnetic-field strength during data acquisition was 590 G. The proton polarization was reversed at 10-min intervals by rotating the holding field through 180°, and the orientation of the spin relative to the magnetic field was reversed approximately twice per day.

Neutron-proton elastic-scattering events were identified by detecting the scattered neutron and recoil proton in coincidence. The detector arrays, which are described elsewhere,[8-10] were left-right symmetric and covered laboratory angles from 24° to 62°. The proton detectors consisted of a thin plastic scintillator followed by two sets of x-y multiwire proportional counters. The scattered neutrons were detected with large liquid scintillators which were segmented to provide angular information. Events from n-p scattering were distinguished from background by imposing a series of "free-scattering" conditions. Specifically, cuts were made on the ΔE signal in the proton scintillator, the vertical and horizontal coordinates of the event origin at the PPT, and the np coincidence time as determined from the proton scintillator and the neutron detector. In addition, we require that the opening angle and coplanarity of the neutron and proton trajectories be consistent with free-scattering kinematics. Events from neutrons with energies below 170 MeV were eliminated by a cut on the neutron arrival time at the PPT measured relative to the cyclotron rf. Further reductions in background were achieved by subtracting results obtained with a "dummy" target, whose composition is similar to that of the PPT except that it is essentially hydrogen free. This effectively eliminates events from "quasifree" scattering (in which a neutron knocks out a proton from some nucleus in the PPT material) and reduces the background to an acceptable level (less than 0.2%). Further details concerning cuts and background tests are given in Refs. 8-10.

The asymmetries associated with reversal of the neutron spin and the proton spin are easily extracted from the raw count rates by taking appropriate combinations of the integrated yields for left and right scattering, and for various beam and target spin states. The measured asymmetries, P_bA_n and P_tA_p (where P_b and P_t represent the beam and target polarizations, respectively), are presented as a function of scattering angle in Fig. 1. In this plot, the statistical errors are roughly one-tenth the size of the plotting symbols. On this scale, the two sets of data appear to be virtually identical except for an overall normalization factor which reflects the fact that P_b and P_t are not equal.

Extracting the quantity of interest, $\Delta A \equiv A_n - A_p$, from these measurements is complicated by the fact that the beam and target polarizations are known only to within a few percent. In practice, this means that if ΔA happens to be proportional to A_n and A_p, our experiment would be incapable of detecting the CS violation. On the other hand, if ΔA is roughly constant as a function of $\theta_{\mathrm{c.m.}}$ (so that A_n is shifted up or down relative to A_p), then the effect can be detected by, for example, extracting the zero-crossing angles of A_n and A_p (as in Ref. 4).

To make these ideas more explicit we define the mean polarization $P \equiv (P_bP_t)^{1/2}$ and the ratio $R \equiv P_t/P_b$. Then ΔA is given in terms of R, P, and the measured asymmetries by

$$\Delta A = [R^{1/2}(P_bA_n) - R^{-1/2}(P_tA_p)]/P . \tag{1}$$

It follows that if one uses values of R and P that are in error by some amount δR and δP, then to first order the extracted value of ΔA will be in error by

$$\delta(\Delta A) = A(\theta)\frac{\delta R}{R} - \Delta A(\theta)\frac{\delta P}{P} , \tag{2}$$

where $A(\theta)$ is the average of A_n and A_p. Note that the uncertainty in P (which we estimate to be $\pm 5\%$) simply gives rise to an acceptable $\pm 5\%$ normalization error in ΔA. The effect of an error in R is to shift ΔA by an amount proportional to $A(\theta)$, and consequently this contribution to the uncertainty will be negligible if $A(\theta)$ is

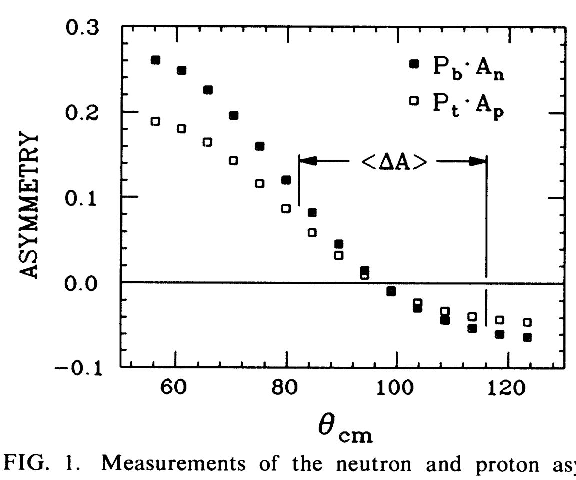

FIG. 1. Measurements of the neutron and proton asymmetries for n-p elastic scattering at $E_n=183$ MeV. The angle range used in determining $\langle \Delta A \rangle$ is indicated.

sufficiently small. These same conclusions hold if the quantity being determined is the *average value* of ΔA over some angular range. (We use simple averages over θ with no cross-section weighting.) In particular, if one chooses an angle range for which $\langle A(\theta)\rangle$ is zero, then $\langle \Delta A\rangle$ for that angle range will be subject only to the 5% normalization uncertainty.

From the measurements shown in Fig. 1 we find that $\langle A(\theta)\rangle$ is zero (to within ± 0.002) for the angle range $82.2° \le \theta_{\text{c.m.}} \le 116.1°$. The average value of ΔA within this range constitutes our main experimental result. The measured value is

$$\langle \Delta A\rangle = (33.1 \pm 5.9 \pm 4.3)\times 10^{-4}, \qquad (3)$$

where the quoted uncertainties represent, in order, the statistical error and our estimate of the systematic error. The result given in Eq. (3) represents clear evidence of charge-symmetry violation in the *np* interaction.

Before discussing the implications of this measurement, we comment briefly on the systematic errors. The error sources considered include the $\pm 5\%$ normalization uncertainty, the effects of possible unsubtracted background, spin-correlation effects, effects due to deflection of the recoil protons in the PPT magnetic field, and possible spin-dependent removal of *np* events by the software cuts. The quoted error also includes the uncertainty in small corrections that have been applied to $\langle \Delta A\rangle$ for spin-dependent event losses due to accidental coincidences, and for effects caused by the variation of the neutron-beam polarization as a function of energy. The net systematic error quoted in Eq. (3) is the sum in quadrature of some eighteen separate error contributions. A full description of the systematic-error evaluation will be given elsewhere.[10]

As a consistency check, the entire data analysis procedure, including event reconstruction, selection of the good *np* events, and extraction of $\langle \Delta A\rangle$, was carried out independently (using independently written computer codes) at IUCF and at the University of Wisconsin. The final results for $\langle \Delta A\rangle$ obtained in the two analyses agree to within 1.2×10^{-4}. This is well within the expected statistical variation that results from differences in the event selection in the two analyses.

In addition to the measurement of $\langle \Delta A\rangle$, our experiment also provides information on the angular dependence of ΔA. A full discussion of these results will be given in Ref. 10. Here we simply present (see Fig. 2) measured values of $\Delta A(\theta)$ extracted by treating the polarization ratio R as a free parameter which is adjusted to optimize the agreement with a particular theoretical prediction (shown in Fig. 2) derived from results reported in Ref. 11. According to Eq. (2) this method for choosing R may introduce into ΔA a spurious component proportional to $A(\theta)$. In spite of this ambiguity, one can see that the measurements have an angular dependence which is consistent with the theoretical curve ($\chi^2 = 13$ for

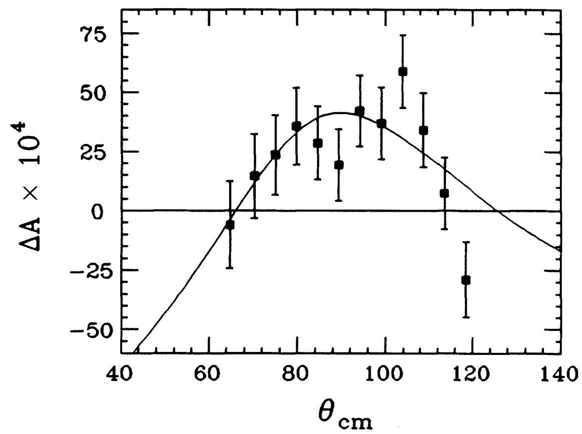

FIG. 2. Experimental results for $\Delta A(\theta)$ obtained by treating R as a free parameter. The displayed errors include statistics only. The curve is a calculation (Ref. 17) based on results (Ref. 11) obtained with the Bonn *NN* potential.

11 degrees of freedom). In particular, the curvature of the ΔA measurements, which is largely unaffected by changes in R, is similar to that of the calculation.

Theoretical predictions of ΔA for n-p scattering have been reported by a number of groups.[11-15] Although it is presumed that the CS violation arises fundamentally at the quark level, most practical calculations are based on meson-exchange models. For the energy range of the present experiment, nonzero values of ΔA arise mainly from three mechanisms: the purely EM (photon-exchange) interaction between the neutron magnetic moment and the proton current; the effect of the n-p mass difference in isovector meson-exchange processes, especially one-pion exchange (OPE); and isospin mixing of the ρ^0 and ω^0 mesons. Each of these effects gives rise to a potential (see, for example, Ref. 12) that depends in a nonsymmetric way on the neutron and proton spins. Predictions of $\Delta A(\theta)$ are generally obtained by calculating the CS-violating mixing parameters[16] using the Born approximation with distorted waves generated from a conventional *NN* potential. The mixing parameters are then used in conjunction with isospin-conserving phase shifts obtained from a potential or a phase-shift analysis.

At 477 MeV, predictions based on meson-exchange models[11-14] generally agree quite well with the earlier ΔA measurement from TRIUMF.[4] At this energy the contribution from ρ-ω mixing is predicted to cross through zero in the angular range of the measurements, and thus ΔA arises almost entirely from the n-p mass-difference effect.

At 183 MeV the situation is different. In Fig. 3 we compare the new measurement of $\langle \Delta A\rangle$ with a number of theoretical predictions.[17] We see that the measurement is clearly incompatible with the assumption of no CS violation in the strong interaction. The predicted EM contribution to $\langle \Delta A\rangle$ is about 8.5×10^{-4}, with little

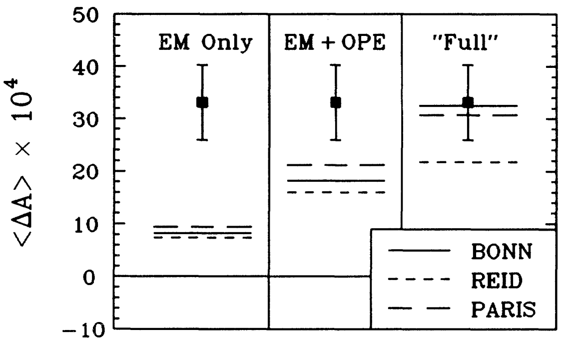

FIG. 3. Comparison of the measured value $\langle \Delta A \rangle$ with various theoretical predictions (Ref. 17). The experimental error bars show the sum in quadrature of the statistical and systematic uncertainties. The calculations are based on published results obtained using the following NN distorting potentials: Reid, Paris (both from Ref. 12), and Bonn (Ref. 11).

dependence on the choice of distorting potential. With the statistical and systematic errors added in quadrature, the measured $\langle \Delta A \rangle$ differs from the EM prediction by 3.4 standard deviations. The measurement is also significantly higher than calculations which include the OPE contribution. However, the "full" calculations, which include ρ-ω mixing (plus a very small contribution from single-ρ exchange) in addition to the EM and OPE terms, are generally in good agreement with the measurement.

These same meson-exchange models are also capable of explaining results from experiments that test CS as it applies to V_{nn} and V_{pp}. In particular, it has been shown[6] that ρ-ω mixing can lead to differences between a_{nn} and a_{pp} of about 1 fm (in agreement with the best available experimental evidence[1]), and can also account for a large portion of the mirror-nucleus binding-energy discrepancy for $A=3$ as well as for heavier nuclei.[6,18]

In summary, we have reported a new measurement of the CS-violating quantity $A_n - A_p$ for n-p elastic scattering at $E_n = 183$ MeV. The measurement differs by 3.4 standard deviations from the result expected for EM interactions alone. Since the EM corrections are small and well understood, this result represents the most clear-cut evidence to date of CS violation in the NN interaction. The measurement is in excellent agreement with calculations based on meson-exchange models of the CS-violating interaction. These results support the suggestion that ρ-ω mixing (which at the quark level is attributed to the u-d quark mass difference[1]) plays an important role in CS violation in the NN system.

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