Test of Charge Symmetry in Neutron-Proton Elastic Scattering at 477 MeV

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An experiment resulting in the first measurement of the isospin-mixing, charge-symmetry–violating component of the n-p interaction has been performed. The experiment determined the difference in the angles of the zero crossing of the neutron and proton analyzing powers A_n and A_p at 477 MeV. In terms of the laboratory scattering angle of the neutron, the measured difference is $\theta_{0n}(A_n) - \theta_{0n}(A_p) = +0.13° \pm 0.06°$ ($\pm 0.03°$), where the second error is a worst-case estimate of systematic error. The resulting difference in the analyzing powers at the zero-crossing angle is $A_n - A_p = +0.0037 \pm 0.0017$ (± 0.0008).

Isotopic-spin invariance or charge independence was the first "internal symmetry" postulated in elementary particle physics. It refers to the invariance of strong-interaction processes under arbitrary rotations in three-dimensional isospin space. Consequently the nucleon-nucleon (N-N) Hamiltonian commutes with the total isospin operator T^2, forbidding mixing of isospin $T = 0$ with isospin $T = 1$ N-N states, and with the three projections of the isospin operator T_i ($i = 1$, 2, and 3). Isotopic-spin invariance is broken by the electromagnetic interaction and thus one expects effects of the order of the fine-structure constant $\alpha = \frac{1}{137}$. Charge symmetry is a lesser symmetry which refers to the invariance only under a rotation in isospin space through π about the 2 (or, the 1) axis, and is represented by the operator $P_{cs} = \exp(i\pi T_2)$. The operator P_{cs} transforms T_3 into $-T_3$, thus replacing any particle by its mirror counterpart, e.g., $p \to n$, $\pi^+ \to \pi^-$, or $u \to d$.

In the isospin classification of the N-N interaction by Henley and Miller[1] it is possible to distinguish three charge-asymmetric, charge-dependent interaction terms denoted by

$$V_{ij} = D[t_3(i) + t_3(j)] + E[t_3(i) - t_3(j)]$$
$$+ F[\mathbf{t}(i) \times \mathbf{t}(j)]_3.$$

The quantities $\mathbf{t}(i)$ and $t_3(i)$ denote the isospin operator of nucleon i and its third component, respectively, while the quantities D, E, and F are functions of space and spin operators. The first term (the class-III interaction) only affects the p-p and the n-n systems; there is no isospin mixing since $[T^2, T_3] = 0$. To study this interaction one compares measurements for two mirror systems which themselves are not eigenstates of the operator P_{cs}. The second and third terms (the

class-IV interaction) are antisymmetric under the interchange of nucleons i and j in isospin space and only affect the n-p system. The n-p system has $T_3 = 0$ and in the absence of the above interaction is an eigenstate of the operator P_{cs} with eigenvalues ± 1 depending on the value of the total isospin quantum number T. The class-IV interaction causes mixing of the $T = 0$ and $T = 1$ isospin states.

On the assumption of conservation of parity and total angular momentum, charge symmetry of the n-p interaction leads to the complete separation of the isoscalar and isovector parts of the scattering matrix. In the even (odd) partial waves the isoscalar part contains spin triplet (singlet) and the isovector part spin singlet (triplet) terms only. Charge symmetry forbids transitions between the two parts of the scattering matrix and thus between the spin triplet and singlet states. The triplet-singlet transition amplitude f_{TS} must vanish. This implies that the analyzing power of polarized neutrons scattering from unpolarized protons $A_n(\theta)$ and the analyzing power for unpolarized neutrons scattering from polarized protons $A_p(\theta)$ must be equal. If, on the other hand, charge symmetry is broken, isospin mixing via spin triplet-singlet transitions becomes possible and a nonzero difference $\Delta A = A_n(\theta) - A_p(\theta)$ will be observed in general. At 477 MeV the most important spin triplet-singlet transitions are $^3P_1 \to {}^1P_1$, $^3D_2 \to {}^1D_2$, and $^3F_3 \to {}^1F_3$. The difference ΔA is directly proportional to the amplitude f_{TS} and can be expressed using the N-N scattering formalism given by Bystricky, Lehar, and Winternitz[2] as

$$\Delta A = (2/\sigma_0) \operatorname{Re}[b^* f_{TS}],$$

where σ_0 is the differential cross section for the scattering of unpolarized particles.

The experiment measured the difference in the angles where the two analyzing powers A_n and A_p cross through zero. Although designed as a null measurement, requiring no accurately known polarization or analyzing-power standards, the experiment was performed as accurately as possible in order to control systematic errors due to instrumental effects. The TRIUMF neutron-beam facility and the detection system for the experiment have been described in detail elsewhere.[3,4] A schematic diagram of the apparatus used is shown in Fig. 1. The two interleaved phases of the experiment, consisting of polarized (unpolarized) proton beams, with an energy of 497 MeV, producing polarized (unpolarized) neutrons incident on the depolarized (polarized) proton target, used identical parameters except for the polarizations of beam and target. Only an outline of the polarized-beam phase of the experiment will be given.

The proton polarimeter and beam energy monitor detected protons scattered from a Kapton foil at 17° (laboratory) in coincidence with recoil protons from p-p elastic scattering; the measured instrumental asymmetry of the polarimeter was stable to ±0.001.
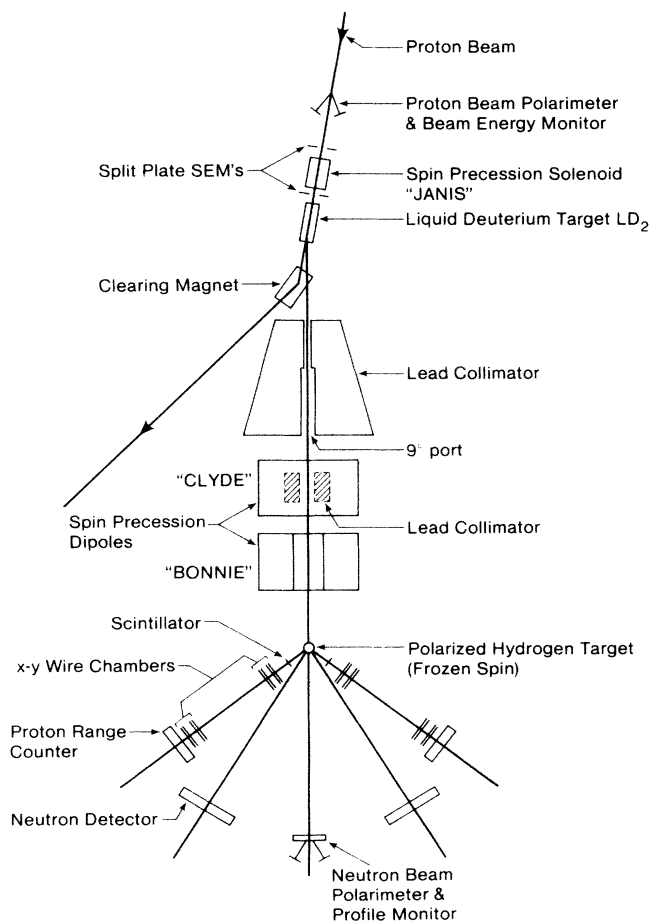

FIG. 1. Schematic representation of beam line and apparatus.

The beam energy monitor consisted of two six-element range counters behind the forward (17°) arms of the proton polarimeter. Continuous monitoring of the beam energy showed that each of the five independent data-taking runs had distributions of the mean energies with a $\sigma \leq 0.123$ MeV and a maximum deviation from the average energy of less than 0.277 MeV, well within the allowed ±0.50 MeV for each complete data set.

Two sets of split-plate secondary-emission monitors (SEM's) were coupled via a feedback system to two sets of steering elements placed upstream of the liquid-deuterium (LD$_2$) target in the beam line. The position and angle of the proton beam impinging on the LD$_2$ target were held constant to within ±0.15 mm and ±0.006°, respectively, in both the horizontal and vertical directions.

The two sets of SEM's were separated by a superconducting solenoid JANIS which rotated the transverse polarization direction of the incident proton beam by 90° clockwise into the horizontal reaction plane. With known transfer coefficients for the reaction $^2H(p_{pol},n)2p$ at 9° (laboratory),[5] a proton beam with a typical polarization in the range of 0.65 to 0.70 produced a neutron beam with a polarization of ~0.50. To reduce differences in beam emittance, both polarized and unpolarized proton beams were extracted from the polarized ion source. After traversing the 0.20-m-long LD$_2$ target, the proton beam was deflected away from the neutron beam and transported to a beam dump.

The neutron beam at the polarized target varied in intensity by less than 15% over an area 40 mm high by 56 mm wide. The neutron energy spectrum consisted of a relatively narrow peak of width (calculated) 11 MeV (FWHM) and a smooth background.[3,6] Approximately half the neutrons were contained in the main peak and the intensity of these neutrons was 9×10^3 s^{-1} cm^{-2} per 100 nA of primary proton beam. The intensity ranged between 200 nA during the first data-taking run and 1.2 μA during the final data-taking run. Variations in the LD$_2$ target density caused shifts in neutron energies of less than 60 keV. Parity conservation ensures that the energy spectrum of the neutron beam is independent of the polarization of the primary proton beam in the scattering plane and is therefore the same for measurement of both A_n and A_p. The mean energy of the neutron beam was determined by time-of-flight to be 477 ± 2 MeV.

The two magnetic dipole magnets BONNIE and CLYDE with horizontal and vertical magnetic fields, respectively, precessed the horizontal component of the neutron polarization into the vertical direction. The component of polarization perpendicular to the reaction plane was precessed simultaneously into the longitudinal direction. This component is small,

$P_y = -0.058 \pm 0.001$,[5] and has negative helicity after precession. Conservation of parity does not allow a component of the polarization in the scattering plane to affect the differential cross section unless the target also has a component of polarization in the same plane. Note also that residual beam polarization caused by P_y during the polarized-target phase of the experiment has negligible effects on the asymmetry since (a) effects due to A_{zz} average to zero over the left- and right-hand arms of the detector system, and (b) effects due to A_{zx}, which in principle can contribute, are negligibly small because A_{zx} crosses through zero at $\sim 73°$ (c.m.).[5] The uncertainty in the direction angle of the neutron spin was $\pm 5.8°$, well within the permissible limits of $\pm 10°$. The two dipole magnets also removed charged perticles from the beam.

The polarizable proton target, of the frozen-spin type (FST), was located 12.55 m from the LD$_2$ target. The target consisted of butanol beads 1.4 mm in diameter placed in the mixing chamber of a dilution refrigerator. The target temperature was 85 mK during the first data-taking run and was improved to approximately 60 mK by the end of the experiment. The target cell was in the form of a vertical cylinder of diameter 40 mm and height 50 mm. Typically, 55 ml of butanol beads were placed in the chamber. The average target polarizations obtained varied between 0.60 and 0.81 for the various data-taking runs. The strength of the holding field was 0.257 T at the FST, causing an average deflection of 1.2° for the recoil protons. The FST holding field was both stable and reproducible to better than 0.25 mT. The position of the target cell with respect to the magnetic field axis (vertical to within $\pm 1.0°$) was determined to within ± 0.5 mm from x-ray radiographs of the FST taken at least once for each data-taking period.

Scattered neutrons and recoil protons originating in the FST were detected in coincidence in two left-right symmetric detection systems, allowing cancellation of many of the systematic errors to first order. Each neutron detection system, placed at an angle of $32.00° \pm 0.01°$ consisted of four elements: a neutron scintillator array at distance of 5.325 m from the FST (center to center), a plane of charged-particle veto scintillators covering the front face of the neutron scintillator array, a set of small scintillators selecting fast protons for monitoring of the gain of the photomultipliers of the neutron scintillator array, and a charged-particle time-of-flight (TOF) scintillator close to the target. Each neutron scintillator array consisted of two consecutive banks of seven NE110 scintillator bars, each bar 1.050 m wide, 0.150 m high, and 0.150 m thick, placed one on top of the other. The bars were viewed at each end by photomultiplier tubes. The gains of the photomultipliers were determined to $\pm 0.5\%$ every two hours. The position resolution for

detected neutrons is ± 7.5 cm in the vertical direction and had a FWHM < 7 cm in the horizontal direction. The efficiency of the neutron scintillator arrays was 0.29 for 320-MeV neutrons, at a threshold setting of 4 MeV for minimum-ionizing particles.

Each proton detection system was supported by a boom placed at an angle of $52.00° \pm 0.02°$. The booms carried three functionally distinct systems: a TOF system for determining proton velocity, consisting of a TOF start scintillator close to the target and an energy scintillator E which served as the TOF stop at a distance of 3.44 m from the FST, a set of four 60-cm by 60-cm delay-line chambers for track reconstruction, and a range counter telescope for removal of high-energy and low-energy background. The elements of the range counter telescope were a pattern counter used for delay-line-chamber position calibration, a ΔE counter, a wedge-shaped degrader which compensated for the kinematic variation of proton energy with angle, the E counter, an absorber, and a veto counter. The delay-line chambers had an intrinsic resolution of ± 1 mm in the horizontal direction, and a vertical resolution of 0.7 mm FWHM. Efficiencies were typically > 0.99 per pair. Each detection system covered an angular range of $\sim 5°$ (laboratory) on either side of the crossover angle. Times and pulse heights were digitized for all scintillator detectors.

A complete measurement cycle lasted four days and consisted of FST holding-field directions up and down, each with positive and negative target polarizations for incident unpolarized neutrons, interleaved with measurements with the target depolarized and the neutron beam polarized. For polarized-beam measurements, the spin state of the beam (up, down, or off) was under computer control and usually randomized.

The data analysis has been carried out by two groups working independently with only discussions of the principles and results of the analysis. The data allow calculation of the neutron time of flight and position and the proton time of flight and trajectory. The proton energy was determined by time of flight between the proton TOF and E scintillators with an average resolution of 22 MeV (FWHM). For the neutrons, the average energy resolution was 41 MeV (FWHM). The resolution in the sum of the proton and neutron energies was 47 MeV (FWHM). The 2.0° (FWHM) spread in the n-p opening angle and 2.8° (FWHM) spread in the azimuthal coplanarity are largely determined by the multiple scattering of the proton in the FST which was estimated to average 1.7° (FWHM) in the scattering angle. Calculation of the proton and neutron energies, the n-p opening angle, and coplanarity for each event allows discrimination against quasifree n-p scattering from nuclei in the FST, e.g., ^{3}He, ^{4}He, ^{12}C, and ^{16}O. The remaining quasifree background is estimated to be about 1% of the elastic n-p

scattering events, based upon measurements with the butanol beads in the FST replaced by carbon beads.

The experimental difference in the zero-crossing angles of A_n and A_p as determined from the neutron laboratory scattering angles is

$$\theta_{0n}(A_n) - \theta_{0n}(A_p) = +0.13° \pm 0.06° \ (\pm 0.03°).$$

The analysis in terms of the proton laboratory scattering angles yields

$$\theta_{0p}(A_n) - \theta_{0p}(A_p) = -0.13° \pm 0.07° \ (\pm 0.03°).$$

These results are converted to a difference in analyzing power by multiplying by the negative of the slope of the analyzing power as a function of laboratory scattering angle. Values from the phase-shift analysis of Arndt et al.[7] were used, resulting in

$$A_n - A_p = 0.0284[\theta_{0n}(A_n) - \theta_{0n}(A_p)]$$

$$= 0.0037 \pm 0.0017 \ (\pm 0.0008)$$

and

$$A_n - A_p = -0.0263[\theta_{0p}(A_n) - \theta_{0p}(A_p)]$$

$$= 0.0034 \pm 0.0017 \ (\pm 0.0008).$$

The slopes from the Saclay-Geneva phase-shift analysis[8] are approximately 3% larger than those from Arndt et al. The analyzing power of the background at the zero-crossing angle is consistent with zero with an uncertainty of ± 0.02. The statistical uncertainty that it contributes to ΔA is ± 0.0002.

The quoted systematic uncertainty of $\pm 0.03°$ (± 0.0008) is the worst-case estimate at the present stage of the analysis. Variations in the difference in the zero-crossing angle due to (i) changes in the kinematic constraints eliminating background, (ii) changes in the pulse-height threshold of the neutron detectors, (iii) use of either neutrons or of protons in setting up the angle scale, and (iv) comparison of the independent data analyses all show fluctuations $\leq 0.01°$ when averaged over all the data runs.

Early calculations[9-12] were successful in predicting the approximate size of the charge-symmetry–breaking effect measured. However, the lack of good quantitative agreement of the result with theory has triggered a more detailed calculation.[13] This new calculation has included the following charge-symmetry–breaking terms: (i) one-photon exchange, (ii) the n-p mass

difference affecting π exchange, ρ exchange, and 2π exchange, (iii) ρ^0-ω mixing, and (iv) short- and medium-range effects of the u-d quark mass difference. The theoretical result at the crossover angle is $\Delta A = A_n - A_p = +0.0054 \pm 0.0004$.

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