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CHARGE SYMMETRY BREAKING IN n-p SCATTERING AT 183 MeV


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Abstract - Spin-dependent left-right asymmetries have been measured over a broad angular range (60° c.m.) for polarized neutrons elastically scattered from polarized protons. Charge symmetry requires the neutron and proton analyzing powers to be equal. Our preliminary result for their difference ΔA(θ) = A_n(θ) - A_p(θ), averaged over the angular range 82.2° < θ_{cm} < 116.1° is (32.1 ± 6.1 ± 6)x10^{-4}, with statistical and systematic uncertainties, respectively. Our experiment is also sensitive to, and we extract, that part of the angular dependence of ΔA, which is orthogonal to A(θ) itself. Overall, our data are well-described by meson-exchange calculations which include the effect of the n-p mass difference on one boson exchange, and comparably large contributions from p-ω mixing. Final replay results substantiate our initial averaged ΔA value and settle several systematic error uncertainties.

1 - INTRODUCTION

Isospin invariance of the strong interaction has been the subject of a large number of investigations. However, the interpretation of experimental tests is often clouded by uncertainties in calculating, and hence properly subtracting, purely electromagnetic effects. While it is now generally accepted that the Coulomb-corrected spin-singlet N-N scattering lengths are not all equal (i.e., a_{nn} ≠ a_{pp}), indicating clear violation of charge independence (Cl) /1/, the evidence concerning charge symmetry breaking (CSB) has been inconclusive until recently. A decade ago, a new generation of experiments was launched at IUCF and TRIUMF to make definitive measurements of CSB in the n-p system. The TRIUMF result has been available for some time now /2/. We report on progress toward final IUCF numbers at this conference.

While charge independence requires the nuclear hamiltonian to be invariant under arbitrary rotations in isospin space, charge symmetry (CS) requires invariance under a rotation of 180° about the T_2 axis, which effectively reverses the sign of the third component of isospin. CS can remain valid even if CI is violated. Most previous tests of charge symmetry in the two-nucleon system have focused on differences between nn and pp potentials. In the classification scheme of Henley and Miller /4/, such tests (e.g., comparison of a_{nn} to a_{pp}, 3H to 3He binding energies) are sensitive to class III CSB potentials, with isovector terms symmetric under interchange of the two nucleons. Potentials giving rise to CSB in the np system must be antisymmetric under nucleon interchange, and are referred to as class IV potentials. Our test of charge symmetry involved measuring polarization observables in np elastic scattering at 183 MeV over a broad angular range. In particular we measured the analyzing powers associated with the neutron beam spin (A_n) and the proton target spin (A_p). In the absence of class IV CSB potentials, ΔA(θ) = A_n(θ) - A_p(θ) = 0.

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The direct electromagnetic contribution to $\Delta A$ in our experiment arises from the spin-orbit interaction between the proton current and the neutron magnetic moment. It is readily calculable, and generally smaller than the predicted short-range effects of interest. CSB in the strong interaction is thought to arise fundamentally from the up-down (bare) quark mass difference and from photon exchange among quarks \cite{4,5}. However, most current CSB calculations in nuclear systems do not attempt to use quark degrees of freedom explicitly. Rather, these effects are incorporated indirectly in a meson-exchange picture, by using the measured manifestations of the quark level CSB. For np scattering at several hundred MeV, the principal class IV CSB mechanisms are: 1) electromagnetic spin orbit (mentioned above); 2) \( p \) mass difference effect on single pion (and to lesser extent, single $\rho$) exchange; and 3) isospin mixing of $\gamma$ (1\textright, T=1) and $\omega$ (1\textleft, T=0) mesons.

2 - EXPERIMENTAL APPARATUS AND ANALYSIS PROCEDURES

200 MeV vertically polarized protons from the IUCF cyclotrons were bent 10\degree downwards and impinged upon a 20-cm long liquid deuterium production target. Neutrons from the charge-exchange reaction \( ^{2}H(p,n)\alpha \) at $\Theta_{lab} = 10$\degree passed through a dipole "sweep" magnet and were then collimated into a beam $5\times 7$ cm\(^2\) at the polarized proton target (PPT). The neutron beam energy peaked at roughly 181 MeV with a FWHM $\approx 15$ MeV. The vertical polarization component of the neutron beam (magnitude 0.57) was reversed every 30 sec by flipping the primary proton beam spin. The sweep magnet precessed horizontal neutron spin components by $\pm 90\degree$, allowing their effective cancellation by averaging data taken with opposite (reversed every two hours) magnet polarities. The PPT consisted of 1.1 g/cm\(^2\) of $\text{Y(C}_{2}\text{H}_{5}\text{SO}_{4})_{3}$ $\times 9\text{H}_{2}\text{O}$ with transverse dimensions matching those of the neutron beam. The magnetic holding field for the PPT was 590G and was used to help flip the proton spin (average magnitude 0.42) every 10 minutes. The orientation of the proton target spin relative to this field was also reversed (by adiabatic fast passage) about twice per day.

Neutron-proton elastic scattering events from the PPT were identified by detecting the scattered neutron and recoil proton in coincidence. The detector arrays were left-right symmetric and were sensitive to both neutrons and protons in the range 24\degree < $\Theta_{lab}$ < 62\degree. Each arm comprised a thin wedge-shaped $\Delta E$ scintillator for fast timing and charged particle identification, followed by two pairs of $\chi$-$\gamma$ wire chambers (MWPC). Neutrons were detected in position-sensitive counters located behind the MWPC's.

Events from free np scattering were distinguished from background (e.g., quasi-free scattering from complex nuclei in the PPT) by imposing various software conditions selecting free-scattering values for the measured event parameters. The result of such a sorting procedure on the opening-angle spectrum reduced the background under the free scattering peak from 40\% to about 8\% when "loose cuts" were applied, and to about 3\% (with 20\% loss of free scattering events) when "tight cuts" were applied. This background was further reduced to order < 0.5\% by use of a "dummy target" subtraction. A more extensive discussion of experimental details may be found in Ref. /6/.

3 - RESULTS AND DISCUSSION

Events that passed all the free-scattering conditions (in either their "loose" or "tight cut" form) were sorted according to left or right proton recoil angle, and the four beam and target spin combinations. From these observables, we calculated (along with other quantities) the neutron asymmetry $P_{b}A_{n}$ and proton asymmetry $P_{t}A_{p}$, where $P_{b}$ and $P_{t}$ are the beam and target spin polarizations, respectively. Precise (< 0.1\%) independent knowledge of these polarizations would allow the extraction of the CSB observable $\Delta A(\theta)$ in a straightforward manner. No techniques are known, however, for determining either polarization to such accuracy. One way to proceed is to compare the analyzing power zero-crossing angles of $A_{n}$ vs. $A_{p}$ by fitting smooth curves to the $P_{b}A_{n}$ and $P_{t}A_{p}$ distributions. This is essentially the procedure used by the TRIUMF group /2/.

We have taken a more general approach in order to achieve sensitivity to shape differences between $A_{n}(\theta)$ and $A_{p}(\theta)$, and hence to CSB effects at angles other than the zero-crossing angle of the average analyzing power. Since our measurements are made simultaneously over the entire angular range, $P_{b}$ and $P_{t}$ act as angle-independent normalization constants (whose values we can roughly deduce, for example, by fitting $P_{b}A_{n}(\theta)$ and $P_{t}A_{p}(\theta)$ to phase shift predictions). What we can actually extract is $\Delta A(\theta) = \Delta A(\theta) - C \times A_{n}(\theta)$, where $A_{n}(\theta) = 1/2A_{b}(\theta) = A_{p}(\theta) + A_{n}(\theta)$, and $C$ is a constant that reflects uncertainty in the ratio $P_{b}/P_{t}$ (order of a few percent). Note, that the form of the relation for $\Delta A$ means one is insensitive to any contribution to $\Delta A(\theta)$ which is proportional to the analyzing power itself.
For one representation of our results, we have generalized the zero-crossing method, and quote the value of $\Delta A$ averaged over a range of angles such that the average value of $A(\theta)$ is 0. Over such a range, the term $C \times A(\theta)$ averages to zero, and $\langle \Delta A \rangle = \langle \Delta A \rangle_{\text{true}}$. Our preliminary 183 MeV result for one such region (82.2° to 116.1°) is $(32.1 \pm 6.1 \pm 6) \times 10^{-4}$ with statistical and systematic errors, respectively /6/. It is compared to theoretical calculations, and the TRIUMF 477 MeV zero-crossing result, in Fig. 1. Combining the IUCF statistical and systematic error bars in quadrature, our result is 4σ away from a null result of zero (i.e., no CSB). More significantly, it is 3σ away from the contribution arising from the electromagnetic spin-orbit term alone (labeled $\gamma$ in Fig. 1), giving the strongest, most clear-cut evidence to date for CSB in the strong interaction.

Meson-exchange calculations of CSB in the np system have been made by a number of groups /7,8/. We show in Fig. 1 the predictions of Holzenkamp, Holinde, and Thomas /7/ (HHT) at the energies of the IUCF and TRIUMF experiments. The dashed lines include, in addition to the electromagnetic contribution, the isovector terms arising from the $n$-p mass difference effect on single-$\pi$ and single-$\rho$ exchange (angle-averaged for the IUCF data comparison). We see that while the calculation including these terms is in fair agreement with the TRIUMF measurement, it falls significantly (about 2σ) below the IUCF result. Relatively good agreement is obtained, however, with the addition of the $\rho$-$\omega$ mixing term (solid line labeled Bonn ($\rho$-$\omega$), using the most recently determined mixing matrix element /9/). Unfortunately, the TRIUMF measurement is insensitive to the $\rho$-$\omega$ term, which, at 477 MeV, is calculated to cross zero very close to the analyzing power zero-crossing at 71°. The magnitude of the $\rho$-$\omega$ contribution also scales with the value of $g_{\rho}$ and $\omega$-NN coupling constants; HHT uses the relatively large values ($g_{\rho}^2/4\pi = 0.77, g_{\omega}^2/4\pi = 23$) characteristic of the Bonn potential.

Information about the angular dependence of CSB can be obtained by selecting a suitable component of $\Delta A_{\text{true}}(\theta)$ via a prescription for determining $P_\rho/P_\omega$. A comparison of measured and predicted angular dependences can then be achieved by extracting analogous components from the data and from the theory. We can select that component of $\Delta A_{\text{true}}(\theta)$ which is uncorrelated with $A(\theta)$ (in the sense that $\langle \Delta A(\theta) \times A(\theta) \rangle = \langle \Delta A(\theta) \rangle \langle A(\theta) \rangle$) by adjusting $P_\rho/P_\omega$ to minimize the variance of the "$\Delta A$" data set. In the case of theory, a term $C \times A(\theta)$ is added to $\Delta A_{\text{true}}(\theta)$, and the value of $C$ similarly adjusted. Data and theory treated in this manner are displayed in Fig. 2. One sees non-zero measured $\Delta A$ values, indicating CSB over nearly the entire angular range covered. Two different calculations are displayed which include all the CSB contributions discussed above. The solid curve is again that of HHT, while the dot-dash curve is a prediction by Beyer and Williams (BW) /6/, which differs from the HHT calculation primarily because BW use smaller $\rho$-NN and $\omega$-NN coupling constants ($g_{\rho}^2/4\pi = 0.55, g_{\omega}^2/4\pi = 8.1$). The variance minimization procedure changes the calculated curves from $\Delta A_{\text{true}}(\theta)$ only slightly over the range of the data.) While agreement with either prediction can be considered to be good, the HHT calculation is clearly favored. We note that the contribution from the $\rho$-$\omega$ mixing has a broad maximum in the region of the $A(\theta)$ zero-crossing (indicated by the arrow), which explains the strong sensitivity to it in our average result for the angle region 82.2° to 116.1° (see Fig. 1).
4 - SYSTEMATIC ERRORS

The CSB observable $\Delta A$ is a left-right asymmetry that changes sign when the spin of either (but not both) beam or target is flipped. Our measurements are sensitive to systematic errors of the same nature. Sources of such errors may be grouped in the following general categories: 1) background subtraction, 2) biased removal of free scattering events, 3) contaminating contributions to $P_b A_n(\theta)$ and $P_t A_p(\theta)$, 4) instrumental asymmetries, 5) variations of $P_b / P_t$, and 6) $\Delta A$ normalization. A major goal of the nearly completed final round of replay was to better understand the dominant systematic errors quoted in our preliminary result, as well as to investigate other possible sources of error. We comment briefly on recent developments.

The major ambiguities in our previous analysis /6/ centered on the relative normalization of dummy-to-PPT runs and on a sizable difference between the complete analysis with "loose" software cuts and one less complete with "tight" cuts. It is now clear these problems are closely related. In particular, an apparent shortfall of quasifree events from the dummy relative to the PPT is attributable to a small spatial misalignment of the two targets. Indeed, with a sufficiently tight beam spot cut, and improved replay software, our result is now essentially independent of whether other cuts are chosen to be "loose" or "tight". The results from two independent analyses (one performed at Wisconsin, one at IUCF) also agree quite well.

The recent analysis has also uncovered two new sources of systematic error requiring small ($\sim 10^{-4}$) corrections, and has improved the calibration of factors contributing to a more substantial ($\sim 5 \times 10^{-4}$) correction accounting for the variation of both $P_b$ and $A(\theta)$ over the neutron beam energy distribution. As evaluation of these corrections is still in progress, we continue to quote systematic errors. We expect, however, that the value of $\langle \Delta A \rangle$ will not change significantly, while the systematic error should shrink appreciably from the preliminary value of $6 \times 10^{-4}$. Final analysis may introduce some change in the angular dependence of "$\Delta A$", but will not alter the qualitative conclusions drawn from the preliminary results in Fig. 2.

5 - SUMMARY AND CONCLUSIONS

We see clear evidence for class IV CSB potentials in np scattering at 183 MeV over a broad angular range. While we are unable to quote our final numbers in time for this conference, results from the final IUCF replay already show that they will differ by only a small fraction of an error bar from our preliminary value for $\Delta A$ average. Our observed CSB signature will remain large.

We also present our results in the form of an angular distribution over the entire range of the measurement, extracting that part of $\Delta A$ uncorrelated with $A(\theta)$ itself. The shape of this distribution, as well as the angle-averaged result, are in good agreement with similarly treated meson-exchange calculations, and suggest the importance of $\varphi$-$\omega$ mixing contributions to CSB at 183 MeV. The best agreement is found utilizing the Bonn prescription for the N-N potential, employing relatively large values for the $\varphi$-NN and $\omega$-NN coupling constants.

The importance of $\varphi$-$\omega$ mixing has been suggested recently in the quantitative explanation of other CSB phenomena /5/, such as the $nn$ vs. $pp$ scattering length and $^3\text{He}$ vs. $^4\text{He}$ nuclear binding energy differences. Such mixing can also produce a spin-orbit CSB potential of the form required for understanding the A-dependence of mirror-nucleus binding energy differences (Nolen-Schiffer anomaly) /10/. Through such attempts to understand CSB of the strong force, in which the current results play a pivotal role, we are learning important new information about the role of vector meson exchange in the NN interaction at $r \lesssim 1$ fm.

REFERENCES