Charge symmetry breaking in $np \to d\pi^0$

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The forward–backward asymmetry in $np \to d\pi^0$, which must be zero in the center-of-mass system if charge symmetry is respected, has been measured to be $[-17.2 \pm 8_{\text{stat}} \pm 5_{\text{sys}}] \times 10^{-4}$, at an incident neutron energy of 279.5 MeV. This charge symmetry breaking observable was extracted by fitting the data with GEANT-based simulations and is compared to recent chiral effective field theory calculations, with implications regarding the value of the $u d$ quark mass difference.

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In the quark model, the breaking of charge independence and charge symmetry arises from the mass difference of the up and down current quarks and the electromagnetic interaction between quarks. The basic np interaction is particularly sensitive to such fundamental effects since the “background” Coulomb force is absent in this system. Indeed, charge symmetry breaking (CSB) has been unambiguously observed in np elastic scattering at three different energies. Measurement of CSB in the inelastic $np \to d\pi^0$ reaction complements the existing data in that it is sensitive to contributions that are absent in the elastic channel. Furthermore, this reaction is unique as a testing ground for effective field theory calculations addressing the important issue of isospin symmetry violation in pion-nucleon scattering. The observable of interest in $np \to d\pi^0$ is the center-of-mass forward–backward asymmetry, $A_{fb}$, which we define as

$$A_{fb}(\theta) = \frac{\sigma(\theta) - \sigma(\pi - \theta)}{\sigma(\theta) + \sigma(\pi - \theta)}$$

where $\theta$ is the angle between the incident beam and the scattered deuteron. Note that the asymmetry must be zero if charge symmetry is conserved. We report on a measurement of this asymmetry at a neutron energy a few MeV above the reaction threshold (275.06 MeV), and compare our result to recent theoretical predictions bearing on such fundamental questions as the $u d$ quark mass difference and our understanding of QCD dynamics and symmetries in low-energy hadronic interactions.

THE EXPERIMENT

The experiment was performed at TRIUMF with a 279.5 MeV neutron beam, a liquid hydrogen target, and the SASP magnetic spectrometer positioned at 0°. With these near threshold kinematics and the large acceptance of SASP, the full deuteron distribution from $np \to d\pi^0$ was detected in one setting of the spectrometer thereby eliminating many systematic uncertainties. These deuterons form a distinct kinematic locus in momentum vs laboratory scattering angle, which is shown in fig. 1 for the collected data.

![FIG. 1: Kinematic locus of $np \to d\pi^0$ data.](image)

The TRIUMF CHARGEX facility produced the neutron beam by passing a high intensity proton beam through a thin $^7$Li target. A sweeping magnet deflected the primary proton beam into a well-shielded dump. The liquid hydrogen target (LH$_2$) was centered 92 cm downstream from the $^7$Li target and was contained within a...
flat cylindrical volume, 10 cm in diameter with a nominal thickness of 2 cm. Two sets of veto counters (FEV1, FEV2) and a trigger counter set (FET) were each composed of a pair of plastic scintillators positioned above one another. This allowed more stable operation in the high (few MHz) particle rate environment. The thick veto scintillators were upstream of the LH$_2$ and shadowed it. The FET counters were positioned immediately downstream of the LH$_2$.

Three multi-wire proportional chambers, positioned upstream of the SASP entrance (FECs i.e. Front-End Chambers), provided tracking information for charged particles. Each FEC consisted of a pair of orthogonal wire planes. The first and last FECs, separated by 33 cm, were mounted to measure vertical and horizontal coordinates. The third FEC was positioned midway between the other two and rotated 40° with respect to them for efficiency measurements and to aid in multi-hit track reconstruction. Particle tracking near the SASP focal plane was provided by two vertical-drift chambers (VDCs). Three sets of scintillators, downstream from the VDCs, provided timing and particle ID information as well as sufficient redundancy to determine the efficiencies of all focal plane area detectors.

Measurements of $np$ elastic scattering with incident neutron beams that filled the same target space and produced protons that spanned the momentum distribution of the $np \rightarrow d\pi^0$ reaction provided a stringent test of the description of the spectrometer acceptance. Further details on the apparatus and other technical aspects of the measurement are found in reference [3].

**EXTRACTION OF $A_n$**

Close to threshold, the $np \rightarrow d\pi^0$ cross-section in the center-of-mass frame is given by

$$\frac{d\sigma}{d\Omega}(\theta) = A_0 + A_1 P_1(\cos \theta) + A_2 P_2(\cos \theta),$$

where $P_1$ and $P_2$ are Legendre polynomials. The $A_0$ and $A_2$ coefficients were previously measured [8] at a number of energies within 10 MeV above threshold. The presence of charge asymmetry breaking is reflected in the $A_1$ term as it is odd in $\cos \theta$. In this standard parametrization, the angle integrated form of $A_0$, is given by $A_{0b} = \frac{1}{2}A_1/A_0$.

For a given beam energy, $\cos \theta$ varies linearly with the longitudinal component of deuteron momentum in the laboratory reference frame. Ideally, the $\cos \theta$ distribution would be found by a suitable, simple projection of the data of fig. [4]. However, the measured deuteron locus is distorted by energy loss, multiple scattering, energy spread of the beam, and spectrometer acceptance making a direct extraction of $A_{0b}$ impossible. Instead, the data were binned according to laboratory momentum and angle (as in fig. [1]) and compared to a model which represented the background due to C($n$, d) reactions as a low-order polynomial and generated the locus of H($n$, d)$\pi^0$ events by Monte Carlo simulation of the beam, target, reaction cross section, spectrometer and detectors.

The simulation was based on GEANT3. It began with a proton beam incident on the $^7$Li target and included energy loss by the proton beam as well as the angular and energy distribution of neutrons from the $^7$Li($p$, n) reaction. Production of deuterons according to the distribution of equation [2] was allowed in the LH$_2$ target and other hydrogenous material such as scintillators and their wrapping. Standard GEANT tracking options were adopted for deuteron energy loss and multiple scattering but the reaction losses, which amount to 1–2% and are momentum dependent, were parametrized from data on deuteron elastic and reaction cross-sections from hydrogen and carbon [10]. Tracking through the SASP dipole used a field map obtained at 875 Amp and scaled up to the operating current of 905 Amp. Data were acquired in 10 different periods spanning two years and the simulation accounted for measured detector efficiencies, scintillator thresholds, missing FEC wires, and known changes in target thickness in a manner consistent with the actual running periods.

To reduce the possibility of psychological bias in matching simulation to data, a blind analysis technique was used which incorporated a hidden offset to the $A_1/A_0$ asymmetry parameter of the $np \rightarrow d\pi^0$ generator. The collaborators developing the simulation and extracting the observable did not know the value of the offset until all consistency checks had been satisfied.

**SYSTEMATIC EFFECTS**

The acceptance of SASP is a function of the initial target position and direction of the deuteron as well as its momentum. Non-uniformities in the momentum acceptance of SASP would systematically produce a false asymmetry and had to be limited. High-statistics data from $np$ elastic scattering were collected and compared to model simulations to determine a fiducial volume of uniform acceptance. For these calibration measurements, the SASP magnets were set to their values for the $np \rightarrow d\pi^0$ running, but the primary beam energy was adjusted so that the elastically scattered protons had a momentum deviation $\delta = (p - p_0)/p_0 = -4.0$ or $+4\%$ compared to the central momentum of the deuterons of interest. Projections of the $np$ elastic data direction for position slices were formed, and the ratios of yields at $-4\%$ vs $+4\%$ were formed for both data and simulation; see fig. [2]. The analysis software acceptance cuts in position and direction were then limited to the regions common to both data and simulation which were uniform in momentum to the statistical precision of the data.
Simulation vs simulation comparisons were carried out to determine how strongly experimental parameters and other effects were correlated with $A_1/A_0$. For example, momentum dependent deuteron reaction losses and detection efficiencies are obvious mechanisms which can mimic the effect of a non–zero $A_1/A_0$. Combining each correlation with the independently-determined uncertainty of its parameter gave the systematic contributions shown in Table I. However, for the LH$_2$ target thickness, the proton beam energy ($T_{\text{beam}}$) and the central momentum of SASP ($p_0$) the independent information was not a sufficient constraint. Therefore, these three parameters, along with $A_1/A_0$, were treated as free parameters and their values extracted from fitting the data. To this end, simulations were made and $\chi^2$ calculated for 81 points in a four-dimensional space, in which each of the four free parameters was stepped above and below a nominal value. $\chi^2$ minimization techniques were then used to obtain the values of the parameters at the global $\chi^2$ minimum, while the local curvature of the $\chi^2$ surface gave their errors and mutual correlations.

RESULTS AND DISCUSSION

As a test of the model, the $\chi^2$ calculations and fitting were repeated on subsets of the data and simulated data, selected according to whether the reaction occurred in the Top or Bottom part of the LH$_2$ target. A second test divided events into those originating in the Left or Right part of the target. The best fit values and errors of $A_1/A_0$ (after removal of the offset) and the other three parameters are presented in Table I.

The root mean square (rms) systematic error for the full acceptance and the four subspaces is $\sim 2.7\%$ with the standard binning scheme of 50 bins in $\delta$ and 20 bins in $\theta$, indicating a substantial discrepancy between data and the simulation. Pixel by pixel examination of the contribution to $\chi^2$ revealed a systematic difference in the profile of the locus along lines of steepest ascent. The sign of the differences tended to be positive at the peak and negative at both the “inner” and “outer” margins of the locus, possibly due to inadequate treatment of deuteron scattering in the simulation.

A change in $A_1/A_0$ will not change the ratio of counts in peak vs margins of the locus because it multiplies $\cos(\theta_{\text{c.m.}})$. In contrast, the LH$_2$ thickness, $p_0$, and $T_{\text{beam}}$ all shift or broaden the locus and thus are sensitive to the ratio of locus counts at the peak vs margins. It is reasonable to expect further rebinning to remove sensitivity to unimportant details of the simulation without losing sensitivity to $A_1/A_0$. We repeated the $\chi^2$ grid search using 20 bins in $\delta$ and 10 bins in $\theta$, and again with 10 bins in $\delta$ and 5 bins in $\theta$. As expected, the fractional error dropped to 2.1% and 1.4%, respectively, with $A_1/A_0$ remaining consistent within errors. A more sophisticated binning scheme which treated the locus as a set of “elliptical” and “radial” bins on top of rectangular background bins produced an rms error of 2.1% for 2500 background bins and 36 locus bins, and an rms error of 1.2% for 100 background bins and 6 locus bins. In all fits and binning

| Parameter                                      | Uncert $\times (10^{-4})$ |
|------------------------------------------------|-----------------------------|
| FEV threshold                                  | 2.5                         |
| Separation between front and rear FEs          | 2.5                         |
| Longitudinal position of $^7$Li                 | 2.5                         |
| $A_2/A_0$                                      | 2                           |
| Deuteron reaction losses                        | 1.5                         |
| Detection efficiencies                          | 1.5                         |
| Primary beam energy spread                      | 1                           |
| Neutron angle                                  | 1                           |
| Background                                     | 1                           |
| FET threshold                                  | 0.5                         |
| **Total**                                      | 5.5                         |

*FIG. 2: The vertical projection of the lab scattering angle for the center acceptance slice, elastic np scattering: A) data yield for $\delta = -4\%$, no cuts; B) data ratio ($-4\%+4\%$), no cuts; C) data ratio ($-4\%+4\%$), full acceptance cuts; D) simulation ratio ($-4\%+4\%$), full acceptance cuts; E) ratio of C to D, normalized to the center bin.*

*TABLE I: Systematic Error Contributions to $A_0$.*
TABLE II: Stability of the four free parameters over target subspaces; b = bottom; t = top; l = left; r = right.

| Parameter | Relative  | Relative | Relative |
|-----------|-----------|----------|----------|
| \( (A_1/A_0) \) | \( LH_2 \) (mm) | \( p_0 \) (MeV/c) | \( T_{beam} \) (MeV) |
| full | 34.4 ± 16 | 0.94 ± 0.05 | 0.365 ± 0.015 | 0.048 ± 0.001 |
| b | 30 ± 26 | 0.39 ± 0.09 | 0.547 ± 0.025 | 0.086 ± 0.002 |
| t | 20 ± 20 | 1.14 ± 0.07 | 0.236 ± 0.018 | 0.021 ± 0.002 |
| l | 29 ± 23 | 1.21 ± 0.08 | 0.273 ± 0.021 | 0.042 ± 0.002 |
| r | 15 ± 22 | 0.75 ± 0.08 | 0.427 ± 0.021 | 0.051 ± 0.002 |

Theoretical predictions of \( A_{th} \) have been made by Niskanen \[4\] using a meson-exchange coupled-channel

\[
A_{th} = -0.28\% \times \left| \frac{g_{\eta NN}}{4\pi(3.68)} \right| \left( \frac{\langle \pi^0 | H | \eta \rangle}{-0.0059 \text{GeV}^2} \right) \left( \frac{0.87}{\text{MeV}} \delta m_N - \frac{\delta m_N}{2} \right)
\]

where the first term arises from \( \pi \eta \) mixing and the second from \( \pi^0 N \) scattering. With the introduction of the new term, \( A_{th} \) changes sign and becomes positive with an estimated upper value around \( +69 \times 10^{-4} \), when large but reasonable values of \( \delta m_N \) and \( \delta m_N \) are used \[3\]. Our positive experimental result strongly suggests, therefore, that such isospin violating \( \pi^0 N \) interactions as outlined in reference \[3\] are indeed significant.

The parameters \( \delta m_N \) and \( \delta m_N \) are also constrained by the proton-neutron mass difference as

\[
\Delta N = m_n - m_p = \delta m_N + \delta m_N = 1.29 \text{ MeV}.
\]

When our \( A_{th} \) result is combined with equations \[3\] and \[4\] and the values given above for the \( \eta NN \) coupling constant and \( \pi \eta \) mixing matrix element, we find that \( \delta m_N = 1.66 \pm 0.27 \text{ MeV} \) and \( \delta m_N = -0.36 \pm 0.27 \text{ MeV} \), assuming no theoretical uncertainties. We emphasize, however, that this last exercise is only meant to illustrate the significance and potential important implications of our \( A_{th} \) result. Further theoretical studies are currently underway \[14\] to accommodate simultaneously the new CSB result of our study and that of a recent cross-section measurement of the isospin forbidden reaction \( dd \to \alpha \pi^0 \).

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\[
A_{th} = -0.28\% \times \left| \frac{g_{\eta NN}}{4\pi(3.68)} \right| \left( \frac{\langle \pi^0 | H | \eta \rangle}{-0.0059 \text{GeV}^2} \right) \left( \frac{0.87}{\text{MeV}} \delta m_N - \frac{\delta m_N}{2} \right)
\]
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