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Test of Charge Symmetry in n-p Elastic Scattering at 480 MeV

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An experiment to investigate the isospin-mixing charge-symmetry breaking components of the n-p interaction has been completed at TRIUMF. The difference ΔA between the neutron and proton analyzing powers A_n and A_p in n-p elastic scattering at 480 MeV has been determined by measuring the difference in the angles at which A_n and A_p cross zero. Since $\Delta A = 0$ in the absence of charge-symmetry breaking, the experiment was performed as a null measurement requiring no accurately known polarization standards. The experiment consisted of two interleaved phases in which polarized (unpolarized) neutrons were scattered from an unpolarized (polarized) proton target of the frozen spin type. The experiment provides an unambiguous evaluation of the magnitude of class IV charge-symmetry breaking effects to the level of $\Delta A \sim 0.001$ corresponding to a laboratory angle difference at zero crossing of $\sim 0.05^\circ$.

§1. Introduction

Charge independence and charge symmetry are consequences of isotopic spin invariance, the first "internal symmetry" to be postulated. Charge independence requires that the Hamiltonian of the system commute with the total isospin operator. Charge symmetry is a weaker constraint being a requirement only that the Hamiltonian be invariant under a reflection through the 1-2 plane in isospin space. In the nucleon-nucleon system, charge independence asserts that the interactions in the systems nn, pp and np are identical in corresponding quantum mechanical states, whereas charge symmetry asserts that if all protons are converted to neutrons and vice versa, there is no change in the behaviour of the system¹⁾.

In the n-p system, charge symmetry leads to a separation of the isoscalar and isovector parts of the interaction. In the even (odd) partial waves, the isovector part contains spin singlet (triplet) contributions only, while the isoscalar part contains only triplet (singlet) parts. If charge symmetry were a good symmetry, there could be no transitions between isoscalar and isovector parts of the scattering matrix and hence between spin singlet and triplet states. In the case where unpolarized neutrons are scattered from unpolarized protons and the polarization of the outgoing particle is observed, the quantity

$$\Delta = P_n(\theta) - P_p(\pi - \theta) = P_n(\theta_n) - P_p(\theta_p) \quad (1)$$

is zero if charge symmetry is conserved.

Experimentally, it is far easier to determine analyzing powers than polarizations. Fortunately, the above results can be expressed in terms of analyzing powers: the analyzing powers for scattering of polarized neutrons (protons) from unpolarized protons (neutrons) must be the same at corresponding angles. In fact, a null experiment is possible since the analyzing power of n-p elastic scattering goes through zero at intermediate energies in the vicinity of 71° center of mass (32° in the lab²⁾). In the absence of charge-symmetry breaking, the center-of-mass angle at which the analyzing power for scattering polarized neutrons from unpolarized protons (A_n) goes

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through zero must be identical to the angle at which the analyzing power for scattering unpolarized neutrons from polarized protons (A_p) goes through zero. The experiment performed at TRIUMF was designed to measure the difference in these angles, and to provide an unambiguous test of charge-symmetry breaking effects to the level of $\Delta A \sim 0.001$ corresponding to a difference in crossover angles of $\sim 0.05^\circ$ in the laboratory.

§2. Sources of Charge Symmetry Violation

Henley and Miller¹⁾ have classified nuclear forces into 4 categories depending on their isospin dependence.

- Class I: Forces of the form $V_I = a + b \vec{\tau}(1) \cdot \vec{\tau}(2)$
These forces are manifestly isoscalar, and hence preserve both charge independence and charge symmetry.
- Class II: Forces of the form $\tau_3(1) \tau_3(2)$
These forces are usually rewritten in the form $V_{II} = c[\tau_3(1)\tau_3(2) - 1/3 \vec{\tau}(1) \cdot \vec{\tau}(2)]$ so as to have better rotational properties in isospin space. Class II forces violate charge independence but preserve charge symmetry.
- Class III: Forces of the form $V_{III} = d[\tau_3(1) + \tau_3(2)]$
These forces violate both charge independence and charge symmetry. However, since they are even in the isospin observables they do not give isospin mixing. Therefore, they do not give an effect in the n-p system although they do distinguish between the n-n and p-p systems.
- Class IV: Forces of the form $V_{IV} = e[\tau_3(1) - \tau_3(2)] + f[\vec{\tau}(1) \times \vec{\tau}(2)]_3$
These forces again violate both charge independence and charge symmetry, but since they are odd in the isospin variables, they allow isospin mixing. As a result they yield an effect in the n-p system while not affecting the n-n or p-p systems. In the case of the n-p system, this implies the mixing of singlet and triplet spin states and the possibility of observing Class IV forces in np spin observables.

The coefficients a-f are functions of spin, angular momentum and position.

It is of interest to distinguish sources of charge symmetry violation which do not require the presence of the nuclear interaction (direct effects) and those that do (indirect effects).

2.1 Electromagnetic

Of the direct effects, the most important are due to the Coulomb interaction. The electromagnetic interaction causes both charge independence breaking (CIB) and charge symmetry breaking (CSB) so that one expects effects on the order of the fine structure constant. Although the direct charge effects do not appear in n-p scattering, there are magnetic couplings which have a significant effect and yield forces of class IV.

2.2 Mass Difference

Three mass differences might be considered. Firstly, there is the large mass difference between the pions equal to more than 3% of the average pion mass. This difference is a source of CIB, but since the masses of π^+ and π^- are equal, there is no CSB in the n-p system. This force and a similar one due to splitting of the ρ meson masses are thus of class II. The nucleon mass differences do play a role in CSB. The mass difference yields forces of both class III and class IV.

The two-pion-exchange potential is also affected by mass differences. The calculations of Chu and Riska⁵⁾ consider the effects of the nucleon mass difference, but lead only to class III forces. When photon exchanges are also allowed, further CIB and CSB violations are to be expected³⁾. Similarly, the splitting of the Δ masses is expected to lead to CIB and CSB. Unfortunately, none of the diagrams pertaining to these two cases have been calculated, and the effects are uncertain.

2.3 Meson Mixing

There are two important cases in which mixing occurs between light mesons of differing isospin: π^0 - η and ρ^0 - ω . Only the latter is of interest to n-p scattering because ρ^0 - ω mixing yields both class III and class IV forces while π^0 - η mixing leads

Fig. 1. Charge symmetry violation in n-p elastic scattering. The curve labelled A is the analyzing power assuming charge symmetry. The other curves indicate the magnitude of charge symmetry violation from various sources: Δ_δ due to np mass difference; Δ_{em} , direct electromagnetic; $\Delta_{\rho\omega}$, ρ^0 - ω mixing; $\Delta(\text{sum})$, sum of previous 3 sources.

to only class III forces. The difference between the two cases is that the ρ^0 is a vector particle and consequently has both tensor and vector coupling to the nucleon (as does the photon) whereas the π^0 and the η do not.

2.4 Two-Boson Exchanges

No results for class IV forces are yet available for forces arising from two-boson-exchange diagrams. This is an important omission since it is known that 2π exchanges are very important in NN scattering and because there are several related terms which may well contribute to CSB. The most important terms yet to be evaluated are radiative corrections (class IV only for ρ exchange), exchange of a photon with a pion, and box diagrams and cross diagrams including a pion with ρ^0 - ω mixing.

Differences in the polarizations Δ have been calculated for n-p elastic scattering spin observables by Cheung, Henley and Miller for energies up to 460 MeV³), by Svenne, up to 500 MeV and by Gersten, up to 750 MeV⁴). The calculations included direct electromagnetic effects, the effect of nucleon mass differences and ρ^0 - ω mixing. Of importance at 500 MeV are 3P_1 - 1P_1 , 3D_2 - 1D_2 and 3F_3 - 1F_3 mixing. Figure 1 shows results from the recent calculations by Svenne. It is seen that the largest effect in the vicinity of crossover is due to the nucleon mass difference, followed by the direct electromagnetic effects. It is predicted that there is very little effect due to meson mixing. The difference in crossover angles is predicted by Svenne to be $\Delta A = -3.5 \times 10^{-3}$ which corresponds to a difference in the proton crossover angles of -0.15° at 500 MeV incident neutron energy.

§3. Experiment

The neutron beam and detection system for this experiment have been described in detail in references 6 and 7. Although the experiment was designed as a null experiment requiring no accurately known polarization or analyzing power standards at any point, effects were made to perform the experiment so that the measurements were nevertheless as accurate as possible in an absolute sense.

Figure 2 shows a schematic diagram of the apparatus used. The two phases of the experiment (polarized and unpolarized beam) used identical parameters aside from the polarizations of the beam and target. The apparatus will be discussed for the polarized beam phase of the experiment. The proton beam of 497 MeV entered the beam energy monitor/polarimeter with its polarization vector vertical. The proton polarimeter detected protons scattered from a Kapton foil at 17° in coincidence with the recoil protons from p-p elastic scattering. The solid angle defining scintillators were

Fig. 2. Apparatus used in the n-p elastic scattering charge symmetry breaking experiment.

made if they were later found to be necessary. In practice, these corrections never amounted to more than 0.2%, and even if neglected would have caused a shift in the crossover angles of less than 0.01° .

The beam energy monitor (BEM) consisted of two six-element range counters placed behind the forward (17°) arms of the polarimeter. The BEM was used to ensure that the proton beam energy remained nearly constant throughout the experiment. Although a variation in the proton beam energy of up to ± 500 keV could have been tolerated, the beam energy was continuously monitored by the data acquisition program and the experiment stopped for retuning whenever drifts of more than about ± 150 keV were detected.

Stability in the position and direction of the proton beam incident on the liquid deuterium (LD_2) target was essential to the experiment. Two sets of split plate secondary electron emission monitors (SEM's) monitored the position of the proton beam both horizontally and vertically at two positions upstream of the LD_2 target. Through a feedback system controlling two sets of steering elements upstream of the SEM's both the position and angle of the proton beam striking the (LD_2) target were monitored and controlled throughout the experiment. The distributions of the asymmetries measured with the SEM's ($\sigma = 0.03$ mm) indicate that in both the horizontal and vertical directions the position and angle of the proton beam striking the LD_2 target were

rotated through 68° so as to make the polarimeter largely insensitive to the proton beam position over the central 4 mm of the polarimeter target. This rotation compensates both solid angle and p-p differential cross-section variations⁸). The measured instrumental asymmetry of the polarimeter was stable to approximately ± 0.001 . Although differences in the degree of polarization in the spin-up and spin-down data cancel out to second order at the crossover angle, in the null experiment the slope of the analyzing power at crossover and hence the precision with which the crossover can be determined is proportional to the beam (or target) polarization. The proton beam polarization was therefore continuously monitored by the data acquisition program to ensure that the polarization was maximized at all times. In addition, the different degrees of polarization of the beam and target constituted one of the few differences between the polarized beam and target phases of the experiment. It was therefore considered essential to obtain detailed data on the polarizations so that even second-order corrections for polarization differences could be

held constant to within ± 0.15 mm and $\pm 0.006^\circ$, respectively. After traversing the LD_2 target, the proton beam was deflected away from the neutron beam and transported to a beam dump.

The most efficient manner to produce a polarized neutron beam using an LD_2 target at 500 MeV is to use transverse polarization transfer in the $D(p,n)2p$ reaction at an angle of about 9°). A superconducting solenoid "JANIS" was used to rotate the proton polarization vector 90° clockwise into the horizontal plane. With transfer coefficient $r_t = -0.748 \pm 0.025^2$) and $r_t' = 0.058 \pm 0.007^2$), a proton beam with a typical polarization in the range 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, and all beam spin reversals were carried out at the source.

From the 20 cm long LD_2 target, the neutrons emerging at 9° passed through a 3.37 m long lead collimator with steel inserts providing a tapered rectangular aperture. A further 0.60 m long lead antiscattering collimator was placed in the magnet "CLYDE". The neutron beam at the polarized target had a "flat-top" in intensity 40 mm high and 56 mm wide. The neutron energy spectrum consisted of a relatively narrow peak of width (calculated) 11 MeV and a smooth flat background⁹). 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 primary proton beam was always at least 300 nA on the LD_2 target in all three polarization states. For one data-taking run the beam averaged nearly 1.0 μ A with peak intensities of 1.2 μ A. For the highest intensity runs a careful search was made for any evidence of a drop in density in the LD_2 target by comparing the ratio of neutron "current" to proton current. This was important since a reduction in LD_2 density could cause a shift in the mean neutron energy. No evidence was found for any reduction in LD_2 density outside that predicted on the basis of the measured LD_2 temperature increase at high intensity. The energy shift calculated in this manner was 60 keV, well within tolerable limits.

The magnetic dipoles "BONNIE" and "CLYDE" were used to remove charged particles from the neutron beam and to precess the neutron spin into the vertical plane. Calibration using the neutron polarimeter ensured that rotation of the neutron spin in the fringe field of the clearing magnet was properly compensated and that components of the neutron spin which did not reverse when the proton beam spin was reversed at the ion source (produced through polarization in the $D(p,n)2p$ reaction with $P_y = -0.058 \pm 0.001^2$) were precessed into the longitudinal direction with negative helicity. Conservation of parity does not allow a polarization component along the direction of motion to affect the cross section unless the target is also polarized. Note also that residual beam polarization caused by P_y during the polarized target phase of the experiment had negligible effects on the asymmetry because A_{zz} is an even function of the scattering angle and because A_{zx} (equal to A_{xz} except for small charge symmetry violation effects) crosses through zero at $\sim 72^\circ$ (c.m.)²). The uncertainty in the precession angle of the neutron spin was $\pm 5.8^\circ$, well within the permissible limits of $\pm 10^\circ$.

The absolute neutron beam mean energy was determined to be 477 ± 1.7 MeV through comparison of the times of flight of neutrons and gamma rays from the decay of π^0 mesons produced in the LD_2 target.

After traversing the polarizable target, the neutron beam passed through a profile monitor consisting of a charged particle veto counter, a scintillator converter and two sets of delay line chambers. Time of flight based on the cyclotron rf signal was used to remove signals arising from gamma rays. The rf signal was phase stabilized using a neutron detector placed close to the LD_2 target in the 6° port of the neutron collimator.

The profile monitor was immediately followed by a polarimeter measuring vertical and horizontal asymmetries. The effective analyzing powers of the neutron polarimeter were determined from the amplitude of precession curves obtained by varying the fields in "BONNIE" and "CLYDE" and assuming the polarization transfer coefficients r_t and r_t' to be known. Zero crossing of the precession curves provided calibration of the precession dipoles and the error estimates for the precession angle quoted above.

The detection apparatus consisted of two proton arms and two neutron arms symmetrically disposed with respect to the neutron beam and a polarized proton target of the frozen spin type (FST) located 12.55 m from the LD_2 target. The target, shown in Fig. 3, consisted of butanol beads 1.2 mm in diameter placed in the mixing chamber of

Table I. Average target polarizations in data-taking run.

Run	Polarizations
1	-0.62 0.58
2	-0.82 0.79
3	-0.75 0.79
4	-0.80 0.73

a dilution refrigerator. The target temperature was 85 mK during the first data-taking run and 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 during each of the 4 data-taking runs are listed in Table I. Polarizations with positive (negative) signs are for the cases in which the polarization was in the same (opposite) direction as that of the holding field. Changes in the polarization direction with respect to the magnetic field directions were effected by a shift in the microwave frequency used during polarization.

As shown in Fig. 3, the magnetic field was established by a superconducting solenoid below the target cell and a room temperature coil placed above the cell. The coil and solenoid were rigidly mounted with respect to each other, but could be moved with respect to the target cell. The target was polarized by raising the magnetic assembly until the cell was centered in the superconducting solenoid. For the n-p measurements, the cell was placed equidistant from the two coils. The holding field then had a central value of 0.257 T. The FST holding field was both stable and reproducible to better than 0.25 mT, which corresponds to an error in ΔA of ± 0.0001 .

Although the precise shape of the magnetic field is immaterial to the null experiment, magnetic field maps were obtained along the neutron beam and perpendicular to it at several heights with respect to the median plane. The field was also checked locally in the vicinity of phototube magnetic shielding close to the proton trajectories. Calculations of the magnetic field were also made on the basis of the known currents in the coils. Fringe fields from the cyclotron were taken into account. To provide correction matrices for deflection of the proton trajectories, typical trajectories were integrated through the field out to a distance of 3.0 m from the FST using spline fits to the magnetic field. The slight ($\sim 0.1^\circ$) deflection of the protons between the first and last delay line chambers was taken into account using spline fits to the trajectories. The mean correction for deflections of the proton trajectories was 1.2° , but the correction varied from approximately 1.02° to 1.47° depending on the initial position and emission angle of the proton. Further corrections were made based on the momentum of each individual proton.

The position of the target cell was determined to within ± 0.5 mm from X-rays of the FST taken at least once for each data-taking period. Based on the precise position of the target cell and the position of the magnetic field assembly, small additional corrections were made to the neutron angle and the proton deflection in the

Fig. 3. Frozen spin target assembly.

magnetic field.

Scattered neutrons and protons were detected in two left-right symmetric detection systems allowing cancellation to first order of many systematic errors in the detector solid angles and efficiencies and due to differences in the neutron beam intensity and polarization in each of the polarization states. The neutron detection system was placed at a nominal mean angle of 32.00° with respect to the surveyed axis of the neutron beam. The centroid of the neutron beam was verified to coincide with this axis to within ± 0.5 mm which corresponds to an angle error of less than $\pm 0.005^\circ$. The angles were surveyed at the beginning and at the end of data-taking and agreed to within $\pm 0.01^\circ$. Each neutron detection system consisted of a neutron scintillator array placed at a distance of 5.235 m from the FST (center to center), an array of charged particle veto scintillators covering the front surface of the neutron scintillator array, a set of small (70 mm wide by 64 mm high by 7 mm thick) scintillators ("button" counters) used for monitoring the neutron scintillator photomultiplier gains and timing by triggering on fast protons, and a charged particle time-of-flight start scintillator used in conjunction with the "button" counters for monitoring. For the phototube gain monitoring, pions were removed by software time-of-flight cuts. Small software corrections to the proton energies and hence energy losses in the scintillators were made. This was done in order to remove effects of the target magnetic field on the energy deposition in the neutron bars.

Each neutron array consisted of two banks of NE110 scintillator bars each consisting of 7 bars of scintillator 1.050 m long by 0.150 m high by 0.150 m deep placed one on top of the other to form a wall of scintillator of area 1.05×1.05 m². The solid angle subtended by the neutron arrays was considerably larger than that subtended by the proton detection system so as to compensate for multiple scattering of the protons and deflection of the protons in the magnetic field of the target. Each end of each bar was observed by a phototube. The phototubes were "daisy chained" together so that each bank of 7 bars (14 phototubes) required 4 TDC channels and 4 ADC channels. Adjacent bars were in different "daisy chains" so as to permit identification of "punch through" events in which the recoil proton triggered two adjacent bars. The gains of the phototubes were monitored and corrected to $\pm 0.5\%$. The efficiency of the neutron arrays was 0.29 for 320 MeV neutrons, at a threshold setting of 1 MeV (electron equivalent). The apparent position of events detected in a given neutron bar could wander slightly due primarily to voltage drifts in the phototubes. This was monitored and corrected on a tape-by-tape basis. For a single bar, the horizontal position was measured with charged particles to have a resolution of 20-25 mm (FWHM) depending on the bar. The vertical resolution was ± 7.5 cm for events in which only one bar was struck and ± 3.8 cm for cases in which two bars were triggered.

Each proton detection system consisted of a time-of-flight start (pTOF) scintillator, a pair of 0.60×0.60 m² delay line chambers at a mean distance of 0.598 m from the center of the FST, a second pair at a distance of 2.917 m from the FST, a "pattern" counter of small scintillator disks embedded in lucite for verifying the positions of the delay line chambers if necessary, a thin (ΔE) scintillator, a brass wedge tapered so that the protons, after passing through, emerged with energies which were independent of angle, a second (E) scintillator (from which time-of-flight information was derived), additional absorber and a veto (V) scintillator. All elements of one detection system were rigidly attached to a single boom levelled to an accuracy of $\pm 0.01^\circ$ and braced so as to avoid lateral, vertical or torsional displacements. Surveys at the beginning and end of the experiment agreed to within $\pm 0.02^\circ$. The central axis of the proton booms was placed at a nominal angle of 52.00° .

The delay line chambers had an intrinsic resolution of ± 1 mm in the "picket fence" horizontal direction and ± 0.7 mm (FWHM) in the vertical direction. Efficiencies were typically $>99\%$ per pair of chambers. The proton detection system covered an angular range of 9° (after software cuts for the ends of the delay lines). Through use of correction matrices for the delay line chambers, residual errors between the observed positions in the chambers and straight-line fits of the trajectories through the chambers were reduced to less than ± 0.1 mm with resolutions of approximately 1.0 mm (FWHM) vertically and 1.4 mm (FWHM) horizontally.

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 unpolarized and the neutron beam polarized. For polarized beam measurements, the spin state ("up", "down" or "off") was under computer control and usually randomized. Data bits indicating spin "up", "down" or "off" or source "busy" were taken from the ion source

itself and recorded with each event. Special event types, under computer clock control, recorded on tape FST status, SEM data, neutron polarimeter and profile data plus other scalars. The time of day was recorded approximately every 10 events.

Table II shows the extent to which a number of possible systematic errors affect the accuracy to which the difference in analyzing power can be obtained in this experiment. The column labelled 'Magnitude' indicates the size of error necessary to obtain an error in ΔA shown in the column labelled 'Effect on ΔA '. The last column shows the accuracy obtained. In all cases, the design criteria were met.

§4. Analysis and Results

The data obtained allow calculation of the neutron time of flight and position and the proton time of flight and trajectory. Calculation of the opening angle and non-coplanarity for each event allows discrimination against quasi-free n-p scattering

Table II. Estimates of systematic errors.

Cause	Magnitude	Effect on ΔA	Obtained
1) Unequal up and down polarization	$P^+=0.8, P^-=0.4$	0 at $A=0$ 4×10^{-5} at $A=0.1$	$ \Delta P < 0.05$
2) Unequal left and right scattering angles	$ \theta_L - \theta_R = 1^\circ$	-2×10^{-4} at $A=0$	$\Delta \theta_p < 0.02^\circ$
3) $P^+ \neq P^-$ and $\theta_L \neq \theta_R$	$P^+=0.8, P^-=0.4$ and $ \theta_L - \theta_R = 1^\circ$	-3×10^{-4} at $A=0$	$\Delta \theta_n < 0.05^\circ$
4) Position modulation of proton beam at LD_2 target	$ x^+ - x^- = 2 \text{ mm}$	$< 4 \times 10^{-4}$	0.15 mm
5) Movement of FST with respect to the holding field	$\Delta r = 1 \text{ mm}$	$< 4 \times 10^{-4}$	$< 0.5 \text{ mm}$
6) Incorrect precession of proton beam spin	$\Delta \phi = 5^\circ$	$< 10^{-4}$	
7) Incorrect precession of neutron beam spin	$\Delta \theta = 5^\circ$	$\sim 10^{-5}$ at $A=0.1$	5.8°
8) Residual transverse neutron polarization when the FST is polarized	$P_n < 0.035$	$< 10^{-4}$ at $A=0.1$	
9) Multiple scattering in the FST	$\theta_{\text{proj}}^{1/e} = 1.0^\circ$	$\sim 4 \times 10^{-5}$	1.0°
10) Irreproducibility of FST holding field	$\sigma_H = 2.5 \text{ G}$	$< 10^{-4}$	2.5 G
11) Quasi-free scattering from target (helium, carbon and oxygen)	1% background, 10% subtraction uncertainty	$< 2 \times 10^{-4}$	
12) Neutron detection instability	1% gain shift with pulse height threshold set at 1% of peak pulse- height	$\sim 2 \times 10^{-4}$	
13) Proton beam energy shift	$\Delta E = 1 \text{ MeV}$	$< 2 \times 10^{-4}$	$ T_1 - \langle T_1 \rangle < 200 \text{ keV}$
14) Proton beam direction modulation	$ \theta^+ - \theta^- = 0.1^\circ$	$< 4 \times 10^{-5}$	0.005°

from nuclei in the FST, e.g. ^3He , ^4He , ^{12}C and ^{16}O . Further constraints on the reconstructed target image, the summed neutron-proton energy (equal to the incident neutron energy for elastic scattering) and the neutron-proton transverse momentum balance allow rejection of the majority of background and the performance of consistency checks.

4.1 Consistency Checks

Analysis has been carried out by two groups (Universities of Alberta and Manitoba) working independently with different computer programs, no exchange of software and discussions only of the principles and results of analysis. The results, however, are very similar.

Proton energy was determined by time of flight between the pTOF and E scintillators and a resolution of approximately 22 MeV (FWHM) was obtained. On the neutron side, the energy resolution was on the order of 41 MeV (FWHM). The resolution of the incident neutron energy, obtained by summing the proton and neutron energies, was 48 MeV (FWHM). The spread in opening angles for the proton and the neutron trajectories is consistent with the sum in quadrature of: (i) the predicted multiple scattering of the protons emerging from the target (1.7°) and (ii) the uncertainty in the neutron angle due to error in determining the position of the neutron interacting in the neutron scintillators (0.5°), both FWHM. Similarly, the observed spread of non-coplanarity angles is consistent with proton multiple scattering and uncertainty in neutron angle, but this time using the larger uncertainty in the vertical direction (2.8°). Corrections for differential nonlinearity in the neutron bar TDC's have shown no measurable effects on the crossover angles although small effects on the absolute opening angles were seen.

Only one effect is known to affect the difference in crossover angles. In the polarized beam phase of the experiment, the scattered neutron is more strongly polarized than in the polarized target phase²). The neutron position determined during polarized beam running is thus biased because neutrons tend to scatter more to one side than the other. This effect is estimated to change the difference in crossover angles by 0.009° if the neutron angle is used to calculate the difference in crossover angles.

4.2 Calculation of Crossover Angles

Since the magnetic field of the target deflects protons to larger angles on one side and to smaller angles on the other, data were available at a given angle on both the right- and left-hand sides over a more restricted angular range than the maximum range covered by the apparatus. This range of angles is referred to as the overlap region; angles outside this range are said to fall into the non-overlap region. The asymmetry was calculated by evaluating

$$\epsilon = \frac{r-1}{r+1}$$

$$r^2 = \frac{L^+R^-}{L^-R^+} \quad (2)$$

for each bin of data in the overlap range of the data, and by evaluating

$$\epsilon = \frac{L^+-L^-}{L^++L^-} \quad (3a)$$

or

$$\epsilon = \frac{R^--R^+}{R^-+R^+} \quad (3b)$$

for each bin in the non-overlap regions. The superscripts + and - indicate the beam or target spin and L and R indicate the left- or right-hand side of the apparatus with respect to the neutron beam. Corrections for different polarizations in the spin "up" and "down" states are proportional to $A\delta$ with

$$\delta = \frac{p^+-p^-}{2} \quad (4)$$

for expressions 3 and to $(A\delta)^2$ for expression 2.

The overlap region was determined by requiring two conditions to be satisfied: (i) the detector efficiency as a function of angle as determined from the quantities $L^{\pm}$ and $R^{\pm}$ was required to show no excursions other than those expected from statistics and the effects of the magnetic field which vary as a function of proton angle and (ii) the minimum number of counts in any angular bin was required to be greater than 100.

Typical angular distributions of the asymmetry for the overlap region are shown in Fig. 4. The error bars were calculated using the expression:

$$\Delta PA = \left\{ \frac{r^2}{(1+r)^4} \left[\frac{1}{L^+} + \frac{1}{L^-} + \frac{1}{R^+} + \frac{1}{R^-} \right] \right\}^{1/2}. \quad (5)$$

It was verified using a Monte Carlo simulation that this expression gives reasonably unbiased Gaussian errors for the conditions described.

The angular distribution of the asymmetry was fit with a straight line by performing a linear least squares minimization of χ^2 .

The minimization was performed in several ways to verify the stability of the calculations: (i) overlap region only using expression 2, (ii) left- and right-hand-

Fig. 4. Asymmetry angular distributions from protons angles (top) and neutron angles (bottom) obtained in one of the four data-taking runs. Data are for polarized target with the FST holding field "up".

side data separately using expressions 3, for the overlap region only, (iii) left- and right-hand-side data separately using expressions 3 for all available data. Calculations were performed for both protons and neutrons. No increase in statistical accuracy is obtained by treating both proton and neutron asymmetry distributions. However, the two angle bases are subject to different systematic errors, and the requirement that the opening angles between the proton and neutron crossover angles be consistent for FST field up and down and for analysis with both expressions 2 and 3 is a meaningful check on the overall consistency of the experiment. The results were consistent.

The experimental difference in crossover angles obtained with essentially all the data analyzed is $+0.13^\circ \pm 0.07^\circ$. This is to be compared with a calculated value of -0.15° . It must be emphasized that the experimental difference in crossover angles presented here has not been corrected for the effects of possible asymmetry in the $\sim 1.5\%$ background, and to this extent the number must still be considered preliminary. Further checks for systematic errors are also continuing. It is expected that the analysis will be completed during the fall of 1985.

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