STATUS OF THE EXPERIMENTAL SEARCH FOR CHARGE SYMMETRY BREAKING IN n-p SCATTERING

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The search goes on (and on). Our aim[1,2] is to measure polarization observables sensitive to charge symmetry breaking (CSB) in n-p scattering at a mean bombarding energy of 188 MeV. Specifically, we plan to measure left-right asymmetries in the scattering of polarized neutrons from polarized protons, to a statistical precision of $\sim\pm 5 \times 10^{-4}$ in a number of angle bins spanning the range $60° < \theta_{cm}(n) < 120°$. From these results we can extract information about the CSB difference $[\Delta A(\theta) \equiv A_n(\theta) - A_p(\theta)]$ between the analyzing powers one would measure with a polarized neutron beam on an unpolarized proton target $[A_n(\theta)]$ and with an unpolarized beam on a polarized target $[A_p(\theta)]$. Without accurate knowledge of the beam and target polarizations we can, in particular, determine the absolute value $\Delta A(\theta_0)$ at the angle where the average analyzing power $A(\theta) \equiv [A_n(\theta)+A_p(\theta)]/2$ crosses zero ($\theta_0^{cm} \cong 90°$ at our energy), and the angular dependence of the ratio $\Delta A(\theta)/A(\theta)$ at angles straddling θ_0. The experiment is designed to yield a sensitivity to $|\Delta A| > 0.001$, at which level CSB effects are expected theoretically on the basis of quark mass differences[3] and various indirect electromagnetic contributions (simultaneous exchange of hadrons and photons) to the nuclear force.[4] In considering possible sources of systematic error in the measurement, it is important to keep in mind that $\Delta A(\theta)$ represents, operationally, a left-right asymmetry which changes sign with a flip of one, <u>but not the other</u>, of the interacting nucleon spins.

The detector hardware, electronics, front-end microprocessor system, and acquisition software for the CSB experiment are now complete. The past year has seen a dramatic improvement in the setup and calibration procedures we have developed to monitor continuously the operation of the extensive hardware and to match the performance of the 192 phototubes used on the multi-celled neutron detectors. Extensive replay of preliminary data acquired with the complete setup during the past year has led to a continuing refinement of our analysis procedures and has stimulated more detailed thought about and design of experimental checks for various kinds of systematic errors. In order to check and cancel one possible source of systematic error, associated with in-plane polarization components in the beam and target, it has become important to add to the polarized neutron facility (PNF) a superconducting precession solenoid for the primary proton beam and the capability of switching from the liquid deuterium (LD_2) neutron production target to a solid carbon production target. These additions to the PNF are currently in progress, along with substantial modifications to improve the performance of the polarized proton target (PPT). Production running on the CSB experiment awaits these remaining hardware modifications and further refinement of our analysis procedures. The major developments of the past year and those still under way are summarized in more detail below.

A photograph of the complete left-right symmetric detector arrays for the CSB experiment is shown in Fig. 1. Each arm consists of a wedge-shaped plastic scintillator providing fast timing and ΔE information for the detected protons, two x-y pairs of multiwire proportional chambers (MWPC's), and a 96-cell liquid scintillator detector sensitive to both neutrons and protons. The detector arrays permit measurement of the opening angle and coplanarity of detected nucleon pairs with sufficient resolution to distinguish n-p free scattering events from most quasifree scattering initiated on nucleons bound in contaminant target nuclei. With the same setup we can also perform various calibration measurements and systematic error checks (described below) in which two charged particles are detected in coincidence. Significant improvements to the detection system during the past year have been made in the physical alignment flexibility, magnetic shielding of wedge scintillator phototubes from the PPT

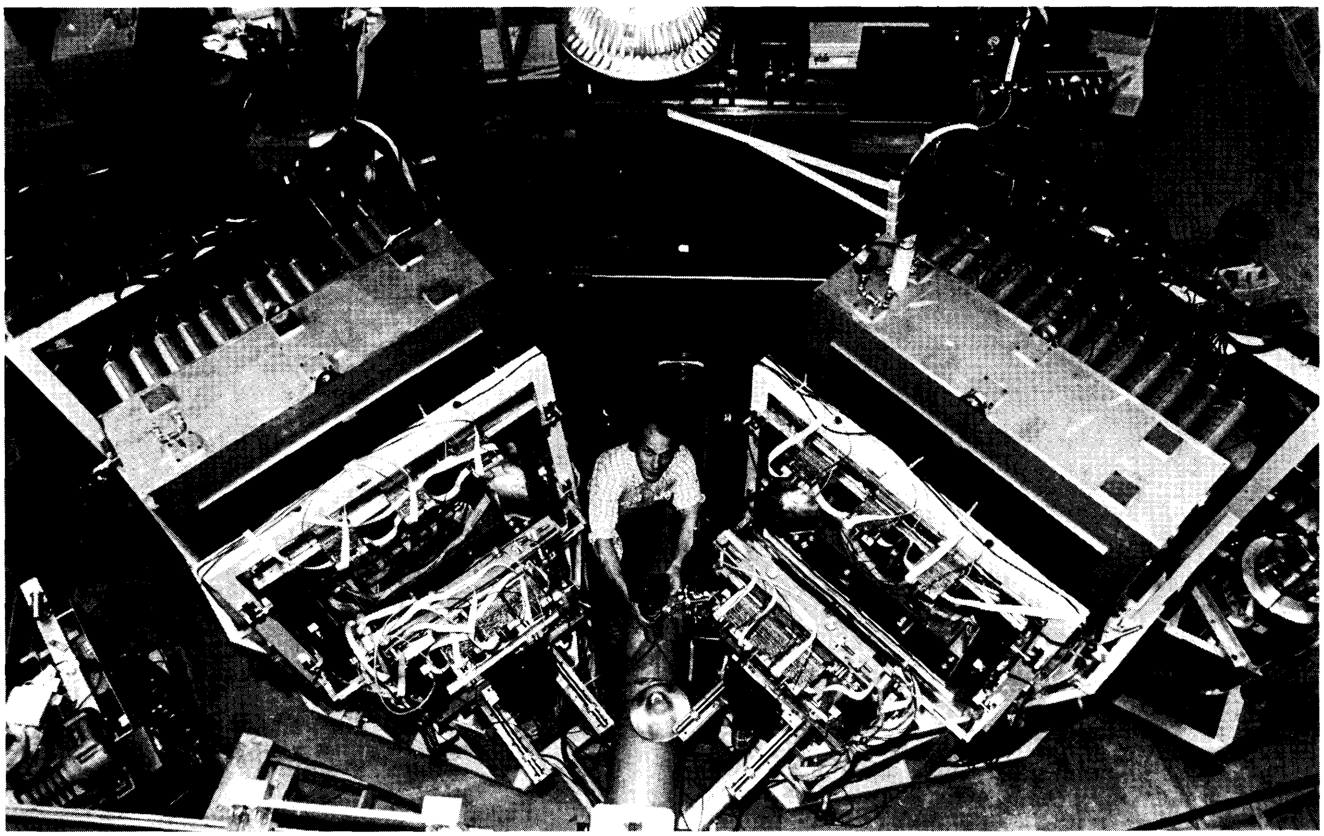

Figure 1. Photograph of the complete left-right symmetric detector arrays for the CSB experiment. During the experiment, the front plastic scintillator and wire chambers on each arm are rolled forward on their respective rails from the locations shown. The polarized neutron beam enters from the bottom of this picture. The polarized target dewar, dismounted from its normal in-beam position, is seen in the lower right corner of the photograph. The laser used for light-pulsing diagnostics is mounted above the shielding wall at the rear of the picture.

superconducting holding field magnet, and uniformity of the firing pattern of neutron-detector phototubes with the laser-fiber optics diagnostic system. In addition, continued debugging of the electronics and front-end microprocessor system have eliminated a few types of infrequent but worrisome events with invalid or missing neutron detector or MWPC information.

A major improvement has been made in the np free-scattering rate capability of the experiment. The count-rate limitation imposed by the front end was improved by more than 50% by replacing an LSI 11/23 microprocessor with an LSI 11/73, and by further streamlining front-end software. We now can process 200 events/second (with an average of ~20 words per event) with dead times < 10%. At the same time, several additional modifications to the detector hardware (most notably, installation of a new veto scintillator to suppress quasifree scattering events initiated on the downstream wall of the PPT dewar) have produced a 50% increase in the ratio of free np scattering to total event rates (currently ~1:5) seen by the computer. In production running, we now expect to use 60-70 nA of primary polarized proton beam (pulse-selected 1:2) on a 20-cm long LD_2 production target, and a 1.0 g/cm^2 yttrium ethyl sulfate (YES) crystal for the PPT. Under these conditions, we will acquire ~35 free np events per second, summed over left and right detectors and over the full angle range covered.

The most important developments of the past year are related to setup and calibration procedures for experiment runs. We have added to the on-line sorting software an extensive series of fast diagnostic checks for a variety of anomalies in the information read in for each event. The checks are designed to provide sensitivity to a wide range of potential hardware (both detector and electronics) problems. The user is notified if any specific type of error occurs in more than a preset fraction of the events acquired during a time interval of ~5 minutes. Additional diagnostic checks, comparing various scaler sums and ratios with expected ranges of values, are performed by the acquisition code every time the PPT spin is being flipped (an operation requiring ~1 minute, performed every 10 to 20 minutes). The automatic software diagnostics have not only vastly improved our speed and efficiency in setting up the experiment, but have made it possible to identify most hardware failures during a run within 10 minutes of their occurrence.

The most important advance in calibration techniques is associated with matching the performances of the 192 neutron-detector phototubes. This is now done in-beam with the aid of software which automatically adjusts all tube voltages (via remote CAMAC control) and software timing offset parameters for each cell, in order to match proton pulse height and neutron time-of-flight information as a function of scattering angle to desired kinematic loci. Since the recoil protons from free np scattering make it into the liquid scintillator detectors only over ~3/4 of the angle range covered (i.e., for $\theta_p^{lab} < 52°$), the n-p data are complemented for the pulse height gain optimization by p-d elastic scattering data (yielding protons in the liquid scintillator for $37° < \theta_{lab} < 61°$). The latter are acquired by switching off the PNF charged-particle sweeping magnet to obtain a secondary proton beam and using a CD_2 secondary target.

The p-d scattering runs also play a vital role in angle and efficiency calibrations of the CSB detectors. For the angle calibration we detect protons and deuterons from elastic scattering events in coincidence on the two arms and adjust detector geometry parameters to match the observed angle correlation to the kinematic expectation. In particular, the well defined kinematic crossing (see Fig. 2) where the protons and deuterons emerge at the same laboratory angle (51.22° for 177 MeV incident protons) allows an absolute calibration of the detector positions. In combination with various consistency checks performed in proton ray-tracing for p-p elastic scattering events, the p-d data allow angle measurements in the CSB experiment with an absolute accuracy ~0.1° and with a relative accuracy (between left and right detector arms) of a few hundredths of a degree. For the purposes of neutron-detector efficiency calibrations we compare d(p,pn) and d(p,2p) yields in quasifree geometry over the entire angle range spanned by the detectors.[5] The complete setup of the experiment and performance of all of the above calibration procedures can now be carried out in 6-7 shifts of beam time.

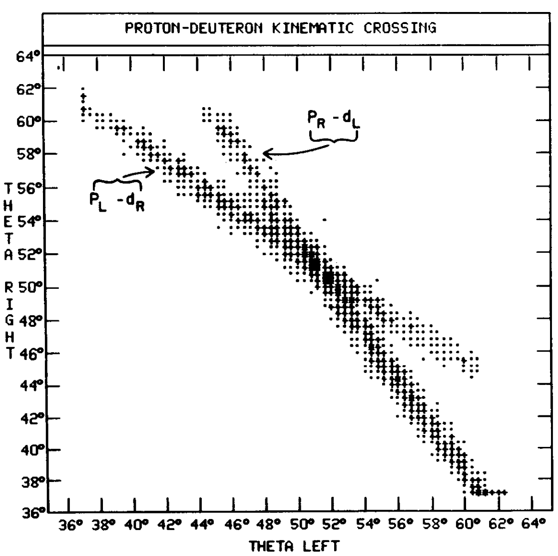

Figure 2. Observed angular correlation between protons and deuterons detected in coincidence with the CSB detectors following elastic scattering of the secondary proton beam from a CD_2 target. Software cuts on the energy losses, flight times, and coplanarity of the detected particles have been used to identify the p-d elastic events cleanly. The two groups correspond to the detection of p vs. d in the left detector arm. These data allow an accurate absolute angle calibration of the detectors (see text).

Replay of preliminary data acquired with n and p secondary beams incident on the PPT has been a major continuing effort during the past year. Most of the replay has been carried out on the Harris acquisition computer, using our now extensively modified version of the code RAQUEL. With this version we now have access to ~50K words of core for histogram storage, which is adequate for most data-sorting purposes. However, we envision some of the replay of CSB data to be carried out at IUCF, and all of the replay to be performed in parallel by collaborators at the University of Wisconsin and Hope College, to utilize VAX 11/750 computers. For this reason significant effort was devoted during the past year to writing appropriate software to analyze CSB event tapes with the VAX version of the code LISA (obtained from Argonne National Laboratory).

The replay of data has been focused primarily on understanding the detector responses in quantitative detail, optimizing the discrimination of free from quasifree np scattering events, and developing analysis procedures which minimize sensitivity to various possible sources of systematic error in the CSB measurement. Experimental results on the neutron detector response can now be compared in detail with predictions of a Monte Carlo code which has been extensively improved and run during the past year. Special emphasis has been placed on searching for possible spin-dependence in the neutron detector response that might produce systematic errors in the CSB measurement; with the exception of small effects in edge cells of the detectors, which can be removed by suitable software gating, we have to date seen no evidence for significant spin-dependence in the response in either the Monte Carlo calculations or in the real data.

Discrimination against quasifree scattering is obtained by placing software cuts appropriate to free scattering on a variety of parameters: opening angle and coplanarity of the detected nucleon pairs; event vertex location (from the proton-arm ray-trace) in the YES target region; proton flight time to the start scintillator with respect to the cyclotron rf signal (providing incident neutron energy information); proton energy loss in the start scintillator vs. scattering angle; neutron time of flight vs. scattering angle; etc. These cuts are applicable over the entire angle range spanned by the detectors ($25° < \theta_{lab} < 61°$); additional cuts available on the pulse height and flight time of protons which make it into the liquid scintillator restrict the angle range to $\theta_p^{lab} < 52°$. Without the latter cuts, we typically obtain ~50:1 free/quasifree event ratio with the PPT (in which there are ~9 bound protons for every free proton), while discarding ~20% of the free-scattering events; the proton information from the liquid scintillator yields another factor of ~2 improvement in this ratio. This discrimination is adequate for performance of the CSB experiment to the desired sensitivity since, as discussed below, we have independent means for measuring the shape of the quasifree background in the region of the free-scattering opening-angle peak, and also because the analyzing power of the quasifree scattering is near zero.

The data from which we actually deduce spin-dependent observables for the $\vec{n}$-$\vec{p}$ scattering are contained in histograms such as shown in Fig. 3. Here spectra of counts vs. measured proton angle, acquired on a single event tape and gated by all the cuts

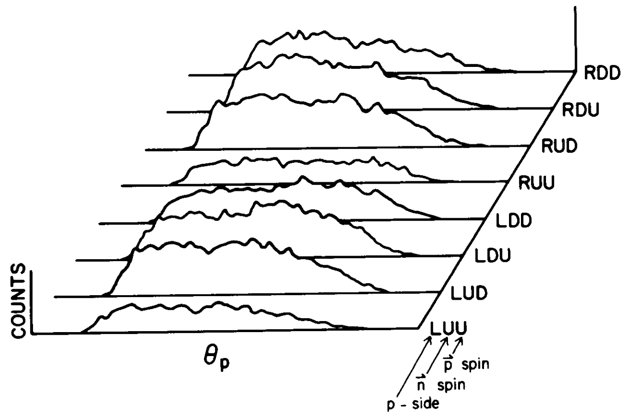

Figure 3. Typical spectra observed in the CSB experiment (here for one event tape's worth of data) for the measured laboratory angle of the protons from free $\vec{n}$-$\vec{p}$ scattering events. Spectra are shown for the eight different combinations of proton detector arm, $\vec{n}$ beam spin projection, and $\vec{p}$ target spin projection. The "wiggles" in each spectrum are statistical fluctuations "smoothed" by the plotting routine. From such spectra we calculate (on-line during the experiment) all polarization observables of interest.

defining free-scattering events, are shown for the eight "spin" states corresponding to the different combinations of proton detector arm (left or right), $\vec{n}$ beam spin (up or down), and $\vec{p}$ target spin (up or down). We have recently implemented software which can be called from the data acquisition program to use such spectra, together with n flux monitor spectra for the various beam-target spin states, to calculate all spin-dependent observables of interest as a function of angle. The calculated observables include, for example: the analyzing power $A_n(\theta)$; the spin correlation parameter $C_{NN}(\theta)$; the target polarization deduced under the assumption that $\Delta A(\theta) \equiv 0$; the ratio of left-to-right detector efficiencies determined independently from runs with beam and target spins parallel and from runs with antiparallel spins; and a CSB observable,

$$Q(\theta) = \frac{[P_{beam}A_n(\theta) - P_{tgt}A_p(\theta)]}{[P_{beam}A_n(\theta) + P_{tgt}A_p(\theta)]} \cong \frac{1}{2}\left[\frac{\Delta P}{P} + \frac{\Delta A(\theta)}{A(\theta)}\right],$$

whose angle-dependence is independent of n beam integration. These calcula-tions permit periodic on-line monitoring of sensitivity to systematic errors and consistency checks on the accumulated data.

The systematic errors of greatest concern in the experiment arise from instrumental effects which directly simulate CSB, in that they cause left-right asymmetries which change sign when one (beam or target), but not the other, of the nucleon spins is flipped. One such effect arises from the analyzing power for $\vec{n}$-p quasifree scattering from bound (hence, unpolarized) protons in the target. In order to minimize this effect, we require accurate knowledge of the shape of the quasifree background underneath the free scattering peak in our opening-angle spectra. We intend to measure this background shape by two complementary methods, one using the secondary proton beam to study $(\vec{p}$,pn) quasifree scattering ("uncontaminated" by free scattering) from the PPT, and the second investigating $(\vec{n}$,np) spectra from an essentially hydrogen-free target similar in other contents to YES. An example of the opening-angle spectrum obtained after subtraction of the quasifree background determined with such a hydrogen-free target is shown in Fig. 4. In a similar way, we intend to make in-beam measurements to test sensitivity to, and aid in cancelling, various other types of systematic error. In many cases, the sensitivity tests involve p-p scattering of the secondary proton beam from the PPT.

Two particularly worrisome instrumental sources of asymmetry which flip with the PPT spin, but not the beam spin, are worthy of mention. The first,

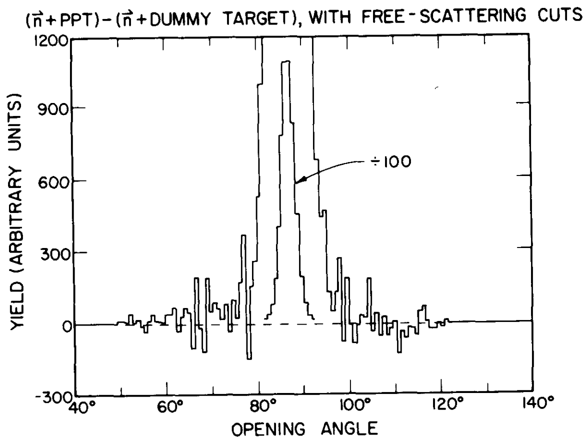

Figure 4. Opening-angle spectrum obtained for neutrons bombarding the polarized proton target [Yb-doped $Y(C_2H_5SO_4)_3 \cdot 9H_2O$], after subtraction of a quasi-free background determined from measurements with neutrons incident on carbon, teflon, KEL-F (C_2F_3Cl), and Y_2O_3 targets. Identical free-scattering cuts (not including proton information from the liquid scintillator) have been applied to the data for all targets before the subtraction. After the subtraction, the background underneath the free-scattering peak is reduced to ~ 0.1% of the peak area.

associated with the bending of protons in the PPT holding field, is illustrated by Fig. 5. When no correction is made in the software for the proton bend (~1° for the usual holding field strength of 0.1 T), the opening angle left-right difference spectra displayed clearly exhibit a spurious asymmetry which changes sign with the PPT field direction. A simple first-order field correction made on an event-by-event basis in the software removes this effect to a large extent (see Fig. 5), but not adequately for the desired CSB sensitivity (for which purpose we must correct for the bend angle to an accuracy ~±0.04° over the entire angle range spanned by the detectors). A software correction based on a more sophisticated field map should provide the necessary accuracy, and can be checked experimentally in $\vec{n}$-$\vec{p}$ scattering runs with the target unpolarized but the holding field on at larger

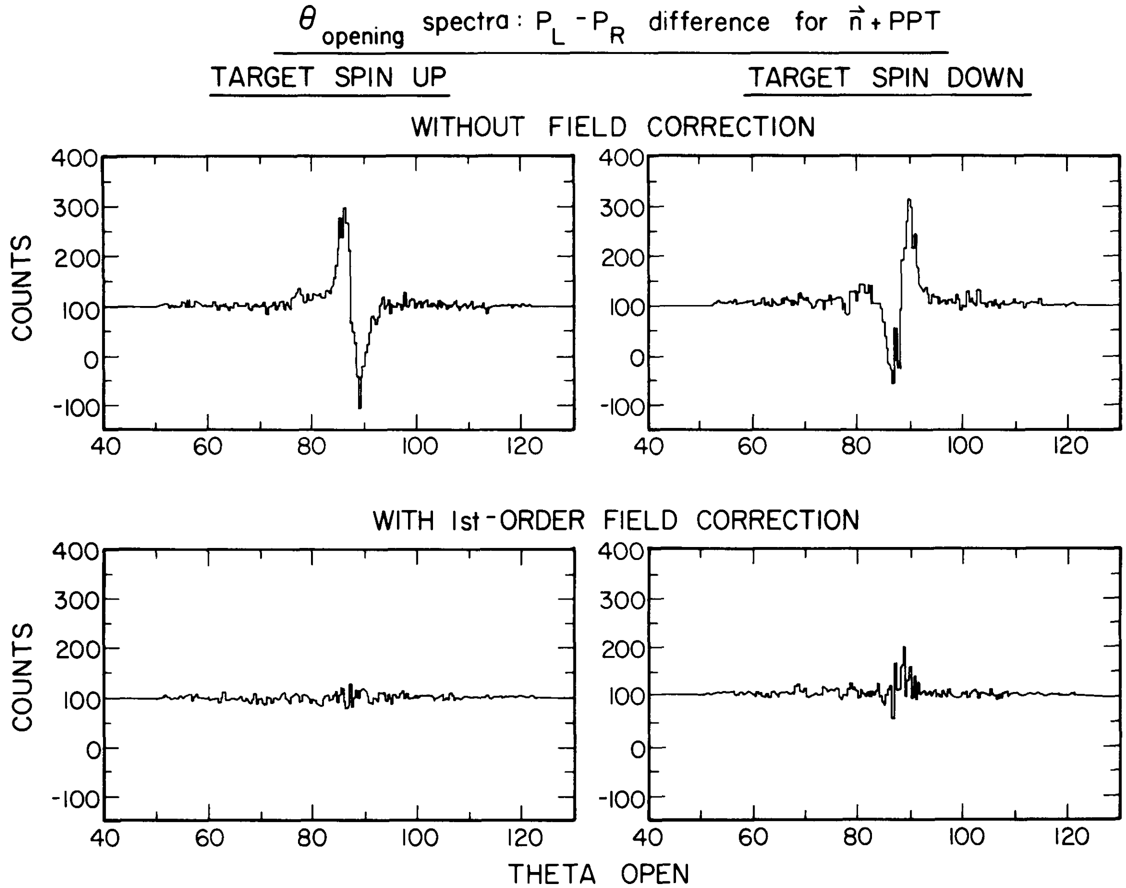

Figure 5. Spectra illustrating the spurious asymmetry associated with the bending of detected protons in the polarized target holding field. All four spectra are for the measured opening angle between detected n-p pairs (without free-scattering cuts), with counts added to the spectrum when the proton is detected on the beam left side and subtracted for beam-right protons. The bipolar peaks in the upper spectra, arising from the bend of the protons toward smaller angles on one side and larger angles on the other, are largely removed by the simple software field correction included in replaying the same data for the lower spectra. More accurate field corrections are needed in the ultimate data analysis.

than normal values. Another, independent, check of the field correction can be made by finding the zero-crossing of the p-p analyzing power measured with an unpolarized secondary proton beam and the PPT. An additional level of insurance against systematic errors associated with the PPT field will be provided by periodically flipping the PPT spin direction without accompanying field reversal, so that roughly half the data will be acquired with PPT spin and field antiparallel. The latter method of spin reversal can be achieved with less than 10% polarization loss by "adiabatic fast passage" of the holding field through the NMR value, in the presence of a high-power rf perturbing field.

Another source of systematic error is associated with in-plane components in the beam and target polarizations. The $\vec{n}$ beam, under all circumstances, has an in-plane component which is uncorrelated with the primary proton beam spin state. This component arises from the polarization in the $d(p,\vec{n})$ production reaction, which has a magnitude ~0.1 at our production angle θ_{lab}=10°. Since our production plane is vertical, the resulting neutrons thus have an unwanted sideways polarization (P_S^{beam}), which can be precessed in the horizontal plane through an angle up to ±40° when the neutrons pass through the PNF sweeping magnet. This non-flipping in-plane beam polarization component, if combined with in-plane components in the target which do flip when the PPT spin is reversed (with or without accompanying field reversal), can produce a spurious CSB asymmetry via the spin correlation parameters C_{SK} and C_{KS} for $\vec{n}$-$\vec{p}$ scattering. These correlation parameters are unfortunately large in magnitude (~0.5) at our energy and angles. In order to attain the desired sensitivity to CSB effects, we need to ensure that the horizontal (especially the longitudinal--P_L) components in the PPT polarization are < 0.5% of its vertical polarization. Cancellation of small horizontal field components can be accomplished with correction coils positioned outside the PPT dewar and high statistics measurements of P_L^{tgt} and P_S^{tgt} via spin correlation studies for $\vec{p}$-$\vec{p}$ scattering. An appropriate secondary proton beam for these correction measurements, with large (~0.6-0.7) sideways polarization, can be produced by scattering a sideways polarized primary proton beam from a spin-zero (e.g., ^{12}C) production target. (Since the production plane is vertical, the primary and secondary beam sideways polarizations are connected by the spin transfer parameter D_{NN}, which must be unity for elastic scattering from a spinless target.) Installation of a suitable superconducting spin precession solenoid in the primary proton beam line and construction of the PPT field correction coils needed for these auxiliary $\vec{p}$-$\vec{p}$ measurements will be carried out during the first few months of 1985.

The polarized proton target, under development for some years at the University of Wisconsin, was transported to IUCF and installed in the PNF area in the spring of this past year. However, further development work on the PPT is now needed in early 1985. Our performance goals for this target are maximum proton polarizations of P_{max} = 0.55-0.60, with relaxation times ($\tau_{1/e}$) ~50 hours. These specifications were met in early tests of the target with a small YES crystal, for which a temperature T = 0.6 K was maintained while spinning the crystal in a B = 1.1 T polarizing field. We have, for a variety of reasons, experienced much poorer performance with the large-area target crystals used to date in $\vec{n}$-$\vec{p}$ test runs at IUCF (P_{max} ~ 0.2, $\tau_{1/e}$ ~ 20 h, T ≅ 1.0 K, B = 0.95 T). Improvements under way to address these problems include growing new YES crystals, rewinding the superconducting polarizing field coil, reducing the target area, and increasing the flow of cold He gas to the bearings and of liquid He spray to the target crystals themselves. We have also recently greatly improved the trapping of contaminant gases in the ^3He inlet lines for the PPT, thereby ameliorating a longstanding problem with periodic freezing in the ^3He tubes inside the dewar. It is hoped that the PPT modifications will be completed in May, 1985, enabling production running on the CSB experiment during the summer and fall.

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