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SEARCH FOR CHARGE SYMMETRY BREAKING (CSB) IN $\vec{n}$-$\vec{p}$ SCATTERING

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1986 saw the first production run for the CSB experiment,[1] as well as numerous continuing developments aimed at improving the ultimate precision of the experiment and of the data analysis. The major aims of the production run, taken in March, 1986, were to: (1) investigate the feasibility of using $\vec{p}$-$\vec{p}$ scattering measurements, induced by a sideways-polarized secondary proton beam, for the purpose of zeroing horizontal components in the "spin refrigerator" (Ref. 2) polarized proton target (PPT) holding field; (2) test the longevity and reliability of PPT operation after a series of technical improvements made during the previous year; and (3) acquire a sufficient statistical sample of $\vec{n}$-$\vec{p}$ scattering events on tape to fuel meaningful development of data analysis techniques and understanding of systematic errors at a level far superior to that gained from earlier runs. On the basis of our experience and results from the March run, we have decided to postpone further production running until we receive two new commercial magnets to replace the superconducting polarizing field assembly in the PPT and the sweeper/precession magnet in the polarized neutron beam line. While designing, ordering, and awaiting delivery of these magnets, we have made considerable progress in analyzing the March, 1986 data and in further improving various other aspects of the CSB apparatus. A number of the equipment upgrades are described in detail in the technical section of this report. A high-quality measurement of the $\vec{n}$-$\vec{p}$ scattering spin correlation parameter $C_{NN}(\theta)$ — a byproduct of the March run — is presented in the following contribution. Here, we present some of the results and concerns specifically relevant to the CSB measurement itself, generated by the March run and by our subsequent work.

The PPT operated continuously for 8 days (longer than ever before) during the March run, with the lowest operating temperatures, longest spin relaxation times, and highest polarizations we had yet achieved with the large-area (5 cm × 7 cm) crystalline (yttrium ethyl sulfate: YES) target sample needed for the experiment. Despite the considerable improvements over earlier performance, the target polarization was still marginal with respect to that needed to test CSB to the desired precision: the peak polarization obtained was typically $P_t^{max} = 0.42$, while the value averaged over our (typically ~ 16-hour) run cycles was 0.37. The polarization was limited most severely by the polarizing field strength. The superconducting polarizing field (saddle-shaped) coil embedded in the PPT dewar had been rewound during late 1985 in an attempt to reach fields ≃ 1.2 T, but its performance deteriorated in the March run, and we were forced to run it at 0.95 T to avoid repeated quenching. This deterioration was the major factor in our decision to seek a commercial supplier for the new superconducting magnet assembly (see Technical section). With the other relevant target parameters (temperature and rotation frequency during polarization) as they were in March, an increase to 1.2 T polarizing field should increase P_t^{max} to 0.55-0.60. The statistical precision and systematic error problems posed by low target polarization were further compounded in March by poor polarized ion source performance. The average polarization of the primary proton beam from the cyclotron was only 0.63, yielding a secondary neutron beam polarization of 0.44. Polarized source performance has been improved in the intervening months, but needs further improvement (to give $P_{beam} \geq 0.75$) before the continuation of CSB production running.

A primary aim of the March run was for the first time to take data relevant for zeroing in-plane components of the PPT holding field, and hence polarization $\vec{P}_t$. Such components are of concern because they may cause systematic errors in the CSB measurement. In particular, such components can combine with suitable in-plane components in the beam polarization to generate, via the $\vec{n}$-$\vec{p}$ scattering spin correlation parameters $C_{SL}(\theta)$ and $C_{LS}(\theta)$, a spurious left-right asymmetry that changes sign when one (but not both) of the beam and target polarizations is flipped. This is precisely the sort of asymmetry that we seek as a signature of a CSB difference $[\Delta A(\theta) \equiv A_n(\theta)-A_p(\theta)]$ between the analyzing powers associated with the beam and with the target polarization. Unfortunately, $C_{SL}(\theta)$ for n-p scattering is sizable in magnitude (up to 0.5) over a substantial fraction of the angle range covered in our experiment, in contrast to its (fortuitously) small magnitude at the energy and (single) angle of the recent TRIUMF CSB experiment.[3] Furthermore, our neutron beam has an unavoidable sideways (S) component of magnitude ≈ 0.1, arising from the $^2H(p,\vec{n})$ production reaction polarization (our beam line employs a vertical $^2H(p,n)$ reaction plane), which does not flip when the primary proton beam spin is reversed at the ion source. In addition, we expect somewhat smaller flipping horizontal components in the beam polarization. With the limited (±40°) spin precession capability afforded for such horizontal components by our existing neutron beam line sweeping magnet (intended primarily to remove secondary charged particles from the beam), we can limit the consequent systematic errors for the CSB measurement to acceptable values ($\lesssim 10^{-4}$) only by zeroing PPT longitudinal (especially) and sideways field components to an accuracy of several Gauss in the presence of the ~ 1 kG vertical holding field. For this purpose, in late 1985 we added to the PPT the capability to produce appropriate longitudinal and sideways correction fields with independently controllable values for the two holding field orientations.

The directions of the worrisome components in $\vec{P}_t$ are defined with respect to the n-p scattering plane; hence, the best way to measure them to the required precision is via another scattering experiment using the same equipment. The best approach is to scatter a sideways-polarized secondary proton beam from the PPT, and to use the known large spin correlation parameters $C_{SS}(\theta)$ and $C_{SL}(\theta)$ for $\vec{p}$-$\vec{p}$ scattering to determine P_t^S and P_t^L. A considerable fraction of the March run was devoted to such measurements, made with a secondary beam produced by 10° (vertical) scattering from a ^{12}C production target of a sideways-polarized primary proton beam (prepared with a superconducting high-energy beam-line precession solenoid we installed during 1985). Measurements were made for two different settings of the PPT correction coils, in order to determine our sensitivity to small P_t^S and P_t^L.

While the $\vec{p}$-$\vec{p}$ data are not yet fully analyzed, it is already apparent that these auxiliary measurements are as difficult in their own right as the main $\vec{n}$-$\vec{p}$ measurement itself. In particular, they require that a completely different set of systematic errors be reduced to comparable limits. Of special concern are the strong sensitivities of the $\vec{p}$-$\vec{p}$ measurements to small errors in beam integration and to small horizontal polarization components in the primary beam out of the cyclotron (which we found to be appreciable and time-dependent, even though cyclotron operation was unusually stable during the run). The statistical precision needed for the $\vec{p}$-$\vec{p}$ measurements poses an additional problem, since we learned that several days of proton bombardment of the PPT causes significant radiation damage to the target crystal, manifested by a reduction in the spin relaxation time (from an initial value of > 200 h to a final value of ~ 60 h, both measured with a holding field of 900 G). Although we found subsequently that the damage symptoms are cured by room-temperature annealing of the crystal, it is still clear that we need to limit the amount of auxiliary p-p running during production runs.

In response to the problems revealed by the $\vec{p}$-$\vec{p}$ running, we have designed and ordered a new neutron beam line sweeper magnet capable of ±90° precession of horizontal $\vec{n}$ spin components. This magnet is described in more detail in the technical section of this report. In subsequent CSB production runs we will then acquire half the $\vec{n}$-$\vec{p}$ data with one polarity of the sweeping magnet and half with the opposite polarity. When the two sets of data are combined, systematic errors from any small in-plane spin correlation effects should be canceled to high order. In particular, if the precession angle is correct to ±2°, and any time-dependent changes in the horizontal $\vec{n}$ beam components have associated rms deviations (averaged over all run cycles) $|\delta P_b^{L,S}|_{rms} \lesssim 0.01$, then we will have gained about one order of magnitude of insulation from the associated systematic errors. We will then need to limit horizontal components in the PPT holding field only to ~ 30 G; field components of this magnitude can be measured to sufficient accuracy (and canceled with the correction coils) by replacing the target shaft with a warm-bore Hall probe assembly currently being fabricated. We will thus be far less reliant on the auxiliary $\vec{p}$-$\vec{p}$ measurements — they will be used only to verify the cancellation of the $P_t^{S,L}$ components to a precision already achievable under present conditions.

While awaiting delivery of the new PPT magnet assembly and the new sweeper magnet (both scheduled for early Spring, 1987), we have concentrated our efforts on replay of the data from the first production run. A major advance in this regard has been the conversion of our extensive replay and analysis software to the VAX-based XSYS system. (Data acquisition for the CSB experiment will continue to be performed with the old Harris computer and our much improved version of the code RAQUEL.) By use of compressed 6250 bpi tapes (each containing 11 800-bpi event tapes written with RAQUEL) and XSYS on our VAX 8600 computer, we can now replay the equivalent of ~ 80 RAQUEL tapes (which take ~ 40 hours of beam time to write) in ~ 10 hours. This development makes it possible for off-line replay (including tape compression) during a run to keep up with data acquisition, and makes multiple-pass replay of all the data after a run practical. Examination of the data from March, 1986 has also led to a number of significant improvements to our replay software, most notably in the treatment of events with missing or multiple-hit wire chamber information or multiple-hit neutron-cell information, thereby improving our analysis efficiency for extracting free-scattering events by 15-20%.

Some results from our first-pass replay of the March $\vec{n}$-$\vec{p}$ data are shown in Figs. 1-3 and discussed below. The $\vec{n}$-$\vec{p}$ data were acquired using ~ 16-hour run cycles, each of which includes 12 tapes of data (containing ~ 4×10^5 free n-p scattering events) taken with the PPT spin orientation parallel to the holding field direction (which itself was flipped once every ~10 minutes), and another 12 tapes with the PPT spin antiparallel to the field. In between these two halves of each cycle, we repolarized the target (by spinning it at ~ 45 Hz in the 0.95 T polarizing field for ~ 2 hours), and acquired 3 tapes of background data from an elaborate "dummy" target constructed to simulate as closely as possible the non-hydrogenic content of the PPT (and hence, the quasifree n-p scattering background). Of the 12 tapes for each PPT mode, 6 were acquired with one polarity of the $\vec{n}$ beam line sweeping magnet field and 6 with the opposite polarity. The results for various observables shown in Fig. 1 correspond to 1.5 run cycles (i.e., 18 tapes for each PPT mode) of accumulated data — about one day of running — and include subtraction of the dummy target data. Of the ~ 1.2×10^6 free-scattering events included on these tapes, the first-pass replay (performed before implementation of the wire chamber and neutron detector software upgrades mentioned above) extracted ~ 1.0×10^6 (summed over all angles). By the time CSB production running is completed, we plan to have acquired ~ 4×10^7 total free n-p events; with the expected (~ 20%) improvements to both the beam and target polarizations, in comparison with performance during the March run, the final data should have statistical uncertainties one order of magnitude smaller than those shown in Fig. 1. For the results in Fig. 1, the data have been collected into 4.8° lab angle bins.

The analyzing power asymmetries $P_bA_n(\theta)$ and $P_tA_p(\theta)$ in Fig. 1 — deduced, respectively, by flipping the beam and target spins — have been used to determine the beam and target polarizations by normalizing analyzing power predictions (based on the Arndt SM86 phase shifts[4]) to the data. The results are $P_b = 0.44 \pm 0.01$ and $P_t = 0.37 \pm 0.02$. These values have then been used to extract the spin correlation parameter $C_{NN}(\theta)$ from the measured count-rate asymmetry for parallel vs. antiparallel orientations of beam and target spins. The C_{NN} results are discussed in more detail in the following contribution. The CSB variable $\Delta A(\theta)$ reflects the differences between the measured values of P_bA_n and P_tA_p, and is extracted from the yields in five different ways, with different sensitivities to potential second-order systematic errors. For the data in Fig. 1 the five methods give completely consistent results, which can be seen to coincide with zero within the present statistical uncertainties (~ ±0.01 for most angle bins). Some effects of possible in-plane components in the beam and target polarizations can be monitored by the asymmetry we call $T_8(\theta)$ in Fig. 1, including the $C_{SL}(\theta)$ and $C_{LS}(\theta)$ spin correlations. Figure 1 shows that $T_8(\theta)$ is also consistent with zero within present uncertainties. The final observable plotted in Fig. 1 is the efficiency-times-solid-angle ratio $\nu(\theta)$ for free-scattering np coincidences with the proton detected in the left vs. right arm. This ratio varies with θ from 0.9 to 1.0, adequate performance for the

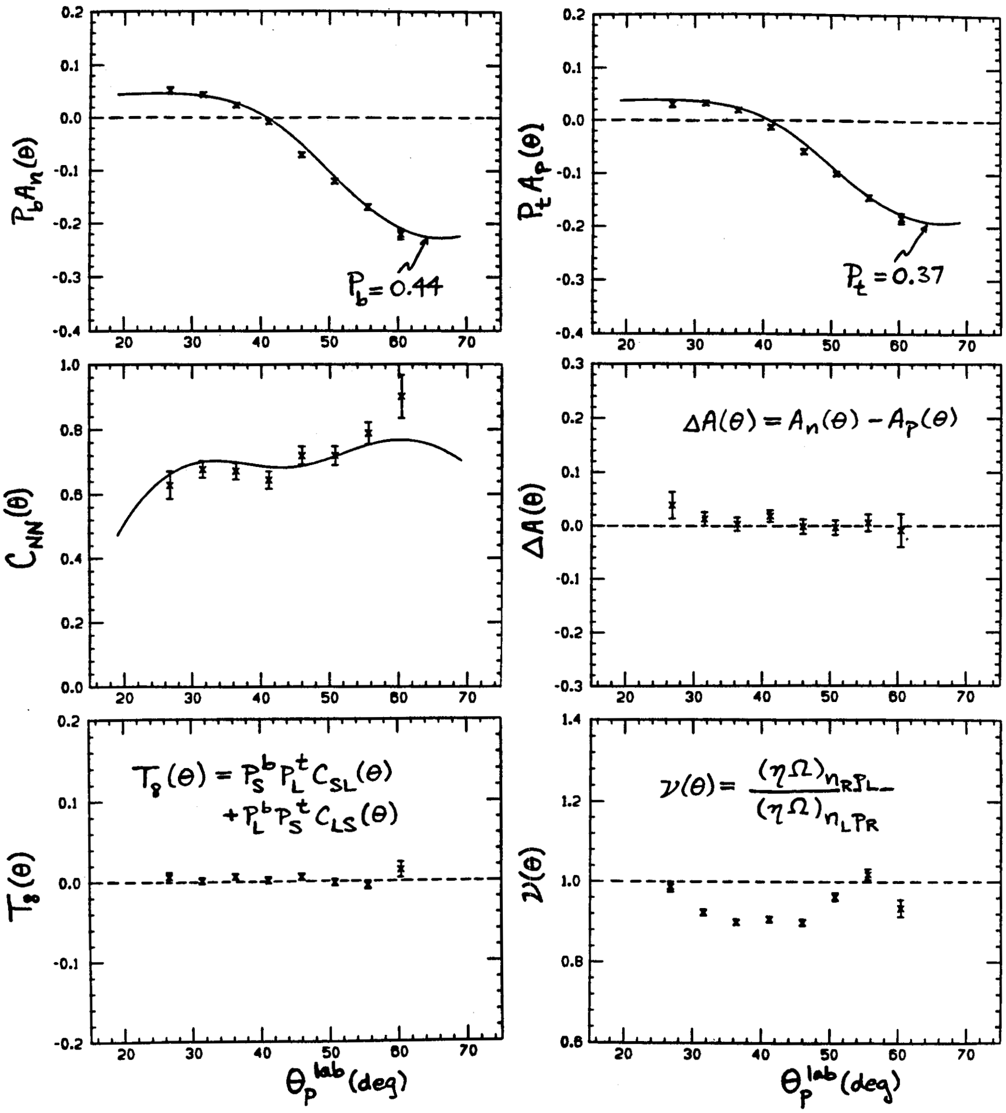

Figure 1. $\vec{n}$-$\vec{p}$ scattering results obtained from a first-pass replay of ~ 1.0 × 10^6 free scattering events acquired during March, 1986 run. The curves represent Arndt SM86 phase shift[4] predictions normalized to our data.

CSB experiment. A number of detector improvements made during the summer of 1986 (described in the technical section of this report) led to a considerably more uniform value of $\nu(\theta)$ in a subsequent short run taken in September.

Another interesting result obtained from the March data is the quasifree n-p analyzing power asymmetry deduced from the dummy target, with all free-scattering kinematic cuts applied. These results are shown in Fig. 2 as a function of θ_p^{lab}, together with the Arndt phase shift prediction for free scattering. The strong similarity between quasifree and free scattering angular distributions is encouraging, since it limits our sensitivity in the CSB measurement to systematic errors arising from imperfect subtraction of the quasifree background. The small, but clear,

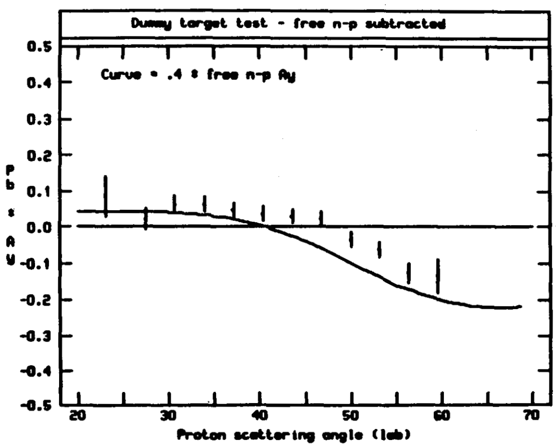

Figure 2. The analyzing power asymmetry $P_b A_y(\theta)$ measured for quasifree n-p scattering from the dummy target, subject to all free-scattering cuts. The curve represents the Arndt SM86 phase shift[4] prediction for free-scattering $A_y(\theta)$, multiplied by $P_b = 0.4$.

differences observed (Fig. 2) between the quasifree and free analyzing powers, however, may be of considerable physics interest. Our kinematic cuts constrain the quasifree scattering processes to include only those events initiated on essentially stationary target nucleons, presumably eliminating Fermi motion effects from the comparison. The differences may then reflect distortions of the nucleon waves by the nuclear field or non-trivial medium modifications, e.g., associated with relativistic reductions in the nucleon effective mass.[5]

While the results from the March $\vec{n}$-$\vec{p}$ data all look reasonable at the present level of statistical uncertainty, the replay has revealed a number of problems which may cause systematic errors significant in comparison with the ultimate statistical precision of the experiment. We are presently trying to understand and eliminate the sources of these problems. Among them is an apparently imperfect subtraction of the quasifree background events, illustrated by the opening angle (θ_{open}) spectra displayed in Fig. 3. After application of all cuts and subtraction of the dummy

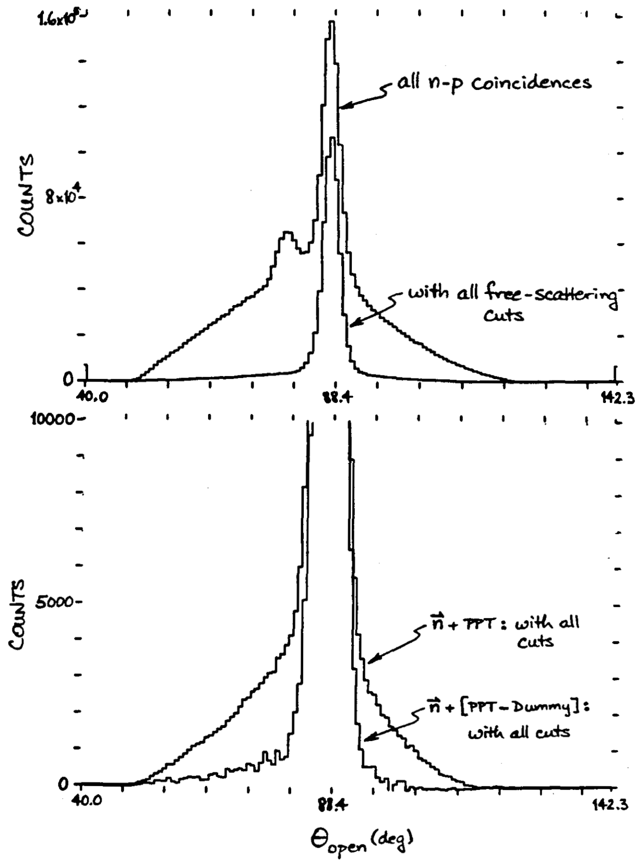

Figure 3. n-p opening angle spectra obtained from the first-pass replay of the March, 1986 production run. The upper frame shows the spectra without any software cuts (including a small secondary peak originating from free scattering in the downstream portion of a veto scintillator located just after the PPT dewar) and with all free-scattering cuts applied. The lower frame shows the effect of the dummy target subtraction, with a counts scale magnified by a factor of 16 relative to the upper frame. The spectrum before dummy subtraction in the lower frame is identical to the spectrum with all cuts in the upper frame.

target data, we still see a small background, highly skewed to the low-θ_{open} side of the free peak, containing ~ 0.5% of the counts under the peak. Eventually, the quasifree subtraction must be performed to an accuracy of ~ 0.1% to keep the associated systematic error in $\Delta A \lesssim 1 \times 10^{-4}$. The background appears insensitive to the software cuts used, and might reflect "misplaced" free scattering events or an imperfect mockup of the PPT by the dummy target. To help us distinguish between these possible origins, we have taken data (as yet unanalyzed) for the YES target mounted in the dummy target container, to permit a more constrained subtraction. The background problem may be related to another effect indicated by our replay: an apparent spatial displacement of the PPT with respect to the dummy target, deduced from proton ray-tracing to the location of the event origin. In the near future, we will be rechecking the optical alignment of all targets we use with respect to the neutron collimator, and instituting additional setup measurements (n-p scattering from YES when the target is warm as well as cold; n-d as well as p-d scattering from a CD_2 target) to further constrain our angle and target location calibration techniques.

Another concern generated by the replay to date is that PPT field-dependent instrumental asymmetry contributions to $P_tA_p(\theta)$ are larger than expected, especially for $\theta_p^{lab} > 50°$. The field-dependent effects can be seen by comparing results extracted from the runs with PPT spin parallel (p-mode) vs. antiparallel (a-mode) to the holding field, and also (with consistent results) from auxiliary runs taken with the target unpolarized but in the presence of a stronger than usual (~ 2.3 kG) holding field. The field effect is not significant for observables other than P_tA_p (and hence, ΔA), and even for these it is cancelled to high order by summing the data acquired in the p and a PPT modes. The success of this cancellation is suggested by simulations of the effect, and is indicated even more strongly by the disappearance in the actual summed data of the otherwise large, unavoidable P_tA_p anomalies in the first and last angle bins, which arise from the sweeping of protons by the holding field into or out of the angle range spanned by the detectors. Since it is, however, unclear whether this cancellation is sufficiently accurate to reach the goal precision of ±0.001 in $\Delta A(\theta)$, it is important to understand the origin of the enhanced field dependence. In ongoing analysis, we are investigating several possible origins: inadequacies in the software correction for the proton bending angle (also suggested by small Θ_{open} anomalies at large Θ_p), possibly associated with our present neglect in this correction of the lab energy and (multiple scattering) angle spread for protons recoiling at a given scattering angle; a significant angle-dependence to the proton detection efficiency, so that the bend of the protons in the holding field changes the probability for detecting them; a subtle field dependence in some measured parameter on which we place a kinematic cut to define free scattering, so that events move into or out of a software window depending on field orientation. In addition to trying to identify, and then eliminate, the source of the field dependence, we are also planning to ameliorate such effects by taking future production data at lower values (~ 0.65 kG) of the holding field. A recent PPT test run has shown that we can still attain spin relaxation times $\gtrsim$ 100 h in such low fields.

In summary, the CSB group has been actively involved during 1986 in data acquisition, hardware upgrade, and data analysis projects central to the eventual success of the experiment. We hope to complete production running (after delivery of the new magnets) during 1987. When the experiment is completed, it will provide a high precision measurement of the CSB variable ΔA not only at a different bombarding energy than the existing datum[3] at $E_n = 477$ MeV, but for the first time as a function of angle.

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A MEASUREMENT OF C_{NN} IN n-p SCATTERING AT 188 MeV

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The charge symmetry breaking (CSB) experiment is designed to make a very precise measurement of the analyzing power difference $\Delta A = A_n - A_p$ for n-p scattering, where $A_{p(n)}$ is the analyzing power measured with polarized protons (neutrons). In performing these measurements we use a neutron beam and proton target simultaneously polarized normal to the scattering plane. As a byproduct of these measurements two n-p elastic scattering observables can also be extracted from the same data. These are the usual analyzing power, $A = 1/2(A_n + A_p)$, and the spin correlation parameter, C_{NN} (also called A_{NN} or A_{yy}). The parameter C_{NN} is particularly interesting since the Bonn and Paris microscopic nucleon-nucleon potential models give quite different predictions for this observable in the angle range covered by the CSB experiment.

In the past year, as part of the early production running for the CSB experiment, we obtained sufficient statistical precision on $C_{NN}(\Theta)$ measurements to constrain significantly our understanding of the n-p interaction. Since the measurement and analysis procedures are the same as for the CSB experiment itself, we refer the reader to CSB contributions in this and earlier reports[1,2] for a detailed discussion of most of the experimental techniques.

The measurement of ΔA is designed to be insensitive to absolute beam and target polarization magnitudes. For measurements of C_{NN} and A, however, we