# SPIN OBSERVABLES IN NN SCATTERING*

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The future spin correlation measurements planned for IUCF site require precise target and beam polarization handling. The fine tuning performed recently in IUCF facility is presented and discussed.

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## 1. Introduction

It has been demonstrated that cooled, stored beams on internal targets are ideally suited for studies of meson production in few-nucleon systems, especially close to threshold. Due to the electron cooling, one benefits from the resulting small energy spread in the beam (which is needed to map out cross sections that vary rapidly with bombarding energy), as well as the possibility of using thin, internal gas targets without entrance or exit windows. With such targets unwanted background is reduced, and energy loss in the target, either by the beam or the reaction product, is negligible. Also, the use of storage-cell *polarized* atomic-beam targets becomes feasible.

## 2. Analyzing powers in meson production

Close to threshold only a single partial wave contributes to the pion production reaction. As the bombarding energy is increased, other partial waves start to contribute. In order to still determine the corresponding amplitudes individually, polarization observables have to be measured. So far, two analyzing power measurements in pion production have been completed at IUCF.

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In the first experiment, cross sections and analyzing powers in the reaction $pp\to d\pi^+$ were measured at nine energies close to threshold. At the lowest energy, the center-of-mass energy was only 100 keV above threshold. Only the outgoing pions were detected (no coincidence with the recoil deuterons), yet it was demonstrated that the background stayed relatively small and was well determined. The cross section can be expressed as $\sigma = A_0 + A_2 \cdot P_2(\cos\theta_{cm})$, where $P_2$ is the second Legendre Polynomial. The results of this experiment are reported in a recent preprint [1] and are shown in Fig. 1. It should be noted that very little was previously known about the analyzing power of this reaction (triangles in the lower panel of Fig. 1). The S-wave strength extracted from the IUCF experiment is about 13% larger than that determined from a TRIUMF measurement of $np\to d\pi^\circ$ [2]. Calculations have not been done as yet to compare to these $pp\to d\pi^+$ analyzing powers. Such calculations would have to reproduce not only the magnitude of the amplitude but also the phase relative to the P-wave amlitude. This, along with existing total cross section data in all the channels, should provide a sensitive test of questions regarding the relative weights of heavy meson exchange *vs.* off-shell rescattering as the forms for the operators are quite different. After correcting the $pp\to d\pi^+$ cross section for Coulomb suppression and after multiplying the $np\to d\pi^\circ$ cross section by two (*i.e.* if one assumes charge independence) the two channels can be compared. Then a recent cross section measurement of $pp\to d\pi^+$ at the newly constructed cooler sychrotron COSY is in agreement with the TRIUMF experiment.

The second experiment was a measurement of cross sections and analyzing powers in the reaction $pp\to pn\pi^+$ by Daehnick et al. Data at 300, 320 and 330 MeV have been obtained and are currently being analyzed. The reaction $pp \to pn\pi^+$ constitutes an important complementary source of information on pion production in the $NN$ system. It may contain an isospin T=0 nucleon pair in the exit channel and can thus proceed via an intermediate $\Delta$ isobar without restrictions (in contrast to $pp\to pp\pi^\circ$). At 320 MeV, analyzing powers as large as 0.26 have been observed.

In a subsequent experiment spin-correlation parameters for this reaction in the energy range of 330 to 450 MeV will be measured. The goal of this experiment is to determine individual pion-production amplitudes close to threshold.

## 3. The polarized, internal target facility at IUCF

In order to perform measurements of spin-correlation parameters a polarized internal target is required. A beam of polarized hydrogen (or deuterium) is provided by an atomic beam source. The source uses the principle of sub-state separation in a sextupole field (provided by permanent magnets)

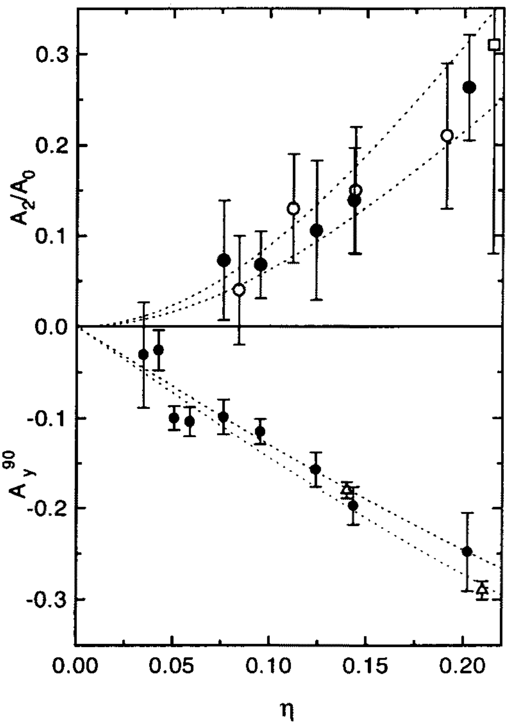


Fig. 1. The anisotropy $A_2/A_0$ of the cross section and the analyzing power Ay at $\theta_{cm} = 90°$ for the reaction $pp \rightarrow d\pi^+$ as a function of $\eta = p_{cm}(\pi)/m_\pi$. Solid symbols are the results of a recent IUCF experiment [1]. The curves are fits to the data as explained in [1].

and rf transitions, and is capable of delivering a narrow beam of $3.5 \times 10^{16}$ atoms/s in a single spin state [3].

A significant gain in target thickness results from injecting the atomic beam into a storage cell (rather than just crossing it with the stored Cooler beam). A target cell consists of a narrow tube through which the stored beam passes with a feed tube joined to its center, pointing toward the source. The wall of the cell has to consist entirely of a material that minimizes the depolarization of colliding atoms. Based on an extensive study of different materials [4], Teflon is used. Optimization of the luminosity, compatibility with ring operation, avoidance of ferromagnetic materials, and observability of reaction products are considerations that further complicate the design of a target cell.

Fig. 2 shows, as an example, the cell as presently used for measurements of spin-correlation parameters in *pp* elastic scattering [5]: its 400 $\mu$g/cm$^2$

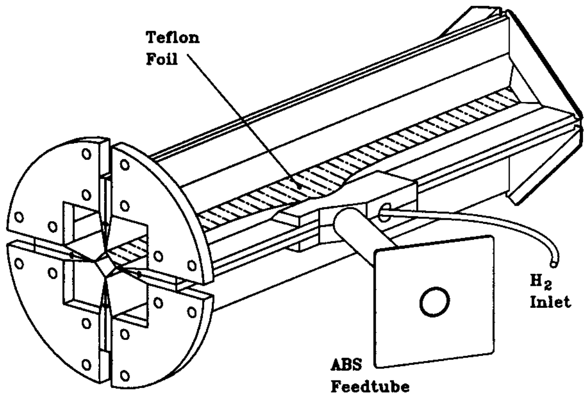


Fig. 2. ABS Target cell assembly. The channel for the stored beam measures 8mm by 8mm by 250mm.

thick teflon walls allow low-energy protons to exit in four azimuthal directions. The reaction planes are inclined by 45° with respect to the horizontal plane in which the incoming atomic beam enters the feed tube. Integrated in the target assembly are four pairs of silicon microstrip detectors, each 4 cm wide and 6 cm long to detect the recoil protons from pp elastic scattering. The entire assembly is mounted on a holder that allows alignment of the cell with respect to the stored Cooler beam. The assembly sits on a flange that also contains the feedthroughs for the signals from the microstrip detectors, as well as the associated read-out electronics which has been manufactured at the TU München [6].

An overall view of the polarized-target facility in the A-region of the Cooler is shown in Fig. 3. The target chamber consists of a 40 cm diameter stainless steel cylinder with ports to mount pumps, the target cell flange, and the connecting flange for the atomic beam source. The latter is tilted by 30° towards the upstream direction in order to free space for detectors in the forward hemisphere.

The direction of the target spin is controlled by a magnetic guide field, uniform in direction. Three sets of Helmholtz coils are provided to generate this field, one for each direction, sideways, vertical, and longitudinal. These coils are water-cooled and mounted outside the target chamber.

From a measurement of the beam current and from the known cross section, one finds a target thickness of typically $3.3 \times 10^{13}$ atoms/cm$^2$, the same as one would deduce from the flux from the source and the conductance of the cell (8mm by 8mm by 250mm). The target polarization is independent of the selected orientation with a typical value of 0.78. The target polarization at different positions along the cell is constant within error which would

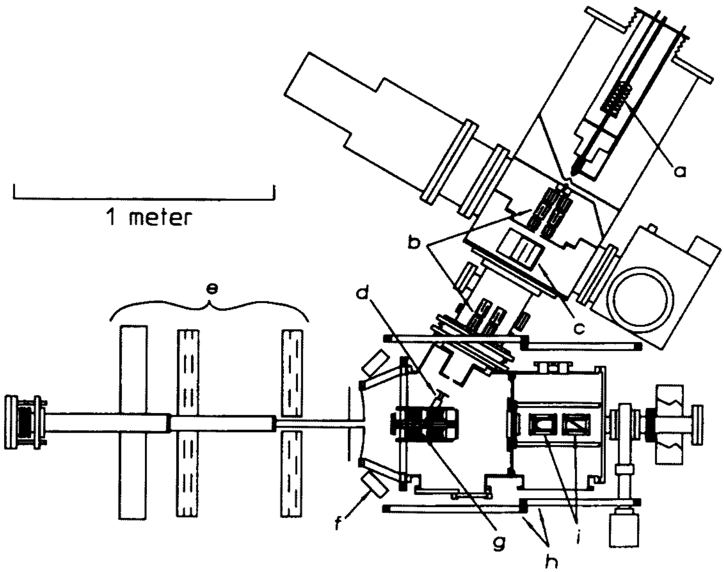


Fig. 3. Polarized target in the A-region of the IUCF cooler ring (a: dissociator; b: sextupole magnets; c: rf transition; d: feed tube; e: detector stack; f: scintillators; g: cell with microstrip detectors; h: guide field coils; i: beam position monitors.) The stored beam travels from right to left in this view.

not be the case if the atoms would significantly depolarize by wall collisions. Target polarization and thickness during a week-long run is shown in Fig. 4. The constant polarization indicates that the original worries that the Teflon surface in the cell might degrade by deposition of dirt or by radiation damage, were unfounded. The long-term reliability of the target facility is well illustrated by the small variations in target thickness seen in the lower part of Fig. 4.

The direction of the polarization is determined by a magnetic guide field in the target region. Three sets of Helmholtz coils allow the production of vertical, horizontal and longitudinal fields. Even when not in use, a small steady current runs in all coils to compensate for the ambient field. The strength of the ambient field (on the order of the earth's magnetic field) determines the minimum guide field necessary to force the polarization into the desired direction (about $3 \times 10^{-4}$ T). The undesired polarization components are found to be smaller than 0.03. The sign of the polarization can be reversed by changing the sign of the current in the guide field coil. Fig. 5 shows the measured polarization as a function of time, illustrating that the sign reversal takes less than 50 ms. The target polarization is

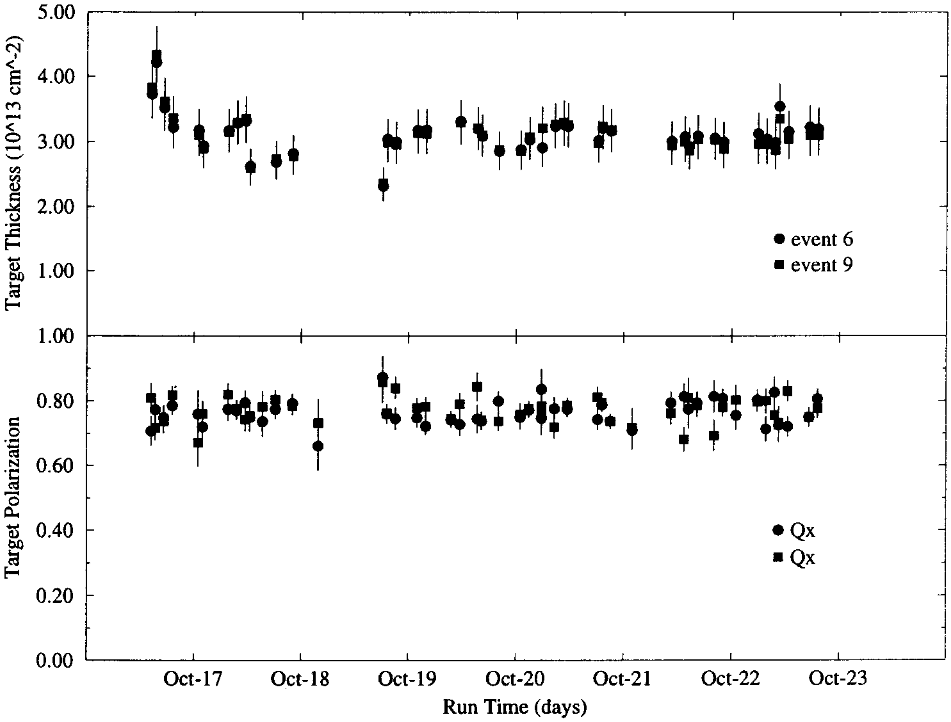


Fig. 4. Target polarization and thickness during a week-long run. Different symbols in the lower panel correspond to horizontal and vertical orientation of the target polarization.

reversed every 2 s during data taking. The target thickness remains the same when the guide field is reversed. Originally, this was not the case, because the horizontal guide field had an effect on the rejection of the unwanted sub-state by the rf transition, This was remedied by a compensating coil in the transition unit, operated in series with the guide field coil.

The recently upgraded detector array in the A-region consists of two pairs of wire chambers, labelled XY and UV in Fig. 6 and a set of scintillators. The scintillators labelled K and E are 15 cm and 10 cm thick stopping detectors respectively. When combined, these two scintillators are capable of stopping protons up to about 200 MeV of kinetic energy, and measuring that energy with about 7% resolution in the range from a few MeV up to this maximum value.

The target cell itself is surrounded by a set of position sensitive silicon micro-strip detectors (R1–8 in Fig. 6). These were oriented to measure position along the beam axis, covering most of the target length and about half

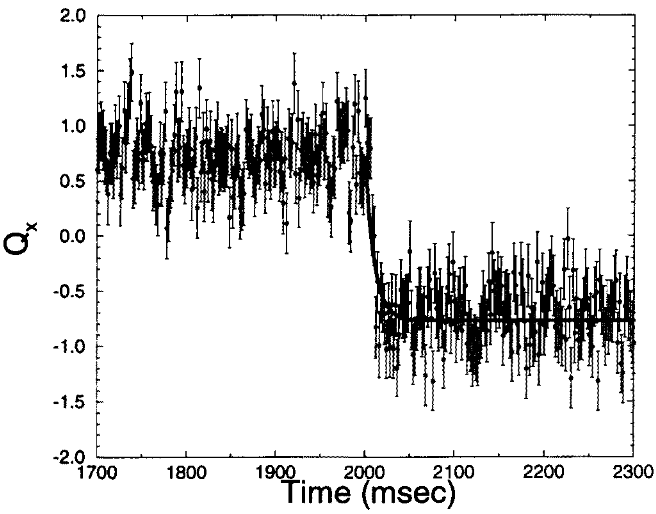


Fig. 5. Measured target polarization during a sign reversal.

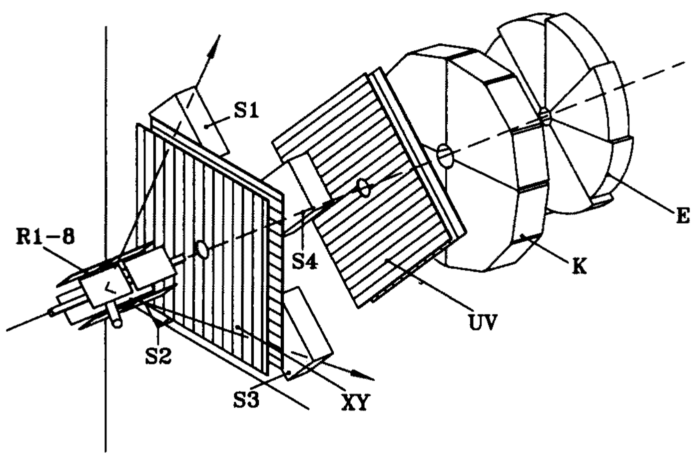


Fig. 6. Perspective view of the A-region detectors, target cell in foreground. See text for identification of each detector.

the azimuthal phase space. This additional position measurement, accurate to about a strip width (2 mm) significantly increases the tracking resolution of the detector system in the case where a definite kinematic relationship between the forward going and recoil particles can be established (*e.g.*, elastic scattering). Particles at angles greater than 30° can be detected efficiently all around the beam.

A further extension of the angular range of the forward detectors is achieved by four additional plastic scintillators at larger scattering angles (S1-4 in Fig. 6). Each of these square scintillators detects charged particles scattered between 30° and 60° in the lab, and they are equally spaced in azimuthal rotation around the beam axis. Thus for proton-proton scattering, for example, a good event triggers two of these detectors on opposite sides of the beam. The XY wire chamber was designed large enough to give position information for most of these events.

## 4. Cooler cycle and beam spin handling

Since the polarized target was installed the capability to decelerate the stored beam has been developed for the Cooler. For experiments running at energies other than the injection energy, it makes it possible to retain the beam stored at the end of an experimental cycle when establishing conditions to inject additional beam. This leads to a significant improvement of the average luminosity.

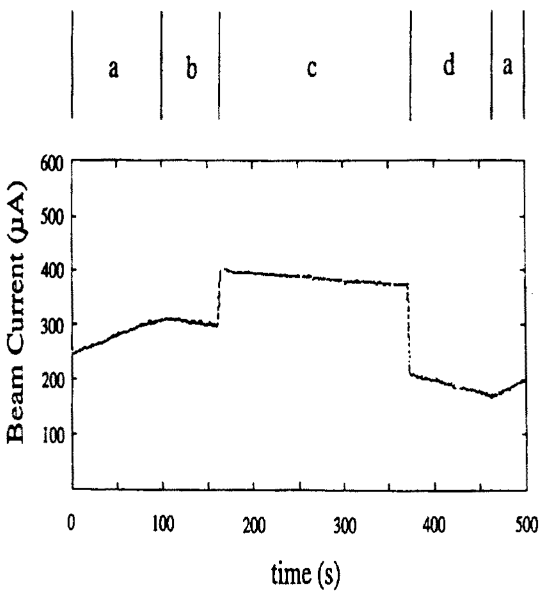


Fig. 7. Beam current versus cycle time during an accel/decel cycle. The data are from CE-42, January, 1996. Shown are the following phases: a) injection, b) data taking at 200 MeV, c) data taking at 400 MeV, d) data taking at 200 MeV.

A measurement of the polarization after deceleration was used to verify that the polarization did not change during the up ramp. This makes it possible to export a precise polarization standard at 200 MeV [7] to any other Cooler energy. Fig. 7 shows the beam current as a function of time for a typical cycle during an experiment where pp elastic scattering between 200 MeV and 450 MeV was measured. In this example, the beam was accelerated to 400 MeV and then decelerated back to 200 MeV with little loss of intensity, and no loss in beam polarization (current precision q0.04).

In order to minimize systematic errors frequent reversals of the polarization direction of the stored beam are desired. A device commonly referred to as the spin flipper [8] is based on adiabatically crossing a depolarizing resonance induced by an rf solenoid whose magnetic field oscillates along the beam axis. The solenoid frequency is ramped through the resonance and thereby induces a spin flip. Using the spin flipper the spin of the stored beam is reversed once per cycle.

## 5. Spin correlation parameters in pp elastic scattering

The nucleon-nucleon force is usually regarded as well known and well reproduced by potential models and phase shift analyses. Nevertheless, new measurements of previously unmeasured observables or large increases in precision often reveal the inability of such analyses and models to reproduce important features of the new data. At IUCF there is an ongoing program that is greatly expanding the nucleon-nucleon data base with high precision data in the intermediate energy range with the purpose of pushing the limits of such models.

Recent measurements of $p - p$ elastic scattering with polarized Cooler beam and an internal, polarized, atomic target have dramatically demonstrated the potential of this new technology. The commissioning experiment of the polarized target facility was the measurement of the analyzing power $A_y$, and the spin-correlation coefficients $A_{xx}$, $A_{yy}$, $A_{xz}$ in $p - p$ elastic scattering at 197.8 MeV. The experiment covered the angle range $\theta_{lab} = 4.5° - 17.5°$. The absolute determination of beam and target polarization is based on a calibration of Ay in pp scattering at $\theta_{lab} = 8.64°$ and 183.1 MeV [7], which was extrapolated to the present energy. The statistical error of the measurements is between 0.003 and 0.006 for $A_y$, and between 0.01 and 0.02 for the $A_{ik}$. In addition, the data are subject to a scale-factor uncertainty (less than 1.5% for $A_y$, and less than 2.5% for $A_{ik}$). Systematic errors are estimated to be smaller than the statistical ones.

Previous measurements of $A_{yy}$ in the energy region 200 MeV to 450 MeV (the Cooler energy range) are quite sparse and data for $A_{xx}$ and $A_{xz}$ practically non-existent, and the IUCF data clearly fill this gap. Neverthe-

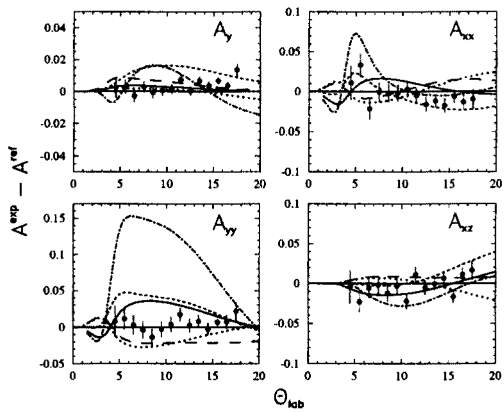


Fig. 8. Comparison of present results with several potential models and phase shift analyses The values calculated from the SAID C200 phase shift analysis [9] are subtracted from the data in order to more clearly represent the differences between the data and the calculations The curves are: solid line, Nijmegen PWA [10]; short dashed line, Nijmegen Nijm93 potential [10]; dot-dashed line, Bonn B potential [11]; long dashed line, Argonne potential [12]; dotted line, 0-1.6 GeV SAID global solution, [13].

less, a significant impact on the very large data base for $p-p$ scattering is possible only because of the high precision of the new data. This is illustrated in Fig. 8 which shows the results from the IUCF measurement (CE-35) together with the predictions by some recent potential models and partial-wave analyses.

A measurement of spin-correlation parameters in pp elastic scattering spanning the range from 200 to 450 MeV in roughly 50 MeV steps, with additional measurements at energies just below and somewhat above the pion production threshold was recently completed. At each energy, the data cover laboratory scattering angles of $\theta_{lab} = 5°$–$90°$. A precision of $\pm 0.02$ for the spin-correlation parameters $A_{xx}$, $A_{yy}$ and $A_{xz}$ is expected per 1° angle bin. At present, the data sample is under analysis.

## 6. Near threshold measurements of spin correlation parameters in $NN \to NN\pi$

Near-threshold measurements of spin observables for $NN \to NN\pi$, will follow the measurements of spin observables in pp elastic scattering. The partial-wave decomposition for $pp \to pp\pi^0$ will be extended by measurements of the spin-dependence of the total cross section, $\Delta\sigma_{L,T}$. Angular distribution measurements for spin correlations, which are needed to make similar model-independent amplitude determinations in the channels $pp \to d\pi^+$ and $pp \to pn\pi^+$ have been proposed.

The first case that will be studied, using polarized beam and target, is the $pp \to pp\pi^0$ reaction, where we plan to measure the spin-dependent cross sections $\Delta\sigma_L$ and $\Delta\sigma_T$ between 300 and 400 MeV. From the knowledge of these two observables (in conjunction with the total cross section), one can deduce, in a model-independent way, the contributions from the next higher partial waves as they gain importance with increasing bombarding energy. In particular, isolating the $p$–wave pion contribution would provide the data necessary to search for axial current contributions to Gamow-Teller matrix elements. This experiment (CE-44) is currently in preparation.

An example of a measurement of an agular distribution (rather than total cross sections) in pion production is the study of $pp \to d\pi^+$ with polarized beam and polarized target. Even though pion production with a two-body final state, $NN \to d\pi$, has received the most attention from theorists, there have been, so far, only two measurements below 400 MeV of a polarization observable (the analyzing power). The first has been carried out at TRIUMF [14] and the second, extending to energies very close to threshold, at IUCF [1].

Close to threshold only $s$– and $p$–wave pions contribute. In this case three amplitudes (with two phases) describe the reaction completely. The smallest of the three is of interest because it involves an intermediate $N\Delta$ ($L$=2) state, and because theoretical predictions of its size range over a factor of five (see [14] and references therein). In previous attempts to deduce these three amplitudes from the total and differential cross section and analyzing power (three pieces of information), the phases of the amplitudes were assumed to be known, based on Watson's theorem which relates the phase of $pp \to d\pi^+$ to the phases of $pp$ and $\pi d$ elastic scattering. It is also assumed that contributions from pion $d$–waves are negligible. Thus, there exists no experimental determination of all $s$–, and $p$–wave amplitudes which is free from theoretical assumptions. If spin-correlation parameters for $pp \to d\pi^+$ were available, some of these assumptions could be tested.

## 7. Longitudinally polarized beam in the cooler

Preparations are now underway to provide longitudinally polarized beam in the A-region. In order to get longitudinal beam polarization in the A-region, spin rotator solenoids need to be inserted elsewhere in the Cooler. The most straight-forward solution, as far as spin dynamics is concerned, would be to install a full Siberian snake (180° spin rotator) opposite of the A-region, *i.e.*, in the I-region. Space constraints exclude this solution. Calculations predict that the optimum solution calls for spin rotators in the C and the T-region, both of which have low dispersion. This scheme makes use of three existing solenoids in the C-region (one of these solenoids is needed to confine the cooling electron beam, the others are normally used in a compensating mode, but can be operated with the same sign as the cooling solenoid, resulting in a longitudinal field integral of up to 1 T-m). One additional solenoid with up to 3.5 T-m in the T-region is then sufficient to allow longitudinal polarization in the A-region for proton beams of up to 500 MeV. Because of the limit on the solenoid field in the C-region, the polarization is not exactly longitudinal for energies above 200 MeV (but the longitudinal component is never less than 90% of the total polarization).

In a short test run with 197 MeV polarized protons, the feasibility of running the Cooler with a 0.81 T-m C-snake was demonstrated [15], and stack injection still worked. The snake strength could be varied relatively easily for the full range 0 to 0.81 T-m. It was also demonstrated that the stored beam can be accelerated in the presence of the (non-ramping) snake. Furthermore, the ratio of the vertical-to-sideways polarization components, measured in the A-region, agreed well with the prediction.

A test run with a 2 T-m superconducting solenoid in the T-region, just upstream of the 6° magnet and jet target, was completed in June 1996. During this run both the C- and T-solenoid were operated simultaneously. It was demonstrated that beam could be accumulated up to 150$\mu$A in the presence of both solenoids. A polarization vector that was within 15° of longitudinal at the location of the polarized target was measured. The measurement assumed that $A_{xz}$ is known.

## 8. Summary and outlook

Near-threshold pion production has been a productive program at IUCF during the past five years. After a series of cross section and analyzing power measurements we are now moving towards such experiments with polarized beam and polarized target. The polarized target has been proven to be stable in polarization and thickness over long periods of time. Decelerated beams and longitudinal beam polarization at the target location are now available after extended accelerator development. We hope to acquire first spin correlation data in pion production early in 1997.

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