Findings

Introduction

The scientific effort at the Indiana University Cyclotron Facility has been grouped into four major areas of effort. (1) We continue to operate the electron-cooled storage ring (Cooler) for experiments in nuclear and accelerator physics. There will be one more year of operation after FY2001. (2) A major effort of the laboratory is centered around the construction of an electromagnetic calorimeter for one end of the STAR detector at RHIC. This calorimeter will provide crucial kinematic coverage for the measurement of the gluonic contribution to the spin of the proton as well as other experiments relating to the polarized proton program at RHIC. This effort includes test running of detector prototypes, involvement with the measurement of proton polarization at the AGS and RHIC, the development of software for the analysis of STAR data, and participation in the ongoing heavy ion program at STAR. (3) We continue our involvement in a series of experiments using the cold neutron facilities available at Los Alamos and the National Institute of Standards and Technology. These involve tests of the Standard Model and the measurement of the properties of weak and low-energy nuclear processes. (4) We are increasing our involvement in the development of the miniBooNE neutrino detector at Fermilab that will search for neutrino mixing using neutrinos from the Fermilab Booster. These areas, summarized below, make up the four section of the Annual Report Findings.

In FY2001, IUCF continued to operate the Cooler for experiments in nuclear physics using beams injected from the CIPIOS ion source and pre-accelerated in CIS. The major achievements were the completion of the elastic scattering phase of the study of three-body force effects and the measurement of the neutron-proton (n+p) cross section using tagged neutrons.

Deviations from the predictions of an exact two-body model have been reported for the cross section and analyzing power in proton-deuteron (p+d) elastic scattering. Agreement with the cross section can be improved if the model is extended to include three-body forces (3NF). But such data is unable to distinguish among several 3NF models based variously on meson-exchange and chiral arguments. It is expected that this new data, which contains a wealth of analyzing power and spin correlation information, will lead to important new constraints on the form of the three-body force.

For the n+p experiment, circulating currents in the Cooler ring routinely averaged between 1.5 and 2 mA, the best performance for any experiment to date. The new data, which covers the backward hemisphere, should have an absolute normalization less than 2% at essentially all scattering angles. This will help to settle ongoing conflicts among older sets of n+p measurements, and in turn more accurate cross sections should reduce the errors in our determination of the charged pion coupling to the nucleon.

This mode of operation requires a balance between running and access time in the Cooler. In addition to the time needed for experimental setup and checking, there were longer access periods to allow for the assembly of the magnetic channel needed for the charge symmetry experiment and to make the tagger equipment ready for production running. During FY2001, we were able to devote nearly half of the available hours to activities that required the Cooler beam. In parallel with the Cooler access time, we were able to devote about three weeks to the continued development of the polarized deuteron beam from CIPIOS. This development required only the use of the RFQ pre-acceleration system and the polarimeter located between the linac and CIS.

Some beam time with the CIS-Cooler facility was devoted to the first commissioning runs for the charge symmetry experiment. One of these demonstrated that, using d+p scattering observed in the Cooler A-region, it is possible to monitor both the vector and tensor polarization of the circulating deuteron beam. Another run commissioned the magnetic channel by observing the ^{3}He recoils from the d(p,π^0)^{3}He reaction. Additiionally, the Cooler G-region was used to investigate the feasibility of detecting intermediate mass fragments emerging at low energy from proton bombardment of a gold foil.

The Cooler program also continued for experiments in accelerator physics. Runs using the Cooler ring investigated improvements to spin-flipping with an RF dipole and the depolarization of beam near Siberian snake resonances. Beam studies of space charge effects were also completed using CIS.

A large fraction of the laboratory's effort is now going into the construction of the endcap electromagnetic calorimeter for the STAR experiment at RHIC. This calorimeter will feature a shower maximum detector with a high degree of segmentation aimed at the discrimination of single high-energy γ-rays from the two γs associated with π^0 decay. This opens a window into a kinematic regime of quark-gluon scattering where it should be possible to observe the spin alignment of the gluons within a polarized proton. If a significant alignment is observed, this would contribute to the polarization that is missing from the quarks alone. We expect that this addition to the STAR detector will be crucial for a broad range of physics applications. For example, the observations of electrons from the decay of the W$^\pm$ can yield information on the flavor dependence of anti-quark polarization within the proton.

A second test run was made at SLAC to verify that the design and components of the electromagnetic calorimeter met the goals of the experiment. For the most part, the results were as expected from calibrations made using cosmis rays. Part of the experimental setup area on the ground floor of IUCF is now devoted to a clean area for the machining of plastic scintillator and the assembly of parts for the calorimeter. A section of the Cooler building has been devoted to the fabrication of the lead and stainless-steel radiators. A number of fabrication projects have been assigned to collaborating institutions with IUCF acting as the hub for the evaluation of the designs and prototype testing.

During the year, a number of reviews were held to gain comments on various aspects of the design and the management plan for calorimeter construction. These reviews generated a number of useful suggestions on the improvement of the construction process.

Other efforts continued in support of the polarized proton program at Brookhaven. The prototype calorimeter, following its tests at SLAC, was taken to Brookhaven where it will be used as part of a prototype polarimeter based on the asymmetry of inclusive π^0 production at large x_F. Support was given to a recalibration of the 200-MeV polarimeter at the Brookhaven linac using the very precise p+d analyzing powers established at IUCF. Discussions and planning continued throughout the year for the experiment that will use proton elastic scattering in the Coulomb-nuclear interference region to finally calibrate the polarization of the beam circulating in RHIC.

Work continued along several fronts in the physics of cold neutrons. Data taking for a more precise measurement of the neutron lifetime was completed at NIST. This value has an impact on the validity of the Standard Model of strong interactions through the unitarity of the CKM matrix. Such tests are also the object of an experiment that is in preparation to measure other decay parameters of the neutron. Preparations continue for the liquid hydrogen target that will be used to look for parity violation in n+p radiative capture. Parity violation will also be the focus of an experiment to measure the degree to which the spin of cold neutrons precess as they pass through liquid helium.

Within the last few years, nuclear physicists have been excited by the new evidence accumulating in support of a finite mass for neutrinos. A positive, but marginal, result from the LSND experiment at Los Alamos will soon be checked by a much more detailed study using the new miniBooNE detector at Fermilab. Tests of the mineral oil that is the key detection ingredient in the new system are underway at IUCF. IUCF personnel are now involved with the management and several key technical aspects of the project.

A. Physics with the IUCF Cooler

Progress on CE71: A Precise Measurement of the Absolute Cross Section for n+p Scattering

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The goal of CE71 is to measure differential cross sections for n+p elastic scattering near 200 MeV bombarding energy to an absolute precision of $\approx \pm 1\%$ in order to settle serious discrepancies in the existing database and to test those partial wave and potential model analyses that have supported a low value ($g_\pi^2/4\pi = 13.6$) for the charged πNN coupling constant. In order to attain this precision, we commissioned a tagged neutron facility in the T-section of the Cooler ring in two runs in December 1999 and May 2000. The layout of the tagged neutron facility is shown in Fig. A1. At its heart is a set of four 6.4-cm square double-sided silicon strip detectors (DSSD's, shown on the left of Fig. A1) with a 0.48-mm readout pitch in two orthogonal directions and self-triggering readout front-end electronics mounted on circuit boards surrounding the detectors. The DSSD's are used to detect the two low-energy ($\sim 1-15$ MeV) recoiling protons from the ^{2}H(p,n)pp charge-exchange reaction induced by a cooled (unpolarized) 200-MeV proton beam on a deuterium gas jet target. Measurements of energy, position and arrival time for both outgoing protons permit reconstruction of each tagged neutron's energy (with a typical resolution $\sigma \sim 150$ keV) and position of impact on the secondary target (with a resolution

$\sigma \sim 2-3$ mm). Some results from analysis of the commissioning runs, demonstrating the attained performance, are shown in Figs. A2 and A3. About 15% of all charge-exchange neutrons headed toward the secondary target were tagged in this setup, and only reactions induced by the tagged neutrons were analyzed.

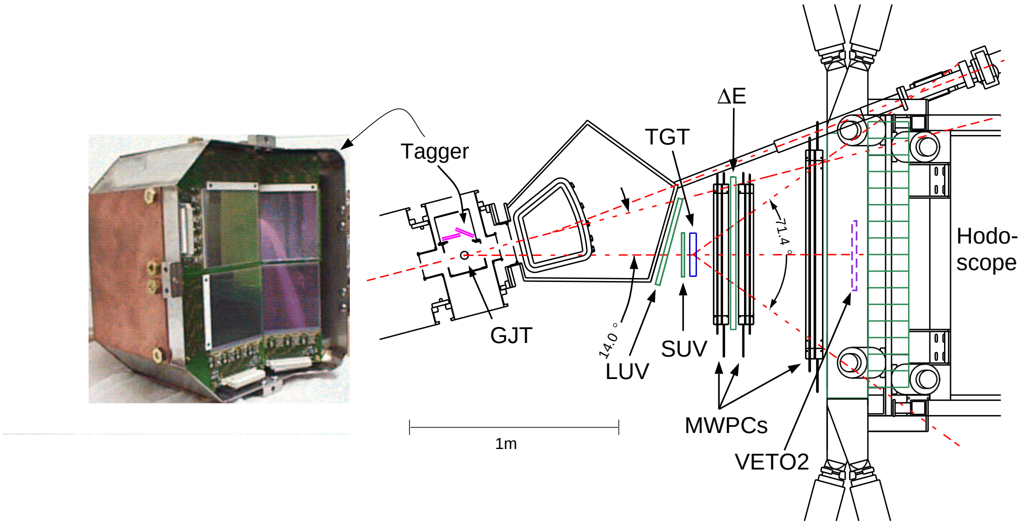


Fig. A1: Layout of the tagged neutron facility in the Cooler T-section. The array of four double-sided silicon strip detectors (photo at the left) is located about 10 cm from the deuterium gas jet target (GJT), where it detects two low-energy recoil protons to tag production of a nearly 200-MeV neutron via the $^2H(p,n)pp$ reaction. Forward protons from n+p scattering induced in the secondary target (TGT) are detected and ray-traced through the forward wire chambers and scintillators.

Production data for the n+p scattering cross section measurement were taken during August and September 2001. The challenging development of a large-area liquid hydrogen target, with a thin-profile dewar, for use as a secondary target in this experiment could not be successfully completed in time for the run. Thus, the production data were taken instead with carefully matched CH_2 and C (poco graphite) targets, each square slabs of side length 20.1 cm, containing 0.993×10^{23} C atoms/cm^2. The target densities and thicknesses were measured to a precision of ±0.4%, and were uniform to at least that precision. While the CH_2 target yielded a quasifree scattering background/free scattering signal ratio several times worse than anticipated with a liquid hydrogen target, it permitted more reliable background subtraction (since the two targets could be swapped frequently, in contrast to the very time-consuming empty/refill cycle anticipated for the liquid) and thickness uniformity. We expect that we will still be able to keep the net systematic uncertainty in the absolute cross sections deduced from the data to the desired 1% level.

After an extensive period of debugging and fixing a wide variety of problems with the RFQ/DTL preinjector to CIS, the Cooler beam tune, the gas jet target, the DSSD's and the electronics, excellent and stable running conditions were finally achieved during the last two weeks of the production run. During this period, we typically had 2.0 mA

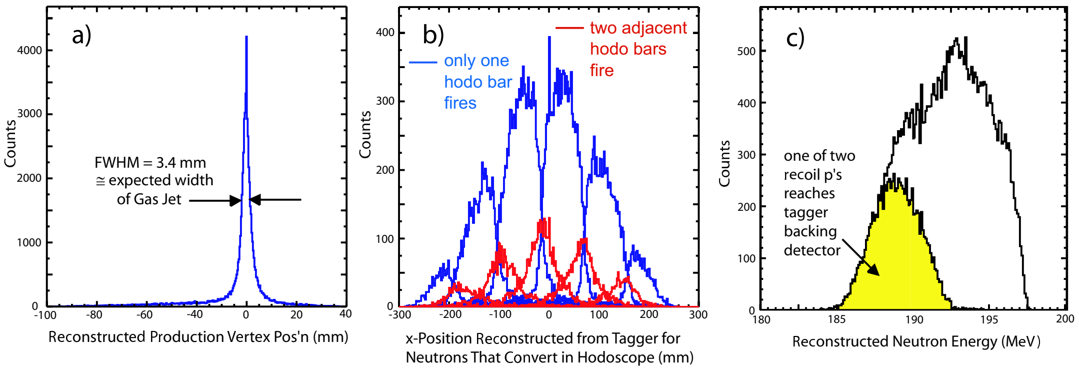


Fig. A2: Tagged neutron properties reconstructed from measurements of the two recoil protons in the tagger during the May 2000 commissioning run. (a) The longitudinal position of the reconstructed primary event vertex shows a width consistent with expectations of the physical width of the gas jet, suggesting that the reconstruction resolution is $\sigma(z) < 2$ *mm. (b) The predicted impact positions of tagged neutrons that convert in the rear hodoscope clearly shows the bar structure of the hodoscope, with transverse position resolution* $\sigma(x,y) \approx$ *few mm over a flight path of about 2 m. (c) The neutron energy is reconstructed event by event with* $\sigma(E) \approx 150$ *keV.*

of stored beam accumulated over five injection shots from CIS, and we used this beam over counting periods of about 48 seconds, resulting in a time-averaged primary beam luminosity of about 1.0×10^{31} cm^{-2}s^{-1}. This yielded a production rate of tagged neutrons impinging on the CH_2 target of typically 250 Hz, and approximately 1 Hz of free n+p elastic scattering events within the essentially complete forward detector acceptance for the c.m. angle range from 90° to 180°. A total of over 400K free-scattering events was accumulated during the run.

One-third of the time during the production run was devoted to background measurements utilizing the graphite secondary target, and a small amount of additional time was used for measurements with no secondary target. Figure A4 displays typical raw forward wire-chamber distributions for events passing the event logic definition of n+p scattering events (with no further software cuts applied), for the CH_2, C and absent secondary targets. Without software cuts, the raw background/signal ratio is about 2:1. It is anticipated from the analysis of data taken during the commissioning runs that this ratio can be reduced to 0.4:1 by a sequence of cuts that are designed to introduce minimal systematic error in the determination of surviving absolute free scattering yields. For example, no cut is imposed on the detected forward proton's total energy measured in the stopping hodoscope in order to free the analysis from assumptions about yield losses associated with the reaction tail in the stopping scintillator. With the anticipated final background, we should be able to achieve a statistical precision in the background-subtracted differential cross sections of ±1% within every 5° c.m. angle bin from 90° to 170°, increasing to ±1.4% and ±2.4%, respectively, in the two bins between 170° and 180°. High statistical precision was also obtained simultaneously for p+p scattering in the same secondary target, initiated by a

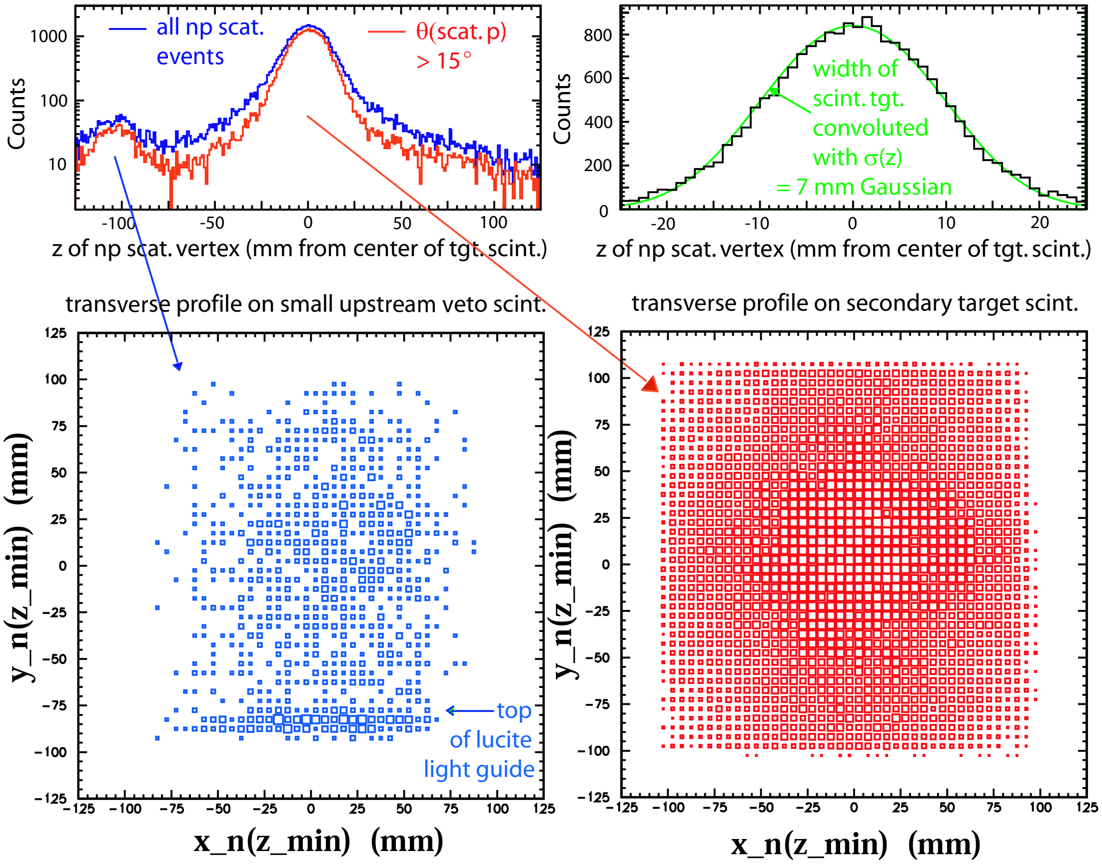


Fig. A3: Distributions of the n+p scattering (secondary) vertex location, reconstructed at the point of closest approach of the tagged neutron path and the ray-traced trajectory of the detected forward proton, from data taken during the May 2000 commissioning run. The longitudinal position represented in the upper frames, reconstructed with resolution $\sigma(z) = 7$ *mm, shows a dominant peak from the secondary target, but also a smaller peak corresponding to the small upstream veto scintillator (SUV). The transverse vertex distributions for events in these two peak regions are shown in the lower frames. Events from the SUV come mainly from its Lucite light guide; sparse events are also seen from the downstream face of the SUV, where the recoil proton deposits too little energy for the event to be vetoed.*

tagged secondary proton beam produced via p+d elastic scattering in the deuterium gas jet target. Analysis of the p+p data, and of the n+p data subdivided into different bins in transverse neutron position on the secondary target, are expected to provide powerful crosschecks on potential systematic errors in the measurement.

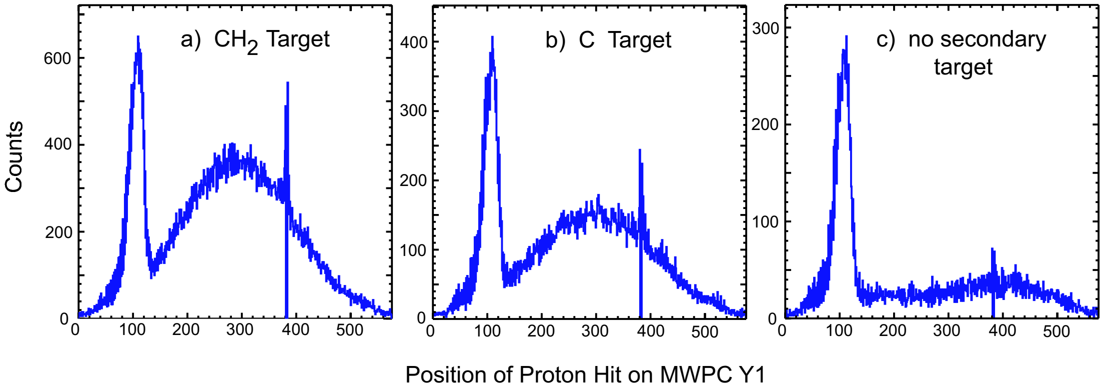


Fig. A4: Typical raw distributions of events falling within the "np scattering" event stream, with respect to the y-position of the forward proton measured in the front wire chamber (following the secondary target by about 14 cm). These spectra are for runs with (a) the CH_2*, (b) the C, and (c) no secondary target taken during the August-September 2001 production run. Low-numbered wires correspond to the top of the wire chamber. Scattering events from the secondary target fall mostly between channels 160 and 380. The sharp peak near channel 100 is independent of the secondary target, because it arises not from double-scattering events, but rather from very selective p+d scattering events induced in the primary gas jet target that conspire to fake n+p scattering. The background not associated with the secondary target, as well as the quasifree scattering background from carbon nuclei in the secondary target, can be reduced substantially by cuts on other measured quantities in the subsequent analysis.*

PINTEX Activities: October, 2000 – December, 2001

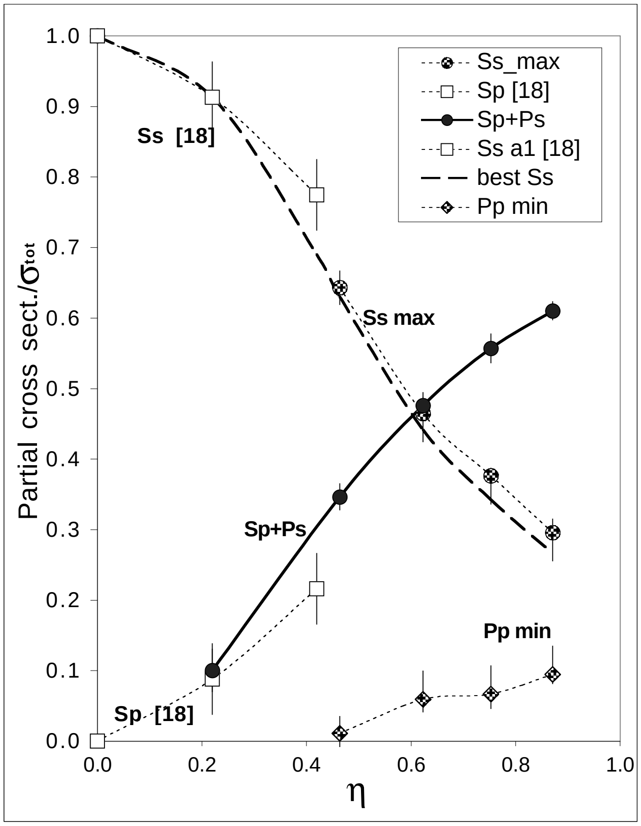
H.O. Meyer for the PINTEX group

Pion Production

Pion production in p+p collisions with both protons polarized has been one of the major experiments of the PINTEX group. By the end of 1998, we concluded the data taking. Early results of spin-dependent total cross sections between 300 and 400 MeV were published soon afterwards (see last Annual Report) but a detailed analysis of the wealth of information that can be obtained from the spin-correlation coefficients in a reaction with a three-body final state required more time. An account of this work was published in June 2001 [Mey01b]. The final result amounts to a complete characterization of the $pp \rightarrow pp\pi^0$ reaction in the first 100 MeV above threshold, over the whole of the five-dimensional phase space of the exit channel. In particular, the available information is sufficient to determine all significant partial-wave reaction amplitudes. This is as far as an experiment can go: now the ball is in the theorist's court.

Data on the reaction $pp \rightarrow pn\pi^+$ were obtained concurrently with the measurements mentioned above. The Pittsburgh contingent of the collaboration took over the responsibility of analyzing this subset of the data. The final account of this analysis is slated to

Fig. A5: Sums of isoscalar and isovector partial wave strengths for the reaction pp $\to$ pnπ^+ *as a function of the interaction energy parameter* η*. The Sp+Ps sum is measured directly. The points labeled "Ss max" represent a close upper limit to the sum of the Ss partial cross sections. Any correction for the unresolved Pp amplitudes (*a_4*,* a_5*,* a_6*, and* b_3*) would lower the Ss curve (as indicated by the estimated errors). The admixtures can be expected to be smaller than Pp(*a_3*). The lower points show the documented Pp strengths only.*



appear in Phys. Rev. C in February 2002 [Dae02]. As a sample, we show in Fig. A5 the relative strength of groups of partial-wave amplitudes in pp $\to$ pnπ^+. A comparison of the spin-correlation observables in pp $\to$ pnπ^+ with the only calculation available to date (a meson-exchange model by the theory group at Jülich, Germany) shows less disagreement with the data than pp $\to$ ppπ^0. A still preliminary finding concerns the longitudinal analyzing power A_z. This observable must be zero by parity conservation for coplanar final states, but is not constrained for out-of-plane configurations. We recall that in pp $\to$ ppπ^0 A_z was found to be quite large [Mey00]. It is therefore somewhat surprising that in the case of pp $\to$ pnπ^+ A_z seems to be very small, consistent with the assumption that the part of the reaction where the nucleons in the final state have T=0, does not contribute measurably to A_z at all.

Three-Nucleon Reactions

1. *General Remarks*

Experiments with three nucleons are motivated by the current interest in the three-nucleon force (3NF). Such a force seems to be the only way to explain the deficiency in the binding energy of the triton when calculated with a pair NN force only. The recent success of the Argonne theory group to calculate the masses of the ground state and first few excited states of light nuclei up to ^{10}B also strongly supports the necessity of a 3N force and provides important insights as to its nature and spin dependence.

Our goal in studying p+d reactions with the Cooler is to provide a testing ground for theoretical calculations involving 3N forces. The strategy is as follows. In recent years, due to a rapid increase in computing resources, Faddeev calculations have matured to a stage where it is believed that they can be used to predict how nature would behave if there were only pair wise NN interactions. Such calculations are now available for p+d scattering and break-up up to 200 MeV proton bombarding energy. A comparison of these NN predictions with the data then would reveal the effect of 3N forces. Clearly, to make such a conclusion believable, one would require that the observed discrepancies be reproduced by the inclusion of a 3N force in the Faddeev calculations. While this step is still a goal for the future, providing a broad basis of spin-dependent observables is a task for the present. The Cooler is uniquely suited to such measurements. For details, see e.g. [Mey01a].

2. Experimental Details

The polarized internal target consists of a 12-mm diameter tube through which the stored beam passes. Polarized atoms are injected into this tube from the side. The purpose of this 'target cell' is to enhance the target density.

The polarized atoms are produced by an atomic beam source. In March 2000 two new transition units with variable average and gradient fields were installed. With this arrangement and a weak guide field at the target, it is possible to produce pure tensor polarization of magnitude $+1$ or -1 and pure vector polarization of magnitude $+2/3$. The sign of the vector polarization can be inverted by inverting the holding field, whereas the sign of the tensor polarization is unaffected by the polarity of the holding field. The fields in the transition units are controlled remotely, making it possible to take data with tensor and vector polarization in the same Cooler cycle.

The PINTEX detector setup is relatively simple and consists of two main parts. In the forward direction, covering a cone of about 45° opening angle, a stack of scintillators and wire chambers measures the energy and the direction of outgoing charged particles. Protons of up to 200 MeV are stopped in this detector. On the other hand, low-energy charged particles emerge sideways through the thin wall of the target cell, and are registered by an array of 18 silicon micro-strip detectors surrounding the target in the form of a barrel, providing full azimuthal acceptance.

A major obstacle encountered in the use of silicon detectors in the target region was the fact that the presence of atomic hydrogen (or deuterium) causes rapid deterioration of the detector performance. This difficulty was eventually overcome by installing thin-foil barriers between the target cell and the silicon detectors and by adding copper surfaces to enhance the recombination of atoms outside the target cell.

For p+d elastic scattering this detector setup covers the polar angles $15^\circ < \theta_{cm} < 70^\circ$ and $90^\circ < \theta_{cm} < 165^\circ$. For d+p break-up (with a deuteron beam on a proton target) about 65% of the total phase space is covered.

With a polarized proton beam on a vector- or tensor-polarized deuteron target the possible observables include the beam analyzing power, four target analyzing powers, five vector correlation coefficients and seven tensor correlation coefficients. The goal of our experiment is to measure as many of these observables, as a function of angle and energy, as is feasible.

Elastic p+d scattering above 100 MeV is not strongly dependent on energy. We have thus decided to carry out the experiment at the two (proton) bombarding energies of 135 and 200 MeV. The first choice is given by the fact that an extensive set of deuteron analyzing powers has been measured at Riken with 270 MeV polarized deuterons [Sak96, Sak00]. The second energy is near the onset of pion production and thus represents an upper limit for reliable Faddeev calculations.

Data taking takes place with vertical beam polarization of different sign in alternating cycles. During each cycle the atomic beam source is set to produce vector-, positive tensor-, and negative tensor-polarized deuterons, in sequence. During each of these periods, the direction of the guide field at the target is switched in 2 s intervals to point in each of the six directions $\pm x$, $\pm y$, and $\pm z$. In addition, data are acquired with the x- and z-fields (or the y- and z-fields) energized simultaneously, in order to produce a t_{21} target tensor moment. At 135 MeV we also use spin precession solenoids in the Cooler to produce longitudinally polarized protons which results in two additional vector correlation coefficients.

During the reporting period, the PINTEX group has used about 8 weeks of beam time in four runs. The first of these runs (c80d, October 2000) was the first real data acquisition effort with vertically polarized protons on a vector and tensor target at both 135 and 200 MeV. At that time we finally overcame the problem that the micro-strip detectors deteriorated in the presence of atomic deuterium. In order to calibrate the beam polarization we took data with a mixture of D_2 and H_2 in the target cell. This links the p+d analyzing power to the well-known p+p elastic scattering analyzing power. Similarly, a calibration of the target analyzing power at 200 MeV was the subject of a run in December 2000 (c80e), where, using an unpolarized beam, we acquired data at 135 and 200 MeV simultaneously by ramping the beam energy between the two energies within one beam cycle.

The subsequent analysis showed that we could really use better particle ID discrimination between the forward-going deuterons (representing the low-cross section region of p+d scattering) and the copious protons from the break-up reaction. Protons are distinguished from deuterons by their measured energy together with a combination of time-of-flight and energy loss in the thin ‘F’ detector just downstream of the target cell. Increasing the thickness of the ‘F’ detector greatly improved this separation. In March 2001 (c80f) we acquired additional data in this new configuration. This was successful at 135 MeV, but the measurement at 200 MeV was compromised by a string of breakdowns (problems with the CIPIOS strong field transition, with the energy matching of CIS to the Cooler, and with the CIS extraction kicker, in addition to three (!) power failures). Prior to this run we made an all-out effort to lower the electronic noise in the micro-strip detector by additional shielding and filtering. However, at the beginning of the run we realized that this cured only part of the problem, and that transient fields induced by the beam bunches was another major contributor. This was alleviated by using coasting beam (RF cavity in the Cooler turned off, the beam energy is determined by the drag of the cooling electrons). For this reason, we devoted half of the last run (June 2001, c80g) to more data taking at 200 MeV. The other half was spent with longitudinally polarized beam at 135 MeV, resulting in two more vector correlation coefficients ($C_{x,z}$ and $C_{z,z}$) at that energy.

The analysis of the data has been going on since the end of the last run in June. The analysis consists of two steps. In the first step the data are subjected to a variety of cuts, in order to cleanly define the elastic scattering events. Here, recent improvements include better understanding of the energy and time response of the detectors, resulting in a better discrimination against the protons from the break-up reaction. This is especially important for the backward angles ($90° < \theta_{cm} < 165°$), where the p+d scattering cross section is two orders of magnitude smaller than in the forward direction. The first step results in yields for all possible beam and target spin combinations as a function of φ and θ_{cm}.

The second step involves the extraction of the observables from these yields. Starting from the general expression of the spin-dependent differential cross section one can establish a method to combine yields into subgroups in such a way that the corresponding asymmetry is sensitive only to one or two observables. The φ dependence of that asymmetry is then given by the cross section angular distribution (a simple trigonometric function of φ). The expected φ dependence can be checked against the measured one, or used to disentangle asymmetries where more than one observable contributes. As an example, we show in Fig. A6 a set of asymmetries observed in p+d scattering at 135 MeV. This kind of analysis is carried out for each polar angle bin separately.

At this time, a first treatment of all data has been completed and θ_{cm} distributions of 15 observables at both energies have been obtained. What remains to be done are a number of refinements in the first step, and a careful study of the available information on the normalization of the data (or, in other words, on the absolute polarization of beam and target).

4. Proton-Deuteron Break-up

Over the course of the next year, a number of runs are planned by the PINTEX group to study spin-correlation in the break-up channel, using a 270-MeV deuteron beam on a polarized hydrogen target. The study of spin-correlation in d+p break-up still awaits the availability of a stored, polarized deuteron beam.

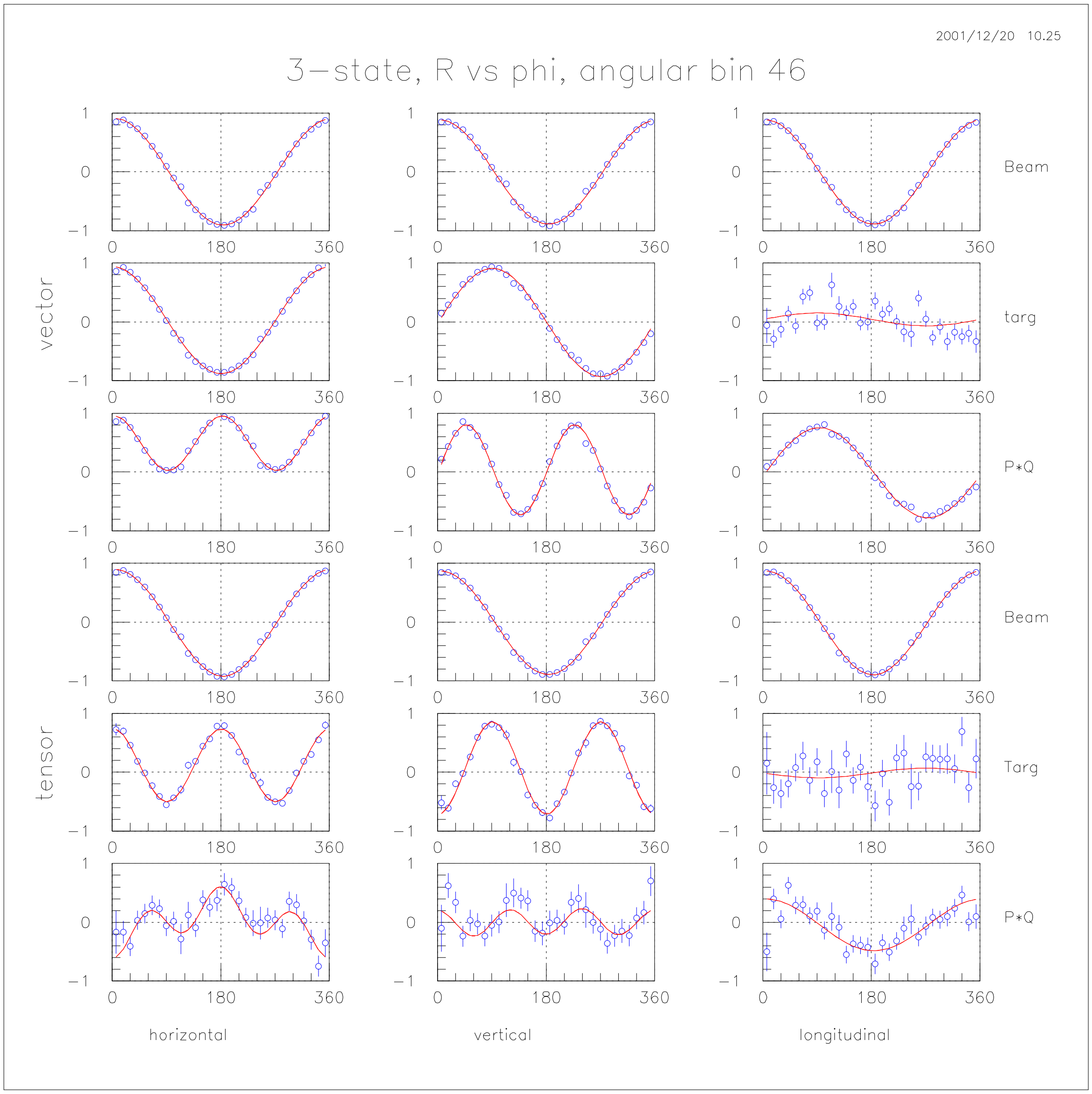


Fig. A6: Azimuthal asymmetries observed in p+d elastic scattering at 135 MeV for the polar angle range $16° < \theta_{cm} < 48°$*. The horizontal axis shows the full* $360°$ *range of the azimuth* φ*. The data in the different panels are measured concurrently and are obtained by combining various spin orientations of the beam and the target. The curves represent the expected* φ *dependence. The three columns correspond to horizontal, vertical and longitudinal target spin orientation. The first three rows show the asymmetries due to polarized beam, polarized target and beam-target correlation when the target is vector polarized, the last three rows are the same for a tensor-polarized target. Note, that the last row clearly shows the* 3φ *dependence of a tensor correlation coefficient.*

Commissioning of the Magnetic Channel to Search for the Isospin-Forbidden dd$\rightarrow\alpha\pi^0$ Reaction

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The dd $\rightarrow \alpha\pi^0$ reaction is isospin-forbidden, so its cross section can only be the square of a charge symmetry breaking amplitude. This amplitude is connected in chiral perturbation theory to a leading term that depends on the mass difference between the up and down quarks. Additional contributions come from Coulomb effects among the quarks. Thus a measure of this cross section would be an important constraint on this theoretical interpretation.

This amplitude is related to other charge symmetry breaking effects in nuclear physics. The same combination of quark mass difference and Coulomb amplitudes also appears as the driving term in the fore-aft cross section asymmetry for the pn $\rightarrow$ dπ^0 near threshold. This asymmetry also receives a large contribution that comes through the mixing of the π meson with the η and η' mesons. Presumably this mixing itself is also an artifact of the underlying symmetry breaking from quark mass and Coulomb effects. Because outgoing P-waves are forbidden in the dd $\rightarrow \alpha\pi^0$ case, meson mixing is not expected to be a large contribution for the search we plan to do at IUCF. Thus these two experimental results, when known, will complement each other.

This summer, the Institute for Nuclear Theory in Seattle hosted a workshop (August 23–25, 2001) on the calculation of the cross section for dd $\rightarrow \alpha\pi^0$. The workshop determined that the calculation is well-motivated theoretically as a good description of the quark mass difference mechanism. Considerable attention was paid to the determination of the important chiral Lagrangians for this process, and to the calculation of the entrance channel distortions. For the distortions, it appears that techniques using three-body t-matrices can usefully be applied to this issue. By the end of the meeting, a power-counting scheme in chiral Lagrangians had been outlined.

Attendees at the workshop were divided into working groups to look into various aspects of the calculation. Two parallel efforts were outlined. A momentum space calculation will be organized by G. Miller and J. Niskanen; and a Monte Carlo coordinate space effort will be organized by C. Horowitz and A. Gardestig. Several people wanted to continue to work on the chiral expansion, including C. Hanhart, B. von Kolck, and F. Myhrer. The entrance channel distortions will be calculated by A. Fonseca.

Considerable progress has been made during this year in the development of the hardware needed for the experiment. A fuller account appears in the "contributions" section. The septum magnet was assembled and mapped. Then it was incorporated, along with three quadrupole magnets, into a magnetic channel whose purpose is to capture the ^{4}He nuclei recoiling from the gas jet target in the Cooler T-region. The channel was outfitted with wire chambers and scintillators and tested in a run in May, 2001. Good planning brought an early success with the observation of the pd $\rightarrow$ ^{3}Heπ^0 reaction as a clean signal. Earlier, in February 2001, the measurement of the deuteron polarization was tested.

Following the successful run of the channel commissioning, we started on the installation of the Pb-glass array and a new target box for the Cooler T-region. These will be commissioned at the start of 2002, with production running to follow.

Experiment CE81: Cluster Emission from Hot, Dilute Nuclear Matter

V.E. Viola for the Nuclear Chemistry Group

Two test runs to study the emission of nonequilibruim nuclear clusters formed in collisions of 400-MeV protons with gold nuclei were performed during the past year. This system represents the simplest case for attempting to understand the formation of complex clusters on a very short time scale ($\sim 20-30$ fm/c) and takes advantage of the unique low background characteristics of the Cooler for such studies.

The experiment involved measurements of $Z = 1 - 10$ isotopes at both very forward and backward angles using LASSA 256-pixel particle-identification telescopes. The test runs with a single LASSA module showed that the experiment was feasible in terms of counting rates and the ability to place the LASSA silicon array very close to the beam. However, in order to perform the full experiment, it was clear that considerable additional development work was required. Given the lifetime of the Cooler and our commitment to develop a high resolution silicon array as part of an NSF MRI project, it was concluded that both projects could not be completed on an acceptable time scale with our limited personnel. As a consequence, it was decided not to proceed with CE81.

B. Physics at RHIC

Research Results from the STAR Spin Program

S.W. Wissink for the STAR Collaboration

The STAR detector [All02], located at the RHIC facility at Brookhaven National Laboratory, is about to complete its second run with relativistic heavy ions, colliding Au on Au nuclei at beam energies of 100 GeV/nucleon. These runs have been very successful, with several papers already published (most in Phys. Rev. Letters) and many more in preparation. The IU group has been participating fully in this effort, helping to acquire and interpret the data, and providing a significant fraction of the shift leaders, detector operators, and crew required to carry out this program.

The primary interest of the IU group, though, is in studies of partonic hard scattering processes, produced in collisions of polarized proton beams at center of mass energies of up to $\sqrt{s} = 500$ GeV, more than an order of magnitude higher than any previous measurement involving polarized protons. While protons have to date been successfully injected into RHIC and accelerated up to 100 GeV, the commissioning of actual polarized proton collisions will not begin until late in 2001. The goal of this upcoming run will be to provide several weeks of useful $\vec{p}+\vec{p}$ running in early 2002, with peak luminosities of order $\mathrm{L} \sim 5 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}{-1}$ and polarizations of close to 50% for each beam. If these benchmarks can be achieved, it should be sufficient to enable the first measurement of a (transverse) spin asymmetry in a polarized collider, via detection of leading neutral pions at large x_F and moderate p_T [Spi01]; this experiment will be discussed in more detail below. Equally important, though, is that this run will provide an opportunity for the STAR Spin group to encounter and learn to overcome some of the many possible sources of systematic error that will arise when carrying out the more complex spin-dependent measurements that form the core of the envisioned polarized proton program.

The main components of the spin program to be carried out at STAR have been described in detail elsewhere [Bla99], and will be summarized only briefly here. A key objective is to understand quantitatively how the gluons within a proton contribute to the proton's intrinsic spin, which can be gauged via the *direct* extraction of the nucleonic gluon helicity distribution function $\Delta G(x)$. This function can be determined by measuring the spin correlation parameter (double-spin asymmetry) A_{LL} in the reaction $\vec{p}+\vec{p} \to \gamma+\mathrm{jet}+X$, detecting a high-energy photon in coincidence with an away-side jet. This reaction is dominated, at the partonic level, by direct photon production in gluonic Compton scattering, *i.e.*, $q + g \to q + \gamma$, whereby a polarized, high-x quark in one proton is used to probe the polarization of the (largely low-x) gluons in another, exploiting the fact that the *partonic* spin correlation $\hat{a}_{LL}$ is calculable in pQCD at these energies, and is close to unity in the kinematic regimes of most interest [Bla00]. One can also disentangle the quark and anti-quark contributions (for both u and d separately) to the proton spin, by observing the large, parity-violating, longitudinal spin asymmetries expected for $W^{\pm}$ production in $\vec{p}\vec{p}$ collisions [Vig00]. In this case, the experimental signature would be detection of an energetic $e^{\pm}$ resulting from decay of the W boson, with the azimuthally opposite side relatively 'quiet' as a ν carries away the matching p_T, rather than a hadronic jet.

To carry out these measurements, as well as other possible studies, [Bla99], extensive electromagnetic calorimetry is required to detect the outgoing energetic photons and electrons. The calorimetry must also extend to very forward angles, due to the large kinematic mis-match between the incident quark (selected at high-x, to maximize its polarization) and the predominantly low-x partons (g or $\overline{q}$) whose polarization is being probed. For this reason, the main thrust of the IU effort for the last few years has been directed towards construction of an endcap electromagnetic calorimeter (EEMC) for STAR. The motivation, design goals, and status of this project are discussed elsewhere in this report. To ensure that the EEMC will be capable of meeting its design requirements, and, more generally, to prepare for extensive polarized proton running in the coming years once the EEMC is installed, the IU group has carried out several ancillary development projects over the past year, including: (*i*) detailed studies of the performance of a prototype EEMC detector at SLAC in test beams; (*ii*) the creation of much of the software required for spin monitoring and efficient data acquisition at STAR in the pp collision environment; and (*iii*) the recent installation of the prototype EEMC at far-forward angles at STAR for leading π^0 detection. Each of these will be described in somewhat more detail below.

In order to check that the EEMC design was functionally sound, a (transversely) scaled-down version was constructed at IUCF, containing 12 towers in a 3 (in ϕ) by 4 (in η) arrangement with projective geometry. Longitudinally, *i.e.*, along the detected particle's momentum direction, the prototype structure matched that of the EEMC quite closely: 24 layers of scintillator were alternated with 24 layers of 5-mm thick lead radiators. Each scintillator layer was machined as a single megatile, consisting of individual, optically isolated tiles. The light from each tile was collected in a 0.83-mm diameter wavelength-shifting (WLS) fiber, then transported in 0.9-mm clear fiber to a photomultiplier tube (PMT), where it was added to the light from other tiles comprising the same tower. As in the full EEMC, the first two sampling layers of the prototype were cut from 5-mm thick scintillator, and were each outfitted with two WLS fibers, to provide 'pre-shower' as well as tower information. The 22 remaining tiles were made from 4-mm SCSN-81 scintillator from Kuraray (though in the EEMC, the final layer will also be 5-mm thick, for use as a post-shower detector). The same tower PMT's and dynode voltage distribution as that of the EEMC were used. The shower maximum detector (SMD) was constructed from triangular scintillating strips extruded as part of the same production run used for the EEMC SMD planes, though their orientation (relative to the tower structure) was into x and y planes, rather than the u and v orientations to be used in the full detector. The SMD strip fibering for light collection and transport, and the 16-channel MAPMT's used to produce signal pulses, were identical to those of the EEMC.

Both the calorimetric towers and the SMD strips of the prototype were extensively calibrated at IUCF using cosmic-ray muons. With the response to minimum ionizing particles understood, the entire 600-kg detector was then disassembled and shipped to SLAC, where it was reassembled and placed in the Final Focus Test Beam (FFTB) facility, along with some simple trigger counters and cosmic-ray paddles (for continued monitoring of the mip response). The FFTB is capable of providing sub-nanosecond pulses of very few (typically 1-5) monoenergetic electrons of essentially any energy up to about 20 GeV. During the period of January 12-16, 2001, we received ten shifts of beam under our control. In addition to changing the beam energy between 5, 10, and 20 GeV, we also translated the prototype detector transversely during the run, to illuminate different towers and strips, and different positions within a given tower.

Most aspects of this test run, designated T-452 at SLAC, were very encouraging, in terms of meeting design requirements and confirming quantitatively expectations based on detailed simulations of the detector response to electromagnetic showers. In retrospect, the operating features provided by the FFTB facility were almost ideally matched to our needs. By examining the raw ADC charge distributions in a given tower for varying numbers of incident electrons of the same energy (the total number of electrons per pulse was determined from the trigger counter pulse heights), the linearity of the tower PMT's was verified, for light output corresponding to up to eight 20-GeV electrons, or '160 GeV worth' of light (*not* necessarily equivalent to that of a single 160-GeV electron). With the PMT and ADC performance under control, comparisons of the tower responses to single 5, 10, and 20-GeV electrons demonstrated that the integrated charge was indeed proportional to the incident electron energy over this range, with peak resolutions in good agreement with those predicted. It also proved useful to compare the signals detected in the pre-shower layers, and those obtained by summing over all strips in each SMD plane, to the signals expected from these layers in simulations. The excellent agreement found here suggests that the longitudinal shower profile (energy deposition as a function of depth) in the EEMC will be well understood, which bodes well for its use in discriminating between incident electrons and charged hadrons that may shower within the EEMC detector volume. Finally, the two planes of highly segmented SMD strips provided insight into the transverse profile of the showers. Though a few small discrepancies, not yet understood, were found between data and simulation, all indications are that the SMD planes being constructed should provide γ/π^0 (photon/di-photon) discrimination at the level required to carry out the spin physics program planned at STAR.

Members of the IU STAR group are also playing pivotal roles in developing much of the software needed for this program. Roughly speaking, there are two categories of effort: software needed to efficiently acquire and analyze *pp* collision data, independent of polarization information; and software that is only required when spin degrees of freedom are considered for the colliding beams. The need for much of the former stems from the fact that STAR, centered as it is on a (large) TPC, is fundamentally a slow detector, and is therefore best suited for processing very large events at a very low rate – the heavy ion environment. During *pp* running, however, when luminosities approaching 2×10^{32} may be reached, the event rate may exceed the bunch crossing rate of 9 MHz, resulting in the tracks from many time-separated collisions being present in the TPC simultaneously. Using fast cluster and track reconstruction, the hope is to eliminate most ($\sim$80%) of these spurious tracks *in real time*, which would reduce the data volume written to tape by a factor of 4–5. Detailed simulations, based on pseudo-events assembled from a large number of individual *pp* scattering events, indicate that such factors are realizable with a 'pile-up filter' developed at IU, allowing for an increase in the data acquisition rate by a comparable amount. A related problem, also unique to *pp* collisions, is that one would like to locate the event vertex of interest as quickly as possible online, despite the fact that the number of tracks produced may be small compared to the total number present in the TPC. Deducing the correct origin for such low multiplicity events has involved considerable effort, but the algorithms developed here will be tested soon on a subset of the heavy ion data.

The wealth of additional information that must be processed and recorded for any spin measurement to succeed has also proven to be daunting. With about 120 bunches stored in each ring, and the protons in each bunch potentially different in spin direction from those in adjacent bunches, software that can monitor luminosity and various rates bunch-by-bunch becomes essential, yet had never been needed during the heavy ion runs. Capabilities for accumulating, archiving, retrieving, and analyzing/displaying this type of information have all been achieved recently, largely through the efforts of IU personnel. Much of this spin monitoring software will be tested in the upcoming $\vec{p}\vec{p}$ run in early 2002.

A third area of preparation for the full spin program at STAR revolves around the use of the previously mentioned prototype EEMC detector as a forward π^0 detector (FPD) at STAR. A more detailed discussion of this project can be found in Ref. [Spi01], but the primary goals are to begin learning how to acquire precise spin data, and obtain publishable, interesting physics results, while waiting for the completion and installation of the full EEMC. The FPD, located far (~7.5 m) from the interaction point and close to the RHIC beampipe, will enable a measurement of the vertical spin asymmetry A_N for the reaction $\vec{p} + p \rightarrow \pi^0 + X$ at $\sqrt{s} = 200$ GeV, in a kinematic regime (x_F ¿ 0.2, 1 ¡ p_T ¡ 4 GeV/c) where spin effects are predicted to be large. Studies of leading pion production in fixed target experiments at much lower energies [Ada91] found spin asymmetries as large as 20–30%, and although there is disagreement over the dynamics that produce such large effects, it is generally believed that these should persist even at RHIC energies.

To convert the prototype EEMC into a pion detection system useful for spin measurements, a set of Pb-glass detectors of comparable transverse area was mounted on the opposite side of the RHIC beamline, along with two other sets mounted directly above and below the beam, to provide (more or less) left/right and up/down symmetric detectors. Only the EEMC, though, with its functioning SMD planes, will allow for invariant mass reconstruction when two photons are detected, a feature that may prove critical in this far-forward region. Integration of the FPD into the STAR trigger and data acquisition system is just now getting underway. The plan is to not only read out the FPD for all STAR-triggered events, but to also use the FPD to trigger itself and (occasionally) all of the other STAR detector systems as well. Accomplishing this will create a very nice device for taking spin measurements during the next $\vec{p}\vec{p}$ run, and also provide much needed experience for the vastly larger, and rapidly approaching, task of integrating the full EEMC into STAR in late 2002.

We should mention here that any viable spin program at RHIC hinges on our ability to determine the beam polarization(s) accurately, rapidly, and absolutely. For this last requirement, it is crucial that an absolute calibration measurement be carried out at RHIC beam energies, since no such standards currently exist. Quite apart from the STAR project, IUCF is also involved in the development of this much needed calibration experiment. Efforts towards this end are described in another section of this report.

Recalibration of the 200-MeV Linac Polarimeter

E.J. Stephenson and R. Toole, *IUCF*
H. Huang, K. Kurita, and A. Zelenski, *BNL*

The proton polarimeter at the end of the 200-MeV linac at Brookhaven National Laboratory makes use of proton-Carbon (p+C) inclusive scattering to measure the proton polarization. This polarimeter was originally calibrated at IUCF [Rob82] in 1982 with the results published as part of the development of the AGS polarized proton beam a number of years later [Khi89]. Since then the older polarized ion source has been swapped for a newer, optically-pumped source with much greater intensity. This higher current overwhelmed the detectors of the original polarimeter, making it unusable at the full current from the linac. The detectors, which consist of a series of two plastic scintillators mounted on either side of the beam, were moved to a much greater distance from the target and surrounded with collimation and extra shielding to reduce the rate. This, plus some inconsistencies uncovered during operations in 2000, suggested that the detector system needed recalibration.

IUCF offered to supply new scintillator detectors and target material to measure the analyzing power in p+d scattering, which is very well known from the absolute calibration made using double scattering in the K600 spectrometer [Ste99]. Work began in June with the help of a student from the Research Experience for Undergraduates program (Robin Toole). Two runs were made in July and August to determine the conditions under which p+d scattering could be observed with little background. The August running found that the polarization from the source should be larger by a factor of 1.08 ± 0.02. Because this represented a large change and the result disagreed with the systematics for p+C scattering published by McNaughton [McN85], it was decided to repeat the calibration when polarized beam operations started for RHIC. This was done in December. A much longer run was made with improved data acquisition hardware and a coefficient was found closer to one (0.986 ± 0.018). Systematic errors were studied, including the dependence of the system (both p+C and p+d) to high rates.

Planning for the Polarization Calibration at RHIC

E.J. Stephenson, *IUCF*

The polarized proton beam at RHIC will be the first to reach the high energies of 100 and 250 GeV. At these energies, there are no reference reactions with a known spin dependence that can be used for calibration. So the calibration experiment will make use of a polarized target. This polarization will be transferred to the ciculating RHIC beam by comparing the spin dependence in proton-proton elastic scattering for polarization in the beam and target. During FY2001, plans were made for the detector system that will eventually be needed to observe the low energy recoils from scattering in the Coulomb-nuclear interference region, a place where the cross section is high and there is a local maximum in the analyzing power for p+p scattering [But99]. Monte Carlo simulations were made for this detector system, and some initial studies were made concerning systematic errors that are likely to arise when the experiment is performed.

C. Weak Interactions

H. Nann and M. Snow, *IUCF*

Neutron Lifetime with NIST

The decay rate of the neutron is an important parameter in low energy weak interactions. In combination with other neutron decay measurements, it can be simply related to one of the parameters of the Standard Model of elementary particle interactions: the CKM matrix element V_{ud} (formerly known as the Cabibbo angle). In the Standard Model, the KM matrix transforms the mass eigenstate basis into the weak interaction eigenstate basis. If the model is correct this matrix must be unitary. A deviation from CKM matrix unitarity, if established, would be indirect evidence for physics beyond the Standard Model.

Precision measurements of neutron decay parameters offer the best hope for improving the accuracy of V_{ud}. V_{ud} has traditionally been determined from measurements of $0^+ - 0^+$ transitions in nuclei. The accuracy of the value for V_{ud} derived from these measurements, while higher than that from the neutron measurements at present, is limited by theoretical uncertainties in nuclear structure corrections to the decay rates. The current values for V_{ud} derived from nuclear decays (0.9734 ± 0.0007) and neutron decay (0.9810 ± 0.0021) are in serious disagreement. In addition, the neutron result causes a 3σ deviation from CKM matrix unitarity [Tow98].

The neutron lifetime also influences the predictions of the theory of Big Bang Nucleosynthesis (BBN) for the primordial helium abundance in the universe and the number of different types of light neutrinos N_ν (and therefore the number of generations) in the Standard Model. About 90% of the uncertainty in the BBN prediction for the primordial helium abundance comes from the accuracy of the neutron decay rate [Lop98]. Improved neutron decay rate measurements are therefore important for sharpening the BBN prediction.

The experiment at the NIST Cold Neutron Research Facility to measure the decay rate of the neutron has been completed. The measurement was performed by confining the protons from in-beam neutron decays in a Penning trap and counting the trapped protons while simultaneously monitoring the neutron flux passing through the trap. The goal of this collaboration is to perform a measurement of the neutron lifetime with an accuracy at the ±0.1% level. A previous version of the experiment reached an accuracy of ±0.5% [Byr96]. The value for the neutron lifetime recommended by the Particle Data Group is $\tau_n = 889.1 \pm 2.1$ seconds, a ±0.24% value.

A new monochromatic neutron beam at NIST (designated NG6M) has been constructed and commisioned by Indiana and NIST for performing absolute neutron flux measurements. The Indiana-designed neutron radiometer was installed and operated successfully using a ^{6}LiMg target and was able to measure the neutron flux at the 0.1% level of absolute accuracy. This measurement formed the Ph.D. thesis of Zema Chowdhuri (now postdoc/instrument scientist at Maryland/NIST). This measurement will be checked by an independent measurement using a liquid ^{3}He target (Greg Hansen's thesis project).

Neutron decay data and all asociated systematic checks were completed in spring 2001 at NIST. The Penning trap operation was flawless. Data analysis is complete and final checks are in progress. The result is being written for publication and will be submitted to Phs. Rev. Lett.

Parity Violation in Neutron Interactions in Simple Systems with LANL, the University of Michigan, the University of California at Berkeley, the University of New Hampshire, NIST, KEK, and PNPI

In the meson exchange picture of the weak NN interaction, weak pion exchange is particularly interesting since it should be dominated by neutral currents. This is the longest range component of the weak NN interaction, and therefore presumably the most reliably calculable in its effects in the NN system. The exchange of neutral currents between quarks, however, has never been isolated experimentally in low energy processes. For all of these reasons, the coupling constant for weak π exchange, h_π^1, is of special interest.

The size of h_π^1 is not known. The most reliable estimate of the size of h_π^1 is believed to come from measurements of the circular polarization of 1081-keV γ-rays from the decay of ^{18}F [Ade85], which gives an upper limit of $h_\pi^1 \leq 1.3 \times 10^{-7}$. New information on h_π^1 may come from the recent observation of nuclear parity violation in the atomic parity violation experiment using ^{133}Cs [Woo97]. This experiment has detected for the first time the (parity violating) nuclear anapole moment.

A measurement in the nucleon-nucleon system sensitive to h_π^1 is needed to determine its value beyond a reasonable doubt. The system must be simple enough that calculations which can connect experimental observables to weak couplings can be performed reliably. In practice, this means that one must perform experiments in light nuclear systems, such as p, d, ^{3}He, or ^{4}He. Measurements of parity violation have been performed in p+p scattering and in p+^{4}He scattering. Nevertheless, neither measurement determines h_π^1. In the case of p+p parity violation, identical particle constraints forbid a contribution from weak charged pion exchange to first order, and weak neutral pion exchange is suppressed because it violates time reversal invariance (Barton's theorem). Therefore, p+p parity violation is quite insensitive to h_π^1. Parity violation in p+^{4}He scattering is sensitive in principle to h_π^1. However, it is also sensitive to other weak meson couplings, and so the observation does not isolate the value of h_π^1 uniquely.

The two measurements with low energy neutrons address the problem of determining h_π^1 in different ways. In low energy neutron reactions, the parity violating observables are primarily sensitive to both weak pion and rho exchange, which are the longest-range contributions (the identical particle constraint that suppresses weak pion exchange in p+p scattering does not apply to n+p). In the case of the n+p system, an analysis of the available low-energy channels shows that the reaction $n+p \to d+\gamma$ is almost entirely due to

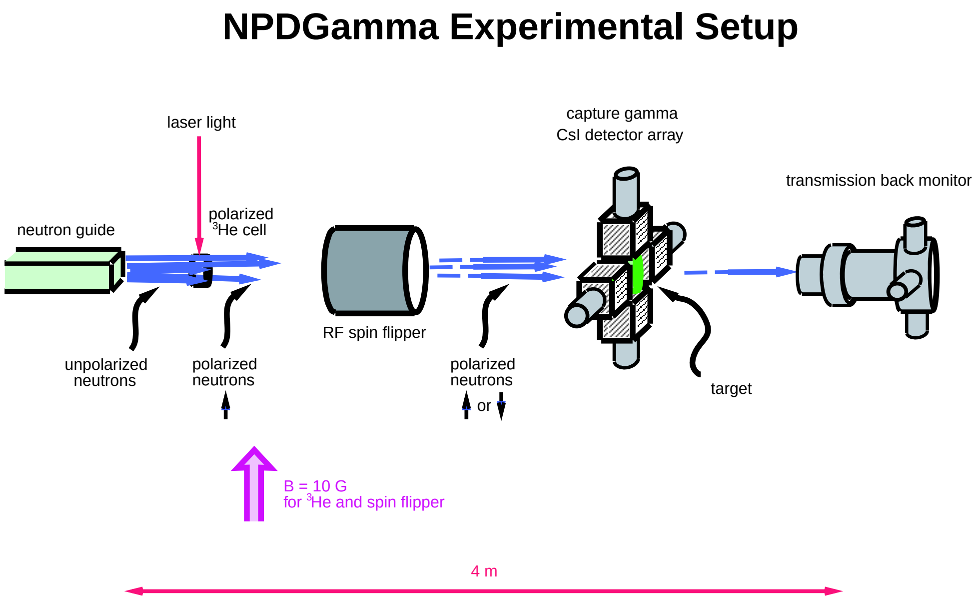


Fig. C1: Diagram of the major components of a test configuration for the $n + p \rightarrow d\gamma$ radiative capture parity violation experiment. IUCF is providing the liquid hydrogen target and the CsI detector array.

weak pion exchange. In particular, the relation between the PNC gamma ray asymmetry and h^1_π is calculated to be $A_\gamma = -0.045\ h^1_\pi + 0.001\ h^1_\rho - 0.001\ h^1_\omega - 0.002\ h'^1_\rho [Des75]$. Relativistic corrections in the n+p system have been estimated and shown to be small. In the case of the n+^{4}He system, the parity violation is also dominated by weak pion and rho exchange, and one can combine a measurement with the existing measurement of parity violation in p+^{4}He to determine both. Calculations of the parity violating neutron spin rotation have been performed: the neutron spin rotation angle per meter is $\phi = -0.97\ f_\pi - 0.32\ H^0_\rho - 0.11\ H^1_\rho - 0.22\ H^0_\omega + 0.22\ H^1_\omega$ rad/m [Dmi83]. The calculations are expected to be reliable partly because the reaction involves only elastic scattering channels.

The final result from the last experiment to search for the PV asymmetry in $\vec{n} + p \rightarrow d + \gamma$ was $A_\gamma = -1.5 \pm 4.7 \times 10^{-8}$ [Alb88]. This result is in mild conflict with one of the h^1_π estimates from the anapole moment measurement [Fla97], but it is not sensitive enough to reach the range of values for h^1_π predicted by theory. The limit reached in the first version of the neutron spin rotation experiment, 1.4×10^{-6} rad/m, is also not sensitive enough to put an interesting constraint on h^1_π. We propose to measure A_γ to a precision of $\pm 5 \times 10^{-9}$ [Sno97], which will determine h^1_π to $\pm 4 \times 10^{-8}$, and to measure ϕ to a precision of $\pm 3 \times 10^{-7}$, which should be sensitive enough to see a nonzero effect. A diagram of the apparatus is shown in Fig. C1. At a minimum, such results will clearly distinguish between the ^{18}F and ^{133}Cs values for h^1_π. In addition, there is also a strong possibility that a non-zero result will be seen in one of the experiments and that the value of h^1_π will finally be known.

To measure the parity-violating gamma asymmetry in the $\vec{n} + p \rightarrow d + \gamma$ experiment, transversely polarized neutrons are absorbed in a liquid hydrogen target and the γ-rays

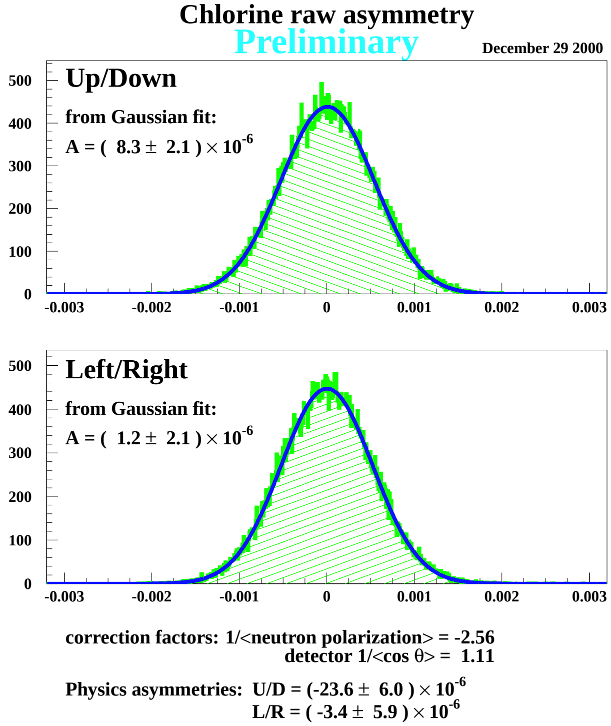


Fig. C2: Sample histograms of the asymmetry measured for the capture of polarized neutrons on ^{35}*Cl.*

are detected in current mode by a segmented cylindrical CsI array surrounding the target. The parity violating signal consists of an up-down asymmetry in the γ intensity correlated with the neutron polarization direction: $d\sigma/d\Omega = (1 + A_\gamma \cos\theta)/4\pi$, where θ is the angle between the gamma direction and the neutron polarization. The basic experimental strategy is to isolate this contribution by flipping the neutron spin and looking for a correlated asymmetry in the signal from the gamma detector array.

This experiment was approved by the DOE in the spring of 1999. The experiment is now in the test phase at Los Alamos. We have analyzed the results from the fall, 2000 test run. We successfully tested all components of the proposed experiment (the RF neutron spin flipper, the polarized ^{3}He target, the current mode ion chamber, the current-mode CsI detector read out with vacuum photodiodes, and the VME data acquisition with the exception of the liquid hydrogen target. In addition, we observed nonzero parity violation in polarized neutron capture in ^{35}Cl. A sample of the data is shown in Fig. C2. This data formed the Ph.D. thesis for Chris Blessinger.

Indiana is responsible for the design and construction of the CsI detector array and the liquid hydrogen target. The design of the LH$_2$ target has passed an external safety analysis with LANL, Jefferson Lab, ORNL, and FNAL participation. The CsI detector array is under construction. Purchase of the CsI(Tl) detectors is supported by an award to IU from the NSF MRI program granted in August, 2001.

Neutron Spin Rotation in ^{4}He with the University of Washington, North Carolina State, and NIST

Indiana is collaborating in a second-generation experiment to search for the parity-violating rotation of a transversely polarized neutron beam as it passes through a target of liquid helium. This measurement is somewhat analogous to the phenomenon of optical dichorism in light optics, in which the plane of polarization of a light beam is rotated as it passes through an "optically active" substance (in practice a substance, like sugar, in which the molecules have a chiral structure). In the case of the neutrons, however, the chirality is present not in the internal structure of the target but in the weak interaction, which violates parity.

The experimental apparatus is analogous to a light optics experiment with crossed polarizers and analyzers. If there is no spin rotation, the experimental signal should be zero. A small spin rotation will lead to an asymmetry in the counting rates for the neutron spin analyzer in its two possible states. We will be looking for a spin rotation angle on the order of a microradian.

Indiana has accepted responsibility for designing a new superfluid ^{4}He target chamber for the experiment. The cryostat was moved from NIST to Indiana in the summer of 2001. This project is the Ph.D. thesis for Chris Bass. We anticipate reducing the systematic efects due to stray magnetic fields by an order of magnitude by using more magnetic shelding. Based on the systematic effects observed in the previous version of the experiment, this should allow the experiment to see an unambiguous parity violation signal.

Indiana is also responsible for the operation of the current-mode ion chamber used in the previous experiment (designed by Steve Penn at Washington). We have tested this device at Los Alamos as part of the test runs in preparation for the neutron-proton weak interaction experiment. Indiana has also accepted responsibility for the simulation of neutron scattering in normal and superfluid ^{4}He in order to optimize the design. This effort, which is making use of the VITESSE neutron optics simulation environment, is in progress.

Polarized ^{3}He with NIST

Precision measurements of neutron decay parameters such as the decay rate and angular correlation coefficients of the decay products are of fundamental importance. In combination with a separate measurement of the neutron decay rate, for example, a measurement of the electron asymmetry coefficient in polarized neutron decay (the A coefficient) can be used to determine the weak polar vector-axial vector coupling ratio $\lambda = g_A/g_V$ and, by comparison with muon decay, the CKM matrix element V_{ud}, one of the parameters of the Standard Model of elementary particle interactions. The unitarity of the CKM matrix is dominated by the accuracy of the large diagonal elements V_{ud}, V_{cs}, and V_{tb}. Study of neutron beta decay offers the best opportunity to probe the unitarity of the CKM matrix. While it is difficult to measure V_{ud} to 0.1%, there is no hope of measuring V_{cs} or V_{tb} to this accuracy in the foreseeable future. Also, measurements of the neutrino asymmetry B in polarized neutron decay can be used to place interesting constraints on possible deviations from the Standard Model in the charged current sector of the weak interactions, such as the possible existence of right-handed weak currents. It is therefore important to improve the accuracy of these measurements.

Unfortunately, both of the most accurate measurements of the A and B coefficients in neutron decay suffer from a common limitation: the absolute accuracy of the neutron beam polarization measurement. To significantly improve the measurements a new technique is needed. One approach is to conduct the measurement with very low energy neutrons known as ultracold neutrons. Ultracold neutrons can be prepared in a definite state of polarization relative to an external magnetic field by passing then through a region in which the $\vec{\mu} \cdot \vec{B}$ interaction is larger than the kinetic energy for one of the spin states. Another strategy is to develop more accurate methods of measuring the polarization of neutron beams. In order to make significant progress, a method of absolute neutron beam polarization measurement with an accuracy significantly better than 0.1% is required.

The measurement of absolute neutron beam polarization is now a serious limitation on the accuracy with which neutron beta decay asymmetry measurements can be performed [Wil00]. We have conducted an accurate absolute measurement of the polarization of a neutron beam polarized using transmission through polarized ^{3}He gas. We have achieved an absolute accuracy of $\pm 0.3\%$, better than previous measurements in this energy range by almost a factor of 5, and we believe that a further order of magnitude improvement is possible.

Precision Measurements of Low Energy Neutron Scattering Lengths using Neutron Interferometry

High precision measurements of neutron scattering lengths are of interest in the area of few-body physics. In the last few years there has been significant theoretical progress in performing accurate calculations of the properties of few-nucleon systems [Car98]. Nevertheless, calculations using realistic two-body NN potentials still underbind ^{3}He and ^{3}H. The n-d scattering length in the doublet S-wave channel, which is strongly correlated to the ^{3}He binding energy in theoretical calculations (the Phillips line), is likewise poorly predicted by two-body NN force models. Convergence between theory and experiment for these important parameters of the 3N system is accomplished only by the addition of 3-nucleon forces. However, there are many possible forms for 3N forces and measurements of many two and three-nucleon observables are required to determine their form.

With the neutron interferometer [Wer00] at NIST, we can make measurements of the coherent scattering length with unprecedented absolute accuracy. In the case of the n+d system, this measurement yields the linear combination $a_{coh} = a_{1/2}/3 + 2a_{3/2}/3$ of the doublet and quartet n-d scattering lengths. The quartet S-wave scattering length $^4S_{3/2}$ can be unambiguously calculated. Because the three nucleons in this channel exist in a spin-symmetric state, and hence have an antisymmtric space-isospin wavefunction, the scattering in this state is completely determined by the long range part of the triplet S-wave NN interaction in the n-p channel; i.e. by n-p scattering and the properties of the deuteron. A recent recalculation of the quartet scattering length using a variety of NN potential models gives results in agreement at the 2×10^{-3} level. A high accuracy determination of the ${}^2S_{1/2}$ scattering length in the n-d system by a combination of experimental measurement and theory should therefore be feasible.

The NIST interferometer instrument has recently been used to successfully measure with high precision the coherent scattering lengths of Si to ±0.005% We have just completed a 10^{-4} precision measurement of the coherent n-d scattering length at NIST, and systematic corrections are close to completion. With the current theoretical precision in the calculation for the quartet n-d scattering length ${}^4S_{3/2}$, we can infer the doublet n-d scattering length ${}^2S_{1/2}$ to 10^{-2} accuracy, which is an improvement from previous determinations by a factor of 5.

Precision measurements of the coherent scattering lengths of ^{3}He and H are also possible using the same techniques. Data was taken at NIST in 2001 on these targets, also with 10^{-4} precision, and analysis is close to completion. The precision of the measurement is at the level of $\pm(2-3)\times10^{-4}$. For D_2 this represents an order of magnitude improvement in the knowledge of the scattering length.

D. Neutrino Physics

Rex Tayloe, *IUCF*

1. miniBooNE

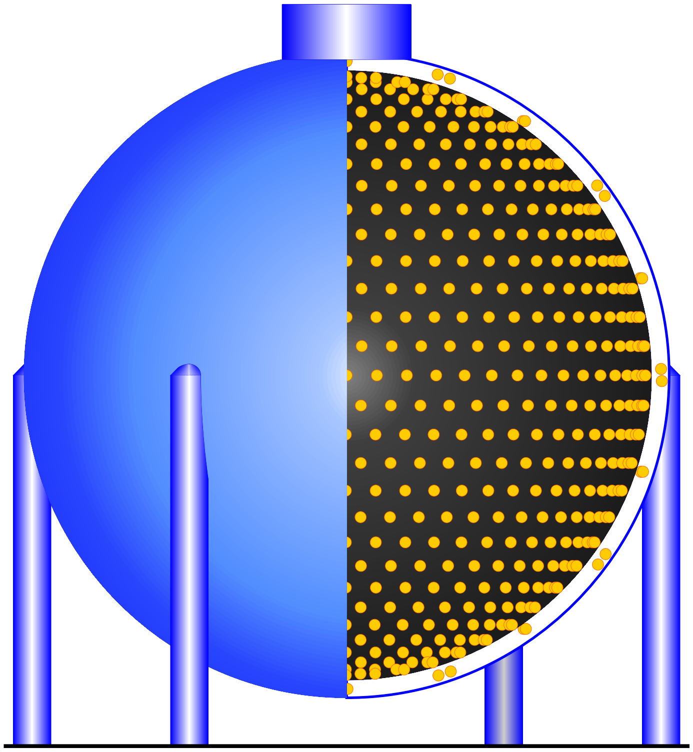
The Booster Neutrino Experiment, BooNE (FNAL-E898), will search for neutrino oscillations of the type $\nu_\mu \to \nu_e$ via appearance of electron-type neutrinos (ν_e) at Fermilab. This search is motivated primarily by the results from the LSND (Liquid Scintillator Neutrino Detector) experiment at Los Alamos National Laboratory which has seen evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. The first stage of BooNE (miniBooNE) will definitively test the LSND results.

The ν_μ will be created by 8-GeV protons from the FNAL booster accelerator impinging on a beryllium target rod embedded in an electrically pulsed horn system.

The miniBooNE detector is located 500 m away from the neutrino source and consists of a 12-m spherical tank filled with 807 tons of mineral oil (CH_2) (see Fig. D1). A thin optical barrier divides the tank into a 445-ton inner fiducial region and an outer, 35-cm thick, veto region. Particles with $\beta > 1/n_{\rm oil}, n_{\rm oil} \sim 1.47$ will produce Čerenkov light which is viewed by 1280 8-in PMTs in the fiducial region and 240 8-in PMTs in the veto region. The veto region allows particles entering or exiting to be tagged.

2. Recent Progress

In the past year, the miniBooNE detector has has been assembled at FNAL. Beneficial occupancy of the detector building and spherical tank occurred in January 2001. Since then, the following components have been installed: PMTs and optical barrier, cables and data acquisition electronics, mineral oil plumbing and monitoring, data acquisition software. As of the first of the year 2002, the filling of the detector tank with mineral oil



A schematic cut away view of the 12-m miniBooNE detector tank with PMTs indicated by the array of spheres.

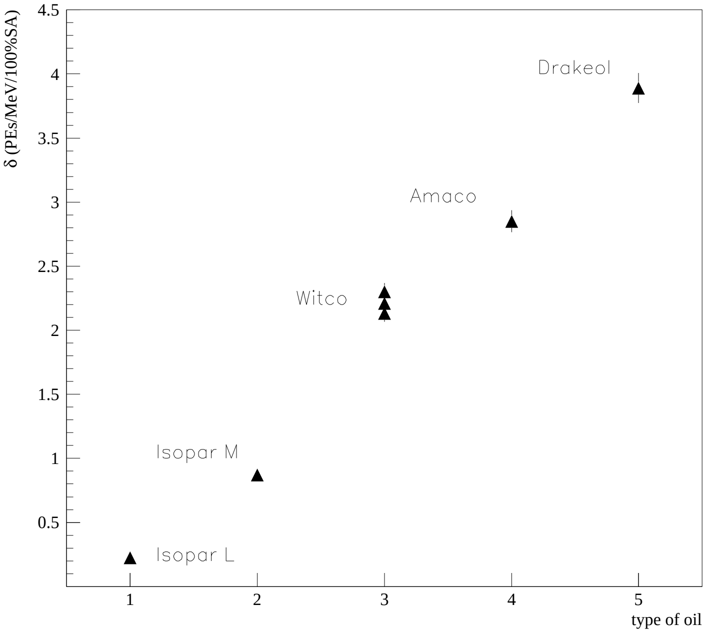
is now commencing. This has been accomplished in parallel with the formation of the new IUCF neutrino group.

The neutrino group at IUCF has lead several important subtasks of the miniBooNE detector installation. Table 1 lists the personnel in the newly-formed IUCF neutrino group along with their major responsibility within the group.

Table 1. Personnel and responsibilities of the IUCF neutrino group

Person	Position	Major responsibility
Rex Tayloe	Faculty Member	Project Manager for detector installation
Hans-Otto Meyer	Faculty Member	IUCF oil tests
J. Andrew Green	postdoc	miniBooNE data acquisition
D. Chris Cox	Graduate Student	neutrino-proton elastic scattering with miniBooNE
Nathaniel Walbridge	Undergraduate Student	miniBooNE slow-monitoring and nitrogen systems
Patrick Ockerse	Undergraduate Student	Cosmic Ray Analysis and IUCF oil tests

As listed in Table 1, tests were performed on mineral oil using 200-MeV protons from the IUCF cyclotron. Five candidate mineral oils were tested for intrinsic light output as well as their response with the addition of organic scintillators. These tests were done on the IUCF radiation effects beam line in March 2001. One of the results obtained (shown in Fig. D2) was that "pure" mineral oil, as obtained from the refinery, produces isotropic (scintillation) light and that different brands of mineral oil produces differing amounts of light. Based on these tests along with attenuation length tests done in parallel at Fermilab, the mineral oil to be used as the target for miniBooNE was selected and purchased.



Mean number of photoelectons per MeV deposited produced in 5 different samples of mineral oil by 200-MeV protons normalized to 100% solid angle.

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