# Findings
## Indiana University Cyclotron Facility

### Fiscal Year 2003

This represents the first year with no nuclear physics experiments running at IUCF. All of the group's experimental efforts are currently located elsewhere: the spin research program with the STAR detector at Brookhaven National Laboratory, parity violation with cold neutrons at Los Alamos, and the search for the appearance of oscillating neutrinos at Fermilab, for example. Results continue to come from Cooler experiments as they are analyzed and make it into print, and these findings will be included in this report. The major technical efforts for nuclear physics within the laboratory during FY2003 were the completion and installation of the second half of the electromagnetic calorimeter on the STAR detector and the completion of the liquid hydrogen target for use in the radiative capture parity-violation experiment at Los Alamos. There still remains some work to be done on the electronics for the readout of the shower maximum detector at STAR. New efforts are underway to define a detector system to measure the axial formfactor of the nucleon in neutrino scattering and to begin work on the parity-violating spin rotation of ultracold neutrons in liquid helium. These efforts are summarized below.

FY2003 contained the second year of running for RHIC with a polarized proton beam. This beam is still being developed, and both the intensity and the polarization are still below what is needed for the physics program. Nevertheless, some new results have emerged. One is the observation of a large asymmetry for uncharged pions emitted close the beam in p+p collisions (pseudorapidity between 3.3 and 4.2). The cross section is in agreement with perturbative QCD calculations, falling within the factor of two spread represented by the present model calculations. The analyzing power, or single spin asymmetry, rises for Feynman $x_F > 0.5$ to about 0.2, assuming that the analyzing power for the CNI polarimeter at $\sqrt{s}$ = 200 GeV is comparable to its value at RHIC injection. Again, this agrees with theoretical expectation for more all models of the origin of the spin dependence. These measurements were made with the prototype electromagnetic calorimeter made at IUCF and a set of Pb-glass detectors on loan from members of the STAR group. They are among the very few measurements of a non-vanishing spin effect made with the proton beam at RHIC.

The major physics effort of the local STAR group is the measurement of the spin dependence for hard, high momentum transfer processes because these are sensitive to the polarization of the gluons inside the proton and the applicability of perturbative QCD to the calculation of proton structure. Hard scattering between the constituents often results in the production of jets, and indications of these were present even in the early data in the form of particles with large transverse momentum in the STAR detector. A first investigation of these data, however, did not show any non-zero single-spin asymmetry given the statistical limitations of these early results. Nevertheless, these results are important because they demonstrate an upper limit on systematic errors associated the extraction of asymmetries from the STAR data.

In the near future, the plan is to search for the spin-spin correlations that will be the mark of the gluon spin structure functions. In preparation, simulations of future data based on jet production are underway. From these simulations one can plan the best methods for extracting the double spin asymmetries from the STAR data. These simulations also have an impact on the design of the jet triggers, reducing noise contributions and accounting for jets that span trigger patches in the electromagnetic calorimeters associated with STAR. As a part of this preparation effort, gain calibration procedures have been developed for the calorimeter phototubes that can be checked in a number of ways against STAR data and radioactive calibration sources. This work has led to the suggestion of an improvement to the STAR detector to improve the tracking capability in the forward and backward regions that is now a part of the STAR decadal plan.

All of these polarization experiments require precise knowledge of the beam polarization. The present calibration plan calls for the construction of a polarized atomic beam target for the 12 o'clock region that will be used as the standard for the measurement of the polarization of the proton beams circulating in RHIC. This year, great progress was made on the construction of the target with the hope that it will be installed and tested during the polarized beam development time scheduled for the coming spring.

Work with cold neutrons has led to the most precise in-beam measurement of the lifetime of the neutron, $886.8 \pm 3.4$ s, which is in agreement with the world average from other experiments. At the same time, lifetime measurements using a Penning trap can be improved if there are better ways to measure the neutron fluence. This technology is being improved by providing better neutron radiometers that precisely measure the energy released in neutron capture. These are devices whose sensitivity is enhanced by operating at very cold temperatures. Improvements have also been made with recently completed measurements of the scattering lengths in few-nucleon systems.

Cold neutrons are also an important component in the exploration of the weak force through measurements of parity-violating processes. The recently completed liquid hydrogen target was taken to Los Alamos where it will be used for the study of the parity-violating radiative capture $n+p \rightarrow d+\gamma$ reaction. In addition, IUCF has also assembled the CsI array that will observe the capture photons from this experiment. Equipment tests and systematic error studies are planned for the next year. Another experiment that is also sensitive to parity violation is the rotation of the neutron spin alignment as it passes through liquid $^4$He. This experiment is in an earlier planning stage. Both of these efforts depend on using a polarized $^3$He cell through which the neutrons pass. Because of the large difference in the total cross sections for different spin states, the emerging neutrons are highly polarized. IUCF continues to be involved in the development of such cells so that the polarization lifetime of the $^3$He is long. A part of this effort has included the precise measurement of the $n+^3$He cross section below 300 eV. With plans now underway to develop nuclear physics beam lines at the Spallation Neutron Source, IUCF is looking into the prospects for locating some of this work at the new facility. In FY2004, IUCF as a part of Indiana University looks forward to membership in the Oak Ridge Associated Universities and the development of a working relationship with ORNL.

This was also the year that the MiniBooNE neutrino detector began operation at Fermilab. First approved in 1998, this detector was built to check on an earlier experiment (LSND) that searched for the appearance of electron neutrinos through neutrino mixing in a beam of muon neutrinos (made from the decay of a pion beam) and obtained a statistically marginal positive result. The detector uses mineral oil as a medium to look for the Čerenkov light produced from neutrino captures. The experiment has been operating since September,

2002. The first year of operation has resulted in a sample of about 10% of the neutrinos needed to test the LSND result. It is hoped that improvements to the Fermilab proton beam intensity will allow the remaining events to be recorded within the next two years. The IUCF group is involved with data acquisition and trigger software, slow controls, and monitoring of the mineral oil quality as well as data analysis.

Plans are now well underway (and a proposal has been submitted to Fermilab) to build FINeSSE, a new detector that will go upstream of MiniBooNE and look at neutrino-proton scattering as a probe of the contribution of the strange quark sea to the proton spin. The detector will contain liquid scintillator and use a fiber system to read out track position. Prototype tests were completed this past summer.

The last year of the operation of the Cooler ring at IUCF concentrated in part on experiments with the three-body system and studies of deuteron spin manipulation in a storage ring, both using the PINTEX detector system. The spin manipulation studies (now being published) demonstrated that an RF solenoid is suitable for flipping the spin of polarized deuterons stored in a ring and also showed that the vector and tensor polarizations depolarize at different rates when the beam is close to a depolarizing resonance. The three-body studies concentrated on breakup with both the deuteron beam and the proton target polarized. From the large set of observables thus generated, the ones that will be emphasized first in the analysis are the so-called "axial" observables that vanish for a parity-conserving two-body final state. At Cooler energies these observables reach large values (0.2 for $A_z$, for example). Work is also underway to match these data to three-body Faddeev calculations that contain three-body force effects.

This year also saw the completion of the first analysis of the charge symmetry breaking experiment and the publication of this result. This experiment made use of a magnetic channel and an array of Pb-glass detectors to observe the isospin-forbidden and charge symmetry breaking $d+d \rightarrow {}^4He+\pi^0$ reaction just above threshold for the first time. Separation of the events from double radiative capture (in which two photons are produced without the pion through purely electromagnetic processes) required careful reconstruction of the pion mass from the momentum of the $^4He$ recoil nuclei. The cross section was normalized to measured d+p elastic scattering cross sections by first transferring the calibration to d+d elastic scattering that was used as an online monitor of the luminosity. As an aid to the theoretical interpretation of this experiment, the d+d elastic scattering cross section and three analyzing powers were measured with the PINTEX detector. Analysis of these data is still underway.

Also close to completion is the final analysis of the n+p back angle cross section using tagged neutrons. The tagger was built to circumvent the problem of knowing the incident neutron flux in n+p scattering experiments by creating the neutrons in a d+p breakup reaction in which the two recoil protons were both observed. This measurement was prompted some time ago by the publication of n+p cross sections within the Cooler energy range that were significantly higher than the predictions of modern phase shift analyses. The preliminary tagger data confirms the normalization of the original phase shift work.

A new effort is emerging to search for an intrinsic electric dipole moment on the deuteron. The observation of such a moment at the levels within reach of this experiment would violate the predictions of the Standard Model and be a signature of super-symmetry. Normally the large electric fields needed for such searches prohibit the use of charged particles. But if the particles are confined to a storage ring, the needed field configuration can be produced. The search works best for particles that have a small anomalous magnetic moment relative to their mass (such as the muon and deuteron). The signal would be the precession of the polarization of the deuteron beam due to the influence of the electric field. Efforts this year have been devoted to calculations of the properties of storage rings and deuteron polarimeters under various operating conditions and the study of systematic errors in the experiment. It is hoped that during the next year this study will mature to the extent needed to write a funding proposal for this experiment.

The two main technical projects for nuclear physics at IUCF have been the construction and installation of the electromagnetic calorimeter for STAR and the construction of the CsI array and liquid hydrogen target for the study of neutron parity violation at Los Alamos. These two efforts are represented in the Contributions section of this report by long summaries that were prepared during the year as individual project reports.

Once again, IUCF was the host to an NSF-sponsored Research Experience for Undergraduates program. A list of the projects and advisors is contained in this report. Next year, the REU program will be administered across the whole Physics Department at Indiana University with only a fraction of the projects located at IUCF.