

## Findings from Previous Years

Included below is a summary of some of the results from research conducted under the National Science Foundation grant PHY-96-02872 prior to FY2002. These include both the cyclotron and Cooler programs. Items are arranged according to the experimental area in which the work was conducted.

### Cyclotron – Beam Swinger

- Charge-exchange (p,n) reactions were used to study the spin-longitudinal and transverse responses of the nuclear medium through a measurement of the polarization transfer coefficients. Targets across the periodic table were examined. Like similar results from LANL, no enhancement was seen. This rules out enhancements predicted on the basis of pion collectivity in the nuclear medium. The  $^2\text{H}(p,n)$  data were compared successfully with Faddeev calculations.

### Cyclotron – K600 Spectrometer

- One of the best ways to test the nucleon-nucleon interaction is through the measurements of polarization observables. Because of concerns about the magnitude of the pion-nucleon coupling, a set of precise measurements was made of the polarization transfer in p+p elastic scattering. The results agree well with the predictions from the Nijmegen group, either phase shift analysis or potential models. This supports the weaker pion-nucleon coupling used in those potentials.
- High-resolution (p,p') spectra were measured with the K600 spectrometer on a variety of light and medium-mass targets in order to compare with charge exchange ( $^3\text{He},t$ ) data from Osaka. Together, these data sets allow a separation of the resonances in the continuum by isospin, a source of important information on nuclear structure.
- The measurement of complete sets of polarization transfer coefficients for (p,p') reactions is a tool that allows a separation of the various spin-dependent parts of the effective NN interaction that contribute to the reaction process. When unnatural-parity stretched states are studied, good information is available on the spin-orbit and tensor components of the force. Studies of isovector transitions were pursued in the hope that a signature for partial chiral restoration would emerge, but careful calculations using prescriptions that left intact the balance between  $\sigma$ -meson attraction and  $\omega$ -meson repulsion showed that such transitions are too peripheral to be sensitive. Nevertheless, such transitions are not always well described by distorted-wave theory, in particular for  $D_{NN}$  in  $^{28}\text{Si}$ . In general, the contributions to spin-longitudinal forces are overpredicted while the contributions to normal-component transverse are underpredicted. Distorted-wave calculations that include Pauli blocking and strong relativistic potential effects do describe natural parity transitions reasonable well. For low spin states, such as the  $1^+$  transition in  $^{48}\text{Ca}$ , there is also evidence that density-dependent folded optical potentials better capture the distorted waves than do best-fit potentials. Nevertheless, such data have proved to be an excellent testing ground for the exploration of density-dependent effects in the nuclear medium.

- As a part of the calibration of the K600 focal plane polarimeter and the upstream polarimeters, a set of very precise proton analyzing power data were generated for p+d elastic scattering as a function of energy. Each measurement is at an angle of  $42.6^\circ$  for the recoil deuteron in the laboratory. These data were compared with Faddeev calculations with and without the three-body Tucson-Melbourne force, and agreed with neither. The shape as a function of energy is similar to the calculation containing the three-body force, but lies below it by almost 0.1.
- Astrophysics models of the production of the elements, through either proton or neutron capture reactions, depend on accurate nuclear structure information in order to predict reaction rates and abundances. The K600 was used as a nuclear structure instrument to explore the excited states of  $^{24}\text{Si}$  through the  $^{28}\text{Si}(^4\text{He}, ^8\text{He})$  four-neutron transfer reaction. A calibration of the excitation energy on the focal place was made using the  $(^4\text{He}, ^6\text{He})$  reaction to known states. The first two excited states of  $^{24}\text{Si}$  were seen for the first time. These states are crucial to the formation of a path around the production of  $^{22}\text{Na}$ , an isotope that has not appeared as expected in nova explosions. While the expected locations of these states were different in the measurement, there is not enough change in the predicted cross section to account for the absence of  $^{22}\text{Na}$ .

### **Cyclotron – Polarized Neutron Facility**

- The coupling of the pion to the nucleon was explored in 187-MeV n+p elastic scattering where the  $K_{\text{NN}}$  polarization transfer coefficient was measured. This experiment made use of polarimeter hardware whose spin response was known from calibrations of the focal plane polarimeter on the K600 spectrometer. The data are in general agreement with the phase shift analysis from the Nijmegen group that uses coupling constants at the lower end of the acceptable range.
- Precise measurements of the analyzing power in n+d elastic scattering were made at 187 MeV using the polarized neutron facility. Such measurements test not only for the presence of three-body forces but also are sensitive to the differences between p+d and n+d scattering generated through electromagnetic effects. The data obtained in this experiment agree with analyzing powers from p+d elastic scattering in the same energy region.

### **Cooler – G-region**

- The Cooler G-region was used to set up and test a polarized deuteron target whose polarization was generated by optical pumping. This target was being developed as a possible target for other experiments outside IUCF. As a part of this program, measurements were made for p+d elastic scattering with both or either of the beam and target polarized. Such calculations are sensitive to the contributions of three-body force effects. Faddeev calculations that include such effects agreed well with the deuteron vector analyzing power and the vertical-component spin vector spin-correlation coefficient. Measurements for the proton analyzing power lay between calculations with and without the Tucson-Melbourne three-body force, in agreement with other similar experiments.

### Cooler – A-region (PINTEX)

- Polarized gas jet targets for storage rings are often exceedingly thin because they are made from atomic beams whose extraction rate from hydrogen gas is limited by the operating parameters of the polarized ion source. In order to enhance this thickness, the atoms can be captured and held briefly in a tube that runs parallel to the beam. If the interior walls are coated with certain materials, such as Teflon, the depolarization rate will be very slow. But such surfaces can also act as sites where hydrogen atoms stick for a while, long enough to encounter other atoms and re-emerge into the target volume as molecules. Up until recently, it was assumed that such molecules were unpolarized, but a test with deuterium at HERMES suggested otherwise. The University of Wisconsin group investigated this phenomenon and found that with a large holding magnetic field it was possible to retain essentially all of the polarization of one of the two hydrogen atoms into the molecule. The measurements involved tests of the polarization using a proton beam and a measurement of the longitudinal spin correlation coefficient.
- A full set of analyzing powers and spin correlation coefficients were measured for the  $p+p \rightarrow p+p+\pi^0$  reaction between 300 and 400 MeV. Such information is sufficient to characterize this process in all of the five kinematic degrees of freedom, and to determine the contributions of all significant partial wave amplitudes. Concurrent data on  $p+p \rightarrow p+n+\pi^+$  also provides the same amplitude separation.
- The Faddeev equation provides an exact coupled-channel solution to the problem of scattering, including bound states, for three bodies based on two-body forces alone. Because of the high precision with which the two-nucleon force is known, one can compare such calculations with the results of precise three-body experiments to determine the nature of any three-body interaction. Using a polarized proton beam and a polarized deuteron target, measurements were made of 15 of the 17 polarization observables for  $p+d$  elastic scattering at 135 and 200 MeV. Comparisons to calculations based on two versions of the Tucson-Melbourne three-body force show mixed results. Some observables improve while others are more poorly described. Nevertheless, these data will become a benchmark for the comparison with new models now under development, in particular using chiral effective field theories as a basis.

### Cooler – S-region (Snake Experiments)

- Most recently, the efforts of this group have focused on schemes for the flipping of the spin of a stored proton beam. In the latest tests, an rf-dipole was ramped through a depolarizing resonance. By adjusting the parameters of the ramp (starting and ending slopes, ramp rate, power, etc.), it was possible to achieve efficiencies well in excess of 99% on each flip. Such a capability is crucial for high energy rings to cancel systematic errors during polarization experiments.

### Cooler and CIS – Accelerator Physics

- Tests were conducted with the Cooler Injector Synchrotron to simulate the compression of long beam bunches into narrow pulses. Such a compression is a crucial aspect of the

design of the Spallation Neutron Source. The mimic experiment worked well, demonstrating the importance of space charge and resonance effects.

### **RHIC – STAR Collaboration**

- During the period of this grant, the decision was taken to launch a new experimental effort as a part of the STAR Collaboration at RHIC to measure the polarized gluon structure function using the colliding polarized proton beams being proposed for that facility. This premier effort would, using data at 250 and 500 GeV, map the  $x_{\text{gluon}}$  distribution over the range where it is expected to be largest and provide a precise value of the integral. Such a measurement is a crucial component of the question of the origin of the proton spin since deep inelastic muon scattering experiments have demonstrated that only a small fraction of the spin resides on the valence quarks. Additional observations of parity-violating scattering would provide information on the contributions of sea quarks and anti-quarks to the overall spin distribution. For this program, it was essential to construct an electromagnetic calorimeter that would fit on one end of the cylindrical STAR tracking detector in order to observe the hard photons and jets from quark-gluon scattering in a useful kinematic regime. A separate proposal was made to the National Science Foundation and approved to support the design and construction of this detector. The detector consists of 23 layers of a lead-scintillator sampling calorimeter arranged in 720 projective towers that will cover the pseudorapidity range from  $1 < \eta < 2$ . A gap at layer 5 is made to accommodate a position-sensitive shower maximum detector whose main purpose is to resolve single photon events from the two-photon decay products of the  $\pi^0$ . A collaborative effort was organized to bring other user groups into the construction activity. Production of the megatile scintillators was organized at IUCF, while the shower maximum detectors were produced at Argonne National Laboratory. Prototype tests were made using electrons at the SLAC test beam facility. The first half of the lead radiator assembly was in place along with 120° of the sampling calorimeter for the FY2003 running period. During this time progress was made on the commissioning of the detector along with its electronic readout and integration into the overall STAR data processing system. Along with this effort, there has been a parallel development, first of simulations of the performance of the calorimeter, then of software needed to operate the detector and process the data that it produces.
- As a part of the effort to equip the STAR detector with the readout needed for a program in spin physics, IUCF has participated in several efforts to measure the polarization of the proton beams at Brookhaven. The prototype electromagnetic calorimeter detector, along with additional arrays of Pb-glass, were installed in the STAR experimental hall to look for an asymmetry from  $\pi^0$  production. A small asymmetry has been observed and reported. Tests were made in 1999 that demonstrated large asymmetries were possible from a deuteron target at RHIC injection energies. A p+d polarimeter was developed for the 200-MeV LINAC. IUCF is also involved with the experiment to install a polarized jet target at the 12 o'clock region that will be used for a precise calibration of the polarization of the circulating RHIC beam.

### **LANSCE – Cold Neutron Experiments**

- One of the ways to determine the weak coupling between nucleons and mesons is to look for places where weak and strong coupling interfere and the relative scale is open to experiment. In many cases, this involves the measurement of a parity-violating asymmetry. There are several such couplings in the model of the weak interaction. A list of the experiments that are needed include the radiative capture reaction  $n+p \rightarrow d+\gamma$ . This experiment is still in preparation at Los Alamos. IUCF is contributing the liquid hydrogen target and the array of CsI detectors that surround it. The signal is expected to appear at the level of roughly 1 part in  $10^8$ .
- A second experiment on the list of those probing the weak meson-nucleon coupling is the measurement of the spin rotation of polarized neutrons. The polarized neutrons are made by transmission through a polarizer and later analyzed in the same way. In between, the neutrons pass through a target of superfluid  $^4\text{He}$ , which will be constructed by IUCF.

### **NIST – Cold Neutron Experiments**

- The low-energy coherent scattering lengths for few-body systems are an important testing point for theories that look for three-body effects in nuclear processes. A neutron interferometer has been built at NIST and the first results have been reported on the measurement of the neutron-deuteron coherent scattering lengths. The results agree with some three-body calculations based on the Illinois-Argonne AV14 potential when a three-body force is included. Other models are excluded, so this becomes an important discriminating parameter.
- Measurements are underway to determine a new, more precise value of the neutron lifetime. A flux of neutrons from the NIST reactor was carefully counted along with a measurement of the number of decay protons caught in a Penning trap. First tests show results with errors of 0.5%. A more precise value requires better monitoring of the absolute neutron flux, a project that is now well underway. The value of the neutron lifetime appears in the  $V_{ud}$  matrix element of the CKM matrix. Precise tests of the unitarity of this matrix may indicate physics beyond the Standard Model.

### **Fermilab – MiniBooNE Collaboration**

- One of the most important recent advances in physics has been the demonstration that neutrinos have mass. Now the challenge is to determine what spectrum of masses and mixing angles suits all the known features of this phenomenon. One aspect that has been known for years is the disappearance of neutrinos made in the nuclear reactions that power the sun. In parallel, one also expects to see neutrinos that appear through flavor mixing. The LSND experiment pioneered this effort by searching behind the beam dump at Los Alamos for electron neutrinos that appeared from the muon neutrinos resulting from the decay of the pion beam. This result was statistically marginal. It is being repeated using a more intense neutrino beam from the Booster at Fermilab. There the MiniBooNE Collaboration has set up a large detector of mineral oil viewed by a large number of phototubes. Construction of this detector has recently been completed and runs are presently underway.

## Nuclear Chemistry

- One of the most intriguing possibilities in the study of heavy nuclei as bits of nuclear matter has been the question of whether such matter undergoes phase transitions. (A change of state to a quark-gluon plasma is one focus of the RHIC program.) With the excitation available from standard nuclear probes, it is possible that the ground state, which resembles a liquid (deformation, etc.) will, with enough energy, become a gas. For this, it is essential to have a complete a characterization as possible of all of the fragments that emerge from nuclear disassembly. This technology was incorporated into the Indiana Silicon Sphere (ISiS) for the identification of energy, mass, and charge. The detector was taken to a number of laboratories where it was run with light-ion beams, thought to be the best probes since they minimized rotational motion in the final system. A number of features of the final distribution were used to characterize the phase change. Time scales were important, and used to look for particles emitted initially and to separate those from particles evaporated later from a cooling system. The phase transition was observed to occur at excitation energies near  $E^*/A \sim 4-6$  MeV.

## Laboratory Developments

- The polarized ion source, CIPIOS, was configured for deuteron beams and developments were made to increase the intensity of the pulsed, polarized beam. The source now features two separation sextupole magnets followed by rf transition units. The combination of strong, medium, and weak fields makes possible the selection of a wide variety of deuteron polarization states: either pure vector or tensor, and any of the three magnetic sublevels independently. Instantaneous beam currents were as much as 1.5 mA with pulse lengths up to 400  $\mu$ s. The repetition rate was limited by the ability to clear the vacuum chambers to 4 Hz.
- Funding, in part from an MRI grant, was used to bring into operation the Cooler Injector Synchrotron. This machine takes negative beam, either polarized or unpolarized, from the CIPIOS source and captures it through strip injection on a thin carbon foil. The pulse length insures that beam accumulates well above the injection intensity. The beam is then bunched and ramped to the transfer energy to the Cooler. The maximum proton energy for transfer is a bit less than 250 MeV. Extraction is on a single turn through the use of an electrostatic kicker. After some initial concerns about the preservation of the proton polarization, a partial Siberian snake magnet was installed to allow the beam to accelerate through the  $G\gamma = 2$  imperfection resonance. The cycle time of the machine was 0.8 Hz. Up to  $5 \times 10^8$  proton/fill were extracted.