Findings

The FY2002 funding from grant PHY-96-02872 went to support the operation of the electron-cooled storage ring (Cooler) and some expenses associated with the experimental program there. Other expenses for the experimental program in nuclear physics were funded from grant PHY-01-00348. The operations support was a one-year extension, discussed and approved in 1999. This allowed IUCF in 1999 to proceed with the acquisition of a new set of vanes for the radio-frequency quadrupole suitable for the acceleration of deuteron beams. In parallel with the existing program using proton beams, work began on the optimization of the deuteron beam and the development of deuteron polarization from CIPIOS, the polarized ion source. This allowed us in 2002 to complete three important experiments using the deuteron beam: (1) the measurement of a large number of polarization parameters for deuteron breakup on the proton, a set of data that illuminates questions concerning three-body forces, (2) the successful observation of the charge symmetry breaking $d+d \rightarrow {}^4He+\pi^0$ reaction, and (3) the first tests of the flipping of deuteron spin in a storage ring, along with measurements of the polarization lifetime close to a depolarizing resonance.

This summary report for grant PHY-96-02872 includes detailed reports on the last year of Cooler operation. A table of the physics highlights of the preceding five years is also included; these items have been covered in detail in previous Annual Reports.

Summary of Cooler Operation

The IUCF Cooler ran for 25 weeks during FY2002. The year began with an access period following the completion of the tagger experiment in the T-region. This allowed the tagger detectors to be removed and the target box replaced with the one for the charge symmetry experiment. Running started with the proton beam at the end of November and continued with a break for the Christmas holidays until the end of January. During that time several tasks were accomplished: (1) Studies continued on the manipulation of proton spin in the Cooler. (2) Data was taken on pion production in the $p+d \rightarrow t+\pi^+$ reaction with polarized beam and target. (3) Commissioning runs were made for the charge symmetry breaking experiment in which the $p+d \rightarrow {}^3He+\pi^0$ reaction was used as a source of pions.

At the beginning of February, the vanes in the radio-frequency quadrupole were changed from proton to deuteron operation, and a series of developments started to maximize the deuteron beam available in the Cooler. Those efforts reached what was presumed to be a space charge limit with roughly 2 mA of circulating beam.

With the polarized deuteron beam, data was taken on the breakup experiment and on the manipulation of deuteron spin in the Cooler. Then the majority of the months of June and July were reserved for production running on the charge symmetry breaking experiment.

Summary of Cooler Physics

The cross sections for p+p or n+p elastic scattering set the scale for the coupling of the pion to the nucleon. Thus it was with great interest that Uppsala published new n+p cross section measurements that seemed to suggest that the strength of the charged pion coupling should be revised upward. At the root of this observation was a measurement of the n+p angular distribution that differed in shape and magnitude from a substantial portion of the data then available. It was thus clear that, with the scatter then present among the sets of cross section data, what was needed was a new measurement that addressed the need for a precise scale.

This need led to the construction of the neutron tagger. This system used a proton beam on a deuteron target to generate a forward-going neutron that carried most of the beam kinetic energy. The two recoil protons were captured in position sensitive silicon detectors. A signal there allowed the reconstruction of the neutron momentum and direction. Since the neutron source was now well known, even on an event by event basis, it was now possible to do experiments with a greater certainty in the cross section normalization.

Data was taken on n+p elastic scattering in the backward hemisphere. Tagged neutrons hit protons in a CH_2 target. Forward-going protons were tracked and their energy measured.

As of this writing, the analysis is approaching completion. Preliminary results show an angular distribution that resembles most closely the original Uppsala cross sections, particularly near 180°. Now both of these cross section sets differ from the phase shift analysis from the Nijmegen group. It is this phase shift analysis which is the present standard for the production of other meson-exchange and effective field theory models of the nucleon-nucleon interaction. Thus this data will call into question whether the selection of n+p data for that analysis is correct.

One can use such two-body forces to explore the question of whether this information alone is sufficient to explain phenomena for the three-body problem. It is expected that there will be some changes, since the formation of the Delta resonance and other effects appear when three nucleons are present. Scattering experiments can, in principle, be predicted using a two-body force and the Faddeev equations. At intermediate energies, authors often point to an increase for the lowest cross sections as an indication in favor of the inclusion of three-body forces. When the scale for such effects is set to reproduce the binding energy of the triton, then below 200 MeV one often finds agreement with the p+d cross section.

This result does not provide enough information to test the structure of such three-body force models, in particular their spin-dependent parts. Thus it is important to also have available data such as analyzing powers, polarization transfer coefficients, and spin correlation coefficients. Indeed, a number of laboratories have fielded experiments aimed at a precise exploration of part of this space of observables.

The PINTEX group is using their large area detector and the polarized target from the University of Wisconsin to make a major contribution to the space of polarization observables. With the proton and deuteron, there are five additional analyzing powers. Data for all of these has been taken at 135 and 200 MeV. In addition, there are also measurements on 10 spin correlation coefficients or combinations of coefficients.

The comparison with Faddeev calculations shows mixed results. Some observables show improvement when three-body forces are included. For others neither calculation agrees well. In this context, it is clear that refinements of the three-body force are needed, and those refinements must take into account the nature of the two-body force model in a self-consistent way. One scheme for achieving this is to use effective field theory in which the force components are consistent with the underlying quark structure on the nucleons and mesons. Usually these theories are established at lower energies with a restriction that the degrees of freedom include only nucleons and pions.

Elastic scattering is not the only three-body channel to consider. Data has also been taken, again with polarized beam and target, for the breakup of the system into two outgoing protons and a neutron. Such an experiment opens up a very large phase space. Thus it is important to decide how to best gather such data for a confrontation with theory. The search for the best scheme is underway. It has been suggested that the breakup system offers some new observables, such as the longitudinal analyzing power A_z, that might carry an enhanced sensitivity to three-body effects.

Three-body force effects can also appear in other reactions channels. Data was taken during this period on the production of a positive pion in the $p+d \rightarrow t+\pi^0$ reaction. At the energies near threshold, there are usually only a few partial waves that can contribute to pion production. Often, polarization observables can be used to separate these contributions. In that spirit, measurements were made of the longitudinal and transverse spin correlations parameters for the total production cross section. That analysis is also underway.

The study of symmetries and symmetry breaking can be an important way to learn about the strong interaction. The first experiment of this sort at IUCF, a comparison of the analyzing powers for the neutron and proton in n+p scattering, became a project that lasted through the 1980's. The effect seen in that experiment was attributed to three causes: (1) the dipole-dipole interaction between the magnetic moment of the neutron and the field of the moving proton, (2) the mass difference between the neutron and the proton, and (3) the mixing of the ρ and ω mesons in the nuclear force.

The common presumption is that these charge symmetry breaking effects arise more fundamentally from the quark structure of the nucleon. In particular, chiral perturbation theories point to two contributions: (1) the mass difference of the down and up quarks, and (2) the energy stored in the electromagnetic fields that surround the quarks. The sum of these two effects produces the neutron-proton mass difference, which is well measured. Within the context of chiral perturbation theory, the other route by which we may learn about the contributions of these two mechanisms quantitatively is through pion-nucleon scattering. Considerable effort has been devoted to the study of this process at low energies. However, it is possible only to have charged pion beams and proton targets, so not all charge combinations are accessible. Unfortunately, in a consideration of these data one must accurately account for the contributions of charge symmetry breaking effects at the meson and nuclear level that arise from the action of the Coulomb and magnetic forces between the pion and the proton. It is not clear that this effort has so far been successful.

A second class of experiments can get around this problem by focusing on the uncharged pion, but only at the expense of having to imbed the pion-nucleon scattering process inside pion production. Two such experiments are possible with light nuclear systems. One involves the measurement of the fore-aft asymmetry in the cross section angular distribution for the $n+p \rightarrow d+\pi^0$ reaction. Results on this have recently been reported from TRIUMF.

A second case is the observation of the isospin and charge symmetry forbidden $d+d \rightarrow {}^4He+\pi^0$ reaction. Searches for this process have been made since the end of the 1950's. The most recent at Saturne claimed a significant cross section near a deuteron energy of 1 GeV, but this claim was questioned because the experiment could not distinguish pion production from double radiative capture, which also produces two photons in the final state.

The Cooler seemed like a particularly clean environment in which to conduct a search near threshold, an energy that also has the advantage of matching best with the calculations from chiral perturbation theory. A new setup was created that used the 6° bending magnet to separate the forward cone of ^4He from the circulating beam. A magnetic channel captured the ^4He and measured the momentum and scattering angle, quantities that were later important for the kinematic reconstruction. Two arrays of lead glass detectors were placed on either side of the target to simultaneously record the photons from the decay of the π^0. Backgrounds were low, and it was possible to make a clean observation of the cross section for this process as well as to measure the size of the continuum from double radiative capture.

A theory collaboration has been formed to calculate the size of the charge symmetry breaking cross section. It is hoped that this effort will also make it possible, along with the result on the fore-aft asymmetry, to address directly the question of the relative contributions of the quark mass difference and electromagnetic effects to the breaking of charge symmetry.

All of these projects are reported in detail in these findings.

At the end of these reports is an additional section that reviews the main achievements of the physics program under PHY-96-02872.