Findings

Summary

Fiscal year 2005 marked the transition from the first to the second 3-year grant since the termination of operational funding for running the Indiana University Cyclotron Facility (IUCF) accelerators for experiments in nuclear physics. It also represented the transition from an October 1 to an April 1 starting date. To bridge this starting date transition, funding was extended for the first six months of FY2005 at the rate of the previous three years (PHY-0100348). During this time, activities associated with the grant continued, including full participation in the Relativistic Heavy Ion Collider (RHIC) run at Brookhaven National Laboratory, preparations for cold neutron experiments at Los Alamos National Laboratory and the National Institute of Standards and Technology (NIST), data collection with the MiniBooNE experiment at Fermilab, and several other smaller activities. The proposal to the NSF for the next three years was based on a continuation of scientific activity at the same level and contained the budget increases to cover those costs.

The actual budget for activities in nuclear physics at the NSF turned out to be lower than that for the preceding year, so we had to absorb a budget reduction for the period from April 1 through September 30 covered by this report (PHY-0457219). Since this came during a period of high salary expense (coverage of summer faculty salaries) and we did not think it prudent to terminate people associated with the project, the savings was realized by sharply curtailing the use of technical support from IUCF, travel, and the purchase of capital equipment. Technicians who had been working on nuclear physics activities were reassigned within IUCF to other projects, mostly to the completion of construction of the treatment gantry for the Midwest Proton Radiotherapy Institute (housed within the IUCF building). Travel was restricted to participation in ongoing experiments and high priority conference talks or collaboration meetings. In several cases, abstracts to meetings (in particular the fall meeting of the Division of Nuclear Physics of the Americal Physical Society) were withheld in anticipation of not having enough funding to cover travel to the meeting. Essentially no items of any value were purchased during this period. With some carryover funds from the old grant and a much appreciated supplement at the end of the fiscal year, we were able to complete FY2005 with no unpaid obligations.

We anticipate an improved budget situation in FY2006 that will allow some equipment purchases, some technical help, and a relaxation of travel restrictions. This is particularly important as the new nuclear physics faculty member, Chen-Yu Liu, starts her work at Indiana with the development of an ultra cold neutron source based on solid oxygen and the continued tests of a scheme to search for an electric dipole moment by looking for the bulk magnetization of a garnet crystal is a strong electric field. While startup funds will cover the expense of a dilution refrigerator, equipping new laboratory space and getting technical help must come from the nuclear physics budget. At the same time, Rex Tayloe and Hans-Otto Meyer hope to be able to build a prototype of their large-volume, position-sensitive detector FINeSSE by obtaining engineering and shop support from the grant. In the long term, restrictive budgets will make it much harder for the nuclear physics group at Indiana to take advantage of the unique resources available within IUCF to initiate large equipment development and construction projects at the scale of the STAR endcap calorimeter. This represents a loss to the national effort in nuclear physics, since such projects can only be accomplished (outside of national laboratories) at places where there are significant laboratory skills and equipment, and a reduction in the opportunities for students and post-docs to obtain experience with current physics technologies and equipment.

The period covered by this report is the last six months of FY2005. Since there has been no report since a year ago, we will include some earlier material for the sake of completeness. Scientifically, good progress has been made on all of the major IUCF projects.

The Indiana group joined the STAR collaboration at RHIC for the purpose of addressing the problem of the origin of the spin of the proton. Experiments with deep inelastic scattering have demonstrated that only a small fraction (~ 20%) of the proton spin can be traced to net helicity preferences for quarks (both valence and sea) and antiquarks. The rest must lie elsewhere with either a spin alignment of the gluons whose exchange holds the quarks together or with relative angular momentum among the constituents of the proton. In order to obtain data on the gluon polarization, head-on collisions between two beams of polarized protons are required. Within those collisions, some events involve high momentum transfer encounters between a spin-aligned quark from one proton and a gluon from the other proton. Changes to the cross section for these events when both protons are spin aligned would be a signature of gluon polarization. Such events are most readily seen as the appearance of a high energy photon from the gluon and a jet (stream of subatomic particles) from the quark. In order to cover the region most likely to yield useful events, IUCF built an electro-magnetic calorimeter to be placed on one end of the STAR solenoidal tracking detector at RHIC. The calorimeter would be particularly sensitive to photons and uncharged pions (π^0), and the time projection chamber at the heart of the STAR detector would carry the information on the charged fragments of the jets.

For STAR, the 2005 running period was the first occasion to operate the fully commissioned endcap calorimeter. This was also the first run with a large enough integrated luminosity (~ 3 pb^{-1}) for polarized protons to make an assessment of the potential physics results. Analysis work has concentrated on the extraction of jets and π^0s as markers of quark-gluon collisions. Along the way it has been necessary to build software algorithms that can be used to characterize various events and to work toward the reduction of backgrounds arising from beam striking parts of the RHIC accelerator well away from the collision region. Even with only a fraction of the available data analyzed, it is already possible to rule out the most extreme models for the polarization of the gluons.

The main motivation for the construction of the STAR detector was to provide a base of data for the evaluation of the state of matter produced in the relativistic collision of two heavy ions. In such collisions, enough energy density is available to allow for the formation of a state of matter (quark-gluon plasma) that may have existed prior to the appearance of protons and neutrons at the time of the Big Bang. There are a number of signatures of such a state of matter. One that is being investigated at IUCF is the production of mesons such as the J/Ψ that contain heavy quarks. A quark-gluon plasma is expected to screen out such mesons. So, there should be a deficit of such mesons in comparison to proton-proton collisions where there is insufficient material to make such a state. Work at IUCF has been devoted to the extraction of J/Ψ spectra from heavy ion collisions. With a clear signal now available, comparisons between proton and heavy ion collisions are possible.

One of the most important physics discoveries of the last decade has been the observation that neutrinos have a small mass and can change from one type to another. From a number of experiments with neutrinos, we have learned the difference in masses, but not the masses themselves. One result in particular from the LSND experiment at Los Alamos National Laboratory suggests that there is an anomalous mass difference in the scheme, which might require the introduction of a fourth type of neutrino to the present list of three in the Standard Model of subatomic physics. The MiniBooNE project at Fermilab was initiated as a higher sensitivity crosscheck on the existence of these anomalous, short-range oscillations seen with LSND. The detector, a large tank of mineral oil doped with a scintillator, looks for the oscillation of muon neutrinos produced by the Fermilab Booster accelerator into electron neutrinos.

Data collection at MiniBooNE has been underway now for three years. In order not to prejudice the results in comparison to what was learned from LSND, candidate oscillations events have been masked from the analysis. Meanwhile, other event types are being studied and the detector performance is being calibrated. Neutrino quasi-elastic scattering from carbon has been analyzed and is in good agreement with theoretical simulations except at the very lowest energies. A similar result is obtained for the production of pions, which are sensitive to the presence of charged and neutral currents. Data taking will continue at least into the spring of 2006, at which point the collaboration expects to analyze the oscillation events and present a result that either confirms of refutes the LSND finding.

For the part of the Indiana group working with cold neutrons to study weak interactions, this has been a year of preparation. At Los Alamos, the group is commissioning an experiment that will combine longitudinally polarized neutrons with unpolarized protons to produce a deuteron and a photon. The longitudinal (along the beam direction) alignment of the neutron spin implies that any photon production asymmetry measured in the reaction must come from some process that violates parity (indicating a particular handedness in the universe). Such effects arise from the weak force that is responsible for the decay of many subatomic particles. A measure of the size of this spin effect would allow us to know the strength of the weak force under various conditions. So far, the group has measured upper limits (less than one part per million in all cases) for any parity-violating asymmetry associated with the materials that make up the experimental apparatus. This work will continue at Los Alamos until the liquid hydrogen target is ready for installation. In the longer term, it is no longer expected that LANSCE will be able to provide the flux of polarized neutrons needed for a definitive measurement of the weak force signal. So the apparatus will be moved in about two years to the Spallation Neutron Source now under construction at the Oak Ridge National Laboratory.

The cold neutron group is also preparing a separate experiment for the NIST reactor in Maryland. This will look for the rotation of the spin transverse direction of neutrons as they pass through a medium, in this case liquid ^{4}He. The phenomenon is similar to the birefringence of light. In this case, the rotation is again an artifact of the weak interaction, and can be used to constrain the strength of the weak force between nucleons. The target chamber, which required a very precise cancellation of any magnetic fields, has been constructed at IUCF along with the cryostats that will be used for the liquid helium. Detectors and sensors have been installed, and the apparatus will be shipped to NIST in early 2006.

The collaboration working on the measurement of the "little a" parameter in the decay of the neutron has received funding through an MRI grant. Their first activity was to produce a preliminary design report based heavily on simulations of the experiment. This is now being used as the basis for a full engineering design of the experiment. The apparatus, which observes the decay of neutrons passing through it, is designed to measure the degree of momentum correlation between the electron and the anti-neutrino that appear whenever the neutron decays. Such information can be used to check the validity and internal consistency of the Standard Model of the electroweak interaction, thereby testing the limits of validity of the Standard Model itself. The plan is to construct the apparatus at IUCF during 2006 and to use neutrons from the LENS facility to commission it. Then the apparatus will be moved to NIST where the larger flux of neutrons will provide a definitive measurement of this correlation parameter.

During the period of this report, results have continued to appear from the analysis of runs made with the Cooler ring in 2001 and 2002. The measurement of the absolute differential cross section for neutron-proton elastic scattering at 194 MeV was published. This experiment was originally motivated by the appearance of results from Uppsala that were larger than expected, suggesting a stronger force coupling between the nucleon and pion. The key feature of the IUCF experiment was the ability to tag each neutron used in the measurement, thereby making it possible to quote a cross section absolutely. The IUCF result was a set of cross sections lower than the Uppsala result and in good agreement with current models of the nucleon-nucleon interaction. In 2003, the positive results from the search for the charge symmetry breaking $dd \rightarrow \alpha\pi^0$ reaction were reported, initiating an intense theoretical effort to match these new cross sections with the systematics of effective field theory. Now, the analysis of deuteron-deuteron elastic scattering, performed at the same time as the charge symmetry breaking experiment, have become available to test a portion of the theory, the treatment of the wave functions that describe two deuterons initiating a reaction. This is also ground-breaking for the theorists, since broad range calculations of such a process have not existed previously. At present the cross sections are larger than the prediction, a result that makes the interpretation of the charge symmetry breaking experiment more difficult. The spin-dependent analyzing powers measured at the same time more nearly agree with the trends of the calculation.

The IUCF group continues to look to future experimental possibilities and the development of equipment to support those experiments. Neutrino experiments in particular require large volume detectors because of the small probability of neutrino interactions. The neutrino group has successfully tested the concept of an inexpensive detector that strings wavelength shifting fiber throughout the sensitive volume of a liquid scintillator to allow much better reconstruction of the precise location where a neutrino was detected and how the evolution of the light generated can be traced back to its parent process. Such a detector concept may also find applications for work with neutrons, or any place where large detector volumes are required. The group is presently seeking approval and funding to build a large-scale prototype detector with a full 3-dimensional fiber grid to determine performance characteristics under realistic conditions. This will hopefully lead to future funding for a full-scale detector to look at neutrino scattering from protons, a process that is sensitive to the contribution of strange quarks to the spin of the proton.

We look forward to the development of apparatus that will be involved in the search for an intrinsic electric dipole moment in nature. If the dipole moment is aligned along the spin direction of a fundamental particle, this combination violates both parity conservation and time-reversal symmetry. The latter violation may hold the key to the question of why the universe contains more matter than anti-matter and point to physics beyond the Standard Model. One aspect of this search will involve the bulk magnetization of garnet crystals exposed to an intense electric field. If an electric dipole moment exists on the electrons in the crystal, there are sufficient degrees of freedom to allow the electrons to reorient along the direction of the electric field. This would produce a simultaneous alignment of the electron's magnetic moment, and the appearance of such a field could be sensitively detected using squid magnetometers. Members of the Indiana group have also been involved with the development of a proposal to build a storage ring to search for an electric dipole moment on charged particles. In the ring, the motion of the particle beam through the field of the bending magnets creates a strong electric field in the frame of the moving beam. This field would cause the beam particle spins to precess, a result that could be detected with sensitive polarimeters. The deuteron is expected to be particularly sensitive to any electric dipole moment arising from quarks, and measurements of the spin sensitivity of deuterons scattering from carbon have been in progress at the KVI in Groningen to develop suitable polarimetry for such an electric dipole moment search.

During the past year, the Indiana group has also been active in educational and outreach efforts that are described in detail in the Contributions section of this report. The nuclear group has supported 5 post-docs, 14 graduate students, and several undergraduates as laboratory helpers and as participants in the REU program. A new IUCF Web site has come online that gives a much more complete picture of activities at the laboratory. This will be the starting point for additional efforts to share the physics output of IUCF and make contact with the public. Through these and many other means, the Indiana nuclear physics group has maintained its commitment to foster scientific education at the college and high school levels and to encourage people of diverse background to choose science as their career.