# Activities and Findings

This report covers NSF Award #0100348, which funded the research activities of the Indiana University Experimental Nuclear Physics group throughout the period 10/01/2001 to 11/30/2005. Annual progress reports covering the group's activities and findings during this period have been filed on 12/13/2002, 12/18/2003, 1/20/2005 and 1/06/2006 (the latter report covering activities carried out in part under Award #0100348 and in part under Award #0457219). We provide below a brief summary of the group's major research efforts and accomplishments during this period, referring the reader to the above Annual Reports for more detail.

## Major Research and Education Activities

The grant began during the latter stages of operation of the Indiana University Cyclotron Facility as a national user facility for basic research in intermediate-energy nuclear physics. It funded the staging and execution of the three final substantial experiments on the IUCF Cooler Ring, the analysis of the data collected in those experiments, and the transition of the group to outside-user research at other national accelerator facilities. The three final Cooler experiments were all highly successful, as described in more detail below:

- A search for the charge-symmetry-forbidden reaction $d+d \rightarrow \alpha+\pi^0$ near its threshold revealed a strikingly clear signal of symmetry violation [1] that attracted a great deal of notice and stimulated much theoretical work to interpret the violation.
- The use of a tagged neutron facility permitted measurement of absolute differential cross sections for neutron-proton elastic scattering to a precision ~±1.5%, and resolved significant discrepancies that plagued the database relevant to determination of the charged pion-nucleon-nucleon coupling constant [2].
- A systematic study of proton-deuteron elastic scattering, breakup and pion production with polarized beams and targets enormously expanded the database needed to constrain three-nucleon forces, revealing significant widespread deviations from state-of-the-art Faddeev calculations employing the best available nucleon-nucleon interactions [3].

The group's leadership roles in experiments at other laboratories followed three primary branches during the grant period:

- The study of nucleon spin structure via polarized proton collisions with the STAR detector at RHIC was launched, with strong contributions from the IU group in hardware (design, fabrication, installation and commissioning of an Endcap Electromagnetic Calorimeter) [4], software, data analysis [5] and intellectual leadership. The group also contributed significantly to aspects of the heavy-ion collision program at STAR.
- The MiniBooNE neutrino oscillation search [6] was launched at Fermilab, and collected the majority of data needed to confirm or refute the anomalous oscillation result reported by the LSND experiment at Los Alamos. The IU group

played special roles as Project Manager for detector installation and as data acquisition and trigger software leaders.

- Fundamental physics investigations with low-energy neutron beams spanned completion of a neutron lifetime measurement at NIST [7,8], precise measurement of few-body neutron coherent scattering lengths at NIST [9-11], and preparations for state-of-the-art experiments searching for parity violation in neutron-proton radiative capture (LANSCE) [12] and in neutron spin rotation in liquid $^4$He (NIST) [13]. The group also made major contributions to the design of a fundamental neutron physics beam line for the Spallation Neutron Source being constructed at Oak Ridge.

Graduate and undergraduate students and post-doctoral assistants were heavily involved in all the research directions mentioned above. During the grant period, this research resulted in 7 Ph.D. degrees from Indiana University. In addition, 18 post-docs received advanced training in experimental nuclear physics techniques. Approximately 20 undergraduate students (including summer REU students) were supervised on aspects of this work. The names of the students and post-docs are included in the Participants section of this report. We have worked in particular to extend our educational efforts to a more diverse cross section of students and post-docs. Of the 18 Post-docs who worked with us in this period, 3 are female and 1 a black African.

## Major Findings

## A. Cooler Research

**Charge Symmetry Breaking Revealed:** The total cross section for the forbidden reaction $d+d \rightarrow \alpha+\pi^0$ was measured near the production threshold by detecting the α-particle near 0° in a magnetic channel in coincidence with two photons in Pb-glass Cerenkov detector arrays. As seen in Fig. 1, the experiment revealed very clear peaks for the pion production, superimposed on a continuum from double radiative capture processes. The cleanliness of these spectra is in marked contrast to those from previous attempts to observe this symmetry-breaking process. Total cross sections were determined at two bombarding energies: 12.7 ± 2.2 pb at 228.5 MeV and 15.1 ± 3.1 pb at 231.8 MeV [1]. The symmetry breaking can arise from several sources tied ultimately to the up-down quark mass difference, including the isospin-mixing of pseudoscalar mesons and of vector mesons. A theoretical collaboration has been launched to provide a coherent chiral effective field theory framework for calculating the nuclear wave functions and reaction amplitudes needed to interpret the measured cross sections in terms of more fundamental parameters [14,15]. This measurement was one of the achievements cited in Physics News in 2003 [16] as well as one of the top 100 experiments in science for 2003 as chosen by the editors of Discover magazine [17].

Using the PINTEX detector system on the Cooler ring, the charge symmetry group also collected angular distributions of *d+d* elastic scattering (cross section and three analyzing powers) at 231.8 MeV. These data were compared with four-body calculations by

Antonio Fonseca. Thse calculations are also used to describe the entrance channel wave function for $d+d \rightarrow \alpha+\pi^0$ [15]. Present limitations on the angular momentum space cause an underestimate of the elastic cross section.

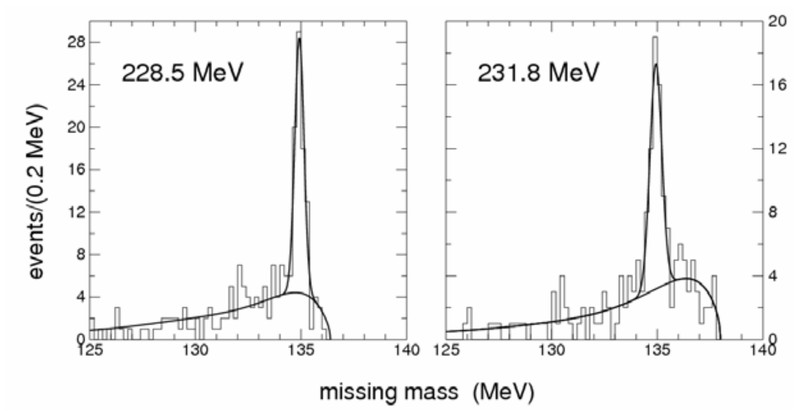



Figure 1. *Missing mass spectra reconstructed from the detected $^4He$ angle and energy in $d+d \rightarrow {}^4He+\gamma+\gamma$ coincidence events at two bombarding energies, in each case exhibiting a clear charge-symmetry violating $\pi^0$ peak above the double radiative capture continuum.*

**Neutron-Proton Elastic Scattering Discrepancies Resolved:** A tagged medium-energy neutron beam from the Cooler was used in a precise measurement of the absolute differential cross section for *np* back-scattering [2]. The results (see Fig. 2) resolve significant discrepancies within the *np* database concerning the angular dependence in this regime, and support the rejection of two recent *np* scattering experiments from the data set used in contemporary partial wave analyses. The tagged beam permitted careful control and study of systematic error sources, including plausible causes of the systematic problems encountered near $\theta_{CM}$=180° in other recent experiments, and allowed determination of the absolute cross section scale with ±1.5% uncertainty [18]. While the cross section scale agrees well with that suggested by the extensive Nijmegen partial wave analysis [19], there remain small systematic deviations in angular shape from the Nijmegen calculations (Fig. 2) that presumably reflect the need for fine-tuning of phase shifts.

**Three-Nucleon Forces Probed:** The unique capability of the Cooler to perform efficient measurements of multiple polarization observables with polarized beams bombarding internal polarized targets was exploited to vastly expand the database of spin measurements for *p+d* scattering, breakup and pion production. Such a systematic set of measurements may permit delineation of the spin-dependence of three-nucleon forces, revealed via deviations of the experimental results from Faddeev calculations employing state-of-the-art two-body forces. The results in Fig. 3 for various vector and tensor analyzing powers and beam-target spin correlation coefficients in *p+d* elastic scattering reveal widespread, sizable deviations from Faddeev calculations. They also reveal that the widely used Tucson-Melbourne model three-nucleon potentials can semi-quantitatively explain only some of the observed deviations. Comparison with this body of data will provide a legacy benchmark from the IUCF Cooler for anticipated future theoretical (*e.g.,* chiral effective interaction) treatments of three-nucleon forces.

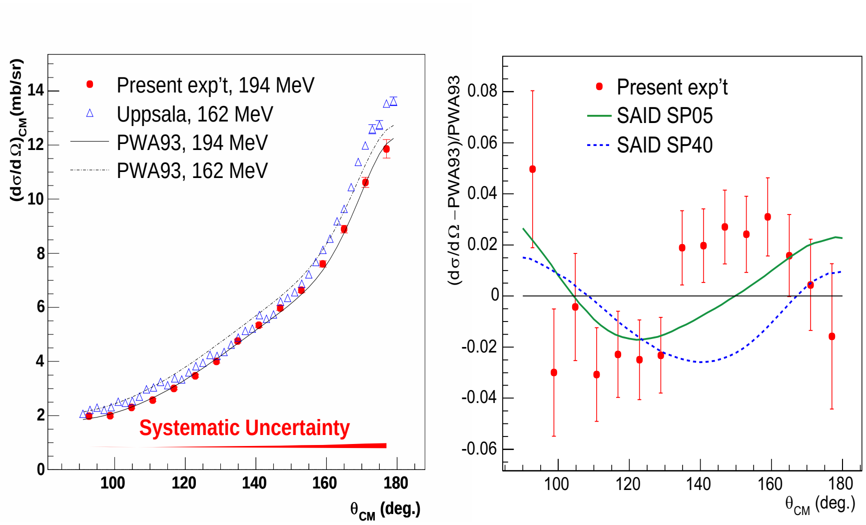
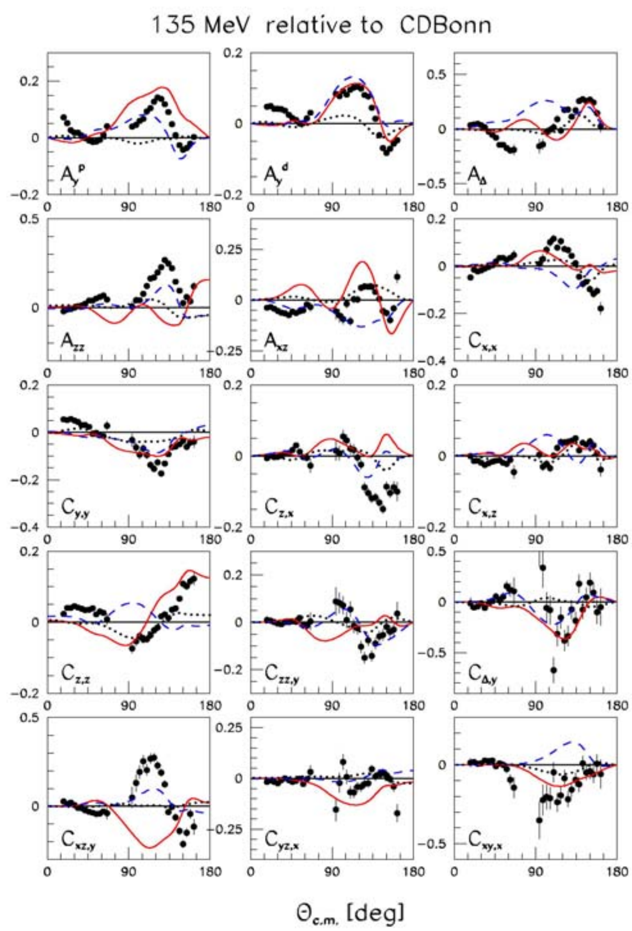



Figure 2. *Absolute differential cross sections for np backscattering measured in the tagged neutron experiment [18], compared with: (left frame) data from Ref. [20] and partial-wave analyses [19] at the two relevant energies; (right frame) three different partial-wave analyses at 194 MeV, all presented via their relative deviations from the Nijmegen prediction [19]. Only the SP05 global analysis included the present data in the fitted database.*

Figure 3. *The difference between spin observables measured for p+d elastic scattering at 135 MeV and a reference Faddeev calculation (i.e., the zero line) by the Bochum group [21] based on the CD Bonn NN potential. The solid and dashed lines show the effect of including the Tucson-Melbourne TM and TM′ three-nucleon potentials, respectively. The dotted line is a Faddeev calculation with the AV18 NN potential plotted relative to the CD Bonn reference.*



## B. Polarized Proton and Heavy-Ion Collision Studies with STAR at RHIC

**Endcap ElectroMagnetic Calorimeter (EEMC) Commissioned:** The EEMC is a lead-plastic scintillator sampling calorimeter [4] designed to provide the STAR detector at RHIC with coverage crucial to the extraction of gluon polarization from polarized proton collisions, in the Bjorken *x*-range where the dominant fraction of the overall gluon contribution to proton spin is anticipated. The IU group led a 7-institution collaboration in the design, fabrication, installation and commissioning of this 30-ton detector. Installation in STAR was completed in Fall 2004 (see Fig. 4), and the detector was fully commissioned during the ensuing 2005 RHIC run. Throughout that run, the 10000 readout channels of the EEMC operated with > 99% reliability, permitting use of the detector to extract important physics. As one example from the 2005 run, we are currently analyzing the two-spin asymmetry for inclusive production of $\pi^0$'s in the endcap region with longitudinally polarized proton beams (see spectrum in Fig. 4), a signal sensitive to the gluon polarization inside a polarized proton.

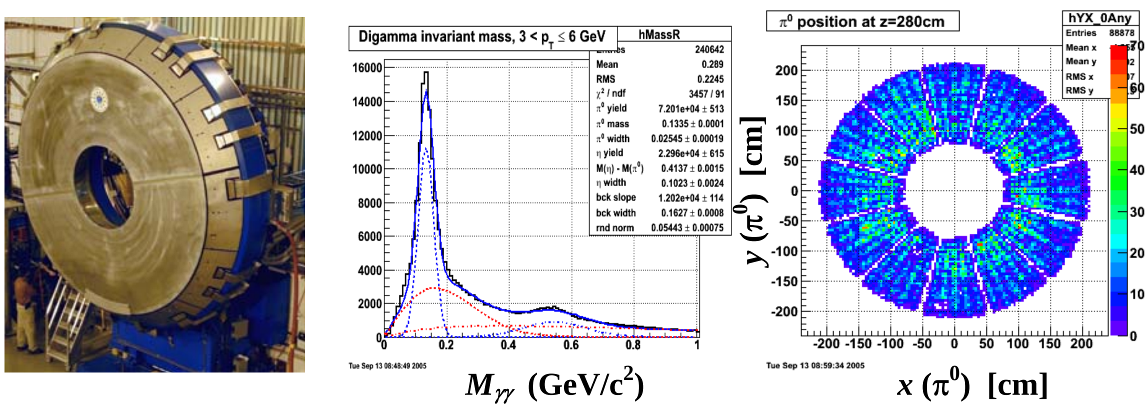



Figure 4. *The STAR Endcap Electromagnetic Calorimeter and data obtained with it during the 2005 RHIC run. The left frame shows the calorimeter mounted on the STAR west magnet poletip. The phototubes and readout electronics are mounted on the rear side of the poletip. The middle frame shows an invariant mass spectrum reconstructed from pairs of photons detected in the EEMC, with prominent $\pi^0$ and $\eta$-meson peaks. The right frame shows the 2-dimensional locus of reconstructed $\pi^0$ positions on the endcap, revealing that nearly all readout channels were working reliably during the 2005 run.*

**Sizable Spin Effects Observed in Region Tractable via Perturbative QCD (pQCD):** One of the major initial questions facing the RHIC spin program is whether the reaction channels of interest for probing nucleon spin structure are tractable in low-order pQCD, and if so, whether substantial spin effects would be observed. This issue was partially addressed in the earliest polarized proton collision runs (2002-3) at RHIC, with the measurement of single-spin transverse asymmetries for inclusive forward (high pseudo-rapidity) $\pi^0$ production. The measurements utilized a prototype of the EEMC mounted as a forward pion detector in STAR, and the analysis was led by an IU post-doc (Greg Rakness). The results [5] (see Fig. 5) reveal differential cross sections that are well described by next-leading-order pQCD calculations down to surprisingly low transverse momenta, and large spin asymmetries strongly reminiscent of measurements from

Fermilab [22] at center-of-mass energies an order of magnitude lower, where pQCD could not account for the measured cross sections. The origin of the asymmetries is generally attributed to some mixture of spin-transverse momentum correlations in the incident proton wave function and in jet fragmentation, combined with higher-twist QCD contributions. The relative roles of these different effects will be probed soon in coincidence measurements.

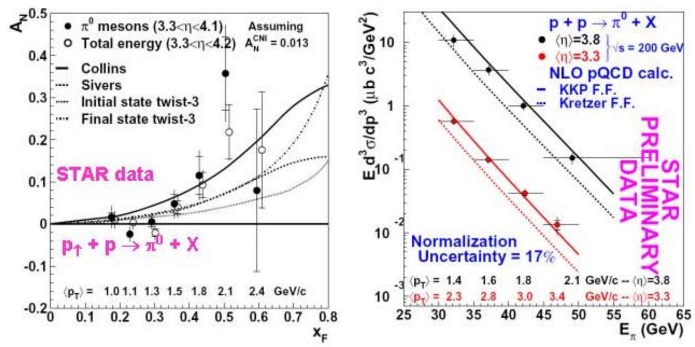



Figure 5. *STAR results for analyzing power and absolute differential cross section of forward $\pi^0$ production in $\sqrt{s}$=200 GeV p+p collisions, compared to pQCD calculations employing different prescriptions for fragmentation functions and for generating transverse spin-dependence [5]. Results are plotted as a function of $x_F \approx E_\pi$ /100 GeV. For fixed detector location, $p_T$ and $x_F$ are correlated as shown on bottom axis.*

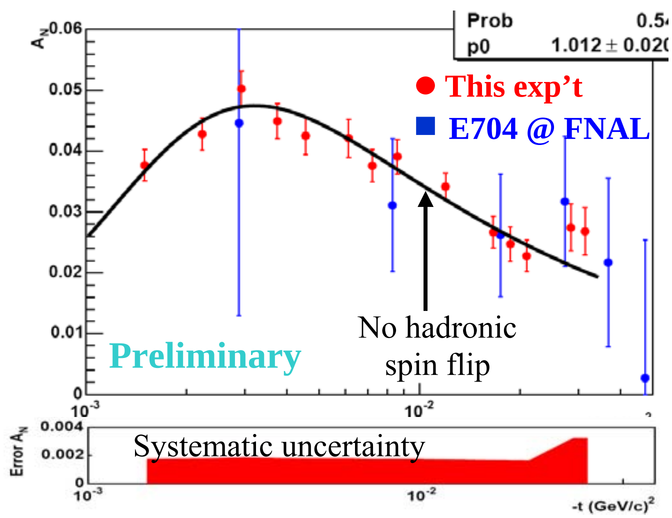



Figure 6. *Preliminary results of the RHIC beam polarization calibration experiment, performed with a 100 GeV polarized proton beam colliding with a fixed polarized gas jet target. The measured quantity is the absolute transverse analyzing power $A_N$, plotted as a function of 4-momentum transfer –t in the Coulomb-nuclear interference region. The results are compared to lower-energy measurements from Fermilab and to theoretical predictions incorporating the electromagnetic, but no hadronic, spin-flip amplitude.*

**RHIC Beam Polarization Calibrated:** A challenge for making spin measurements in a completely new energy regime is to provide a theoretically and experimentally robust method to calibrate the beam polarizations absolutely. The IU group has participated in an experiment at RHIC to do this via measurements of *pp* scattering in the Coulomb-nuclear interference (CNI) region with a polarized beam impinging on a fixed internal polarized hydrogen gas jet target (designed by the University of Wisconsin). The analyzing power associated with beam spin-flip is then equal to that associated with target spin-flip, by the indistinguishability of the two protons. This allows calibration of the beam polarization against the independently measured target polarization. The experiment was mounted at RHIC in 2004, and provided the preliminary results shown in Fig. 6. Further data has been acquired in 2005, and it is expected that these measurements will allow absolute calibration of the proton-carbon CNI polarimeters used in every polarized proton fill at RHIC to a precision of ±5%.

**Near-Perfect Liquid Formed in Relativistic Heavy-Ion Collisions:** The STAR experiment, among others at RHIC, has provided seminal measurements revealing the unique properties of the strongly interacting matter formed in the early stages of nearly head-on relativistic heavy-ion collisions. The flow patterns in the momentum spectra of the many soft emitted charged hadrons – especially the quadrupole component, or so-called "elliptic flow" – are quite consistent with hydrodynamic expectations for an ideal relativistic fluid expanding from a small, rapidly thermalized source formed with azimuthally anisotropic pressure gradients. The rapid attainment of full or nearly full thermal equilibrium is further suggested by the relative yields of different hadrons, containing *u, d* and *s* valence quarks. Hadrons of higher transverse momentum are characterized by saturation of the elliptic flow, but at different values for mesons *vs.* baryons, consistent with an important production mechanism being the recombination of quarks from a thermal bath. The yield of, and correlations among, high transverse momentum hadrons demonstrate that the matter is nearly opaque to quarks and gluons, although quite transparent to high-energy photons. These features (see Fig. 7), taken together, point to matter that evolves for a significant fraction of its lifetime as a *low-viscosity, pre-hadronic liquid*, quite different from the ideal gas of non-interacting quarks and gluons many theorists originally predicted. The liquid appears to be the most nearly perfect – as measured by the ratio of viscosity to entropy density – ever formed.

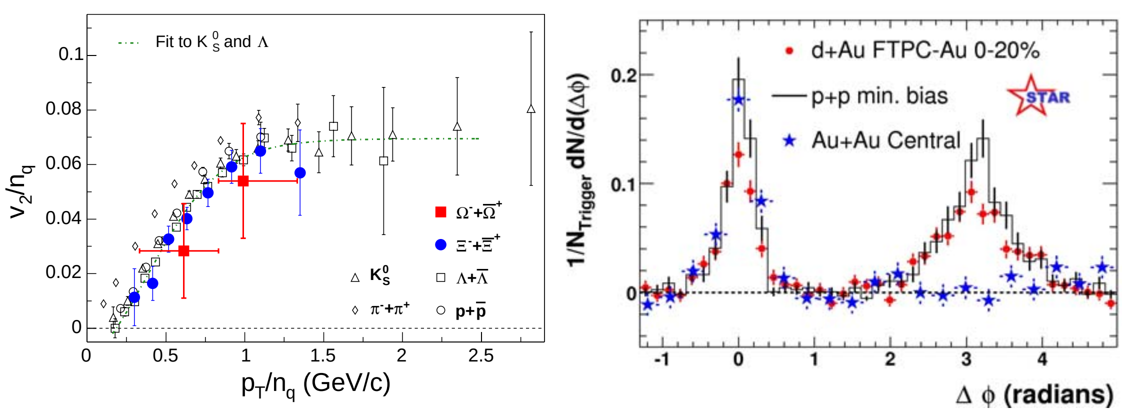


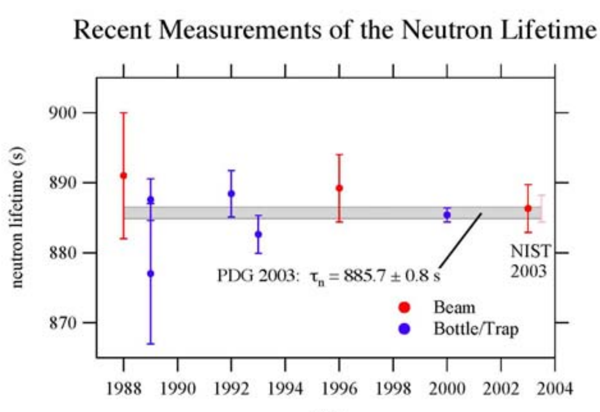

Figure 7. *Some of the STAR collision data delineating unique properties of the hot strongly interacting matter formed in near-central Au+Au collisions. The left frame shows elliptic flow results for many different hadron species as a function of transverse momentum, with both flow and momentum scaled by the number of valence quarks in the detected hadron. Below 1 GeV/quark, the measurements are quite consistent with hydrodynamics calculations for an ideal relativistic liquid (not shown); above 1 GeV/quark, they reveal a saturation behavior whose scaling with number of quarks is suggestive of recombination of quarks from a thermal bath. The right frame shows di-hadron azimuthal angle correlations measured for high-$p_T$ hadron pairs in p+p, d+Au and central Au+Au collisions. The correlations exhibit a clear jet structure, but with the away-side ($\Delta\phi \simeq \pi$) jet accompanying a high-$p_T$ trigger particle disappearing for central Au+Au. This disappearance reflects the opacity of the matter to partons, and is attributed to parton energy loss in a medium of high gluon density.*

While the efforts of the IU group in STAR are not focused primarily on heavy-ion collisions, we nevertheless led the preparation of a long review paper [23] summarizing and interpreting STAR findings, and assessing the evidence for formation of a quark-gluon plasma. Along with similar papers from the other three RHIC collaborations [24-26], this paper led to the announcement by RHIC in April 2005 of the discovery of this near-perfect strongly interacting liquid state. This discovery was named the top Physics News story of 2005 [16].

### C. Low-Energy Neutron Interactions

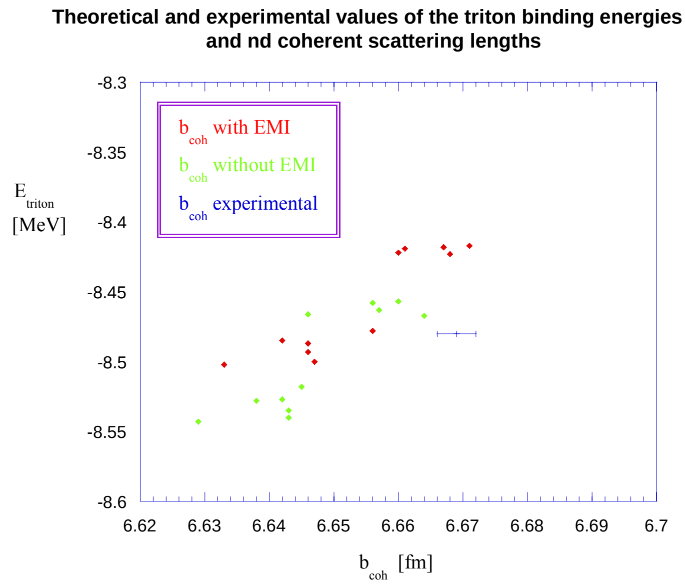
**Neutron Decay Lifetime Confirmed:** The neutron lifetime $\tau$ is important for weak interaction theory, where it helps to determine the CKM matrix element $V_{ud}$, and also as input for Big Bang nucleosynthesis (BBN) calculations of $^4$He abundance [27]. The 2.2 $\sigma$ deviation from unitarity for the CKM matrix using the Particle Data Group (PDG) value of $V_{ud}$ from $0^+$ to $0^+$ nuclear decays [28] has motivated a number of new measurements to determine $V_{ud}$ and $V_{us}$ from neutron and kaon particle decays, and the current experimental situation is in a period of rapid flux [29]. We recently completed a precision measurement of the neutron lifetime using a proton trap at NIST [7,8]. The fluence from a highly collimated cold neutron beam was continuously monitored while the decay protons were trapped and subsequently counted. The result $\tau$ = 886.8±3.4 s represents the most precise measurement of $\tau$ via an in-beam technique. It is in good agreement with the world average (see Fig. 8) as compiled by the PDG [30], which is dominated by bottle-type measurements using ultracold neutrons. The agreement is particularly significant because these two experimental techniques have very different systematic uncertainties. We are currently working to reduce the error on the new measurement to approximately 2 seconds by improving the calibration of the neutron flux monitor used in the experiment with a cryogenic neutron radiometer.

Figure 8. *Recent history of neutron lifetime measurements using in-beam methods (red symbols) and ultracold neutron traps (blue), including the current NIST result.*




**Precise Coherent Neutron Scattering Lengths Test Few-Body Theory:** Recent advances in effective field theories and Monte Carlo calculation techniques facilitate calculation of neutron scattering lengths for few-nucleon systems from first principles with experimental input from the NN system. We used the new neutron interferometer facility at NIST to conduct high precision measurements of coherent scattering lengths to test these theories in the low-energy limit. For example, the results from measurements at NIST of the *n-p* ($b_{np} = -3.738 \pm 0.002$ fm) and *n-d* ($b_{nd} = 6.665 \pm 0.004$ fm) coherent scattering lengths [10] show serious discrepancies (see Fig. 9) between almost all existing n-d calculations and the present measurements, which are now sufficiently precise to sense possible three-body force and charge symmetry-breaking effects. Similar discrepancies from the best existing calculations have been found for *n*-$^3$He [10, 31].

Figure 9. *Calculations of the triton binding energy and the n-d coherent neutron scattering length with a variety of modern NN and 3N potentials and with and without electromagnetic effects (EMI). None of the models match the data (horizontal error bar) from Refs. [9,10].*




**Preparations for the *np* → *dγ* Parity Violation Search Completed:** Non-leptonic weak interactions among *u* and *d* quarks at low energy are not yet understood because they are trapped in hadrons where strong QCD takes over. The interactions are often expressed in terms of effective weak meson-nucleon couplings. The NPDGamma Collaboration has planned a high-precision measurement of the parity-violating photon asymmetry in the radiative capture of polarized neutrons on protons to measure the most poorly known of these effective couplings, that associated with pion exchange [12]. The IU group has provided the current-mode CsI photon detectors and the high-power liquid hydrogen target needed for this experiment, as well as considerable work on studying systematic error limits. The CsI array was delivered to LANSCE in 2003, and construction of most of the infrastructure for the testing and installation of the $LH_2$ target was completed in September 2005. In parallel with these technical developments, the collaboration has used the existing apparatus to search for parity-violating gamma asymmetries in a series of A~50 nuclei. The scientific motivation is to test the statistical theory of parity violation developed by the TRIPLE collaboration [32] for interpreting epithermal neutron resonances in A~100 and A~240 nuclei in a new mass regime. Preliminary experimental results, along with theoretical predictions, for medium-mass nuclei are given in the table below. After initial measurements at LANSCE in 2006, it is anticipated that the NPDGamma experiment will move to the new fundamental neutron physics beamline at SNS for whose design the IU group has played a major role.

| nucleus | Theory RMS PV asymmetry | Experiment RMS PV asymmetry | Error on RMS PV asymmetry |
|---|---|---|---|
| $^{45}$Sc | $1.6 \times 10^{-7}$ | $-7 \times 10^{-7}$ | $3 \times 10^{-7}$ |
| $^{48}$Ti | $2.3 \times 10^{-7}$ | $+7 \times 10^{-7}$ | $4 \times 10^{-7}$ |
| $^{55}$Mn | $1.3 \times 10^{-7}$ | $+5 \times 10^{-7}$ | $8 \times 10^{-7}$ |
| $^{59}$Co | $1.6 \times 10^{-7}$ | $+6 \times 10^{-7}$ | $3 \times 10^{-7}$ |
| $^{51}$V | $1.3 \times 10^{-7}$ | Under analysis | |

## D. Neutrino Research:

**MiniBooNE Test of Anomalous Neutrino Oscillations Nearing Definitive Stage:** The evidence for three generations of weakly interacting neutrinos, whose interaction eigenstates are admixtures of the corresponding mass eigenstates, is by now well established. This picture cannot accommodate the positive $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation signal reported by the LSND experiment [33] in a higher range of mass-squared differences, $\Delta m^2 \sim 0.1$—1 eV$^2$ than other accepted neutrino oscillation signals. The MiniBooNE experiment, utilizing beams from the Fermilab Booster Ring to explore the same $\Delta m^2$ region, has been commissioned and collected most of the integrated luminosity needed for a definitive test of the LSND result during this grant period. The IU group made critical contributions to MiniBooNE in managing the detector installation, writing the data acquisition and triggering software, making performance measurements to optimize the choice of mineral oil liquid scintillator, and developing the slow monitoring system for the experiment. While analysis of the $\nu_\mu \rightarrow \nu_e$ oscillation channel is "blinded", with a result anticipated for 2006, preliminary results for various neutrino scattering channels are becoming available. Figure 10 shows, in particular, comparisons of measurements and simulations for charged-current quasielastic scattering $(\nu_\mu C \rightarrow \mu^- X)$ and neutral-current $\pi^0$ production $(\nu_\mu C \rightarrow \nu_\mu \pi^0 X)$.

**Novel Tracking Detector for Neutrino Scattering Designed:** A detector has been designed to reconstruct the tracks of recoil protons of 100-500 MeV kinetic energy produced in neutral-current interactions by ~1 GeV neutrinos. This would open the possibility of a definitive measurement of the nucleon's axial form factor, and thereby, of the net contribution of strange and anti-strange quarks to the spin of the nucleon [34]. The proposed detector consists of a light-tight container filled with ~10 tons of mineral-oil-based liquid scintillator. Scintillation light from the ~10 cm long recoil proton tracks would be collected and guided to phototubes by a three-dimensional grid of wavelength-shifting optical fibers embedded in the liquid, as illustrated in Fig. 11. A proof of principle for the detector concept was made with a small prototype containing fibers running in only one direction, subjected to 200 MeV proton beam from the IUCF cyclotron entering the detector along an axis transverse to the fibers. This prototype provided position (3.0 mm) and angular (3.5°) resolution for the proton tracks in good agreement with simulations of the light production, propagation and detection processes. The next stage in developing this concept for use in both neutrino and neutron scattering experiments requires construction and testing of a sizable (~ 50 $cm^3$) prototype with full 3-dimensional fiber grid.

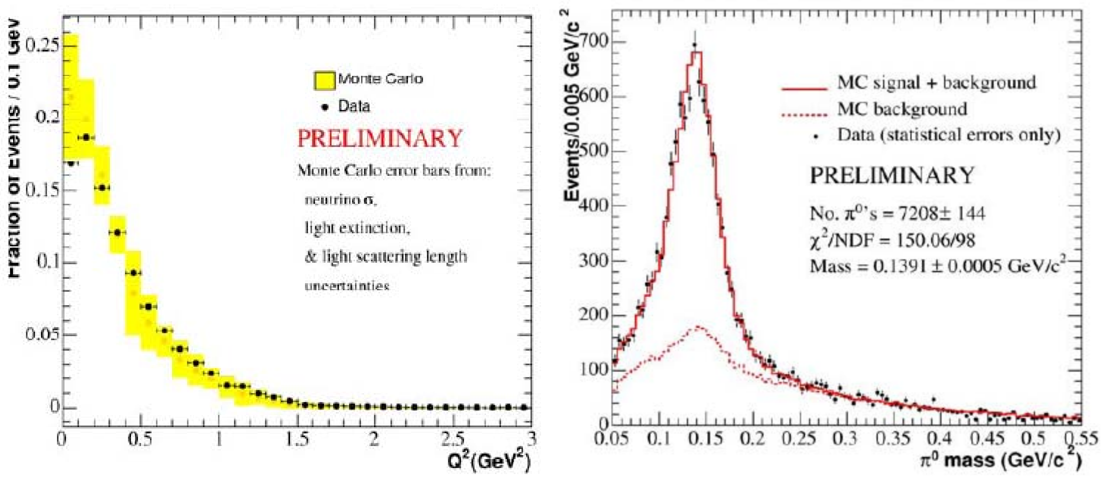
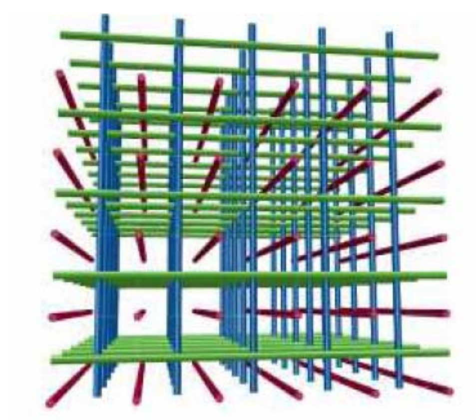



Figure 10. *Comparisons of preliminary MiniBooNE data to Monte-Carlo simulations for charged-current quasielastic events (left frame) and for $\pi^0$ invariant mass reconstruction in neutral current events (right frame).*

Figure 11. *Schematic layout of the 3-dimensional readout fiber grid proposed for a tracking detector in moderate-energy neutral current neutrino-nucleon scattering experiments. The fibers would be embedded in a liquid scintillator tank and would collect and carry scintillation light to external photo-tubes to permit reconstruction of ~10 cm long recoil proton tracks.*



## E. Other Research

**Deuteron EDM Polarimetry:** A proposal has been made [35] to search for the electric dipole moment of a charged particle by looking for the precession caused by the large electric field (from **v×B**) that appears in the particle frame when the particles circulate in a storage ring. By adding a radial electric field to the ring, the precession due to the anomalous magnetic moment can be brought almost to a halt, allowing polarization that is initially along the direction of the velocity to rotate slowly into the vertical direction. Particles with small anomalous moments are preferred, so the deuteron is an excellent candidate (a = –0.14). The particles must be scattered in order to determine their polarization. Data for the design of a highly efficient (~1%) polarimeter required new deuteron-Carbon elastic scattering data in the energy regime from 70 to 130 MeV. The data, shown in Fig. 12, were measured with the Big-Bite Spectrometer and an array of NaI detectors at the KVI in Groningen, the Netherlands. The vector analyzing power rises quickly with angle, generating high figure-of-merit values in the range from 10º to 30º.

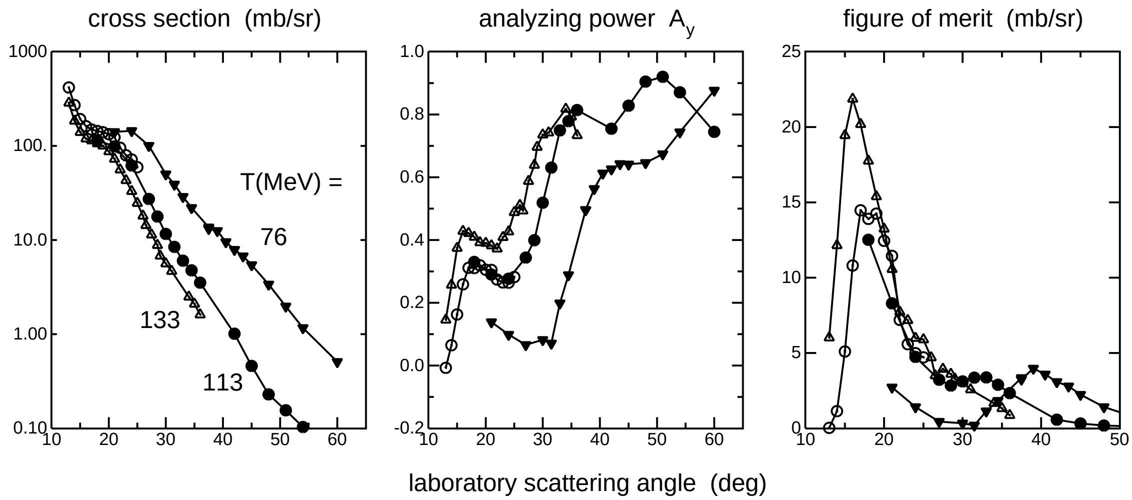



Figure 12. *Angular distribution measurements of deuteron-Carbon elastic scattering at 76, 113, and 133 MeV, showing the cross section and vector analyzing power $A_y$. The right-hand panel shows the figure of merit (=$\sigma A_y^2$) out to 50º.*

## Training and Development Opportunities

The research carried out by the group has been central to the training of approximately 21 graduate students, 20 undergraduate students and 18 post-doctoral workers during the period of this grant. These young scientists were trained in a broad cross section of the techniques and skills needed in experimental science. They were given opportunities to participate in, and in some cases to lead: (1) forefront basic research on the strong and weak interactions of nucleons and nuclei; (2) development of innovative hardware, such as the STAR Endcap Electromagnetic Calorimeter; the scintillator bath neutrino detector concept; state-of-the-art fast readout electronics; the precise magnetic shielding needed for the NIST neutron spin rotation test of parity violation; and (3) application of contemporary computational resources to the multi-dimensional analysis of complex data sets of quite large volume. They were exposed to the modes of collaboration in projects requiring teams of anywhere from several to several hundred scientists. They received training in the written and oral organization and presentation of results to audiences large and small. Above all, they were trained in the problem solving, critical thinking and professional skepticism essential to achieving breakthroughs in a wide range of endeavors.

The transition during the period of this grant from research centered on the local facilities to the current outside user mode has presented new challenges in graduate recruitment.

The group has worked very hard to advertise the new opportunities in Nuclear Physics at IU and this is beginning to pay dividends. As part of this effort the group has played a major role in graduate student recruitment, with Mike Snow in particular providing the driving force behind vigorous and extensive new recruiting efforts by the IU Physics Department as a whole. An important part of our recruitment efforts is the annual Graduate Student Visitation Day, where students who have been admitted to the program, but have not yet accepted our offer, are invited to spend a day visiting the Physics Department, with half the time spent at IUCF, culminating in an informal reception at IUCF with prospective students mixing with faculty and staff. Offers have been made to all qualified minority and female applicants, though we expect our success rate in attracting these candidates to improve markedly with our recent hire of minority and female faculty members in nuclear physics.

Both past and present graduate students from the group have received several special awards during the past four-year period. Todd Peterson, who received his Ph.D. in 2000 for the development of the tagged neutron facility at the IUCF Cooler, went on to exploit the experience he gained in state-of-the-art solid-state detector technology in a post-doctoral appointment with a medical imaging group at the University of Arizona. His research there and his potential earned him one of a few nationally awarded Burroughs-Wellcome Fund Career Awards at the Scientific Interface, carrying $0.5M of research support starting in 2002. Peterson has since gone on to a faculty position in Bio-Engineering at Vanderbilt University, where he is using his training in experimental nuclear physics to develop miniaturized detectors for *in vivo* medical imaging. In more recent achievements, Mike Gericke was awarded the William Koss award for the best overall graduate student in the IU Physics department in 2004, and was also nominated for an IEEE Radiation Instrumentation Early Career award. Mike was awarded a certificate for outstanding achievement and was invited to Rome to receive this. Dan Hussey was selected to attend the DOE Nobel Laureate Conference in Lindau, Germany and also received a National Research Council post-doctoral award.

The nuclear physics faculty and staff are equally dedicated to providing undergraduates with research and technical training, in order to instill in them the excitement of discovery at a critical time in their careers. This includes undergraduates both from Indiana University and from other institutions through several programs. About 10 IU physics and chemistry undergrads are involved each year in research and development activities at IUCF. After graduation typically half of these students enter graduate school in physics/chemistry or some other scientific field. One recent example is Sara Breitzmann who worked with the IUCF neutrino group in 2001-2002. Working with H.-O. Meyer, she measured the solubility of gases in the MiniBooNE mineral oil, leading to a MiniBooNE technical note and presentation to the Collaboration. She has gone on to graduate studies in accelerator physics with S.Y. Lee at IU.

IUCF also hosts a very successful NSF-REU program. Each year, about a dozen undergraduate physics majors, mainly from schools outside IU, are selected from a pool of about 50 applicants. They spend 10 weeks at IUCF working on individual research projects with a member of the IUCF faculty or staff. In addition to fundamental research in nuclear physics and accelerator physics, these projects include interdisciplinary research activities in medical physics and radiation effects. Examples of REU projects from the most recent summers are the design and implementation of magnetic shielding for the neutron spin rotation experiment and development of a 3D magnetic field mapping system. Each year, several of our REU students are selected to present a poster about their research at the Fall Meeting of the DNP as part of the Conference Experience for Undergraduates (CEU) activity. This program is now in its seventeenth year of operation with over 240 alumnae (28% of whom are female). The NSF-REU program will continue in the future as a joint REU site that includes both IUCF and the IU Physics Department, with 7-8 students working on projects at IUCF each year.

The grant typically supports five post-docs. During 2005, two of these were female and one was a black male. Post-doctoral associates are encouraged to work on more than one project and to broaden their background and experience in preparation for future employment in physics research. At the end of their first year each post-doc has an extensive interview with three members of the group, who review the post-doc's work and discuss potential career paths. Beginning in 2003 the group decided to offer one special post-doctoral position occasionally, named in honor of Larry Langer, who performed pioneering research at IU on beta decay and neutrino mass measurements. This position offers a higher salary and an allowance for research to encourage especially promising candidates at an early point in their career. The first Langer post-doctoral fellow, Chris Polly (Ph.D. from Illinois on the muon g-2 experiment), is currently working under Rex Tayloe's supervision on the MiniBooNE experiment at Fermilab.

In addition to our training of recent and soon-to-be Ph.D.'s, the group's research efforts and willingness to take on major equipment development projects on which we have limited past experience (*e.g.,* the STAR Endcap ElectroMagnetic Calorimeter, EEMC) have afforded IUCF professional and technical staff members the opportunity to expand their own horizons and receive updated training in state-of-the-art techniques. One recent example is Bill Lozowski, the laboratory's highly skilled target maker, who has expanded his expertise to include cryogenic systems by leading the technical design and development of the high-power liquid para-hydrogen target for the NPDGamma experiment at LANSCE. Another is Gerard Visser, the laboratory's electronics engineer, who had the opportunity to design a state-of-the-art fast, low-noise digitization system for readout of the EEMC. A third is John Puskar-Pasewicz, a young mechanical engineer who cut his teeth (before moving on to another position) on the design and construction of the intricate (and successful) mechanical assembly of the EEMC.

In all these ways, we have made a significant contribution to the development of a highly skilled and diverse technical workforce for the U.S.

## Outreach Activities

The members of the group each devote a small fraction of their time to outreach activities aimed at explaining what we do, and how it affects their lives, to members of our local community, K-12 students and other occupants of the Indiana University campus. The impressive infrastructure at IUCF is a great attraction for tours from middle and high schools. It also plays an important part in the annual Physics and Astronomy Open House. Tours are provided throughout the year and are frequently conducted by faculty, post-docs and students from the nuclear physics group.

Since former IUCF Director Paul Singh launched it, the NPR program *A Moment of Science* (AMOS) has gone on to produce more than 2875 programs on a wide spectrum of topics, telling us where science touches our lives in ways both unexpected and amusing. This general science program is aimed at connecting common observations to the science principles that govern them, in ways that can be explained quickly with little reference to prior knowledge. About 260 programs are produced each year for distribution to some 70 NPR radio stations. Mike Snow is currently developing several topics in subatomic physics for AMOS, including: (1) You are made of unstable matter; (2) Matter is *very* close to electrically neutral; (3) All atoms of the same type are absolutely identical; (4) Why do we think the universe is expanding? (5) Where is the antimatter? For example, in the first of these Mike points out that almost all our mass is in protons and neutrons, and then asks why we don't just fall apart, given that free neutrons only live for about 15 minutes.

Members of the nuclear physics faculty participate in a number of programs aimed at establishing direct connections with pre-college students, to improve participation and retention in science and engineering. The College of Arts and Sciences Summer Pre-college Institute is directed at eleventh- and twelfth-graders looking to get an early taste of the university by working with an IU professor on a summer project. We have hosted several students from this program. One worked with Rex Tayloe on a neutrino detector project, wrote a report, and presented a seminar at IUCF. This student later decided to enroll in physics at IU and is now in the Honors Physics (undergraduate) program and is an IU STARS (Science, Technology, and Research Scholars) awardee, working with Rex Tayloe. Tayloe has also been the faculty liaison for the past two years for the IU Advanced College Project, a partnership between IU and select high schools in Indiana, Ohio, and Michigan. This program offers college credit for high school seniors who take Introductory Physics (P221) with their high school physics teacher. An IU faculty member oversees the program, trains the teachers and conducts annual site visits to the participating schools. New teachers are trained in a summer workshop and all teachers attend an annual workshop, both held on the IU-Bloomington campus. The workshops also offer an opportunity for the teachers to learn about research in the Physics Department and at IUCF. Several members of the group also help with the Science Olympiad, a yearly competition for high school students eager to meet challenges in all areas of science and technology.

We are also working to improve communications about what we do with the rest of the largely liberal-arts campus on which we reside. High-profile research efforts of the nuclear physics group have been occasionally described at a suitable lay level in the IU College of Arts and Sciences quarterly glossy magazine, *Research and Creative Activity*. A recent issue highlighted our research in the STAR Collaboration, both on the search for a state of matter believed to have last existed in the earliest infancy of the universe and on our attempts to understand what makes the proton spin. Meanwhile, Hans Meyer is taking advantage of the time students (with many different majors) wait in the Physics building between classes, to introduce them to what we do by using display space in the main hallway outside the large lecture halls to showcase our research areas in a series of colorful, inviting posters.

Members of the Nuclear Physics group have long been among the most active IU faculty in organizing our annual Physics Department Open House, which typically attracts ~1000 visitors from the local community and from high schools around the state of Indiana. An outgrowth of these annual Open Houses was the establishment by Catherine Olmer (a former co-Principal Investigator on the Experimental Nuclear Physics grant) and others of WonderLab, a Bloomington science museum aimed at young children. The museum is highly successful and attracts close to 100,000 visitors per year. Several group members have donated significant amounts of time over the past several years to helping to set up and man WonderLab programs.

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# Contributions

**Contributions to Principal Discipline:** As outlined in the Major Findings section above, the group's research accomplishments throughout the grant period had significant impact within the field of nuclear physics, and more broadly in science. Two of the results for which the IU group were leaders or prominent contributors (charge symmetry violation in $dd \to \alpha\pi^0$ and the RHIC collision results leading to the discovery of "perfect liquid" behavior) were selected among the top Physics News stories of their respective years, and were featured prominently among the top 100 science stories of the year selected by Discover Magazine. A number of the results represent "first" measurements of their type (*e.g.*, spin correlations in three-nucleon scattering processes, hadronic polarization measurements in the perturbative QCD regime), and others represent the achievement of unprecedented levels of sensitivity (*e.g.*, the observation of $dd \to \alpha\pi^0$) or precision (*e.g.*, on absolute *np* scattering cross sections and coherent neutron scattering lengths). We designed and constructed innovative detectors for nuclear and particle physics, and exploited novel techniques we'd earlier developed on the IUCF Cooler ring.

Members of the group have played important leadership roles in large national collaborations. Steve Vigdor served during most of the grant period as Deputy Spokesman for the STAR Collaboration, while Will Jacobs was Project Manager for the Endcap Calorimeter project. Rex Tayloe was Project Manager for the MiniBooNE detector installation at Fermilab, and leader of the development team for MiniBooNE data acquisition and triggering software. Mike Snow has been a leader of the national effort to install a Fundamental Neutron Physics beamline at the Spallation Neutron Source at Oak Ridge, a project now under way. Many group members have devoted considerable effort to work on various major review and advisory committees within our field.

**Contributions to Other Disciplines of Science or Engineering:** The facilities developed at IUCF for basic nuclear physics research have now been adapted to a much broader set of missions. The cyclotrons are currently used for proton radiation therapy of cancer patients at the Midwest Proton Radiotherapy Institute (MPRI), and for prototype tests of radiation sensitivity in solid-state devices to be flown on space flights. John Cameron led the development of facilities for both of these missions. The ion source and pre-injector for the Cooler ring are being re-commissioned to provide a Low-Energy Neutron Source (LENS) intended for a combination of: soft condensed matter and biophysics investigations via neutron scattering; development of fundamental nuclear physics experiments (such as a precise measurement of neutron beta-decay correlations to pin down the quark mixing matrix element $V_{ud}$); and development of state-of-the-art neutron beam production techniques (*e.g.,* ultra-cold neutron beams generated with a solid oxygen moderator) and scattering detectors (*e.g.,* a Spin-Echo Small-Angle Neutron Spectrometer) ultimately to be deployed at the Spallation Neutron Source (SNS) at Oak Ridge, Tennessee. It is envisioned that the LENS facility at IUCF will also provide a training center for eventual SNS users spanning a wide range of disciplines. The concept for LENS originated with Mike Snow, and he remains a very active participant in that (separately funded) development.

Novel technical developments we have led for nuclear physics detectors are beginning to see much broader application. The innovative fast-digitization readout electronics we developed for multi-anode photomultiplier tubes as part of the EEMC project for STAR are being adapted for use in other types of detectors employing arrays of scintillating or wavelength-shifting optical fibers. One example is the scintillator bath detector concept developed within our group for tracking recoiling protons from neutral-current neutrino scattering at moderate energies. This detector concept is also the subject of recently approved funding to extend applicability of the concept to a portable detector for low-energy neutrons, to be used in national security applications.

A number of the group's recent nuclear physics results have impact in other subfields of physics. The "perfect liquid" formed in RHIC collisions is of great interest to plasma physicists, as an extreme example of a type of strongly coupled plasma that has received intensive recent study. The neutron lifetime measurement confirms significant constraints on Big Bang nucleosynthesis, that form an important component of cosmological models. The scintillator bath detector technology has the potential to permit measurement of many neutrino reaction cross sections needed in modeling astronomical processes, such as supernova explosions.

**Contributions to the Development of Human Resources:** The primary path for our contributions to other scientific disciplines remains the training of a suitable scientific workforce. Ph.D.'s from the IU nuclear physics group have gone on to positions in such other technologically advanced disciplines as medical physics, bio-medical imaging and national security planning and monitoring. Professional and technical staff at IUCF who have been trained on the development of nuclear physics accelerators and detectors have moved on to a variety of positions in high-tech industry. The problem-solving skills and critical thinking developed in the service of basic nuclear physics experiments are in high demand in the commercial, government laboratory and academic sectors. Of course, a fair fraction of the young scientists we train also remain within the nuclear physics research community.

**Contributions to Research and Education Infrastructure:** IUCF has developed from a sole-purpose national user facility for intermediate-energy research into a broad-based research laboratory with diverse missions, as noted above. The space, technological resources and technical support staff available are currently facilitating research in nuclear and particle physics and chemistry, in condensed matter and biophysics, in accelerator physics, in cancer therapy, and in radiation effects. For example, the MPRI center fed by beams from the IUCF cyclotrons is the only proton beam therapy facility in the U.S. Midwest region, and thereby is available to serve a large fraction of the U.S. population. IUCF is a major source of technical and engineering expertise and infrastructure at the predominantly liberal arts Indiana University campus in Bloomington.

Individuals in the group have made significant contributions to educational infrastructure, as outlined in the Outreach Activities section above.

**Contributions to Public Welfare:** The main contributions in this area are: the development of MPRI; the exploitation of detector technology devised by group members for applications in national security; and the training of a technologically skilled workforce who have made contributions to fields as diverse as radiotherapy, *in vivo* medical imaging, national security planning and monitoring, and financial planning and management. Since retiring as IUCF Director, John Cameron has started a company (PartTec) to develop commercial applications of several of the innovative technological developments made during the course of the group's basic nuclear physics research experiments.

# IUCF Publications
# 2002 – 2005

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