EXPERIMENTAL STUDIES OF QUARK-GLUON STRUCTURE OF NUCLEONS AND NUCLEI

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Contents

1 Introduction

The NMSU group has a lengthy history in the study of the nucleon structure and in particular its spin structure in terms of its fundamental constituents. This line of research is continuing in our current involvement in experiments at Brookhaven National Lab and the Thomas Jefferson National Accelerator Facility. At Jefferson Lab, the G^0 experiment is studying the contribution of strange quarks in the distribution of the proton's charge and magnetism, with the possibility of adding information about the spin in the future. At BNL, with the PHENIX experiment we aim to probe the role played by gluons in shaping the proton's total angular momentum. In a new neutrino-scattering experiment at BNL, called FINeSSE, we join a group proposing to measure the strange quark contribution to the proton spin, Δs, in addition to a suite of neutrino-nucleus cross sections that are critical to the understanding of neutrino experiments at other locations around the world. In the following report, only the activities in which our group is focusing are described in detail.

2 The PHENIX Experiment at RHIC

Academia Sinica, Abilene Christian University, Bhabha Atomic Research Centre, Univesite' Blaise Pascal Clermont-Fd, Brookhaven National Laboratory, Banaras Hindu University, University of California at Riverside, China Institute of Atomic Energy, University of Tokyo, University of Colorado, Columbia University and Nevis Laboratories, Dapnia CEA Saclay, Debrecen University,Eötvös Lordnd University, Ecole Polytechnique Saclay, Florida State University at Tallahassee, Georgia State University at Atlanta, Hiroshima University, Institute for High Energy Physics Protvino, University of Illinois Urbana-Champaign, Iowa State University at Ames,JINR Dubna, KEK High Energy Accelerator Research Organization,KFKI Budabest, Korea University, Kurchatov Institute, Kyoto University, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Lund University, McGill University, University of Muenster, Myongji University, Nagasaki Institute of Applied Science, University of New Mexico, State University of New York at Stony Brook, Oak Ridge National Laboratory,IPN-Orsay,Peking University, PNPI Gatchina, RIKEN, RIKEN BNL Research Center, Universidade de São Paulo,SEL Seoul, SUBATECH, St. Petersburg State Technical University, University of Tennessee at Knoxville, Tokyo Institute of Technology, Advanced Research Institute for Science and Technology Tokyo, University of Tokyo, University of Tsukuba, Vanderbilt University, Waseda University, Weizmann Institute, Yonsei University, and NMSU (Al-Bataineh, Al-Jamel, Ar-

mendariz, Brown, Hoover, Kyle, Papavassiliou, Pate, Stepanov, Wang); W.A. Zajc, Columbia, Spokesman

The PHENIX (for Pioneering High-Energy Nuclear-Interaction eXperiment) detector is a general-purpose apparatus designed to cover the wide range of physics topics that can be studied at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Lab. RHIC is a relatively new accelarator, designed to accelerate counter-circulating beams of heavy ions, typically gold nuclei, at nucleon-nucleon center-of-mass energies of up to 200 GeV, and polarized protons up to $\sqrt{s} = 500$ GeV. There have been several runs already since the commissioning of the accelerator and detectors and another run is under way at the time this report is written.

The primary goal of the RHIC program is to search for new phenomena under extreme conditions of density and temperature, such as obtained in head-on collisions of high-energy heavy-ion beams. Prominent among them is the potential deconfinement of the constituents of the nucleon, quarks and gluons, and the formation of a new state of matter, the quark-gluon plasma [1], predicted by Quantum Chromodynamics, the commonly accepted theory of the strong interaction. The PHENIX collaboration and the other experiments at RHIC are already presenting tantalizing evidence that such behavior may be on the verge of being confirmed.

A second goal of the physics program at RHIC, and the main focus of the NMSU group, is the study of the internal spin structure of the nucleon and in particular the contribution of gluons. Deep-inelastic lepton-nucleon scattering experiments over the last two decades have painted a complex picture [2] of the nucleon which defied early naive expectations that mainly valence quarks would determine the nucleon spin properties. It is now understood that sea quarks and gluons play a very important role; however, the gluon contribution has not yet been directly probed, as gluons do not contribute to the scattering cross section to leading order. A hadron collider, such as RHIC, is the best environment to explore this topic [3].

One promising method for studying gluon distributions in the nucleon is via production of heavy flavors, charm and beauty, which is dominated by the gluon-gluon fusion subprocess $gg \to c\bar{c}(b\bar{b})$. At the currently available center-of-mass energies at RHIC (200 GeV), only charm production is relevant for the high-statistics studies required for the measurement of small spin asymmetries. Open-charm production is the most transparent from a theoretical point of view, being described by a purely perturbative QCD process: the cross section is given by a factorized expression of the form [4]

$$\sigma_{c\bar{c}} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu) f_j(x_2, \mu) \hat{\sigma}_{ij}(x_1 x_2 s, \mu^2)$$

in terms of the calculable parton-level cross sections $\hat{\sigma}_{ij}$ and the parton distribution functions f_i, derived from global fits to a large set of measurements, mainly from deep-inelastic scattering. Assuming gluon dominance, experimental longitudinal asymmetries can then be related to the gluon polarization $\Delta g/g$ by an expression of the form

$$A_{LL}(x_1, x_2, p_T) = \frac{\Delta g}{g}(x_1) \times \frac{\Delta g}{g}(x_2) \times \hat{a}_{LL}(\hat{s}, \hat{t}, \hat{u}),$$

where the parton-level asymmetries $\hat{a}_{LL}$ can be calculated. However, identifying charm events independent of specific final states is experimentally challenging. Hidden harm (charmonium), on the other hand, presents a much cleaner experimental signature through its decay to a lepton pair with well-defined invariant mass, but suffers from additional theoretical uncertainties, related to the long-distance (non-perturbative) binding process of a $c\bar{c}$ pair into a ψ or χ_c meson. There has been some recent progress in the theoretical understanding of charmonium (and bottomonium) production within the framework of the non-relativistic QCD factorizations formalism [5], but the situation is far from settled. Both open and hidden charm can be studied through its decay into muons, either a single muon (open charm) or a dimuon pair (charmonium).

The NMSU group was heavily involved in the design, construction, and commissioning of the PHENIX end-cap (North and South) muon arms, which were proposed mainly for the goals of the spin program. Both have been fully operational and muon data with polarized-proton beams are available from the 2003 and 2004 runs. One graduate student (Al-Jamel) successfully defended his Ph.D. dissertation in the summer of 2004; the topic of his thesis was the study of features of J/ψ production in polarized p-p scattering. While the low statistical precision of the data did not allow conclusive results, he developed several important analysis techniques that will be used by future students. The long-term goals of this program are twofold: to understand better the J/ψ production mechanism in the context of NRQCD, by applying tests not available in unpolarized interactions, such as the dependence of the polarization of the produced J/ψ on beam helicities, and to make use of NRQCD in studying J/ψ production asymmetries to gain insight in the gluon contribution to the nucleon spin.

Of the current graduate students, one (Stepanov) has completed his service work on the experiment and is at present analyzing the 2003 data for his Ph.D. thesis on open-charm production. His goal is to develop a procedure for obtaining a sample of single-muon events enriched in charm content, by combining muon features with global event characteristics in a multivariate analysis. A second graduate student (Armendariz) is resident at BNL, participating in data taking and other run-related support activities. In parallel, he developing a research project in heavy-ion physics, studying the transverse-energy (E_T) distributions and fluctuations in Au-Au and *p-p* interactions in search of an E_T component in central heavy-ion collisions that is not present in *p-p* reactions.

A new graduate student (Al-Bataineh) has recently joined the group and spent part of the summer at BNL; he will return to BNL after he completes his course work. A postdoctoral associate (Wang) is also full-time at BNL and is contributing to the J/ψ and single-muon analysis, in addition to run-related duties. Students and postdocs resident at BNL are participating in the run by taking shifts as subsystem experts for the muon detector, as well as regular data-taking shifts.

The next physics run with polarized-proton beams, with much higher integrated luminosity, perhaps by an order of magnitude, is expected during 2005. Even higher luminosities are anticipated in later years, with running at $\sqrt{s} = 500$ GeV by 2009. The NMSU group has a long-term commitment in this line of research, with the current student work pioneering the tools and techniques for exploring the gluon contribution to the proton helicity.

3 G^0: Measurement of the Strange Electromagnetic Form Factors of the Proton

California Institute of Technology, Carnegie-Mellon, College of William & Mary, IPN Orsay, ISN Grenoble, Louisiana Tech University, Thomas Jefferson National Accelerator Facility, TRIUMF, University of Illinois, University of Kentucky, University of Manitoba, University of Maryland, University of Northern British Columbia, Virginia Polytechnic Institute and State University, Yerevan Physics Institute, and NMSU (Papavassiliou, Pate, Rauf, MacLachlan, McKee, Schaub, Flores); D. Beck, Illinois, Spokesman.

The G^0 experiment is measuring the parity-violating asymmetries in elastic polarized-electron–unpolarized-proton scattering at momentum transfers in the range $0.1 \leq Q^2 \leq 1.0$ GeV^2. These asymmetries depend on the electromagnetic form factors of the proton G_E and G_M and the analogous weak form factors G_E^Z and G_M^Z:

$$A = -\frac{G_F Q^2}{\pi\alpha\sqrt{2}}(A_E + A_M + A_A)/A_D,$$

where

$$A_E = \epsilon G_E G_E^Z,$$

$$\begin{aligned} A_M &= \tau G_M G_M^Z, \\ A_A &= -\frac{1}{2}(1-4\sin^2\theta_W)\sqrt{\tau(1+\tau)(1-\epsilon^2)}\,G_M G_A^e, \\ A_D &= \epsilon(G_E)^2 + \tau(G_M)^2, \end{aligned}$$

and ϵ and τ are functions of the kinematic variables. Using the known proton and neutron form factors from unpolarized scattering experiments, the flavor-singlet electric and magnetic form factors G_E^0 and G_M^0 of the proton can be extracted. This allows measurements of the corresponding strange form factors, G_E^s and G_M^s. The effective axial form factor in electron scattering, G_A^e, is related to the normal weak axial form factor seen in neutrino scattering, G_A^Z, through a set of multiplicative and additive electroweak radiative corrections[6]. As the calculation of these corrections is not yet entirely verified, the form factor G_A^e must be measured together with G_E^s and G_M^s. This necessitates three measurements:

- A measurement of forward electron-proton scattering, sensitive mainly to G_E^s and G_M^s
- A measurement of backward electron-proton scattering, sensitive mainly to G_M^s and G_A^e
- A measurement of backward electron-deuteron scattering, sensitive to G_M^s and G_A^e in a different way

These considerations are reviewed in detail in a recent proposal of the G^0 Collaboration[7] to Jefferson Lab.

The collaboration built a new spectrometer for Hall C of Jefferson Lab, now in use for this experiment. The spectrometer consists of a superconducting air-core toroidal magnet with scintillation counters approximately at the focal plane. Because of the two-body kinematics, only one particle needs to be detected in the final state, provided backgrounds from inelastic scattering or other sources are eliminated by the geometry, by means of appropriate sets of collimators, or at least well-enough understood that reliable corrections can be made. A second set of scintillators at the exit of the magnet cryostat, since added to the design, provides a coincidence measurement for the outgoing track, further reducing non-elastic backgrounds.

During the experiment's first production run in 2003-2004, the spectrometer detected the elastically-scattered proton at forward angles in the Q^2 range 0.1–1.0 GeV^2 with a beam energy of 3.0 GeV. For measurements of the asymmetry for backward-angle scattering, the spectrometer has been rotated by 180^0 and the scattered electron will be detected. In this mode, each Q^2 bin must be measured in a different run. Running at several beam energies, from 340 MeV to 930 MeV, is anticipated; this will require lowering the nominal Jefferson Lab beam energy. Measurement of both forward and backward scattering angles is required for a precise separation of G_E^Z and G_M^Z.

The asymmetry is expected to be at the few $\times 10^{-6}$ level — in order to achieve a measurement with a 5% statistical precision, 10^{13} counts will be needed. A 20-cm long liquid-H_2 target is being used with a 40 μA beam current, giving a luminosity $\mathcal{L} = 2.1 \times 10^{38} \text{cm}^{-2}\text{s}^{-1}$.

For the forward-angle measurement, the main background is due to pions coming from inelastic events. Discriminating these pions from the elastically-scattered protons can be done with time-of-flight measurements, since at these energies a pion is much faster than a proton of the same momentum. Monte-Carlo simulations have shown the feasibility of this approach. For the backward-angle measurements with a proton target, the backgrounds are expected to be much less important. (On the other hand, for the planned backward-angle deuterium measurements, a large flux of background pions is expected, and a Cherenkov detector has been developed for event-by-event π/e rejection.)

During the period October–December 2002 the collaboration conducted its first full engineering run, in which the full forward-scattering apparatus was tested. This engineering run was a great success, and paved the way for the first production run in late 2003 and early 2004, already mentioned above.

Our group leads the design, fabrication and operation of a detector gain-monitoring system (Pate, Rauf, McKee, MacLachlan and Flores), now fully operational, and is responsible for the design and implementation of the slow-control software and a database-management system (Papavassiliou, Rauf, and McKee), to hold data sets for analysis by the collaborators. Pate is a member of the G^0 Publications Committee, along with Wim van Oers (TRIUMF) and Serge Kox (LPSC-Grenoble). Prior to and during the first Engineering Run, Pate acted as one of the Run Managers, along with David Armstrong (College of William and Mary) — they coordinated the planning and operation of the activities of the engineering run.

Recently, it was demonstrated[8] that a combination of parity-violating electron-proton forward scattering data and elastic νp and $\bar{\nu} p$ scattering data can be used to extract the strange form factors G_E^s, G_M^s, and G_A^s simultaneously. This greatly extends the reach of the G^0 project, which formerly did not anticipate being able to extract the strange axial form factor. Our analysis effort (Papavassiliou, Pate, McKee, and MacLachlan) is presently focused on that part of the detector overlapping in Q^2 with the BNL E734 neutrino-scattering experiment[9], which just happens to be that part of the detector with the most complex convolution of signal and background.

4 FINeSSE: Measurement of the Strange Quark Contribution to the Proton Spin, Δs, and of Important Neutrino-Nucleus Cross Sections

Columbia University, Fermi National Accelerator Laboratory, University of Illinois, Indiana University, Los Alamos National Laboratory, Louisiana State University, University of Virginia, Yale University, and NMSU (Papavassiliou, Pate); B. Fleming, Yale, and R. Tayloe, Indiana, Spokespersons.

Our group has joined the early stages of an effort to measure the strange quark contribution to the proton spin, Δs, via a measurement of neutrino-proton elastic scattering. The project also proposes to measure a suite of important neutrino-nucleus cross sections, needed for the understanding of neutrino experiments at other laboratories — these measurements were listed among the "recommendations for the future" in the recent APS report on the future of neutrino physics[10]. The main focus of the experiment (and of our group) is the Δs measurement, and that will be the focus of the following brief discussion.

The contribution of the strange quarks to the spin of the proton, Δs, also known as the strange axial charge because of it relation to the strange axial form factor, has been the subject of much investigation for two decades. During the early years of the "spin crisis" there was a great interest in Δs because it was thought to be the "solution" to the problem of the missing valence quark contribution to the proton spin. By the 1990's it was clear that the complete solution involved also the gluon and orbital angular momentum sectors, and the focus of the spin community began to shift in those directions.

The pioneering inclusive polarized deep-inelastic scattering experiments at CERN and SLAC produced useful (but assumption-laden) estimates of Δs. (For a review see Ref. [2].) The two principal assumptions which affect these estimates are:

- An assumption of SU(3)-flavor symmetry: this is needed so that hyperon-decay data can be combined with the DIS data to enable the simultaneous extraction of Δu, Δd, and Δs;

- An assumption concerning the low-x behaviour of the measured polarized structure function $g_1^p(x, Q^2)$: this is needed because the experiments are limited in their x-coverage but the structure function must be integrated over the full range $0 < x < 1$ in order to make possible the extraction of the axial charges.

There is little understanding of the systematic errors associated with these two assumptions, and so the values of Δs produced from these analyses, typically in the range 0 to -0.2, have a large and unknown theoretical uncertainty.

The BNL E734 experiment[9] in the 1980's measured absolute cross sections for νp and $\bar{\nu} p$ elastic scattering for $0.45 < Q^2 < 1.05$ GeV^2, and at these low Q^2 values these cross sections are very sensitive to the strange axial form factor, G_A^s, which is related to the strange axial charge: $\Delta s = G_A^s(Q^2 = 0)$. The E734 data, however, were not precise enough, nor at a low enough Q^2, to extract the strange axial charge. Subsequent re-analyses[11, 12] of the E734 data also did not produce a satisfactory result.

The FINeSSE (FIne-grained Neutrino Scattering Scintillator Experiment) project proposes to measure instead a ratio of two cross sections:

$$R_{\mathrm{NC/CC}} = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu p \to \mu^- p)}.$$

The elastic process, in the numerator, at low Q^2 is sensitive to the form factor combination $-G_A^{CC} + G_A^s$, where G_A^{CC} is the charged-current portion of the proton axial form factor, and is related to the triplet axial charge: $\Delta u - \Delta d = G_A^{CC}(Q^2 = 0)$. G_A^{CC} is already well measured. The quasi-elastic process, in the denominator, is only sensitive to G_A^{CC}. Measurement of this ratio, instead of a measurement of absolute elastic cross sections, largely eliminates uncertainties in neutrino flux, detector efficiency, and nuclear target effects. Simulations show that a 6% measurement of $R_{\mathrm{NC/CC}}$ down to $Q^2 = 0.2$ GeV^2 can provide a ± 0.04 determination of Δs.

The collaboration is currently exploring two different detector technologies. One involves a three-dimensional grid of wavelength-shifting optical fibers in a bath of liquid scintillator ("SciBath"). Neutrino interactions that produce charged particles (a single proton in elastic scattering, a muon-proton pair in quasi-elastic scattering) will produce light in the scintillator bath, and that light will be picked up in the fibers. A down-stream muon identifier will serve to identify and crudely measure the energy of produced muons. A prototype of the SciBath concept has been built and tested at FNAL and Indiana. The other technology being investigated is a Liquid Argon Time Projection Chamber. This alternate method has not been prototyped by FINeSSE, but prototypes produced by other experiments are being studied.

The FINeSSE Collaboration submitted a Letter of Intent to the BNL PAC in Fall 2004, and it was very positively received. One of us (Pate) was a lead author (with Rex Tayloe) of the physics motivation section devoted to the Δs measurement. To quote from the PAC report: "The PAC considers the physics of this experiment compelling. While deep inelastic scattering provides tantalizing information about the spin carried by the strange quarks, the proton isoscalar axial form factor can only be uniquely obtained by such a measurement." The Collaboration will produce a full proposal to be submitted to BNL in the spring of 2005.

References

[1] Helmut Satz. The search for the QGP: A critical appraisal. *Nucl. Phys. Proc. Suppl.*, 94:204–218, 2001.

[2] B. W. Filippone and Xiang-Dong Ji. The spin structure of the nucleon. *Advances in Nuclear Physics*, 26:1–88, 2001.

[3] Gerry Bunce, Naohito Saito, Jacques Soffer, and Werner Vogelsang. Prospects for spin physics at RHIC. *Ann. Rev. Nucl. Part. Sci.*, 50:525–575, 2000.

[4] J. A. Appel. Hadroproduction of charm particles. *Ann. Rev. Nucl. Part. Sci.*, 42:367–399, 1992.

[5] Geoffrey T. Bodwin, Eric Braaten, and G. Peter Lepage. Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium. *Phys. Rev.*, D51:1125–1171, 1995.

[6] Shi-Lin Zhu, S. J. Puglia, Barry R. Holstein, and M. J. Ramsey-Musolf. The nucleon anapole moment and parity-violating e p scattering. *Phys. Rev.*, D62:033008, 2000.

[7] The G^0 Collaboration, D. Beck, Spokesperson. *The G^0 Experiment Backward Angle Measurements*, May 2001.

[8] Stephen F. Pate. Determination of the strange form factors of the nucleon from νp, $\bar{\nu} p$, and parity-violating $\vec{e}p$ elastic scattering. *Phys. Rev. Lett.*, 92:082002, 2004.

[9] L. A. Ahrens et al. Measurement of νp and $\bar{\nu} p$ elastic scattering. *Phys. Rev.*, D35:785, 1987.

[10] APS Multidivisional Neutrino Study Group. The neutrino matrix. http://www.aps.org/neutrino/, American Physical Society, 2004.

[11] G. T. Garvey, W. C. Louis, and D. H. White. Determination of proton strange form-factors from νp elastic scattering. *Phys. Rev.*, C48:761–765, 1993.

[12] W. M. Alberico et al. Strange form factors of the proton: A new analysis of the $\nu(\bar{\nu})$ data of the BNL-734 experiment. *Nucl. Phys.*, A651:277–286, 1999.

5 Publications and Presentations

The following is a list of publications of the NMSU group between October 1, 2002, and December 31, 2003, and those not listed in previous NMSU Progress reports.

5.1 Published Papers

1. *Nuclear Transparency From Quasielastic A(e,e'p) Reactions up to* $Q^2 = 8.1$ $(GeV/c)^2$, K. Garrow, D. McKee *et al.*, Phys. Rev. C66 (2002) 044613.

2. *Flow Measurements via Two-particle Azimuthal Correlations in Au + Au Collisions at* $\sqrt{s_{NN}} = 130$ *GeV*, K. Adcox *et al.*, The PHENIX Collaboration, Phys. Rev. Lett. 89 (2002) 212301.

3. *Centrality Dependence of the High* p_T *Charged Hadron Suppression Measurement in Au + Au Collisions at* $\sqrt{s_{NN}} = 130$ *GeV*, K. Adcox *et al.*, The PHENIX Collaboration, Physics Letters B561 (2003) 82.

4. *Evidence for Quark Hadron Duality in the Proton Asymmetry* A_1, A. Airepetian *et al.*, The HERMES Collaboration, Physical Review Letters 91 (2003) 092002.

5. *The PHENIX Muon Arms*, H. Akikawa *et al.*, The PHENIX Muon Arm Collaboration, Nucl. Inst. and Meth. A 499 (2003) 537-548.

6. *PHENIX Detector Overview*, K. Adcox *et al.*, The PHENIX Collaboration, Nucl. Inst. and Meth. A 499 (2003) 469-479.

7. *Suppressed* π^0 *Production at Large Transverse Momentum in Central Au+Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*," S. Adler *et al.*, The PHENIX Collaboration, Physical Review Letters 91 (2003) 072301.

8. *Absence of Suppression in Particle Production at Large Transverse Momentum in* $\sqrt{s_{NN}} = 200$ *GeV d+Au collisions*, S. Adler *et al.*, The PHENIX Collaboration, Physical Review Letters 91 (2003) 072303.

9. *Scaling properties of proton and anti-proton production in* $\sqrt{s_{NN}} = 200$ *GeV Au + Au collisions*, S. Adler *et al.*, The PHENIX Collaboration, Phys. Rev. Lett. 91 (2003) 172301.

10. *Elliptic Flow of Identified Hadrons in Au+Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, Phys. Rev. Lett. 91 (2003) 182301.

11. *J/ψ Polarization in 800 GeV p-Cu Interactions*, T.H. Chang *et al.*, E866/NuSea Collaboration, Phys. Rev. Lett. 91 (2003) 211801.

12. *Mid-Rapidity Neutral Pion Production in Proton-Proton Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, Phys. Rev. Lett. 91 (2003) 241803.

13. *Optical Alignment System for the PHENIX Muon Tracking Chambers,* J. Murata *et al.*, Nucl. Inst. and Meth. A500 (2003) 309.

14. *Single Identified Hadron Spectra from* $\sqrt{s_{NN}} = 130$ *GeV Au+Au Collisions*, K. Adcox *et al.*, The PHENIX Collaboration, Physical Review C 69 (2004) 024904.

15. *Identified Charged Particle Spectra and Yields in Au-Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, Physical Review C 69 (2004) 034909.

16. *J/ψ Production in Au-Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV at the Relativistic Heavy Ion Collider*, S. Adler *et al.*, The PHENIX Collaboration, Physical Review C 69 (2004) 014901.

17. *Determination of the strange form factors of the nucleon from* νp, $\bar{\nu} p$, *and parity-volating* $\vec{e}p$ *elastic scattering*, S.F. Pate, Physical Review Letters 92 (2004) 082002.

18. *Measurement of Non-Random Event-by-Event Fluctuations of Average Transverse Momentum in* $\sqrt{s_{NN}} = 200$ *GeV Au+Au and p+p Collisions*,S. Adler *et al.*, The PHENIX Collaboration, Physical Review Letters 93 (2004) 092301.

19. *J/ψ production from proton-proton collisions at* $\sqrt{s} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, Physical Review Letters 92 (2004) 051802.

20. *High-*p_T *Charged Hadron Suppression in Au+Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, Physical Review C 69 (2004) 034910.

21. *Measurements of electron-proton elastic cross sections for* $0.4 < Q^2 < 5.5$ *(GeV/c)*^{2}, M.E. Christy *et al.*, Physical Review C 70 (2004) 015206.

22. *Bose-Einstein Correlations of Charged Pion Pairs in Au+Au collisions at* $\sqrt{s_{NN}} =$ 200 *GeV*, S. Adler *et al.*, The PHENIX Collaboration, Physical Review Letters 93 (2004) 152302.

23. *Absolute Drell-Yan Dimuon Cross Sections in 800 GeV/c pp and pd Collisions*, J.C. Webb *et al.*, E866/NuSea Collaboration, submitted to Physical Review Letters.

5.2 Papers Submitted for Publication

1. *Jet Structure of Baryon Excess in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.* (The PHENIX Collaboration), submitted to Physical Review Letters.

2. *Deuteron and anti-deuteron production in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.* (The PHENIX Collaboration), submitted to Physical Review Letters.

3. *Double Helicity Asymmetry in Inclusive Mid-Rapidity neutral pion Production for Polarized p+p Collisions at* $\sqrt{s} = 200$ *GeV*, S. Adler *et al.* (The PHENIX Collaboration), submitted to Physical Review Letters.

4. *Systematic Studies of the Centrality and* $\sqrt{s_{NN}}$ *Dependence of* $dE_T/d\eta$ *and* $dN_{\rm ch}/d\eta$ *in Heavy Ion Collisions at Mid-rapidity*, S. Adler *et al.* (The PHENIX Collaboration), submitted to Physical Review C.

5. *Centrality Dependence of Charm Production from Single Electrons in Au+Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.* (The PHENIX Collaboration), submitted to Physical Review Letters.

6. *Measurement of* $R = \sigma_L/\sigma_T$ *and the Separated Longitudinal and Transverse Structure Functions in the Nucleon Resonance Region*, Y. Liang *et al.*, submitted to Physical Review Letters.

5.3 Papers Presented at Conferences

1. *First Measurements of High* p_T *Muons in Proton-Proton Collisions with the PHENIX Muon System*, D.S. Brown for the PHENIX Collaboration, VIIth International Conference on Strangeness in Quark Matter, Atlantic Beach NC, March 12-17, 2003.

2. *Charmonium Production at PHENIX: Current Status and Future Goals*, A.S. Hoover for the PHENIX Collaboration, VIIth International Conference on Strangeness in Quark Matter, Atlantic Beach NC, March 12-17, 2003.

3. *Strange nucleon form factors from elastic electron and neutrino scattering*, S.F. Pate, APS Division of Nuclear Physics Fall Meeting, Tucson AZ, 31-October-2003.

4. *Quarkonium Polarization Study at RHIC*, X. Wang for the PHENIX Collaboration, APS Division of Nuclear Physics Fall Meeting, Tucson AZ, 31-October-2003.

5. *Don't Forget to Measure* Δs, S.F. Pate, International Workshop on Parity Violation and Hadronic Structure, Grenoble, France, 8-11 June 2004.

6. R_{dA} *measurement with muons from light meson decay in p-p and d-Au collisions at* $\sqrt{s_{NN}} = 200\ GeV/c^2$ *at RHIC*, X. Wang for the PHENIX Collaboration, APS Division of Nuclear Physics Fall Meeting, Chicago IL, 29-October-2004.

6 Personnel

The persons listed received full or partial support from this grant.

Faculty:

Gary S. Kyle

Vassili Papavassiliou

Stephen F. Pate

Postdoctoral Research Associates:

David Brown (until 22-July-2003)

Aamer Rauf (via University of Manitoba and TRIUMF, until 1-August-2003)

David McKee (as of 8-January-2003)

Xiaorong Wang (as of 1-October-2003)

Glen MacLachlan (as of 1-July-2004)

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Ahmed Al-Jamel

Raul Armendariz

Andrew Hoover

David McKee

John Schaub

Mikhail Stepanov

Jason Webb

Undergraduate Students:

Gilberto Flores

7 Degrees Awarded

On 26-September-2002, Jason Webb defended his thesis, "Measurement of Continuum Dimuon Production in 800 GeV/c Proton-Nucleon Collisions."

On 6-December-2002, David McKee defended his thesis, "Nuclear Transparency and Single Particle Spectral Functions from Quasi-elastic electron scattering reactions up to Q^2 of 8.1 GeV^2."

On 20-March-2003, Andrew Hoover defended his thesis, "The PHENIX Muon Spectrometer and J/ψ Production in $\sqrt{s} = 200$ GeV Proton-Proton Collisions at RHIC."

On 1-June-2004, Ahmed Al-Jamel defended his thesis, "J/ψ Production Properties from Polarized Proton-Proton Collisions at 200 GeV."