EXPERIMENTAL STUDIES OF QUARK-GLUON STRUCTURE OF NUCLEONS AND NUCLEI

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New Mexico State University
Las Cruces, NM 88003

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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 the following, only the activities in which our group is focusing are described in detail.

2 The PHENIX Experiment at RHIC

Academia Sinica, Bhabha Atomic Research Centre, Brookhaven National Laboratory, Banaras Hindu University, University of California at Riverside, China Institute of Atomic Energy, University of Tokyo, Columbia University and Nevis Laboratories, Florida State University at Tallahassee, Georgia State University at Atlanta, Hiroshima University, Institute for High Energy Physics Protvino, Iowa State University at Ames, KEK, High Energy Accelerator Research Organization, 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, PNPI, RIKEN, RIKEN BNL Research Center, Universidade de São Paulo, SUBATECH, St. Petersburg State Technical University, University of Tennessee at Knoxville, Tokyo Institute of Technology, University of Tokyo, University of Tsukuba, Vanderbilt University, Waseda University, Weizmann Institute, Yonsei University, and NMSU (Al-Jamel, Armendariz, Brown, Dias, Kyle, Papavassiliou, Pate, Stepanov, Wang); W.A. Zajc, 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 currently under way.

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 one in which the NMSU group is most interested in, 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 $gg \rightarrow c\bar{c}(b\bar{b})$. At the currently available center-of-mass energies at RHIC (200 GeV), only charm production is relevant. 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. 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 are now fully operational and data with polarized-proton beams are available from the 2003 run. Two graduate students (Al-Jamel, Stepanov) are currently analyzing the 2003 data for their Ph.D. theses; one of them is study the production properties of J/ψ in order to help elucidate the production mechanism and reduce the theoretical uncertainty in the interpretation of the J/ψ production in terms of gluon densities in the proton, while the other is attempting to develop a procedure for obtaining a sample of single-muon events enriched in charm content, based on the shape of the muon p_T spectrum and, potentially, global event characteristics.

Both students are at an early stage of their research, having recently completed their shift-taking and service work on PHENIX. Preliminary results from their work are expected to start appearing within a year. A third student (Armendariz) is currently participating in the data taking and providing service work, while a fourth (Dias) has just joined our group and is expected to be at BNL in the summer. A postdoctoral associate (Wang) is also full-time at BNL, replacing another (Brown) whose appointment expired in late 2003 and is contributing to the J/ψ analysis, in addition to run-related duties.

During this report period, the NMSU group, and especially the graduate students and postdocs, were heavily involved in the installation and commissioning of the north muon arm (the south arm had been installed the previous year). The work involved testing, repairs, and improvements on the drift chambers necessary for more reliable operation under conditions of high humidity, as well as the actual installation of the detectors and their cables in the experimental hall. It also included development of an optical-alignment system [6] and associated software for monitoring relative displacements of the drift chambers during the run. Additional work involved development of software for monitoring and control of the high voltage. Other service work for the students included subsystem-expert shift duties through the run, in addition to the 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 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, McKee); D. Beck, Illinois, Spokesman.

The G^0 experiment will measure 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

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

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[7]. 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 the most recent proposal of the G^0 Collaboration[8] to Jefferson Lab.

The collaboration has built a new spectrometer for Hall C of Jefferson Lab to be used 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.

The experiment will detect 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 will be 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. In both cases the accelerator will be operated in a pulsed-beam mode with 32-ns bucket spacing, to allow using time-of-flight techniques for background suppression.

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. It is planned to use a 20-cm long liquid-H_2 target with a 40 μA beam current, giving a luminosity $\mathcal{L} = 2.1 \times 10^{38} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

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 is being 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, showing as it did that the spectrometer, detector, and electronics could perform as designed under realistic conditions. Since that time, a great deal of analysis of the data collected during the engineering run has taken place, and has been reported on at conferences by various members of the collaboration. A second engineering run has taken place during October–December 2003, and the first production run will take place early in 2004. The forward-scattering data will be taken during 2004 and the detector will be turned around for the backward-scattering data runs expected to begin in 2005.

Our group is involved in the design and fabrication of a detector gain-monitoring system (Pate, Rauf, and McKee), 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 (IPN-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.

References

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

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[7] 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.

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

4 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.

4.1 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.

4.2 Papers Submitted for Publication

1. *Single Identified Hadron Spectra from* $\sqrt{s_{NN}} = 130$ *GeV Au+Au Collisions*, K. Adcox *et al.*, The PHENIX Collaboration, accepted by Physical Review C.

2. *Identified Charged Particle Spectra and Yields in Au-Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, accepted by Physical Review C.

3. *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, accepted by Physical Review C.

4. *High-*p_T *Charged Hadron Suppression in Au+Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, accepted by Physical Review C.

5. *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, submitted to Physical Review Letters.

6. *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, submitted to Physical Review Letters.

7. *J/ψ production from proton-proton collisions at* $\sqrt{s} = 200$ *GeV*, S. Adler *et al.*, The PHENIX Collaboration, submitted to Physical Review Letters.

8. *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.

4.3 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 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)

Graduate Students:

Ahmed Al-Jamel

Raul Armendariz

Andrew Hoover

David McKee

Mikhail Stepanov

Jason Webb

6 Degrees Awarded

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

On December 6, 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 March 20, 2003, Andrew Hoover defended his thesis, "The PHENIX Muon Spectrometer and J/ψ Production in $\sqrt{s} = 200$ GeV proton-proton collisions at RHIC."