IV. MEDIUM-ENERGY NUCLEAR PHYSICS RESEARCH

OVERVIEW

The overall goals of the Medium-Energy Physics research program in the Argonne Physics Division are to test our understanding of the structure of hadrons and the structure of nuclei, and to develop and exploit new technologies for high-impact applications in nuclear physics as well as other national priorities. In order to test our understanding of the structure of hadrons and the structure of nuclei within the framework of quantum chromodynamics, the medium-energy research program emphasizes the study of nucleons and nuclei on a relatively short distance scale. Because the electromagnetic interaction provides an accurate, well-understood probe of these phenomena, primary emphasis is placed on experiments involving electron scattering, real photons and Drell-Yan processes. The electron beams of the Thomas Jefferson National Accelerator Facility (JLab) are ideally suited for studies of nuclei at hadronic scales and represent one center of the experimental program. Staff members led in the construction of experimental facilities, served as spokespersons or co-spokespersons for 17 experiments and were actively involved in others. The group constructed the general-purpose Short Orbit Spectrometer (SOS) which forms half of the coincidence spectrometer pair that is the base experimental equipment in Hall C. Last Spring, Argonne had a major role in re-establishing the SOS in Hall C for a series of five experiments. Argonne led the first experiment to be carried out at JLab in Fiscal Year 1996 and has completed 13 other experiments.

Recently, staff members have focused increasingly on studies of the nucleon and the search for exotic phenomena. In Fiscal Year 2003 a preliminary analysis was completed for the ratio of the electromagnetic elastic form factors of the proton using a modified Rosenbluth method. These results agree with data recorded previously with the traditional Rosenbluth method, but strongly disagree with the polarization transfer data. Early in Fiscal Year 2003 measurements of polarization were performed for two-body photodisintegration of the deuteron at high energy. The exclusive reaction for charged photopion production from a neutron in ^{4}He was measured up to a photon energy of 4 GeV as a test of color transparency. A new initiative to search for color transparency in ρ production in nuclei was begun in August 2003 in Hall B at JLab. This work represents an important extension of Argonne's earlier rho electro-production studies at HERMES. A new proposal to search for partners of the θ^+ pentaquark was approved by the JLab Program Advisory Committee.

HERMES, a broadly based North American-European collaboration is studying the spin structure of the nucleon using internal polarized targets in the HERA storage ring at DESY. Deep inelastic scattering has been measured with polarized electrons on polarized hydrogen, deuterium and ^{3}He. Argonne has concentrated on the hadron particle identification of HERMES, a unique capability compared to other spin structure experiments. In 1999 and under Argonne leadership, the dual-radiator ring imaging Cerenkov counter (RICH) was brought into operation at the design specifications to provide complete hadron identification in the experiment. The RICH has been operating routinely since its installation. This has allowed HERMES to make decisive measurements of the flavor dependence of the spin distributions. Subsequently, HERMES has performed a five-component decomposition of the proton's spin structure function and the first measurement of the x-dependence of the strange sea polarization. During 2001, HERMES installed a transversely polarized target. With this target, HERMES has provided direct evidence for the Sivers' and Collins' effect. In addition, HERMES has provided evidence for the Θ^+ pentaquark. Finally, HERMES has provided information on quark fragmentation to pions, kaons and protons in the nuclear environment.

Measurements of high mass virtual photon production in high-energy proton-induced reactions have determined the flavor dependence of the sea of antiquarks in the nucleon. These measurements gave insight into the origin of the nucleon sea. In the same experiment, the high-x absolute Drell-Yan cross sections were measured. The final results demonstrate that modern high-x parton distributions are significantly in error. In Fiscal Year 2001, a new initiative was approved by the FNAL PAC to continue these measurements with much higher luminosity at the FNAL Main Injector. These Drell-Yan experiments not only provide the best means to measure anti-quark distributions in the nucleon and nuclei, but represent an outstanding opportunity to perform these measurements at an ideal proton beam energy of 120 GeV. A next-to-leading order analysis of pionic Drell-Yan data has led to a substantial change in the accepted pion structure function at high x, and thereby has resolved a long-standing issue.

The technology of laser atom traps provides a unique environment for the study of nuclear and atomic systems and represents a powerful new method that is opening up exciting new opportunities in a variety of fields, including nuclear physics. In particular, the group has developed a high-efficiency, high-sensitivity magneto-optical trap for rare, unstable isotopes of krypton. The group has dated the Sarahan ground water by performing atomic trap trace analysis (ATTA) of ^{81}Kr. The direction of flow and the velocity of the ground water were deduced from these measurements. The group has demonstrated the principle of using ATTA for $^{41}Ca/Ca$ analyses by successfully analyzing $^{41}Ca/Ca$ in urine samples from an osteoporosis patient under a medical study. Recently, an optical trap was set up at ATLAS for the purpose of measuring the charge radius of ^{6}He. The ^{6}He atoms were observed for the first time in the optical trap.

A new initiative to search for an electric dipole moment (EDM) of ^{225}Ra was begun. The ultimate goal is to search for a non-zero EDM for ^{225}Ra and improve the sensitivity for nuclear EDM searches by approximately two orders of magnitude. This test of time-reversal symmetry represents an outstanding opportunity to search for new physics beyond the Standard Model. A new optical trapping laboratory for radium was established for this experiment. The Fiscal Year 2003 milestone of observing a ^{225}Ra beam from the oven system was accomplished during the past year. A Zeeman slower and optical trap for ^{225}Ra are under construction. In addition, a study was performed to determine the feasibility of measuring $\sin^2\theta_W$ in parity violating deep inelastic electron scattering from deuterium at either JLab or SLAC.

A. HADRON PROPERTIES

a.1. New Measurement of (G_E/G_M) for the Proton (J. Arrington, R. Beams, K. Hafidi, R. J. Holt, E. C. Schulte, K. Wijesooriya, X. Zheng, B. Zeidman, and the JLab E01-001 and E94-110 Collaborations)

The structure of the proton is a matter of universal interest in nuclear and particle physics and the electromagnetic form factors, $G_E(Q^2)$ and $G_M(Q^2)$, yield information on the spatial distribution of the proton. The form factors can be isolated by performing a Rosenbluth extraction: measuring the cross section as a function of the virtual photon polarization ε, or by measuring the polarization transfer components in polarized electron-proton scattering. Rosenbluth measurements have been performed since the 1960s, and global fits to these measurements[1] showed that the ratio $\mu_p G_E/G_M$ was consistent with unity, indicating identical distributions of charge and magnetization within the proton. Recent polarization transfer measurements at Jefferson Laboratory[2] found that the ratio of G_E/G_M was unity at low Q^2, but fell linearly with increasing Q^2, reaching a value of 0.3 at Q^2=5.6 GeV^2.

A global reanalysis of the world's e-p cross section data and the new polarization data determined that the discrepancy is not the result of errors in a single data set, nor can it be explained by "reasonable" adjustments of the experimental normalization factors.[3] To be confident in our knowledge of the proton form factors, we must determine not only which result is correct, but also why these two techniques disagree. A systematic problem with either set of measurements would most likely affect other measurements which use the same techniques, as well as having possible implications for other experiments which rely on knowledge of the elastic form factors.[4] Jefferson Lab experiment E94-110 made additional Rosenbluth measurements of the form factors at large Q^2 values, and yielded form factor ratios consistent with previous Rosenbluth results,[5] supporting the conclusion that there is a systematic difference between the two techniques. However, the experiment has comparable uncertainties to previous SLAC results and, as with the previous experiments, the presence of large ε-dependent corrections makes it difficult to exclude the possibility of systematic error.

Experiment E01-001 was designed to provide a Rosenbluth measurement with both significantly improved sensitivity and greatly reduced corrections compared to previous Rosenbluth measurements, as a definitive test of the consistency of the two techniques. The elastic cross section was measured by detecting the struck proton, rather than the scattered electron. This has several important advantages: (1) no ε-dependence to the momentum of the detected proton at fixed Q^2, (2) much smaller ε-dependence to the measured cross section, (3) larger cross sections at low ε values, and (4) reduced size and ε-dependence of the radiative corrections.

The experiment ran at Jefferson Lab in May 2002, and preliminary results are now available. Figure IV-1 shows the preliminary extraction of the reduced cross sections from E01-001, compared to the ε-dependence predicted by global fits to previous Rosenbluth extractions (dashed lines) and polarization transfer measurements (solid lines). The new results disagree with the polarization transfer measurements, but are in excellent agreement with the previous Rosenbluth extraction. This rules out most possible explanations of the discrepancy in terms of experimental systematic errors, and also sets significant constraints on any possible error in the radiative corrections related to the scattered electron (which is not detected in this experiment). While this does not determine the source of the discrepancy, it does eliminates all of the explanations proposed to explain the discrepancy suggested when the polarization transfer results were found to differ. In addition, the confirmation of previous Rosenbluth results indicates that there are not any significant errors in our collection of elastic cross section measurements. This indicates that there should not be errors in previous experiments which normalize to elastic scattering or assume these cross sections are well known in analysis of their data.

Recently, it has been suggested[6] that two-photon contributions may be responsible for the discrepancy, and indications of such two-photon corrections have been seen in comparisons of positron and electron scattering at low ε and Q^2 values.[7] Two proposals, designed to further study this discrepancy, were submitted to the Jefferson Lab PAC in January 2004. The first proposed experiment[8] would provide a check on the polarization transfer results, utilizing a completely independent experimental technique to measure the polarization components. The other proposal[9] would extend the high precision Rosenbluth measurements of E01-001, and would allow extraction of two-photon contributions in a combined analysis of the improved Rosenbluth data along and existing polarization transfer and positron measurements.

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[1]R. C. Walker *et al.*, Phys. Rev. D **49**, 5671 (1994).
[2]M. K. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000); O. Gayou, *et al.*, Phys. Rev. Lett. **88**, 092301 (2002).
[3]J. Arrington, Phys. Rev. C **68**, 034325 (2003).
[4]J. Arrington, Phys. Rev. C **69**, 022201(R) (2004).
[5]M. E. Christy *et al.*, arXiv:nucl-ex/0401030 (2004).
[6]P. A. M. Guichon and M. Vanderhaeghen, Phys. Rev. Lett. **91**, 142303 (2003); P. G. Blunden, W. Melnitchouk, and J. A. Tjon, Phys. Rev. Lett. **91**, 142304 (2003).
[7]J. Arrington, Phys. Rev. C **69**, 032201(R) (2004).
[8]Jefferson Lab proposal PR04-014, "Measurement of G^p_E/G^p_M using elastic polarized $\vec{p}(\vec{e},e')p$ up to Q^2=3.50 (GeV/c)^2," X. Zheng, J. R. Calarco and O. A. Rondan, spokespersons.
[9]Jefferson Lab proposal PR04-020, "A measurement of two-photon effects in unpolarized electron-proton scattering," J. Arrington, spokesperson.

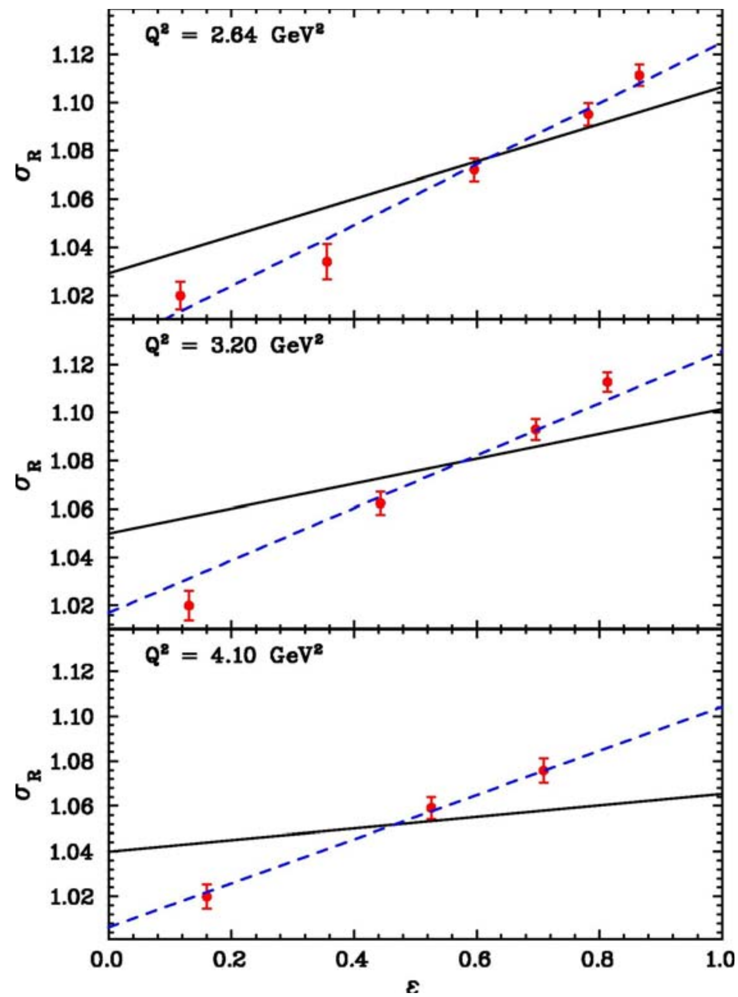


Fig. IV-1. Preliminary results for the reduced cross section (arbitrary normalization) as a function of ε for the three Q^2 values measured in the experiment. The uncertainties shown combine the statistical and uncorrelated systematic uncertainties. The dashed lines show the ε dependence expected from the global analysis of previous Rosenbluth measurements,[4] while the solid line shows the projection based on the polarization transfer results.[2]

a.2. **N → Δ Transition Form Factors** (J. Arrington, K. Hafidi, R. J. Holt, P. E. Reimer, E. C. Schulte, X. Zheng, and the JLab E01-002 Collaboration)

Measurements of the nucleon transition form factors provide additional information on the structure of the nucleon and nucleon excitations, which complement the measurements of the nucleon elastic form factors. Experiment E01-002 was performed in the spring of 2003 and measured electroproduction of the Δ(1232) and S_{11}(1535) baryon resonances. The experiment is an extension of previous, lower energy electroproduction experiments at Jefferson Lab, and was designed to probe the relevant degrees of freedom in high momentum exclusive reactions. By extending these measurements to higher momentum transfers, up to 7.5 GeV^2 in this experiment, we can probe the transition to the high energy region where perturbative QCD is expected to describe the reaction. Data were taken to separate out the magnetic dipole (M1), electric dipole (E2), and Coulomb (C1) contributions to the N → Δ transition. The data are currently under analysis.

These measurements also tie in with work in the theory division. T.-S. H. Lee has done extensive work on a dynamical model for pion electroproduction in the Δ region. A. Krassnigg and C. D. Roberts are exploring the effects of axial-vector diquark and pion cloud contributions to the nucleon elastic and N → Δ transition form factors, while F. Coester has performed similar explorations of relativistic effects in the elastic and transition form factors.

a.3. **The Charged Pion Form Factor** (J. Arrington, K. Hafidi, R. J. Holt, P. E. Reimer, E. C. Schulte, X. Zheng, and the JLab E01-004 Collaboration)

A complete understanding the structure of the nucleon is the defining problem in QCD. However, while experiments on the proton are easy, the complicated structure of a three light-quark system makes modeling of the proton in realistic, QCD-based models, difficult. The pion structure is simpler, and can in some cases provide a better meeting ground between theory and experiment in the study of QCD. Experiment E01-004 is an extension to the previous Jefferson Lab measurement of the pion form factor, and will improve measurements of the form factor at 1.6 GeV^2, the highest value at which the form factor has been measured, as well as extend measurements to 2.5 GeV^2. These measurements can be used to test models of hadron structure in a simpler system than the nucleon, where more advanced calculations can be performed. The form factor provides information on spatial distribution of the pion constituents, complementary to the information on the quark momentum distributions from the pion structure function measurements.

a.4. **Separated and Unseparated Structure Functions in the Nucleon Resonance Region** (J. Arrington, D. Gaskell, D. F. Geesaman, K. Hafidi, R. Holt, B. A. Mueller, T. G. O'Neill, D. Potterveld, P. Reimer, E. C. Schulte, X. Zheng, and the E94-110, E00-002, E00-108, and E00-116 Collaborations)

High energy inclusive electron scattering provides a clean and well understood probe of the quark distributions in nucleons and nuclei. At lower energies, this simple picture of quasifree electron-quark scattering is expected to break down, and the scattering is better understood in terms of resonance excitations and pion production. Measurements of the structure functions in unpolarized inclusive scattering can be extended down from high energies to yield a smooth connection between the deep inelastic quark scattering to the resonance excitation regions.

Early measurements of the F_2 structure function of the proton and deuteron at Jefferson Lab[1] were made to better study the phenomenon of Local Duality. It was observed at that the structure function in the resonance region was, on average, identical to the structure function in the DIS region when taken as a function of ξ, the Nachtmann variable. While the structure function does change at low Q^2 values, and resonance structure was clearly visible, the total strength in the region of any of the prominent resonances is identical to the strength in the DIS region to better than 10% down to Q^2=0.5 GeV^2. Furthermore, for very low ξ values, the structure function shows a valence-like behavior,[2] becoming very small as ξ decreases.

A more recent experiment, E94-110, extended these measurements by making a Rosenbluth separation of both F_1 and F_2. These data provided the first observation of duality in both the longitudinal and transverse channels for the proton. They also provided the first indication of significant longitudinal contributions to resonance electroproduction. Final results have been obtained for the L-T separation of both the resonance region structure function and the elastic electron-proton cross sections, and manuscripts for both these results are nearly ready to be submitted. In 2003, three additional measurements were performed in Hall C to further investigate the nature of duality: E00-116, E02-002, and E00-108. Measurements of F_2 for both the proton and deuteron were extended to higher Q^2 values than in the initial investigations. Measurements of the separated structure functions, F_1 and F_2, were performed at very low x and Q^2, to investigate in more detail the valence-like nature of the resonance region structure functions. Finally, these measurements were extended beyond inclusive scattering, to determine if a similar duality is observed in semi-inclusive scattering, where a single high-momentum pion is tagged in the final state. These experiments were completed in the summer of 2003, and are the data are currently under analysis.

[1]I. Niculescu, *et al.*, Phys. Rev. Lett. 85, 1182 (2000).
[2]I. Niculescu, *et al.*, Phys. Rev. Lett. 85, 1186 (2000).

a.5. Search for QCD Oscillations in the $\gamma N \rightarrow \pi N$ Reactions (R. J. Holt, J. Arrington, D. F. Geesaman, H. E. Jackson, P. E. Reimer, K. Hafidi, E. C. Schulte, and JLab E02-010 Collaboration)

A proposal to search for QCD oscillations in exclusive charged photopion reactions was approved by the Jefferson Laboratory Program Advisory Committee. The goal of the experiment is to search in photopion reactions for the oscillatory effect observed in exclusive high-energy proton-proton elastic scattering. In p-p elastic scattering, the cross section was found to oscillate about the $1/s^{10}$ dependence expected from the constituent counting rules. This oscillatory behavior has been ascribed[1] to a short distance (hard-scattering) amplitude which interferes with a long-distance amplitude (Landshoff). This process is analogous to coulomb-nuclear interference observed in low energy charged particle scattering; however, the QCD oscillations arise from soft gluon radiation rather than from photon radiation as in the QED case. This interference also can give rise to polarizations observed in high energy exclusive hadron-hadron scattering processes. In the proposed experiment, the cross sections will be measured in a fine energy scan up to the highest energy available at JLab.

[1]S. J. Brodsky, C. E. Carlson, and H. Lipkin, Phys. Rev. D **20**, 2278 (1979); J. P. Ralston and B. Pire, Phys. Rev. Lett. **65**, 2343 (1990).

a.6. Search for Pentaquark States at Jefferson Laboratory (P.E. Reimer, J. Arrington, K. Hafidi, R. J. Holt, E. C. Schulte, X. Zheng, and the E04-012 Collaboration)

Quantum Chromodynamics (QCD) governs the way in which quarks and gluons are bound into hadrons. Until recently, only two different configurations of quarks and antiquarks have been observed: mesons ($\bar{q}q$) and baryons (qqq). These are not the only configurations which can satisfy the basic QCD requirement that hadronic matter is color-neutral—many other configurations exist that also satisfy this condition. One example is the pentaquark ($qqqq\bar{q}$) configuration. Recently, experimental evidence and theoretical work have strongly suggested the existence of a pentaquark state, known as the Θ^+ with a mass near 1540 MeV. This state should be a member of a set of 10 pentaquark states known as the anti-decuplet. Using

Hall A at Jefferson Laboratory, a search is underway for one of these states, the Σ^0, in the reaction H(e,e'K^+)X and the partner state Θ^{++} in the H(e,e'K^-)X reaction with very high sensitivity and mass resolution. In addition, we are proposing to use the Hall A spectrometers' high resolution to study carefully the intrinsic width of the Θ^+ with better than 3 MeV resolution, providing valuable information on the nature of this state.

B. HADRONS IN THE NUCLEAR MEDIUM

b.1. Proton Polarization Angular Distribution in Deuteron Photodisintegration

(R. J. Holt, J. Arrington, K. Hafidi, P. E. Reimer, E. C. Schulte, K. Wijesooriya, and JLab E00-007 Collaboration)

The overall goal of experiment E00-007 is to determine the mechanism that governs photoreactions in the GeV energy region. Our previous measurements[1] of induced polarization in deuteron photodisintegration produced surprising results at photon energies between 1 and 2 GeV. First these results disagreed markedly with previous experiments and secondly there was a remarkable disagreement with the meson-exchange model. The induced polarizations above 1 GeV and at $\theta_{cm} = 90^{\circ}$ were near zero, consistent with hadron helicity conservation; however, it might be expected that the results could have been accidentally zero because of a $\sin(n\theta)$ dependence where n happens to be even. Thus, the goal of this experiment was to determine the angular dependence of the polarization. The experiment was completed in October 2002 and data were taken at five center-of-mass angles: 37°, 53°, 70°, 90° and 110°. The induced polarizations as well as polarization transfers were measured. Presently, the data are undergoing analysis.

[1]K. Wijesooriyia *et. al.*, Phys. Rev. Lett. **86**, 2975 (2001).

b.2. Measurements of the Nuclear Dependence of $R = \sigma_L/\sigma_T$ at Low Q^2

(J. Arrington, D. F. Geesaman, T. G. O'Neill, D. Potterveld, and the E99-118 Collaboration)

Inclusive electron scattering is a well understood probe of the partonic structure of nucleons and nuclei. Deep inelastic scattering has been used to make precise measurements of nuclear structure functions over a wide range in x and Q^2. The ratio $R = \sigma_L/\sigma_L$ has been measured reasonably well in deep inelastic scattering at moderate and high Q^2 using hydrogen and deuterium targets. However, R is still one of the most poorly understood quantities measured in deep inelastic scattering and few measurements exist at low Q^2 or for nuclear targets. Existing data rule out significant nuclear effects in R only at moderate to large values of Q^2.

Jefferson Lab Experiment E99-119 is a direct measurement of R at low x and low Q^2. The experiment was performed in July of 2000 and data were taken for hydrogen, deuterium, and heavier nuclei. The data are largely analyzed, but the cross section extraction at extremely small values of x and Q^2 involve large radiative corrections. While the radiative corrections will limit the region for which R can be extracted, these data are ideal for testing the radiative correction procedures in these extreme kinematics, and in particular the corrections coming from the nuclear elastic contributions.

In addition, further studies of the separated structure functions in nuclei have been approved. Experiment E02-109 will measure both the F_1 and F_2 structure functions for deuterium over a broad kinematical range. Experiment E04-001 was approved by the latest Jefferson Lab PAC to make similar measurements for a variety of heavier targets. These measurements will further the studies of duality and the nuclear structure functions at large x, but will also provide important data for experiments measuring neutrino-nucleus scattering. The MINOS experiment at Fermilab is searching for direct evidence of neutrino flavor oscillation by comparing neutrino-nucleus scattering at detectors stationed near to and far from the neutrino beamline. To precisely understand the comparison of scattering in the near and far detectors, the luminosity and energy spread of the beams must be well understood, and the scattering cross sections in a variety of detector materials must be well known. The structure functions measured in electron scattering must be used as input, and while the structure functions are well known in the DIS region, a large portion of the scattering in the MINOS experiment will come from resonance and quasielastic scattering. Thus, an improved data base for both the elastic form factors and the structure functions is necessary for a precise interpretation of the neutrino scattering measurements.

b.3. Electroproduction of Kaons and Light Hypernuclei (J. Arrington, K. Bailey, F. Dohrmann, D. F. Geesaman, K. Hafidi, B. Mueller, T. G. O'Neill, D. H. Potterveld, P. Reimer, B. Zeidman, and the E91-016 Collaboration)

Jefferson Lab experiment E91-016, "Electroproduction of Kaons and Light Hypernuclei is a study of the production of Kaons on targets of H, D, ^{3}He, and ^{4}He at an incident electron energy of 3.245 GeV and $Q^2 \approx 0.37$ GeV^2. For H and D targets, additional data were obtained at an energy of 2.445 GeV and $Q^2 \approx 0.5$ GeV^2. The scattered electrons and emergent kaons were detected in coincidence with the use of the HMS and SOS spectrometers in Hall C. Particle identification utilizing time-of-flight techniques together with Aerogel Cerenkov detectors provided clean missing-mass spectra and allowed subtraction of random backgrounds. In addition to obtaining spectra, angular distributions were measured at forward angles with respect to the virtual photons.

The fundamental interaction being studied is the $N(e,e'K^+)Y$ where Y is either Λ or Σ and N is a nucleon, either free or bound in a nucleus. For H, the final state can only be a Λ or Σ^0, with a missing mass spectrum consisting of two sharp peaks. For heavier targets, however, not only can Σ^- be produced on the neutron, but the relative motion of the bound nucleons results in quasi-free broadening of the peaks. Since there is no known bound state in the mass 2 hyper-nuclear system, only quasi-free production is observed. For the heavier targets, ^{3,4}He, both Fermi broadening and a rapidly increasing number of final state configurations makes it more difficult to separate the various contributions. Because of the small mass difference between Σ^0 and Σ^-, distinguishing between these contributions is not possible without assuming that the Λ/Σ^0 ratio is the same as that for the free proton. Subtraction of the normalized Σ^0 contribution yields the first accurate value for Σ^- production on the neutron.

The analyses of the data for ^{4}He provide unambiguous evidence for the formation of the bound hypernucleus hyper-^{4}H; the first observation of electroproduction of a hyper-nuclear bound state. From other reactions, a 1^+ excited state bound by ~ 1 MeV is known to exist in this nucleus; the 0^+ ground state is bound by 2.04 MeV. For ^{3}He, the evidence for the electroproduction of the hypertriton, *i.e.*, the p-nΛ state bound by ~ 130 keV, is less convincing. While barely discernible near zero degrees, because of kinematic effects, the bound state becomes more evident away from zero degrees.

Extraction of cross sections for specific channels becomes more difficult with increasing mass because of the rapidly growing number of possible final configurations. However, the various models that have been utilized for the helium isotopes yield simulations that are in reasonable agreement with the shapes of the spectra. Since it is not possible to distinguish between Σ^0 and Σ^-production, the analyses assume the Λ/Σ^0 ratio data for H obtained at the same laboratory settings as input to extract the Σ^- yields. Publication of these results is expected shortly.

In addition, the excellent particle identification allowed an ancillary study of the electroproduction of ω mesons on the proton. The relatively large cross section for this process, combined with kinematic focusing of the residual protons, provided high yields and excellent statistical accuracy over a wide range of cm angles. The data result in new insights into the fundamental production mechanisms. A paper reporting these results has been submitted to Physical Review C.

During the course of the experiment, extensive data were obtained for the H target as well as additional calibration data for C and Al. These latter data have been analyzed to ascertain the general mass dependence of the cross section for Kaon electroproduction. E91-016 has provided all or a substantial fraction of the thesis data for five students from Hampton University, University of Pennsylvania, and Temple University.

b.4. Measurement of High Momentum Nucleons in Nuclei and Short Range Correlations

(J. Arrington, D. F. Geesaman, K. Hafidi, R. Holt, H. E. Jackson, P. E. Reimer, E. C. Schulte, X. Zheng, and the E02-019 Collaboration)

Inclusive scattering from nuclei at low energy transfer (corresponding to $x > 1$) is dominated by quasielastic scattering from nucleons within the nucleus. As the energy transfer is decreased, the scattering probes nucleons of increasing momentum and we can map out the distribution of high momentum nucleons in nuclei. Experiment E89-008[1] measured inclusive scattering for deuterium, carbon, iron, and gold at $x > 1$ using 4 GeV electrons at Jefferson Lab. These data can be used to constrain the high momentum components of nuclear spectral functions. In addition, as the high momentum nucleons are dominantly generated by short range correlations (SRCs), these data allow us to examine the strength of two-nucleon correlations in heavy nuclei.

Experiment E02-019[2] will extend these measurements to higher values of x and Q^2 using the 6 GeV electron beam at Jefferson Lab. In addition to measuring scattering from deuterium and heavy nuclei, data will be taken on ^{3}He and ^{4}He. The higher Q^2 values in this experiment should simplify the extraction of the high momentum components, as effects such as final state interactions should be reduced as Q^2 is increased. Measurements with few-body nuclei (^{2}H, ^{2}He, and ^{4}He) allow contact with theoretical calculations via essentially "exact" calculations for few-body systems. This can be used to study in detail contributions to the interaction beyond the impulse approximation (*e.g.*, final state interactions). Data on heavy nuclei can then be used to constrain the high momentum components of their spectral functions, as well as allowing an extrapolation to infinite nuclear matter.

The extension to higher energies will provide us will significantly greater sensitivity to the high momentum components of the nuclear wave function, probing nucleons with momenta in excess of 1000 MeV/c. This will improve our ability to study the structure of nucleon correlations in nuclei. Direct comparisons of heavy nuclei to deuterium at large x will allow us to map out the strength of two-nucleon correlations in both light and heavy nuclei. These data will also be significantly more sensitive to the presence of multi-nucleon correlations. Just as the ratio of heavy nuclei to deuterium at $x > 1.5$ shows that the distribution in heavy nuclei is dominated by two-nucleon correlations, a similar ratio of heavy nuclei to ^{2}He at $x > 2.5$ may provide the first experimental signature of three-nucleon correlations.

In addition to probing nucleon distributions and short range correlations, these data fill in a significant void in our knowledge of the nuclear structure function. Little data exist for nuclei at large x, yet such data are important in the study of scaling and duality, higher twist effects, and nuclear dependence of the structure function. Results from the 4 GeV experiment show that the nuclear dependence of the structure function in the resonance region is identical to the EMC effect observed in the DIS region[2], while also extending the precision of high-x measurements of the structure function and showing for the first time an A-dependence to the shape of the structure function ratio at large x. In addition, while the $x > 1$ structure function is often neglected, it must be included in studies of the energy-momentum sum rule or analysis of the QCD moments. While E02-019 will focus on the study of the high momentum nucleons in nuclei, it provides the data necessary for a variety of studies. The experiment is scheduled to run in the fall of 2004.

[1] J. Arrington *et al.*, Phys. Rev. Lett. **82**, 2056 (1999).
[2] J. Arrington, R. Ent, C. E. Keppel, J. Mammei, and I. Niculescu, arXiv:nucl-ex/0307012.

b.5. Measurement of the EMC Effect in Very Light Nuclei (J. Arrington, D. F. Geesaman, K. Hafidi, R. J. Holt, H. E. Jackson, D. H. Potterveld, P. E. Reimer, E. C. Schulte, X. Zheng, B. Zeidman, and the E00-101 Collaboration)

For more than twenty years, it has been known that the quark momentum distribution of nuclei is not simply the sum of the quark distributions of its constituent protons and neutrons. The structure function is suppressed in heavy nuclei at large values of x (corresponding to large quark momenta), and enhanced at low x values. Measurements to date indicate that the overall form of this modification is the same for all nuclei, but the magnitude of the enhancement and suppression is larger for heavier nuclei. Many attempts have been made to explain the EMC effect, but none of the proposed models can fully reproduce the observed modifications, and there is still no consensus on which effect or combination (if any) explain the data.

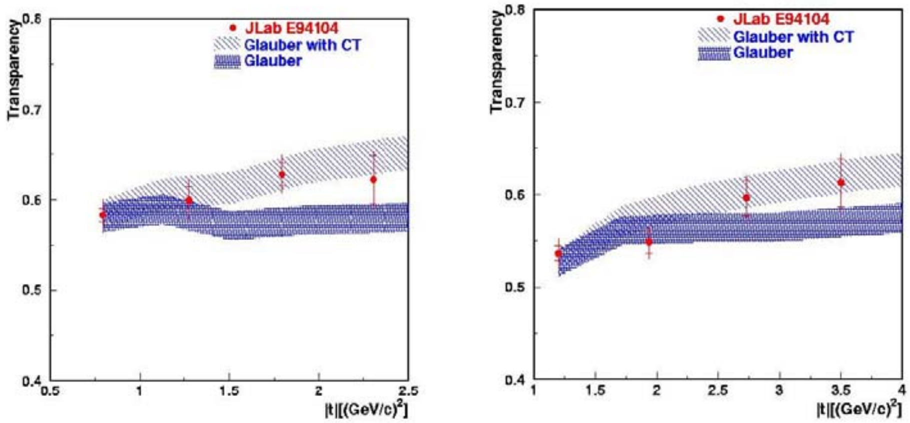
Experiment E00-101[1] will measure the EMC effect for ^{3}He and ^{4}He. Because ^{4}He has an anomalously large density for a light nucleus, it is the most sensitive test to determine if the EMC effect scales with A or with nuclear density. More importantly, these measurements of the EMC effect can be compared to exact few body calculations. If the EMC effect is caused by few nucleon interactions, the universal shape observed in heavy nuclei may be a result of a saturation of the effect, and the shape may be different in few-body nuclei. While the existing data on heavy nuclei all show the same x-dependence, calculations predict significantly different dependences for very light nuclei. By making precise measurements in light nuclei, we will be able to distinguish between different models of the EMC effect based on their predictions for few-body nuclei.

Finally, a measurement of $A \leq 4$ nuclei will help constrain models of the EMC effect in deuterium. Models of nuclear effects in deuterium and ^{3}He must be used to extract information on neutron structure, and a high precision measurement including ^{1}H, ^{2}H, ^{3}He, and ^{4}He will give a single set of data that can be used to evaluate these models in several light nuclei. This will help to quantify the model dependence of the neutron structure functions inferred from measurements on ^{2}H and ^{3}He. The experiment is scheduled to run in Hall C at Jefferson Lab, at the end of 2004.

b.6. Measurement of the Transparency Ratio for the A(γ,π^-p) Reaction in Helium and Deuterium (R. J. Holt, J. Arrington, K. Bailey, P. E. Reimer, F. Dohrmann, K. Hafidi, T. O'Connor, E. C. Schulte, K. Wijesooriya, and JLab E94-104 Collaboration)

The transparency for the ^{4}He(γ,π^-p) reaction compared with the D(γ,π^-p)p reaction was measured as a function of photon energy in Hall A at JLab. The fundamental process $\gamma n \rightarrow \pi^- p$ exhibits a scaling behavior consistent with the constituent counting rules above a photon energy of 2.5 GeV. Thus, one may be able to use this reaction in the nuclear medium to determine whether the onset of color transparency has been observed. The pion is expected[1] to exhibit the phenomenon of color transparency more readily than the proton since the pion has only two constituent partons. The measured transparency ratios[2] as a function of the Mandelstam variable t are shown below. The curves that include color transparency are in somewhat better agreement with the data than those with just the Glauber model. Clearly, the data must be extended to higher values of t to test for color transparency.

[1]B. Blättel *et al.*, Phys. Rev. Lett. **70**, 896 (1993).
[2]D. Dutta *et al.*, Phys. Rev. **C 68**, 021001(R) (2003).



(a) (b)

Fig. IV-2. The left panel (a) contains the transparency ratios for θ_{cm} = 70°, while the right panel (b) contains those for θ_{cm} = 90°.

b.7. Search for the Onset of Color Transparency: JLab E02-110 Experiment

(K. Hafidi, B. Mustapha, J. Arrington, A. El Alaoui, L. El Fassi, D. F. Geesaman, R. J. Holt, D. Potterveld, P. E. Reimer, E. C. Schulte, X. Zheng, and Hall B Collaboration)

According to QCD, pointlike colorless systems, such as those produced in exclusive processes at high Q^2 have a vanishingly small transverse size. Therefore, they are expected to travel through nuclear matter experiencing very little attenuation. This phenomenon is known as color transparency (CT). An analogous mechanism is well known in QED: the interaction cross section of an electric dipole is proportional to its square size. As a result the cross section vanishes for objects with very small electric dipole moments. Since color is the charge of QCD, and by analogy to QED, the cross section of a color-neutral dipole, as formed by a pair of oppositely colored quarks for instance, is also predicted to vanish for small sized hadrons. Color transparency cannot be explained by Glauber theory and calls upon the quark's degrees of freedom. Earlier measurements were mainly focused on quasi-elastic hadronic (p,2p)[1] and leptonic (e,e'p)[2] scattering from nuclear targets. None of these experiments were able to produce an evidence for CT up to Q^2 ~ 8 GeV^2. The strongest evidence for CT so far comes from Fermilab experiment E791 on the A-dependence of coherent diffractive dissociation of 500 GeV/c pions into di-jets.[3] A recent measurements perfomed by the HERMES collaboration using exclusive ρ^0 electroproduction off nitrogen add further evidence for the existence of CT.[4]

The main goal of E02-110 experiment[5] is to look for the onset of CT in the incoherent diffractive ρ^0 electro and photoproduction on deuterium, carbon and copper. In this process (see Fig. IV-3), the virtual photon fluctuates into $q\bar{q}$ pair which travels through the nuclear medium evolving from its small initial state with a transverse size proportional to 1/Q, to a "normal size" vector meson detected in the final state. Therefore, by increasing the value of Q^2 one can squeeze the size of the produced $q\bar{q}$ wave packet. The photon fluctuation can propagate over a distance which is known as the coherence length l_c. The coherence length can be estimated relying on the uncertainty principle and Lorentz time dilation as $l_c = 2\nu/\left(Q^2 + M_{q\bar{q}}^2\right)$, where ν is the energy of the virtual photon and $M_{q\bar{q}}$ is the mass of the $q\bar{q}$ pair dominated by the ρ^0 mass in the case of exclusive ρ^0 electroproduction. What is measured in the reaction is how transparent the nucleus appears to "small size" ρ^0 by taking the ratio of the nuclear per-nucleon (σ_A/A) to the free nucleon (σ_N) cross sections, which is called nuclear transparency $T_A = \sigma_A/A\sigma_N$. Consequently, the signature of CT is an increase in the nuclear transparency T_A with increasing hardness (Q^2) of the reaction. Recent theoretical calculations by Kopeliovich *et al.*,[6] predicted an increase of more than 40% at Q^2 ~ 4 GeV^2. However, one should be careful about other effects that can imitate this signal. Indeed,

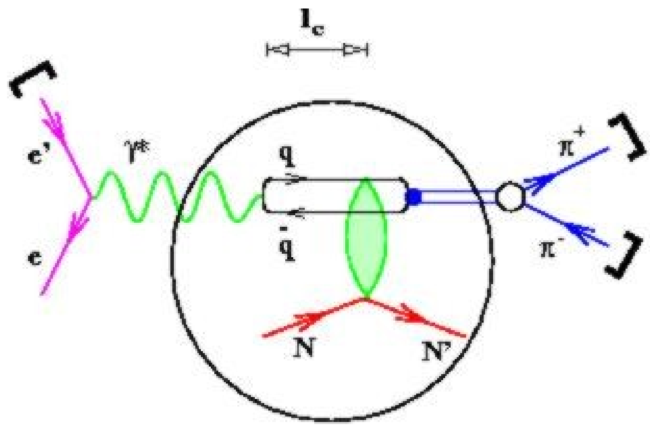


Fig. IV-3. Exclusive leptoproduction of the ρ^0 meson.

measurements by HERMES have shown that T_A increases when l_c varies from long to short compared to the size of the nucleus. This so-called coherence length effect can mock the signal of CT and should be under control to avoid mixing it with CT effect. Therefore, E02-110 experiment intends to measure the Q^2 dependence of the transparency T_A at fixed coherence length l_c.

The experiment was performed using the CEBAF Large Acceptance Spectrometer (CLAS)[7] in Hall B of the Thomas Jefferson National Accelerator Facility. The data were taken with both 4 and 5 GeV electron beam incident on 4 cm liquid deuterium target and a solid target (0.4 mm thick ^{56}Fe and 1.72 mm thick ^{12}C) simultaneously. The run period was from December of 2003 to March of 2004. The data were recorded at an instantaneous luminosity of 2 x 10^{34} cm^{-2} s^{-1}. Figure IV-4 shows the projected uncertainties for complementary l_c values to map the whole Q^2 region up to 4 GeV^2 using 6 GeV electron beam and 2 GeV photon beam on ^{56}Fe versus deuterium. Because the experiment was allocated only 70% of the approved beam time and the highest beam energy available was 5 GeV instead of 6 GeV, the photoproduction measurements will be performed later and the highest Q^2 the measurements will be 3 GeV^2 with a statistical error comparable to the one at 4 GeV^2. The data analysis is in progress.

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[1]A.S. Carroll *et al.,* Phys. Rev. Lett. **61** 1698 (1988); Y. Mardor *et al.*, Phys. Rev. Lett. **81** 5085 (1998); A. Leksanov *et al.*, Phys. Rev. Lett. **87**, 212301 (2001).
[2]N. C. R. Makins *et al.*, Phys. Rev. Lett. **72,** 1986 (1994); T. G. O'Neill *et al.*, Phys. Lett. **B351**, 87 (1995); D. Abbott *et al*., Phys. Rev. Lett. **80**, 5072 (1998); K. Garrow *et al.*, Phys. Rev. C **66** , 044613 (2002).
[3]E. M. Aitala *et al.*, Phys. Rev. Lett. **86**, 4773 (2001).
[4]A. Airapetian *et al.*, Phys. Rev. Lett. **90**, 052501 (2003).
[5]Jefferson Lab Experiment E02-110, "Q^2 Dependence of Nuclear Transparency for Incoherent ρ^0electroproduction," K. Hafidi, B. Mustapha and M. Holtrop, spokespersons.
[6]B. Kopeliovich *et al.*, Phy. Rev. C **65**, 035201 (2002).
[7]B. Mecking *et al.*, Nuclear Instrum. Methods **A503/3**, 513 (2003).

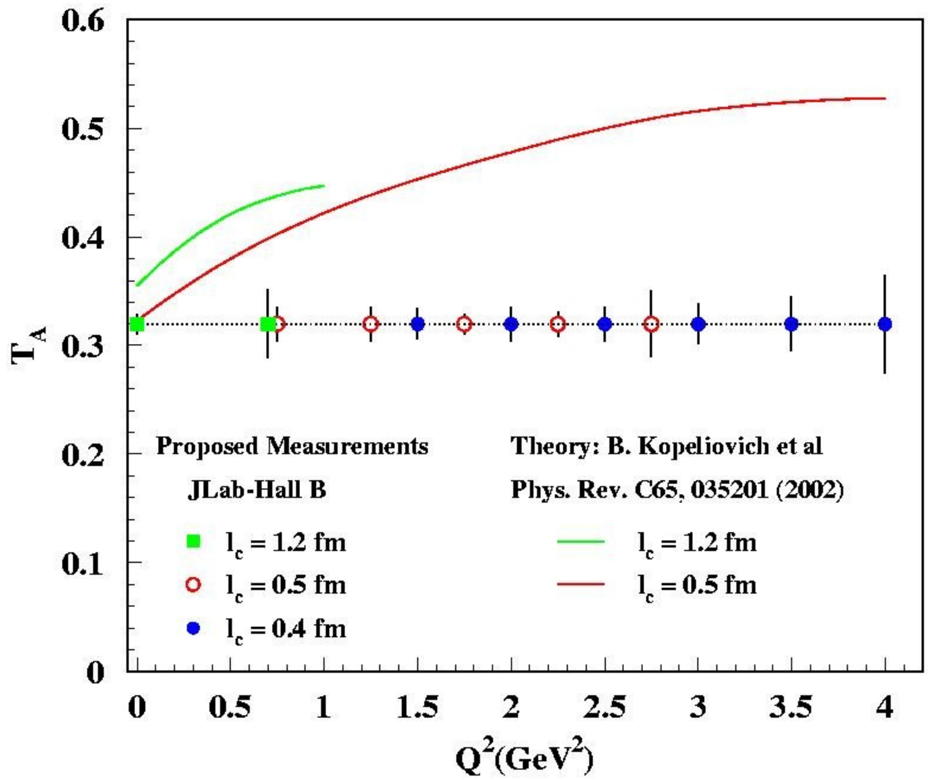

Fig. IV-4. Theoretical predictions and expected statistical accuracy.

C. QUARK STRUCTURE OF MATTER

c.1. The Structure Function of the Pion (P. E. Reimer, R. J. Holt, and K. Wijesooriya)

The light mesons have a central role in nucleon and in nuclear structure. The masses of the lightest hadrons, the mesons, are believed to arise from chiral symmetry breaking. The pion, being the lightest meson, is particularly interesting not only because of its importance in effective theories, but also because of its importance in explaining the quark sea in the nucleon and the nuclear force in nuclei. Most of our information about the pion structure function in the valence region originates from π p Drell-Yan scattering on a W target. A long-standing mystery is the marked deviation of the high-x pion structure function from perturbative QCD. At a Q^2 of 16 GeV^2 where Drell-Yan measurements are performed, one might expect pQCD to be valid. In addition, the high x behavior of the pion structure function was questioned[1] recently on more fundamental grounds. We re-analyzed the Drell-Yan data[2] and made the following improvements: next-to-leading order analysis, modern nucleon structure functions and modern nuclear effects, and a less-restrictive formula for the pion structure function. The results of this re-analysis indicate that the pion structure function at high x deviates significantly from the earlier[2] leading-order analysis and is in better agreement with Dyson-Schwinger calculations[1] as well as perturbative QCD.

Studies were completed to examine the feasibility of making measurements at JLab using an 11-GeV incident electron beam. With the relatively high luminosity which can be achieved at an upgraded JLab, the pion structure can be measured, over a limited range in x. Additional investigations are being made of this reaction using a future electron-ion collider.[3]

[1]M. B. Hecht *et al*., Phys. Rev. C **63**, 025213 (2001).
[2]J. S. Conway *et al.*, Phys. Rev. D **39**, 92 (1989).
[3]R. J. Holt and P. E. Reimer, Proceedings of the Second Workshop on the Polarized Electron Ion Collider, MIT (2000).

c.2. Measurements of Spin-Structure Functions and Semi-Inclusive Asymmetries for the Nucleon at HERA (H. E. Jackson, A. El Alaoui, K. G. Bailey, T. P. O'Connor, K. Hafidi, D. H. Potterveld, P. Reimer, Y. Sanjiev, and the HERMES Collaboration)

HERMES, HERA measurement of spin, is an international collaboration of 31 institutions formed to address a basic question of hadronic structure. How do the spins of its constituent quarks combine with the spin of the glue and the angular momentum of the partons to give the proton its spin of ½? The HERMES experiment uses polarized internal targets in the HERA 30 GeV lepton storage ring at the DESY laboratory, in Hamburg Germany. By emphasizing semi-inclusive deep inelastic scattering (SIDIS) in which a hadron is observed in coincidence with the scattered lepton, HERMES brings a new dimension to studies of spin structure. The collaboration has collected and analyzed millions of deep-inelastic scattering events using longitudinally polarized electrons and positrons incident on longitudinally polarized internal gas targets of ^{1}H, ^{2}H, and ^{3}He, as well as thicker unpolarized gas targets. One of the primary goals of the program remains a precise flavor decomposition of the quark helicities in the nucleon, but with the recent addition of transverse target polarization, it is now possible to address physics issues involving the transverse motion of quarks, a topic of wide interest in understanding the structure of the nucleon. While the focus of the program remains on the spin structure of the nucleon, the availability of higher luminosity unpolarized data from deep-inelastic scattering on light and heavy nuclear targets has been of great value in addressing a broad range of subjects which includes quark fragmentation, quark propagation in nuclear matter, color transparency effects in hadron production, and the existence of exotic quark states. The scope of the HERMES program has evolved far beyond the original focus on the spin structure of the nucleon and now encompasses many topics in polarized and unpolarized physics, but all with the common goal of providing fundamental insights into the underlying quark-gluon structure of hadronic matter.

The study of the spin structure of the nucleon continues to be of highest priority. Spin asymmetries have been measured using longitudinally polarized targets of hydrogen, deuterium, and ^{3}He. Analysis of the inclusive and semi-inclusive deep-inelastic scattering data from these unique undiluted targets has resulted in the world's most precise determination to date of the separate contributions of the up, down and sea quarks to the nucleon spin. Final analysis of this data is nearing completion. The results are providing unexpected answers to important questions concerning the origin and properties of the nucleon spin. The details of the quark sea polarization, its symmetry properties, and tests of chiral quark models for its composition are among the issues addressed. While this analysis proceeds, new data is being accumulated with a transversely polarized target to probe the effects of the transverse motion of quarks. With transverse target polarization it will be possible to measure asymmetries related to the third and last structure function, transversity, required to describe nucleon spin structure in leading order. Preliminary data already provide indications that it will be possible to separate two competing reaction mechanisms for generating transverse spin asymmetries, the Sivers effect and Collins fragmentation. The measurement of the Collins chiral-odd fragmentation function could make feasible at HERMES the first measurement of transversity. Inclusive measurements continue to be a calibration benchmark for SIDIS studies, and HERMES now provides the world's most precise inclusive cross sections. Using the unique properties of the HERMES polarized target, the tensor polarized structure function for the deuteron has been measured. The result shows the promise of a new probe of nuclear effects at the partonic level.

Recent measurement of a lepton-beam spin asymmetry in the azimuthal distribution of detected photons in Deeply Virtual Compton Scattering (DVCS) has provoked wide interest. Interference with the indistinguishable but well-understood Bethe-Heitler process fortuitously gives rise to a rich variety of such asymmetries, which will continue to emerge from HERMES data. DVCS is considered to be the most reliable of the various hard exclusive processes that constrain the generalized or "skewed" parton distributions, which are now the subject of intense theoretical development as, *e.g.*, they embody information about *orbital* angular momenta of partons. This type of measurement has been extended to exclusive and semi-inclusive electroproduction of pions and kaons where HERMES is releasing regularly new data showing for the first time substantial single-spin and beam-charge azimuthal asymmetries.

The ability to run with high density unpolarized targets provides HERMES with a tool reaching far beyond spin structure studies. The large momentum and solid angle acceptance of the HERMES spectrometer open a broad range of physics topics to exploration, and have resulted in a tool for the general study of photon-hadron interactions. The study of quark propagation and hadronization in nuclear matter has been of particular interest for testing models of parton interaction and energy loss in the strong interacting quark-gluon medium. The kinematics of the HERMES experiment are ideal for such studies and the spectrometer with its particle identification capabilities has allowed the separate measurements of hadronization into pion, kaon, and nucleons. These data are providing a new dimension to the subject, and frequently discussed in connection with understanding signatures for quark deconfinement in heavy ion reactions at the RHIC accelerator. Among other topics of interest are tests of factorization, measurement of fragmentation functions, measurement of spin transfer to Λ^0 hyperons, and vector meson electroproduction. A search is continuing for additional evidence for the existence of pentaquark exotic hadron states. Recent developments and new results pertaining to these physics topics are discussed in more detail below.

The spectrometer and associated equipment continue to perform at design capability. As time and resources permit, systems are continually upgraded and new capabilities are added. The data acquisition software has been completely revamped to run under linux. The RICH particle identification system provides hadron separation over almost the full HERMES acceptance. A new transversely polarized target has been installed for operations during the 2002-2004 running period. A system of silicon strip detectors for enhanced detection of Lambda decay products is operational. Design work is in progress for a large acceptance recoil detector array to be used to enhance solid angle acceptance and missing mass resolution in planned measurements of DVCS. Current planning calls for the continued operation of the HERA accelerator until August of 2007. These ongoing investments in enhanced capability ensure that HERMES will continue to produce results at the forefront of the field until final beam. HERMES has a broad physics program and has had scientific impact on a number of fundamental questions about the strong interaction. HERMES is playing an important role in the worldwide experimental investigation of QCD.

c.2.1. Flavor Decomposition of the Sea Quark Helicity Distributions in the Nucleon from Semi-inclusive Deep-inelastic Scattering (H. E. Jackson, A. El Alaoui, K. G. Bailey, T. P. O'Connor, K. Hafidi, D. H. Potterveld, P. Reimer, Y. Sanjiev, and the HERMES Collaboration)

The HERMES experiment represents a new approach to study the spin structure of the nucleon. It has been running at the HERA electron accelerator at the DESY laboratory in Hamburg Germany since 1995, measuring spin asymmetries in DIS. Its combination of a polarized high energy electron beam in a storage ring with undiluted polarized atomic gas targets is unique in this field, and has important experimental advantages. Furthermore, the spectrometer detecting the scattered electrons has substantial acceptance and the capability to identify all types of hadrons produced in coincidence. The main goal of the collaboration was to determine precisely the helicity distributions, $\Delta q(x)=q^{+}(x)-q^{-}(x)$, of the quarks and antiquarks of all light flavors: q = up; down; and strange. Here the superscripts on the probability densities indicate whether the quark's helicity (spin alignment with the beam direction) is equal or opposite to that of the nucleon, and x is the Bjorken scaling variable representing the momentum fraction of the target carried by the parton in the frame where the target has "infinite" momentum. The determination of these distributions requires the combination of longitudinal spin asymmetries on both hydrogen and deuterium polarized targets. To distinguish the contributions of the quark flavors and in particular of the virtual sea quarks, a leading hadron is detected in coincidence with the deep-inelastic scattering of a lepton. As mentioned above, this method exploits the correlation between the quark flavour and the type of leading hadron produced from the struck quark. The HERMES collaboration has reported[1] results from an analysis of their complete data set recorded in the period 1996-2000. These results, shown in Fig. IV-5, constitute the most precise information on quark helicity distributions, and for the first time provide separate determinations of the polarizations of the up, down and strange sea quarks. They reveal that the sea quark polarisations are all small. There is little evidence of the "cancellation" between the contributions of valence and sea quarks that had been hypothesized to explain the small net contribution inferred from inclusive data under the assumption of SU(3) flavor symmetry. In particular, there is no evidence that Δs is negative as was indicated by that model-dependent analysis.

[1] HERMES collaboration, A Airapetian *et al.*, Phys. Rev. Lett. **92**, 012005 (2004).

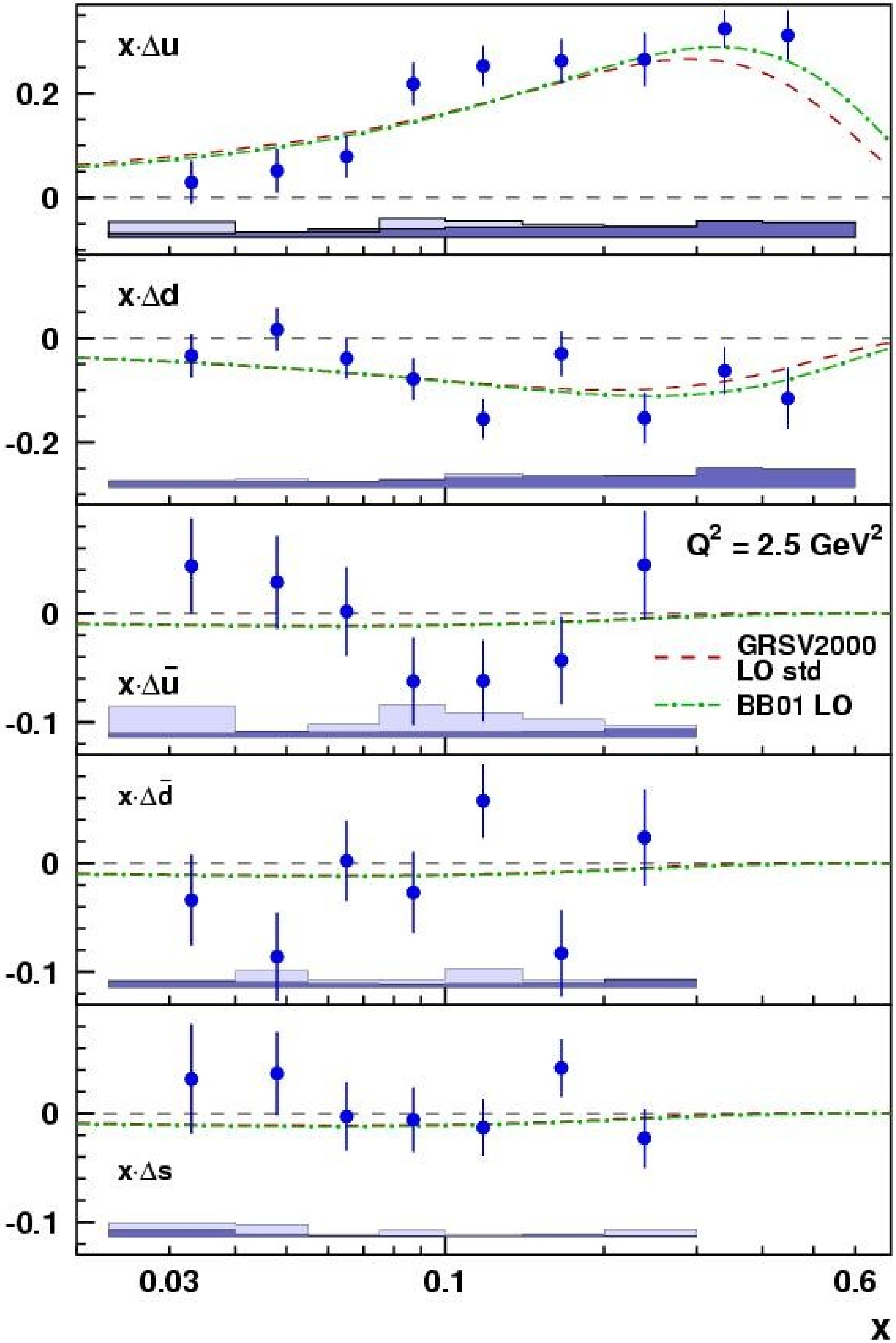

Fig. IV-5. Quark helicity distributions as a function of Bjorken-x. The curves are the different LO QCD parameterizations of previous world inclusive data assuming SU(3) flavor symmetry.

c.2.2. Evidence for a Narrow |S| =1 Baryon State at a Mass of 1528 MeV in Quasi-real Photoproduction (H. E. Jackson, A. El Alaoui, K. G. Bailey, T. P. O'Connor, K. Hafidi, D. H. Potterveld, P. Reimer, Y. Sanjiev, and the HERMES Collaboration)

After 30 years of searching, several experiments have finally found evidence for particles containing five quarks. Most particles are either mesons, which contain a quark and an antiquark, or baryons, which comprise three quarks (or antiquarks). In the last year physicists in Japan, Russia, the US and Europe have found evidence for the existence of a particle with a mass near 1530 MeV that contains two up quarks, two down quarks and a strange antiquark. Additional experimental evidence for the pentaquark[1] comes from the HERMES collaboration at the DESY laboratory in Hamburg. In this experiment high-energy positrons, which are accelerated and stored in the HERA electron-proton collider at DESY, were scattered of a deuterium target. The reaction products were detected and analyzed in a spectrometer that surrounds the interaction point of the experiment in the forward region. By looking for K^0 mesons in coincidence with protons, a spectrum could be constructed that revealed a peak at an energy of 1528 MeV (see Fig. IV-6). As compared to the other experiments, the HERMES collaboration carried out their measurements at a substantially higher incident energy thus reducing complications that may arise due to the unknown production mechanism of the pentaquark. Moreover, for the first time the measured spectrum has been compared to the results of a detailed Monte-Carlo simulation. This enabled the HERMES physicists to conclude that the peak could not originate from an unfortunate combination of kinematical requirements as they are usually applied in searches for new particles. In fact, the results of the Monte-Carlo simulation could even be varied by making artificial combinations of kaons and protons belonging to different scattering events. This sophisticated analysis also showed that -most likely- several known so-called Σ^* resonances have also been produced in the experiment. The statistical significance of the pentaquark signal has been estimated as well. The new HERMES results yield a significance of about 4 to 6 standard deviations, similar to what has been found by other experiments. Moreover, a detailed comparison has been made of the mass of the pentaquark as reported by the various experiments. If the weighted average is taken, the value of the pentaquark mass is found to be 1537.8 ± 2.7 MeV. The HERMES experiment also searched for a similar signal in a spectrum constructed from positive kaons and protons. No signal was found, suggesting that a doubly charged pentaquark does not exist near 1535 MeV. This already rules out some of the models that have been proposed since the first report of the pentaquark particle appeared. Still it is not yet clear if the pentaquark observed in the experiments is a tightly bound five-quark state or a sort of molecule made of a kaon and a nucleon.

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[1]HERMES collaboration, A. Airapetian *et al.*, Phys. Lett. **B585**, 213 (2004).

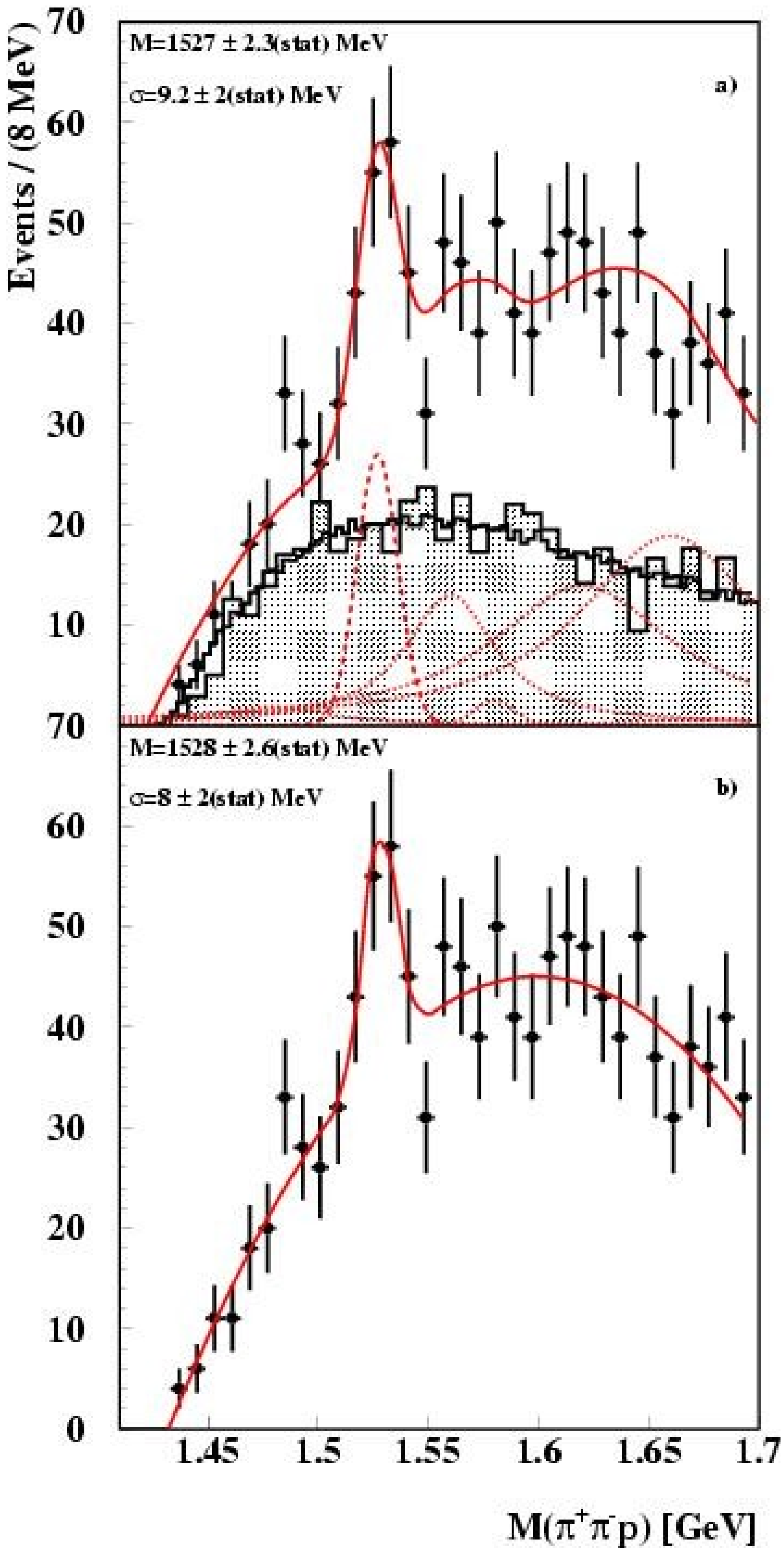

Fig. IV-6. Spectrum of kaon-proton combinations as found by the HERMES experiment. The top panel shows the result of a sophisticated analysis in which the background is treated on the basis of a Monte-Carlo simulation in combination with the assumed production of several Σ resonances. The bottom panel represents the results of the common analysis technique also adopted by previous reports on the pentaquark.*

c.2.3. Quark Fragmentation to Pions, Kaons, and Nucleons in the Nuclear Environment

(H. E. Jackson, A. El Alaoui, K. G. Bailey, T. P. O'Connor, K. Hafidi, D. H. Potterveld, P. Reimer, Y. Sanjiev, and the HERMES Collaboration)

Recently HERMES reported multiplicities measured on krypton relative to that of deuterium, which includes for the first time data for various identified hadrons: charged and neutral pions, kaons of both charges, protons and antiprotons. The complete particle identification in HERMES achieved with the installation of the RICH detector in 1998, allows information for different hadrons to be fully disentangled. This is shown in Fig. IV-7 where the multiplicity ratios between Kr and D nuclei are presented as a function of z (the fraction of the energy of the struck quark carried by the hadron) for the first time for various identified hadrons. The multiplicity ratios for pions are seen to be in agreement with what was already found on N shown in the upper panel of the figure. The different results for different hadrons may reveal differences in the modification of q and qbar fragmentation functions, thus leading to a more significant difference between the multiplicity ratios of protons and antiprotons than between those of pions and kaons.

The observed differences in the multiplicity ratios may also suggest different formation times of protons and antiprotons compared to that of pions and kaons, due to the fact that nucleons are composed of three quarks instead of two quarks which characterize meson states. The different hadron-nucleon interaction cross sections can also play a role: while this cross section is similar for positive and negative pions, it is larger for negative kaons as compared to positive kaons, and even larger for antiprotons than protons, in agreement with the trend shown by the data.

An interesting insight for the mass number dependence of the nuclear attenuation ratio comes from the comparison between krypton and nitrogen data for charged pions. The experimental data are found to be consistent with the $A^{2/3}$-dependence predicted by theoretical models containing a so-far untested prediction, *i.e.*, the energy loss of a quark transversing a length L of nuclear matter is proportional to L^2 (or equivalently to $A^{2/3}$). Data on more nuclei are needed to enable systematic studies of the A-dependence of nuclear attenuation effects.

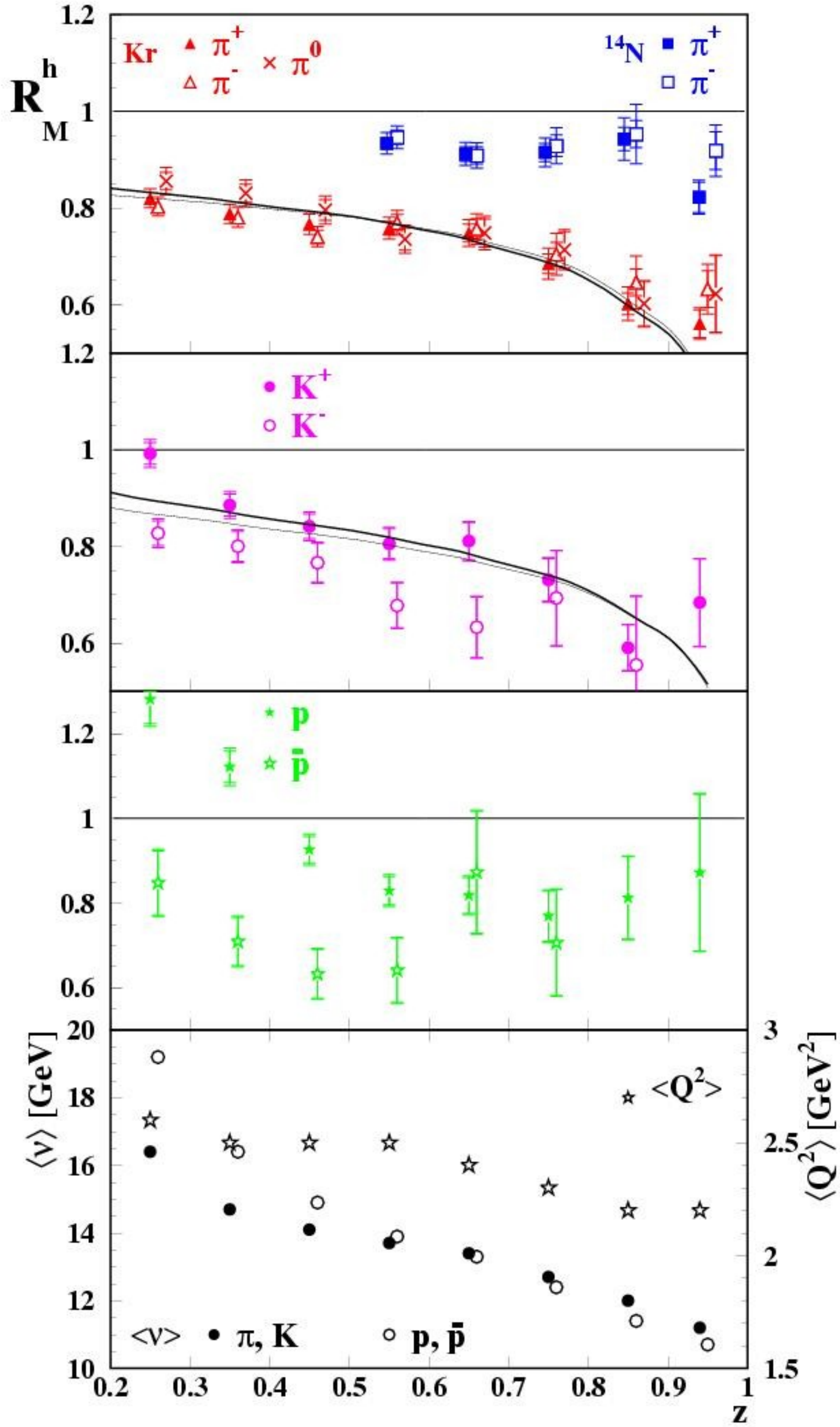

Fig. IV-7. HERMES multiplicity ratio Kr/D for various identified hadrons as a function of z. The multiplicity ratio N/D for identified pions is also shown. The thick (thin) solid lines represent recent theoretical calculations for positive (negative) charge states. The lower panel indicates the energy transfer (left vertical axis label) and square of the momentum transfer (right axis label) vs. z.

c.2.4. Azimuthal Asymmetries and Transversity (H. E. Jackson, A. El Alaoui, K. G. Bailey, T. P. O'Connor, K. Hafidi, D. H. Potterveld, P. Reimer, Y. Sanjiev, and the HERMES Collaboration)

Recent measurements of single-spin azimuthal asymmetries by HERMES have been recognized as a potentially powerful source of information about the spin structure of the nucleon,[1] complementary to inclusive deep-inelastic scattering. Significant azimuthal target-spin asymmetries in electroproduction of charged and neutral pions on a longitudinally polarized hydrogen target has been published.[2,3] It has been suggested that these single-spin asymmetries may provide information on the transversity distribution, which describes the probability to find a quark with its spin parallel or antiparallel to the spin of the nucleon that is polarized transversely to its infinite momentum. Transversity is a chiral-odd distribution function, which implies that it is not observable in an inclusive measurement. Therefore, a second chiral-odd object must be involved in the process to conserve chirality. In semi-inclusive scattering this has been postulated to be a chiral odd fragmentation function, the Collins function. The HERMES results on target single-spin asymmetries have elicited a number of phenomenological studies to evaluate these asymmetries in the framework of the Collins mechanism. Theoretical predictions have also been made for single-spin asymmetries in DIS off the nucleons in a deuterium target.

Recently it has been pointed out that a completely different mechanism might also give rise to single spin asymmetries. This effect, already suggested by Sivers[4] a decade ago, involves a T-odd distribution function. Through the admixture of $l = 1$ states an interference of amplitudes is possible, allowing the existence of the Sivers function despite its T-odd nature. The Collins and the Sivers effects are indistinguishable when scattering from a longitudinally polarized target. The additional degree of freedom , the azimuthal angle of the target spin vector ϕ_S of the target spin vector, when running with a transversely polarized target enables one to distinguish the two underlying mechanisms. The Collins mechanism results in a $\sin(\phi+\phi_S)$ modulation of the cross section whereas the Sivers effect manifests itself in a $\sin(\phi-\phi_S)$ modulation. The definitions of the azimuthial angles are given in Fig. IV-8.

HERMES is currently taking data on hadron single spin asymmetries with the goal of extracting the transversity distribution and the Sivers function from the the $\sin(\phi+\phi_S)$ and the $\sin(\phi-\phi_S)$ moments of these asymmetries. A transversely polarized hydrogen target has been installed and to date about 1200k events have been accumulated. Preliminary analysis of the data show clear signatures for both Collins and Sivers effects. HERMES will continue to take data in this mode to allow a more precise determination of these asymmetries, and to explore other channels to access transversity, *e.g.*, double-spin asymmetries in pion leptoproduction or two-hadron (interference fragmentation).

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[1]P. J. Mulders and R. D. Tangermann, Nucl. Phys. B **461**, 197 (1996).
[2]HERMES collaboration, A. Airapetian *et al*., Phys. Rev. Lett. **84**, 4047 (2000).
[3]HERMES collaboration, A. Airapetian *et al*., Phys. Rev. **64**, 097101 (2001).
[4]D. Sivers, Phys. Rev. D **43**, 261 (1991).

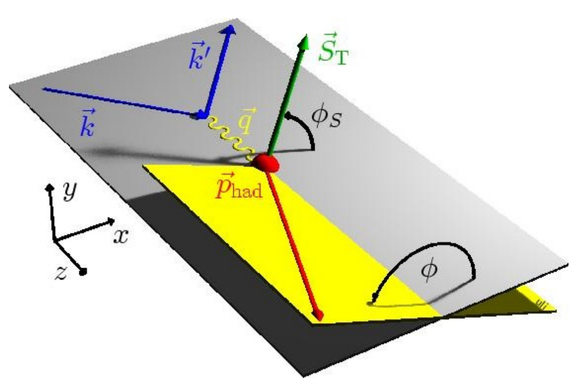

Fig. IV-8. The definitions of the azimuthal angles in deep-inelastic scattering from a transversely polarized target.

c.2.5. First Measurement of the Deuteron Tensor Polarized Structure Function b_1

(H. E. Jackson, A. El Alaoui, K. G. Bailey, T. P. O'Connor, K. Hafidi, D. H. Potterveld, P. E. Reimer, Y. Sanjiev, and the HERMES Collaboration)

The deep inelastic scattering (DIS) of leptons by nucleons is characterized by four fundamental structure functions, F_1, F_2, g_1, and g_2. The latter two require polarized beams and targets in order to be measured, and the study of g_1 has been a primary goal for HERMES. When a deuteron is the scatterer, there are four additional fundamental structure functions,[1] b_{1-4}, that arise because the deuteron has spin 1, but which were never before measured. The first, b_1, is of considerable interest. It is sensitive to differences in the quark momentum distribution between the 0 helicity (q^0) and the spin-averaged ±1 helicity ($q^+ + q^-$) states of the hadron. Of leading twist, b_1 should be identically zero for a simple composition of nucleons in the s state. However, a non-zero b_1 is possible through nuclear effects such as binding, the d state of the deuteron, and shadowing effects such as coherent double scattering.[2,3] If non-zero, it should properly be taken into account when extracting the neutron structure functions from deuterium data (hitherto it was ignored.) Moreover, a non-zero value could indicate that the quark sea becomes tensor polarized in the deuteron, which is unexpected in the naïve quark parton model.

HERMES was measured b_1 for the first time, using the same gaseous, tensor-polarized deuterium target developed for its nucleon structure function measurements.[4] An atomic beam source injected deuterium atoms of specific nuclear polarization states into a windowless storage cell in the HERA positron ring, and scattered particles were detected and identified in the HERMES detector. The tensor asymmetry of the DIS cross section, A_{zz}, is given by: $A_{zz} = [(\sigma^+ + \sigma^-) - 2\sigma^0]/(3\sigma_u T) \approx -2b_1/(3F_1)$, where σ^0, σ^+, and σ^- are the cross sections measured in the zero helicity and ±1 helicity target states, σ_u is the unpolarized cross section, and T is the degree of tensor polarization in the target. The measured tensor asymmetry and inferred b_1 are shown as a function of the Bjorken variable x in Fig. IV-9.

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[1]P. Hoodbhoy *et al*., Nucl. Phys. B **312,** 571 (1989).
[2]J. Edelmann *et al*., Phys. Rev. C **57,** 3392 (1998).
[3]K. Bora and R.L. Jaffe, Phys. Rev. D **57,** 6906 (1998).
[4]K. Ackersdtaff *et al*., Nucl. Instr. Meth. A **417,** 230 (1998).
[5]F. E. Close *et al.,* Phys. Rev. D **42**, 2377 (1990).

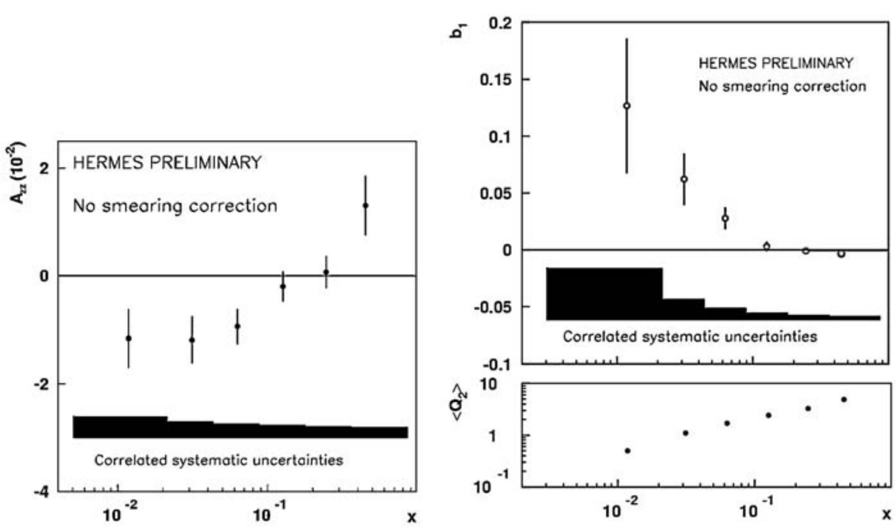

Fig. IV-9. Preliminary HERMES results for the tensor asymmetry A_{zz} (left plot) and b_1 (right plot) as a function of Bjorken x. The error bars are statistical only, and the shaded bands show the estimated systematic uncertainties. The Q^2 range of the measurements is shown in the lower panel on the right, in GeV^2.

A_{zz} is found to be less than 0.02 over the measured range, and therefore its neglect in extracting g_1 from HERMES deuterium data is estimated to cause less than a 1% error. The data indicate that b_1 is small but different from zero, with a rise at low x that is qualitatively consistent with models of coherent double scattering, suggesting a significant tensor polarization of the sea quarks that could violate the Close-Kumano sum rule.[5] Further calculations of b_1 by the theoretical community are eagerly anticipated.

c.2.6. Study of Factorization and Flavor Content of the Nucleon in Unpolarized Semi Inclusive Deep Inelastic Scattering at HERMES (K. Hafidi, A. El Alaoui, K. G. Bailey, T. P. O'Connor, H. E. Jackson, D. Potterveld, P. E. Reimer, and the HERMES Collaboration)

Semi Inclusive Deep Inelastic Scattering (SIDIS) has been used extensively in recent years as an important testing ground for QCD. Indeed, SIDIS offers a great opportunity for studying the spin and the flavor content of the nucleon. However, using SIDIS relies on the factorization assumption between the hard scattering process and the hadronization of the struck quark. Although at high energy the scattering and production mechanisms factorize, it remains unclear to what extent factorization applies at lower energies. HERMES has shown that within the experimental precision which was dominated by the statistical error, factorization works reasonably well at the HERMES kinematics conditions.[1] By accumulating an order of magnitude more statistics, it is now possible to perform a more precise test of factorization.

In this analysis, all HERMES unpolarized and averaged polarized hydrogen and deuterium data have been used. Four independent yields have been determined; $Y_p^{\pi+}(x,z)$, $Y_p^{\pi-}(x,z)$, $Y_n^{\pi+}(x,z)$ and $Y_n^{\pi-}(x,z)$ for fixed x-bins as a function of z, where z is the fraction of photon energy carried by the detected hadron. The neutron yield can be obtained from the deuteron yield via $Y_d^{\pi} = \left(Y_p^{\pi} + Y_n^{\pi}\right)/2$. Assuming isospin symmetry between protons and neutrons $u_p(x)=d_n(x), d_p(x)=u_n(x)$ as well as charge conjugation invariance $\bar{u}_p(x)=\bar{d}_n(x), \bar{d}_p(x)=\bar{u}_n(x)$, one can form two ratios in which the fragmentation functions cancel out:

$$R_1(x)=\frac{Y_p^{\pi+}+Y_p^{\pi-}}{Y_d^{\pi+}+Y_d^{\pi-}}=\frac{2}{5}\frac{4u(x)+d(x)+4\bar{u}(x)+\bar{d}(x)}{u(x)+d(x)+\bar{u}(x)+\bar{d}(x)}$$

$$R_2(x)=\frac{Y_p^{\pi+}-Y_p^{\pi-}}{Y_d^{\pi+}-Y_d^{\pi-}}=\frac{1}{3}\frac{4u(x)-d(x)-4\bar{u}(x)+\bar{d}(x)}{u(x)+d(x)-\bar{u}(x)-\bar{d}(x)}$$

Defining the valence quark distribution as: $q_v(x)=q(x)-\bar{q}(x)$ the sea contribution cancels exactly in the difference of charge multiplicities and one obtains the following expression for the valence $d_v(x)/u_v(x)$ ratio:

$$\frac{d_v(x)}{u_v(x)}=\frac{4-3R_2(x)}{1+3R_2(x)}$$

The observation of the z-scaling behavior of $R_1(x)$ and $R_2(x)$ would be a test of factorization. In such case, the yield ratios R_1 and R_2 will be a direct measurement of the quark distributions and not related to the fragmentation functions. The kinematic range is $0.02 < x < 0.6$ at the average Q^2 of 2.5 GeV^2. As it is shown in both Figs. IV-10 and IV-11, the projected statistical precision of the ongoing analysis represents a considerable improvement of our ability to check factorization. In addition, measuring d_v / u_v will provide an additional test of factorization by comparing HERMES result with QCD fit of other high energy data.

In conclusion, with the ongoing analysis, we will be able to quantify with high precision the validity of the factorization assumption. We will also extract the valence quark distribution ratio of the nucleon d_v / u_v (see Fig. IV-12) using π^+/π^- yield ratios on hydrogen and deuterium.

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[1]K. Ackerstaff *et al.*, Phys. Rev. Lett. **81**, 5519 (1998).
[2]EMC Collaboration, J. Ashman *et al.*, Z. Phys. C **52**, 361 (1991).
[3]G. T. Jones *et al.*, Z. Phys. C **62,** 601 (1994).

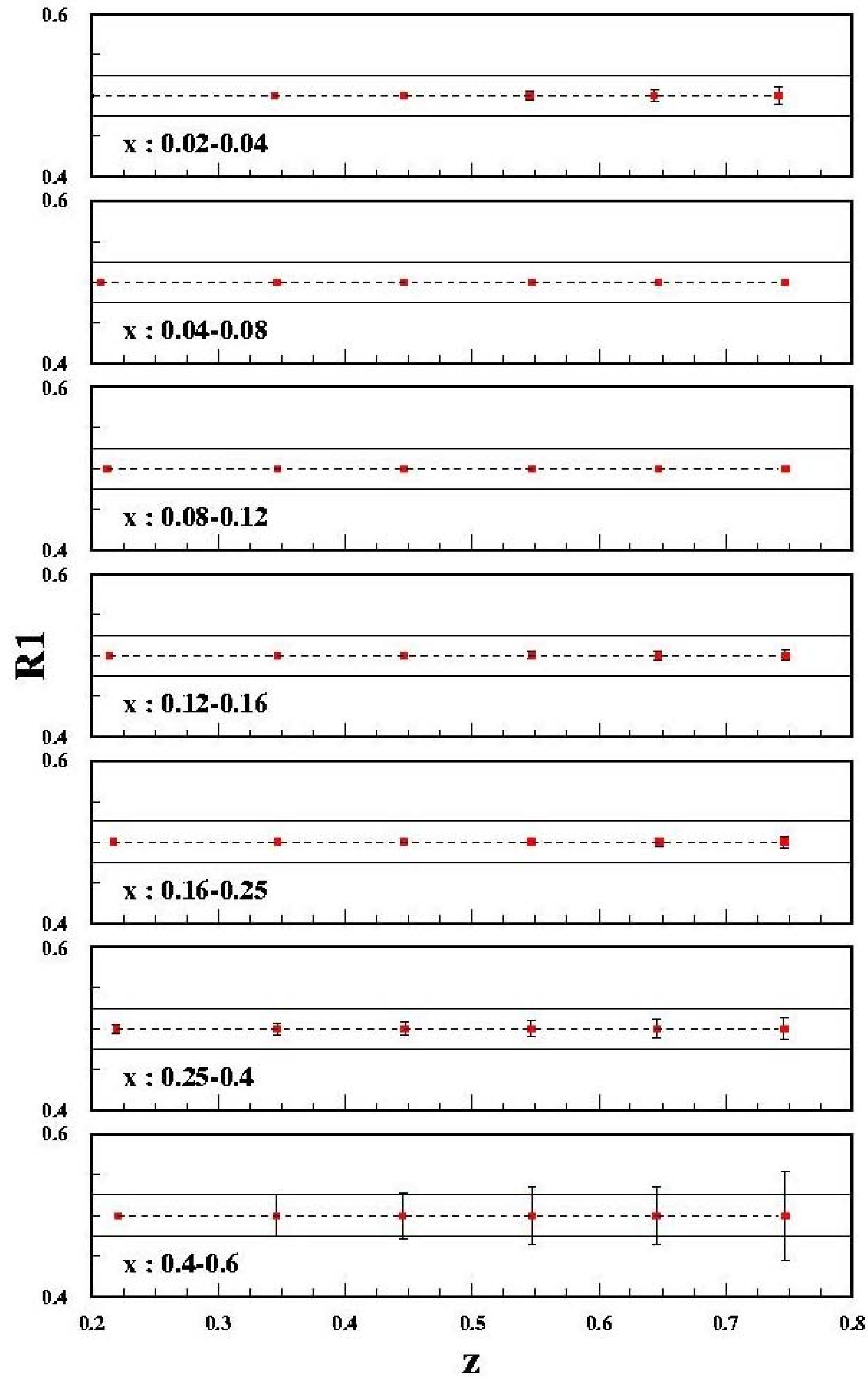

Fig. IV-10. The projected statistical precision for the R1 ratio. The solid lines reflect ±5% relative deviation from the factorization assumption.

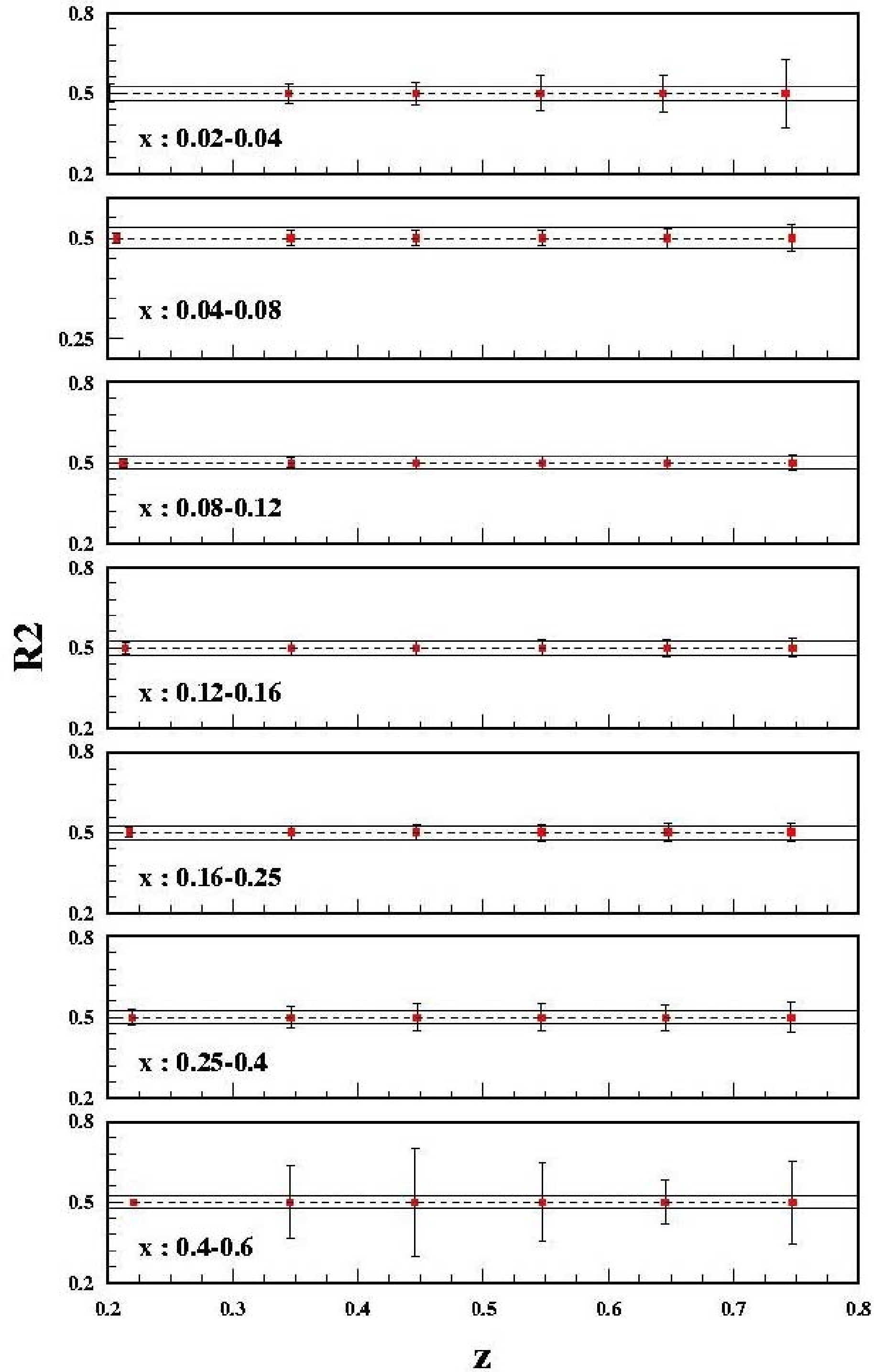

Fig. IV-11. The projected statistical precision for the R2 ratio. The solid lines reflect ±5% relative deviation from the factorization assumption.

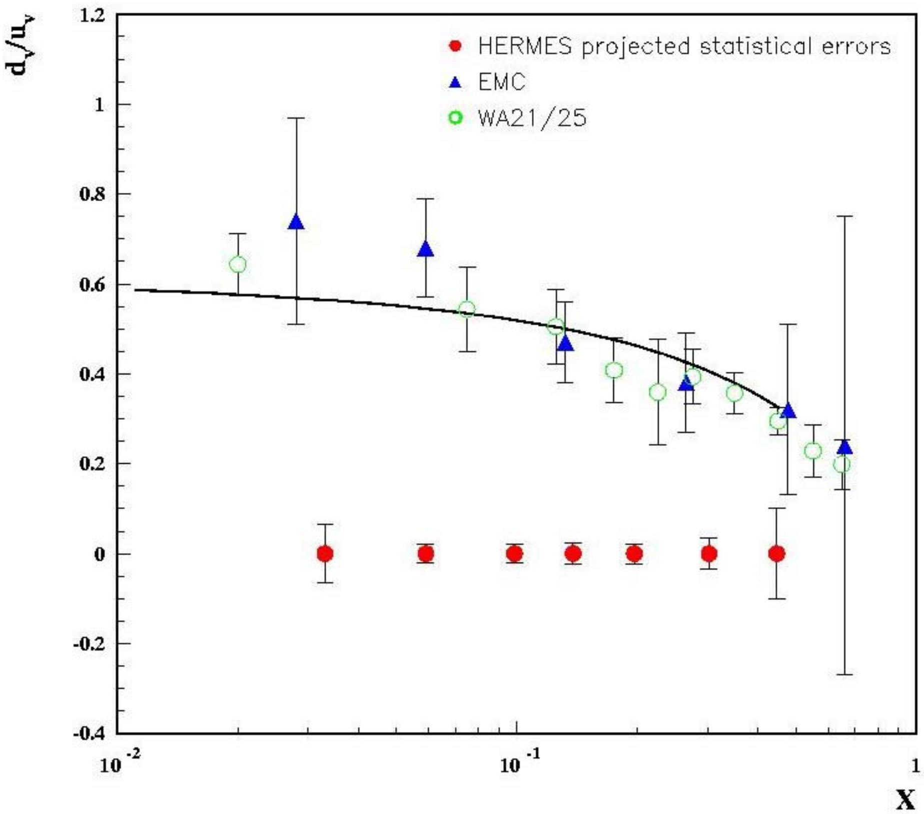

Fig. IV-12. The projected statistical precision of the ratio d_v/u_v compared with previous results from CERN.[2,3]

c.3. Measurement of the Absolute Drell-Yan Cross Section on Hydrogen and Deuterium
(P. E. Reimer, D. F. Geesaman, S. B. Kaufman, N. C. R. Makins, B. A. Mueller, and the FNAL E866/NuSea Collaboration)

Very little is known about the regime in which only one parton carries much of proton's momentum—different theoretical treatments prescribe different behaviors as $x \rightarrow 1$ (where x represents the fraction of the proton's momentum carried by the interacting parton) and there is very little data available to serve as a guide. The Drell-Yan process is sensitive to the high-x behavior of the *beam's* quarks and the low- and intermediate-x behavior of the target antiquarks. E866 has measured the absolute cross sections for *proton-proton* and *proton-deuterium* Drell-Yan. As $x \rightarrow 1$, these data are dominated by the beam proton's quark distribution of $4u(x)+d(x)$. The measured absolute cross sections, relative to a next-to-leading order (NLO) calculation are shown in Fig. IV-13. Recent work has focused on calculating the effect of radiative corrections to the Drell-Yan cross section. These corrections appear to account for approximately 4% of the effect at large-x, and intermediate-x. As can be seen in the figure, even after accounting for radiative corrections, the quark distributions used in the calculation *over predict* the measured cross sections at large-x by a significant amount.

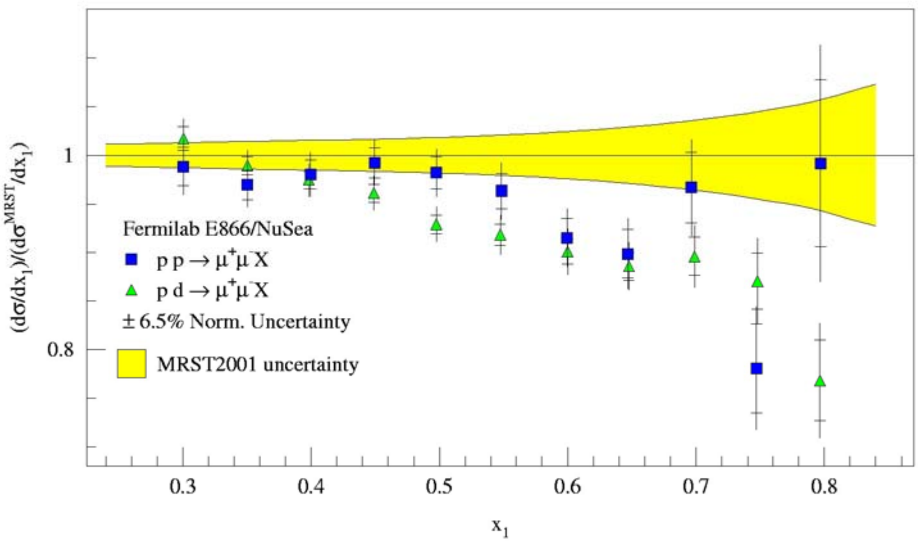

Fig. IV-13. The ratio of Drell-Yan cross section measured by Fermilab E866/NuSea for proton-deuterium (triangles) and proton-proton (squares) to calculated NLO cross section based on the MRST2001 parton distributions. The yellow band represents the uncertainty given by MRST2001 on 4u(x)+d(x).

c.4. **Drell-Yan Measurements with 120 GeV Protons, FNAL E906** (P. E. Reimer, D. F. Geesaman, J. Arrington, K. Hafidi, R. J. Holt, D. H. Potterveld, and the FNAL E906 Collaboration)

The proton and the neutron are composite objects, made of quarks, antiquarks and gluons, collectively known as partons. While many of the properties of the proton may be attributed to its three valence quarks, it is, in fact, much more complicated, with over 50% of its momentum being carried by the its non-valence (sea) quarks and gluons. To understand the structure of the proton, it is necessary to understand the sea quarks, their origins and their interactions with the gluons that bind the proton together. E906 is specifically designed to use Drell-Yan scattering to probe the sea quarks of the proton.

The Drell-Yan mechanism provides a powerful tool to study the structure of the proton at the quark level. In Drell-Yan scattering a quark (or antiquark) in the proton beam annihilates with an antiquark (or quark) in the target. The resulting annihilation produces a virtual photon that decays into a pair of leptons, which are seen in the detector. The kinematics of the detected leptons can be used to select interactions between beam valence quarks and target antiquarks. This was successfully exploited by Fermilab E866/NuSea using an 800 GeV/c proton beam provided new insight into the antiquark sea in the proton and nuclear dependence phenomena. FNAL E906 has been approved by Fermilab to extend Drell-Yan measurements to larger values of x (the fraction of the proton's momenta carried by the struck quark) using the new 120 GeV Main Injector at Fermilab. The new data obtained by this experiment will address several outstanding questions.

Vacuum polarization accounts for the creation of a flavor symmetric sea. Previous E866 Drell-Yan data, however, exhibit a large asymmetry between $\bar{d}$ and $\bar{u}$ for $x < 0.25$ (where x represents the fraction of the protons momentum carried by the interacting quark) clearly indicating a non-perturbative origin to the sea. Above $x > 0.28$ these data, albeit with poor statistical uncertainty, indicate the ratio $\bar{d}/\bar{u}$ returns to unity. This result dramatically changed the sea quark parton distribution fits and was completely unpredicted by meson cloud and other non-perturbative models. The return of $\bar{d}/\bar{u}$ to unity clearly signals a change in the mechanism by which the sea is generated. Fermilab E906 will determine $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ for $0.1 \leq x \leq 0.45$, encompassing the non-perturbative region and extending well into the region where the sea appears to return to symmetry, allowing for the study of the relative importance of the perturbative and non-perturbative sea. The current parton distributions now reproduce the previous Drell-Yan data for $0.28 < x$

<0.3, but allow $\bar{d}/\bar{u} < 1$ as *x* increases above 0.3. This is not expected by *any* models of the proton, either meson or perturbative, and is simply indicative of the complete lack of data. E906 will provide this data, as shown in Fig. IV-14.

Very little is known about the regime in which only one parton carries much of proton's momentum—different theoretical treatments prescribe different behaviors as $x \rightarrow 1$ and very little data is available to serve as a guide. Through the partons in the beam proton, Fermilab E906 will access these distributions. The Drell-Yan cross section is dominated by the distribution of $4u(x)+d(x)$ as $x \rightarrow 1$. E906 will extend the data provided by Fermilab E866 to higher *x* and provide much more precise *proton* data than is currently available.

Models based on the hypothesis that nuclear binding in governed by the exchange of mesons have been used to quite successfully describe the nuclear force. Given the success of these models, it is natural to look for direct experimental evidence for the presence of these mesons in nuclei. Thus far, however, no direct evidence has been found. If present, these mesons will lead to an enhancement of antiquarks in the nucleus, and Drell-Yan is ideally suited to measure this enhancement. Fermilab E906 will collect data using nuclear targets, in addition to hydrogen and deuterium to look for these effects.

From deep inelastic scattering (DIS) experiments, we know that the quark level structure of a nucleon within a nucleus *is* different from that of a free nucleon. In the range $0.10 < x < 0.25$, a surplus of quarks (approximately 2-4%) in nuclei, known as antishadowing, is clearly observed in DIS data. To understand these phenomena, it is important to determine if it is a general property of the quark and antiquark distributions, or just a property of the valence or sea quarks. Drell-Yan, with its ability to measure sea-only quark effects, is the ideal reaction in which to measure this. Early Drell-Yan data indicate that this surplus might not be present, but with poor statistical uncertainty (3-5%). Fermilab E906's measurements will clearly determine if there is antishadowing in the sea, with statistical uncertainties of less than 1% throughout this region (see Fig. IV-14).

Using the same nuclear target data, Fermilab E906 will also study the propagation of colored partons in strongly interacting, cold nuclear matter. By comparing the Drell-Yan yields from different nuclear targets and looking for apparent shifts in the beam parton's momentum distributions between nuclei, E906 will be able to measure the beam parton's energy loss. Previous Drell-Yan studies have placed upper limits on parton energy loss. With increased sensitivity from the 120 GeV beam and better statistical accuracy, Fermilab E906 will turn these upper limits into measurements. These measurements will aid in the understanding of jet suppression data from RHIC.

FNAL E906 is able to make these improvements over previous measurements because of the lower beam energy available at the Fermilab Main Injector. For fixed x_{beam} and x_{target} the cross section scales as the inverse of the beam energy. Thus a factor of seven more events for the same integrated luminosity can be achieved. At the same time, the primary background to the measurement, muons from J/ψ decays, decreases with increasing beam energy, allowing for an increase in instantaneous luminosity by another factor of seven. These two factors combine to provide roughly 50 times more events for the same beam time.

FNAL E906 has been approved by the Fermilab PAC and will begin collecting data in 2009. In the mean time, a number of new detector elements must be constructed, the most significant of which is a new large dipole magnet to focus the Drell-Yan muons.

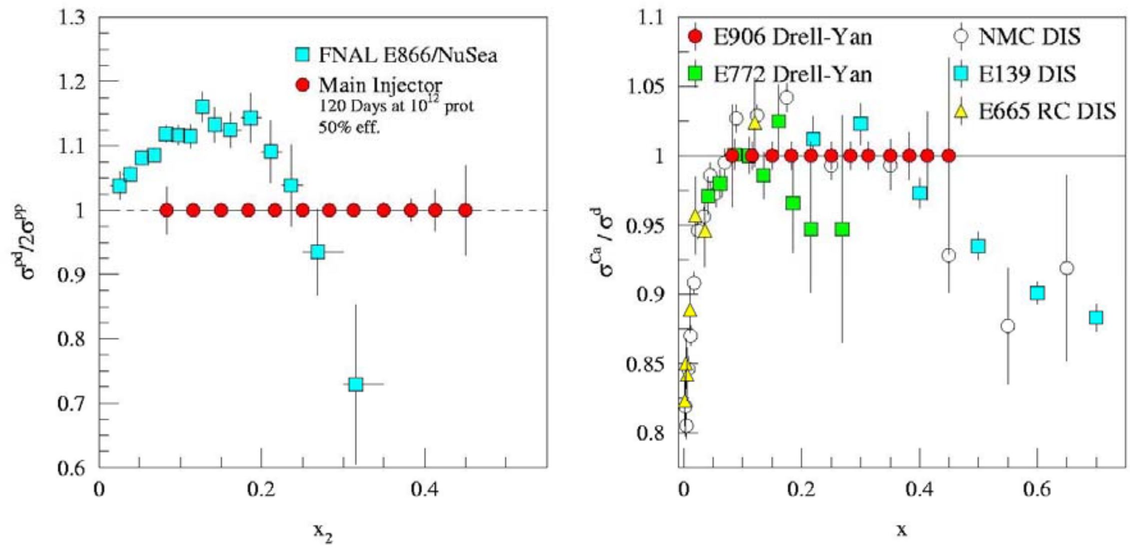

Fig. IV-14. The statistical uncertainty of E906's measurement of the ratio of hydrogen to deuterium cross sections (arbitrarily plotted at 1) compared with the E866 measurements of the same quantity (left). The statistical uncertainty of E906's measurement of the ratio of deuterium to Calcium cross sections (arbitrarily plotted at 1) compared with previous Drell-Yan and deep inelastic scattering (DIS) measurements (right).

D. ATOMIC TRAP TRACE ANALYSIS

d.1. One Million Year Old Groundwater in the Sahara Revealed by Krypton-81

(Z.-T. Lu, A. M. A. Abdallah,* K. Bailey, R. Becker,† T. Bigler,‡ Y. Dawood,* X. Du,§ Z. El Alfy,¶ B. El Kaliouby,* B. E. Lehmann,‡ R. Lorenzo,‡ P. Mueller, T. P. O'Connor, J. Patterson,|| R. Purtschert,‡ N. C. Sturchio, || M. Sultan,† and L. Young**)

One of the more challenging problems in earth sciences is to determine the residence times and flow velocities of groundwater circulating deeply through Earth's crust. It has been known for decades that ^{81}Kr (half-life = 229,000 year), which is produced by cosmic ray-induced spallation in the atmosphere, could be an ideal chronometer for determining fluid residence times on the 10^5-10^6 year time scale. However, since ^{81}Kr is such a rare isotope (isotopic abundance ^{81}Kr/Kr ~ 10^{-12}), it has been extremely difficult to measure its abundance.

Atom Trap Trace Analysis (ATTA), a laser-based method first demonstrated in 1999 in this Division,[1] has been developed to count individual atoms of ^{81}Kr and measure its abundance. In 2003, we have completed the development and calibration of the second generation ATTA system for ^{81}Kr analysis,[2] and have successfully performed the first application of this new method by determining the mean residence time of old groundwater in the Nubian Aquifer located underneath the Eastern Sahara Desert.[3]

In the first application of ATTA to a groundwater study, this collaboration of physicists and geologists from the U.S., Switzerland, and Egypt made an expedition to the Western Desert of Egypt to sample Kr from the Nubian Aquifer groundwater, which is reputedly old but previously of unknown age. Following extraction of Kr from thousands of liters of water at six deep wells, the ^{81}Kr/Kr ratios measured by ATTA indicated groundwater ages ranging from 200,000 to 1,000,000 yr. (Fig. IV-15). These results revealed the age and hydrologic behavior of this huge aquifer, with important implications for climate history and water resource management in the region. With this demonstration, widespread application of ^{81}Kr in earth sciences now appears feasible.

*Ain Shams University, Cairo, Egypt, †SUNY, Buffalo, ‡University of Bern, Switzerland, §ANL and Northwestern University, ¶Egyptian Geological Survey and Mining Authority, Cairo, Egypt, ||University of Illinois at Chicago, **Chemistry Div, ANL.

[1]C. Y. Chen *et al*., Science **286**, 1139 (1999).
[2]X. Du *et al*., Geophys. Res. Lett. **30**, 2068 (2003).
[3]N.C. Sturchio *et al*., Geophys. Res. Lett. **31**, 5503 (2004).

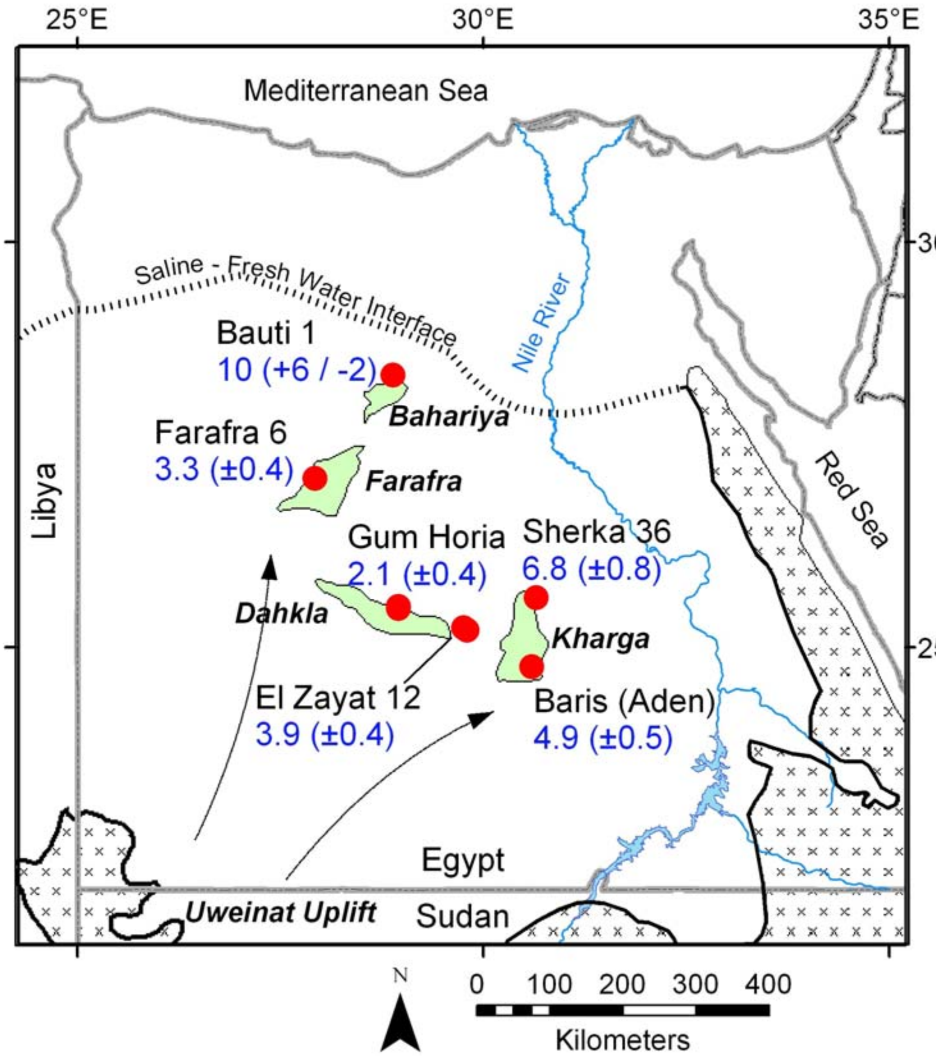

Fig. IV-15. Map showing sample locations (red circles) and their ^{81}Kr ages (in units of 10^5 years) in relation to oasis areas (shaded green), Precambrian basement outcrops (patterned), and other regional features. Groundwater flow in Nubian Aquifer is toward northeast.

d.2. ^{41}Ca Analysis for Biomedical Applications (Z.-T. Lu, K. Bailey, J. P. Greene, I. D. Moore, P. Mueller, T. P. O'Connor, L. Young,* C. Geppert,† and K. D. A. Wendt†)

Calcium is one of the most abundant elements on earth, and is of vital importance for the metabolism of biological organisms. Consequently, the analysis of its long-lived radioactive isotope, ^{41}Ca (half-life = 103,000 year), has important applications in both earth and life sciences. Cosmogenic ^{41}Ca is a candidate for dating bones ranging from fifty thousand to one million years of age. On the other hand, man-made ^{41}Ca tracer can be used to monitor the bone-loss and retention rates of human subjects in both research and diagnosis of osteoporosis. Indeed ^{41}Ca analyses for biomedical applications are successfully performed using Accelerator Mass Spectrometry (AMS) at several high-end (energy ~ 10 MeV) facilities.

In 2003, we successfully demonstrated a new ATTA system for the analysis of ^{41}Ca/Ca in biomedical samples.[1] ATTA was used to count individual atoms of ^{41}Ca present in biomedical samples with isotopic abundance levels between 10^{-8} and 10^{-10} (Fig. IV-16). ATTA was calibrated against Resonance Ionization Mass Spectrometry, demonstrating a good agreement between the two methods. The present ATTA system has a counting efficiency of 2×10^{-7}. Within one hour of observation time, its 3-σ detection limit on the isotopic abundance of ^{41}Ca reaches 4.5×10^{-10}. A more challenging and distant goal for this research is to push the detection sensitivity down to the natural isotopic abundance level of $^{41}Ca/Ca \sim 10^{-15}$ and perform ^{41}Ca-dating of ancient bones.

*Chemistry Div., ANL, †Institut fur Physik, Johannas Gutenberg-Universitat Mainz, Germany.
[1]I. D. Moore *et al.,* Phys. Rev. Lett. **92**, 153002 (2004).

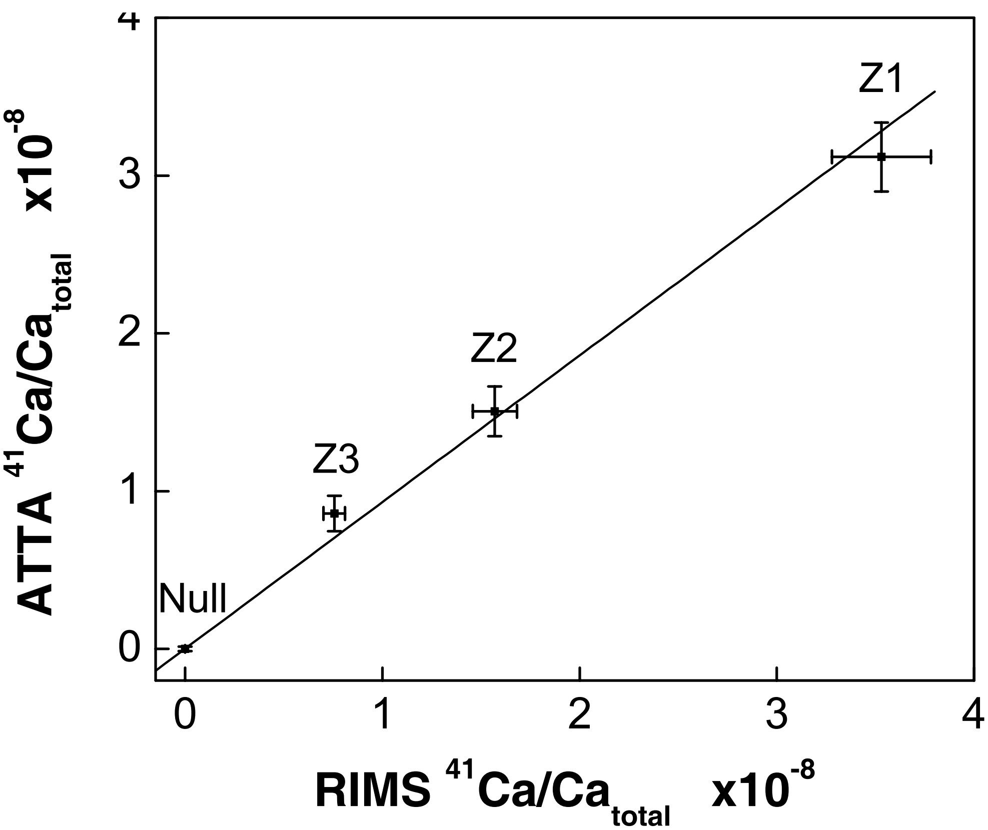

Fig. IV-16. Comparison between ATTA and RIMS results on biomedical samples. Sample Z1, Z2 and Z3 are biomedical samples provided by the Osteodiet project. Sample Null is a non-enriched calcium nitrate solution. A best-fit line to the data yields a reduced chi-squared value of 1.0.

d.3. Laser Spectroscopic Determination of the Nuclear Charge Radius of ^{6}He

(Z.-T. Lu, K. Bailey, G.W.F. Drake,* J. Greene, D. Henderson, R. J. Holt, R. V. F. Janssens, C. L. Jiang, P. Mueller, T. P. O'Connor, R. C. Pardo, M. Paul,† K. E. Rehm, J. P. Schiffer, X. Tang, and L.-B. Wang‡)

Laser spectroscopic measurements of atomic isotope shifts offer unique access to probe the nuclear charge distribution of short-lived isotopes. Here we present a new high-resolution technique based on laser spectroscopy of single atoms in a magneto-optical trap (MOT). The isotopes of interest are ^{6}He ($t_{1/2}$ = 807 ms) and ^{8}He ($t_{1/2}$ = 119 ms), which exhibit a loosely bound neutron halo around a ^{4}He like core. Charge radii measurements of these isotopes will provide corroboration for their halo structure and test theoretical models of light nuclei. In particular, they will probe the isospin 3/2 part of the three-nucleon force.

The atomic structure of helium can be calculated very precisely, which is in this case a precondition for extracting the difference in nuclear charge distribution. The isotope shifts are dominated by the mass effect, causing shifts of tens of GHz. The contribution of the change in charge radii is only on the order of 1 MHz. Consequently, the isotope shifts have to be measured with an error much smaller than 1 MHz and nuclear masses have to be accurately known to calculate the mass effect.

Measurements on ^{6}He and ^{8}He require an on-line experiment with extremely high sensitivity and selectivity. To achieve this a MOT setup has been constructed for trapping helium using the closed 2s $^3S_1$ – 2p $^3P_2$ transition at 1083 nm out of the metastable triplet state. The metastable atoms are populated in a RF driven discharge source and decelerated in a Zeeman slower for efficient trapping. The overall trapping efficiency is on the order of 10^{-8}. Single atom detection and isotope shift measurements are performed using the 2s $^3S_1$ – 3p $^3P_2$ transition at 389 nm.

In a recent on-line run with the MOT setup at the ATLAS facility at Argonne single atoms of ^{6}He were successfully trapped and detected at a rate of up to 200 atoms per hour (see Fig. IV-17). This number agrees well with the rate expected from the overall trapping efficiency and the ^{6}He production rate at ATLAS of about 10^6/s. The spectroscopic precision achieved for determining the line center of the ^{6}He transition was better than 100 kHz. Furthermore, off-line tests were conducted with the stable isotopes ^{4}He and ^{3}He. Measurements of the fine structure splitting in ^{4}He and the ^{4}He – ^{3}He isotope shift yielded an accuracy of better than 100 kHz for the MOT results. While data analysis is still in progress, the final uncertainty on the nuclear charge radius of ^{6}He based on existing data is expected to be 1-2%.

*University of Windsor, Canada, †Hebrew University, Jerusalem, Israel, ‡University of Illinois, Urbana, and ANL.

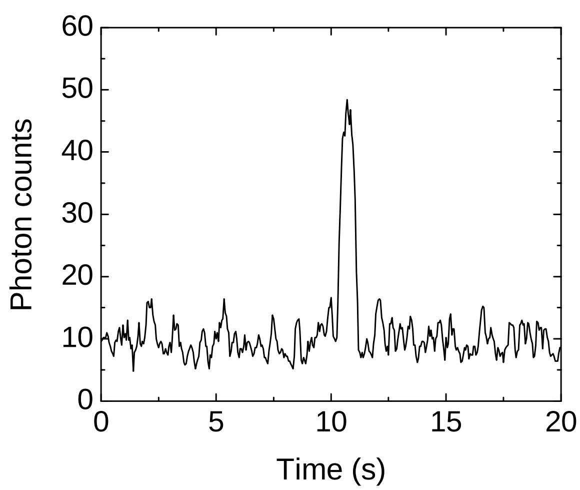

Fig. IV-17. The fluorescence signal of a single trapped metastable ^{6}He atom. The count rate of the 389 nm fluorescence photons emitted from a single trapped atom is 35 counts in 30 ms, or $1 \times 10^3\ s^{-1}$ while the rate of background photons scattered off walls and windows is at $3 \times 10^2\ s^{-1}$.

E. TESTS OF FUNDAMENTAL SYMMETRIES

e.1. Optical Trapping of Radium and the Electric Dipole Moment (R. J. Holt, I. Ahmad, K. Bailey, Z.-T. Lu, T. O'Connor, D. H. Potterveld, E. C. Schulte, and N. Scielzo)

We propose to investigate the feasibility of laser trapping and cooling of radium-225 (^{225}Ra) atoms. The realization of this proposal would enable us to measure the electric dipole moment (EDM) of ^{225}Ra and test the fundamental time-reversal symmetry (T-symmetry). The violation of time-reversal symmetry is among the most fundamental issues in physics. It is strongly believed that the underlying mechanism of the violation of T-symmetry holds the key to new physics beyond the Standard Model.

Radium-225 is an especially good case for the search of the EDM because it has a relatively long lifetime ($t_{1/2}$ = 14.9 d), has spin ½ which eliminates systematic effects due to electric quadrupole coupling, is available in relatively large quantities from the decay of the long-lived ^{229}Th ($t_{1/2}$ = 7300 yr), and has a well-established octupole nature. The octupole deformation increases the enhancement of the atomic EDM by increasing the Schiff moment collectively and by the parity doubling of the energy level. For example, the sensitivity to T-odd, P-odd effects in ^{225}Ra is expected to be a factor of several hundred larger than in ^{199}Hg, which has been used by previous searches to set the lowest limit (< 2 x 10^{-28} e cm) so far on the atomic EDM.

The FY2003 milestone of observing a ^{225}Ra beam emerging from an oven into the vacuum system was met. A three-dimensional Monte Carlo simulation atoms propagating from the oven system and into a Zeeman slower and magneto-optical trap was developed and used to optimize the design. The slower and trap are presently under construction.

e.2. Measurement of $sin^2\theta_W$ through Parity Violation in Deep Inelastic Scattering on Deuterium (P. E. Reimer, J. Arrington, K. Hafidi, R. J. Holt, H. E. Jackson, D. H. Potterveld, E. C. Schulte, and X. Zheng)

One of the basic parameters of the Standard Model is $sin^2\theta_W$, which represents the relative coupling strength of the weak and electromagnetic forces. The value of this parameter is predicted to vary (or run) as a function of Q^2, the energy at which it is probed. Measurement of this "running" provides a strict test of the Standard Model. At an energy equivalent to the mass of the Z-boson ($Q^2 = M_z^2$), $\sin^2\theta_W$ is very well known; but away from this Q^2, only a few other measurements exist. The asymmetry from parity violation in polarized electron-deuterium deep inelastic scattering (DIS) is proportional to $sin^2\theta_W$ and relatively large ($A_d \approx 10^{-4}$ Q^2), making it experimentally quite accessible. Historically, DIS parity violation from a deuterium target was first observed by Prescott *et al.* at SLAC in the mid-1970 and was used to establish the Weinberg-Salam model. Investigations are underway to repeat this experiment, focusing on facilities at an upgraded 12 GeV Jefferson Laboratory, with a preliminary 6 GeV measurement. Interest in $sin^2\theta_W$ has burgeoned recently after the NuTeV collaboration at Fermilab found a *three standard deviations* difference between the Standard Model and their neutrino-iron measurement of $sin^2\theta_W$ at $Q^2 \approx 20$ GeV^2. In a relatively short experiment, a DIS parity violation experiment could achieve the statistical sensitivity needed to investigate the NuTeV result, and using a deuterium target, it will not suffer from the uncertainties in nuclear effects and nuclear parton distributions present in the NuTeV iron measurement.