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I

INTRODUCTION

This report summarizes experimental work in basic nuclear physics carried out between October 1, 2000, and February 14, 2004 at the Nuclear Physics Laboratory of the University of Colorado, Boulder, under contract DE-FG03-95ER-40913 with the United States Department of Energy.

II EXPERIMENTAL PROGRAM

A. NUCLEON SPIN STRUCTURE AND EXCLUSIVE REACTIONS

1. The HERMES Experiment – Overview

J.T. Brack, J. Ely, B. Fox, D. Gaskell, G. Hofman, E.R. Kinney, A. Kisselev, M. Pallas, U. Stössllein (University of Colorado), The HERMES Collaboration

The HERMES experiment is designed to use deep inelastic scattering of polarized electrons from polarized targets to study the quark spin distributions within the nucleon. Earlier experiments found that only 30-40% of the nucleon spin is carried by the quarks, which is surprising given the simple explanation of the baryon static magnetic moments in terms of simple quark spin wavefunctions. In general, one expects the spin to arise from the spins of the up, down, and strange quarks, ΔU , Δd , and Δs respectively, as well as a contribution from the gluonic field ΔG and the angular momentum of the quarks L_q , as shown in the following heuristic formula:

$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + \Delta G + L_q.$$

Inclusive lepton scattering basically determines the sum from the quark spins only, though there is a contribution coming from the gluons via the axial anomaly. In fact, in the simple quark model, the spin structure function g_1 is just the difference between the distributions of quarks polarized parallel and antiparallel to the nucleon spin, summed over the quark flavors. These distributions are function of Bjorken x which can be thought of as the momentum fraction of the nucleon carried by the quark (strictly true in the infinite momentum frame).

In contrast to inclusive lepton scattering experiments at SLAC and CERN, the HERMES experiment uses a pure polarized gas internal target, through which the 27.5 GeV electron (or positron) beam of the HERA synchrotron passes. The electrons are polarized in the ring via the radiation of synchrotron light which has a spin dependent asymmetry in the production rate. The transverse polarization so produced is rotated into and out of the direction of the beam momentum by a magnet chicane before and after the experiment; a schematic of the HERA ring configuration is shown in Fig. 1.1.

Typical beam polarizations were in the range 50%–60%, occasionally reaching 70%. Fig. 1.2 displays the average polarization per fill for the period 1996–2000.

Figure 1.1: Schematic of the HERA electron and proton rings.

Figure 1.2: Average polarization of electrons(positrons) for each fill of the Electron storage ring at HERA.

In spring 2001 the HERA luminosity upgrade was completed and the accelerator began re-commissioning. Unfortunately, this commissioning has been long and arduous, requiring several shutdowns and extensive accelerator studies. In Fall 2002, the accelerator began a somewhat better mode of operation, delivering beam to HERMES and the HERA-B experiment several days each week. Backgrounds at the collider experiments ZEUS and H1 remain extremely high however, and further studies were needed to support a 4 month shutdown in spring 2003, which is hoped to bring the operations close to the goals of the luminosity upgrade. The shutdown work was completed in July 2003, and at present, injection of positrons is underway.

HERMES has published its measurements of g_1 on both proton and neutron (^3He) targets; preliminary results of the measurement of g_1^d from deuterium are being prepared for publication. The results are in agreement with those of the other experiments, confirming that the contribution of the quarks helicities to the nucleon spin is small. Figure 1.3 shows the x weighted spin structure function g_1 from hydrogen, deuterium and ^3He . In addition, the unique capabilities of the HERMES polarized deuterium target have been used to make the first measurement of the tensor spin structure function $b_1(x)$. This structure function is directly related to nuclear properties as opposed to those of a nucleon. Both deuteron structure functions are discussed below.

HERMES has moved beyond these inclusive measurements because of its use of an open geometry spectrometer instrumented to identify hadrons as well as the scattered leptons. This allows the measurement of so-called semi-inclusive reactions where a high energy hadron is detected in coincidence with the scattered lepton, as shown schematically in Fig. 1.4

Since the hadron type is correlated with the type of quark which absorbed the virtual photon, one can deduce the fraction of the quark spin carried by the various quark flavors. In late 1999 a flavor decomposition of the spin using the hydrogen and ^3He data sets was published which is at present the most direct determination of the contributions from up, down, and sea quarks, since the original work of the SMC experiment. These data sets had only limited hadron identification information from the gas threshold Čerenkov detector then in use; now the spectrometer has been upgraded to identify pions, kaons, and protons, using the world's first dual radiator RICH detector using a new ultraclear aerogel. It is now possible to measure kaon semi-inclusive asymmetries which will allow the world's most direct measure of the strange quark contribution to the nucleon spin. The data collection in 1999–2000 was especially successful, with nearly twice the statistics expected, as shown in Figure 1.5. A new preliminary extraction of the flavor decomposition using all of the deuterium data set has been performed using the pion and kaon asymmetries, and is presented below.

In addition to the longitudinal spin structure functions discussed above, additional spin-

Figure 1.3: Compilation of the World's measurements of xg_1 from proton, deuteron and ^3He polarized targets.

Figure 1.4: Schematic of a deep inelastic scattering reaction.

distribution functions have been identified, but remain unmeasured. One of these is called transversity and corresponds to the distribution of transverse quark spin in a nucleon polarized transverse to its (infinite) momentum. This and related distribution functions are predicted to be measurable via single-spin asymmetries, where only the beam *or* target are polarized, in certain lepton and hadron scattering experiments. During the 2000–2001 HERA shutdown, a transversely polarized hydrogen target has been installed at the HERMES interaction point in order to make a first measurement of the transversity. Using the small data set collected in 2001, it has been possible to extract a single spin asymmetry; first results are expected to be released in the fall of 2003.

In simple models based on hadrons consisting of non-interacting collinear partons (quarks and gluons), single-spin asymmetries are expected to vanish. This follows from the conservation of parity, total angular momentum and helicity of the individual partons. Correspondingly, in the language of perturbative QCD, single-spin asymmetries vanish at the “twist-2” level, i.e. when multi-parton correlations and parton transverse momenta internal to hadrons are ignored. However, single-spin asymmetries have been observed in a few hadron-hadron scattering experiments. In these measurements, a scattered hadron was detected with a momentum transverse to the beam direction in the range $P_\perp \simeq 1\text{--}2$ GeV, which is not much larger than either the scale parameter of QCD ($\Lambda_{QCD} \sim 0.2$ GeV) or typical parton transverse momenta of a few hundred MeV. Therefore these asymmetries may arise from non-collinear parton configurations or from multi-parton correlations (“higher twist” effects), which are suppressed at large $P_\perp$ where perturbative QCD becomes effective.

Hermes Running 1996-2000

Figure 1.5: Integrated HERMES Luminosity for runs in 1996–2000.

Transversity and related spin-distribution functions are as yet unmeasured because their unusual chiral-odd structure implies that they are not directly observable in inclusive lepton-nucleon scattering experiments. However, it has been suggested by Collins *et al.* that the needed sensitivity can be provided by semi-inclusive production of pions with modest $P_\perp$. An observable single-spin dependence is predicted to appear in the dependence of the cross section on the angle between the spin axis of a *transversely* polarized target and the plane defined by the virtual photon momentum and the momentum of the pion (known as the Collins angle). Here the pion is produced from the struck quark in soft processes described by a fragmentation function having a chiral-odd structure like that of the spin-distribution functions of interest. This Collins fragmentation function describes how the probability for producing a pion depends on its direction with respect to the direction of transverse polarization of the struck quark. It has also a time-reversal odd structure resulting from the final-state interactions in the fragmentation process, rather than from any fundamental violation of time-reversal invariance. Such T-odd fragmentation (and distribution) functions can thus be considered as effective parameterizations of specific complex processes. There is preliminary evidence from $Z^0 \rightarrow 2$ -jet decay that the Collins fragmentation function has a substantial magnitude – of order 10% of the well-known chiral-even spin-independent one. If this can be confirmed, it could provide experimental sensitivity to the transverse polarization of scattered quarks in future experiments designed to make the first measurements of transversity.

Figure 1.6: Schematic of reaction and kinematics in the Azimuthal Asymmetry

In the case of semi-inclusive pion production in lepton scattering from a *longitudinally* polarized nucleon, chiral-odd quark spin-distribution functions closely related to transversity can be manifest. In such experiments, the Collins angle becomes the azimuthal angle ϕ of the pion around the virtual photon direction, with respect to the lepton scattering plane. Recent theoretical studies by P. Mulders *et al.* have shown how each chiral-odd spin-distribution function coupled with the Collins fragmentation function gives rise to a specific single-spin dependent moment of the pion yield distribution in ϕ .

Figure 1.7: Analysing power in the $\sin \phi$ moment for π^+ , π^0 , π^- and K^+ mesons for deuterium (solid circles) and hydrogen (open squares) targets. The results are plotted as a function of the meson fractional energy z , the Bjorken variable x and of the meson transverse momentum P_T . Error bars include the statistical uncertainties only. The upper bands at the bottom of the panels represent the systematic uncertainties for the moments from the hydrogen target; the lower bands represent the systematic uncertainty for the moments from the deuterium target.

The kinematics of the process are illustrated in Fig. 1.6. The relevant variables are the 4-momentum transfer squared $-Q^2 = q^2 = (k - k')^2$, the energy transfer $\nu = E - E'$, the virtual photon fractional energy $y = \nu/E$, the invariant mass of the photon-proton system $W = \sqrt{2M\nu + M^2 - Q^2}$, the Bjorken variable $x = Q^2/2M\nu$, and the pion fractional energy $z = E_\pi/\nu$. Here k and k' are the 4-momenta and E and E' the laboratory energies of the incoming and outgoing leptons, respectively. E_π is the pion laboratory energy and M the proton mass. The transverse momentum ($P_\perp$) of the pion is defined with respect to the virtual photon direction in the initial photon-proton center-of-mass frame.

Figure 1.8: World's measurement of the photon asymmetry A_1 from DIS on the proton compared with HERMES results from the resonance region, as a function of x . The curve is a power law fit to the data at $x > 0.3$.

The first observation of a $\sin\phi$ moment from semi-inclusive π^+ , π^0 and π^- electroproduction was reported in 2001 by the HERMES collaboration. An analysis of the azimuthal asymmetry in from the pions and also K +s has now also been performed for both hydrogen and deuterium targets. The $\sin\phi$ moment as a function of z , x and $P_\perp$ is shown in Fig. 1.7. Such relatively large asymmetries for the longitudinal case suggest that transverse asymmetries will be large and easy to accurately measure. The apparent increase of $A_{UL}^{\sin\phi}$ with increasing x suggests that the sea contribution does not dominate the effect, in agreement with existing interpretations of single-spin asymmetries as being associated with valence quark contributions.

Recently Brodsky, Hwang and Schmidt have suggested that these asymmetries may arise from a gluon exchange in the final state. These can be related to the so-called Sivers distributions developed in the study of the Drell-Yan reaction. HERMES will be able to disentangle the two affects using the fact that the the Sivers-type asymmetry goes as $\sin \phi_h - \phi_s$ while the Collins asymmetry goes as $\sin \phi_h + \phi_s$, where ϕ_h is the azimuthal angle between the lepton scattering plane and the hadron production plane, and ϕ_s is the azimuthal angle between the scattering plane and the target spin vector.

Several other interesting results have been found in the last year using the existing data set. The first involves the use of the now well known polarized DIS asymetries to directly measure the polarization of molecules in the target. The polarized atomic hydrogen (or deuterium) which is injected in to the target cell contains a small fraction of molecules which arise from recombination of the polarized atoms. It has been extremely difficult to find a means of determining the average nuclear polarization within these molecules. The results are presented below. The second result uses data from polarized scattering in the nucleon resonance region, $W < 2$ GeV. This kinematic region is excluded from the measurements of deep inelastic scattering because of the limited energy available in the hadronic final state, which might affect the scattering process from “free” partons. The recent resurgence in the study of Bloom-Gilman duality fostered by the experimental program of C. Keppel *et al.* at Jefferson Lab has led to an investigation of whether the polarized cross sections exhibit the same duality. Bloom-Gilman duality is observed if one shows that inclusive scattering from the resonance region, when average over finite ranges in W agrees with the deep inelastic scattering at the same x or more properly ξ . The HERMES data for the photon asymmetry A_1 from the proton, shown in Fig. 1.8, do exhibit this behavior. If one accepts that scaling does exist, then one has infact determined A_1 at high values of x which would be extremely difficult to measure directly.

One of the unexpected frontiers encountered by the HERMES experiment is the explosion of interest in exclusive reactions, initiated by deeply virtual photons, and resulting in a final state of a nucleon and a single meson or photon. This interest has been driven by theoretical proof of factorization of the amplitudes for these processes into a hard scattering part governed by QED and soft parton distribution functions which describe the structure of the target nucleon and the meson. A new formalism has been developed to describe these reactions; the new soft parton distributions for the nucleon are known as Generalized Parton Distributions (GPD). In addition to dependence on the longitudinal momentum fraction of the parton, these new distributions also depend on the momentum transfer t to the nucleon, and hence explore quark-quark and quark-gluon correlations. In the limit of zero momentum transfer, the GPDs are just the regular parton distribution functions of DIS; if integrated over the longitudinal

Figure 1.9: The isoscalar-corrected ratio R_A/R_D for several nuclei (A) with respect to deuterium as a function of Q^2 for four different x bins. The open triangles (^{12}C) and crosses (^4He) have been derived from NMC data. The other SLAC and NMC data displayed have been derived from published values of $\Delta R = R_A - R_D$ and a parameterisation for R_D . The inner error bars represent the statistical uncertainty and include the correlated error in F_2^A/F_2^D . The outer error bars represent the quadratic sum of the statistical and systematic uncertainties. In the upper panel the HERMES results at the lowest Q^2 value have been suppressed because of its large error bar.

momentum fraction dependence, one gains the elastic form factors. Thus one set of functions is able to connect these different facets of nucleon structure. The cleanest reaction to study in terms of the soft/hard separation is that in which there is a hard (real) photon in the final state, known as Deeply Virtual Compton Scattering, which is discussed in some detail below. HERMES has also studied exclusive reactions leading to single pions and vector mesons in the final state.

The HERMES experiment also has a strong program studying the production cross sections and tensor polarization observables of the vector mesons ρ^0 , ϕ , ω and J/Ψ .

In addition to its spin program, HERMES also is approved to measure reactions on unpolarized gas targets which have the advantage of high density. For example, semi-inclusive measurements on H,D, and ^3He have yielded a determination of the asymmetry in the distributions of the light sea quarks. In addition to these light nuclei, event data has been collected from ^4He , ^{14}N , ^{20}Ne , and ^{84}Kr .

Measurements of the ratio of inclusive yields from ^{14}N and ^2H have been studied to investigate a possible nuclear dependence at very low Q^2 . When this analysis was extended to include the new krypton data, it became apparent that some discrepancy existed between the raw data and that corrected for radiative effects. In the end, it was found that events in which a high energy photon was radiated tended to cause a shower in the tracking chambers which resulted in the removal of the event from the data stream. The radiative corrections applied to the collected yields were calculated assuming such events were included in the data set. This discrepancy has been removed and the corrected results for the and the new results from krypton are shown in Fig. 1.9.

These data have also been used to determine the energy dependent attenuation of hadrons as they traverse the nuclear medium. These results, discussed below, not only help understand the process of hadronization but also supply useful empirical data for understanding the heavy ion collisions at RHIC. New studies underway at Colorado hope to characterize the broadening of the p_T spectrum in light hadrons created within the nuclear medium; initial results are also presented below.

1.a The Deuteron Spin Structure Function g_1^d

U. Stösslein (University of Colorado), The HERMES Collaboration

A primary goal of the 1999-2000 run was the collection of a high statistics measure of polarized inclusive DIS from vector polarized deuterium. As mentioned in the overview, the actual data collection was very successful. In order to check the data at a high level of analysis,

a subset of the entire set consisting of the data collected in spring 1999 was isolated and the spin structure function g_1^d extracted. This analysis has been extended to allow the extraction of g_1^d at low values of x and Q^2 from the full data set. This extended analysis requires a careful correction of the data for the effects of smearing and radiation, achieved by binning the data set in a much finer array in x and y . This allows the use of data at higher values of y than normally used in the standard inclusive analysis. However, as these high y events correspond to the lowest energy electrons, careful attention must be paid to the performance of the spectrometer, especially the trigger and PID efficiencies. Figure 1a.1 displays the bins chosen for the present analysis.

Further studies of possible uncertainties arising from yield normalization by the luminosity monitor and possible misalignment of the beam were carried out, both indicating only extremely small uncertainties in the results. Numerous other studies and checks were performed, including the Mann-Whitney and Wilcoxon tests. Studies were also performed to investigate the effects of possible hadron contamination. Special care was required to numerically apply the radiative corrections which correct the observed asymmetry to be that from single hard photon exchange, the so-called Born asymmetry. In the case where the asymmetry passes through zero, multiplicative corrections will fail, and additive methods must be used. Numerous monte carlo simulations and much discussion were carried out within the collaboration in order to ensure that the correction and its contribution to the uncertainty was properly handled. At high y these contributions are dominant.

The results of this analysis, including the previously released results on $g_1^d/F_1^d \approx A_1^d$ are shown in Fig. 1a.2 compared with the results from previous experiments; one sees that the HERMES results are in good agreement with these other measurements and brings new information to the low x region. Figure 1a.3 shows the results for the spin structure g_1^d as a function of x .

1.b Preliminary Flavor Decomposition of Nucleon Spin Structure

The HERMES Collaboration

Using the entire deuterium data sample, a new analysis of the quark flavor decomposition of the spin structure of the nucleon has been performed. Previous analyses had used charged hadron asymmetries from the 1995 ^3He data set combined with charged hadron asymmetries from the 1996–1997 ^1H data set ([1]–[6]). In these analyses, no identification between different hadron species is performed, hence the purities used to extract the quark polarizations are based on standard HEP monte carlo generators tuned to the HERMES kinematics and hadron

Figure 1a.1: Schematic of bin definitions in x and y used for the low x analysis. The bottom panel displays the average Q^2 for each x bin.

Figure 1a.2: The asymmetry g_1^d/F_1^d vs x including low x points, superimposed with world data; the lower panel indicates the Q^2 of each measurement.

Figure 1a.3: The spin structure function g_1^d from HERMES.

yields. With the installation of the dual imaging RICH counter in 1998, the 1999–2000 data set can now use the identification of the hadron subspecies, which has in turn allowed the separate determination of both strange and light quark sea polarizations in addition to the regular valence distributions.

The hadron asymmetries from the deuterium data subset are shown in Fig. 1b.1 where they are compared with previous measurements of the SMC experiment[9]. The first ever direct measurements of pion and kaon asymmetries are shown in Figs. 1b.2 and 1b.3. The K^- asymmetry is especially important in determining the sea polarizations, since it only contains sea quarks of the nucleon.

The preliminary quark polarization and helicity distributions results of the 5-parameter flavor decomposition are shown in Figs. 1b.4 and 1b.5, respectively, in comparison with the SMC results in the latter. One can see that the polarized valence up distribution is now very well determined over the x range of the experiment. The use of the full deuterium data set has significantly increased the accuracy of the polarized down distribution as well. It is clear that the data prefer a solution in which the both the light and strange sea quarks have negligible polarization. In fact, the strange sea seems to prefer a slightly positive value, in contrast to the widely held expectation that it be negative in order to “explain” the failure of the Ellis-Jaffe sum rule.

The separate extraction of the $\bar{u}$ and $\bar{d}$ helicity distributions allows one to determine the light sea asymmetry in these distributions. This is of particular interest in light of models used to explain the light sea asymmetry in the unpolarized distributions. The HERMES results are shown in Fig. 1b.6; unfortunately they are not of high enough statistical precision to say much, but do not appear to strongly agree with the models available.

A short paper presenting these results has been submitted to Physical Review Letters in July 2003. A longer manuscript giving all the details of the analysis is in preparation.

References

- [1] K. Ackerstaff *et al.*, The HERMES Collaboration, Phys. Lett. **B 464** (1999) 123.
- [2] H. Tallini, Ph.D. dissertation, University of Liverpool (1998).
- [3] M.-A. Funk, Ph.D. dissertation, University of Hamburg (1998).
- [4] B. Tipton, Ph.D. dissertation, Massachusetts Institute of Technology (1999).
- [5] M. Ruh, Ph.D. dissertation, University of Freiburg (1999).
- [6] M. Beckmann, Ph.D. dissertation, University of Freiburg (2000).

Figure 1b.1: Preliminary charged hadron asymmetries from the deuterium data set of HERMES. The semi-inclusive asymmetries are compared to data from the SMC experiment[9]. The error bars indicate the statistical uncertainties of each data point, the shaded bands give the systematic uncertainty for the HERMES results.

Figure 1b.2: Preliminary charged pion asymmetries from the deuterium data set of HERMES. The error bars indicate the statistical uncertainties of each data point, the shaded bands give the systematic uncertainty for the HERMES results.

Figure 1b.3: Preliminary charged kaon asymmetries from the deuterium data set of HERMES. The error bars indicate the statistical uncertainties of each data point, the shaded bands give the systematic uncertainty for the HERMES results.

Figure 1b.4: The preliminary results for the flavor separated quark polarizations $\Delta u/u$, $\Delta d/d$, $\Delta \bar{u}/\bar{u}$, $\Delta \bar{d}/\bar{d}$, and $\Delta s/s$ as a function of x , where a symmetric strange sea has been assumed.

Figure 1b.5: The preliminary results for the polarized quark distributions $x \cdot \Delta u$, $x \cdot \Delta d$, $x \cdot \Delta \bar{u}$, $x \cdot \Delta \bar{d}$, and $x \cdot \Delta s$ at a scale of $Q^2 = 2.5 \text{ GeV}^2$. The error bars represent the statistical uncertainties, the shaded bands represent the size of the systematic uncertainties. The dashed lines indicate the positivity limits, the full line is a parameterization from Glück *et al.* ("LO, standard scenario") [10]; the dot-dashed line is a parameterization from Blümlein and Böttcher ("LO, scenario 1") [11].

Figure 1b.6: The $\Delta\bar{u} - \Delta\bar{d}$ distribution derived from the HERMES 5 parameter fit, compared with statistical and chiral quark soliton models.

- [7] M. Beckmann *et al.*, HERMES Internal Analysis Report (2000); J. Wendland *et al.*, HERMES Internal Analysis Report (2002).
- [8] T. Lindemann, Ph.D. dissertation, University of Hamburg (2001).
- [9] B. Adeva *et al.*, The SMC Collaboration, Phys. Lett. **B 420** (1998) 180.
- [10] M. Glück, E. Reya, M. Stratmann, W. Vogelsang, Phys. Rev. **D 53** (1996) 4775.
- [11] J. Blümlein and H. Böttcher, hep-ph/0203155 (2002).

1.c First Measurement of the Deuteron Tensor Spin Structure Function $b_1(x)$

Uta Stösslein (University of Colorado), The HERMES Collaboration

In 2000 a dedicated data set on tensor polarized deuterium had been successfully taken. Based on these data the so far unknown tensor asymmetry A_T was measured for the first time over the kinematic range, $0.0021 < x_{Bj} < 0.85$ and $0.1 < Q^2 < 20 \text{ GeV}^2$. The asymmetry A_T gives access to the deuteron structure function b_1 which in the quark-parton model depends upon the correlation of the partonic momentum distribution with the spin of the nucleus.

The lepton-nucleon deep inelastic scattering cross section can be described as the product of

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4} \frac{E'}{E} \mathbf{L}^{\mu\nu} \mathbf{W}_{\mu\nu}$$

of the lepton tensor $\mathbf{L}_{\mu\mu}$ with the hadronic tensor $\mathbf{W}^{\mu\nu}$, where in addition to the well known terms for a spin $\frac{1}{2}$ nucleon (Hydrogen), extra terms account for the new degree of freedom ($m = 0$) for a spin 1 nucleus (Deuterium):

$$\begin{aligned} \mathbf{W}_{\mu\nu} = & -\mathbf{F}_1 g_{\mu\nu} + \mathbf{F}_2 \frac{p_\mu p_\nu}{\nu} \\ & + i\epsilon_{\mu\nu\lambda\sigma} \frac{q^\lambda}{\nu} [\mathbf{g}_1 s^\sigma + \frac{\mathbf{g}_2}{\nu} ((pq)s^\sigma - (sq)p^\sigma)] \\ \text{(for spin 1)} \quad & -\mathbf{b}_1 r_{\mu\nu} + \frac{1}{6} \mathbf{b}_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\ & + \frac{1}{2} \mathbf{b}_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} \mathbf{b}_4 (s_{\mu\nu} - t_{\mu\nu}). \end{aligned}$$

Here p_μ and q_μ are the 4-vectors of the target and virtual photon, respectively, while s^σ , $s_{\mu\nu}$, $t_{\mu\nu}$, $r_{\mu\nu}$, and $u_{\mu\nu}$ are kinematic factors including polarization vectors.

The partonic interpretations of the leading-twist structure functions in the Quark-Parton-Model (QPM) are summarized in the following table (where the sum is over (anti)quark flavors;

the dependencies on the photon squared 4-momentum $-Q^2$ and on the Bjorken scaling variable x are omitted for simplicity):

	Proton	Deuteron
F_1	$\frac{1}{2} \sum_q e_q^2 [q^+ + q^-]$	$\frac{1}{3} \sum_q e_q^2 [q^+ + q^- + q^0]$
F_2	$2xF_1$	$2xF_1$
g_1	$\frac{1}{2} \sum_q e_q^2 [q^+ - q^-]$	$\frac{1}{2} \sum_q e_q^2 [q^+ - q^-]$
b_1	$-$	$\frac{1}{2} \sum_q e_q^2 [2q^0 - (q^+ + q^-)]$
b_2	$-$	$2xb_1$

where $q^+(q^-)$ is a quark with the same (opposite) helicity with respect to the nucleus' spin and q^0 is a quark inside a $m = 0$ nucleus.

The sum over all the helicity states of the quarks is measured with the unpolarized structure function F_1 . The polarized structure function g_1 is sensitive to the spin structure of the nucleon, and measures the number of quarks with same (q^+) or opposite (q^-) helicity with respect to the nucleon they belong to. For targets of spin 1 such as the deuteron, the tensor structure function b_1 compares the quark momentum distribution in the $m = 0$ (q^0) or $m \neq 0$ ($q^+ + q^-$) helicity state of the hadron.[1]

Two points should be stressed. First, b_1^d enters in the symmetric part of the hadronic tensor, therefore it is not sensitive to the beam polarization. This also means that it is not sensitive to the inner spin structure of the nucleon since $q^+ + q^-$ and q^0 are states with no net quark polarization. Secondly, if b_1^d is different from zero, then

$$\frac{1}{3} \sum_f e_f^2 [q^+ + q^- + q^0] \neq \frac{1}{2} \sum_f e_f^2 [q^+ + q^-]$$

and the assumption

$$\frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{g_1}{F_1}$$

is no longer valid for deuterium, and a possible contribution from the tensor polarization of the target should be considered. Here, the usual $\sigma_{1/2}$ ($\sigma_{3/2}$) anti-parallel (parallel) cross section is rewritten as target helicity dependent cross-section σ^+ (σ^-) simply considering a positive beam helicity.

Although b_1^d is foreseen to be so small as to have a negligible effect on the g_1^d measurement, it has not been measured yet for deuterium in deep elastic scattering. The HERMES gaseous target has the unique feature of being easy to give a tensor polarization, allowing for the world's first measurement of b_1^d . In 2000 a dedicated run was proposed to achieve two goals: (1) perform the first measurement of b_1^d and (2) quantify the tensor effects on the g_1^d measurement. At the end of 2000 data taking period, a dedicated DIS data set from the tensor polarized deuterium target was successfully recorded.

In case of a spin-1 target, the measured cross-section (σ_{meas}) depends not only on the well known unpolarized cross section (σ_{unp}) and longitudinal (vector) cross-section asymmetry ($A_{||}$) but also on the tensor asymmetry (A_T):

$$\sigma_{meas} = \sigma_{unp}[1 + P_b V A_{||} + \frac{1}{2} T A_T],$$

where P_b , V and T are beam, target vector and target tensor polarization, respectively.

In order to present how the the structure functions will be extracted from measurements of the cross section, we use the following simplified formalism, where only positive beam helicity will assumed. In this case the usual $\sigma_{1/2}$ ($\sigma_{3/2}$) anti-parallel (parallel) cross-section can be regarded as target helicity dependent cross-section σ^+ (σ^-). Using ideal 100% target polarization, one finds

Polarization	V	T	Cross Section ($P_b = +1$)
Vector +	1	1	$\sigma^+ \approx \sigma_{1/2} \approx \sigma_{unp}[1 + A_{ } + \frac{1}{2}A_T]$
Vector -	-1	1	$\sigma^- \approx \sigma_{3/2} \approx \sigma_{unp}[1 - A_{ } + \frac{1}{2}A_T]$
Tensor +	0	1	$\sigma_T^+ \approx \sigma_{unp}[1 + \frac{1}{2}A_T]$
Tensor -	0	-2	$\sigma_T^- \approx \sigma_{unp}[1 - A_T]$

As one would expect, the unpolarized cross section is regained from the average over the three independent states of the target nucleon helicity:

$$\sigma_{unp} = \frac{\sigma^+ + \sigma^- + \sigma_T^-}{3},$$

while the vector asymmetry is different is different from the usual expression if T (and A_T) is different from zero:

$$A_{||} = \frac{\sigma^+ - \sigma^-}{2\sigma_{unp}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \cdot [1 + \frac{1}{2}T A_T] \approx \frac{g_1}{F_1}.$$

The tensor asymmetry can be determined in two independent ways in combination with the tensor-minus measurement (σ_T^-), using the sum of the vector states ($\sigma^+ + \sigma^-$) or directly using the tensor-plus state (σ_T^+) of the target:

$$A_T = \frac{(\sigma^+ + \sigma^-) - 2\sigma_T^-}{3\sigma_{unp}} \approx -\frac{2b_1}{3F_1}$$

or

$$A_T = 2 \frac{(\sigma_T^+ - \sigma_T^-)}{2\sigma_T^+ + \sigma_T^-}.$$

As a cross-check, the following asymmetry should be zero:

$$\frac{(\sigma^+ + \sigma^-) - 2\sigma_T^+}{(\sigma^+ + \sigma^-) + \sigma_T^+}$$

Polarization	Injected States	V	T
Vector+	$-1\hat{i} + -6\hat{j}$	0.927 ± 0.017	0.871 ± 0.011
Vector-	$-3\hat{i} + -4\hat{j}$	-0.915 ± 0.010	0.929 ± 0.012
Tensor+	$-3\hat{i} + -6\hat{j}$	-0.011 ± 0.003	0.971 ± 0.010
Tensor-	$-2\hat{i} + -5\hat{j}$	-0.011 ± 0.005	-1.803 ± 0.014

Table 1c.1: Average Vector and Tensor Target Polarizations in b_1 running

In the actual experimental measurement, all four target modes were used and the Table 1c.1 indicates the actual target polarizations and their respective uncertainties. The analysis of the event data was identical to that of the standard g_1^d data analysis with the exception of the use of a smaller number of bins in x . Further details of the analysis and numerous systematic studies can be found in Ref. [2].

Figure 1c.1 shows the preliminary results for the tensor asymmetry A_T . As expected the asymmetry is small and roughly consistent with zero within the systematic uncertainty. Using

$$b_1^d = -\frac{3}{2}A_T F_1^d$$

and calculating F_1^d from parameterization of the world's data[3, 4, 5] one obtains the values of b_1^d shown in Fig. 1c.2.

In this analysis, A_T was found to be compatible with zero within the total statistical and systematic uncertainties, i.e. with values of at most $\pm 2 \cdot 10^{-2}$. This result of a small A_T favours our picture of the deuteron as a loosely bound state of p and n . Furthermore, this measurement allows for the first time to constraint a possible effect from the tensor polarization on the $A_{||}$ measurement to be less than $(0.5 \sim 1) \cdot 10^{-2}$.

References

- [1] F.E. Close and S. Kumano, Phys. Rev. **D 42** (1990) 2377.
- [2] M. Contalbrigo *et al.*, HERMES Internal Analysis Note “Measurement of A_T tensor asymmetry from polarized deuteron target at HERMES” (2002).
- [3] H. Abramowicz and A. Levy, hep-ph/9712415 (1997).
- [4] P. Amaudruz *et al.*, Nucl. Phys. **B 371** (1992) 3.
- [5] L.W. Whitlow *et al.*, Phys. Lett. **B 250** (1990) 193.

Figure 1c.1: Preliminary Tensor Asymmetry as a function of x . The systematic error is indicated by the shaded band.

Figure 1c.2: Preliminary spin structure function b_1^d as a function of x . The systematic error is indicated by the shaded band.

1.d Deeply Virtual Compton Scattering

James Ely, David Gaskell (Univerisity of Colorado), The HERMES Collaboration

Introduction

Generalized parton distribution functions (GPDs) are generalizations of the parton distributions measured in deep inelastic scattering (DIS) experiments on nucleons. These new types of distribution functions describe the soft components of processes in which a nucleon recoils elastically after receiving a non-zero momentum transfer from a probe as a result of a hard interaction involving one of its quarks or gluons. In the limit of zero four-momentum transfer to the nucleon (t), these functions are equal to the standard parton distribution functions. With a non-zero momentum transfer, these functions have an extra degree of freedom, and therefore contain more information about the quark/gluon wave functions. Specifically, the first moment of the four leading twist GPDs with respect to the longitudinal momentum fraction (x) of the active quark results in form factors measured in elastic electron scattering experiments. In this way, the GPDs provide a link between elastic form factors and the parton distribution functions of inelastic scattering (DIS). Also, the second moment of the GPDs with respect to x is related to the total angular momentum of the partons in the nucleon. This relationship is very intriguing in light of the Spin Puzzle as it could provide a solution to determining the angular momentum components.

Until recently, when factorization into hard and soft pieces was proven, the interpretation of interactions involving a non-zero momentum transfer to the nucleon was not clear. Therefore, there has been very little experimental data gathered. However, efforts are now underway to measure these processes at several laboratories around the world. The experimentally observable reactions which can be described in terms of the GPDs are the exclusive production of photons and mesons. In both of these cases, the measurements are challenging. In the case of meson production, the theoretical description of the interaction involves an additional soft component associated with the wave function of the quarks in the produced meson. This additional factor complicates the extraction of the GPD functions from the measured quantities. In contrast, photon lepton production is theoretically cleaner because the dominant single photon exchange in the hard interaction with the active quark is well described by QED using the handbag diagram of Fig. 1d.1(a). Unfortunately, this process, called deeply virtual Compton scattering (DVCS), is typically hidden beneath the Bethe-Heitler (BH) background which has the identical final state as the DVCS process (see Fig. 1d.1(b)). In fact, to date, only the collider experiments ZEUS and H1 at HERA have observed the DVCS signal in a direct cross-section measurement [1][2].

During the last few years, it has been proposed that it might be possible to isolate the DVCS amplitude from the BH amplitude by exploiting spin degrees of freedom [3]. Due to the interference of the DVCS and BH processes, additional terms are present in the cross-section. These terms, unlike either the DVCS or BH squared amplitudes, have spin, charge and angular dependencies. Here, the angular dependency is with respect to the azimuthal angle between the scattered lepton plane and the real photon production plane around the virtual photon direction as shown in Fig. 1d.2. By measuring spin and charge asymmetries with respect to the azimuthal angle, experiments can isolate the interference terms of the cross-section and extract the DVCS amplitude.

As the BH process dominates over the DVCS process in the kinematic range of the HERMES experiment, we have attempted to access the DVCS process via the asymmetries mentioned above. A first measurement of the single spin azimuthal asymmetry in photon lepton production has been made using a polarized lepton beam and unpolarized target. The single spin (beam) asymmetry has a $\sin \phi$ angular dependence and has been shown to be proportional to the imaginary part of the interference term, or in other words, the phase difference between the DVCS and BH amplitudes. Taking a $\sin \phi$ moment of the signal is an obvious choice to extract the asymmetry. Data collected in the 1996 and 1997 running period were used for the asymmetry measurement. Events from an unpolarized and spin-averaged polarized hydrogen target were selected if they contained exactly one positron track with momentum larger than 3.5 GeV and exactly one photon with an energy deposition greater than 0.8 GeV in the calorimeter. Photons were identified by the detection of an energy deposition in the calorimeter and preshower detector without any associated track. This sample includes exclusive and semi-exclusive events since the recoiled proton was not detected. The following requirements were imposed on the positron kinematics: $Q^2 > 1 \text{ GeV}^2$, $W^2 > 4 \text{ GeV}^2$, and $\nu < 24 \text{ GeV}$, where Q^2 is the 4-momentum transfer, ν is the virtual photon energy and W denotes the photon-nucleon invariant mass. The opening angle between the virtual photon and the real photon ($\theta_{\gamma\gamma^*}$) was constrained to be greater than 15 mrad, due to the position resolution of the calorimeter, and less than 70 mrad to ensure full ϕ -coverage.

HERMES also has a unique opportunity to measure the beam-charge asymmetry associated with deeply virtual Compton scattering in that the HERA accelerator at DESY is the only facility currently capable of running with both positron and electron beams. In this case, the asymmetry accesses the real part of the BH-DVCS interference, which should manifest in $\cos \phi$ dependence to the asymmetry. A preliminary extraction of the $\cos \phi$ moment of the beam-charge asymmetry was carried out making use of electron-beam data taken in 1998 in combination with positron data taken in 2000. The analysis was quite similar to that already described for the beam-spin asymmetry.

The Colorado group worked on four aspects of the DVCS analysis of HERMES data. First, systematic uncertainties of the single spin (beam) asymmetry were investigated. Second, kinematic dependences, including full corrections for acceptance effects, were extracted. Third, preliminary studies of the complementary single target–spin asymmetry (using an unpolarized beam and polarized target) were begun. And finally, the first ever extraction of the azimuthal dependence of the beam–charge asymmetry was carried out.

Systematic Uncertainties in the Beam–Spin Asymmetry

The previously published extraction of the azimuthal dependence of the beam–spin asymmetry is shown in Fig. 1d.3. Below, we discuss studies of contributions to the systematic uncertainty in this result.

Beam Polarization

The uncertainty in the beam polarization has been estimated from the polarimeter group to be 3.8% of the measured value [4, 5]. The average beam polarization for the 96/97 dataset is $\sim 0.53 \pm 0.02$, which contributes a systematic uncertainty of 0.02 to the single spin asymmetry. The beam polarization is not dependent on the event kinematics, therefore a constant 0.02 is used for all kinematic binning.

Contamination From Neutral Particle Decay

The single photon production in the non-exclusive (high missing mass) region for the kinematics of HERMES is observed from a Monte Carlo (MC) simulation to be primarily a result of the decay of π^0 mesons, where only one decay photon is detected. The single photons may also arise from other neutral particle decay, but have been observed from the MC simulation to have a negligible contribution to the single photon production.

One of the decay photons from the π^0 may not be detected and the event selected in the single photon analysis for several reasons. First, the granularity of the calorimeter is finite, as the face of a calorimeter block is $9 \times 9 \text{ cm}^2$. Two decay photons which are separated by less than $\sim 10 \text{ cm}$ at the calorimeter face can not be distinguished as two distinct photons and therefore appear as a single photon. Also, if one decay photon has an energy less than the calorimeter threshold of 0.8 GeV, the photon can not be reconstructed as an independent cluster. It may, however, be associated with another cluster if the (low energy) photon is incident on one of the blocks used in forming the cluster. Finally, one decay photon could be outside the physical acceptance of the spectrometer. These spectrometer constraints allow a large π^0 contribution in the high missing mass region. In the exclusive region, the contribution from the π^0 mesons is reduced due to the energy conservation constraint for exclusive processes, since the detected decay photon must have most of the π^0 momentum or the event could not have a reconstructed

missing mass in the exclusive region.

To estimate the total contamination from π^0 decay, the HERMES Monte Carlo (HMC) simulation was used. As the DIS generator used in the HMC simulation does not contain exclusive processes, a combination of two MC generators (exclusive photon and DIS) were used.

The contamination from the decay photons of non-exclusively produced π^0 mesons which appears in the exclusive missing mass region in the single photon analysis was estimated using the MC simulation (DIS generator). The BH process dominates in this region, however the simulation indicates that $\sim 6\%$ of the photons arise from a (DIS produced) π^0 meson decay in the exclusive region from -1.5 to 1.7 GeV. The simulation showed negligible contamination from other production mechanisms but does not account for exclusively produced π^0 mesons, which could also contribute, and must be estimated separately.

The calculation of the amount of exclusive π^0 proceeded in two steps. First, the ratio of the number of detected “single photons” to “double photons” arising from exclusive π^0 decay was estimated. Then this ratio was multiplied by an estimate of the number of exclusive π^0 mesons detected in the 1996 and 1997 datasets, yielding an estimate of the number of single photons arising from exclusive π^0 production.

The amount of exclusive π^0 mesons which might be reconstructed as single photon events was estimated with a MC exclusive π^0 generator and the HMC program. The exclusive π^0 was generated randomly in the kinematic variables Q^2 , ν , and t , and weighted with a simple $1/Q^6$ weighting. The exclusive π^0 MC data were analyzed for both the “single photon” and “double photon” events, yielding a 12.5% single to double photon detection ratio for the missing mass region of -1.5 to 1.7 GeV.

Having the ratio of single to double photons, an estimate of the number of exclusive π^0 mesons detected in the 96/97 experimental dataset was obtained from the ratio of exclusive to non-exclusive π^+ mesons in the π^+ analysis [6], which amounts to $\sim 20\%$ in the missing mass region of -1.5 to 1.7 GeV. This ratio is very dependent on the width missing mass bin, so is not reflective of the ratio quoted in the exclusive π^+ analysis. This method of estimating the exclusive π^0 rate assumes that π^+ and π^0 mesons have the same ratio of exclusive to non-exclusive production. In fact, the exclusive π^+ cross section is enhanced by the π^+ pole which results in an overestimate of the ratio (20%) of exclusive to non-exclusive π^0 production. However, to be conservative, a ratio of 20% was used for the exclusive to non-exclusive production for the π^0 meson.

The 12.5% (single/double photon) ratio was used in combination with the 20% (exclusive/non-exclusive π^0) ratio, resulting in an estimated 2.5% of the “single photon” π^0 events in the exclusive missing mass region of -1.5 to 1.7 GeV arising from exclusively produced π^0 mesons.

Combining the estimates for the exclusively and non-exclusively produced π^0 mesons in the exclusive missing mass region of the single photon analysis results in a contribution of 8.5%.

Although the π^0 meson has been shown to have azimuthal dependence [7], the photons from the decay of π^0 mesons which are reconstructed as single photon events should have very little azimuthal angle dependence since only one of the decay photons is detected. However, to be reconstructed in the exclusive region, the single decay photon must carry a majority of the π^0 momentum, and so may display some azimuthal dependence. The contribution to the single spin asymmetry from the decay photons of π^0 mesons in the exclusive region was estimated by performing a single beam-spin analysis for the π^0 meson production of the 1996 and 1997 datasets. This two-photon analysis was performed in a similar manner as the single photon analysis, with the added constraint on the π^0 invariant mass of 0.115 to 0.150 GeV, and resulted in an estimate of $\approx -0.15 \pm 0.12$ for the π^0 single beam-spin asymmetry in the missing mass region of -1.5 to 1.7 GeV. The single spin π^0 asymmetry extracted from experimental data contains both exclusive as well as non-exclusive production π^0 production.

Combining the π^0 asymmetry estimate with the 8.5% contamination can give an indication of the uncertainty in the single spin asymmetry arising from the π^0 meson

$$A_{meas} = 0.915A_{int} + 0.085A_{\pi^0}, \quad (1)$$

where A_i is the measured (meas) asymmetry arising from the actual BH-DVCS interference (int) and the contribution from the decay of the π^0 meson.

Varying the π^0 asymmetry from -0.02 to -0.27 results in a maximum variation of the asymmetry at the minimal π^0 asymmetry estimate of -0.02 . In other words, the largest effect on the single spin asymmetry arises when the asymmetry contribution from the π^0 background is the most different from the measured single spin asymmetry value.

As an estimate, the asymmetry of the single photons arising from π^0 decay was assumed to be zero. In that case, the dilution of the asymmetry arising from the π^0 mesons to the asymmetry is simply:

$$\text{Dilution} = A_{int} - A_{meas} = A_{meas} \left(\frac{1}{0.915} - 1 \right) = 0.0929A_{meas}. \quad (2)$$

Therefore, a value of 9.29% of the measured asymmetry is assigned to the systematical uncertainty arising from the π^0 background.

Contamination From Associated Exclusive Production

Another source of contamination in the exclusive region may be the associated DVCS and BH processes, where the interaction proceeds as $\gamma^*p \rightarrow \gamma\Delta^+$. The production of the Δ^+ can not be distinguished from the truly exclusive process with the HERMES spectrometer, as the difference in the Δ^+ and proton masses is $1.232 - 0.938 = 0.294$ GeV, and the resolution of

the detector ~ 0.77 GeV. It has been argued by Frankfurt *et al.* [8], that the contributions may not significantly affect the single spin asymmetry.

However, for this analysis, an estimate of the effect of the possible associated processes is not made, since a straightforward estimate is not possible without the use of some type of model for the associated processes.

External Bremsstrahlung and Detector Effects

The finite resolution of the HERMES detector may result in a variance or smearing of the reconstructed kinematic variables in relation to the true values. A variance may also arise if the positron interacts with the detector material and emits an external (not from the target interaction) bremsstrahlung photon. Photons produced from bremsstrahlung in the target interaction region (internal bremsstrahlung) constitute the BH process and are part of the observed signal. The azimuthal angle ϕ is the only variable used in the construction of the single spin asymmetry, and a variance in ϕ may lead to a shift in the asymmetry value. Smearing due to the finite resolution of the detector tends to flatten out any structure in the azimuthal distribution, reducing the amplitude of the asymmetry. External bremsstrahlung tends to shift the reconstructed virtual photon closer to the beam line as the scattered positron is reconstructed with less energy. This in turn causes a shift of events to larger (absolute) values of ϕ .

The effects of external bremsstrahlung and detector smearing was studied using the MC simulation. Events were generated using the standard DIS generator, tracked through the simulated detector with the Monte Carlo program and reconstructed. Events which are reconstructed in the detector (accepted events) are used to compare the generated and reconstructed variables. The effect of the external bremsstrahlung and detector effects can be seen in Fig. 1d.4, where the azimuthal distribution of the MC simulated accepted and reconstructed events is shown. The events tend to shift from the peak at zero radians in ϕ to larger (absolute) values of the azimuthal angle as expected.

The MC simulation does not contain the same $\sin \phi$ components observed in the experimental data therefore an additional weight was applied to the MC simulation:

$$1 + B \sin \phi. \quad (3)$$

The difference in the generated (gen) and reconstructed (rec) azimuthal distributions was then used to estimate the effect on the experimental asymmetry.

$$\delta B = B_{gen} - B_{rec} \quad (4)$$

$$= 2\langle \sin \phi_{gen} \rangle - 2\langle \sin \phi_{rec} \rangle \quad (5)$$

$$= \frac{\sum_{i=1}^N \sin \phi_{gen}^i (1 + B \sin \phi_{gen}^i) w_i - \sin \phi_{rec}^i (1 + B \sin \phi_{rec}^i) w_i}{\sum_{i=1}^N w_i} \quad (6)$$

The sum is over the N number of MC events labeled by i , with the original MC weight denoted with w_i . For the exclusive region of $-1.5 - 1.7$ GeV, the experimentally measured single spin asymmetry value of -0.23 is used for the B parameter. The difference in the reconstructed and generated asymmetry is -0.00187 , leading to an effect of $\sim 0.8\%$ on the asymmetry value. The external bremsstrahlung and detector effects therefore, have a small effect in comparison to the statistical accuracy of the asymmetry (± 0.04). Instead of including these small effects directly, the bremsstrahlung and detector smearing were included in the estimate of the acceptance correction, by using the MC reconstructed variables. The systematic uncertainty associated with the acceptance, external bremsstrahlung and detector smearing is estimated in the following section.

Systematical Uncertainty from Acceptance, External Bremsstrahlung and Detector Smearing
The acceptance correction has some associated systematical uncertainty. To estimate the size of the uncertainty, two MC simulations were used. The first MC simulation was produced using the DIS generator which includes the BH process, but no exclusive process. The acceptance coefficients were extracted from this MC simulation and used for the acceptance correction as was explained in the section on the acceptance correction. To estimate the systematic uncertainty, the acceptance coefficients were extracted from the exclusive BH production only. This was accomplished by insuring the generated missing mass corresponded to the proton mass. The coefficients from the exclusive production were extracted in order to compare to the second MC simulation.

The second MC simulation used an exclusive single photon generator which was weighted using the exact BH calculation. This BH calculation was performed using the exclusive code of Vanderhaeghen, Guichon, and Guidal [9]. This MC simulation was then weighted with a $\sin \phi$ weighting, using amplitudes (asymmetry values) from 0.0 to -0.50 in steps of 0.05. The sine and cosine moments were extracted and acceptance corrected using the exclusive coefficients from the totally independent DIS MC simulation. The difference in the extracted $\sin \phi$ moment and the amplitude of the $\sin \phi$ weighting was extracted, and the standard deviation of the differences calculated, yielding an estimate of the systematic uncertainty of 0.03 associated with the acceptance correction.

QED Radiative Corrections

The QED radiative corrections to the BH and DVCS handbag diagrams have been studied in Ref. [10]. The corrections to the cross section have been estimated for the BH and DVCS processes for kinematics relevant at JLAB. The corrections reduce the total (BH plus DVCS) cross section by $\approx 20\%$. The same calculation was completed for the single beam-spin asymmetry, for the kinematics of JLAB. The radiative corrections have a small effect on the asymmetry, reducing the asymmetry by $\approx 5\%$. The radiative corrections are proportional to the inverse

beam energy and hence are smaller at HERMES kinematics than they are for JLAB kinematics. Therefore, the radiative corrections to the single spin asymmetry of the HERMES measurement should be marginal ($< 5\%$) compared to the present statistical accuracy. Without an calculation for the HERMES kinematics an estimated systematic uncertainty of $0.05 \times$ the asymmetry is assigned for the QED radiative effects. For example, for the single-spin asymmetry of -0.23 , the systematic uncertainty is estimated as $0.05 \times -0.23 = -0.0115$.

Stability of Asymmetry

Vertex Constraint

To decrease any contamination from interactions other than the gas target, a constraint was placed on the vertex position of the positron to be within ± 18 cm of the center of the target cell. To investigate the effect of the vertex position on the asymmetry, the asymmetry in the exclusive region was formed for different minimum and maximum constraints.

The asymmetry is quite stable against variations in the positron vertex constraint between $\pm(16 - 21)$ cm. Although this is a rather large variance (5 cm), the majority of the events originate from the center of the target, so the variation does not significantly affect the statistics. The maximum asymmetry variation from this vertex study is used for the estimated systematic uncertainty of 0.0058 for the minimum constraint and 0.0088 for the maximum constraint.

Since this systematic uncertainty is small compared to others, and there is not a strong correlation between the kinematic bins and the positron vertex, the same values were assigned for all bins in the kinematic plots.

Opening Angle (θ_{γ^γ}) Constraint*

The opening angle $\theta_{\gamma^*\gamma}$ between the virtual and real photon was constrained with a lower and upper constraint. The lower constraint was implemented at 0.015 rad, to ensure minimal effect on the azimuthal angle calculation arising from the variance in the cluster position reconstruction. The upper constraint was placed at 0.07 rad to have a more uniform azimuthal distribution for the exclusive region.

A variance of the single spin asymmetry for the exclusive region as a function of the opening angle $\theta_{\gamma^*\gamma}$ is most likely due to the changing of the ratio of the BH to DVCS process. The acceptance of the HERMES spectrometer only allows events with near zero azimuthal angle to be detected for large values of the opening angle, which are dominated by the BH process (in-plane angles). Therefore, the upper opening angle constraint reduces the amount of BH compared to the DVCS. The lower opening angle constraint also changes the BH-DVCS ratio, by removing a larger percentage of DVCS compared to BH events.

The change in the asymmetry from the opening angle constraint is therefore most likely due

to physics and not a systematic uncertainty associated with the measurement and therefore has not been included.

Missing Mass Constraint

The exclusive region is defined by constraining the reconstructed missing mass to be between -1.5 GeV and 1.7 GeV. The lower bound was chosen to remove the few extraneous events which might have a large negative value of missing mass and is approximately 3 times the estimated missing mass resolution of 0.8 GeV. Since the actual value of the missing mass can be only 0.938 GeV or larger, the events with a reconstructed missing mass less than the proton mass due to the limited detector resolution should be enriched with exclusively produced events. The investigation of the lower missing mass constraint has a small effect producing a maximum asymmetry variance of ≈ 0.0033 .

The upper limit missing mass constraint was placed at 1.7 GeV which is a $\sim 1 \sigma$ value of the missing mass resolution above the mass of the proton. The upper limit was chosen to include as many statistics as possible without introducing a large background contamination to the event sample. As the upper constraint is moved to higher values of the missing mass, more background from the non-exclusive processes is included in the data sample. The magnitude of the asymmetry reflects the expected decrease with the increase of the upper missing mass constraint.

Since the uncertainty associated with the missing mass constraint is minimal for the lower constraint it has been neglected. The uncertainty associated with the upper missing mass constraint is primarily due to the amount of background (semi-inclusive π^0 which reconstruct as single photons) which has already been accounted for, and so is not included in the systematic uncertainty calculation.

Systematic Uncertainty Summary

The systematic uncertainty of the single spin asymmetry measurement has been investigated for the background contributions, detector effects, and the effects of constraints on the data. The estimated uncertainty contributions to the asymmetry value are summarized in Table 1d.1. The largest systematic uncertainties of the single spin asymmetry arise from the acceptance correction, the background contribution, and beam polarization measurement. For an estimate of the total systematic uncertainty, the above estimates are added in quadrature. For an example, using the asymmetry value of -0.23 from the DVCS paper, the total systematic uncertainty is estimated at $0.0447 \approx 0.04$.

Kinematic Dependences

The kinematic dependences of the single spin asymmetry are interesting to investigate for several reasons. First, the dependence on the Q^2 value can be used as in DIS to check

Source of Uncertainty	
Beam Polarization	0.020 absolute
π^0 background	9.29% relative
Acceptance, smearing and external bremsstrahlung	0.03 absolute
QED radiative effects	5% relative
Positron vertex minimum constraint	0.0058 absolute
Positron vertex maximum constraint	0.0088 absolute

Table 1d.1: Systematic uncertainties associated with the single spin asymmetry measurement.

that the process is indeed arising from hard scattering. If the hard scattering regime has not been reached, the asymmetry will be difficult to interpret in terms of the generalized parton distributions. Secondly, the recent interest in the GPD formalism has arisen from the connection of the GPDs to the total angular momentum of the partons [11]. This connection has been shown to exist in the limit of zero momentum transfer to the final nucleon (Mandelstam $t = 0$). DVCS by definition has a non-zero momentum transfer, therefore, the GPDs must be extracted and interpolated to $t = 0$. As a result the t -dependence of the GPDs (and therefore the DVCS asymmetry) is quite important. Finally, the dependences of the asymmetry on various kinematic quantities could be useful to differentiate between theoretical calculations. The kinematic dependence of the single beam-spin asymmetry on the variable Q^2, t and Bjorken- x (x_{Bj}) were extracted.

The single beam-spin asymmetry was binned and plotted as a function of the variables Q^2 , t , and x_{Bj} , where $x_{Bj} = Q^2/2M_p\nu$ as in DIS analysis. Constraints were placed on the variables:

$$\begin{aligned}
1 < Q^2 < 10 \text{ GeV}^2 \\
-0.2 < -t < 1.0 \text{ GeV}^2 \\
0.03 < x_{Bj} < 0.3
\end{aligned}$$

These constraints reduced the event sample from 4015 events in the nominal exclusive region ($-1.5 < M_x < 1.7$) to 3838 for an ≈ 10 % data reduction.

Acceptance Corrections

The main acceptance effects of the detector should, in principle, cancel out in an asymmetry of the beam spin, as long as the acceptance is constant over time and the luminosity in both beam states is the same. However, there is a non-trivial complication which arises from convolution of the acceptance and cross section. The measured azimuthal angle dependence arises from two contributions, one from the true cross section and another contribution from

the acceptance:

$$\frac{dN}{d\phi} = \frac{d(\sigma L)}{d\phi} \times \epsilon(\phi) \quad (7)$$

with L representing the measured luminosity, and $\epsilon(\phi)$ the acceptance function, assumed here to be only a function of the azimuthal angle ϕ . The true cross section can be expressed in a Fourier series, hence it is convenient to expand the acceptance function in a Fourier series also, rewriting the measured angular dependence as a product of the two:

$$\begin{aligned} \frac{dN}{d\phi} &= \frac{\sigma L}{2\pi} [1 + \sum_m (a_m \cos m\phi + b_m \sin m\phi)] \\ &\times \frac{\int \epsilon(\phi) d\phi}{2\pi} [1 + \sum_n (A_n \cos n\phi + B_n \sin n\phi)] \end{aligned} \quad (8)$$

where a_m and b_m are the cross section coefficients and A_n and B_n are the acceptance coefficients. The multiplication of the two Fourier series results in a new single Fourier series, where the coefficients are complicated expressions of the original coefficients. The new series is the experimentally measured azimuthal dependence which can be represented as [12]:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} [1 + \sum_m (\alpha_m \cos m\phi + \beta_m \sin m\phi)] \quad (9)$$

where an explicit example of the β_1 coefficient of the $\sin \phi$ term is:

$$\beta_1 = N_F \left(b_1 + B_1 + \frac{1}{2} \sum_n (A_n b_{n+1} - b_n A_{n+1} - B_n a_{n+1} + a_n B_{n+1}) \right). \quad (10)$$

with N_F representing a normalization factor which arises from the multiplication of the two Fourier series having the value of:

$$N_F = \frac{1}{1 + \frac{1}{2} \sum_n (A_n a_n + B_n b_n)} \quad (11)$$

Since the acceptance function for the HERMES detector has a predominant $\cos \phi$ dependence, the largest contribution to the measured moment from the acceptance should be the value of $A_1 b_2$, where the $\sin 2\phi$ moment of the cross section couples to the $\cos \phi$ moment of the acceptance. Eq. 10 can also be written in matrix form:

$$\beta_m = N_F \sum_n M_{mn} b_n \quad (12)$$

where M_{mn} is a matrix element composed of the acceptance values. The acceptance corrected moments can be obtained by inverting the matrix equation:

$$b_m = \frac{1}{N_F} \sum_n M_{mn}^{-1} \beta_n. \quad (13)$$

The statistical uncertainty on the acceptance corrected moments is calculated using experimentally measured moments and the (MC simulated) acceptance matrix elements:

$$\delta(b_m) = \frac{1}{N_F} \sum_n \left[M_{mn}^{-1} \delta(\beta_n) + \delta(M_{mn}^{-1}) \beta_n \right]. \quad (14)$$

The uncertainty is difficult to calculate in this form due to the variance in the inverted matrix elements $\delta(M_{mn}^{-1})$, which is unknown, and is therefore expanded into a more useful form. The inverse of a matrix is related to its cofactor and determinant:

$$a_{ij}^{-1} = \frac{C_{ji}}{|a|} \quad (15)$$

where C_{ji} is $(-1)^{j+i}$ times the cofactor of the matrix element a_{ij} . The relationship is used to expand the statistical uncertainty (Eq. 14) as:

$$\delta b_m = \frac{1}{N_F} \sum_n \left[M_{mn}^{-1} \delta \beta_n + \beta_n \left(\frac{|\delta M|}{|M|} \delta M_{mn}^{-1} - M_{mn}^{-1} \left[\sum_{k,l} (M_{lk}^{-1} \delta M_{kl})^2 \right]^{\frac{1}{2}} \right) \right] \quad (16)$$

where δM is the matrix composed of the uncertainties in the M elements. The variance of Eq. 16 must be squared yielding squared terms as well as covariant terms. For this calculation, the uncertainties in the acceptance matrix elements (from MC acceptance coefficients) and the statistical uncertainties in the measured moments (from experimental data) are uncorrelated. However, the acceptance matrix is symmetric, and furthermore, several elements in the matrix are composed of the same acceptance coefficient. These covariances, of maximum correlation value (+1), are included in the statistical uncertainty calculation.

The coefficients of the HERMES acceptance function were extracted from the HERMES MC using the DIS generator. The BH process dominates in the exclusive region of -1.5 to 1.7 GeV, however, has a large inherent $\cos \phi$ dependence. To cancel out the BH $\cos \phi$ dependence in order to obtain the azimuthal dependence arising from the detector acceptance, the MC weight was renormalized using a BH calculation. The BH process cross-section was made the calculation of exclusive processes of Vanderhaeghen, Guichon, and Guidal [9]. For each MC event in the exclusive region that was produced via the BH process, the MC weight was renormalized by a ratio of the BH cross-section calculated at $\phi = \pi/2$ and at the event angle ϕ :

$$\text{new weight} = \text{mc weight} \times \frac{\sigma_{BH}(\phi = \pi/2)}{\sigma_{BH}(\phi = \phi_{event})} \quad (17)$$

Multiplying by this ratio cancels out the $\cos \phi$ dependence of the BH process. The reconstructed events weighted with this new weight should reflect the ϕ dependence arising from the detector acceptance.

Q^2	$\langle Q^2 \rangle$	$\langle -t \rangle$	$\langle x_{Bj} \rangle$	$A^{\sin \phi}$
1.0-1.5	1.24	0.178	0.064	$-0.195 \pm 0.110 \pm 0.043$
1.5-2.5	1.94	0.219	0.093	$-0.190 \pm 0.092 \pm 0.043$
2.5-3.5	2.96	0.283	0.125	$-0.260 \pm 0.131 \pm 0.047$
3.5-7.0	4.64	0.366	0.174	$-0.284 \pm 0.152 \pm 0.048$
7.0-10.0	7.80	0.390	0.256	$-0.016 \pm 0.686 \pm 0.038$

Table 1d.2: The average kinematic values along with the acceptance corrected analyzing power $A_{LU}^{\sin \phi}$ for the exclusive region of -1.5 to 1.7 GeV for the Q^2 binning.

The MC acceptance coefficients were extracted using the method of moments for the first four sine and cosine moments. All MC acceptance coefficients were derived from the reconstructed variables, and so contain the simulated detector smearing and external bremsstrahlung. Using the reconstructed variable allows a correction of the acceptance, detector smearing, and external bremsstrahlung effects in a single calculation.

Shown in Figs. 1d.5, 1d.6, 1d.7 are the kinematic dependences of the single beam-spin asymmetry with and without the acceptance correction. In the majority of the bins, the acceptance correction is quite small. The largest correction occurs in the x_{Bj} bin of $0.14 < x_{Bj} < 0.20$, which is primarily driven by the large $\sin 2\phi$ moment of the asymmetry. This kinematic bin has the largest $\sin 2\phi$ moment of all the kinematic bins studied, and the largest acceptance correction. This large $\sin 2\phi$ moment is most likely due to a statistical fluctuation, since it is not present in either the Q^2 or t binning of the asymmetry.

The acceptance corrected asymmetry contains information from higher order sine and cosine moments of the experimental data as well as the acceptance coefficients from the MC simulation. Therefore, the statistical uncertainty of these higher order moments will contribute in the acceptance corrected asymmetry. There may also be a systematical uncertainty associated with the acceptance correction, which has been estimated in the previous section on the systematical uncertainties.

The kinematic dependences of the single spin asymmetry are shown in Figs. 1d.8, 1d.9, and 1d.10. Here the acceptance corrected values, along with the estimated systematical uncertainties are plotted as a function of the respective kinematic variables. In addition, the average values for the different variables, along with the acceptance corrected asymmetry are tabulated in Tables 1d.2, 1d.3, and 1d.4.

Target Spin Asymmetry

The single beam-spin azimuthal asymmetry arising from the interference of the Bethe-Heitler (BH) and deeply virtual Compton scattering (DVCS) processes has been extracted for the 96/97 data sets and the results published [13]. For the beam-spin asymmetry, polarized

$-t$	$\langle Q^2 \rangle$	$\langle -t \rangle$	$\langle x_{Bj} \rangle$	$A^{\sin \phi}$
-0.2-0.05	2.35	-0.018	0.110	$-0.343 \pm 0.157 \pm 0.052$
0.05-0.2	2.06	0.129	0.090	$-0.152 \pm 0.088 \pm 0.041$
0.2-0.4	2.44	0.286	0.106	$-0.240 \pm 0.107 \pm 0.045$
0.4-0.6	3.07	0.479	0.128	$-0.222 \pm 0.183 \pm 0.044$
0.6-1.0	3.78	0.753	0.151	$-0.299 \pm 0.242 \pm 0.049$

Table 1d.3: The average kinematic values along with the acceptance corrected analyzing power $A_{LU}^{\sin \phi}$ for the exclusive region of -1.5 to 1.7 GeV for the t binning.

x_{Bj}	$\langle Q^2 \rangle$	$\langle -t \rangle$	$\langle x_{Bj} \rangle$	$A^{\sin \phi}$
0.03-0.07	1.40	0.208	0.055	$-0.177 \pm 0.152 \pm 0.042$
0.07-0.10	1.92	0.207	0.085	$-0.234 \pm 0.111 \pm 0.045$
0.10-0.14	2.66	0.241	0.118	$-0.131 \pm 0.138 \pm 0.040$
0.14-0.20	3.74	0.329	0.165	$-0.253 \pm 0.162 \pm 0.046$
0.20-0.30	5.38	0.407	0.234	$-0.253 \pm 0.334 \pm 0.046$

Table 1d.4: The average kinematic values along with the acceptance corrected analyzing power $A_{LU}^{\sin \phi}$ for the exclusive region of -1.5 to 1.7 GeV for the x_{Bj} binning.

target data was spin-averaged yielding an unpolarized target. However, this polarized target data could be used to extract a single spin asymmetry (target), which also arises from the interference of the BH and DVCS processes. This single spin asymmetry (target) has slightly different kinematic dependences, and accesses the generalized parton distributions (GPD) differently than a beam-spin asymmetry, so in principle could be used as an independent measurement [14].

An average polarization value was used in this initial investigation of the single target-spin asymmetry. The average polarization (P_T) was 0.748 ± 0.057 in 1996 and 0.85 ± 0.05 in 1997. Therefore, unlike the beam spin analysis, the moments are defined in terms of the average polarization and do not include the target polarization (measured $\approx$ every 10 sec) included at the event level:

$$A_{UL}^{\sin \phi^\pm} = \frac{2}{N^\pm \langle |P_T| \rangle} \sum_{i=1}^{N^\pm} \sin \phi_i, \quad (18)$$

where the superscript $\pm$ refers to the helicity of the target. As in the beam-spin analysis the $\sin \phi$ moments can be combined into a target-spin analyzing power $A_{UL}^{\sin \phi}$:

$$A_{UL}^{\sin \phi} = \frac{2}{N \langle |P_T| \rangle} \left\{ \sum_{i=1}^{N^-} \sin \phi_i - \sum_{i=1}^{N^+} \sin \phi_i \right\}, \quad (19)$$

where $N = N^+ + N^-$, and the difference explicitly shown due to the use of the average

polarization (weighted for the different years) instead of the event-by-event polarization of the beam spin analysis [13]. Since events in the negative target spin state have the opposite sign of the $\sin \phi$ moment from event in the positive target state, the difference effectively combines the statistics of both target states.

For a single target-spin asymmetry, an unpolarized beam is desirable. With an unpolarized beam, terms which are proportional to both the beam and target polarizations (double spin terms) [15] drop out and do not contribute. In principal, the $\sin \phi$ amplitude can be extracted from data using a polarized beam, via a fit procedure or method of moments, however, the results may have larger acceptance corrections. Therefore, for this initial investigation, the polarized target data have been helicity balanced with respect to the beam polarization by using the sum of the luminosity weighted beam polarization. More data was taken with the negative beam helicity for the polarized target, therefore, the negative beam helicity data sample was reduced by removing data at the end of the negative beam helicity running period. By reducing the sample with a constraint on the run number, the data was helicity balanced to within 1/10 of 1%. The need to helicity balance, as well as the requirement of a polarized target, greatly reduces the available statistics and the precision of this type of asymmetry. For the beam spin analysis the final number of selected events was 4015 in the exclusive region of $-1.5 < M_x < 1.7$ GeV, whereas there are only 1560 events in the same region for the polarized target sample (beam helicity balanced).

Shown in Fig. 1d.11 is the single spin (target) asymmetry of the beam-helicity balanced data from the 96/97 polarized hydrogen target data set in the exclusive region of $-1.5 < M_x < 1.7$ GeV. The single spin asymmetry does not have a simple $\sin \phi$ distribution as expected. There is an additional large $\sin 2\phi$ contribution as illustrated by the fit with a simple Fourier series. The expected $\sin \phi$ behavior is consistent with zero. The presence of the large $\sin 2\phi$ term is not expected, and is presently under investigation.

As in the single spin (beam) asymmetry analysis, $\sin \phi$ moments were extracted to illustrate the asymmetry behavior as a function of missing mass. In Fig. 1d.12, the target helicity moments are displayed, along with the average. The average of the moments is consistent with zero, indicating negligible false asymmetry arising from the detector.

The data can be combined into a target spin analyzing power as shown in Fig. 1d.13. The analyzing power in the exclusive region (around the proton mass of 0.938 GeV) does not display a large asymmetry and is in fact consistent with zero.

An initial target spin asymmetry has been extracted from the 96/97 polarized hydrogen target data. This asymmetry is -0.01 ± 0.04 (consistent with zero) for the exclusive region of $-1.5 < M_x < 1.7$ GeV. In addition, a large (~ -0.10) $\sin 2\phi$ moment is observed, which is not expected. With the observation of the rather large $\sin 2\phi$ moment, more systematic

studies need to be completed to determine if the moment is a detector effect or arising from some physical process. At present the origin is unknown and is under investigation.

Beam Charge Asymmetry

As mentioned earlier, the beam–charge asymmetry associated with DVCS is sensitive to the real part of the BH–DVCS interference while the beam–spin and target–spin asymmetries sample the imaginary contribution. Accurate descriptions of the Generalized parton distributions clearly requires as much information as possible and the beam–charge asymmetry gives us another observable with which to constrain GPD models.

Preliminary results for the azimuthal dependence of the beam–charge asymmetry have been extracted from 1998 electron and 2000 positron data from an unpolarized hydrogen target. The data analysis (particle identification and event selection) was quite similar to that carried out for the beam–spin asymmetry so will not be described in detail here.

The azimuthal dependence of the beam charge asymmetry, A_C , is shown in Fig. 1d.14. The asymmetry is defined as,

$$A_C(\phi) = \frac{N^{e+}(\phi) - N^{e-}(\phi)}{N^{e+}(\phi) + N^{e-}(\phi)}, \quad (20)$$

where N^{e+} (N^{e-}) denotes the normalized photon yield from the positron (electron) data. Here we have normalized the photon yield to the number of DIS events from the positron and electron samples. Note that, ideally, one would like to form this asymmetry using an unpolarized beam to avoid contributions from the $\sin \phi$ moment of the beam–spin asymmetry. Unfortunately, the electron data was taken with only one beam helicity. Hence it was necessary to “helicity–cancel” the positron and electron data sets. In this procedure, the positron data is restricted such that the mean beam polarization is equal (and of the opposite helicity) to the electron sample. Hence, the beam polarization dependent contribution from the beam–spin asymmetry subtracts away in the numerator of Eq. 20 (however the contribution in the denominator is doubled, although this should be relatively small relative to the other contributions in the denominator).

One can see that the ϕ distribution is clearly consistent with the expected $\cos \phi$ shape, although the statistical precision of the $\cos \phi$ amplitude is rather poor. We can also investigate the missing mass dependence of the beam charge asymmetry to ensure that the signal is really associated with exclusive single photon production. In this case we assume that the distribution has a $\cos \phi$ shape and calculate moment of the distribution, i.e.,

$$A_C^{\cos \phi^{+(-)}} = \frac{2}{N^{e+(e-)}} \sum_{i=1}^{N^{e+(e-)}} \cos \phi_i. \quad (21)$$

Note that the Bethe–Heitler process also has a significant $\cos\phi$ dependence so we can not look at each charge state individually to extract the $\cos\phi$ amplitude of the interference term. However, since the BH contribution is charge–symmetric, we can subtract that term away and extract the interference amplitude via,

$$A_C^{\cos\phi} = \frac{A_C^{\cos\phi^+} - A_C^{\cos\phi^-}}{2}. \quad (22)$$

Note that the above equation is not strictly applicable if there is some constant term in the interference, but such a contribution is expected to be small and that is born out in Fig. 1d.14. One advantage of this moment calculation is that we are no longer sensitive to contributions from the $\sin\phi$ moment of the beam–spin asymmetry, so we do not have to discard any data to achieve our helicity–canceled sample.

The $\cos\phi$ moment of the beam charge asymmetry is plotted as a function of missing mass in Fig. 1d.15. The moments are non–zero in the region near the proton mass $M_x \approx 1$ GeV, while at higher missing mass are largely consistent with zero. In the region for $M_x < 1.7$ GeV, the moment 0.11 ± 0.04 . The systematic uncertainty coming from acceptance effects, π^0 decay, and detector effects is estimated to be 0.03.

This preliminary analysis of the beam–charge asymmetry associated with DVCS looks very promising. Currently, the significance of the signal is limited by electron statistics. This should improve with a new calorimeter position reconstruction algorithm which will allow us to relax the opening angle constraint of $\theta_{\gamma^*\gamma} > 0.015$. Further studies of systematic effects will hopefully further reduce the uncertainty in the current measurement.

Results and Conclusions

Systematic uncertainties of the single spin asymmetry of leptonproduced photons have been investigated for the 1996/1997 data at HERMES. Combining the studied systematics quadratically results in a total systematic uncertainty of 0.04.

The kinematic dependences of the single spin asymmetry have been extracted for the 1996/97 datasets for the kinematic variables Q^2 , t and x_{Bj} . The single spin asymmetry has weak dependence on the three different variables, however the limited statistical precision prohibits a definite conclusion. In addition, due to the limited acceptance of the HERMES spectrometer, there may be correlations between the variable, which has not been taken into account in this study.

A single spin asymmetry has been initially investigated using an unpolarized beam and polarized target. This study uses a subset of the same data used in the beam–spin asymmetry, where a polarized target was present. The beam polarization was averaged to zero by helicity balancing the dataset. A single target–spin asymmetry was extracted from this reduced

dataset, which results in a $\sin \phi$ moment consistent with zero. An unexpected $\sin 2\phi$ moment arises in this analysis, which is presently under investigation.

The beam-charge asymmetry has been extracted from the 1998 electron and 2000 positron data on an unpolarized hydrogen target. The expected $\cos \phi$ dependence is present, although the current results is limited by electron statistics. Future analyses should allow us to include a larger portion of the available electron data and possibly reduce the systematic uncertainties.

References

- [1] P. R. Saull, Zeus Collaboration, hep-ex/0003030.
- [2] H1 Collaboration, C. Adloff *et al.*, Phys. Lett. **B517** (2001) 47.
- [3] P. Kroll *et al.*, Nucl. Phys. **A598** (1996) 435.
- [4] HERMES Collaboration, A. Airapetian *et al.*, Phys. Lett. B **422** (1998) 484.
- [5] M. Beckmann *et al.*, Nucl. Instr. Meth. (2001), in press, [physics/0009047]
- [6] E. Thomas, *Single Spin Azimuthal Asymmetries in Electroproduction of Exclusive π^+* , 9th International Workshop on Deep Inelastic Scattering and QCD (DIS 2001), Bologna, Italy (2001).
- [7] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. D **64** (2001) 097101.
- [8] L.L. Frankfurt, M.V. Polyakov, and M. Strikman, *$N \rightarrow \Delta$ DVCS, exclusive DIS processes and skewed quark distributions in large N_c limit*, Contribution to the Workshop “Jefferson Lab Physics and Instrumentation with 6-12 GeV Beams”, Newport News, VA, hep-ph/9808449, (1998).
- [9] M. Vanderhaeghen, P. A. M. Guichon, and M. Guidal, Phys. Rev. **D60** (1999) 094017.
- [10] M. Vanderhaeghen *et al.*, Phys. Rev. C **62** (2000) 025501.
- [11] X. Ji, Phys. Rev. Lett. **78** (1997) 610; Phys. Rev. D **55** (1997) 7114.
- [12] J. Ely, “Measurement of the single spin azimuthal asymmetry in the predominantly exclusive electroproduction of photons from the proton”, Ph.D. Thesis, University of Colorado, Boulder, Colorado (2002)
- [13] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett. **87** (2001) 182001

- [14] A. V. Belitsky and D. Müller, L. Niedermeier, and A. Schäfer, Nucl. Phys. B **593** (2001) 289.
- [15] A. V. Belitsky, D. Muller and A. Kirchner, arXiv:hep-ph/0112108.
- [16] N. Kivel, M. V. Polyakov, and M. Vanderhaeghen, Phys. Rev. **D63** (2001) 114014.

Figure 1d.1: (a) Feynman diagram for deeply-virtual Compton scattering, and (b) photon radiation from the incoming and scattered lepton in the Bethe-Heitler process.

Figure 1d.2: Definition of the azimuthal angle between the scattering and photon production planes.

Figure 1d.3: Beam-spin asymmetry, A_{LU} , for the hard electroproduction of photons as a function of azimuthal ϕ .

Figure 1d.4: The azimuthal distribution of the accepted and reconstructed MC events.

Figure 1d.5: The single beam-spin asymmetry as a function of Q^2 comparing the measured asymmetry to the acceptance corrected asymmetry.

Figure 1d.6: The single beam-spin asymmetry as a function of t comparing the measured asymmetry to the acceptance corrected asymmetry.

Figure 1d.7: The single beam-spin asymmetry as a function of x_{Bj} comparing the measured asymmetry to the acceptance corrected asymmetry.

Figure 1d.8: The single beam-spin asymmetry as a function of Q^2 .

Figure 1d.9: The single beam-spin asymmetry as a function of t .

Figure 1d.10: The single beam-spin asymmetry as a function of x_{Bj} .

Figure 1d.11: The target single spin asymmetry A_{UL} from the 96/97 hydrogen polarized target data fit with a series in $\sin \phi$.

Figure 1d.12: The target helicity moments $A_{UL}^{\sin \phi^\pm}$ as a function of missing mass for the 96/97 hydrogen polarized target data.

Figure 1d.13: The target analyzing power $A_{UL}^{\sin \phi}$ as a function of missing mass for the 96/97 hydrogen polarized target data.

Figure 1d.14: The beam-charge asymmetry, A_C , as a function of ϕ . Note that the electron and positron samples have been “helicity-canceled” as described in the text.

Figure 1d.15: The $\cos\phi$ moment of the beam-charge asymmetry, $A_C^{\cos\phi}$, as a function of missing mass M_x . Note that the moment is non-zero only in the region near the proton mass, $M_x \approx 1$ GeV, while at larger missing mass it is consistent with zero.

1.e Nuclear Polarization of Molecular Hydrogen Recombined on Drifilm

U. Stösslein (University of Colorado), The HERMES Collaboration

During the past years, increased use has been made of polarized hydrogen and deuterium gas targets, which are placed in the circulating beams of storage rings. In order to increase the target thickness over that obtained by a jet of polarized H atoms, the beam from atomic beam sources is directed in an open, cooled cell (*storage cell*) in which the atoms make several hundred collisions before escaping. In order to inhibit recombination and depolarization processes, the cells are usually coated with teflon like materials. The HERMES experiment uses such a target to study deep inelastic scattering of the 27.6 GeV positrons of the HERA storage ring from polarized H/D nuclei. The polarization of the atoms is measured by a Breit-Rabi atomic polarimeter (BRP) which determines the populations of the four hyperfine states of H . However a fraction of the atoms recombines to form H_2 , whose amount is measured, but whose molecular polarization is not known; this reflects itself in an increased systematic uncertainty in the target polarization.

The nuclear polarization of recombined H_2 molecules has been recently studied in a separate

experiment [1]: a polarized atomic beam has made recombine using a copper surface and the nuclear polarization of the molecules has been measured by elastic proton scattering. This result is not directly applicable to the HERMES storage cell which is coated with Drifilm [2] so that it exhibits different surface characteristics. The only other existing measurement on this subject concerns recombination of tensor polarized D atoms, but has also been performed on a copper surface [3]. The present work reports the first measurement of the molecular polarization of recombined atoms on Drifilm.

The Hermes experiment is installed in the HERA ring where the positrons self-polarize by emission of synchrotron radiation in the transverse direction respect to their momentum. Two spin rotators provide the longitudinal polarization at Hermes interaction point. The HERMES spectrometer is described in [4].

A beam of Hydrogen atoms is generated in a radio-frequency dissociator which forms part of the atomic beam source (ABS) [5]. The beam of nuclear polarized atoms is injected into the center of a thin-walled storage cell [6] via a side tube and the atoms then diffuse to the open ends of the cell where they are removed by a high speed pumping system. The storage cell is coated with Drifilm in order to minimize wall interaction effects. A magnetic holding field provides a quantization axis for the spins and inhibits nuclear spin relaxation by decoupling nucleon and electron spins. The beam emerging from a second side tube is analysed by a Breit-Rabi polarimeter (BRP) [7] to measure its atom polarization and a target gas analyser (TGA) [8] to determine its atomic fraction [9]. During the atom diffusion process, relaxation by wall and spin exchange collisions and wall recombination [10] changes the polarization and the atomic fraction of the target gas. The atom polarization and atomic fraction values measured by the BRP and TGA must be corrected for these effects to obtain the average target polarization as seen by the positron beam [11], which is described by the following expression:

$$P_T = \alpha_0 [\alpha_r + (1 - \alpha_r)\beta] P_a, \quad (1)$$

where α_0 is the atomic fraction accounting for unpolarized molecules (i.e. not coming from recombination), α_r is the relative atomic fraction surviving recombination, $(1 - \alpha_r)$ is the relative fraction of recombined atoms, P_a is the nuclear polarization of the atoms and $\beta = P_m/P_a$ the relative polarization of the recombined molecules respect to the atomic polarization ($0 \leq \beta \leq 1$), which is the quantity we extracted in the measurement presented below.

The reported measurement is based on the 1997 data taking period using a Hydrogen target. The method adopted to extract the molecular polarization, exploits the double spin asymmetry of a longitudinally polarized lepton beam from a longitudinally polarized proton target. The asymmetry can be derived from the cross sections difference for the positron and

the proton spin aligned antiparallel ($\overleftarrow{\rightleftharpoons}$) and parallel ($\overrightarrow{\rightleftharpoons}$) respectively:

$$A_{||}^{meas} = \frac{\sigma^{\overleftarrow{\rightleftharpoons}} - \sigma^{\overrightarrow{\rightleftharpoons}}}{\sigma^{\overleftarrow{\rightleftharpoons}} + \sigma^{\overrightarrow{\rightleftharpoons}}} = \frac{1}{P_b P_T} \frac{(N/L)^{\overleftarrow{\rightleftharpoons}} - (N/L)^{\overrightarrow{\rightleftharpoons}}}{(N/L)^{\overleftarrow{\rightleftharpoons}} + (N/L)^{\overrightarrow{\rightleftharpoons}}}. \quad (2)$$

Here, N denotes the number of events per spin state corrected for the background arising from charge symmetric processes and L is the corresponding luminosity measured with Bhabha scattering. P_b (P_T) is the beam (target) polarization.

According to Eq. 2, the sensibility to measure the relative molecular polarization β is best if the conditions are such that the recombination rate is high (low α_r). This could be achieved by increasing the temperature of the target cell from 100 K (normal running conditions) to 260 K. The temperature dependence of the recombination is described in [10].

Employing the fact that the cross section asymmetry is nearly independent from the experimental conditions, $A_{||}$ has to be the same for both target conditons. This leads to:

$$\frac{C_{||}^{100K}}{P_T^{100K}} = \frac{C_{||}^{260K}}{P_T^{260K}} \quad (3)$$

where $C_{||}$ indicates the quantity:

$$C_{||} = \frac{1}{P_b} \frac{(N/L)^{\overleftarrow{\rightleftharpoons}} - (N/L)^{\overrightarrow{\rightleftharpoons}}}{(N/L)^{\overleftarrow{\rightleftharpoons}} + (N/L)^{\overrightarrow{\rightleftharpoons}}} \quad (4)$$

and P_T^{100K} and P_T^{260K} are the target polarizations at 100 K and 260 K, which, by using Eq. (2), can be expressed by:

$$P_T^{100K} = \alpha_0^{100K} [\alpha_r^{100K} + (1 - \alpha_r^{100K}) \beta^{100K}] P_a^{100K} \quad (5)$$

$$P_T^{260K} = \alpha_0^{260K} [\alpha_r^{260K} + (1 - \alpha_r^{260K}) \beta^{260K}] P_a^{260K} \quad (6)$$

The values for $\alpha_0^{100K, 200K}$, $\alpha_r^{100K, 200K}$, $P_a^{100K, 200K}$ are reported in Table 1e.1. As the surface conditions at 100 K and 260 K are different, β^{100K} and β^{260K} has to be considered independently, so that two unknowns are present in equations (5) and (6) and enter in Eq. 3. For the determination of β^{260K} a minimization procedure has been adopted where the sum goes over the number of kinematic bins of the asymmetry measurement:

$$F(\beta) = \sum_{i=1}^{bins} \left[\frac{\frac{C_{||}^{260K}}{P_T^{260K}(\beta^{260K})} - \frac{C_{||}^{100K}}{P_T^{100K}(\beta^{100K})}}{((\sigma_{C||}^{260K})^2 + (\sigma_{C||}^{100K})^2)^{1/2}} \right]^2 = min. \quad (7)$$

	P_a	α_0	α_r
100 K	0.906 ± 0.01	0.96 ± 0.03	0.945 ± 0.035
260 K	0.939 ± 0.015	0.96 ± 0.03	0.26 ± 0.04

Table 1e.1: Atomic polarization and atomic fraction at 100 K and 260 K

The result is depicted in Fig. 1e.1. The plot shows that the assumption taken for β^{100K} have low impact on the result for β^{260K} .

The following value has finally been extracted for β^{260K} (for $0 \leq \beta^{100K} \leq 1$):

$$\beta^{260K} = 0.68 \pm 0.09_{stat} \pm 0.06_{syst} \quad (8)$$

The systematic uncertainty is mainly given by the uncertainty in the target polarization introduced by the sampling technique.

Under the experimental conditions in which the measurement has been performed, the main mechanism responsible for recombination active in the target cell is the Eley-Rideal mechanism [12] in which an atom coming from the volume hits a chemically bound atom on the surface with enough kinetic energy to overcome the activation barrier [10]. Assuming that the nucleons act as spectators in the recombination process, the nuclear polarization of the molecule at its formation (P_m^0) can be evaluated by taking the average value between the polarization of the atom coming from the volume (P_a) and of the one sitting on the surface (P_s):

$$P_m^0 = \frac{P_a + P_s}{2} \quad (9)$$

The loss of polarization of the molecule after recombination has been well described in [1]. In free flight, internal molecular fields B_c from the spin rotation interaction and the direct dipole-dipole interaction, cause the nuclei to rapidly precess around a direction which is skew to the external field by B_c/B . The orientation of B_c is randomized at each wall collision. Between successive wall collision, the component of the polarization along the external field decreases by an amount $(B_c/B)^2$ and after n wall bounces:

$$P_m = P_m^0 e^{-n(B_c/B)^2} \quad (10)$$

where B_c for H is 6.1 mT. For the HERMES cell, we have the values: $n \approx 300$ [11], $B \approx 330$ mT so that Eq. 10 allows to conclude $P_m \approx P_m^0$. From the extracted value of β^{260K}

Figure 1e.1: $F(\beta)$ as a function of β^{260K} for fixed values of β^{100K} in the allowed range $0 \leq \beta \leq 1$.

and making use of Eq. 9 and of the value for P_a^{260K} (see Table 1e.1), we are able to give an estimation for the residual polarization of the atoms on the surface:

$$P_s^{260K} = 0.34 \pm 0.22_{tot}. \quad (11)$$

The longitudinal double spin asymmetry in positron proton scattering has been used to measure for the first time the nuclear polarization of the molecules produced by recombination of Hydrogen atoms on a Drifilm coated storage cell. The measurement indicates that the atoms on the surface show nonzero nuclear polarization and can represent an important point in the possible development of a polarized molecular target. The extension of the result to the normal working conditions of the HERMES target (100 K), will sensibly decrease the systematic uncertainty of the target polarization.

References

- [1] Wise T. et al. *Phys. Rev. Lett.* **87**, 042701, (2001).
- [2] Thomas G. E. et. al.; *Nucl.Instrum. and Meth. A* **257**, 32 (1987).
- [3] van den Brand J.F.J et al. *Phys. Rev. Lett.* **78**, 1235 (1997).
- [4] Ackerstaff et al.; *Nucl. Instr. Meth. A* **482**, 606 (2002).
- [5] Nass A. et al. *The HERMES polarized Atomic Beam Source*, submitted.
- [6] Baumgarten C. et al. *The polarized H/D internal target storage cell for the HERMES experiment at HERA*, to appear on NIM A.
- [7] Baumgarten C. et al. *Nucl. Instrum. and Meth. A* **482**, 606 (2002).
- [8] Simani M. C. et al. *The gas analyzer of the target of the HERMES experiment*, submitted.
- [9] a schematic representation of the HERMES target is given in the contribution by Nass A.: *The Atomic Beam Source of the HERMES Target* to the forthcoming SPIN2002 proceedings.
- [10] Baumgarten C. et al. *Measurements of recombination at the HERMES H/D gas target* to appear on NIM A.
- [11] Baumgarten C. et al. *Eur. Phys. J. D* **18**, 37 (2002)
- [12] Haeberli W.; *Ann. Rev. Nucl. Sci.* **37**, 297 (1967)

1.f Alignment Studies for the HERMES Spectrometer

A. Kisselev (University of Colorado), The HERMES Collaboration

It was realized in early 2003 that possible displacement of the positron beam in HERMES target region can bring unwanted biases into a number of analyses, especially those which are sensitive to the acceptance symmetry. Unfortunately the beam position monitors (BPMs) of HERA provide in fact only a relative measurement, and their internal calibration was always questionable. Therefore it was highly desirable to develop an offline procedure which could provide information on beam position and slopes from the reconstructed particle tracks themselves.

Such a procedure was developed during a course of 2003. It is based on a complicated algorithm which minimizes average deviation of a set of tracks from a 4-parameter straight line in space. The minimization procedure is performed iteratively, with the correct error matrix effectively calculated on each step, for all tracks. This is used internally instead of the errors provided by HRC (the official HERMES reconstruction program), which are underestimates.

The procedure allows one to determine X and Y beam positions in the target region with the statistical accuracy of up to 20 microns, beam X -slope with an accuracy up to $100\mu\text{rad}$, and beam Y -slope up to $300\mu\text{rad}$, on a fill-by-fill basis.

It was demonstrated that if the corrected beam parameters are used instead of the default assumption that the beam is going strictly along the Z axis, through the point $(0,0,0)$ in space, the significant asymmetry of top *vs* bottom detector observed in a number of geometrical and kinematical plots, either disappears or becomes much smaller.

The results of this study clearly demonstrated that a typical shift of the beam line from point $(0,0,0)$ in XY -plane with respect to the tracker can be as big as ~ 1 mm, while inclination to the Z axis can be more than 1 mrad. Besides the top and bottom detectors “seeing” the beam in slightly different places, since the relative difference is of the same scale as the numbers quoted above, this indicates a significant top-bottom misalignment.

Incorporation of this correction in the HERMES reconstruction chain is presently impossible because of the systematics introduced by the reconstruction program into track parameter determination (see “HERMES tracking code upgrade” below for more details).

Results of this study were reported during the HERMES Analysis week in February 2003 and to the HERMES Collaboration at its meeting in April 2003.

Figure 1f.1: The distribution of interaction vertices in the transverse direction for top and bottom HERMES detectors before correction.

Figure 1f.2: The distribution of interaction vertices in the transverse direction for top and bottom HERMES detectors after correction.

1.g Support and Upgrade of HERMES Tracking Codes

A. Kisselev (University of Colorado), The HERMES Collaboration

After the threshold Čerenkov counter was replaced by the RICH in 1998, it was noticed that the spectrometer momentum resolution was degraded substantially, especially for lower momentum particles. The reason was clear, since the RICH detector included aerogel tiles and a lucite plate dividing the aerogel and C_4F_{10} gas volumes, which together contribute more than 0.04 radiation lengths. The RICH is placed inbetween two sets of rear drift chambers, therefore the angular resolution for this part of the tracker deteriorates due to the increased multiple Coulomb scattering, and this in turn has an impact on momentum resolution.

It was demonstrated using Monte-Carlo techniques that the angular resolution of the back tracker can be partly recovered if one uses a non-diagonal metric for track fitting. Indeed due to the multiple scattering, hit residuals in the drift chamber planes behind the RICH detector are correlated. Therefore the best possible metric for track fitting (which is an inverse one to the residual correlation matrix according to the Gauss-Markov theorem) becomes non-diagonal. This metric is momentum-dependent and can be calculated from a set of simulated Monte-Carlo events with a realistic geometry setup.

Results of this study were reported to the HERMES Tracking meeting in November 2002.

HERMES Tracking Code Upgrade

It turns out that there is no easy way to incorporate new developements in tracking into the existing HERMES reconstruction program (HRC), as well as to design a standalone “correction” code to be run on the output files of the standard HERMES reconstruction. Beam line position fits can not be implemented because the present HRC tracking code introduces significant bias into front tracks depending on the scattering angles and momenta. Therefore beam positions and slopes appear to be dependent on the kinematics of the event sample taken for fitting. Back track fitting can not be applied easily because the “best” metric is momentum-dependent and therefore fitting and momentum determination should be included alternatingly into the iterative procedure inside HRC, and this task does not seem to be feasible.

There are also a number of other intrinsic limitations in HRC (relative rotations of tracking planes around the Z axis are not incorporated, a bias of the front track parameter determination for so-called short tracks exists, momentum errors are not given at all, track covariance matrices are not realistic because multiple scattering is not taken into account, etc). Besides this the code base of HRC is not sufficiently transparent to incorporate flawlessly new tracking detectors such as the Lambda Wheels.

Also, it has been known for years that the HERMES alignment code is suboptimal since it basically deals with the so-called internal alignment and does not provide any means to determine relative position of top versus bottom detector and both of them with respect to the beam line. Even the internal alignment procedure has an intrinsic arbitrariness in its parameter definition and also does not provide an easy way to fix once forever positions of those detectors which were not moved since the very first shutdown in 1996.

In general it is rather unnatural to have a drift chamber calibration code, alignment program, reconstruction code itself and efficiency calculation routines in different places, being maintained by several people with different programming experience. Of course the authors and original maintainers of this software left HERMES long ago.

In view of the HERMES Run II, it was decided to revisit all these different pieces of code, rewriting from scratch where appropriate and putting them into one place. Here is the present status of this work:

I. Alignment code

“internal” alignment	→ a working skeleton is ready
top vs bottom alignment	→ not started yet
beam alignment	→ ready

II. Drift chamber calibration code

→ not started yet, present code
should suffice to the moment

III. Track reconstruction code

input/output routines and command line interface	→ not started yet
separate front & back region track finder (tree search based)	→ in a test phase (proven to find tracks, to be tuned for performance and efficiency)
front/back track matching & mom. determination	→ not started yet
track fitting	→ ready
“short track” finder and fitting procedure	→ not started yet

IV. Drift chamber efficiency code

→ not started yet, present code should suffice to the moment

As seen from this list, the alignment code and a key component of the track reconstruction code (track finder) are well advanced. Another key component (momentum determination) does exist on a conceptual level only at the moment. Other parts look less complicated for implementation. It is assumed that a preliminary version of the track reconstruction code can be ready by the end of 2003 (except for the “short tracks” where the Magnet chamber hits are used to define track parameters), as well as a functioning version of alignment program. It is also assumed that calibration and efficiency codes can in principle be taken “as is” if it turns out that time constraints do not allow us to develop new software versions from scratch.

1.h Management of HERMES PC farm

A. Kisselev (University of Colorado), The HERMES Collaboration

The HERMES Offline PC farm in its present state was available to users in the beginning of 2002. It is a unique self-contained cluster setup suited for the needs of experiment up to the end of HERA Run II. At the moment it features 48 CPUs available for physics analysis and data production purposes, and around 5TB of shared disk space.

Management is done on a shared basis by 2 persons and includes participation in regular maintainance, troubleshooting and taking decisions on necessary upgrades. Since November 2000 one additional 1.4TB File server was installed, another 2.2TB box is ordered and is due to be installed in September.

Data from different years of HERMES data acquisition needs to be reprocessed from time to time as long as our understanding of the detector improves (which implies better calibration) and/or more advanced versions of reconstruction code appear.

Data production management includes setting up the software configuration directories specific to any given year, collecting detector calibrations, actual running the production on the HERMES Offline PC farm and being the primary expert on the produced output files.

Since November 2002 data taken 1997-1999 years have been reanalyzed, as well as 2 more iterations over the latest 2002 data set.

Figure 1h.1: Schematic of the HERMES PC farm setup.

2. A New Measurement of G_E/G_M for the Proton

David Gaskell, Edward Kinney (University of Colorado), the E01-001 Collaboration, J. Arrington, R.E. Segel, spokesmen.

Introduction

The electric and magnetic charge distributions of the proton, described by the elastic form factors G_E and G_M , have become a topic of renewed interest in the last few years. Historically, G_E and G_M have been measured via the Rosenbluth technique. This technique makes use of the fact that the elastic ep cross section, σ_{el} , can be written,

$$\sigma_{el} = \sigma_{Mott} \left(G_E^2 + \epsilon^{-1} G_M^2 Q^2 \kappa \right), \quad (1)$$

where σ_{Mott} is the Mott cross section, ϵ is the virtual photon polarization, and $\kappa = \frac{\mu_p}{2M_p} = 2.212$. By measuring the elastic cross section at constant Q^2 but at several values of ϵ (by varying the beam energy and scattered electron angle) one can extract G_E and G_M via a simple linear fit of the ϵ dependence. Several experiments have made such measurements [1, 2, 3, 4, 5, 6] and global fits [1, 7] have found that $\mu_p G_E/G_M$ is consistent with unity out to $Q^2 \approx 5 \text{ GeV}^2$.

Recent experiments in Hall A at Jefferson Lab [8, 9, 10] have made use of the recoil polarization technique, in which a polarized electron transfers its polarization to the recoiling proton, to achieve high precision results for $\mu_p G_E/G_M$. In this case, the ratio of the elastic form-factors is proportional to the ratio of the transverse and longitudinal components of the recoiling proton polarization, i.e., $G_E/G_M \sim P_t/P_l$. These experiments found that the ratio of form factors drops linearly as a function of Q^2 and is ≈ 0.3 at $Q^2 = 5.6 \text{ GeV}^2$.

The Hall A recoil polarization results are clearly incompatible with fits to previous world data. One possibility is that either the Rosenbluth or recoil polarization technique is not totally understood, hence resulting in an incorrect interpretation of the data. Alternatively, there may be some experimental systematic effect not accounted for in either the Hall A recoil polarization results or the Rosenbluth data.

In order to provide some insight into the disagreement in these results, an improved version of the Rosenbluth technique for measuring $\mu_p G_E/G_M$ was run in Hall A. This measurement reduces common Rosenbluth separation systematic uncertainties by detecting the recoiling proton in the elastic scattering reaction. In this case, momentum dependent systematic uncertainties cancel because the proton momentum is constant (at constant Q^2), the sensitivity of the cross section to the kinematics of the detected particle is less, and rate dependent systematics are reduced because the proton cross section is much less dependent on ϵ . In addition, uncertainties due to absolute normalization of cross sections (i.e. target thickness and beam

current) are largely avoided by taking data simultaneously at low Q^2 where the form factors are considered to be well known. Projected uncertainties are shown in Fig. 2.1, along with Rosenbluth and recoil polarization results.

Jefferson Lab Experiment 01-001 ran in Hall A in May of 2002. The Colorado group played a major role in the running of this experiment: participating in pre-run preparations, taking shifts, and providing the Run Coordinator for half the run period. The analysis of the data is ongoing and preliminary results are not yet available.

References

- [1] R. C. Walker *et. al.*, Phys. Rev. **D49** 5671 (1994).
- [2] L. Andivahis *et. al.*, Phys. Rev. **D50** 55491 (1994).
- [3] A. F. Sill *et. al.*, Phys. Rev. **D48** 29 (1993).
- [4] W. Bartel *et. al.*, Nucl. Phys. **B58** 429 (1973).
- [5] L. E. Price *et. al.*, Phys. Rev. **D4** 45 (1971).
- [6] J. Litt *et. al.*, Phys. Lett. **31B** 40 (1970).
- [7] P. E. Bosted, Phys. Rev. **C51** 409 (1994).
- [8] M. .K. Jones *et. al.*, Phys. Rev. Lett., **84** 1398 (2000).
- [9] O. Gayou *et. al.*, Phys. Rev., **C64** 038202 (2001).
- [10] O. Gayou *et. al.*, Phys. Rev. Lett., **88** 092301 (2002).

Figure 2.1: $\mu_p G_E / G_M$ as a function of Q^2 . The open circles are from a global analysis of existing absolute cross section data [1] with G_E / G_M extracted via the Rosenbluth technique, while the crosses denote results of recoil polarization measurements made in Hall A [8, 9, 10]. The dotted line is extracted from a parameterization of cross section data [7] and the dashed line is a fit to the Hall A results assuming a linear dependence of $\mu_p G_E / G_M$ on Q^2 . The solid squares denote predicted uncertainties from the improved Rosenbluth technique (E01-001) assuming the results coincide with the Hall A results (bottom) or the older Rosenbluth data (top).

3. Spin-Flavor Physics Studies For an Electron-Ion Collider

U. Stösslein, E.R. Kinney (University of Colorado)

Precise determination of the quark spin and flavor structure of the nucleon remains one of the central goals in the study of the quark-gluon dynamics. While the structure is becoming well determined in the range of intermediate Bjorken x where valence quarks predominate, there is still large uncertainty in the structure of the virtual sea at low x as well as in the valence structure at high x . Inclusive lepton scattering alone is unable to resolve the details of this structure as the charge weighted sum of all the quark distributions is measured, rather than individual flavor. Significant progress can be made by using semi-inclusive scattering in which hadrons produced in a photon-quark reaction are detected in coincidence with the scattered lepton. Knowledge of the identity of these hadrons and their kinematic correlation with the momentum and energy of the virtual photon allow one to separate the contributions from the different quark flavors. Combined with the use of polarized targets and beams, one learns the spin contribution of the individual flavors as well. The spin contribution of the strange quarks is especially important as knowledge of their role in nucleon structure has been one of the most highly sought pieces of information in recent years. This relatively tiny component of the nucleon wavefunction appears to have a much more significant role than expected in determining the properties of the nucleon, such as spin.

Fixed target experiments suffer from the fact that the so-called current hadrons are produced at forward angles in the lab frame simply due to the Lorentz boost of the beam, which is difficult to instrument adequately, especially as one tries to increase the luminosity to gain significant statistical accuracy. In addition, almost all of the fragments of the remaining target nucleon are lost at small angles and energies. Correlation of these target fragments with the directly produced hadrons would likely enhance the power of the semi-inclusive technique, as the dilution due to hadron production in the fragmentation process would be lessened.

A polarized ion-electron collider such as the proposed EIC would be an ideal facility for semi-inclusive studies. The collider kinematics would open up the final state into a large solid angle in the lab, allowing much more complete identification of the hadronic final state, both in the current and target kinematic regions of fragmentation phase space, and at the same time allow high luminosity operation.

Initial studies of spin-flavor structure have focused on semi-inclusive asymmetries measured on the proton only; deuteron beams will allow study of the neutron, which typically increases the sensitive to the down valence quarks. The simulation used events generated by the standard deep inelastic generator LEPTO [1] for collisions of 5 GeV electrons on 50 GeV protons,

here parton distribution functions were taken from [2]. Hadronization is performed using the LUND string model, implemented in JETSET. Inclusive and semi-inclusive cross sections as well as the flavor tagging probabilities (co-called purities) were determined from the reaction products where a specific leading hadron ($z = E_{hadron}/E_{photon}$, $0 < z < 1$, and $x_F = 2p_{h||}/W$, $0 < x_F < 1$) is detected and identified (perfectly) in coincidence with the scattered lepton. Lepton and leading hadron are required to have polar angles greater than 5° from the axis of the colliding beams, and momenta greater than 1 GeV; no other assumptions are made about the detector capabilities. For the sake of concreteness an integrated luminosity of 1 fb^{-1} has been used to determine the size of the simulation sample. For the statistical precision of the polarized sample for each of the beams a polarization of 70% was taken into account.

The inclusive and semi-inclusive asymmetries were combined from the simulated flavor tagging probabilities and polarized parton distributions [5]. The asymmetries have been analyzed using the purity method developed at the SMC [3] and HERMES [4] experiments. This method relates the set of measured asymmetries to the polarization of flavor separated quark distributions via a matrix of purities derived from knowledge of the unpolarized quark distributions and the fragmentation functions which describe the hadronization of a particular flavor quark into a specific type of hadron. We assume here that these functions are known. A leading order formalism in perturbative QCD is used throughout.

Two different analyses have been performed. In the first, more conservative case, the four hadron asymmetries from both charge states of pions and kaons are used are used to derive quark polarizations for up and down distributions, the polarization of the up and down (light anti-quark) sea, and the polarization of the strange sea quarks, see in Ref.[6] for further details. The results are shown in Fig. 3.1, in which only statistical uncertainties are displayed by the error bars.

In the second analysis, it is assumed that the up and down quark distributions are known sufficiently well, that one make take them as given, and directly determine the strange quark distribution from any of the specific hadron asymmetries, as all of them depend on the strange quark distribution. A sample of the results on the polarized strange distribution extracted from the K^- asymmetry is shown in Fig. 3.2 in which the asymmetry is also displayed. As in the previous figure, only statistical uncertainties are indicated. The results are compared with the precision expected from currently planned measurements are the HERMES experiment.

Both of the figures show that the use of standard analysis techniques on semi-inclusive data will yield a much more precise determination of the nucleon spin-flavor structure, especially when combined with the results expected from RHIC, CERN and DESY in the next five years. If one assumes that advances are made in the detailed understanding and description of the fragmentation process, and in making such analyses consistently in next-to-leading order, then

Figure 3.1: Expected statistical precision of the quark polarizations for up, down, the light anti-quarks and the strange quarks, using polarized [5] and unpolarized [2] parton distribution functions. Here the four charged pion and Kaon asymmetries were chosen as input. The measured average Q^2 values per x bin are not shown here and are in the range of 1.1 GeV^2 at lowest x to 40 GeV^2 at highest x .

Figure 3.2: The upper plot shows the simulated K^- asymmetry ($p > 1$ GeV) at measured Q^2 values (not shown). The lower plot shows the expected statistical precision of the strange quark distribution for an EIC simulation in comparison to the projected result of a HERMES analysis [7]. The positivity constraint given by the unpolarized strange quark distribution [2] is also plotted.

it is likely that even more precision will be obtained as well as a deeper understanding of the nucleon structure.

References

- [1] Information and code via WWW page <http://www3.tsl.uu.se/thep/lepto/> .
- [2] M. Glück, E. Reya, and A. Vogt, Z. Phys. **C 67** (1995) 433.
- [3] SMC, B. Adeva *et al.*, Phys. Lett. **B369** (1996) 93; Phys. Lett. **B420** (1998) 180.
- [4] HERMES Collab., K. Ackerstaff *et al.*, Phys. Lett. **B464** (1999) 123.
- [5] M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. **D 53** (1996) 4775.
- [6] H. Kobayashi, PhD thesis, Tokyo Institute of Technology (2000).
- [7] HERMES Collaboration, “The HERMES Physics Program and Plans for 2001–2006,” HERMES Report No. 00-003 (2000).

B. FUNDAMENTAL SYSTEMS AND NUCLEAR INTERACTIONS

1. Main Injector Particle Production

R. J. Peterson and the MIPP collaboration

Fermilab E907 [1] will provide particle-identified and momentum-analyzed beams of protons, kaons and pions of either sign onto a range of nuclear targets, with a detector system to collect and analyze a very broad range of reaction products. Low momentum ejectiles will be treated in a time projection chamber, to analyze multiplicities of up to ten. Higher momentum ejectiles will be analyzed with a dual magnetic spectrometer and extensive particle identification. Most of the system has been installed, and first beam is expected in late 2003. A wide range of high energy hadronic reaction studies is planned [1].

Our interests are focussed on the opportunities for extended quasifree nuclear processes, with elastic quasifree scattering as reported elsewhere continued to regions of higher beam momentum. This is especially desired for the pion beam studies, where our experiments to date have been at beam energies still susceptible to the role of discrete resonances. The MIPP project will provide beam momenta up to 100 GeV/c, which is too much for these studies, but also will provide a range of lower momenta. An explicit nuclear quasifree study has been designed. The design resolution of the MIPP system will permit data of suitable quality for beam momenta up to perhaps 20 GeV/c.

The Colorado contribution to the setup has been the provision of the nuclear thin target system. A filter wheel system designed for optical work has been purchased, modified, and installed in the MIPP hall, operating under remote computer control. An array of nuclear targets suited to the goals of the MIPP collaboration has been obtained.

References

- [1] see ppd.fnal.gov/experiments/e907 for the proposal and status reports

2. Measurement of Elastic π^+/π^- -proton Elastic Analyzing Powers

J. D. Patterson, G. J. Hofman, R. J. Peterson, (University of Colorado) and the CHAOS Collaboration

The analysis of CHAOS data for π^+ -proton elastic analyzing powers A_y at 139 MeV and those for π^- -proton at 139, 117, 98, 87, 67, and 57 MeV is complete, and accepted in the Ph.D. thesis of J.D. Patterson. A manuscript is in circulation among members of the collaboration.

These data extend to lower energies the data base for A_y , sensitive to interference of partial waves, and thus to small partial waves. With better determinations of these small partial wave amplitudes, a more reliable extrapolation of the S-wave scattering length to the nonphysical Cheng-Dashen point can be carried out. The value thus obtained for the $\pi - N \sigma$ term can be a measure of the explicit breaking of chiral symmetry in the π -nucleon system.

The low beam energy and resulting low energies for recoil protons required development of new analysis methods for CHAOS data. A “short track” method was developed and compared where appropriate to results using more complete information. Another advance was a very fast replay system, which permitted a thorough understanding of the effects of cuts and tests for the events on the final result. This resulted in a good understanding of the systematic uncertainties in A_y . It was also necessary to develop a means to average A_y over the energy spread of the low energy pions in the polarized target.

Analyzing powers at the three lowest energies are shown in Figs. 2.1a and b, 2.2a and b, and Fig. 2.3. These data are compared to a solid line which is the SM95 SAID result, averaged over the angle bins of the experiment and over the energy spread of the beam. The striking extremum at back angles for 57 MeV is not so strong as SM95 would provide without these averaging effects. The dashed curves show results using the dated KH80 phase shifts.

Table 2.1 lists the χ^2/DOF comparisons of these data to SM95. We see no trends with beam energy to indicate a systematic problem with this solution. The overall comparison yields $\chi^2/\text{DOF}=1.156$.

There is a 3.7% systematic normalization uncertainty from the measurement of the target polarization. If we allow the normalization to shift for a fit to SM95, the resulting χ^2/DOF decrease some, but again show no systematic problem with SM95.

We conclude that SM95, which did not include low energy π -p A_y data, gives a good match to these new data. It would appear that extrapolations to determine the sigma term using this solution are unaltered.

Table 2.1: Comparison of the present data to predictions with SAID using SM95 are listed as the χ^2/DOF . The SAID outputs were averaged over the angular acceptance of CHAOS and the beam energy profile.

Energy(MeV)		χ^2/DOF
139	π^+	2.306
139	π^-	0.328
117	π^-	2.379
98	π^-	0.817
87	π^- standard	0.958
87	π^- short track	0.577
67	π^- standard	1.066
67	π^- short track	1.000
57	π^- short track	0.976

Figure 2.1a: The analyzing powers for π^-p 87.18 MeV, 1LT = 'Doubles', 2LT = 'Standard'. The bottom axis is the pion scattering angle in the lab frame. Error bars reflect statistical uncertainties only. The solid curve is the averaged SM95 prediction and the dashed curve is the averaged KH80 prediction.

Figure 2.1b: The analyzing powers for π^-p 87.18 MeV, 1LT = 'Doubles', 2LT = 'Short Track'. The bottom axis is the pion scattering angle in the lab frame. Error bars reflect statistical uncertainties only. The solid curve is the averaged SM95 prediction and the dashed curve is the averaged KH80 prediction.

Figure 2.2a: The analyzing powers for π^-p 66.95 MeV, 1LT = 'Doubles', 2LT = 'Standard'. The bottom axis is the pion scattering angle in the lab frame. Error bars reflect statistical uncertainties only. The solid curve is the averaged SM95 prediction and the dashed curve is the averaged KH80 prediction.

Figure 2.2b: The analyzing powers for π^-p 66.95 MeV, 1LT = 'Singles', 2LT = 'Short Track'. The bottom axis is the pion scattering angle in the lab frame. Error bars reflect statistical uncertainties only. The solid curve is the averaged SM95 prediction and the dashed curve is the averaged KH80 prediction.

Figure 2.3: The analyzing powers for π^-p 57.20 MeV. The bottom axis is the pion scattering angle in the lab frame. Error bars reflect statistical uncertainties only. The solid curve is the averaged SM95 prediction and the dashed curve is the averaged KH80 prediction.

3. y -Scaling in Nuclear Reactions

3.a Mesonic y -scaling at KEK

R. J. Peterson and J. T. Brack, (University of Colorado), Y. Fujii, O. Hashimoto and T. Takahashi, (Tohoku University), M. Itoh and H. Sakaguchi, (Kyoto University)

The y -scaling analysis of non charge exchange meson scattering cross sections is now complete for 624 MeV/c pions from LAMPF, 715 MeV/c K^+ from the AGS and 780-1050 MeV/c π^- from KEK. The manuscript presenting the quasielastic cross sections has been accepted for publication in the Physical Review C [1], and the y -scaling manuscript has been submitted to this journal.

The major addition since last year's Progress Report is that the same y -scaling methods and parameters have been applied to separated longitudinal electron scattering responses. Response data are for carbon at $q = 550$ and 400 MeV/c [2], carbon at 500 MeV/c [3], calcium at 400 MeV/c [4] and iron at 570 MeV/c [5]. The proton dipole form factor we used took a length parameter of 840 MeV/c. Our longitudinal y -scaled responses are just the same as those published by the electron scattering community.

Figure 3a.1 shows the carbon y -scaling responses on scales that allow overlay. We note that the meson responses are about 3.3 times greater than found for the electrons. We take this to indicate a strong medium enhancement of the largely isoscalar, nonspin pion-nucleon differential cross sections.

References

- [1] Y. Fujii et al., Phys. Rev. C **64** (2001) 034608.
- [2] P. Barreau et al., Nuc. Phys. **A 402** (1983) 515.
- [3] M. Bergmann et al., Phys. Lett. **B 243** (1990) 185.
- [4] C. F. Williamson et al., Phys. Rev. C **56** (1997) 3152.
- [5] J. Jourdan, Nucl. Phys. **A 603** (1996) 117.

Figure 3a.1: Y-scaling responses are shown for 950 MeV/c π^- scattering at a range of momentum transfers, and for longitudinal (charge) electron scattering at three momentum transfers. For the electron data, circles show data at 500 MeV/c [3], crosses for 400 MeV/c and diamonds for 550 MeV/c.[2] Note that the pion responses are stronger by about a factor of 3.3.

3.b y -Scaling in Pion Single Charge Exchange

R. J. Peterson, D. E. Prull and the Crystal Ball Collaboration

AGS Experiment 913/914 primarily used the 4π Crystal Ball detector for pion and kaon reactions on a hydrogen sample, but some time was also devoted to π^- single charge exchange (SCX) studies at 750 MeV/c on CD_2 , C, Al and Cu. Earlier results were shown in previous Progress Reports [1]. Here, the final π^0 cross sections from the entire angular range of 35 to 145 degrees are used for a study of pion SCX y -scaling. The clean case of CD_2 permitted data at 155 degrees to be used for deuterium.

If we can demonstrate that the continuum π^0 spectrum shows y -scaling [2], we will have proven that the peak seen near free proton SCX kinematics is due to one and only one incoherent quasifree charge exchange on a target proton in the complex nucleus. We can then use these data to infer the in-medium pi-nucleon charge exchange differential cross section. The methods are similar to those used for π^- non charge exchange (NCX) scattering in our KEK experiment [3, 2], although the 4π coverage of the Crystal Ball and use of a charged particle veto counter make the present data highly exclusive to reactions with only a single final π^0 .

Conservation of energy and momentum suggest that a single scaling variable

$$y = \sqrt{\omega(\omega + 2m)} - q,$$

with a recoil correction not shown here, and data transformed as

$$F(y) = \frac{d^2\sigma/d\omega d\Omega}{Z_{eff}} \frac{1}{d\sigma/d\Omega(free)} \frac{q}{\sqrt{(q - y)^2 + m^2}}.$$

should provide a universal plot for each nuclear target, as seen in electron scattering [2]. The effective number of protons Z_{eff} eligible to be seen once and only once is computed by our Glauber method [5]. We use free proton SCX cross sections as measured in the same experiment with CH_2 targets to cancel many uncertainties.

Cross sections for carbon are shown in Fig. 3b.2, with fits using the high energy face of the spectra without a background. When transformed as y -scaling, these data give Fig. 3b.3. Although a typical y -scaling peak is seen, centered near $y=0$, the magnitudes do not scale at all.

Similar results are seen for Al and Cu samples. We can use this range of masses to check our means to compute Z_{eff} by the idea of superscaling [3], where Fermi momenta as determined from electron scattering are used to transform all data to a single format, using $Y=y/k_F$ and $f(Y)=F(y) k_F$. Our data at 45 degrees are shown in this format in Fig. 3b.4. The concurrence of the data indicates the validity of the Glauber method, as also shown for π^- NCX [2].

Figure 3b.2: Measured doubly-differential cross sections for $750 \text{ MeV}/c$ π^- SCX on carbon are shown, with fits determined by the high energy face of the prominent quasifree peaks.

Figure 3b.3: Data as in Fig. 1 are transformed to the y -scaling format. Although data show the same shape for each angle, the magnitudes do not agree.

Figure 3b.4: Data for SCX on C, Al and Cu at a single angle are shown to demonstrate the validity of our Glauber method to determine the number of protons seen once and only once in pion SCX.

Table 3b.1: Scaling and superscaling maximum responses are shown and compared to results from electron scattering on similar nuclei [3].

Nucleus	$F_0(y=0)$ GeV^{-1}	$F_1(y=0)$ GeV^{-1}	$f_0(Y=0)$	$f_1(Y=0)$	$f_L(Y=0)$	$f_T(Y=0)$
C	4.33(0.29)	2.35(0.14)	0.95(0.06)	0.52(0.03)	0.59	0.83
Al	3.75(0.40)	2.84(0.19)	0.86(0.09)	0.65(0.04)	0.54	0.83
Cu	4.91(0.21)	1.37(0.15)	1.15(0.05)	0.32(0.04)	0.56	0.82

Since y-scaling is not observed for our targets, indicating that in-medium cross sections are not the same as those in free space, we consider an analogy to the Rosenbluth decomposition for electron scattering for our spin-zero pions.. We use the ratio of spin to nonspin squared amplitudes from [5] to sense the mixture of spin and nonspin quasifree cross sections. Figure 3b.5 shows the results, plotting $(1+x) F(y=0)$ against x . The quality of the data permits good determinations only of the peaks of the doubly differential cross sections, near $y=0$. As with electron scattering, a straight line fit is used to determine the $\Delta S=0$ scaling maximum $F_0(y=0)$ by the $x=0$ intercept and the $\Delta S=1$ $F_1(y=0)$ maximum by the fitted slope. These values are listed in Table 1 for the three targets.

Also shown in Table I are the superscaling maxima for these scaling functions and the

Figure 3b.5: The spin separation process described in the text is used to determine the $x=0$ intercept and the slope of the scaling maxima. These fits yield the $\Delta S=0$ and $\Delta S=1$ responses shown in Table 1.

corresponding longitudinal ($\Delta S=0$) and transverse ($\Delta S=1$) results from electron scattering [3]. The pion isovector f_1 and the transverse electron scattering f_T are formally sensing the same responses, but their magnitudes are found to differ. They would be brought into agreement if the pion $\Delta S=1$ SCX cross section in the medium were smaller than in free space, as used to create our scaling functions.

The isovector f_0 response is not probed by electrons. We find the pion results to be greater than those for electron scattering f_L . Both are from reactions on protons. These would be brought into agreement if the in-medium SCX $\Delta S=0$ cross sections were larger than those in free space.

Our data for deuterium use the integrated singly differential cross sections, since the sharp peak in the spectra allowed reliable fits. The spin analysis seen in Fig. 3b.6 gives an intercept at $1.37(0.07)$ and the slope is found to be $0.77(0.04)$. The $\Delta S=0$ enhancement and $\Delta S=1$ quenching are thus seen for deuterium as well as heavier nuclei.

Parity conservation demands that there be no $\Delta S=1$ cross section for pion SCX at 180 degrees. We have used the D data only from 105 through 155 degrees to extrapolate to $x=0$ at 180 degrees, and find that the $\Delta S=0$ pion SCX cross section at $q=1028$ MeV/C ($Q^2=0.83$ GeV $^{-2}$) is $0.94(0.10)$ times that on free protons. There is thus little or no quenching of this cross section in deuterium. The $\Delta S=1$ transverse (almost isovector) response of deuterium at

Figure 3b.6: Singly differential cross sections for deuterium and hydrogen are used for the spin separation. The $x=0$ intercept shows an enhancement of the $\Delta S=0$ cross section and the slope shows a decrease of the $\Delta S=1$ cross section.

large momentum transfers has been studied with care [8].

This work has been resubmitted for publication after suggestions from a referee.

References

- [1] University of Colorado Progress Report 2000, p. 81.
- [2] D. B. Day *et al.*, Ann. Rev. Nucl. Part. Sci. **40**, (1990) 357.
- [3] Y. Fujii *et al.*, Phys. Rev. C
- [4] R. J. Peterson *et al.*, Phys. Rev. **C 65**, (2002) 054601.
- [5] J. Ouyang *et al.*, Phys. Rev. **C 47**, (1993) 2809.
- [6] T. W. Donnelly and I. Sick, Phys. Rev. **C 60**, (1999) 065502.
- [7] Scattering Analysis Interactive Dialin, SM95 solution
- [8] H. J. Bulten *et al.*, Phys. Rev. Lett. **74**, (1995) 4775.

3.c y -Scaling in Proton Scattering to the Continuum

R. J. Peterson

As part of our program to determine in-medium interactions between hadronic projectiles and bound nucleons, we have examined spectra of protons scattered to the continuum. The format is the y -scaling transformation, as used elsewhere in this report.

Our first test of the quasifree scattering model must be that of the computed number of bound nucleons to be seen once and only once by the scattering hadron, using the superscaling method. The data shown in Fig. 3c.7 are from 795 MeV proton scattering at 20 deg.[2], with a free proton-nucleon scattering momentum transfer q of 503 MeV/c. Decent concurrence of the y -scaling maxima is found for nuclei with the mass of carbon and above. The low maximum for ${}^6\text{Li}$ is reminiscent of the same feature found for quasifree π^- scattering at this momentum transfer [2]. Figures 3c.8 through 3c.10 show the y -scaling responses for ${}^6\text{Li}$, C and Pb for these 795 MeV proton data at several angles. The shape of these responses seems correct, but the magnitudes are surely far from equal.

Figure 3c.7: Superscaling plots, using Fermi momenta from electron scattering, for 795 MeV proton scattering at 20 degrees, where the free proton-nucleon momentum transfer is 503 MeV/c. Data from [2].

These results show that at 795 MeV, the in-medium proton-nucleon differential elastic scattering cross sections cannot be equal to those in free space, else a single y -scaling response

Figure 3c.8: Y-scaling responses computed from the 795 MeV data of [2] for ${}^6\text{Li}$ at several angles.

Figure 3c.9: As Fig. 3c.8, but for carbon.

Figure 3c.10: As Fig. 3c.8, but for lead.

would be found for each target nucleus. In contrast to the π^- case [2], even ${}^6\text{Li}$ fails to yield a consistent y -scaling response.

Older proton continuum scattering data at 1014 MeV are reliable only for carbon [3]. The cross sections at this energy for several angles do yield a single y -scaling response, as seen in Fig. 3c.11.

One further data set has been considered to date, at a beam energy of 392 MeV [4]. This is somewhat low to meet all the conditions for quasifree scattering. All these data for carbon, at three beam energies, are combined in Fig. 3c.12 for momentum transfers from 400-600 MeV/c. These responses are quite nearly exhibiting a universal y -scaling response. The magnitude of the related $q=500$ MeV/c π^- y -scaling response on carbon is higher, at 6 GeV^{-1} [2].

There have been many theoretical efforts towards an understanding of the nucleon-nucleon interaction within the nuclear medium. Here, the scaling has been computed only with free-space proton-nucleon scattering [5], and a more thoughtful consideration of the changes is underway before these results are prepared for publication.

These results are hampered by the lack of total cross section measurements for protons on nuclei at suitable energies [6]. Our mesonic studies of quasifree scattering could benefit from total cross sections as an independent test of our Glauber method.

Figure 3c.11: As Fig. 3c.8, but for 1014 MeV proton scattering [3].

Figure 3c.12: Data for 1014 MeV [3], 795 MeV [2] and 392 MeV [4] scattering to the continuum of carbon are shown for angles yielding free momentum transfers from 400 to 600 MeV/c.

References

- [1] R. E. Chrien *et al.*, Phys. Rev. **C 21**, 1014 (1980).
- [2] R. J. Peterson *et al.*, Phys. Rev. **C 65**, 054601 (2002).
- [3] D. M. Corley *et al.*, Nucl. Phys. **A 184**, 437 (1972).
- [4] A. A. Cowley *et al.*, Phys. Rev. **C 62**, 064604 (2000).
- [5] Scattering Analysis Interactive Dialin, solution SM95.
- [6] R. F. Carlson, At. Data Nucl. Data Tables **63**, 93 (1996).

3.d y -Scaling in (p,n) reactions

R. J. Peterson

It was shown in last year's Progress Report that recent (p,n) spectra on complex nuclei at suitable angles for quasifree scattering did not exhibit the y -scaling familiar from other probes. The data [1] were scant at the portions of the energy spectra relevant for that test.

Here we use instead the (p,n) data of Prout [2] at 795 MeV on a few nuclear targets. The angular range included 18 degrees with good accuracy, for a lab frame momentum transfer $q=454$ MeV/c, just on the edge of the standard of twice the Fermi momentum to avoid Pauli blocking effects.

The arithmetic for the y -scaling transformation for this charge changing reaction included the Coulomb energy and the p-n Q -value. The effective number of neutrons N_{eff} to be seen for a quasifree process was computed by our Glauber method. To check this term in the scaling function $F(y)$, we use the superscaling format, with Fermi momenta from electron scattering [3]. Results for carbon and lead are shown in Fig. 3d.13. It is seen there that the agreement is not as good as for other cases, but it is to be remembered that the range of masses is large here. The transverse electron scattering data shown in Fig. 11 of Ref.[3] yield a maximum $f(Y)$ near 0.6, with a strong mass dependence. This agreement between hadron and electron quasifree scattering is not as seen in our other studies.

Figure 3d.14 compares the 795 MeV 18 degree (p,n) data for carbon at $q=454$ MeV/c to the pion SCX results shown elsewhere in this report, at angles giving $q= 431$ and 534 MeV/c. The difference shows that these two reactions encounter different alterations of their in-medium cross sections from free-space values.

Further (p,n) cases are being analyzed, and the final conclusions will be created also including the medium effects seen in proton quasifree scattering.

Figure 3d.13: Doubly-differential cross sections for neutrons seen with 795 MeV protons on C and Pb have been transformed by the superscaling algorithm with $k_F=220$ MeV/c for C and 240 MeV/c for Pb. The free momentum transfer (at $Y=0$) for this angle is 434 MeV/c. Effective numbers of neutrons used were 1.20 for C and 4.384 for Pb.

Figure 3d.14: The carbon data from Fig. 3d.13 are shown in the y-scaling format, compared to 750 MeV/c (π^-, π^0) spectra at similar momentum transfers.

References

- [1] X. Ledoux *et al.*, Phys. Rev. Lett. **82**, 4412 (1999); S. Leray *et al.*, Phys. Rev. **C 65**, 044621 (2002).
- [2] D. L. Prout, Ph.D. Thesis, University of Colorado (1992).
- [3] T. W. Donnelly and I. Sick, Phys. Rev. **C 60**, 065502 (1999).

3.e Testing for Incoherence in Hadron Continuum Scattering

R. J. Peterson

If nuclear attenuations are not included, the inclusive scattered spectrum of a projectile could be expected to include coherent scattering, with amplitudes proportional to the number of nucleon participants (remember the Z^2 in the Rutherford cross section) at low excitations to incoherent scattering at larger energy losses, with cross sections, not amplitudes, proportional to the the number of nucleons on hand. The best example of the latter is the direct counting of twenty protons to hold the charge of calcium, as measured by longitudinal electron scattering [1].

The relation between coherence and kinematics is clear only at its extremes, with the recoil energy of the entire target for coherent scattering and with a single nucleon recoiling for incoherent, or truly quasifree, scattering. The spectrum between must evolve in some fashion between these limits.

Here we use the commonly-used power law to sense the number of nucleons contributing to the yield at each energy loss ω . In order to compare measurements at different momentum transfers, we use the scaling variable y , as elsewhere in this Report, to specify the region of the spectra being considered.

For each energy loss ω , for a range of nuclear targets as large as possible, usually Li through Pb, we extract the exponent α from

$$d^2\sigma/d\omega d\Omega = \sigma_0(w)A^{\alpha(w)},$$

and transform ω at each momentum transfer q to the variable y . Cases considered include 795 MeV proton scattering at 15, 20, and 25 degrees on ${}^6\text{Li}$, ${}^7\text{Li}$, C, Al, Ca, V, Zr and Pb [2], 500 MeV π^- single charge exchange at 30 and 50 degrees on ${}^7\text{Li}$, C, Al, Fe, Cu, Zr, Sn, Ta and Bi [3], 705 MeV/c K^+ at 42 degrees on C, Ca and Pb [4], and 950 MeV/c π^- on ${}^6\text{Li}$, C, Ca, Zr and Pb [5]. The angles used covered the range from where nuclear pionic enhancements might be expected near $q=350$ MeV/c to where nuclear interactions are expected to be unimportant,

beyond $q=500$ MeV/c. These reactions cover a range of nucleon spin and isospin couplings, and a range of projectile-nucleon total cross sections.

Figure 3e.15 shows the fitted exponents for these cases, dropping smoothly from large negative values of y (small energy losses ω) to $y=0$, the peak of the expected incoherent quasifree scattering.

Figure 3e.15: Exponents α obtained from fits to the doubly-differential cross sections for hadron and electron scattering to the continuum are shown, transforming from the measured energy loss w to the scaling variable y . Diamonds are for K^+ [4], circles are for protons [2], squares are for 500 MeV pion SCX [3], and crosses are for 950 MeV/c π^- [5]. Plus signs show fits to electron scattering data [7]. Large points at the $y=0$ edge show results from the Glauber model.

The eikonal or Glauber model can be used to compute the number of target nucleons within a complex target eligible to be seen once and only once, a necessary standard for quasifree scattering and y -scaling. Larger symbols in Fig. 3e.15 at $y=0$ indicate results for the exponents α for the reactions considered here. We do indeed find the fitted exponents to approach these theoretical values, beyond about $y=-200$ MeV/c.

Electron scattering studies of quasifree scattering claim to determine the momentum distribution of nucleons within complex nuclei, by assuming incoherent scattering. The failure of the hadron data in Fig. 3e.15 to show consistent exponents would indicate that hadron

quasifree scattering is not suited to determine these momentum distributions, being overly contaminated with increasingly coherent yields for more negative values of y .

Also shown in Fig. 3e.15 are the exponents from fits to the spectra of 2.02 GeV electrons scattered from ^4He , C, Fe and Au [8]. These exponents are near unity, as expected for the smaller cross sections available to electrons.

Near $y=0$, we conclude that the continuum spectra of hadron spectra do indeed exhibit the expected incoherent mass dependence, and that we may use this fact to measure in-medium hadron-nucleon differential cross sections by quasifree scattering.

This work has been prepared for publication.

References

- [1] C. F. Williamson *et al.*, Phys. Rev. **C 56**, 3152 (1997).
- [2] R. E. Chrien *et al.*, Phys. Rev. **C 21**, 1014 (1980).
- [3] J. Ouyang, Ph.D. thesis, University of Colorado (1992).
- [4] C. M. Kormanyos *et al.*, Phys. Rev. **C 51**, 669 (1995).
- [5] Y. Fujii *et al.*, Phys. Rev. **C 64**, 034608 (2001).
- [6] J. Ouyang *et al.*, Phys. Rev. **C 47**, 2809 (1993).
- [7] D. B. Day *et al.*, Ann. Rev. Nucl. Part. Sci. **40**, 357 (1990).
- [8] D. B. Day *et al.*, Phys. Rev. **C 48**, 1852 (1993).

4. Deep Inelastic Scattering from Nuclear Targets at HERMES

The HERMES Collaboration, E.R. Kinney (University of Colorado)

Understanding the difference between the quark structure of nucleons seen inside the nuclear medium by deep inelastic scattering and Drell-Yan reactions relative to that seen for isolated nucleons remains a major goal of high energy nuclear physics. Moreover, one can look at the nuclear medium as a laboratory or scale in which to study the deep inelastic process itself. HERMES kinematics are ideal for studying the process of hadronization which occurs over approximately 1 or 2 fermis at HERMES energies. Thus by varying the size of the nucleus and examining changes in the distribution of hadrons produced in the DIS process, one learns about the length scale over which the struck quark dresses itself with antiquark and then forms a particular meson. Such a picture of hadronization involves empirical parameters such as the quark-nucleus scattering cross section and formation times(lengths). Understanding such effects tests the present models of fragmentation in significant new ways. As the Relativistic Heavy Ion Collider begins producing results, understanding these processes becomes critical to interpreting the signal of the creation of a quark-gluon plasma; the particle detectors in the end will only see real hadrons so one must try to understand their formation from the plasma on the way to detection.

As a specific example, in the gluon-bremsstrahlung model, the struck quark is assumed to lose energy via the emission of gluons until, in the case of meson formation, a $q\bar{q}$ configuration is formed consisting of the struck quark and an antiquark originating from the last emitted gluon [1, 2, 3, 4]. If this last step occurs inside the nucleus, the nuclear environment affects the hadron multiplicity because the meson interacts with the nuclear medium with a sizable cross section. Moreover, the interaction of the initial quark with the nuclear medium causes the emission of additional soft gluons. On the other hand, the initial — possibly small — $q\bar{q}$ configuration represents a color dipole which may have a reduced probability of interaction with its environment (Color Transparency [5, 6]). An estimate of the combined effect of the soft gluon radiation and Color Transparency on the multiplicity ratio in the framework of the gluon-bremsstrahlung model [1] yields 2–3% for the kinematics of the present experiment.

The HERMES collaboration has reported measurements of the attenuation of hadrons from DIS from ^{14}N in 2001 [7]. In this work, the experimental results are presented in terms of the multiplicity ratio R_M^h , which represents the ratio of the number of hadrons of type h produced per DIS event for a nuclear target of mass A to that from a deuterium target (D):

$$R_M^h(z, \nu) = \frac{N_h^A(z, \nu)}{N_e^A(\nu)} \bigg/ \frac{N_h^D(z, \nu)}{N_e^D(\nu)} \quad (2)$$

where z represents the fraction of the virtual photon energy ν transferred to the hadron, and with $N_h(z, \nu)$ the number of semi-inclusive hadrons in a given (z, ν) -bin, and $N_e(\nu)$ the number of inclusive DIS positrons in the same ν -bin. For the purpose of the present analysis, the multiplicity ratio was determined as a function of ν and z , while integrating over all other kinematic variables. The data for R_M^h are only weakly dependent on either Q^2 or p_T^2 [8].

In 1999 HERA beam time was granted to HERMES to extend their measurements on ^{14}N and collect new data from DIS on ^{84}Kr by using a much higher density gas target. This high target thickness strongly affected the positron beam lifetime, in effect making the beam unusable by the collider experiments, and hence was dedicated for HERMES use. In addition, HERMES gained approval to use high density running in the last 30 minutes of each positron fill of HERA during normal luminosity running. In this way, significant statistics have been collected for DIS on ^4He and ^{20}Ne . Preliminary results for the z dependence of R from ^{84}Kr [9] for charged hadrons were obtained in 2001 and show a consistent increase in attenuation in both nitrogen and krypton at high z .

A perhaps more natural dependence to study is that of ν directly. All models predict a general decrease in attenuation as ν increases because of the time dilation effect which slows the formation time of the hadron and at the same time decreases the time of the quark or hadron within the nucleus. Any increase in nuclear size increases the chance of interaction so that one expects an increase in attenuation in krypton, which is observed in the data.

Analysis of the new helium and neon data is underway; further data is also expected from the HERMES run starting in 2002. Further A-dependence may be achieved with argon and xenon targets.

References

- [1] B. Kopeliovich, J. Nemchik and E. Predazzi, Proceedings of the workshop on Future Physics at HERA, Edited by G. Ingelman, A. De Roeck and R. Klanner, DESY, 1995/1996, vol 2, 1038 (nucl-th/9607036); and B. Kopeliovich, J. Nemchik, private communication.
- [2] B.Z. Kopeliovich, Phys. Lett. **B 243** (1990) 141.
- [3] B.Z. Kopeliovich and F. Niedermayer, Sov. J. Nucl. Phys. **42** (1985) 504.
- [4] S.J. Brodsky and P. Hoyer, Phys. Lett. **B 298** (1993) 165.
- [5] S.J. Brodsky and A.H. Mueller, Phys. Lett. **B 206** (1988) 685.

- [6] L.L. Frankfurt et al., Ann. Rev. Nucl. Part. Sci. **45** (1994) 501; B.Z. Kopeliovich et al., Phys. Lett. **B 324** (1994) 469; P. Jain et al., Phys. Rep. **271** (1996) 67; O. Benhar et al., Journ. Exp. Theor. Phys. **84** (1997) 421.
- [7] A. Airapetian *et al.*, Eur. Phys. J. **C 20** (2001) 479.
- [8] J.J. van Hunen, Ph.D. dissertation, Utrecht University (2000).
- [9] N. Bianchi, P. DiNezza, V. Muccifora, J.J. van Hunen, G. van der Steenhoven, HERMES Internal Note 00-002 (2000).

4.a Nuclear Attenuation and p_T Broadening

M. Pallas, D. Gaskell, E.R. Kinney (University of Colorado), The HERMES Collaboration.

After 40 years of high energy lepton- and hadron-nucleus scattering, little experimental information is available which allows a reliable extraction of the physics of a fast parton moving through a nucleus. Experiments in this epoch have focused on determining the structure functions in the nucleon, or fragmentation into leading hadrons. While the modification of the F_2 structure function in the nucleus as first reported from the EMC experiment has been known and studied for years, the efforts have focussed almost entirely on the structure aspects; comparatively small effort has put into determining nuclear effects on the fragmentation process. Given the present well defined models of fragmentation, further tests of this process will require using experiment to test the details. However, work in HEP has been focussed on eliminating details of fragmentation to uncover underlying hard process. Despite this, a topic of great interest at the Tevatron is the observation of the so-called “event structure” which is basically a violation in factorization in the remnants. In DIS this would be in the target fragments, but these are totally unknown experimentally.

Most of the present understanding rests on the platform of factorization of the hard interaction from the soft initial parton distributions as well as the subsequent fragmentation of the struck parton. By now, the initial parton distributions in the nucleon are relatively well known, though the sea distributions remain to be precisely determined. Fragmentation functions derived from 2-hadron jet production from e^+e^- collisions and single hadron jets from deep inelastic lepton scattering (DIS) from hydrogen and deuterium are more poorly determined except for leading hadrons. While Drell-Yan has helped to determine the sea distributions significantly more precisely, the lack of nuclear dependence in the cross section, has not helped unravel the EMC effect and in fact raises further questions.

An well known early measurement is the study of the transverse momentum (p_T) spectrum, as a measure of interaction of partons on the way out by Cronin *et al.*[1] The NMC and E665 experiments were hampered in extending this study by detector acceptance, statistics and large coherence length. Studies at HERMES are more promising.

Many observables are possible in principle. Here we are performing a study of the p_T spectrum of pions produced from DIS from electrons in ^{14}N and ^{84}Kr . With these spectra one can calculate the average p_T^2 of the distribution. The average from the proton and deuteron is used as the benchmark for the basic process; this value is subtracted from the average determined for a nucleus, in order to find the broadening introduced by multiple interactions of the parton and its fragments as they traverse the nucleus. Using p_T is different from comparing z distributions, which not only involves energy loss of the parton, but also the number of interactions. In the case of p_T broadening, the energy loss is de-emphasized while it is thought to leave the sensitivity to the collision number much the same. Hence these should be complementary to attenuation studies. In fact, Guo and Qiu[2] have shown that this average broadening may be interpreted as a measure of the long range correlations between gluons and quarks within the nucleus, and is visible via an $A^{1/3}$ dependence.

In the past year, HERMES event data with leading hadrons (mostly pions) have been extracted from the data set and histogrammed as a function of p_T and azimuthal angle ϕ , both relative to the virtual photon direction. Figure 4a.1 shown the results. The next studies are to characterize the ϕ dependence in order to understand acceptance effects which might modify the p_T distribution.

References

- [1] J.W. Cronin *et. al.*, Phys. Rev. Lett. **31** (1973) 1426.
- [2] X. Guo and J. Qiu, Phys. Rev. **D 61** (2000) 096003.

Figure 4a.1: Two dimensional histogram of leading hadrons binned in p_T and ϕ , relative to the virtual photon direction.

C. PUBLIC POLICY ISSUES

1. Domestic Nuclear Security

R. J. Peterson

Recent emphases on our national vulnerability to terrorism have led to new efforts to prevent the ultimate danger of nuclear weapons directed at our nation from shadowy groups. Following the July 2002 Workshop on the Role of the Nuclear Physics Research Community in Combating Terrorism, the Division of Nuclear Physics established an ad hoc committee to focus on the needs and opportunities. Professor Peterson is a member of this group.

Activities to date have been aimed towards organizing the talents and assets of our nuclear community, learning to work with federal agencies newly charged with unfamiliar responsibilities, and local outreach. Training and discussion sessions have been carried out with summer seminars and courses for national journalists and Colorado first responders.

Materials have been assembled to enable further relevant local, regional and national training at relevant levels.

D. PUBLICATIONS AND REPORTS (October 1, 2000 - February 14, 2004)

Published Articles

We list here articles published or pending for refereed journals, from the approximate date we closed the bibliography for our 2000 proposal. These are sorted by theme in order to make a more coherent list.

1. **Nucleon Spin Structure and Polarized DIS** These are the main results from the HERMES experiment at DESY which seek to determine the quark spin structure of the nucleon with polarized deep inelastic scattering reactions.
 - a. “Single spin azimuthal asymmetries in electroproduction of neutral pions in semi-inclusive deep inelastic scattering,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, G. Hofman, E. Kinney, G. Rakness, and U. Stosslein of the University of Colorado, Phys. Rev. D **64**, 097101 (2001).
 - b. “Lambda and anti-lambda polarization from deep inelastic muon scattering,” M.R. Adams et al., including E.R. Kinney of the University of Colorado, Eur. Phys. J. C **17**, 263 (2000).
 - c. “Measurement of longitudinal spin transfer to Lambda hyperons in deep inelastic lepton scattering,” The HERMES Collaboration, A. Airapetian et al., including J.T. Brack, J. Ely, B.D. Fox, E.R. Kinney, G.L. Rakness, R.A. Ristinen and U. Stosslein of the University of Colorado, Phys. Rev. D. **64**, 112005 (2001).
 - d. “Multiplicity of charged and neutral pions in deep inelastic scattering of 27.5-GeV positrons on hydrogen,” The HERMES Collaboration, K. Ackerst et al., including J.T. Brack, B.D. Fox, E.R. Kinney, G.L. Rakness, R.A. Ristinen, W.R.Smythe and U. Stosslein of the University of Colorado, Eur. Phys. J. C **21**, 599, (2001).
 - e. “Measurement of single-spin azimuthal asymmetries in semi-inclusive electroproduction of pions and kaons on a longitudinally polarised deuterium target,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, D. Gaskell, E. Kinney, A. Kisselev, and U. Stosslein of the University of Colorado, Phys. Lett. B **562**, 182 (2003).
 - f. “Flavor decomposition of the sea quark helicity distributions in the nucleon from semiinclusive deep inelastic scattering,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, F. Ellinghaus, B. Fox, D. Gaskell, E. Kinney, A. Kisselev, J. Seele, and U. Stoesslein of the University of Colorado, Phys. Rev. Lett. **92**, 012005 (2004).
 - g. “The Q^2 -dependence of the generalized Gerasimov-Drell-Hearn integral for the proton,” HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, G. Hofman, E. Kinney, G. Rakness, R. Ristinen, and U. Stoesslein of the University of Colorado, Phys. Lett. **B494**, 1 (2000).
 - h. “The Q^2 -dependence of the generalised Gerasimov-Drell-Hearn integral for the deuteron, proton and neutron,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, D. Gaskell, E. Kinney, A. Kisselev, and U. Stosslein of the University of Colorado, Eur. Phys. J. C **26**, 527 (2003).

- i. “Evidence for quark-hadron duality in the proton spin asymmetry A_1 ”, The HERMES Collaboration, A. Airapetian et al., with J. Brack, J. Ely, B. Fox, G. Hofman, E. Kinney, and U. Stosslein of the University of Colorado, Phys. Rev. Lett. **90**, 092002 (2003).

2. Diffractive and Exclusive Reactions Diffractive and Exclusive reactions at HERMES energies may be used to constrain the newly developed Generalized Parton Distributions; lower energy photoreactions at Jefferson Lab test the quark structure of nucleons and light nuclei at high momentum transfer.

- a. “Exclusive leptonproduction of ρ^0 mesons from hydrogen at intermediate virtual photon energies,” HERMES Collaboration, A. Airapetian et al., including J.T. Brack, J. Ely, B.D. Fox, G. Hofman, E.R. Kinney, G.L. Rakness, R.A. Ristinen and U. Stoesslein of the Univeristy of Colorado, Eur. Phys. J. **C17**, 389 (2000).
- b. “Measurement of angular distributions and $R = \sigma(L)/\sigma(T)$ in diffractive electroproduction of ρ^0 mesons,” HERMES Collaboration, K. Ackerstaff et al., including J.T. Brack, B.D. Fox, E.R. Kinney, G.L. Rakness, R.A. Ristinen, W.R. Smythe and U. Stoesslein of the University of Colorado, Eur. Phys. Jour. **C18**, 303 (2000).
- c. “Measurement of the beam-spin azimuthal asymmetry associated with deeply virtual Compton scattering,” The HERMES Collaboration, A. Airapetian et al., including J.T. Brack, J. Ely, B.D. Fox, G. Hofman, E.R. Kinney, G.L. Rakness and U. Stosslein of the University of Colorado, Phys. Rev. Lett. **87**, 182001 (2001).
- d. “Single-spin azimuthal asymmetry in exclusive electroproduction of π^+ mesons,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, G. Hofman, G. Rakness, and U. Stosslein of the University of Colorado, Phys. Lett. B **535**, 85 (2002).
- e. “The Q^2 -dependence of nuclear transparency for exclusive ρ^0 production,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, D. Gaskell, E. Kinney, and U. Stosslein of the University of Colorado, Phys. Rev. Lett. **90**, 052501 (2003).
- f. “Nuclear transparency from quasielastic $A(e,e'p)$ reactions up to $Q^2 = 8.1 \text{ GeV}^2$,” K. Garrow et al., including B. Fox, D. Gaskell, and E. Kinney of the University of Colorado, Phys. Rev. C **66**, 044613 (2002).
- g. “Nuclear transparency with the gamma $N \rightarrow \pi^- p$ process in He-4,” The Jefferson Lab E940104 Collaboration, D. Dutta et al., including E. Kinney of the University of Colorado, Phys. Rev. C **68**, 021001 (2003).
- h. “A study of the quasielastic $(E,e' p)$ reaction on C-12, Fe-56 and Au-97,” The Jefferson Lab E91013 Collaboration, D. Dutta et al., including E. Belz, E. Kinney, and D. van Westrum of the University of Colorado, Phys. Rev. C **68**, 064603 (2003).
- i. “Double spin asymmetry in the cross-section for exclusive ρ^0 production in lepton-proton scattering,” HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, G. Hofman, E. Kinney, G. Rakness, R. Ristinen, and U. Stoesslein of the University of Colorado, Phys. Lett. **B 513**, 301 (2001).

- j.* “Double-spin asymmetries in the cross section of ρ^0 and ϕ production at intermediate energies,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, D. Gaskell, E. Kinney, A. Kisselev, and U. Stosslein of the University of Colorado, Eur. Phys. J. C **29**, 171 (2003).
- k.* “Measurement of the high energy two-body deuteron photodisintegration differential cross section,” E.C. Schulte et al., including B. Fox, D. Gaskell, and E.R. Kinney of the University of Colorado, Phys. Rev. Lett. **87**, 102302 (2001).
- l.* “Polarization measurements in high-energy deuteron photodisintegration,” K. Wijesooriya et al., including B. Fox and E.R. Kinney of the University of Colorado, Phys. Rev. Lett. **87**, 202301 (2001)
- m.* “High energy angular distribution measurements of the exclusive deuteron photodisintegration reaction,” E. C. Schulte et al., including B. Fox and E. Kinney of the University of Colorado, Phys. Rev. C **66**, 042201 (2002).
- n.* “Polarization measurements in neutral pion photoproduction,” K. Wijesooriya et al., including B. Fox and E. Kinney of the University of Colorado, Phys. Rev. C **66**, 034614 (2002).
- o.* “Polarization measurements in neutral pion photoproduction,” K. Wijesooriya et al., including E. R. Kinney of the University of Colorado, Phys. Rev. C **66**, 034614 (2002).
- p.* “Cross section measurement of charged pion photoproduction from hydrogen and deuterium,” Jefferson Lab Hall A Collaboration, J. Arrington et al., including E. R. Kinney of the University of Colorado, Phys. Rev. Lett. **91**, 022003 (2003).
- q.* “Measurements of the elastic electromagnetic form-factor ratio $\mu_p G_{Ep}/G_{Mp}$ via polarization transfer,” O. Gayou et al., including B. Fox and E. Kinney of the University of Colorado, Phys. Rev. C **64**, 038202 (2001)
- r.* “Measurement Of The Tensor Analyzing Powers T(20) And T(21) In Elastic Electron Deuteron Scattering,” D.M. Nikolenko et al., including E. R. Kinney of the University of Colorado, Phys. Rev. Lett. **90**, 072501 (2003).

3. Nuclear Effects in Deep Inelastic Scattering

- a.* “Hadron formation in deep inelastic positron scattering in a nuclear environment,” HERMES Collaboration, A. Airapetian et al., including J. Brack, J. Ely, B. Fox, G. Hofman, E. Kinney, G. Rakness, R. Ristinen, and U. Stoesslein of the University of Colorado, Eur. Phys. J. C **20**, 479 (2001).
- b.* “Quark fragmentation to $\pi^\pm$, π^0 , $K^\pm$ and anti-p in the nuclear environment,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, F. Ellinghaus, B. Fox, D. Gaskell, E. Kinney, A. Kisselev, J. Seele, and U. Stoesslein of the University of Colorado, Phys. Lett. B **577**, 37 (2003).

4. Hadronic Reactions in Elementary Systems

The nucleon itself is a complex and dynamic hadronic system and we have studied nucleon, deuteron and meson systems to develop and test modern understanding.

- a.* “Search for CP forbidden decay $\eta \rightarrow 4\pi^0$ ”, S. Prakhov, W. B. Tippens, C. Allgower, V. Bekrenev, E. Berger, W. J. Briscoe, M. Clajus, J. R. Comfort, K. Craig, D. Grosnick, G. M. Huber, D. Isenhowe, N. Knecht, D. Koetke, A. Koulbardi, N. Kozlenko, S. Kruglov, T. Kycia, G. J. Lolos, I. Lopatin, D. M. Manley, A. Marusic, R. Manweiler, S. McDonald, B. M. K. Nefkens, J. Olmsted, Z. Papandreou, D. Peaslee, R. J. Peterson, N. Phaisangittisakul, M. Pulver, A. F. Ramirez, M. E. Sadler, A. Shafi, I. Slaus, H. Spinka, S. Stanislaus, A. Starotsin, H. M. Staudenmaier, I. Supek and C. W. Wong, Phys. Rev. Lett. **84** 4802-4805 (2000).
- b.* “Evidence for a three nucleon force effect in proton-deuteron elastic scattering,” R.V. Cadman et al., including J. Brack, B.D. Fox, and E.R. Kinney of the University of Colorado, Phys. Rev. Lett. **86**, 967 (2001).
- c.* “Analyzing powers for π -p elastic scattering between 57 and 139 MeV,” J. D. Patterson, G. J. Hofman, J. T. Brack, P. Camerini, J. Clark, P. P. J. Delheij, L. Felawka, E. Fragiaco, E. F. Gibson, N. Grion, B. Jamieson, E. L. Mathie, R. Meier, D. Ottewell, R. J. Peterson, K. Raywood, R. A. Ristinen, R. Rui, M. E. Sevier, G. R. Smith, R. Tacik, G. Tagliente, G. J. Wagner and D. M. Yeomans, Phys. Rev. C **66**, 025207 (2002).

5. Meson Reaction Mechanisms

Although our experimental program with intermediate energy meson beams is complete, data analysis has continued these last three years.

- a.* “Semiexclusive pionic double charge exchange on ^4He ”, The CHAOS Collaboration, J.L. Clark et al., including J.T. Brack, G. Hofman, R.A. Ristinen of the University of Colorado, Phys. Rev. C **66**, 054606 (Sept. 2002).
- b.* “Pion-induced transport of π mesons through complex nuclei,” S. G. Mashnik, R. J. Peterson, A. J. Sierk and M. R. Braunstein, Phys. Rev. C **61**, 034601-1 through 13 (2000).
- c.* “Reaction and total cross sections for 400-500 MeV π^- on nuclei,” C. J. Gelderloos, J. T. Brack, M. D. Holcomb, M. V. Keilman, D. J. Mercer, R. J. Peterson, R. A. Ristinen and A. Saunders, Phys. Rev. C **62**, 24612 (2000).
- d.* “Measurement of $\pi^0\pi^0$ production in nuclear matter by π^- at 0.408 GeV/c,” A. Starotsin, H. M. Staudenmaier, C. Allgower, V. Bekrenev, E. Berger, W. J. Briscoe, M. Clajus, J. R. Comfort, K. Craig, D. Grosnick, D. Isenhowe, N. Knecht, D. Koetke, A. Koulbardi, N. Kozlenko, S. Kruglov, T. Kycia, G. Lolos, I. Lopatin, D. M. Manley, B. Manweiler, S. McDonald, B. M. K. Nefkens, J. Olmsted, Z. Papandreou, D. Peaslee, R. J. Peterson, N. Phaisangittisakul, S. Prakhov, M. Pulver, A. F. Ramirez, M. Sadler, A. Shafi, I. Slaus, H. Spinka, S. Stanislaus, I. Supek and W. B. Tippens, Phys. Rev. Lett. **85**, 539 (2000).

- e. “Fission probabilities across the pi-nucleon delta resonance,” R. J. Peterson, S. deBarros, H. Schechter, S. G. Mashnik, A. G. da Silva and J. C. Suita, Eur. Phys. J. **10**, 69-71 (2001).
- f. “Local optical potential model studies of pion-nucleus scattering,” Md. A. E. Akhter, S. S. Sultana, H. M. Sen Gupta and R. J. Peterson, J. Phys. G. **27**, 755-771 (2001).
- g. “Pion production of heavily ionizing particles from aluminum,” R. J. Peterson, G. J. Hofman, R. W. Pollock and H. H. K. Tang, Radiation Measurements **35**, 565-569 (2002).

6. Incoherent Nuclear Reactions

We have combined our interests in nucleon structure and dynamics with our history of reactions on complex nuclei to develop and continue a program to study quasifree scattering of hadrons from complex nuclei to examine incoherent hadron-nucleon interactions within the nuclear medium.

- a. “Quasifree π^- -nucleus scattering at 950 MeV/c,” Y. Fujii, O. Hashimoto, T. Nakagawa, Y. Sato, T. Takahashi, J. T. Brack, C. J. Gelderloos, M. V. Keilman, R. J. Peterson, M. Itoh, H. Sakaguchi, H. Takeda, K. Aoki, H. Hotchi, H. Noumi, Y. Ohta, H. Outa, M. Sekimoto, M. Youn, S. Ajimura, T. Kishimoto, H. Bhang, H. Park and R. Sawafuta, Phys. Rev. C **64**, 034608 (2001).
- b. “Mesonic γ -scaling,” R. J. Peterson, J. T. Brack, Y. Fujii, O. Hashimoto, T. Takahashi, M. Itoh and H. Sakaguchi, Phys. Rev. C **65**, 054601-1-8 (2002).
- c. “Y-scaling in quasifree pion single charge exchange,” R. J. Peterson, C. E. Allgower, V. Bekrenev, W. B. Briscoe, M. Clajus, J. R. Comfort, K. Craig, D. Groznick, D. Isenherwer, N. Knecht, D. Koetke, A. A. Kulbardis, G. Lolos, V. Lopatin, D. M. Manley, R. Manweiler, A. Marusic, S. McDonald, B. M. K. Nefkens, J. Olmstead, Z. Papandreaou, D. C. Peaslee, N. Phaisangittisakul, J. Price, D. E. Prull, A. F. Ramirez, M. Sadler, A. Shafi, H. Spinka, T. D. S. Stanislaus, A. Starotsin, H. M. Staudenmaier, I. Strakovsly, I. Supek and W. B. Tippens, submitted to Phys Rev C.
- d. “Testing for incoherence in hadron quasifree scattering, R. J. Peterson, submitted to Nucl Phys A.
- e. “In-medium hadron-nucleon total cross sections inferred from quasifree scattering,” R. J. Peterson, Nuclear Physics A, in press.

7. Instrumentation

Some of our efforts have gone into the development of new instruments, techniques and applications of nuclear science.

- a. “Light hadron-induced SER in 16Mb and 64Mb dRAMS and scaling relations,” G. J. Hofman, R. J. Peterson, R. A. Ristinen, C. J. Gelderloos, H. Muhlfeld, J. F. Ziegler and M. E. Nelson, IEEE Trans. Nucl. Sci. **47**, 403-407 (2000).

- b.* “Cosmic ray induced soft error rates of commercial 16Mb and 64Mb DRAMs at aircraft altitudes,” M. E. Nelson, J. A. Sarlese, J. F. Ziegler, H. P. Muhlfeld, R. J. Peterson, A. Campbell, J. S. Melinger, K. Clark and A. K. Thompson, *Jour. Radiation Effects, Research and Engineering* **19**, 100 (2001).
- c.* “Measurement of neutron detection efficiencies in NaI using the Crystal Ball detector,” T. D. S. Stanislaus, D. D. Koetke, C. Allgower, V. Bekrenev, K. Benslama, E. Berger, W. J. Briscoe, M. Clajus, J. R. Comfort, K. Craig, A. Gibson, D. Grosnick, G. M. Huber, D. Isenhower, T. Krasprzyk, N. Knecht, A. Koulbartis, N. Kozlenko, S. Kruglov, T. Kycia, G. J. Lolos, I. Lopatin, D. M. Manley, R. Manweiler, A. Marusic, S. McDonald, B. M. K. Nefkens, J. Olmsted, Z. Papandreou, R. J. Peterson, N. Phaisangittasukul, M. Pulver, A. F. Ramirez, M. Sadler, A. Shafi, I. Slaus, H. Spinka, A. Startosin, H. M. Staudenmaier, I. Supek, J. Thoms, and W. B. Tippens, *Nucl. Instrum. Meth. in Physics Research A* **462**, 463-473 (2001).
- d.* “Radiation-induced errors in memory chips,” R. J. Peterson, *Brazilian Jour. Phys.* **33**, 246 (2003).
- e.* “The HERMES forward tracking chambers: construction, operation, and aging effects,” J.T. Brack, J.E. Belz, S. Clark, J. Ely, B. Fox, G.J. Hofman, E.R. Kinney, D.J. Mercer, G. Rakness, R.A. Ristinen, W.R. Smythe, and D. Warner, *Nuclear Inst. and Methods in Physics Research, A*, **469/1**, 47 (2001)
- f.* “Experimental test of virtual photon theory via electrodisintegration and photodisintegration of the deuteron,” M. Yuly, M., Mittelstaedt, J., Matthews, J. L., Kinney, E. R., Maher, C, Sapp, W. W., Soos, S., Owens, R. O., *Phys. Rev. C* **68**, 014601 (2003).

8. Miscellaneous

We continue to include a broad range of activities in nuclear science including some based on older interests.

- a.* “The ISGQR: How giant is it and where is it isoscalar?” R. J. Peterson, *Nucl. Phys. A* **690**, 288-293 (2001).
- b.* “Measurement of the nuclear reaction ${}^7\text{Li}(3\text{He},p){}^9\text{Be}$ at low energies,” J. Yan, F. E. Cecil, U. Greife, C. C. Jewett, R. J. Peterson and R. A. Ristinen, *Phys. Rev. C* **65**, 048801 (2002).
- c.* “Second Eurasian Conference on Nuclear Science and its application,” J. D. Lambert and R. J. Peterson, *Nuclear News* **45**, 57.61 (2002).
- d.* “A new selection rule for isovector reactions at zero degrees,” R. J. Peterson, to appear in *Ricerca Scientifica ed Educazione Permanente*, Università degli Studi di Milano (2003).
- e.* “Empirical distributions of protons within nuclei,” J. D. Patterson and R. J. Peterson, *Nucl. Phys. A* **717**, 235 (2003).
- f.* “Evidence for a narrow $|s| = 1$ baryon state at a mass of 1528-MeV in quasireal photoproduction,” The HERMES Collaboration, A. Airapetian et al., including J. Brack, F. Ellinghaus, J. Ely, B. Fox, D. Gaskell, E. Kinney, A. Kisselev, J. Seele, and U. Stosslein of the University of Colorado, *Phys. Lett. B* **585**, 213 (2004).

- g.* “Future possibilities for lepton hadron collider physics and detectors,” G. Fleming et al., including E. Kinney of the University of Colorado, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. R. Davidson and C. Quigg.
- h.* “Summary: Working group on QCD and strong interactions,” E.L. Berger et al., including E.R. Kinney of the University of Colorado, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. R. Davidson and C. Quigg.
- i.* “Semi-inclusive studies of the quark spin and flavor structure of the proton,” U. Stoesslein and E. Kinney, Proc. 2nd Workshop on *Physics with a Polarized Electron Light Ion Collider*” Sept 2000, MIT, AIP Conf. Proc. **588**, 171 (2001)
- j.* “Absence of suppression in particle production at large transverse momentum in $S(NN)^{1/2} = 200$ -GeV D + Au collisions,” The PHENIX Collaboration, S.S. Adler et al., including E. Kinney of the University of Colorado, Phys. Rev. Lett. **91**, 072303 (2003).

E. NUCLEAR PHYSICS LABORATORY PERSONNEL

(Experimental Program)

1. Academic and Scientific

J. T. Brack	Lecturer
F. Ellinghaus	Research Associate
B. D. Fox ¹	Research Associate
D. J. Gaskell ²	Research Associate
G. J. Hofman ¹	Research Associate
A. Kisselev	Research Associate
E. R. Kinney	Associate Professor
R. J. Peterson	Professor
R. A. Ristinen	Professor Emeritus
U. Stösslein ³	Research Associate

2. Technical and Support Staff

D. E. Prull	Professional Research Assistant
S. Spika	Administrative Assistant

3. Research Assistants

M. Austin
J. Ely⁴
J. D. Patterson⁵
J. Seele

4. Undergraduate Students (part-time)

B. Haber⁶
S. Kayes
M. Pallas

¹Appointment ended January 2001

²Appointment ended September 2002

³Appointment ended August 2002

⁴Appointment ended July 2002

⁵Appointment ended June 2001

⁶Appointment ended May 2002