Jefferson Laboratory

Physics Division

Annual Report

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Contents

1 Hall A

1.1 Hall A Overview

The Hall A spectrometers have been designed to provide high angular and spatial resolution in the detection of the scattered electron, often in coincidence with one of the reaction products. In conjunction with a luminosity of up to $10^{39}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a beam polarization of over 75 % and the possibility to measure the polarization of a proton reaction product, a highly successful and diversified research program has emerged in Hall A.

By the end of 2001 twenty-four experiments have been completed in Hall A. Five of those experiments were at least partially completed during 2001: E94-104, E98-108, E99-107, E97-103 and E00-102. E94-104 (Gao, Holt) wsa focused on the fundamental $\gamma n \to \pi^- p$ process in ^2H and ^4He. Most of E98-108 (Baker, Chang, Frullani, Iodice, Markowitz), separating the longitudinal and transverse response functions in the electroproduction of kaons, was completed. E99-107 (Meziani, Souder, Chen) measured the neutron asymmetry A_1^n at three values of $x_{Bjorken}$ with great precision. E97-103 (Averett, Korsch) studied the Q^2-dependence of the neutron spin structure function g_2^n at $x_{Bjorken} \approx 0.2$. Finally, E00-102 (Bertozzi, Fissum, Saha, Weinstein) investigated the proton knock-out reaction on ^{16}O over a large large of missing momentum p_m and missing energy E_m. Both E99-107 and E97-103 used the polarized ^3He target, E94-104 and E98-108 the standard cryo-target and E00-102 the waterfall target. On the completion of E001-102 the installation of the lead-glass calorimeter for the Real Compton Scattering experiment E99-114 (Hyde-Wright, Nathan, Wojtsekhowski) was started.

Both the Møller and the Compton polarimeters were used reliably during the year 2001 by those experiments which used a polarized beam. The systematic error for the Compton polarimeter was further reduced to 1.4 %. Continuous improvements on the polarized ^3He target resulted in an average polarization of over 40 % with 12 μA beam on the target cell. Optics calibration data accumulated over the past few years have been used to calibrate the two Hall A High Resolution spectrometers over their complete momentum ranges. Resolutions close to the spectrometer design values have been achieved (i.e. the momentum resolution is 0.02% (FWHM)). Both spectrometers are capable of measuring the angle of reaction products to within 0.1 mrad.

Further commissioning of the Ring Imaging Čerenkov (RICH) counter (to be used in 2003) identified shortcomings in the design of the multi-wire proportional chambers, which are being resolved. The construction of the septum magnets has been subjected to continuing delays. The design of the related support hardware (i.e. cryogenics transfer lines and support platforms) is progressing well. The design and implementation of the detector system and support platform for a third magnetic spectrometer for Hall A (so-called " Big Bite") has seen significant progress.

In summary, Hall A has been running efficiently since 1997 and it has a broad physics program covering the nucleon, few-body and transition electromagnetic form factors, electroweak form factors, few-body systems and heavier nuclei. The user collaboration is very active with many invited talks and numerous conference contributions. Publication of experimental results is coming along well.

1.2 E94-104

The Fundamental $\gamma n \rightarrow \pi^- p$ Process from ^{2}H, ^{4}He, and ^{12}C in the 1.2 - 6.0 GeV Region
Spokespersons: H. Gao and R.J. Holt, JLab Hall A collaboration and E94-104 Collaboration

1.2.1 Introduction

The major objective of the experiment is to investigate the transition from nucleon-meson degrees of freedom to quark-gluon degrees of freedom in the description of exclusive processes via studying photopion productions at high energy and large momentum transfer. The experiment is focused on investigations of exclusive processes of $\gamma p \rightarrow \pi^+ n$ from hydrogen, $\gamma n \rightarrow \pi^- p$ in deuterium and ^4He, as well as semi-inclusive processes of $\gamma d \rightarrow \pi^- X$ and $\gamma d \rightarrow \pi^+ X$ in deuterium target.

1.2.2 Experiment Status

The experiment was carried out in Hall A in the spring of 2001. An incident electron beam at a beam current of 30 μA impinging on a 6% copper radiator was employed to produce bremsstrahlung photons. Liquid hydrogen, deuterium and high-pressure cryogenic ^{4}He targets were used for the $\gamma p \rightarrow \pi^+ n$, and the $\gamma n \rightarrow \pi^- p$ processes. The two Hall A High Resolution Spectrometers (HRS) were used for this experiment. Singles π^+ measurements from a hydrogen target for the $\gamma p \rightarrow \pi^+ n$ process and coincidence measurements of π^- and p for the $\gamma n \rightarrow \pi^- p$ process from deuterium and ^{4}He targets were carried out in this experiment. While the right-arm HRS was employed for the π^+ measurement in the singles case, the left-arm HRS and the right-arm HRS were used for the π^- and p measurement, respectively, for the coincidence measurement. In addition, semi-inclusive charged pion production data were taken using a deuterium target during the experiment, with the right-arm HRS for the π^+ detection and the left-arm HRS for the π^- measurement.

1.2.3 Preliminary Results

The exclusive $\gamma n \rightarrow \pi^- p$ measurement was conducted to search for the onset of the constituent quark counting rule scaling behavior in a previously unexplored region of $\sqrt{s} > 2.0$ GeV for this process using a deuterium target. Photon energies(E_γ) are reconstructed with measured momenta and angles of π^- and proton from coincidence events. To exclude multiple pion production, a 100 MeV cut on E_γ at the high end of the E_γ spectrum is used to

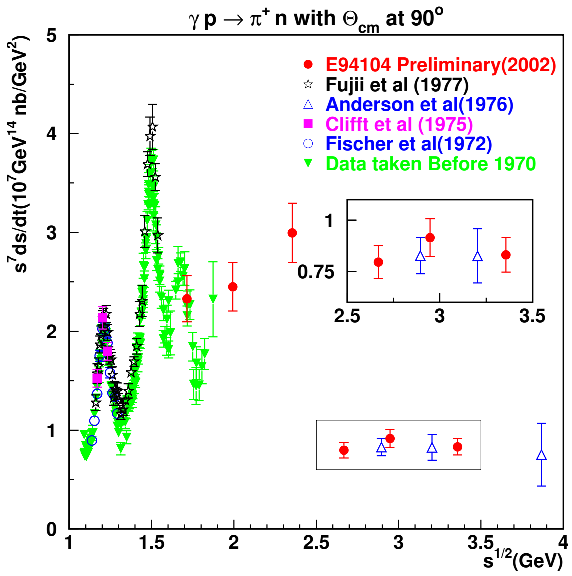

Figure 1: The scaled differential cross-section $s^7\frac{d\sigma}{dt}$ for the $\gamma p \to \pi^+ n$ at a center-of-mass angle of 90°. The preliminary data from this work are shown as red solid circles; also shown are the existing data prior to this experiment.

extract the yield. The MCEEP, the Monte Carlo simulation program for JLab Hall A spectrometers, is used to calculate the phase space and to extract the differential cross section.

Fig. 1 shows preliminary results from E94-104 with combined statistic and systematic uncertainties on the scaled differential cross-section ($s^7\frac{d\sigma}{dt}$) for the $\gamma p \to \pi^+ n$ process at a center-of-mass angle of 90°. Systematic uncertainties dominate in the preliminary E94-104 results, which are expected to be reduced to $\sim 5\%$ in the final results. Our preliminary results are consistent with existing data, however with much improved precision. Our preliminary results confirm the quark counting scaling behavior for this channel at a center-of-mass angle of 90° above a center-of-mass energy of 2.5 GeV as suggested by previous measurements.

Fig. 2 shows results on the scaled differential cross-section ($s^7\frac{d\sigma}{dt}$) for the $\gamma n \to \pi^- p$ process at a center-of-mass angle of 90°. The E94-104 preliminary results are shown with statistic and systematic uncertainties combined dominated by systematic uncertainties, which are expected to be reduced to $\sim 5\%$ in the final results. While our preliminary results are

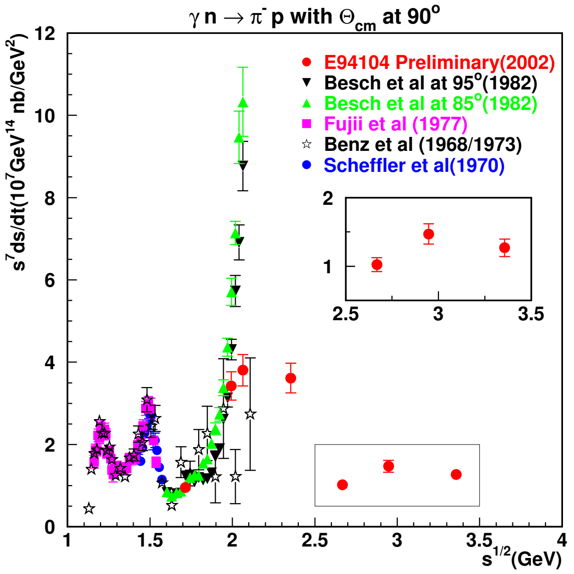

Figure 2: Scaled differential cross section $(s^7 \frac{d\sigma}{dt})$ for process of $\gamma n \rightarrow \pi^- p$ in ^2D target at a center-of-mass angle of 90°. The preliminary results from E94-104 are shown as red solid circles.

consistent with existing data in the overlapping region ($\sqrt{(s)} \leq 2.0$ GeV), the present work extended the existing measurements for this channel to a center-of-mass energy about 3.5 GeV. Our data show **for the first time** the approaching of the global scaling behavior above a center-of-mass energy of 2.5 GeV for the $\gamma n \rightarrow \pi^- p$ process, similar to what has been observed in the $\gamma p \rightarrow \pi^+ n$ channel.

Furthermore, our data suggest possible oscillatory scaling behavior similar to what has been observed in pp elastic scattering. Such oscillatory scaling behavior might be more pronounced for the $\gamma n \rightarrow \pi^- p$ channel than the $\gamma p \rightarrow \pi^+ n$ channel as suggested by our data. Unfortunately, the coarse energy setting of the present work does not allow any conclusive statement about the oscillatory scaling behavior. Measurements with much finer energy settings are planned at JLab [1] which are essential for the verification of oscillatory scaling behavior. With the future 12 GeV energy upgrade at JLab, the charm production threshold can be crossed. Thus, the extension of photopion measurements to 12 GeV will be crucial for the understanding of the origin of the oscillatory scaling behavior and the exact mechanism governing the onset of scaling behavior. It is important for the mapping of the transition from the nucleon-meson degrees of freedom to the quark-gluon degrees of freedom in the description of exclusive processes.

Data were also taken for the exclusive process of $\gamma n \rightarrow \pi^- p$ in ^{4}He target to study the final state interaction of hadrons with nucleons inside the nucleus. In fact, E94-104 provides the first nuclear transparency data for the $\gamma n \rightarrow \pi^- p$ process in ^{4}He. Shown in Figure 3 is a preliminary result of the extracted nuclear transparency with statistical uncertainties only, compared with a calculation for the process of $\gamma n \rightarrow \pi^- p$ in ^{4}He [2] both with and without color transparency effect. Currently, this analysis is being finalized.

The analysis of cross section data for the exclusive d($\gamma, \pi^- p$)p reaction will form the Ph.D thesis work of Lingyan Zhu from MIT, who has essentially finished the $\theta_{cm} = 90^o$ data set and started to prepare a draft for eventual submission to PRL in the summer of 2002. Hong Xiang, a postdoc from MIT Medium Energy Physics Group has been working extensively on analyzing the semi-inclusive π^- and π^+ data. The analysis of this part of the data is complete and a paper is being prepared. The coincidence $^4He(\gamma, \pi^- p)$X results at 90° are being finalized and a paper will be prepared shortly. The goal is to finish analyzing the rest of the data set at all other angles by the end of the year.

References

[1] Jefferson Lab Experiment E02-010, Spokespersons: D. Dutta, H. Gao, R.J. Holt.

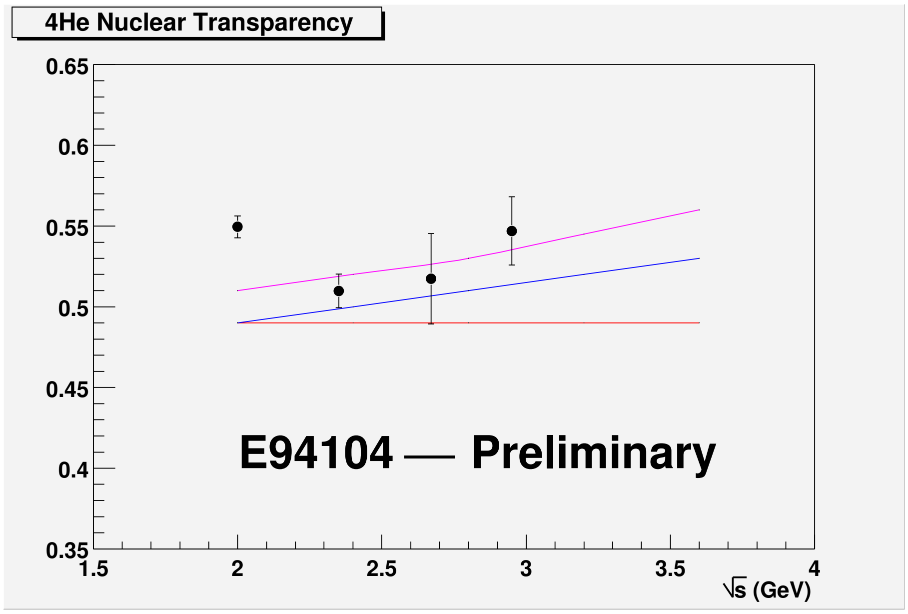

Figure 3: Preliminary E94-104 results of nuclear transparency of $\gamma n \rightarrow \pi^- p$ reaction from ^{4}He as a function of photon energy at a center-of-mass angle of 90°.

[2] H. Gao, R. Holt and V. Pandharipande, PRC **54**, 2779 (1996).

1.3 E94-012

Photoproton Polarization in the ^{1}H(γ,$\vec{p}$)π^0 Reaction

R. Gilman, R. Holt, Z.-E. Meziani, K. Wijesooriya,
and the Jefferson Lab Hall A Collaboration

1.3.1 Introduction

Hall A experiment E94-012 [Gi94] was designed to survey recoil proton polarization in pion photoproduction across and above the resonance region. We measured the longitudinal and transverse polarization transfer components $C_{z'}$ and $C_{x'}$ for the first time in this reaction, as well as the induced polarization p_y. In the resonance region, polarization results from the interference of various resonances and nonresonant background processes. There are few polarization data, mainly only the linearly polarized photon Σ asymmetry and p_y; these data are predominantly at energies below about 1.5 GeV. Thus, additional measurements are important to check theoretical assumptions that enter phase shift analyses and resonance extractions.

Above the resonance region, quark model predictions are possibly applicable to the data at large scattering angles and high momentum transfer. The general signature of these mechanisms is polarizations that vary smoothly with angle and slowly with beam energy. Calculations so far have assumed helicity conservation, leading to $p_y = C_{x'c.m.} = 0$. $C_{z'c.m.}$ does not generally vanish; it is model dependent, and is generally expected to be positive.

1.3.2 Experiment Status

The experiment ran during fall 1999. Data were taken over an angle range of $\theta^{\pi^0}_{c.m.} = 60 - 120°$, in 15° steps, and over an energy range of 0.8 – 4.1 GeV. Analysis is complete, and a paper has been submitted for publication. [Wi02]

1.3.3 Results

Figure 1 shows a sample of our data, for C'_x in the lab frame as a function of beam energy at three angles, $\theta^{\pi^0}_{c.m.} = 60°$, 75°, and 90°. Including other angles and the observables C'_z and p_y, the full data set is about six times as large. Our p_y data agree well with previous measurements. The data are compared with four theoretical curves - the theories are generally calculated in the c.m. system, but have been boosted to the laboratory frame here.

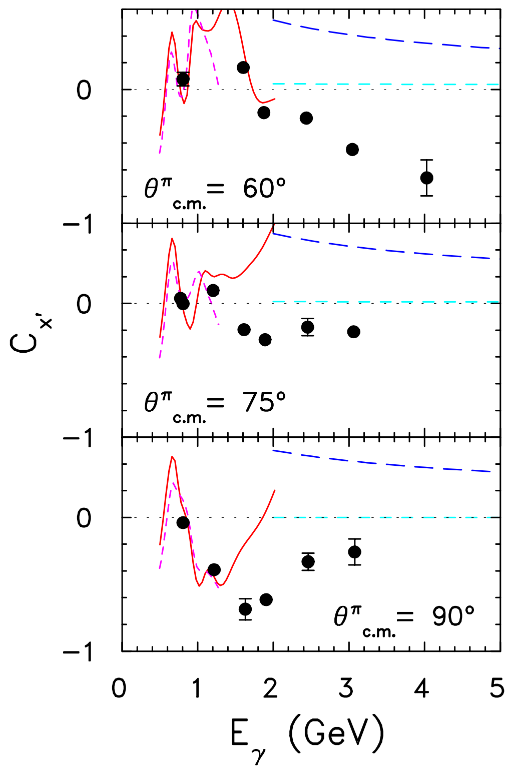

Figure 1: Polarization transfer component C_x' in the lab frame compared to several calculations, described in the text.

The two curves for energies above 2 GeV are quark model predictions. The short dashed curve is a perturbative QCD calculation. [Fa91] The long dashed curve is a calculation of pion photoproduction from a quark. [Af97] This calculation assumes factorization; the soft physics involving the nucleon can be separated from the hard physics of the photoproduction. Putting in a nucleon wave function should dilute the polarization. Comparison of these predictions with the rest of our data yields a similar conclusion, that these quark model predictions do not appear to be applicable in our kinematic range.

The two curves for energies below 2 GeV are predictions from the phase shift analyses MAID [Dr99] (short dash) and SAID [Ar96] (solid). The analyses appear to agree well at the lower energies, but to increasingly diverge from the data as the energy increases. This observation points to the need to include these data in future analyses, as well as the need for systematic sets of precise spin observables to strongly constrain the reaction amplitudes. Comparison of these analyses with the rest of our data at other angles, and for C_z' and p_y, yields similar conclusions.

References

[Gi94] R. Gilman, R. Holt, Z.-E. Meziani, *et al.*, Jefferson Lab Experiment 94-012, (1994).

[Wi02] K. Wijesooriya *et al.*, accepted by Phys. Rev. C.

[Fa91] G.R. Farrar, K. Huleihel, and H. Zhang, Nucl. Phys. B **349**, 655 (1991).

[Af97] A. Afanasev, C. Carlson, and C. Wahlquist, Phys. Lett. B **398**, 393 (1997); A. Afanasev, private communication.

[Dr99] D. Drechsel *et al.*, Nucl. Phys. A **645**, 145 (1999), Version MAID 2000.

[Ar96] R.A. Arndt, I.I. Strakovsky, and R.L. Workman, Phys. Rev. C **53**, 430 (1996) and Phys. Rev. C **56**, 577 (1997); R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, and R.L. Workman, preprint nucl-th/0205067.

1.4 E99-008

High-Energy Angular Distribution Measurements of the
Deuteron Photodisintegration Reaction
R. Gilman, R. J. Holt, Z.-E. Meziani,
E. C. Schulte, and the Hall A Collaboration

The study of nuclear reactions in the intermediate energy range, a few GeV, is an area of nuclear physics rich with complexity. Among the questions nuclear physicists seek to answer is the role of the quantum chromodynamic (QCD) degrees of freedom in nuclear reactions in the intermediate energy range. The deuteron photodisintegration, $d(\gamma,p)n$, reaction is well suited to studies of the intermediate energy regime. This reaction affords several advantages. One example is it is an exclusive reaction during which a large amount of momentum is transferred to that constituent nucleons.

The $d(\gamma,p)n$ reaction has been well studied, because of its importance in understanding the complexities of intermediate energy nuclear reactions. As a result of previous high-energy studies, an apparent threshold indicating the onset of constituent counting rule behavior has been observed [1]. This reaction has also been the subject of many theoretical studies, resulting in several models, in an effort to understand the high-energy behavior. The models which have resulted from these studies range from classical meson-exchange [2, 3] to Regge-phenomenological models [4] and quark-interchange models [5].

In the Summer of 1999, an opportunity presented itself to further investigate the high-energy behavior of the $d(\gamma,p)n$ reaction. Hall A experiment E99-008 was performed to measure the deuteron photodisintegration differential cross section at three different incident photon energies and at angles symmetrically spaced about 90° in the center-of-mass. By measuring the angular distribution of the differential cross section, more information about the high-energy behavior could be obtained.

The overall goal of experiment E99-008 was to help determine the possible mechanism which governs photoreactions in the few GeV energy region. If the incoming photon couples to a quark, then one would expect [1] the angular distribution for the $d(\gamma,p)n$ reaction to be symmetric about 90°. If the photon couples to a nucleon, however, one would expect [3, 7] that the differential cross section in the forward direction to be substantially larger than in the backward direction. Previous measurements [8] extend only to a photon energy of 1.6 GeV. The previous data are consistent with the meson-nucleon picture rather than the quark-gluon models.

In E99-008 the angular distribution was measured from $\theta_{cm} = 30°$ to $143°$ at photon energies from 1.6 to 2.4 GeV. The high resolution spectrometer (HRSL) in Hall A was used to detect photoprotons which emerged from a 15-cm liquid deuterium target that was irradiated by bremsstrahlung photons.

The results of E99-008 are presented in Figure 1 along with previous data. Also presented are model calculations for the $d(\gamma, p)n$ reaction. Notice that the asymmetry previously observed in the NE8 data [8] persists up to the highest energies measured. As a result, the data are more reasonably described by those models which give an asymmetric rather than symmetric description of the $d(\gamma, p)n$ reaction. The results of E99-008 are presently in preparation for submission as a *Physical Review C Rapid Communication.*

References

[1] E. C. Schulte, et al., Phys. Rev. Lett. 87, 102302-1 (2001).

[2] J.M. Laget, Nucl. Phys. **A312**, 265 (1978).

[3] T.-S. H. Lee, Argonne National Laboratory Report No. PHY-5253-TH-88; T.-S. H. Lee, in Proceedings of the International conference on Medium and High Energy Nuclear Physics, Taipei, Taiwan, 1988 (World Scientific, Singapore, 1988), P. 563.

[4] V. Yu. Grishina, et al., Eur. Phys. J. A 10, 355 (2001).

[5] L. L. Frankfurt, et al., Phys. Rev. Lett. 84, 3045 (2000).

[6] S. J. Brodsky and J. R. Hiller, Phys. Rev. C 28, 475 (1983).

[7] S. I. Nagornyi, Yu. A. Kasatkin, and I. K. Kirichenkov, Sov. J. Nucl. Phys. 55, 189 (1992).

[8] S. J. Freedman, et al., Phys. Rev. C 48, 1964 (1993).

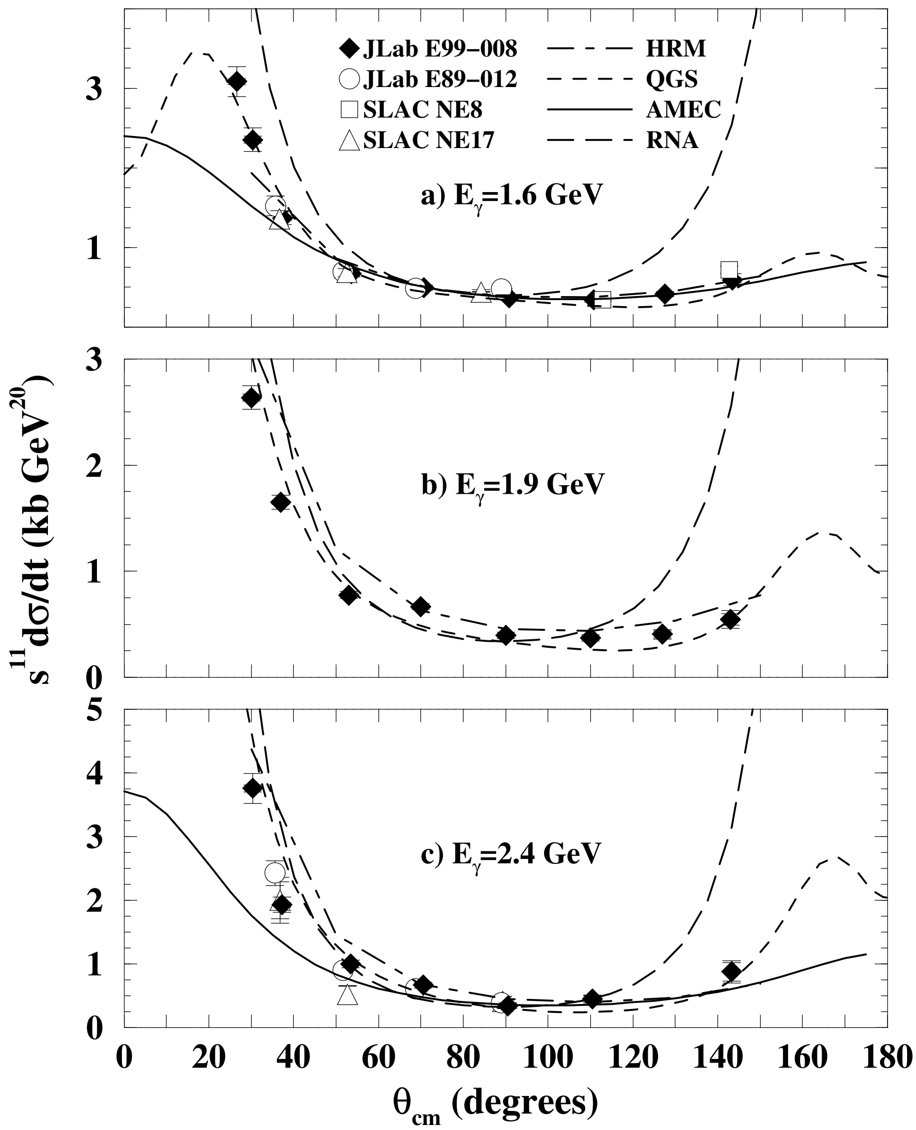

Figure 1: Angular distribution of the deuteron photodisintegration differential cross section at constant energy, measured during E99-008, plotted as $s^{11}d\sigma/dt$, compared to previous data at forward angles. The E99-008 data are the solid diamonds. The previous data shown are from JLab E89-012 (open circles), SLAC NE17 (open triangles), and SLAC NE8 (open squares). The curves are the AMEC [7] calculation (solid) and the RNA [1]prediction (dashed), QGS [4] (short-dashed), and HRM [5] (long-short dashed).

1.5 E99-114

Exclusive Compton Scattering on The Proton
Ch. Hyde-Wright, A. Nathan, B. Wojtsekhowski
and the Hall A Collaboration

1.5.1 Introduction

Real Compton scattering or RCS ($\gamma + p \rightarrow \gamma + p$) at high energy ($s$) and high momentum transfer (t) is a potentially powerful probe of the short-distance structure of the nucleon. It is a natural complement to other studies of nucleon structure, including high Q^2 measurements of the elastic electric and magnetic form factors, virtual Compton scattering, and deep inelastic scattering. In this experiment we realized a full survey of Compton scattering from the proton up to an energy 5.4 GeV.

The goals of the RCS experiment are to study the reaction mechanism and to measure new form factors of the proton. These will be accomplished through accurate determination of the unpolarized scattering cross section over a broad range of s and t and a measurement of the longitudinal polarization transfer K_{LL} at a single kinematic point. Together, these measurements should provide a stringent test of the two competing reaction mechanisms. In the handbag mechanism, there is a single active quark that couples to both the incoming and outgoing photon and which couples to the proton via the overlap of soft components of the proton wave function, leading to new form factors that are similar to but distinctly different from those measured in elastic electron scattering. In the pQCD mechanism, all three valence quarks actively participate in the reaction, which is mediated by the exchange of two hard gluons. The two mechanisms differ in their predictions of the absolute scale of the cross section, the scaling behavior of the cross section at fixed θ_{cm} and fixed t, and in the magnitude and even the sign of various polarization observables. The analysis of the experiment should shed light on all these aspects of RCS.

This experiment is the subject of four Ph.D. theses: M. Roedelbronn (UIUC), D. Hamilton (Glasgow), A. Danagulian (UIUC), and V. Mamyan (Yerevan). The very preliminary results of the experiment were presented in the workshop "Exclusive Processes at High Momentum Transfer" at JLab in May 2002.

1.5.2 Experiment Status

We took the complete E99-114 data set in January-February of 2002. Data were obtained in a total of 24 kinematic settings. Figure 1.5.2 indicates the values of s and t of the data points.

The electron beam intensity for some of these points was 40 μA or 4 times larger than

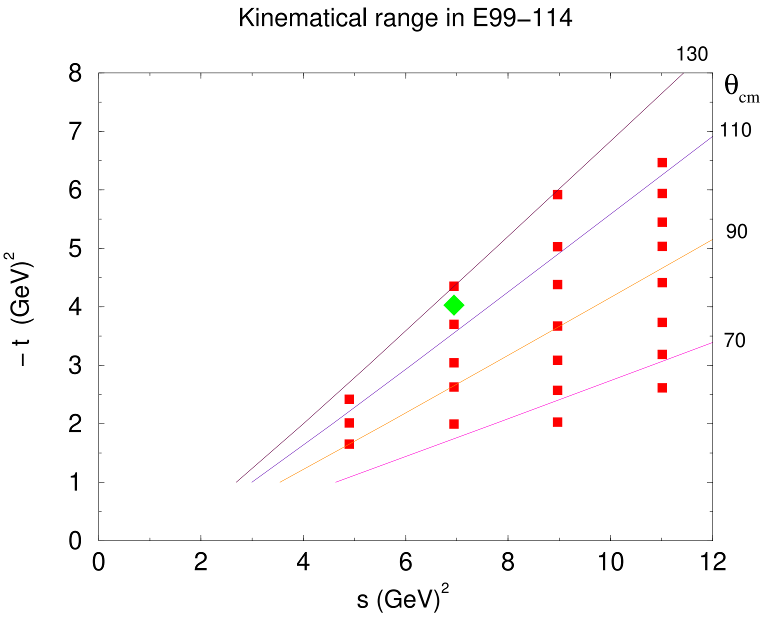

Figure 1: Kinematic coverage of E99-114 measurements.

projected in the proposal. The photon flux was up to 1200 times higher than in the Cornell experiment [1].

1.5.3 Expected Results

A partial but crude analysis of the raw data was done on line. The analysis of the polarization transfer part of the data is in progress. The preliminary result on parameter K_{LL} is shown in Fig. 1.5.3. This indicates an agreement with the handbag (or soft overlap) calculation but not with the pQCD calculation.

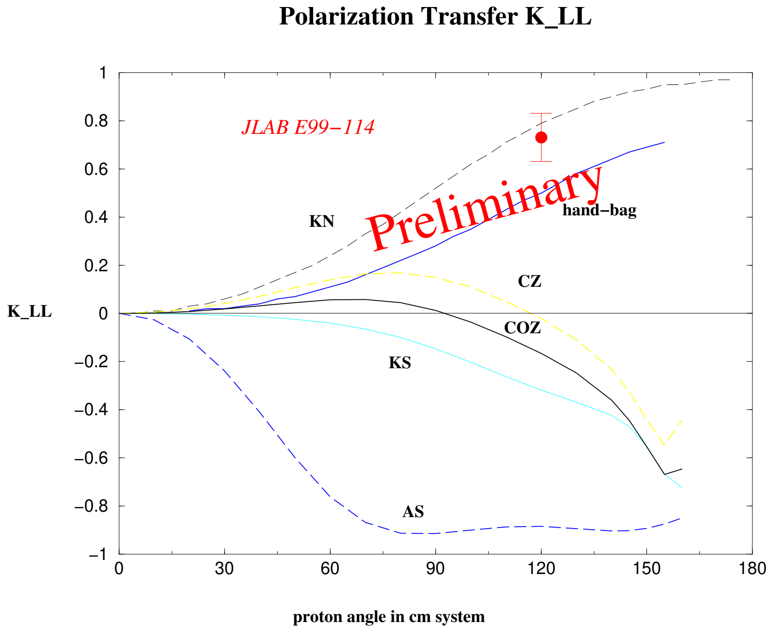

Figure 2: Polarization transfer in the RCS process. The labels on the curves are KN for the asymmetry in the hard subprocess; the pQCD calculations [2] with AS for asymptotic distribution amplitudes, CZ for Chernyak-Zhitnitsky, COZ for Chernyak-Ogloblin-Zhitnitsky, and KS for King-Sachrajda; handbag for calculations in Soft overlap approach [3].

References

[1] M.A. Shupe *et al.*, Phys. Rev. **D 19** (1979) 1929.

[2] T. Brooks and L. Dixon, Phys.Rev. **D 62** (2000) 114021.

[3] H.W. Huang, P. Kroll, T. Morii, Eur. Phys. J. **C 23** (2002) 301.

1.6 E93-027 and E99-007

Measurement of the proton's G_{Ep}/G_{Mp} ratio to large Q^2 at JLab

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1.6.1 Introduction

The ratio of the electric and magnetic proton form factors, G_{Ep}/G_{Mp}, has been obtained in two Hall A experiments, from measurements of the longitudinal and transverse polarization of the recoil proton, P_ℓ and P_t, respectively, in the elastic scattering of polarized electrons, $\vec{e}p \rightarrow e\vec{p}$. Together these experiments cover the Q^2- range 0.5 to 5.6 GeV^2. The nucleon elastic form factors describe the internal structure of the nucleon. In the non-relativistic limit, for small values of the four-momentum transfer squared, Q^2, they are Fourier transforms of the charge and magnetization distributions inside the nucleon. At high Q^2 values, the nucleon is treated as consisting of three valence quarks, and perturbative QCD provides predictions of their Q^2-dependence[1]. At Q^2 between 1 and 10 GeV^2, the Vector Meson Dominance (VMD) model (see e.g. Ref. [2, 3]) has been successful in modeling the nucleon form factors. Relativistic versions of the constituent quark models [4, 5] currently provide the best understanding of the nucleon form factors, with the strongest dynamical input in the same Q^2 range of 1 to 10 GeV^2. In Fig. 1, we show all data obtained by the Rosenbluth separation method prior to the JLab experiments. Above $Q^2 \approx 1$ GeV^2, systematic differences between different experiments are evident. The JLab results have been obtained by measuring the recoil proton polarization in $\vec{e}p \rightarrow e\vec{p}$; this is the better way to obtain G_{Ep}, even in the presence of a dominant magnetic form factor. Assuming one-photon exchange, the scattering of longitudinally polarized electrons on unpolarized hydrogen target results in a transfer of polarization to the recoil proton with only two non-zero components, P_t perpendicular to, and P_ℓ parallel to the proton momentum in the scattering plane [6]; the two components are:

$$I_0 P_t = -2\sqrt{\tau\,(1+\tau)}G_{E_p}G_{M_p}\tan\frac{\theta_e}{2} \tag{1}$$

$$I_0 P_\ell = \frac{1}{M_p}\left(E_e + E_{e'}\right)\sqrt{\tau\,(1+\tau)}G_{M_p}^2\tan^2\frac{\theta_e}{2} \tag{2}$$

where $I_0 \propto G_{E_p}^2 + \frac{\tau}{\epsilon} G_{M_p}^2$ is the unpolarized cross section. Measuring simultaneously these two components and taking their ratio directly leads to the ratio of the form factors:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2M_p}\tan(\frac{\theta_e}{2}). \tag{3}$$

Neither the beam polarization, nor the analyzing power of the polarimeter used to measure P_t and P_ℓ appear in Eqn.3.

1.6.2 Experiment Status

In 1998 at JLab, the ratio G_{Ep}/G_{Mp} was measured for Q^2 from 0.5 to 3.5 GeV^2 in experiment 93-027,[7]. In this experiment, the protons and electrons were detected in coincidence in the two high-resolution spectrometers (HRS) of Hall A. The two polarization components of the recoiling proton were measured simultaneously in a focal plane polarimeter (FPP) with graphite analyzer. In the Fall of 2000 we made new measurements of G_{Ep}/G_{Mp} at $Q^2 = 4.0$, 4.8 and 5.6 GeV^2 with overlap points at $Q^2 = 3.0$ and 3.5 GeV^2 in experiment E99-007,[8]. To extend the measurement to these high Q^2, two changes were made to the setup of the experiment. First, to increase the figure-of-merit of the FPP, a CH_2 analyzer was used,

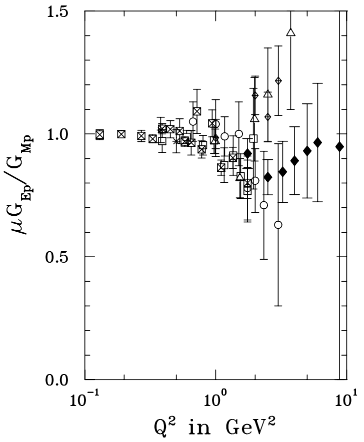


Figure 1: *World data from Rosenbluth separation method for $\mu_p G_{Ep}/G_{Mp}$ versus Q^2 [9, 10, 11, 12] as open triangles; [13] as solid triangles.*

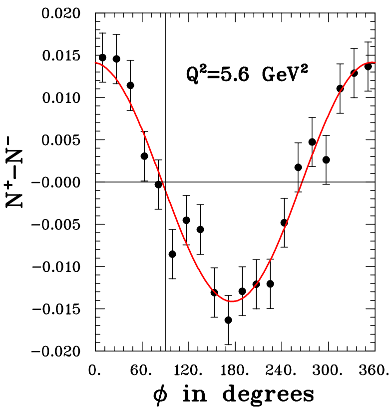


Figure 2: *The azimuthal asymmetry distribution in the FPP for Q^2=5.6 GeV^2. The distribution is shifted relative to a* cos*-curve; the shift is proportional to the ratio P_t^{fpp}/P_ℓ^{fpp}.*

instead of graphite used in the first experiment, and the thickness was increased from 50 cm of graphite to 100 cm of CH_2 (60 cm of CH_2 for Q^2 = 3.5 GeV^2).The performance of the polarimeter is illustrated in Fig. 2, which shows the azimuthal asymmetry distribution in the polarimeter for the Q^2=5.6 GeV^2 data point. The amplitude is mainly determined by the normal component at the FPP, P_n, which by itself would have a pure $\cos\phi$ distribution, whereas the small transverse component, P_t, which produces a $\sin\phi$ distribution, produces a phase shift of - 6.3±3.7°. Note that the absolute uncertainty on the G_{Ep}/G_{Mp} ratio is independent of the size of this phase shift, and is entirely determined by the number of events in the ϕ-distribution. Second, in experiment 99-007, electrons were detected in a

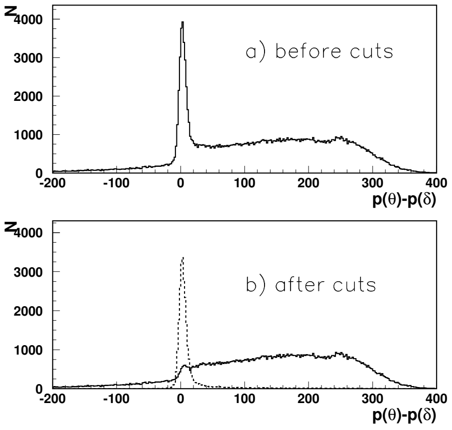


Figure 3: *Momentum difference for singles in the HRS (top), and after cut on time and angle in calorimeter (bottom), for Q^2=5.6 GeV^2.*

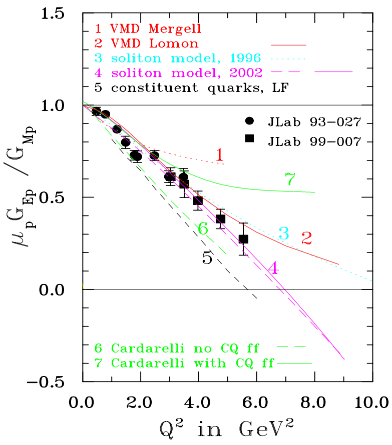


Figure 4: *Comparison between $\mu_p G_{Ep}/G_{Mp}$ measured at JLab and several theoretical models; the JLab data are from Refs. [7] and [8]*

lead-glass calorimeter built for this experiment, except for the Q^2 = 3.5 GeV^2 data point, for which a spectrometer was used to detect the coincident electron. A lead-glass calorimeter with 2.55 × 1.35 m^2 frontal area was assembled, in an array of 9 columns and 17 rows of 15 × 15 × 35 cm^3 blocks. The placement of the calorimeter was chosen such that its solid angle matched the acceptance of the HRS detecting the proton. At the largest Q^2 of this experiment the solid angle subtended by the calorimeter was 42 msr, to be compared to the HRS solid angle of 6.8 msr. The segmentation of the calorimeter was sufficient to distinguish elastic *ep* events by their two-body angular correlation. Fig. 3 shows the HRS singles proton spectrum at the top; the elastic peak and the background subtracted using the calorimeter are shown separately at the bottom.

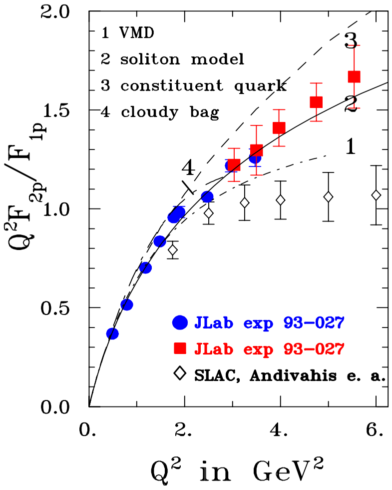


Figure 5: *The ratio Q^2F_{2p}/F_{1p} from the JLab experiments, compared with the data of Ref.[13].*

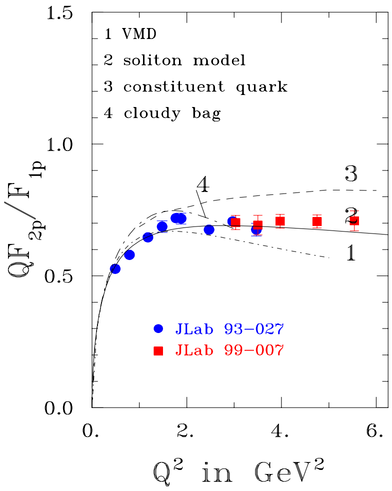


Figure 6: *The ratio QF_{2p}/F_{1p} discussed in the text.*

1.6.3 Results

The combined results from both experiments are plotted in Fig. 4 as the ratio $\mu_p G_{Ep}/G_{Mp}$. The ratio obtained from both JLab experiments have the same slope. If the Q^2 dependence of $\mu_p G_{Ep}/G_{Mp}$ continues the linear decrease with the same slope, then it will cross zero at Q$^2 \approx 7.5$ GeV^2. Many theories naturally predict that G_{Ep} falls off faster with Q^2 than G_{Mp}. In Fig. 4 , the calculations of $\mu_p G_{Ep}/G_{Mp}$ from the vector meson dominance (VMD) model [2], a relativistic constituent quark (CQ) model [4], and a soliton model [14] are shown. Also shown are recent results with a relativistic CQ model [5], with and without a CQ form factor. The parameters of the VMD model [2] were fitted to previous nucleon form factor data, and the fall-off of $\mu_p G_{Ep}/G_{Mp}$ with Q^2 did not match the fast decrease with Q^2 of the JLab data. But recently Lomon [3] has reworked the Gari-Krumpelman VMD approach and obtained good agreement with the data with reasonable parameters for the vector-meson masses and coupling constants. In Fig. 5 the JLab data are shown as Q^2 times F_2/F_1; pQCD predicts quenching of the spin flip form factor F_2, or equivalently helicity conservation; higher order contributions should make Q^2F_2/F_1 asymptotically constant. The data clearly contradict this prediction. Shown in Fig. 6 is Q times F_2/F_1; the quantity reaches a constant value at Q^2 ∼2 GeV^2. J. Ralston et al. [16] have discussed this unexpected behavior of the ratio $\sqrt{Q^2}F_{2p}/F_{1p}$ and concluded that it is expected if one takes the contribution to the proton quark wave function, from states with non-zero orbital angular momentum, into account. In a different approach, Miller and Frank [17] have shown that imposing Poincare invariance leads to violation of the helicity conservation rule, which results in the behavior of F_2/F_1

observed in the JLab data. The precise new data on $\mu_p G_{Ep}/G_{Mp}$ presented here show that the ratio continues to drop off linearly with increasing Q^2 up to 5.6 GeV^2. Comparison of model calculations to $\mu_p G_{Ep}/G_{Mp}$ provide a stringent test of models of the nucleon.

References

[1] S.J. Brodsky and G.P. Lepage, Phys. Rev. D **22**, (1981) 2157.

[2] P. Mergell, U.G. Meissner, D. Drechsler Nucl. Phys. B **A596**, 367 (1996) ; and A.W. Hammer, U.G. Meissner and D. Drechsel, Phys. Lett. B **385**, 343 (1996).

[3] E. Lomon, Phys. Rev. C **64** 035204 (2001) and nucl-th 0203081

[4] M.R. Frank, B.K. Jennings and G.A. Miller, Phys. Rev. C **54**, 920 (1996).

[5] E. Pace, G. Salme, F. Cardarelli and S. Simula, Nucl. Phys. A **666**&**667**, 33c (2000). F. Cardarelli and S. Simula, Phys. Rev. C **62**, 65201 (2000).

[6] A.I. Akhiezer and M.P. Rekalo, Sov. J. Part. Nucl. **3**, 277 (1974); R. Arnold, C. Carlson and F. Gross, Phys. Rev. C **23**, 363 (1981).

[7] M. K. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000).

[8] O. Gayou et al., Phys. Rev. Lett. **88** 092301 (2002)

[9] J. Litt *et al.*, Phys. Lett. B **31**, 40 (1970).

[10] Ch. Berger *et al.*, Phys. Lett. B **35**, 87 (1971).

[11] L.E. Price *et al.*, Phys. Rev. D **4**, 45 (1971).

[12] W. Bartel *et al.*, Nuc. Phys. B **58**, 429 (1973).

[13] L. Andivahis *et al.*, Phys. Rev. D **50**, 5491 (1994).

[14] G. Holzwarth, Z. Phys. A **356**, 339 (1996).

[15] D.H. Lu, S.N. Yang, A.W. Thomas, J.Phys. **G26**, L75 (2000).

[16] J. Ralston *et al.*, in Proc. of 7th International Conference on Intersection of Particle and Nuclear Physics, Quebec City (2000), p.302, and private communication (2001).

[17] G.A. Miller and M.R. Frank, nucl-th 0201021

2 Hall B

2.1 Hall B Overview

Hall B's mission is to carry out experiments that require the detection of multi-particle final states, or experiments that can only be performed at low luminosity. Final states with several particles are typical in reactions involving the production of excited mesons and baryons, or in nuclear break-up reactions. The luminosity may have to be limited to keep accidental coincidences low, e.g. for a tagged bremsstrahlung photon beam or for experiments requiring the coincident detection of particles that are only loosely correlated. Solid-state polarized targets can only be operated at low luminosity. High detection efficiency for multi-particle events and a useful event rate at limited luminosity both require a detection system with a large acceptance.

To carry out this program, Hall B is equipped with a large acceptance magnetic detector, the CEBAF Large Acceptance Spectrometer (CLAS). CLAS is a magnetic toroidal multi-gap spectrometer. Its magnetic field is generated by six super-conducting coils arranged around the beam line to produce a field which is oriented primarily in the ϕ-direction. The particle detection system consists of drift chambers to determine the track of charged particles, gas Cerenkov counters for electron identification, scintillation counters for triggering and measuring the time-of-flight, and electromagnetic calorimeters to detect showering particles (electrons and photons) as well as neutrons. The gaps are individually instrumented to form six independent magnetic spectrometers. This facilitates pattern recognition and track reconstruction at high luminosity.

For electron scattering experiments, a small normal-conducting toroid (”mini-torus”) surrounding the target keeps (low momentum) charged electromagnetic background from reaching the innermost drift chamber.

For tagged photon experiments, a radiator is inserted in front of the bremsstrahlung tagging spectrometer which occupies an enlarged tunnel section at the entrance of the hall. The primary electron beam is deflected vertically into a low-power beam dump. Equipment to monitor the tagged photon beam is located behind CLAS in the downstream tunnel section.

A Møller polarimeter to measure the polarization of the incident electron beam is located in the upstream beam tunnel. For electron scattering experiments, the primary electron beam - after passing through the target - is stopped in a Faraday cup to measure the beam current.

A two-stage trigger system is used to initiate data conversion and readout. The Level I trigger makes use of the fast information from the time-of-flight counters, the Cerenkov counters, and the electromagnetic calorimeters. Level 2 adds track finding using the hit pattern in the drift chambers.

The data acquisition system collects the digitized information on the events, and transfers it to the counting house for temporary storage on disk. Periodically, the data get transferred to the Computer Center's tape silo for later off-line analysis. An event rate of 4,000 events/sec corresponding to a steady data rate of approximately 20 Mbytes/sec has been reached.

Physics research with CLAS began in December 1997. Since then, data were collected on a total of 54 PAC-approved experiments. Due to the use of an open trigger, different experiments can often share the same beam conditions, and be executed simultaneously.

2.2 E89-004

ELECTROMAGNETIC PRODUCTION OF HYPERONS

Reinhard Schumacher, *Carnegie Mellon University*
for the CLAS Collaboration

2.2.1 Introduction

The CEBAF Large Acceptance Spectrometer (CLAS) [Br99] at Jefferson Lab has been used to measure the elementary photoproduction of kaons and hyperons at center-of-mass energies from threshold up through the nucleon resonances. Data have been obtained for the charged kaon reactions

$$\gamma + p \rightarrow K^{+} + \{\Lambda,\ \Sigma^{\circ}, \Lambda(1405)/\Sigma^{\circ}(1385),\ \Lambda(1520)\}\,. \tag{1}$$

These reactions can be analyzed in terms of chiral-perturbation theory near threshold, in terms of hadrodynamic models in the nucleon resonance region, and with Regge models at higher energies. Since the reactions are related by SU(6), they are complementary to each other in theory, while experimentally it helps to measure them all simultaneously, as we have done at CLAS. The results of these measurements should be: (1) improved understanding of the electromagnetic associated-strangeness production mechanism, and (2) an investigation of the higher-mass region of the nucleon resonance spectrum using these reaction channels.

As an example of the recent interest in this area, recently-published data from the SAPHIR experiment at Bonn [Tr98] has provided some evidence [Be99] for a resonance structure at a total c.m. energy of $W = 1900$ MeV. If confirmed by our data from CLAS, it would be very interesting, since there are few well-established nucleon resonances in that mass range, and none that are known to couple strongly to strange particle final states. It would be an example of the kind of "missing resonance" discussed in quark models [Ca98]. The interpretation of that data, however, is controversial [Sa99], and has awaited new and better data from CLAS.

Our goal is to produce differential cross sections for the ground-state hyperons suitable for partial wave analysis, as well as several polarization observables: the hyperon recoil polarizations P_{Λ} and $P_{\Sigma^{\circ}}$, and the beam-recoil double-polarization observables $C_{x'}$ and $C_{z'}$. For the excited hyperons we aim to measure only the differential cross sections.

2.2.2 Experiment Status

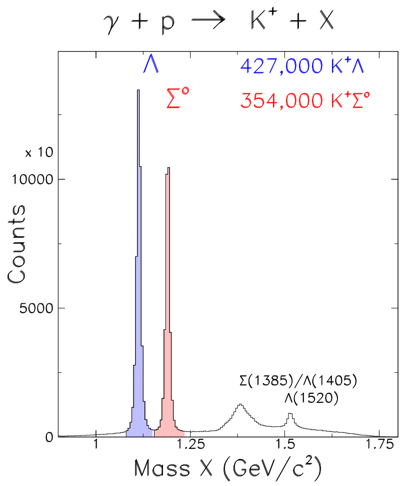
In this report we concentrate on the data for Λ and Σ° production. Data under analysis now come from the *g1c* run in late 1999. Since last year we took a big step by ending work on the older g1a data set from 1998 and moving over to g1c. Not only does the g1c data set offer 5 times larger statistics, but the quality of the data, in terms of normalizability and calibrations, is much higher. The cooking of the g1c data set was the work of CMU post-doc Luminita Todor, and the photon normalization was developed by Eugene Pasyuk and Jim Ball of Arizona State, with help from other members of the Real Photon Working Group. The analysis of the 2.4 GeV endpoint strangeness production cross sections and recoil polarization data form the thesis work of CMU graduate student John McNabb. The excited state cross-sections are being extracted by Henry Juengst (U. Minnesota), while the complimentary K° channel analysis is underway at Catholic University by Brian Carnahan. Higher endpoint (up to 3 GeV) data for the cross sections and for the double polarization observables have become the thesis project of CMU graduate student Robert Bradford.

2.2.3 Results

Kaons with momenta up to 2 GeV/c were identified using momentum and time-of-flight measurements, with an average signal-to-noise ratio with respect to pions of about 4:1. Sideband subtraction of the remaining pion background was used. Before sideband subtraction, the hyperon missing mass spectrum shown in Figure 1 already shows cleanly separated Λ and Σ° samples, as well as several well-known excited hyperons.

Kaon events were normalized using the integrated photon flux, and corrected using Monte Carlo techniques for acceptance and in-flight kaon decay. The systematic uncertainties associated with both the normalization and the acceptance are under study. At the present time we believe that both the point-to-point and the overall normalization uncertainty is $\pm 10\%$. Final uncertainties will be under $\pm 7\%$. Sample differential cross sections are shown in Figure 2 for both Λ and Σ° photoproduction. The forward peaking of the Λ cross section is due, in a current hadrodynamic model [Be99], to both the interference of S and P wave isobar resonances, and the strong contribution of t-channel processes. The Σ° cross section is of comparable size at $Q^2 = 0$, in contrast to our results for electroproduction, but it is not forward peaked, which may be explained by a much less dominant role of the t-channel relative to resonance excitation.

Total cross sections were obtained from Legendre polynomial fits to the angular distributions at each photon energy. Figure 3 shows σ_{tot} compared to several previous calculations [Ma99]. There is considerable disagreement among the calculations and the data. The cal-



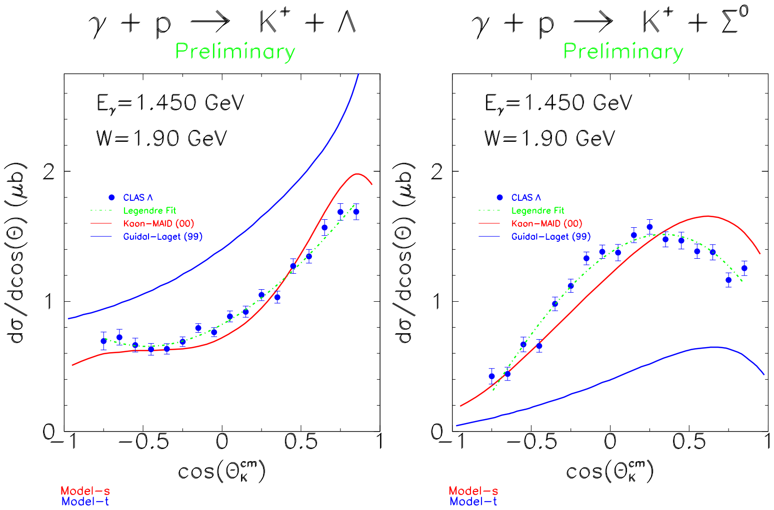


Figure 1: (left) Missing mass spectrum for $\gamma + p \to K^+ + X$ for $W > 1.6$ GeV. The events span all of CLAS in angle, momentum and photon energy. The resolution of the Λ peak is $\sigma = 6.2$ MeV, and for the Σ^o peak $\sigma = 5.8$ MeV.

Figure 2: (middle and right) Preliminary differential cross sections for photoproduction of the ground state hyperons at one photon energy (25 MeV bin width). In each case, the data points (blue) are the sideband-subtracted cross sections. The solid curves are hadrodynamic (red) and Regge-based (blue) models. The dashed curves (green) are second-order Legendre fits.

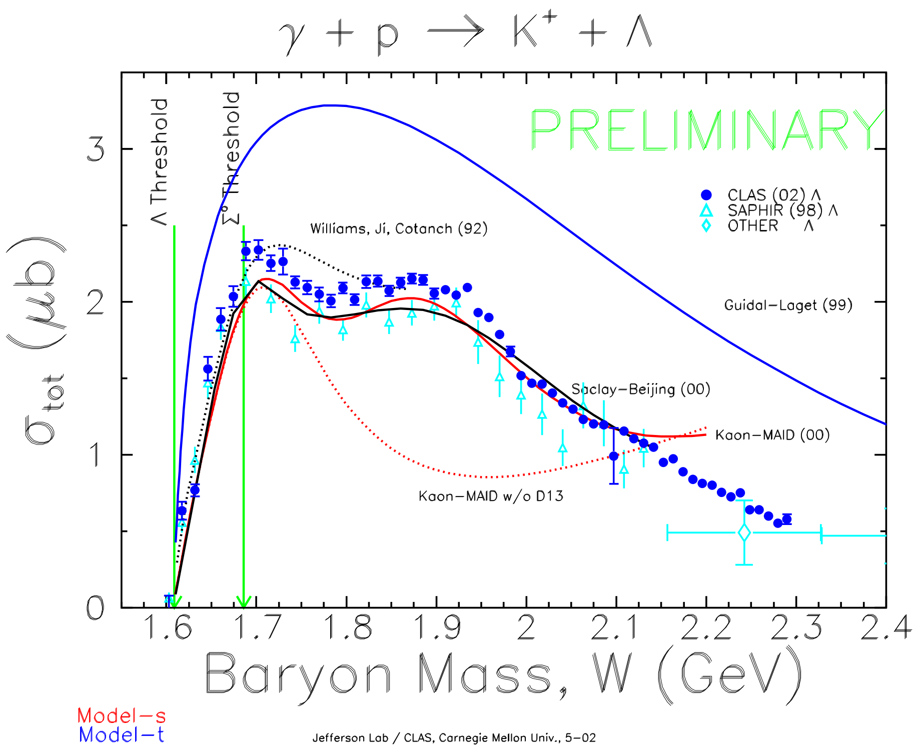


Figure 3: Preliminary total cross sections for $\gamma + p \to K^+ + \Lambda$. The data were acceptance corrected; uncertainties are statistical only, and do not reflect a $\pm 10\%$ systematic uncertainty. CLAS data are the solid (blue) circles. Open triangles (cyan) are from Bonn [Tr98]. The curves are cited in the text.

culations of Ref [MAID] were fitted to the data of Ref [Tr98], and invoked a "missing" $D_{13}(1900)$ resonance to explain the observed total cross section bump at 1.9 GeV (red). The dashed (red) curve shows sensitivity of the model to the purported D_{13}. The calculation of Ref [Sa99] invokes only "known" resonances and provides a similar fit (black). The calculation in Ref [La99] is a Regge model applied outside its range of (higher energy) applicability (blue). The CLAS results confirm the strong structure at 1.9 GeV, as well as small additional structure at higher mass. None of the presently available models do a better than qualitative job at reproducing these data.

More detailed comparison of these reaction models with our results is in progress, and we will soon show preliminary hyperon polarization data as well.

References

[Br99] W. Brooks *et al*, Nucl, Phys. **A663**, 1077c (2000).

[Be99] C. Bennhold, H. Haberzettl, and T. Mart, nucl-th/9909022, Proceedings of "Trieste 99" World Scientific; T. Mart and C. Bennhold, $nucl-th/9906096, 30Jun1999$

[Ca98] S. Capstick and W. Roberts, Phys. Rev. **D58**, 1 (1998).

[Ha98] H. Haberzettl, C. Bennhold, T. Mart, and T. Feuster,Phys. Rev. **C58**, R40 (1998).

[La99] J.-M. Laget, private communication, based on M. Guidal, J.-M. Laget, and M. Vanderhaegen, Nucl. Phys. **A627**,645 (1997); M. Vanderhaegen, M. Guidal, and J.-M. Laget, Phys. Rev. **C57**,1454 (1998).

[Ma99] T. Mart provided code for several published models, private communication.

[MAID] Kaon-MAID calculation, Mainz Website, C. Bennhold, T. Mart, authors.

[Sa99] Bijan Saghai, Hampton Workshop, 12/99, and private communication.

[Tr98] M. Q. Tran *et al*, Phys. Lett. **B445**,20 (1998).

[Wi92] R. Williams, C. R. Ji, and S. R. Cotanch Phys. Rev. **C46**, 1617 (1992).

2.3 E89-039

Eta Electroproduction
S.A. Dytman, J.A. Mueller and the CLAS COLLABORATION

2.3.1 Introduction

This experiment measures quantities based on electroproduction experiments where there is an eta meson in the final state. These include cross sections and single polarization observables for eta electroproduction. There can be a nucleon in coincidence with the eta. The first results were published in Physical Review Letters [Th01].

The first interest is in the reaction $ep \to e'p\eta$. Near threshold, W=1.485 GeV, previous experiments have seen a strong inelastic excitation that has most often been associated with a *single* N^* state, the $S_{11}(1535)$. This brings a significant advantage in uniquely identifying an individual resonance signal. Further, this state has the unique properties of a very strong (50%) branching fraction to ηN and a very slow decrease of the transition form factor for $\gamma N \to N^*$, $A_{1/2}(Q^2)$. These data further elucidate the microscopic structure of $S_{11}(1535)$.

The second interest is to examine the reaction at energies above threshold where the previous data are far less complete. Before this experiment, eta production data has produced no strong signals for resonances other than $S_{11}(1535)$.

Interplay between this experiment and complementary photoproduction results is of great interest. Recent photoproduction experiments[Aj98] have shown the value of precise data in seeing the signs of interference between the dominant $S_{11}(1535)$ and other resonances. That theme has continued in this experiment.

2.3.2 Experiment Status

Data for this reaction have been taken in each of the e1 run periods. The published results were based on the first e1 run period (February-March, 1998) data. The second run period (January-March, 1999) data are reported here. This run period contains an order of magnitude improvement in statistics over the published data. Cross sections have been measured for W from threshold to about 2.2 GeV and at Q^2 from 0.13 to 3.0 GeV^2. The great advance of CLAS is to simultaneously collect data over a broad kinematic range. For this reaction, cross sections are determined for the full range of meson decay angles (θ^*_η and ϕ^*_η).

2.3.3 Results

For each W, Q^2 and $cos\theta_\eta$ bin the ϕ_η dependence of the differential cross sections was fit to extract the response functions $R_T + \epsilon_L R_L$, R_{TT}, R_{LT}.

$$\frac{d^2\sigma}{d\Omega^*_\eta} = \frac{q}{k}[R_T + \epsilon_L R_L + R_{LT}\sqrt{2\epsilon_L(1+\epsilon)} \cdot \cos\phi^*_\eta + R_{TT} \cdot \epsilon \cdot \cos 2\phi^*_\eta] \tag{1}$$

Results for $R_T+\epsilon_L R_L$ are shown in Figure 1. A new model based on the MAID formalism[Ch02] has been developed for η electro and photoproduction using the data of previous experiments as well as quark models for input. The predicted shape of $R_T + \epsilon_L R_L$ from this model is also shown in Figure 1. In this figure, the experimental results and the MAID predictions have been scaled by the average value for that W and Q^2 in order to compare the shape of theory and experiment. The fall-off of the cross section predicted by the model at forward angles does not match the linear rise of the data for W around 1.7 GeV.

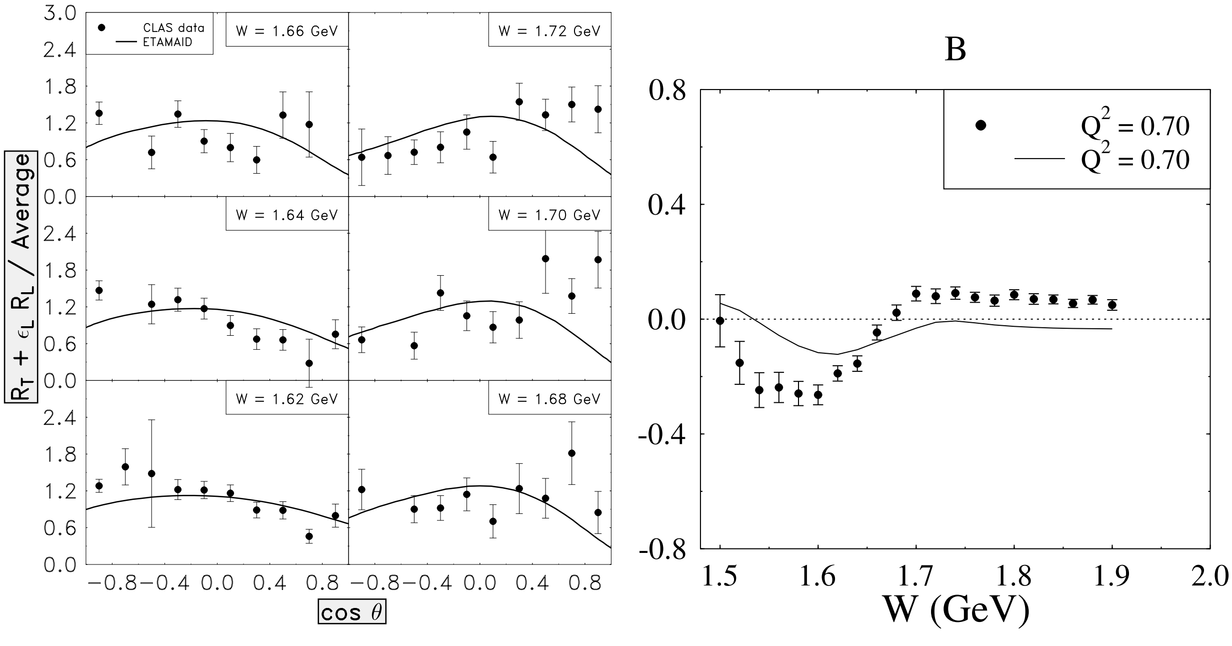


Figure 1: The result of the fit to the differential cross section using eqn 1 and eqn 2. This is for $Q^2 = 0.7(GeV/c)^2$. Curves are predictions from Mainz calculation.

This feature of the data can be seen more clearly by expanding $R_T + \epsilon_L R_L$ as a series of Legendre Polynomials

$$R_T + \epsilon_L R_L = A + B \cdot \cos\theta^*_\eta + C \cdot P_2(cos\theta^*_\eta) + ... \tag{2}$$

The B parameter is plotted versus W in figure 1. This confirms the results from the published paper[Th01], but with much greater precision. Photoproduction experiments generally have poor coverage in the forward direction and need models to extrapolate to the unmeasured region. The near total angular coverage of this experiment will allow this shape to be well determined. This can reduce the model dependence of the extrapolation by the experiments with less complete coverage.

The simplest explanation for a non-zero B is interference between S and P partial waves. In that case, the rapid change in B around 1.7 GeV would be due to changing phase difference between the S and P waves. The $P_{11}(1710)$ resonance is close and provides the necessary phase motion; it has no known ηN decay listed by the Particle Data Group[Gr00].

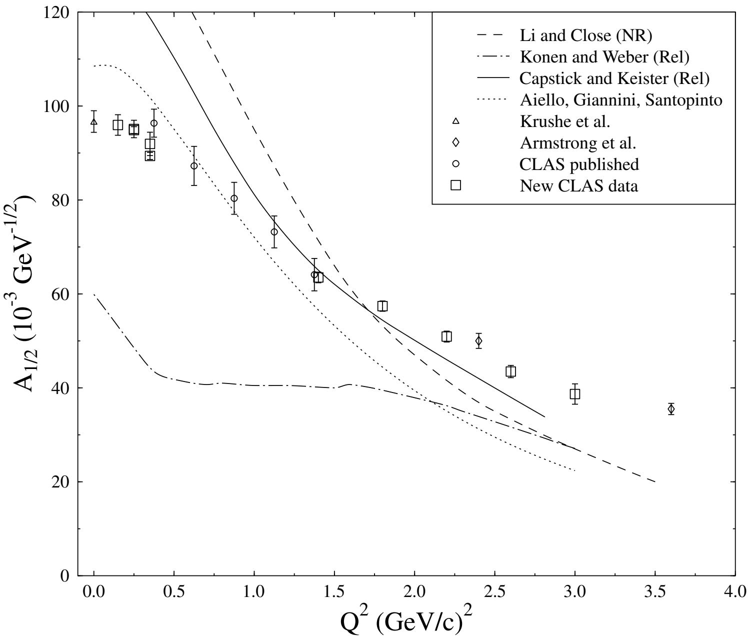


Figure 2: Values of the $A_{1/2}$ from single resonance analysis of this experiment compared to selected previous data and CQM calculations.

A single resonance analysis for the properties of $S_{11}(1535)$ was also done. $A_{1/2}$ was calculated by the standard formula [Kn95] for this and all previous electromagnetic experiments. The slow falloff seen in previous experiments is confirmed, but with much greater clarity. These data along with that of Refs. [Kr95] and [Ar99] and our published results are shown in Figure 2. These show a consistent smooth falloff.

The interpretation of these results is unclear in terms of the microscopic resonance structure of $S_{11}(1535)$. The lines shown in Figure 2 come from various constituent quark model (CQM) analyses[Li90, Ko90, Ca95, Ai98]. They don't agree well with each other or with the data, with the calculations of Aiello yielding the best agreement with the data. Perhaps this is due to a breakdown in the CQM decay assumptions. In addition, there is uncertainty about resonance character of the strong threshold enhancements seen in these and other data. In any case, these data provide very strong constraints for any model of $S_{11}(1535)$.

References

[Th01] R. Thompson, S. Dytman, K.Y. Kim, J. Mueller et al., Phys. Rev. Lett., **86**, 1702 (2001).

[Aj98] J. Ajaka et al., Phys. Rev. Lett. **81**, 1797 (1998).

[Kr95] B. Krusche et al., Phys. Rev. Lett. **74**, 3736 (1995).

[Kn95] G. Knochlein, D. Drechsel and L. Tiator, Z. Phys. **A352**, 327 (1995); L. Tiator, C. Bennhold, and S.S. Kamalov, Nucl. Phys. **A580**, 455 (1994).

[Ar99] C. S. Armstrong et al., Phys. Rev. **D60**, 052004 (1999).

[Re02] F. Renard et al., Phys Lett **B528** 215 (2002).

[Ch02] W. Chiang, S. Yang, L. Tiator, D. Drechsel Nucl.Phys. **A700**, 429 (2002).

[Gr00] D. E. Groom et al., Eur. Phys. J. **C15**, 1 (2000).

[Li90] Z. Li and F. Close, Phys. Rev. D**42**, 2207 (1990).

[Ko90] W. Konen and H. J. Weber, Phys. Rev. D**41**, 2201 (1990).

[Ca95] S .Capstick and B. D. Keister, Phys. Rev. D**51**, 3598 (1995).

[Ai98] M. Aiello, M.M. Giannini, and E. Santopinto, J. Phys. G **24**, 753 (1998)

2.4 E93-008

Inclusive η Photoproduction in Nuclei

M. F. Vineyard (Union College)
and the CLAS Collaboration

2.4.1 Introduction

Jefferson Lab Experiment 93-008 uses the CEBAF Large Acceptance Spectrometer (CLAS) and the photon tagging system in Hall B to measure inclusive η photoproduction in nuclei. The primary motivation of this experiment is to investigate nuclear medium modifications of nucleon resonances and the η-nucleus interaction. This experiment is part of both the g2 and g3 run groups of the CLAS Collaboration.

Through the study of the excitation, propagation, and decay of nucleon resonances in the nuclear environment one ultimately expects to understand how the strong interaction is affected by baryon structure. A wealth of information on the $\Delta(1232)$ and its dynamics within the nuclear medium has been obtained through pion studies. However, very little is known about medium properties of the higher-energy excited states of the nucleon. This is primarily due to the fact that the dominance of the Δ and the overlapping of higher resonances prevents the study of only a single specific state by π-production experiments. The η meson, on the other hand, couples only with isospin-$\frac{1}{2}$ N^* resonances since it is an isoscalar particle, and therefore provides a way to isolate these resonances. In this experiment, inclusive measurements of the photoproduction of η mesons in nuclei are performed to investigate medium modifications of the $S_{11}(1535)$ and possibly other isospin-$\frac{1}{2}$ resonances.

These measurements will also provide information on the η-nucleus interaction. Due to the lack of η beams, very little is known about the interaction of η mesons with nuclei. In this experiment, final-state interactions of the η meson propagating through the nucleus will be used to investigate the η-nucleus interaction. The study of η interactions with nucleons and nuclei can provide significant tests of our understanding of meson interactions which has been developed through pion studies.

Data were obtained several years ago at MAMI for the inclusive reaction on ^{12}C, ^{40}Ca, ^{93}Nb, and ^{nat}Pb nuclei for photon energies up to 790 MeV [Ro96]. However, though these data are of high quality, the energy range covered is from threshold to just below the peak of the $S_{11}(1535)$ resonance. From the analysis of these data, it was concluded that the total cross section scales as $A^{2/3}$ and a Glauber model analysis indicated an η-N cross section of about 30 mb. No evidence of a shift in mass or a depletion of strength of the $S_{11}(1535)$ was observed from a comparison with an effective Lagrangian model [Ca93]. However, it should be stressed that this conclusion was drawn from a comparison of the slopes of the data and calculations on the low-energy side of the $S_{11}(1535)$ rather than over the entire line shape of the resonance.

Recently, the $^{12}C(\gamma,\eta)$ reaction was investigated at photon energies between 0.68 and 1.0 GeV at the 1.3-GeV electron synchrotron at KEK-Tanashi [Yo00]. The cross section as a function of incident photon energy was observed to increase with photon energy up to 0.9 GeV and then begin to decrease. This was interpreted as the first observation of the $S_{11}(1535)$ resonance in the carbon nucleus. It was shown that some of the differences between the shapes of the cross sections measured on carbon and hydrogen can be accounted for by medium effects such as Fermi motion, Pauli blocking, and η-N and N-N* collisions in quantum molecular dynamics calculations.

There have been a number of theoretical results on η photoproduction from nuclei in the last decade. In the effective Lagrangian approach of Carrasco *et al.* [Ca93], the η-N final state interactions are taken into account by a Monte Carlo code using calculated reaction probabilities. In the work of Lee *et al.* [Le96], the quasifree production is calculated in the distorted-wave impulse approximation and the final state interactions are treated with an η-A optical potential. Effenberger *et al.* [Ef97] use the production cross sections on the free nucleon as input and take into account the final state interactions with a coupled-channel Boltzmann-Uehling-Uhlenbeck model. Recently, Hedayati-Poor and Sherif [He98] introduced a relativistic model in which an effective Lagrangian approach is used to describe the elementary production process and the dynamics of the nucleon motion are based on a relativistic mean field theory. Several of these models provide reasonable descriptions of the MAMI total cross sections. However, detailed agreement with the differential cross sections is not obtained with any of the models.

The Jefferson Lab experiment discussed here will extend the MAMI and KEK-Tanashi measurements to higher energies and more targets. The extended energy range will completely cover the region of the $S_{11}(1535)$ resonance and allow for a more thorough investigation of possible nuclear medium modifications. It will also allow for the measurement of contributions to the cross section from other resonances and non-resonant production. The measurements are being made on a variety of targets enabling the study of the evolution of medium effects with target mass and the investigation of the η-nucleus interaction.

2.4.2 Experiment Status

Data are currently being analyzed for η photoproduction on ^{1}H, ^{2}H, ^{3}He, and ^{4}He targets. Future measurements on ^{12}C and Pb targets are planned.

Shown in Figure 1 are preliminary invariant mass spectra for $\gamma\gamma$ events from hydrogen, deuterium, and ^{3}He targets. The spectra are fitted with a function consisting of a quadratic piece to describe the background in the mass region 0-0.23 GeV, an exponential part to fit the background at higher mass, and two gaussians to fit the π^0 (mass = 0.135 GeV) and η (mass = 0.547 GeV) peaks. These spectra represent a small fraction ($\leq$ 5%) of the total data set on each target.

References

[Ro96] M. Roebig-Landau, *et al.*, Phys. Lett. **B373**, 45 (1996).

[Ca93] R.C. Carrasco, Phys. Rev. **C48**, 2333 (1993).

[Yo00] T. Yorita *et al.*, Phys. Lett. **B476**, 226 (2000).

[Le96] F.X. Lee, L.E. Wright, C. Bennhold, and L. Tiator, Nucl. Phys. **A603**, 345 (1996).

[Ef97] M. Effenberger *et al.*, Nucl. Phys. **A614**, 501 (1997).

[He98] M. Hedayati-Poor and H.S. Sherif, Phys. Rev. **C58**, 326 (1998).

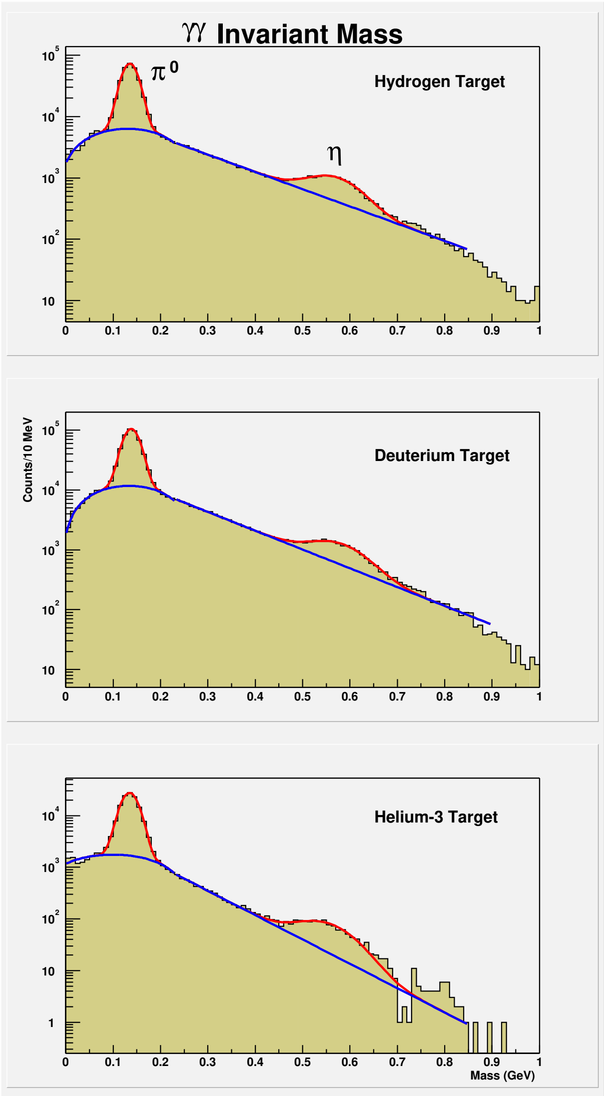


Figure 1: Preliminary invariant mass spectra for $\gamma\gamma$ events from hydrogen, deuterium, and ^{3}He targets. The spectra are fitted with a background function and two gaussian functions. The background function has a quadratic form over the range 0-0.23 GeV and an exponential form at higher mass. The π^0 (mass = 0.135 GeV) and η (mass = 0.547 GeV) peaks are fitted above the background with the gaussian functions. These spectra represent a small fraction ($\leq 5\%$) of the total data set on each target.

2.5 E94-017

The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Electron-Neutron to Electron-Proton Scattering in Deuterium

W. K. Brooks (Jefferson Lab), M. F. Vineyard (Union College)
and the CLAS Collaboration

2.5.1 Introduction

The e5 run of the CLAS Collaboration in Hall B consists of a single experiment, E94-017. The goal of this experiment is to determine the neutron magnetic form factor over a Q^2 range from 0.2 to 4.8 $(GeV/c)^2$ from precision measurements of the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium.

Nucleon structure is one of the most fundamental issues in hadronic physics. Elastic electron scattering can be used to probe the electromagnetic structure of the nucleon. The differential cross section for elastic electron-nucleon scattering in the one-photon-exchange approximation is given by the Rosenbluth formula [Ro50] in which the nucleon structure information is contained in the Sachs electromagnetic form factors, G_E and G_M. These form factors provide information on the distributions of charge and magnetization current within the nucleon and are used for comparison between experiment and theoretical models of nucleon structure.

Until recently, the electromagnetic form factors for the proton have been determined experimentally from elastic ep scattering using the Rosenbluth separation technique [Ro50]. The magnetic form factor of the proton, G_M^p, appeared to be rather well determined over the range $0 < Q^2 < 30$ $(GeV/c)^2$, while the electric form factor, G_E^p, was determined with much less precision, particularly at high Q^2 where the cross section is dominated by G_M^p [Bo95]. These results indicated that the ratio $\mu_p G_E^p / G_M^p \simeq 1$, where $\mu_p = 2.79$ is the magnetic moment of the proton.

Recent measurements of $\mu_p G_E^p / G_M^p$ in Hall A at Jefferson Lab using a polarization transfer technique have shown that the form factor ratio decreases significantly from unity above $Q^2 = 1$ $(GeV/c)^2$ [Jo00, 4]. These results have led to intense theoretical activity [Bl00, De00, Ca00, Mi02] and a reanalysis of most of the world ep elastic cross section data using these new data as a constraint [Br02].

The neutron form factors have been determined with much less precision than those of the proton [Bo95]. Until the last decade most of the neutron form factor data came from analyses of inclusive quasielastic electron scattering from deuterium that introduce a number of significant systematic errors. More recently progress has been made in measurements [Ma93, Br95, An94, An98] of the neutron magnetic form factor, G_M^n, at low Q^2 values by measuring the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium, a method in which many of the systematic uncertainties cancel. However, there are discrepancies among these measurements. Recently, measurements [Xu00] of inclusive quasielastic scattering of polarized electrons off a polarized ^3He target were performed in Hall A at Jefferson Lab and used to extract G_M^n at $Q^2 = 0.1$ and 0.2 $(GeV/c)^2$ with an experimental uncertainty of less than 2%. Also, significant progress is being made on the extraction of G_E^n from measurements of the $\overrightarrow{d}\,(\overrightarrow{e}, e'n)\,p$ [Zh01] and $d\,(\overrightarrow{e}, e'\overrightarrow{n})\,p$ [Ma93] reactions in Hall C at Jefferson Lab.

In this experiment, precise measurements of the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium have been made over a broad range in Q^2 with the CLAS. The neutron magnetic form factor will be extracted from this ratio with the use of the more accurately known proton form factors. Data were taken simultaneously on separated hydrogen and deuterium targets. The $e + p \rightarrow e' + n + \pi^+$ reaction on the hydrogen target is used to measure the neutron detection efficiency. The data from electron-proton and electron-neutron scattering in deuterium are treated in an identical way insofar as possible. The use of this ratio technique, with the simultaneous calibration of the neutron detection efficiency, significantly reduces or eliminates many of the systematic errors associated with inclusive quasielastic scattering from deuterium. The results of this experiment will provide a significant improvement in our knowledge of the neutron magnetic form factor over the Q^2 coverage of existing measurements, and will extend the range to 4.8 $(GeV/c)^2$. In addition to providing accurate information on the magnetic structure of the neutron, these data will be important for the extraction of the electric form factor of the neutron from measurements of polarization observables which determine a linear combination of the electric and magnetic form factors (see for example Refs. [Zh01, Ma93]) and will allow a more accurate extraction of the strange quark form factor [An99].

2.5.2 Experiment Status

Data for E94-017 were collected during the e5 run in April and May of 2000 with the CLAS detector in Hall B at Jefferson Lab and are currently being analyzed. Approximately 2.3 billion triggers were acquired, about half at an electron beam energy of 2.6 GeV and half at 4.2 GeV. The low beam energy data were divided into two-thirds normal torus polarity and one-third reversed torus polarity. The reversed torus polarity data were taken to reach the lowest possible limit in Q^2. There is considerable overlap in Q^2 between the data taken at the two beam energies that provide important systematic cross-checks.

Shown in Figure 1 is a Q^2 distribution for quasielastic events in which a nucleon is detected from the deuterium target for an incident electron energy of 4.2 GeV. This spectrum represents less than 7% of the 4.2-GeV data set and shows that a large range in Q^2 is covered with good statistics for the reaction of interest. The lower Q^2 range is covered by the 2.6-GeV data set with a significant overlap with the 4.2-GeV data.

2.5.3 Expected Results

The data from the e5 run will provide the magnetic form factor of the neutron over the Q^2 range from 0.2 to 4.8 $(GeV/c)^2$, with uncertainties of a few percent over most of the range, with many systematic cross-checks. These measurements should eclipse and extend the entire world's data for this fundamental quantity. We anticipate having some preliminary results for G_M^n in early 2003. In addition, there are a number of other interesting physics quantities which will be extracted from this data set.

References

[Ro50] M.N. Rosenbluth, Phys. Rev. **79**, 615 (1950).

[Bo95] P.E. Bosted, Phys. Rev. **C51**, 409 (1995); and references therein.

[Jo00] M.K. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000).

[Ga01] O. Gayou *et al.*, Phys. Rev. **C64**, 038202 (2001).

[Bl00] J.C.R. Bloch, C.D. Roberts, and S.M. Schmidt, Phys. Rev. **C61**, 065207 (2000).

[De00] M. De Sanctis *et al.*, Phys. Rev. **C62**, 025208 (2000).

[Ca00] F. Cardarelli and S. Simula, Phys. Rev. **C62**, 065201 (2000).

[Mi02] G.A. Miller, private communication (2002).

[Br02] E.J. Brash *et al.*, Phys. Rev. **C65**, 051001 (2002).

[Ma93] P. Markowitz *et al.*, Phys. Rev. **C48**, R5 (1993).

[Br95] E.E.W. Bruins *et al.*, Phys. Rev. Lett. **75**, 21 (1995).

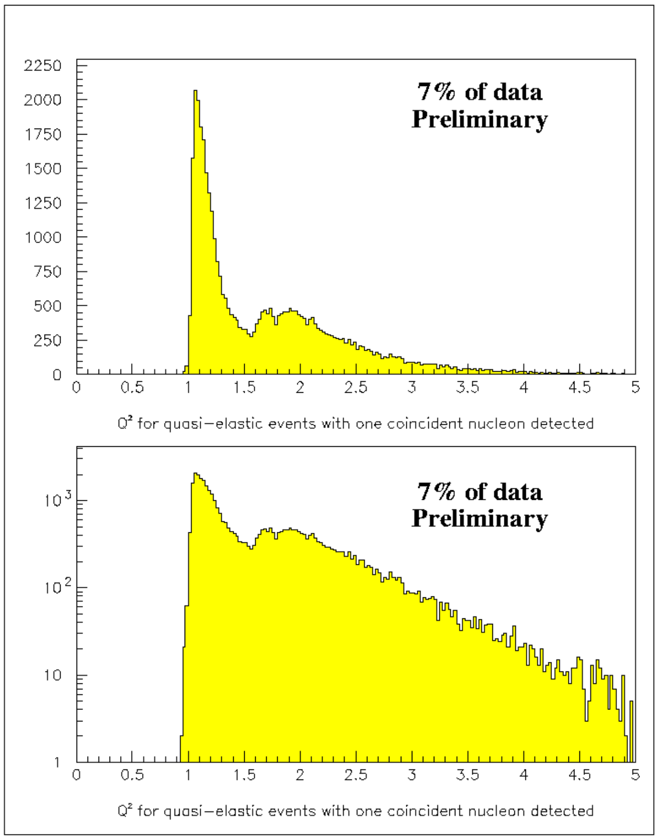


Figure 1: Q^2 distribution for quasielastic events in which a nucleon is detected from the deuterium target for an incident electron energy of 4.2 GeV. This spectrum represents less than 7% of the 4.2-GeV data set.

[An94] H. Anklin *et al.*, Phys. Lett. **B336**, 313 (1994).

[An98] H. Anklin *et al.*, Phys. Lett. **B428**, 248 (1998).

[Xu00] W. Xu *et al.*, Phys. Rev. Lett. **85**, 2900 (2000).

[Zh01] H. Zhu *et al.*, Phys. Rev. Lett. **87**, 081801 (2001).

[Ma93] R. Madey (spokesperson), CEBAF Experiment Proposal E-93-038 (1993).

[An99] K.A. Aniol *et al.*, Phys. Rev. Lett. **82**, 1096 (1999).

2.6 E89-038

Measurements of $p(e,e'\pi^+)n,\ p(e,e'p)\pi^o$, and $n(e,e'\pi^-)p$
in the Second and Third Resonance Regions

V. Burkert, R. Minehart, and the CLAS collaboration

2.6.1 Introduction

The goal of the experiment is to measure the transition form factors of several of the higher resonances that populate the mass region near 1.5 GeV and 1.7 GeV. States with masses near 1.5 GeV are the "Roper" $N(1440)P_{11}$, $N(1520)D_{13}$, and $N(1535)S_{11}$, while there are seven well known states near 1.7 GeV, the most prominent ones in electromagnetic interactions being the the $N(1680)F_{15}$, $N(1650)S_{11}$, and $\Delta(1700)D_{33}$. As many of these states have isospin 1/2 it is very important to measure not only the "easy" $\gamma^*p \rightarrow p\pi^o$ but the charged $n\pi^+$ final state as well. Note that the I=1/2 states couple preferentially to the charged pion final state. A combined analysis of both final states as well as the channel $\gamma n \rightarrow p\pi^-$ from deuterium targets gives the complete isospin information for single pion production from nucleons.

2.6.2 Experiment Status

Data have been taken mostly at 1.5 GeV and 2.5 GeV during the E1c and E1d run periods in spring 1999 and 2000 with a hydrogen target. Data on deuterium were also taken at 2.5 GeV during the E1d run period but have not been analyzed yet. This report deals only with the 1.5 GeV data from the E1c run period.

Two field settings were used to optimize the acceptance and cover a Q^2 range from 0.3 to 0.65 GeV^2. Data taken at different torus field settings will also help determining systematic uncertainties in the acceptance calculation. Some complications in the analysis came from the performance of the liquid hydrogen target which, due to insufficient thermal shielding when using a new cell, was never completely full, and emptied itself at numerous occasions in course of the run. Although this bevavior can be fully accounted for when analyzing the data, it introduced some delay in the analysis.

To complete data taking for this experiment additional runs with the deuterium target at 1.5 GeV will be needed.

2.6.3 Expected Results

The 1.5 GeV data have been nearly completely analyzed for the $n\pi^+$ channel. Hovanes Egiyan, while he was a graduate student from the College of William and Mary, completed his PhD thesis based on the analysis of these data taken with a torus setting of 1500 A. The data cover mainly the 1.5 GeV mass range for $Q^2 = 0.3 - 0.6\text{GeV}^2$. The kinematical coverage of the analyzed data and the binning used in the analysis are illustrated in Fig. 1. Full GSIM simulations have been carried out using MAID2000 and AO as parameterization of the process. Radiative corrections have been applied using the procedure by Mo and Tsai in a full Monte Carlo simulation without applying the "peaking" approximation. In conjunction with I. Akushevich [1] a new approach for radiative corrections has been developed that applies to exclusive reactions. This approach is currently being tested. Differential cross sections have been extracted over nearly the complete center-of-mass angular distribution.

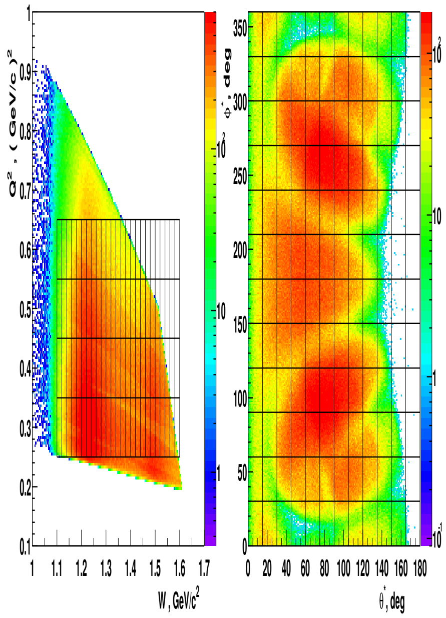


Figure 1: Kinematical region covered by the analyzed data.

A set of differential cross section data in the 2nd resonance region are shown in Figure 2. These plots show the angular distributions for $n\pi^+$ electroproduction at fixed invariant mass W off protons at different azimuthal angles, ϕ. The angle ϕ is the angle between the decay plane of the resonance and the electron scattering plane. The curves represent the MAID200 parametrization.

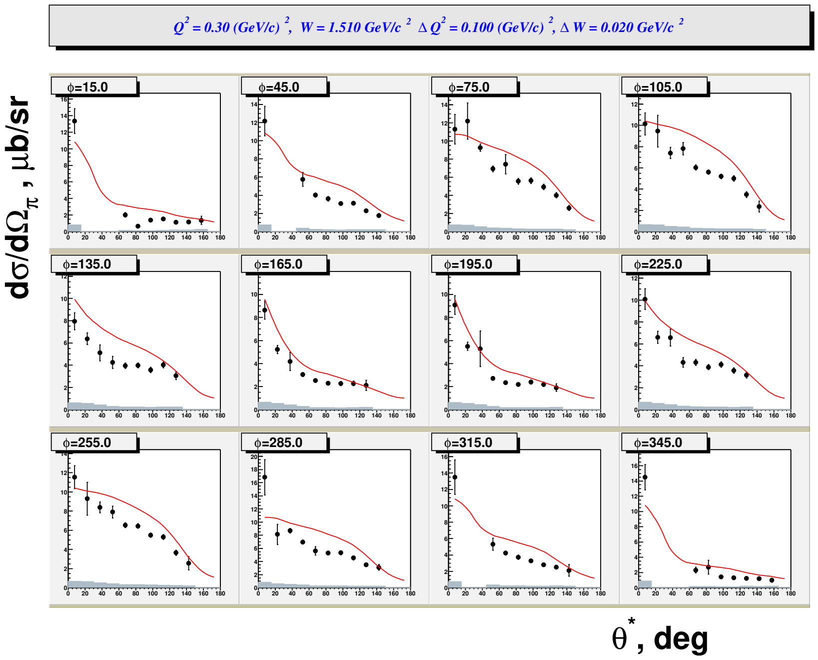


Figure 2: Preliminary angular distributions for $n\pi^+$ electroproduction cross section in one W and Q^2 bin for different values of ϕ, the angle between the electron scattering plane and the $p\pi$ plane. The data are compared with the Maid2000 model (red curves). The shaded regions at the bottom are the systematic error estimates.

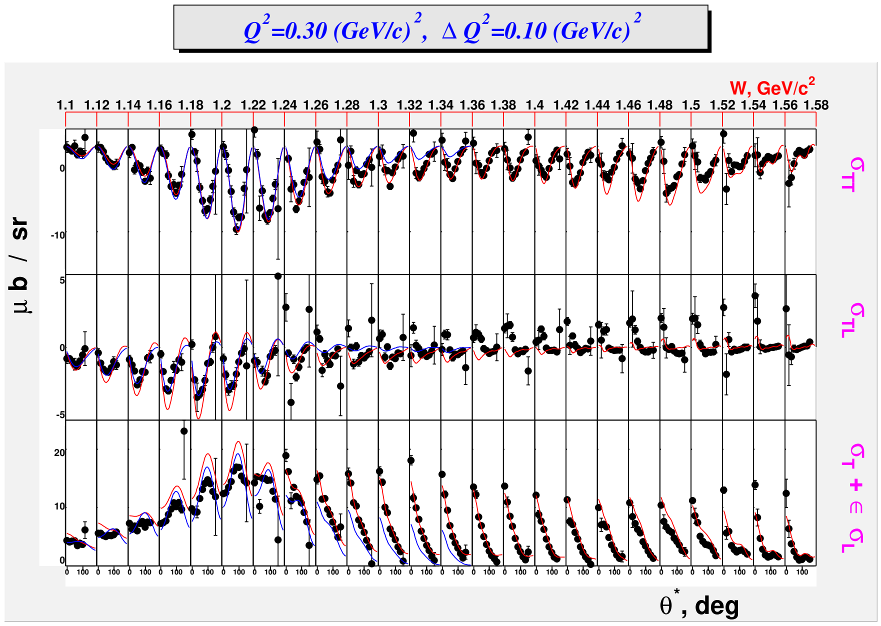


Figure 3: Structure functions vs theta, for various W bins at Q^2=0.3GeV^2. The curves are from the Maid2000 model (red curves) and the Sato-Lee model (blue curves). 2.

Since the acceptance covers the full azimuthal angle for π^+ production, we can also determine the response functions $\sigma_t + \epsilon\sigma_L$, σ_{TT} and σ_{LT} using a fit to a function $a + b\cos(\phi) + c\cos(2\phi)$. The response functions have been further analyzed using a power expansion in $\cos\theta$. Preliminary results are shown in Figure 3. This is the first time that this information could be extracted from electroproduction experiments over such a large 0cm range.

In collaboration with Inna Aznauryan, a theorist from Yerevan, and Stepan Stepanyan from CNU, a Fortran code (JANR) [2] was developed that allows fitting of all single pion production data in an energy-dependent fashion. The analysis implements basic features of MAID2000 and allows fitting of cross section data. The code was tested on π^o production in the $\Delta(1232)$ region. In the future, JANR will be used to analyze π^o and π^+ in a coupled channel analysis, including polarization observables. In addition, the GWU group is analyzing these data together with the world data to assess their impact on the extraction of resonance parameters.

An article on π^+ electroproduction is to be prepared for publication in Phys. Rev. C. During the collaboration meeting in June 2002, Paul Stoler appointed an SON committee to review the analysis paper. The members of the committee are Gerry Gilfoyle, Ioachim Kuhn and Raffaella Devita.

References

[1] A. Afanasev, I. Akhushevich, V. Burkert, K. Joo, to be published

[2] I. Aznauryan, V. Burkert, S. Stepanyan, JANR - Jlab Analysis of Nucleon Resonances, internal report.

2.7 E89-037

Electroproduction of the $P_{33}(1232)$ Resonance

V. Burkert and R. Minehart (Spokespersons)
K. Joo, L.C. Smith
and the CLAS Collaboration

2.7.1 Introduction

The $\Delta(1232)$ resonance is the lowest energy excitation of the proton and the most prominent evidence of internal structure. While QCD prescribes quarks and gluons as the elementary constituents of hadrons in the hard scattering limit, there is still no clear picture of the confinement mechanism or how these degrees of freedom contribute to low energy phenomena like resonance formation and decay. Under SU(6), the $\Delta(1232)$ is classified as a simple quark spin-flip excitation, which explains the observed dominant magnetic dipole (M_1+) photon coupling. However, the Δ can be excited using both electromagnetic and hadronic probes and a unified description of these transition processes is an area of active research. Because of the absence of overlapping resonances which can complicate the analysis, the low-lying $\Delta(1232)$ provides a simple and unique system in which to test QCD in the non-perturbative regime.

The status of the $\Delta(1232)$ as a benchmark for testing nucleon models has inspired a number of experimental programs worldwide to improve the database of differential cross sections and polarization observables using photon and electron beams and polarized targets. The CLAS N^* program is studying the transition form-factors for nucleon resonances using electroproduction of single pions. These measurements so far cover a range in Q^2 from about 0.3 to 4.0 GeV^2 and span the resonance region up to W=2 GeV, and in some cases beyond. For the current proposal, the emphasis is on measuring the longitudinal and transverse components of the $N \rightarrow \Delta(1232)$ quadrupole transition strength, which are believed to be very sensitive to non-valence quark degrees of freedom. This is accomplished using the large solid angle of CLAS to completely map out the phase space of the $N\pi$ final state, which has not been possible previously.

2.7.2 Experiment Status

The E1 run group has completed data taking for the run periods E1a,b,c,d and E1-6, most recently during the winter of 2001-2002. Over 75% of the approved data set for E89-037 has been taken, using beam energies over the range 1.5-6.0 GeV. Calibration of the low energy data is mostly complete and the first result from π^0 electroproduction of the $\Delta(1232)$ based on analysis by Kyungseon Joo and Cole Smith was published [1] in Physical Review Letters in April 2002. Analysis of the π^+ data set formed the basis for the Ph.D. thesis of Hovanes Egiyan (William and Mary) and those data will be published later this year. Calibration and analysis of higher energy π^+ and π^0 data sets is in progress by Mauri Ungaro of RPI and Kijun Park of Kyungpook University.

The next E1 running period is scheduled for the fall of 2002, where low energy data at roughly 1 GeV will be taken to extend our Q^2 coverage down to 0.1 GeV^2. This will provide overlap of existing measurements at Bates and Bonn but over a more extensive kinematic range.

2.7.3 Results

We have analyzed 1.5-2.5 GeV data from the E1a,b,c running periods, using this set to develop the analysis techniques which we believe can be applied with only a small amount of fine-tuning to the rest of the data set. The analysis required extensive modeling of the CLAS acceptance, tracking efficiency, and resolution, using a GEANT model. Software fiducial cuts were used to define the solid angle for electrons and hadrons. Radiative corrections were calculated using a Monte-Carlo integration of the Mo-Tsai [7] formula without the peaking approximation. Calculations with various values of cuts and other parameters have been made to estimate the magnitude of systematic errors.

A longstanding question in hadronic physics is the origin of the quadrupole strength experimentally observed in the $\gamma N \rightarrow \Delta$ transition. Besides the dominant magnetic dipole (M_{1+}) excitation mode, in which a single quark spin is flipped, small but non-zero electric (E_{1+}) and Coulomb (S_{1+}) quadrupoles are seen, indicating strong tensor correlations among the hadronic constituents and an intrinsic nucleon deformation. A crucial experimental test for models of nucleon deformation is the Q^2 dependence of the multipole ratios $R_{EM} = E_{1+}/M_{1+}$ and $R_{SM} = S_{1+}/M_{1+}$. Recent precision measurements of the $p(\gamma,\pi^o)p$ and $p(\gamma,\pi^+)n$ reaction channels at LEGS and MAMI found $R_{EM} \approx -2.5 - 3.0\%$ at $Q^2 = 0$. A $p(e,e'p)\pi^o$ experiment in Hall C at JLAB found $R_{EM} = -2.0\%$ at $Q^2 = 4$ (GeV/c)^2, while R_{SM} was 5-6 times larger and increasingly negative with Q^2. These results clearly rule out the influence of perturbative QCD, which favors helicity conserving amplitudes for which $E_{1+} \rightarrow M_{1+}$ and $S_{1+} \rightarrow constant$ as $Q^2 \rightarrow \infty$. At the same time, QCD-inspired constituent quark models account for $< 10\%$ of the value of R_{EM} obtained by the new measurements at $Q^2 = 0$. Although recent models incorporating the effects of chiral symmetry breaking and a dynamical pion cloud [5, 6] are more successful, they make different predictions for the Q^2

evolution of R_{EM} and R_{SM}.

Under the one-photon-exchange approximation, the electroproduction cross section factorizes as follows:

$$\frac{d^5\sigma}{dE_{e'}d\Omega_{e'}d\Omega_\pi^*} = \Gamma_v \frac{d^2\sigma_u}{d\Omega_\pi^*} \tag{1}$$

where Γ_v is the virtual photon flux. For unpolarized beam and target the center-of-mass (c.m.) differential cross section $d^2\sigma_u$ depends on the transverse ϵ and longitudinal ϵ_L polarization of the virtual photon through four structure functions: σ_T, σ_L and their interference terms σ_{LT} and σ_{TT}:

$$\begin{aligned}\frac{d^2\sigma_u}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma^*}(\sigma_T &+ \epsilon_L\sigma_L + \epsilon\,\sigma_{TT}\,sin^2\theta_\pi^*\,cos\,2\phi_\pi^* \\ &+ \sqrt{2\epsilon_L(\epsilon+1)}\,\sigma_{LT}\,sin\,\theta_\pi^*\,cos\,\phi_\pi^*)\end{aligned} \tag{2}$$

where $(p_\pi^*, \theta_\pi^*, \phi_\pi^*)$ are the π^o c.m. momentum, polar and azimuthal angles, $\epsilon_L = (Q^2/|k^*|^2)\epsilon$, and the virtual photon c.m. momentum and equivalent energy are $|k^*|$ and k_γ^*. Multipoles are obtained from a partial wave expansion of the structure functions, where M_{1+} dominance is assumed and the $p\pi^o$ final state is fitted up to l_π=1:

$$\begin{aligned}\sigma_T + \epsilon_L\sigma_L &= A_o + A_1\,cos\,\theta_\pi^* + A_2\,P_2(cos\,\theta_\pi^*) \\ \sigma_{TT} &= C_o \\ \sigma_{LT} &= D_o + D_1\,cos\,\theta_\pi^*\end{aligned} \tag{3}$$

To simplify the analysis, only terms which interfere directly with M_{1+} are retained. Thus, $|M_{1+}|^2$ and its projection onto the other s- and p-wave multipoles $E_{1+}, S_{1+}, M_{1-}, E_{0+}, S_{0+}$ are given in terms of the six partial-wave coefficients by [4]:

$$\begin{aligned}|M_{1+}|^2 &= A_0/2 \\ Re(E_{1+}\,M_{1+}^*) &= (A_2 - 2\,C_0/3)/8 \\ Re(M_{1-}\,M_{1+}^*) &= -(A_2 + 2\,(A_0 + C_0))/8 \\ Re(E_{0+}\,M_{1+}^*) &= A_1/2 \\ Re(S_{0+}\,M_{1+}^*) &= D_0 \\ Re(S_{1+}\,M_{1+}^*) &= D_1/6\end{aligned} \tag{4}$$

Typical results for extracted structure functions obtained in the region of the $\Delta(1232)$ for Q^2 = 0.9 GeV^2 are shown in Figure 1 along with the predictions of the MAID [9], Sato and Lee [10] and Dubna-Mainz-Taipei [6] reaction models. These models attempt to describe the resonance production amplitudes in the presence of non-resonant pion multiple scattering backgrounds. Since the resonant amplitudes are usually calculated from quark models, coupling between resonant and non-resonant processes may play a crucial role in the interpretation of measured multipoles.

The Q^2 dependence of the partial wave coefficients extracted from fits to the structure functions are compared to models in Figure 2 for $W = 1.18$ GeV, below the peak of the $\Delta(1232)$. In this region sensitivity to backgrounds is large and differences between models more dramatic. Our data are clearly able to resolve between the different predictions.

The Q^2 dependence of the multipole ratios,

$$\begin{aligned} R_{EM} &= Re(E_{1+}M_{1+}^*)/M_{1+}^2 \\ R_{SM} &= Re(S_{1+}M_{1+}^*)/M_{1+}^2 \end{aligned} \tag{5}$$

at the $\Delta(1232)$ resonance are shown in Figure 3. Recent results from Mainz, LEGS, Bates, and JLab, are also shown, as are the calculations of several models. Our results favor models which include the pion cloud in a dynamical framework (see Figure 4.)

More extensive general analyses extending beyond the Δ region are also being applied. Our data are being included in the SAID electroproduction database and fitted by the GW group using models satisfying unitarity and threshold contraints [2]. Unitary-type isobar models based on MAID, as well as dispersion theoretic tools are being developed by Aznauryan [3].

References

[1] K. Joo *et al.*, Phys. Rev. Lett, **88**, 122001 (2002).

[2] R.A. Ardnt *et al*, MENU 2001, nucl-th/0110001 (2001).

[3] I.G. Aznauryan, nucl-th/0206033 (2002).

[4] A.S. Raskin and T.W. Donnelly, Ann. Phys., **191**, 78 (1989).

[5] A. Silva, D. Urbano, T. Watabe, M. Fiolhais and K. Goeke, hep-ph/9905326.

[6] S.S. Kamalov and Shin Nan Yang, Phys. Rev. Lett., **83**, 4494 (1999); S.S. Kamalov *et al*, Phys. Rev. C, **64**, 032201R, (2001).

[7] L.W. Mo and Y.S. Tsai, Rev. Mod. Phys., **45**, 205 (1969).

[8] O. Hanstein *et al*, Nucl. Phys., **A632**, 561 (1998); L. Tiator *et al*, nucl-th/0012046.

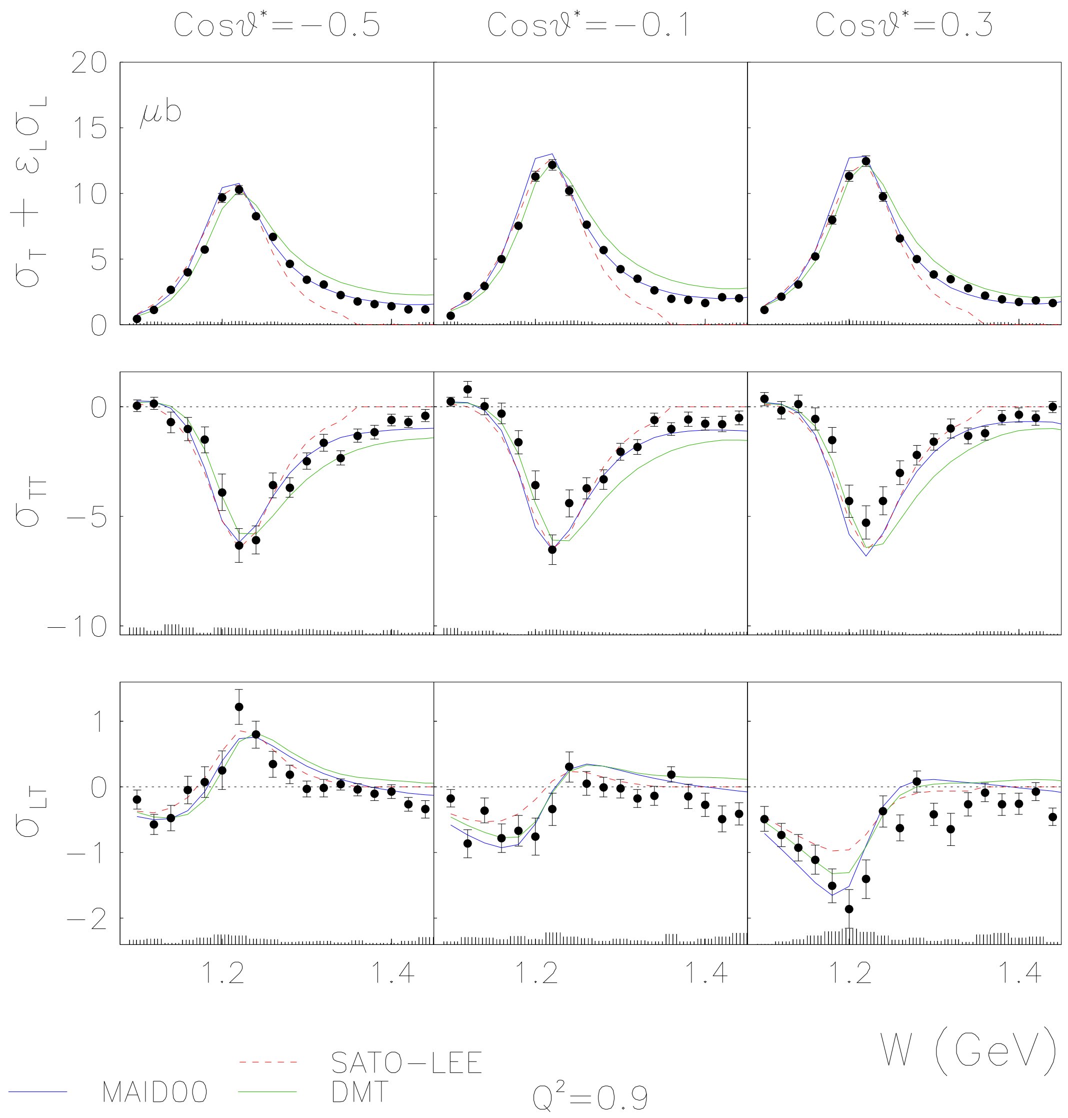


Figure 1: Structure functions extracted from CLAS $p(e,e'\,p)\pi^o$ data at $Q^2 = 0.9\,\mathrm{GeV}^2$. Each data point represents a fit of Eq. 2 to ϕ^*_π distributions at a fixed W and $cos\,\theta^*_\pi$ bin. Curves show predictions of various unitarized phenomenological reaction models.

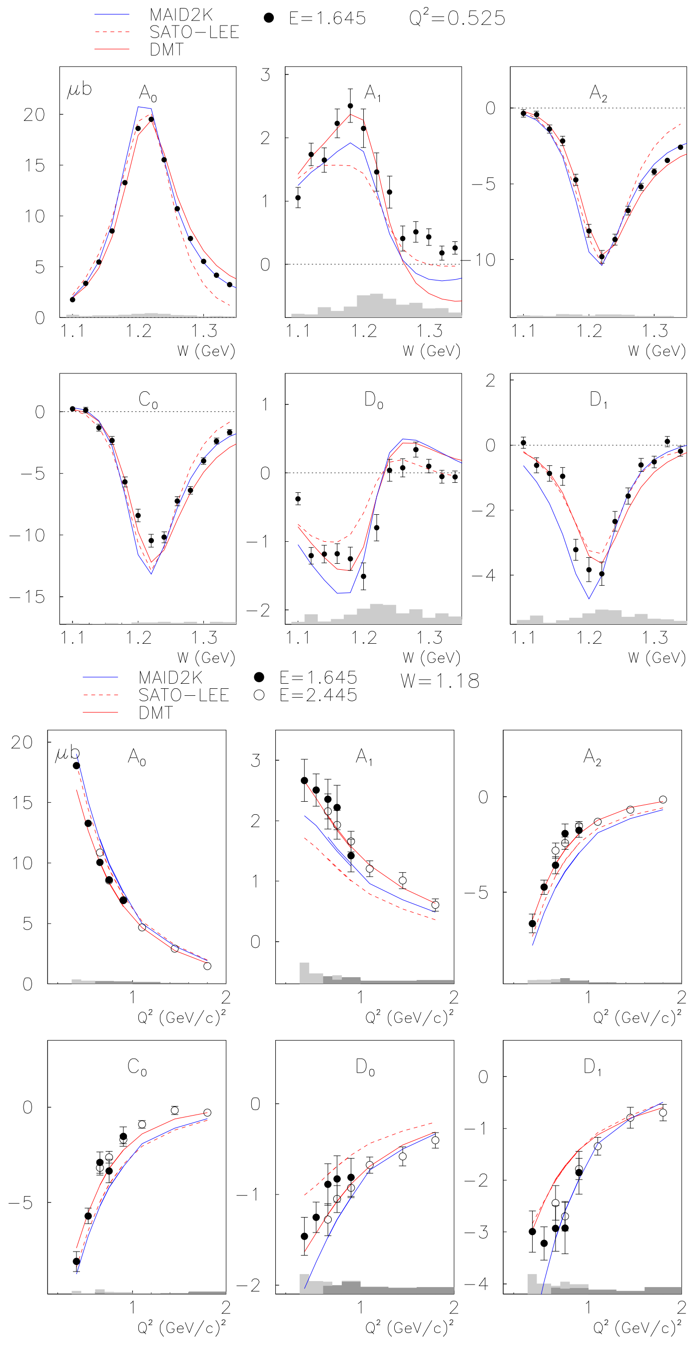


Figure 2: W dependence (top) and Q^2 dependence (bottom) of partial wave coefficients $A_0, A_1, A_2, C_0, D_0, D_1$ in the $\Delta^+ \rightarrow \pi^o p$ charge channel extracted from fits to CLAS measurements of structure functions using Eq. 3. Prediction of various pion cloud models [6, 8, 10] are shown.

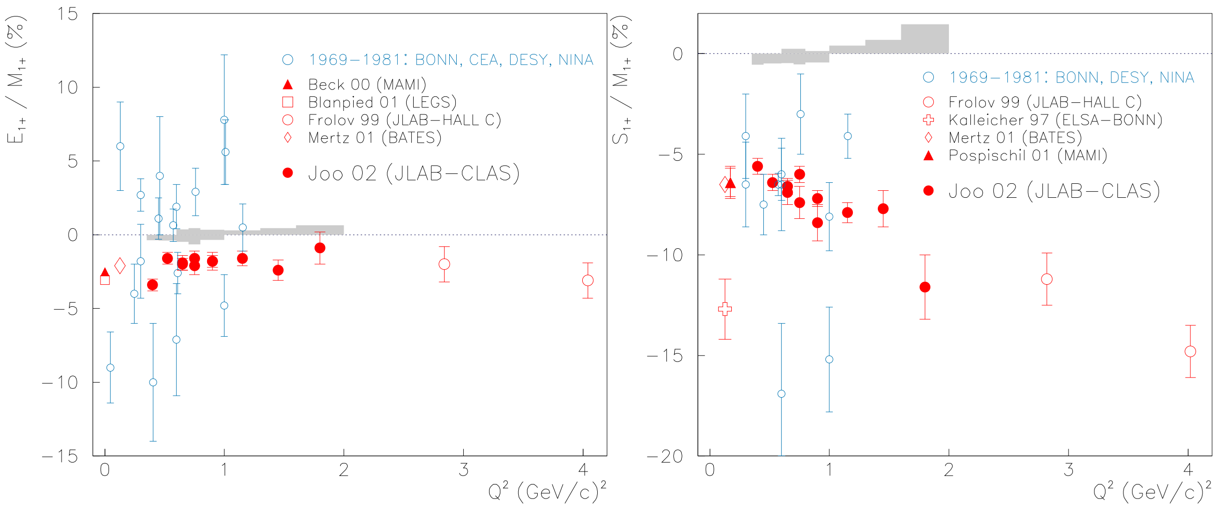


Figure 3: CLAS measurements (•) of the Q^2 dependence of multipole ratios R_{EM} and R_{SM} averaged over the W range 1.20-1.24 GeV compared to previous and recent measurements [12, 13, 14, 15, 16].

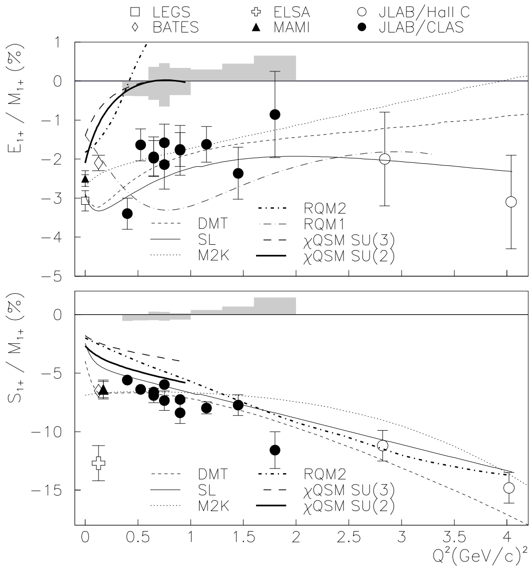


Figure 4: Comparison of CLAS measurements (•) of R_{EM} and R_{SM} to recent quark and dynamical pion models [5, 6, 8, 9, 10, 11].

[9] D. Drechsel, O. Hanstein, S.S. Kamalov, L. Tiator, Nucl. Phys., **A645**, 145 (1999).

[10] T. Sato and T.-S.H. Lee, Phys. Rev., **C63**, 055201 (2001).

[11] M. Warns, H. Schroder, W. Pfeil and H. Rollnik, Z. Phys. C, **45**, 627 (1990).

[12] R. Beck *et al*, Phys. Rev. Lett., **78**, 606 (1997).

[13] G. Blanpied *et al*, Phys. Rev. Lett. **79**, 4337 (1997).

[14] C. Mertz *et al*, Phys. Rev. Lett. **86**, 2963 (2001).

[15] T. Pospischil *et al*, Phys. Rev. Lett. **86**, 2959 (2001).

[16] V.V. Frolov *et al*, Phys. Rev. Lett., **82**, 45 (1999).

2.8 E99-006

Polarization Observables in the ^{1}H($\vec{e}$,e$'$K$^+$)$\vec{\Lambda}$ Reaction

D.S. Carman, K. Joo, B.A. Raue

2.8.1 Introduction

E99-006 was designed to provide the first ever beam-recoil double-polarization measurements in the nucleon resonance region for the associated strangeness production reactions $p(\vec{e}, e'K^+)\vec{\Lambda}, \vec{\Sigma}^0$. The electroproduction reaction provides insight into the basic reaction mechanism for the open-strangeness production process, as well as information regarding fundamental hadronic structure. Both of these aspects are expected to provide insight into the nature of QCD in the confinement domain.

This experiment will provide data at beam energies of 2.5 and 4.2 GeV using the Hall B CLAS spectrometer. The large acceptance of CLAS enables us to detect the final-state electron and kaon, as well as the proton from the mesonic decay of the Λ hyperon over a range of Q^2 from 0.4 to 2.7 (GeV/c)^2 and W from 1.6 to 2.4 GeV. Using CLAS provides a unique opportunity to probe the interaction well beyond the usual parallel or in-plane kinematics of typical dual spectrometer experiments, through study over a broad range of momentum transfers and kaon azimuthal angles. This allows for simultaneous study of the reaction over varying kinematical regions where the different reaction channel processes have varying strengths. Thus we can effectively limit the intermediate baryonic or mesonic resonances involved in the reaction. An important aspect of our analysis is the search for the so-called "missing" N^* resonances predicted by constituent quark models but not seen through $N\pi$ or $N\gamma$ channels. Many of these states are predicted to have sizeable branching fractions to hyperons [1].

In hadrodynamic models, polarization observables are sensitive to the details of the reaction mechanism, that is, the specific intermediate resonances involved in the reaction, as well as their coupling constants. From the point of view of quark models, double-polarization observables will shed light on descriptions of strong decays through $q\bar{q}$ pair production and address the ambiguity in the quantum numbers of the $s\bar{s}$ pair created in the intermediate state. As well, our kinematics span the transition regime where it is expected that the hadrodynamic formalism will begin to give way to a description in terms of quarks and gluons. Newly developed gauge invariant models based on Regge exchanges may provide a convenient formalism over these kinematics, as well as above the resonance region.

2.8.2 Data Analysis

During the 1999 run period, the beam was longitudinally polarized to an average value of nearly 70%. Data for this experiment were acquired at beam energies of 2.567 GeV and 4.247 GeV. Event readout was triggered by a scattered electron candidate whose signal was a coincidence between a forward calorimeter and a Cerenkov counter hit in the same CLAS sector. Further substantial improvement in the electron sample was performed during the analysis.

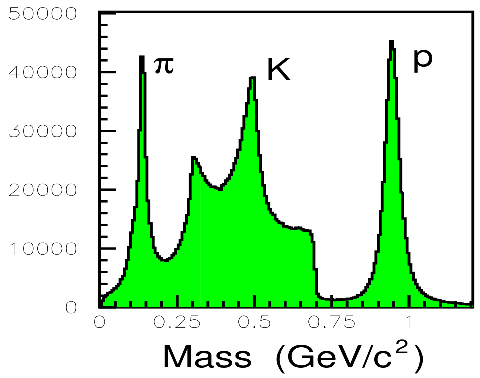


Figure 1: Reconstructed positive-hadron mass distribution from the kaon filtered data files.

Once the electron sample was isolated, the coincident charged-hadron spectrum was reconstructed. The primary technique for selecting charged hadrons is a cut on the reconstructed hadron mass spectrum, which is derived from the reconstructed track momentum divided by the particle velocity measured by the time-of-flight system. Fig. 1 highlights the positive hadron mass distribution as reconstructed from our data set filtered with loose requirements on particle identification of the $e'K^+$ final state. Cuts on this distribution are used to identify the detected charged particles in the final state.

The main analysis technique for identifying the final-state hyperons relies on missing-mass reconstructions of the $e'K^+$ final state. This is highlighted in Fig. 2 from analysis of the 4.247 GeV data. The main source of background beneath the hyperon missing-mass peaks comes from pions misidentified as kaons from the reaction $ep \to e'\pi^+n$. The majority of these background pions can be eliminated with cut on the π^- mass from the reconstructed $p(e, e'K^+p)X$ distribution. This results in a very clean spectrum with essentially only the Λ and Σ^0 peaks remaining. The hyperons of interest are then selected with a cut on this last distribution. The width of the hyperon peaks in this spectrum, summed over all Q^2 and W, is about 14 MeV.

Summing over all Q^2 and W, we have roughly 20k (15k) Λ (Σ^0) hyperons at 4.2 GeV and roughly 35k (20k) Λ (Σ^0) hyperons at 2.5 GeV whose polarization we can measure. With our detected three-body final state, CLAS has an average acceptance of ≈6% for typical Q^2 and W values.

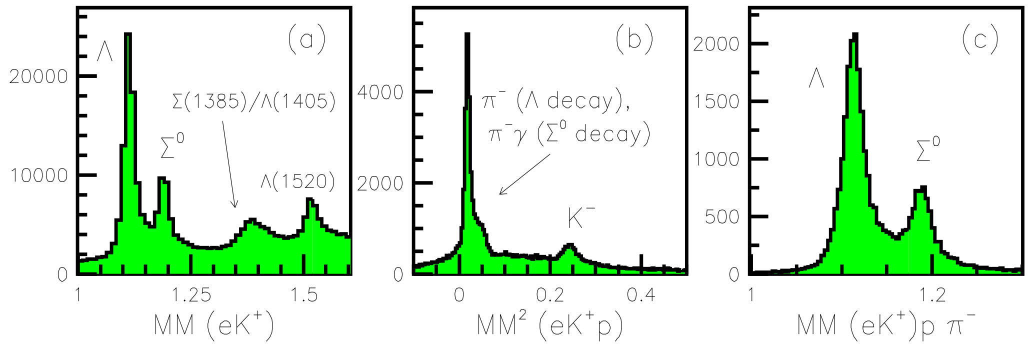


Figure 2: Hyperon missing-mass reconstructions from 4.247 GeV CLAS data. (a) Missing-mass spectrum for $p(e, e'K^+)X$, (b) missing-mass for the $p(e, e'K^+p)X$ reaction, and (c) hyperon distribution after cutting on the missing π^- (Λ decay) or $\pi^-\gamma$ (Σ^0 decay) peak.

2.8.3 Polarization Extraction

The Λ hyperon decays mesonically via $\Lambda \to p\pi^-$ (B.R.=64%). The measured angular correlation of the decay proton with respect to a given spin quantization axis in a given bin of Q^2, W, and $d\Omega_K^*$, allows for the determination of the average hyperon polarization in that bin. In the hyperon CM frame, the decay-proton angular distribution is of the form:

$$\frac{dN}{d\theta_p^{RF}} \propto 1 + \alpha P_\Lambda \cos\theta_p^{RF}, \qquad P_\Lambda = P^0 + hP_bP'. \tag{1}$$

Here, P_Λ is the Λ polarization, P_b is the electron beam polarization, α is the weak-decay asymmetry parameter (measured to be 0.642±0.013 [2]), and θ_p^{RF} is the decay-proton polar angle in the hyperon rest frame relative to the spin-quantization axis. A standard choice is the so-called ℓ,n,t system, defined with $\hat{\ell}$ along the Λ direction and $\hat{n}$ normal to the hadronic plane. The Λ polarization is given by the sum of two terms, the induced and transferred polarizations. P^0 represents the induced Λ polarization when the electron beam is unpolarized, and P' represents the spin-transfer polarization to the Λ.

The analysis of the transferred polarization employs the technique of extracting the yield asymmetries for the two different electron beam helicity states (h=±1) of the form:

$$A_i = \frac{N^+ - N^-}{N^+ + N^-} = \frac{\alpha P_b \cos\theta_p^{RF} P_i'}{1 + \alpha \cos\theta_p^{RF} P_i^0}, \qquad i = \ell, n, t. \tag{2}$$

This asymmetry is formed separately for each of the three spin-quantization axes of the decaying hyperon. In forming these asymmetries and integrating over all Φ, the angle between the electron and hadron planes, the form of the cross section dictates that $P_t^0 = P_\ell^0 = P_n' = 0$. Thus A_n must be zero, but A_ℓ and A_t can be non-zero and provide a direct measure of the transferred polarization, as $A_i = \alpha P_b \cos\theta_p^{RF} P_i'$. Fig. 3 shows results of our asymmetry fits at 4.247 GeV to indicate the quality of our data in a representative bin of Q^2, W, and $\cos\theta_K^*$, integrated over Φ.

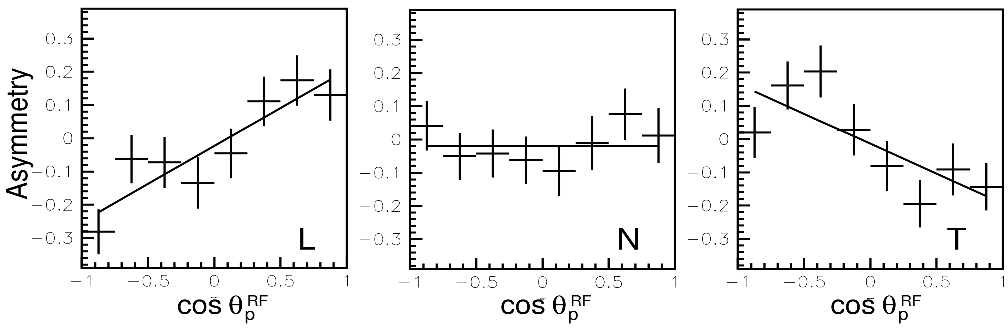


Figure 3: Polarization yield asymmetries for Λ production at 4.247 GeV integrated over all Φ for the bin defined by Q^2:[1.3-1.8 (GeV/c)^2], W:[1.6-1.9 GeV], and $\cos\theta_K^*$:[0.75-1.0].

The advantage of studying spin asymmetries is that they are relatively insensitive to the detector acceptance and efficiency, where the common factors associated with the two beam helicity states appear in both the numerator and denominator. Due to limited statistics in the present analysis, we have decided to study integrated quantities, in which the numerator and denominator are integrated over the angle Φ. This requires that the helicity-gated yields then be corrected for the acceptance of CLAS.

In this analysis, geometric fiducial cuts are employed for the electrons and hadrons. These define a precise region of the detector where events are accepted. The acceptance within the fiducial region can be calculated and used to apply an acceptance correction (including bad detector components, kaon in-flight decays, etc.) on an event-by-event basis. This approach has been shown to agree well with Monte Carlo simulations.

At the present time, the results of the analysis have been presented at several conferences and work is progressing towards first publication of the results. Inherent in this work is performing detailed comparisons between the analysis results and the predictions of the existing theoretical models.

References

[1] S. Capstick and W. Roberts, Phys. Rev. D **58**, 74011 (1998).

[2] C. Caso *et al.*, Rev. of Particle Physics, Eur. Phys. J **C3**, 1 (1998).

2.9 EG1

The EG1 Run Group in Hall B

Sebastian Kuhn, Experimental Coordinator

2.9.1 Introduction

The EG1 run group comprises a large program of spin structure measurements on the proton and the deuteron, using polarized electron scattering ($Q^2 = 0.05 \ldots 5.0$ GeV^2 and $W \leq 3.2$ GeV) and circularly polarized photon absorption on dynamically polarized cryogenic ammonia targets ($^{15}NH_3$ and $^{15}ND_3$) in Hall B. The run group is composed of experiments 91-015 (Helicity Structure of Pion Photoproduction; D. Sober, spokesperson), 91-023 (Measurement of Polarized Structure Functions in Inelastic Electron Proton Scattering; V. Burkert, D. Crabb, R. Minehart, spokespersons), 93-009 (The Polarized Structure Function G_{1n} and the Q^2 Dependence of the Gerasimov-Drell-Hearn Sum Rule for the Neutron; S. Kuhn, M. Taiuti, G. Dodge; spokespersons) and 93-036 (Measurement of Single Pion Electroproduction from the Proton with Polarized Beam and Polarized Target; R. Minehart, M. Anghinolfi, H. Weller, spokespersons). The total allocated beam time for these experiments is 100 days. In addition, a conditionally approved experiment (94-003 - Study of the $\Delta(1232)$ Using Double Polarization Asymmetries; V. Burkert, R. Minehart, P. Stoler, spokespersons) will also receive data from EG1 running.

The EG1 program addresses many physics topics of high current interest, including

- Valence quark structure of the nucleon and duality of resonant and deep inelastic polarized structure functions
- Perturbative and higher-twist scaling violations at small to moderate Q^2
- The approach from the DIS region to the real photon point for moments of the spin structure functions, including the GDH sum rule [1] and its extensions [2]
- Nucleon resonance structure (using both inclusive scattering and exclusive meson production)
- Novel single and double spin asymmetries in meson production with deeply virtual photons.

2.9.2 Run Group Status

The EG1 run group took first data for the 3 electron beam experiments (91-023, 93-009 and 93-036) in Fall of 1998 (September through December - see the 2001 Jefferson Lab Annual Report). Data from this run have yielded one published paper [3] and three more papers presently under CLAS collaboration review. They have been widely presented in invited and contributed talks at international conferences, including NSTAR2000, GDH2000, DNP2000, SPIN2000, Baryons2002, and GDH2002, and numerous workshops.

The second run of EG1 completed data taking for the electron beam experiments at beam energies of 1.6–1.7 GeV, 2.3–2.6 GeV, 4.2 GeV and 5.6–5.7 GeV and took first exploratory data with real photons at 5.6 GeV. A total of over 23 billion events were recorded during the time period of September 2000 through April 2001. At all beam energies, electron data were taken for both targets ($^{15}NH_3$ and $^{15}ND_3$) with polarization along as well as opposite to the beam direction, and for two torus field configurations (one yielding inbending electron tracks for optimum coverage at high Q^2 and the other with outbending electron tracks to reach the lowest possible Q^2). Data were also taken on auxiliary targets of Carbon, pure ^{15}N and liquid Helium coolant to precisely determine the fraction of events coming from polarized target nuclei. Detector calibrations for most of the 5.6–5.7 GeV runs (including the real photon test) and the inbending 1.6 GeV electron runs have been completed, with calibrations for the remaining run conditions underway. The massive effort to convert the raw detector signals to data summary files of physics quantities (dubbed "cooking") has been completed for the inbending 5.6 GeV and 1.6 GeV data and is continuing for the other data sets. The higher level analysis code for the 5.6 GeV data has been developed and first results for both photon and electron physics asymmetries have been extracted and will be presented at conferences later this year.

References

[1] S. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966); S.D. Drell and A.C. Hearn, *Phys. Rev. Lett.* **16**, 908 (1966).

[2] X. Ji, C.W. Kao, and J. Osborne, *Nucl. Phys.* **A684**, 363 (2001).

[3] R. De Vita *et al.*, *Phys. Rev. Lett.* **88**, 082001 (2002).

2.10 E91-015

Helicity Structure of Pion Photoproduction
Daniel Sober (spokesperson)

2.10.1 Introduction

Experiment 91-015 was originally envisioned as a first experimental look at the helicity decomposition of the differential cross sections for 1π and 2π photoproduction which contribute to the Gerasimov-Drell-Hearn (GDH) sum rule [1]. With the appearance of the first data from the GDH collaboration at Mainz and Bonn [2], much of the urgency disappeared from this part of the JLab program, and it was decided to defer the measurements until a frozen-spin target is available. The revised experiment was re-approved by PAC-20 as Experiment 01-104.

In the meantime, the recent GDH results from Europe inspired a different type of real-photon measurement. Before the Mainz and Bonn experiments, it was generally expected that the sum rule (-205 μbarns) would be essentially saturated by the contribution of the $\Delta(1232)$ resonance at photon energies below 400 MeV, and that very little would be contributed by photon energies above 1 GeV. The surprising result of the first round of experiments [2] was that the experimental integral from threshold to 1.65 GeV (experiment to 800 MeV, the remainder based on partial-wave-analyses) "overshoots" the sum rule by some 30 μbarns, requiring a substantial contribution of opposite sign from photon energies above the resonance region if the GDH sum rule is to be satisfied.

A Regge-model-based parameterization of deep inelastic electron scattering data by Bianchi and Thomas [3], extrapolated to $Q^2 = 0$, predicts that non-negligible contributions to the GDH sum rule continue to very high energies, and an experiment has been proposed at SLAC [4] to measure the contributions to the sum rule between 5 GeV and 40 GeV.

The region between 3 GeV and 5 GeV is not planned to be covered by either the Bonn or the SLAC measurements, but according to the Bianchi-Thomas parameterization it would be expected to contribute about 6 μbarns (3%) to the sum rule, more than the expected contribution of the 5-40 GeV region. Thus it was considered interesting to see whether the EG1 experimental program in Hall B could make a useful contribution to the subject.

2.10.2 Experiment (The GDH Photon Test Run)

In order to measure contributions to the GDH integral, it is necessary to measure the difference between the helicity-1/2 and helicity-3/2 contributions to the $\gamma + p$ total cross section, or, alternatively, the helicity asymmetry of the total cross section. The CLAS detector system is not well suited to measuring total cross sections because of its incomplete angular acceptance at forward angles, and the acceptance at large angles was even further restricted by the polarized target magnet. It was estimated by Monte Carlo calculations that about 70-85% of the total cross section could be measured in the EG1 configuration. There is no way to correct for the missing acceptance without having a complete dynamical model for every exclusive process. Nonetheless it was decided to make a measurement of the helicity asymmetry in the total detected cross section, and to analyze the data by assuming that this asymmetry also characterizes the total cross section.

Three days of photon beam running were dedicated to this project in January 2001, at a beam energy of 5.67 GeV. The events were recorded when there was a coincidence between the forward calorimeter (spanning angles from about 8 to 45 degrees in the laboratory) and the tagged photon system, with photon energies between 2.5 and 5.34 GeV.

2.10.3 Preliminary Results

The initial analysis used only events with at least one charged-particle track (the analysis of all-neutral events is in progress.) The helicity asymmetry in 6 photon energy bins of width 0.5 GeV was determined to a statistical uncertainty of about +/-0.025 (compared to asymmetries of 0.035 to 0.075 predicted by the Bianchi-Thomas parameterization.)

The experimental data 1 are statistically consistent with an asymmetry of zero, and are on average significantly lower than those predicted by the Bianchi-Thomas model. However, the data are consistent with a transition from zero asymmetry below 3 GeV to values close to the Bianchi-Thomas predictions at 5 GeV. This is a reasonable result in view of the fact that the Bianchi-Thomas model is entirely non-resonant, and is not expected to be valid at energies where the tails of resonances are significant.

References

[1] S. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966); S.D. Drell and A.C. Hearn, *Phys. Rev. Lett.* **16**, 908 (1966).

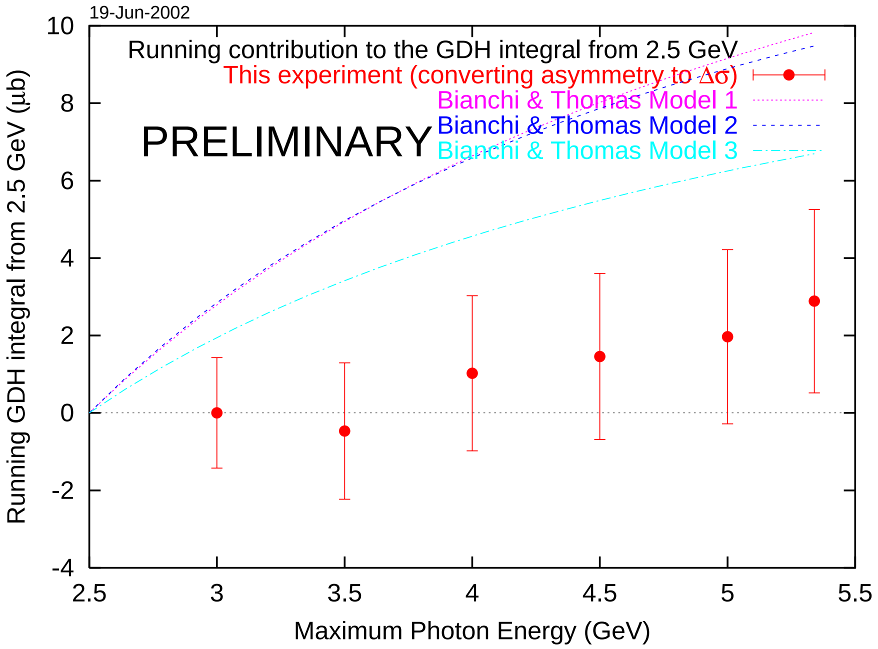


Figure 1: The running GDH integral starting at 2.5 GeV for the 3 variants of the Bianchi-Thomas parameterization and for the preliminary results of this measurement, with the asymmetry converted to a cross section difference by using the Particle Data Group Regge model fit to the $\gamma + p$ total cross section.

[2] J. Ahrens et al., *Phys. Rev. Lett.* **84**, 5950 (2000); J. Ahrens et al., *Phys. Rev. Lett.* **87**, 022003 (2001); G. Zeitler, contribution to MENU 2001 Conference, Washington, DC, (2001).

[3] N. Bianchi and E. Thomas, *Phys. Lett. B* **450**, 439 (1999).

[4] SLAC Proposal E-159, P. Bosted and D. Crabb, spokespersons (2000).

2.11 E91-023

Measurement of Polarized structure Functions
in Inelastic Electron Scattering using CLAS

Volker Burkert, Donald Crabb and Ralph Minehart (Spokespersons)
and the CLAS Collaboration

2.11.1 Introduction

Experiment 91-023 is a major part of the EG1 run group in Hall B. Polarized electrons are scattered from longitudinally polarized NH_3 targets in the CEBAF Large Acceptance Spectrometer (CLAS) to study inclusive polarization observables. The beam-target spin asymmetries are sensitive to interference between small and large amplitudes, and are expected to help in disentangling the contributions of overlapping resonances as well as to measure amplitudes not otherwise accessible. A focal point of the experiment is the determination of the resonant contribution to the integral of $\int g_1^p(x, Q^2)\, dx$ which is constrained by the Gerasimov-Drell-Hearn (GDH) sum rule [1] at $Q^2 = 0$ and by the quark axial charges at high Q^2.

2.11.2 Experiment Status

During the first run of EG1 in the fall of 1998, about 35% of the approved data set for 91-023 was taken with beam energies of 2.5 GeV and 4.2 GeV with a 50%–70% polarized $^{15}NH_3$ target. By taking data with different values of the CLAS torus field (magnitude and polarity) we were able to accumulate data over a large range of Q^2 (from $Q^2 = 0.1$ to $Q^2 = 2.7$) and W (up to a maximum of $W \approx 2.5$ GeV). The analyses of the inclusive data set were the bases for the Ph.D. theses of Renee Fatemi (U.Va.) and Alex Skabelin (MIT), which were completed in the autumn of 2001. First results from these analyses have been presented in several invited and contributed talks (NSTAR2000, GDH2000, DNP2000, SPIN2000). The second EG1 run extended from September, 2000, into April, 2001, during which time we completed the data set on NH_3 with beam energies of 1.6, 2.5, 4.2 and 5.7 GeV.

2.11.3 Results

The analysis of inclusive scattering using the EG1a data was carried out in two ways. One method used count rate asymmetries, where CLAS acceptance and detector efficiencies cancel out. The other extracted the polarization dependent part of the absolute cross section. The first method required a subtraction of the contribution of the nitrogen, helium and windows, which was accomplished through the use of measurements with a carbon target and an empty target. Since these contributions are to a good approximation unpolarized they did not contribute in the second method, which, however, required an accurate knowledge of the detector acceptances and beam flux. The measured inclusive asymmetries and the polarization dependent cross section term can be expressed as follows in terms of two fundamental asymmetries, $A_1(Q^2, W)$ and $A_2(Q^2, W)$ for polarized ep scattering.

$$A_1 + \eta A_2 = \frac{1}{D\ P_e P_t} \frac{N_+ - N_-}{N_+ + N_- - N_{bkg}}$$

where N_+(N_-) is the number of events accumulated in one (W,Q^2) bin with the target polarization anti-parallel (parallel) to the beam helicity, normalized by the charge accumulated in the Faraday cup for each orientation. The term N_{bkg} accounts for the contribution of the unpolarized material(^{15}N, He, and windows) in the beam. Figure 1 shows a typical spectrum of counts vs. W (the invariant hadronic mass for inclusive ep scattering) for NH_3, background, and the difference attributed to ep scattering.

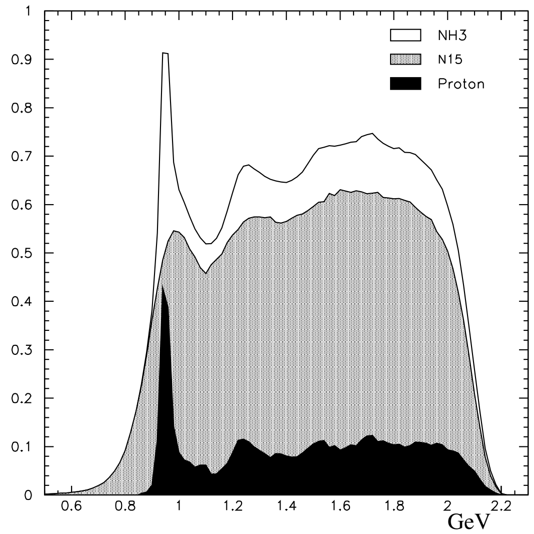


Figure 1: W spectrum for E_e= 4.3 GeV. The upper curve is from NH_3, the middle curve is the background derived from the carbon and empty target measurements, and the lower curve is the difference, attributed to scattering from the free protons in NH_3.

The factor D, in the above equation is the virtual photon depolarization parameter, which includes a dependence on R, the ratio of the longitudinal and transverse ep cross sections. Parametrizations of the world data were used to estimate R to extract the combination $A_1 + \eta A_2$. Typical results, corrected for radiative effects, are shown in Figure 2. The estimated systematic error is indicated by the shaded region. Also shown on the graph are some model expectations.

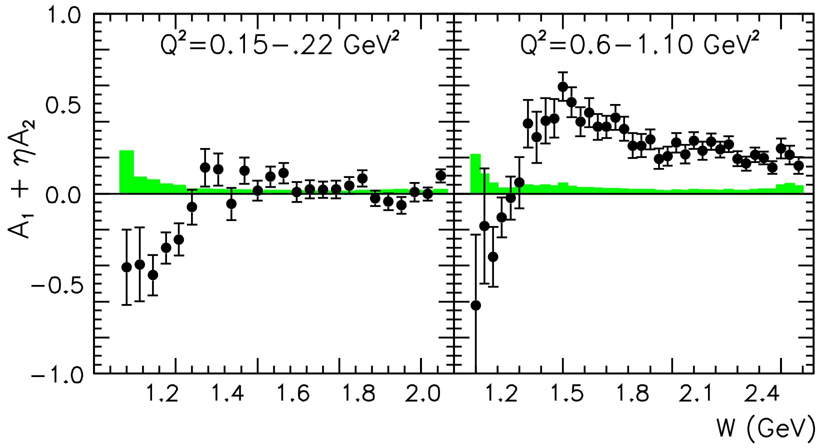


Figure 2: $A_1 + \eta A_2$ vs. W(GeV) for the proton in two Q^2 bins, the one with lower Q^2 obtained with a beam energy of 2.6 GeV and the other at 4.3 GeV. The error bars denote statistical errors, and the histogram near the axis indicates the magnitude of the systematic errors.

Using a parametrization of world data on the scattering of polarized electrons from polarized protons to estimate A_2, which makes a small contribution to the asymmetry in Figure 2, a value for A_1 can be obtained. This can be used along with the world data on the unpolarized structure function $F_1(x, Q^2)$ to extract the structure function $g_1^p(x, Q^2)$.

The analysis based on cross section differences allows the extraction of $g_1^p(x, Q^2)$, without requiring any knowledge of $F_1(x, Q^2)$ or any correction for the ^{15}N contribution. Because it depends on the absolute acceptance of the detector, a smaller subset of the data in a region of uniform acceptance and efficiency was analyzed. The two analysis methods are statistically in good agreement. A paper on these results and intended for publication in Phys. Rev. Lett. is under review by the Structure of the Nucleon working group

With the much larger data sample available from the second EG1 run, the statistical errors will be reduced substantially, and the measured region in W will be extended up to 3.0 GeV. With this larger data set it should be possible to use a Rosenbluth technique to determine A_1 and A_2, thereby eliminating the role of model uncertainties in the extraction of $g_1^p(x, Q^2)$.

References

[1] S. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966); S.D. Drell and A.C. Hearn, *Phys. Rev. Lett.* **16**, 908 (1966).

2.12 E93-009

The Polarized Structure Function G_1^n and the Q^2 Dependence
of the Gerasimov-Drell-Hearn Sum Rule for the Neutron

Sebastian Kuhn, Gail Dodge and Mauro Taiuti
(Spokespersons) and the CLAS Collaboration

2.12.1 Introduction

Experiment 93-009 is part of the EG1 program of spin structure measurements in Hall B (see overview). The goal of this experiment is to study asymmetries and spin structure functions of the deuteron by scattering polarized electrons from a longitudinally polarized ND_3 target. In connection with the data taken on the proton (e91-023), we can extract information on neutron resonance amplitudes and spin structure functions from the deuteron data. These data are important to unravel the spin-isospin structure of resonances and non-resonant background, and to study their dependence on momentum transfer. Of particular interest is the Q^2-dependence of the first moments of the structure functions $g_1^d(x, Q^2)$ and $g_1^{p-n}(x, Q^2)$. The former is directly related to the "spin puzzle" (the small contribution of quark spins to the nucleon spin) in the perturbative regime and it is constrained by the Gerasimov-Drell-Hearn (GDH) sum rule [1] at the photon point. The latter is known to fulfill the Bjorken sum rule [2] at high Q^2, while the convergence of the corresponding GDH sum rule has been thrown open to question. In addition to these inclusive quantities, we also measure double polarization asymmetries for single π^- production in the resonance region, which will increase our understanding of the spin structure of nucleon resonances.

2.12.2 Experiment Status

During the first run of EG1 in the fall of 1998, about 10% of the approved data set for 93-009 was taken with a beam energy of 2.5 GeV and a $\approx$ 20% polarized $^{15}ND_3$ target (the polarization was limited by insufficient microwave power). We took data over a range of $Q^2 = 0.3 \ldots 1.2$ GeV^2 and for W up to 2 GeV. The analysis of the inclusive data (the Ph.D. thesis of Junho Yun) is complete. A publication of the results is presently under internal CLAS collaboration review. The data on π^- production from the deuteron, which are primarily sensitive to the polarized neutrons in the target, have also been analyzed (Ph.D. thesis of Mehmet Bektasoglu). Results from this analysis have been presented in several talks, and a publication is being prepared.

The second EG1 run (from September 2000 through April 2001) completed the data set on ND_3 with beam energies of 1.6, 2.5, 4.2 and 5.7 GeV. The full data set now in hand covers a much larger kinematic region ($Q^2 = 0.05 \ldots 5$ GeV^2 and W up to 3.2 GeV), with an order of magnitude better statistics. In addition, the polarized target was considerably improved, yielding an average polarization of 30%. These data are presently under analysis. Very preliminary results for the uncorrected parallel asymmetry $A_{||}$ are shown in Fig. 1. We expect to completely analyze at least the 5.6 GeV (and possibly the 1.6 GeV) data until the end of this year and plan to show first results at conferences in Summer and Fall of 2002.

References

[1] S. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966); S.D. Drell and A.C. Hearn, *Phys. Rev. Lett.* **16**, 908 (1966).

[2] J.D. Bjorken, Phys. Rev. **148**, 1467 (1966).

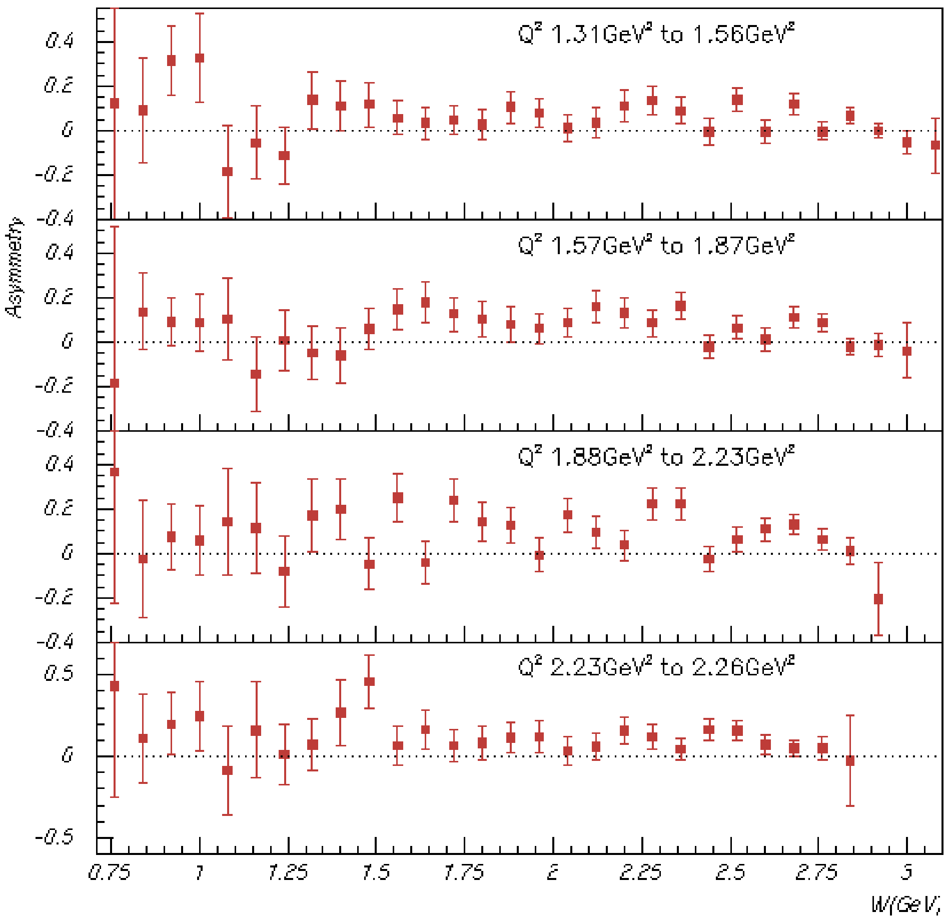


Figure 1: Preliminary results from the second run of EG1 at 5.6 GeV on the double spin asymmetry $A_{||} = (\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow})/(\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow})$ on deuterium. The data have been corrected for background from unpolarized target material (dilution) and beam and target polarization, but not for radiative and other systematic effects. The data shown represent about 1/2 of the statistics taken with 5.6 GeV beam and inbending torus polarity.

2.13 E93-006 (E99-108)

TWO PION DECAY OF ELECTROPRODUCED
LIGHT QUARK BARYON RESONANCES

M. Ripani, V. Burkert and the CLAS collaboration

2.13.1 Introduction

The excitation of baryon resonances is genuinely a non-perturbative phenomenon. Measurements of the transition amplitudes from the nucleon to its excited states are sensitive to the spatial and spin structure of the transition. Many of the nucleon excited states in the mass region around and above 1.7 GeV tend to decouple from the single-pion and eta channels, while πN scattering experiments have shown that many of them decay predominantly in multipion channels, such as $\Delta\pi$ or $N\rho$, leading to $N\pi\pi$ final states[1]. A measurement of the transition form factors of these states is very important for testing symmetry properties of the quark model. Moreover, SU(6) symmetric quark models[2, 3] predict more states than have been found in experiments. QCD mixing effects could decouple many of these states from the pion-nucleon channel[2], with consequent lack of evidence in elastic πN scattering, while strongly coupling them to two-pion channels such as $\Delta\pi$[2, 4, 5, 6]. However, other models such as the Quark Cluster Model[7] predict fewer states than the symmetric model, more in accordance with experimental observation. Search for the states still missing from the experimental evidence is therefore crucial in understanding the basic degrees of freedom in baryon structure. The present experiment is devoted to a precise measurement of the cross sections for reaction $ep \rightarrow e'p\pi^+\pi^-$, to extract information on poorly known baryon states and to investigate the existence of new, unobserved states.

2.13.2 Experiment Status

A first data taking period on hydrogen has been successfully completed during 2000 and the detector reconstruction required for the physics analysis has been performed. Physics analysis has been performed for a subset of the data taken at beam energies of 2.567 and 4.247 GeV, with the goal of extracting cross sections for a few momentum transfers and in a broad range of CMS energy W, where we expect to see significant contributions from excited baryons production. A higher momentum transfer extension of this experiment (approved by the PAC as E-99-108) is included in the so-called "E1-6" running period, which is characterized by the highest available beam energy, 5.76 GeV. This experiment has successfully taken data in the winter of 2001-2002. Complete data reconstruction is expected to be finished within the fall of 2002. A second running period of E-93-006 is planned during

2003, with the goal of measuring the higher mass portion of the baryon spectrum (W >1.8 GeV) at low momentum transfer (Q^2 <0.5 GeV^2/c^2).

2.13.3 Results - or Expected Results

Among several detailed results obtained up to now, in Figure 1 (left panel) we report the total cross sections measured with CLAS at three different Q^2 intervals and for W in the resonance region. To perform a first physical analysis of the data, we started from a phenomenological calculation[9], which provides a reasonable description of the two important intermediate isobar production mechanisms, $\gamma p \rightarrow \Delta\pi \rightarrow p\pi^+\pi^-$ and $\gamma p \rightarrow \rho^0 p \rightarrow p\pi^+\pi^-$; a third mechanism, the direct $\gamma p \rightarrow p\pi^+\pi^-$, often called "phase space", was included as a pure phase space amplitude and fitted from the data. In our "reference" calculation, we described resonance excitation and decay using a Single Quark Transition Model fit[10] for the electromagnetic part and partial decay widths from a previous analysis of hadronic data[11], renormalised in order for the total width to be consistent with PDG. The comparison of our calculation with the data is also reported in the left panel of Figure 1. We see that there is a significant discrepancy in the region around $W = 1.7$ GeV, where the bump observed in the data is not reproduced. The right panel of Figure 1 shows the pion-pion mass distribution measured at a particular value of W at the bump. It seems that not only the overall strength is understimated, but the particular ρ meson decay channel is manifesting through a peak in the calculation that is not seen in the data. Further analysis has shown that such anomalous behavior may be ascribed to the particular $P_{13}(1720)$ PDG state. In the assumption that its hadronic couplings are correct, our results may be indicative of possible missing state contributions. Otherwise, a fit to the data without introducing new states is likely to require a significant modification of the hadronic properties of this resonances, with respect to the PDG. The physics analysis of this data is about to be concluded and is expected to be published soon.

References

[1] Particle Data Group, 1998.

[2] R. Koniuk and N. Isgur, Phys. Rev. Lett. **44**, 845 (1980); Phys. Rev. **D21**, 1868(1980).

[3] M.M. Giannini, Rep. Prog. Phys., **54**, 453 (1990).

[4] R. Koniuk, Nucl. Phys. , **B195**, 452 (1982).

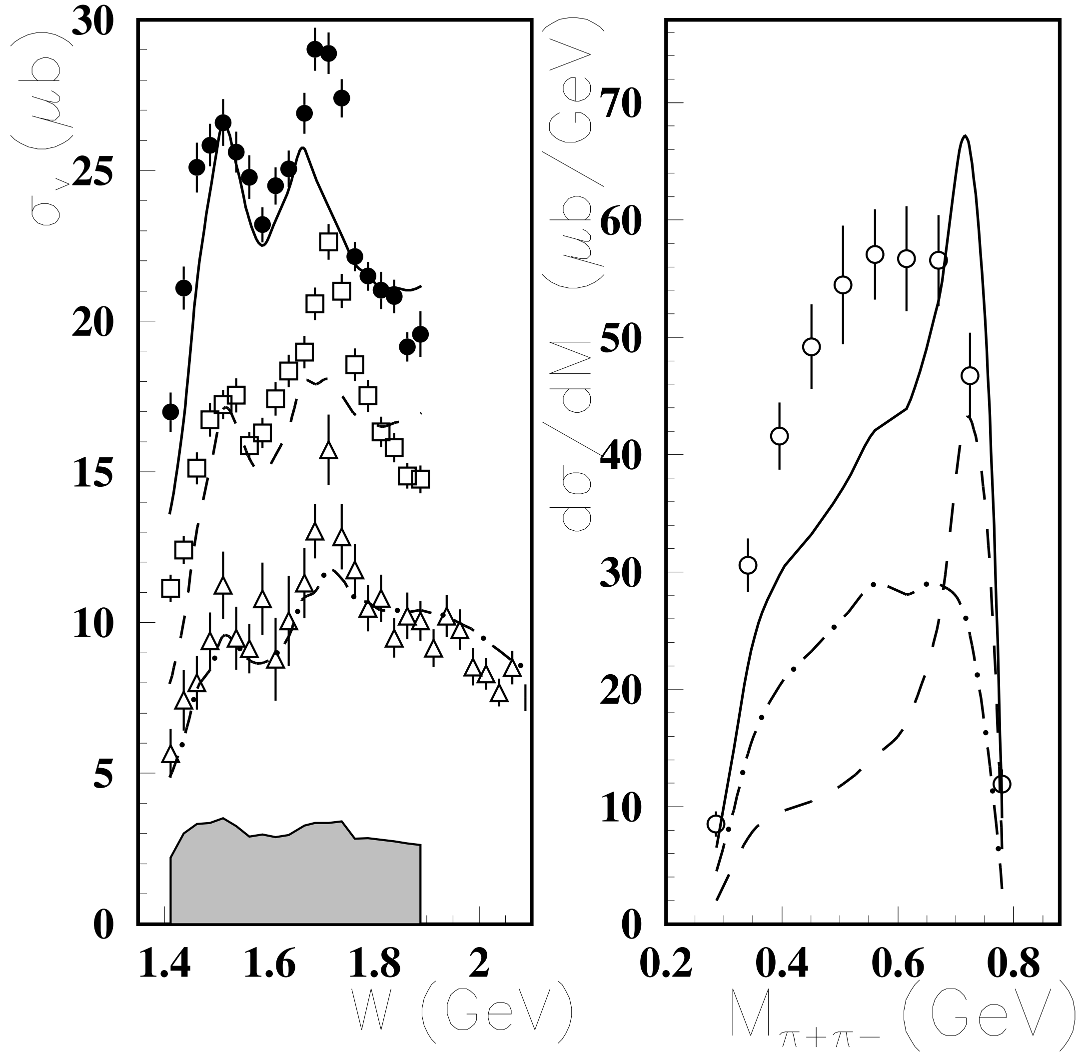


Figure 1: Left: total cross section for $\gamma_v p \to p\pi^+\pi^-$ as a function of W. Data from CLAS are shown at Q^2=0.5-0.8 (GeV/c)^2 (full points), Q^2=0.8-1.1 (GeV/c)^2 (open squares), and Q^2=1.1-1.5 (GeV/c)^2 (open triangles). Error bars are statistical only, while the bottom band shows the sytematic error for the lowest Q^2 bin. The curves represent our reference calculation. Right: $\frac{d\sigma_v}{dM_{\pi^+\pi^-}}$ from CLAS at Q^2=0.8-1.1 (GeV/c)^2 and W=1.7-1.725 GeV (statistical error bars only). The curves represent our reference calculation. The dashed line includes all resonances, the dot-dashed line includes only the non-resonant part, and the solid line is the full calculation.

[5] S. Capstick, W. Roberts, Phys. Rev. **D49**, 4570 (1994).

[6] F. Stancu and P Stassart, Phys. Rev. **D47**, 2140 (1993).

[7] K.F. Liu and C.W. Wong, Phys. Rev. **D28**, 170 (1983).

[8] V. Eckart et al. , Nucl. Phys. **B55**, 45 (1973); P. Joos et al., Phys. Lett., **B52**, 481 (1974); K Wacker et al., Nucl. Phys., **B144**, 269 (1978).

[9] M. Ripani et al., Phys. of At. Nucl., **62**, 1437 (1999); M. Ripani et al., Nucl. Phys. **A 672**, 220 (2000); M. Ripani et al., Phys. of At. Nucl., **63**, 76 (2000); M. Ripani et al., Phys. of At. Nucl., **63**, 1943 (2000).

[10] V. D. Burkert, Czech. Journ. of Phys., **46**, 627 (1996).

[11] D.M.Manley, E.M.Salesky, Phys. Rev. **D45**, 4002 (1992).

3 Hall C

3.1 Hall C Overview

Eighteen experiments have been executed in Hall C, covering a broad spectrum of topics in nuclear physics, since the fall of 1995. Forty nine graduate students have conducted their Ph.D. research using the Hall C facility. Presently, twenty nine of these students have obtained their Ph.D. degree. The research program has produced twenty refereed experimental publications, not counting 3 instrumentation papers.

The initial complement of equipment in Hall C includes two general purpose magnetic spectrometers: the High Momentum Spectrometer (HMS), which has a large solid angle, moderate resolution (δp/p=10^{-3}), and a maximum momentum of 7.3 GeV/c; and the Short Orbit Spectrometer (SOS), which has a large momentum acceptance and a very short (7.4 meter) optical path length to facilitate the detection of particles having short lifetimes, such as low momentum πs and Ks. This base set of equipment has been used to conduct experiments measuring: The Energy Dependence of Nucleon Propagation in Nuclei in (e,e′p), Photodisintegration of the Deuteron, Inclusive Scattering from Nuclei at x > 1 and High Q^2, Electroproduction of Kaons and Light Hypernuclei, L/T Separation in p(e,e′K^+), Δ (1232) Form Factor at High Momentum Transfer, Charged Pion Form Factor, Pion Electroproduction in ^{2}D, ^{3}He, and ^{4}He, Color Transparency, Measurement of R = σ_L/σ_T in the Resonance Region, and Correlated Spectral Function & (e,e′p) Reaction Mechanism.

By now, the understanding of the base equipment of Hall C is nearly complete. The optics and acceptances of the magnetic spectrometers are well understood. The ARC energy measurement system agrees, within the total error of ±0.06%, with the independent beam energy measurements of Hall A. Precision L/T separations have been proven with correlated systematic uncertainties between 1.1 and 1.5%.

New Hall C base equipment under construction in 2001 consists of a “diffuse” aerogel Cerenkov counter for the HMS and a novel, highly uniform, fast raster system to scan the JLab electron beam over the cryogenic targets.

Hall C also supports the installation of specialized detectors designed to investigate specific problems. Up to now, four of these have been completed. The T_{20} experiment (E94-018) was the first major installation experiment in Hall C, and separated the elastic form factors of the deuteron to high momentum transfer. The HNSS experiment (E89-009) was an investigation of the feasibility of performing hypernuclear physics experiments in which a proton in the nucleus is replaced by its strange counterpart, the Λ hyperon. After the successful completion of the HNSS experiment, the next phase of this program has been approved. It consists of the Enge split-pole spectrometer used in the original hypernuclear experiment plus a new High resolution Kaon Spectrometer system (HKS) constructed and funded by the Japanese collaborators. The system will have $\sim$350 keV resolution and a 50 fold increase in data collection rate with respect to the first generation experiment.

The year 2001 saw the completion of two complementary measurements of the electric form factor of the neutron; one using a neutron detector in conjunction with a polarized target and low-current polarized beam (E93-026), and the other employing a neutron polarimeter together with an unpolarized deuterium target and high current polarized beam (E93-038). In addition, during this year large steps were made for the preparation for the next major installation experiment in Hall C, the G0 experiment (E00-006). The aim of the latter experiment is precision measurements of parity violation in the scattering of polarized electrons from protons to investigate their weak neutral current structure and possible contributions from strange quarks. The superconducting magnet at the heart of the G0 experiment is funded by the NSF.

Beyond the mentioned G0 and HKS experiments, two major installation efforts in preparation are an experiment measuring the ratio of the proton charge to magnetic form factor to the highest momentum transfer achievable at a 6-GeV JLab, and an experiment to conduct a search for physics beyond the standard electroweak model via a precision measurement of the weak charge of the proton (Qweak).

3.2 E97-006

Correlated spectral function and (e,e′p) reaction mechanism

D. Rohe, I. Sick, Spokespersons
and collaborators from
University of Basel, Hampton University, Jefferson Lab (Hall C), University of Virginia, Yerevan Physics Institute, Istituto Nazionale di Fisica Nucleare Roma, University of Tűbingen, Washington University

3.2.1 Introduction

The purpose of our JLAB experiment is to shed light on the quantitative effect of short range (SRC) and tensor correlations as well as to elucidate contributions to the reaction mechanism, such as multi-step processes and Δ-excitation, which complicate the interpretation of the (e,e′p)–data. SRC are due to the strong interaction between the two colliding nucleons, which results in scattering to high initial momentum P_m and high missing energy $E_m \simeq {P_m}^2/(2M_p)$. Here the maximum of the spectral function $S(E_m,P_m)$ is expected. The reaction mechanism can be studied by comparing the experimentally determined spectral function (SF) in parallel and perpendicular kinematics. Because of the transverse character of the Δ–resonance, its influence in perpendicular kinematics is expected to be much larger than in parallel kinematics. Previous experiments and recent analyses [1][2] do confirm the importance of multi-step processes for perpendicular kinematics. As rescattering of the proton inside the nucleus should depend on the size of the nucleus, our experiment uses different nuclei as targets.

3.2.2 Status of the experiment

The experiment was performed using the 3.2 GeV electron beam at JLAB with electron currents between 10 and 60 μA. C, Al, Fe and Au targets were used. The scattered electrons and protons were detected using the magnetic spectrometers HMS and SOS. To study the reaction mechanism, data were taken in three parallel and two perpendicular kinematics. In perpendicular (parallel) kinematics the range of P_m covered is 0.2 to 0.8 (0.2 to 0.7) GeV/c. Missing energies of up to 600 MeV were achieved, but the higher E–region ($\geq$ 250 MeV) is entirely dominated by the Δ–resonance. In addition, H_2–data for calibration purposes and data in quasi elastic kinematics for C were taken as well. The cross section for p(e,e’p) agrees well with previous experiments.

Assuming Plane Wave Impulse Approximation (PWIA) the S(E_m,P_m) can be extracted from the (e,e'p) cross section, which factorizes into an e–p off shell cross section [3] and the SF. In this picture the missing momentum is then equal to the initial momentum. To account for absorption of the protons in the nucleus, the nuclear transparency is taken into account. For C, Al, Fe, Au the values 0.6, 0.5, 0.4, 0.3 are chosen, which are $\approx$ 10 % higher than published recently [4], but the values are in good agreement with previous determinations. The data are binned in E_m and P_m. Depending on the statistics, the bin sizes vary between 10 and 50 MeV in E_m. The bin size for P_m is always 40 MeV/c. To evaluate the cross section, the phase space is taken from the Monte Carlo simulation. The background subtraction is performed using the coincidence time spectrum. The SF has to be corrected for radiative processes, which shifts events from one (E_m,P_m)–bin to another. The correction due to radiative processes is calculated from the ratio of the yield obtained with the Monte–Carlo code without and with radiative processes. For this a model of the SF is needed. Therefore the SF resulting from the first iteration is fed into the Monte Carlo simulation again, and after a few iterations good agreement between data and Monte Carlo spectra is obtained.

3.2.3 Preliminary Results

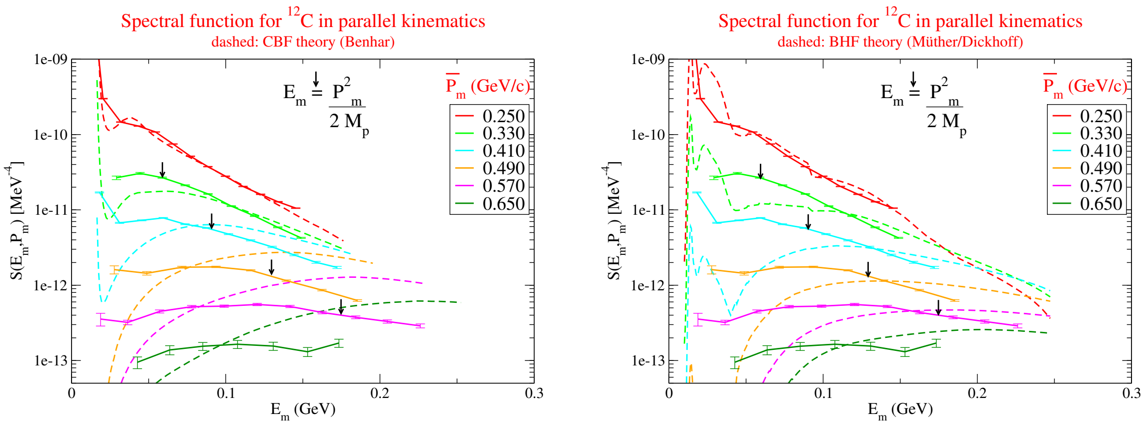


Figure 1: Distorted spectral function in parallel kinematics (solid) compared to the theory (dashed) of Benhar [5] (left) and to the HBF theory of [6][7] (right) for a selected choice of missing momenta (see legend). The arrows indicate the position at which one would expect the maximum of the SF according to the simple picture described in the text.

The SF extracted from the carbon data is shown in Fig. 1 and compared to theories based on Correlated Basis Function (CBF) and Local Density Approximation [5] (left figure) as well as Brűckner–Hartree–Fock [6][7], which also takes long range correlations into account (right figure). In the former the nuclear matter correlated SF is combined with a Independent

Particle Shell Model SF to cover the quasihole part. The Δ–resonance in the experimental SF is removed by a cut in the (k,θ_{kq})–plane, where θ_{kq} is the angle between the inital momentum k and the momentum transfer q. This is possible only in parallel kinematics; the transversal character of the Δ–excitation leads to strength mainly at large θ_{kq} [8]. The arrows indicate the position, where the maximum of the SF is expected. As can be seen in Fig. 1 the maximum of the experimental SF is shifted to lower E as compared to both calculations. The region of low $E_m (\leq 50$ MeV) and P_m above the Fermi momentum is underestimated by both theories, whereas at $P_m = 250$ MeV/c the experimental result is well described by both theories. It should be mentioned that the experimental SF is not yet corrected for rescattering processes; calculations are underway [9].

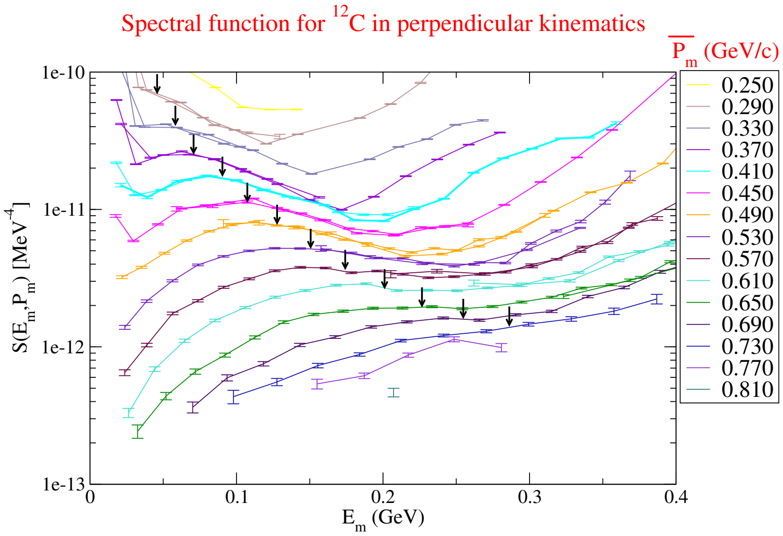


Figure 2: Spectral function taken in perpendicular kinematics at carbon.

In Fig. 2 the SF is shown for the perpendicular kinematics. It turns out to be quite different from the one obtained in parallel kinematics. The perpendicular SF is a factor of 3 higher than theory in the entire range covered by experiment. This is an indication for the strong influence of multistep processes and the Δ–resonance. In addition the SF seems to have its maximum at the expected position (see arrows in Fig. 2). One has to be careful to take this as a signature of SRC because of the complications of the reaction mechanism [10].

In Fig. 3 the SF extracted from the data taken for C, Al, Fe and Au in parallel kinematics are shown and normalized to Z = 1. As expected the SF increases for heavier nuclei. In the correlated region ($E_m \leq 100$ MeV) the SF for Al, Fe, Au are a factor of ≈ 1.05, 1.2, 2 higher than for C, which means a linear increase with the mass number A. From the simple argument that rescattering processes should increase with the nuclear radius ($\propto A^{1/3}$) one would expect a larger rise of 1.3, 1.7 and 2.5 for Al, Fe and Au respectively.

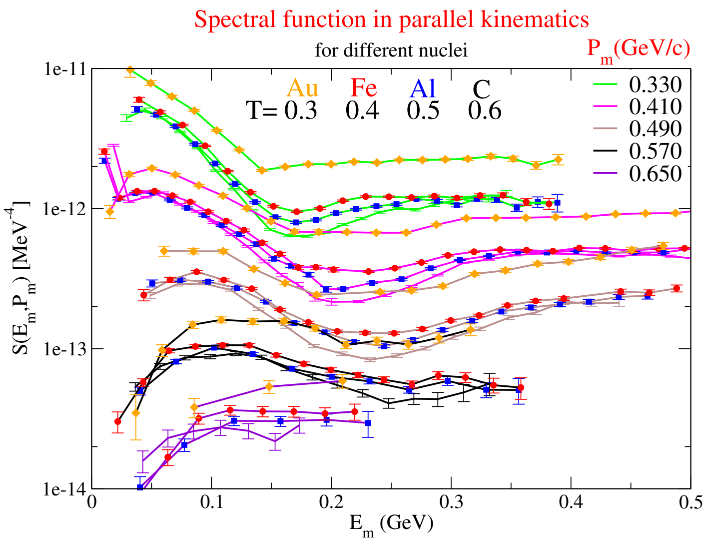


Figure 3: The spectral function for C (solid) is compared to the one for Al (blue squares), Fe (red circles) and Au (orange diamonds) in parallel kinematics.

References

[1] C. Marchand *et al.*, Phys. Rev. Lett. **60** , (1988) 1703
J. M. LeGoff et al., Phys. Rev. **C50** , (1994) 2278

[2] M. van Batenburg, NIKHEF thesis

[3] T. de Forest, Nucl. Phys. **A 392**, 232(1983)

[4] K. Garrow *et al.*, hep-ex/0109027

[5] O. Benhar *et al.*, Nucl. Phys. **A579**, 493(1994)

[6] H. Műther, G. Knehr A. Polls *et al.*, Phys.Rev. **C52** (1995) 2955

[7] Kh. Gad, H.Műther, nucl-th/0205025

[8] J. Ryckebusch *et al.*, Phys. Rev. **C49** , (1994) 2704

[9] C. Barbieri, private communication

[10] J. Ryckebusch, private communication

4 Theory

4.1 Overview

A. ORGANIZATION OF THIS REPORT

This report summarizes the work done by the Jefferson Laboratory (JLab) Theory Group from January 1, 2001 to December 31, 2001. This Overview Section includes a list of staff supported by the Theory Group, and a Summary of some of the major research results. Section II presents a more complete summary of the research work. Publications and talks are listed in Section III, and an Appendix lists visitors and seminars for the period covered by the report.

In this report we include only work done by the Senior Staff, including the Distinguished Visiting Fellow, and Post-doctoral fellows associated with the group during the past year (2001). The JLab Theory Group interacts with many faculty, post-doctoral associates, and students. However, the work done by these associates and visitors is not included in the present report.

B. MEMBERS OF THE THEORY GROUP

The JLab Theory Group currently consists of 9 Senior Staff, 3 post-doctoral associates, and 3 active Associate Senior Staff (i.e., those who spend several days per month with the Theory Group). In the past year (2001), the Theory Group senior staff also included the JLab Distinguished Visiting Fellow. The Senior Staff are listed in Table I, the JLab Distinguished Visiting Fellow in Table II, post-doctoral associates in Table III, and the active Associate Senior Staff in Table IV.

The JLab Theory Group environment is also enhanced by several post-docs and students supported by neighboring institutions. In 2001, these included post-docs Gary Prezeau (Hampton), Cetin Savkli (W&M), Dirk Lehmann (Germany and Hampton), and Carlos Schat (Argentina and JLab).

Table I
JLab Senior Staff

	half-time affiliation (if any)
Ian Balitsky	Old Dominion University
Robert Edwards	
Josè Goity	Hampton University
Franz Gross	College of William and Mary
Anatoly Radyushkin	Old Dominion University
David Richards	
Winston Roberts	Old Dominion University
Rocco Schiavilla	Old Dominion University
Wally Van Orden	Old Dominion University

Table II
JLab Distinguished Visiting Fellow

	period	home institution
Yuri Simonov	10/01–04/02	ITEP, Moscow

C. RESEARCH HIGHLIGHTS

In this section highlights of the research undertaken by the JLab Theory Group are described in less technical language. The discussion is organized into four overlapping topics: *quark structure of hadrons, few-nucleon systems, deep inelastic scattering and duality, and solving QCD*.

1. QUARK STRUCTURE OF HADRONS

The word *hadrons* refers to neutrons and protons (referred to collectively as nucleons), their excited states, and the mesons that interact with them and bind them together into

Table III
JLab Post-docs

	period of employment
Deirdre Black	10/01–present
Sabine Jeschonnek	10/99–09/2001
Wally Melnitchouk	08/01–present
Igor Musatov	10/01–present

Table IV

JLab Associate Senior Staff	(active)
	home institution
Carl Carlson	College of William and Mary
Chris Carone	College of William and Mary
Marc Sher	College of William and Mary

nuclei. These are the nuclear building blocks we observe in nature, yet they are not elementary particles. Nucleons are composed of three quarks surrounded by a sea of gluons and quark-antiquark pairs. Mesons are composed of a sea of quark-antiquark pairs and gluons. The force that binds the quarks and gluons into hadrons *confines* them, so that it is impossible to study quarks and gluons as free particles. Hence, an understanding of the structure of nuclear matter begins with the study of the structure of hadrons, the simplest pieces of nuclear matter we can observe in the laboratory.

At JLab these theoretical studies are carried out using a variety of tools. Models that treat the quarks relativistically are being developed (Gross and Savkli). In systems where one of the quarks is very heavy, so that it moves very slowy, an approximate theory known as Heavy Quark Effective Theory (HQEF) has been developed that works very well (Roberts). For light quark systems, one may sometimes exploit the fact that the bare quark masses are very small. This gives rise to an approximate symmetry known as chiral symmetry, and leads to the development of Chiral Perturbation Theory, also being studied at JLab (Goity and Roberts). At high energy the charge structure of hadrons can be calculated using QCD sum rules (Radyushkin), and the structure of the quark-antiquark sea inferred from arguments based on chiral symmetry (Melnitchouk). Finally, in a few cases exact results for the masses of hadrons can be obtained by solving QCD on the lattice (Richards).

2. FEW-NUCLEON SYSTEMS AND THE NN FORCE

The simplest nuclei consisting of a "few" nucleons (in practice 2 to 10 nucleons) are easiest to study both theoretically and experimentally. The force between two nucleons can be inferred from the structure of the deuteron, the only bound state of two nucleons, and the scattering of two free nucleons. Then, using the forces inferred from two-nucleon studies, the properties of three-, four-, . . ., ten-nucleon systems can be predicted. Comparison of these results with experiment confirms the correctness of the *NN* force, and tells us whether or not three-nucleon (*NNN*) or many-nucleon forces are important. The goal of this work is to fully determine the nuclear forces and currents, explain the structure and interactions of few nucleon systems, and then to explain these forces and currents in terms of the underlying quark structure of matter and QCD.

It has recently been shown by the ANL-UIUC-LANL collaboration that it is possible to reproduce quite well the observed low-lying energy spectra of nuclei with mass number $A \leq 10$ by including NN and NNN forces. Using the resulting wave functions and electroweak current operators constructed consistently with these forces, it has also been shown that a variety of nuclear properties ($A \leq 7$), such as elastic and inelastic electromagnetic form factors, radiative widths, β-decay and electron-capture rates, are well predicted by theory (Schiavilla). In collaboration with the Pisa group and members of the ANL-UIUC-LANL team, studies of low-energy radiative and weak capture reactions involving systems with $A \leq 7$ have also been carried out based on the same realistic forces and currents (Schiavilla). Some of these processes are of considerable interest in astrophysics in relation to energy and neutrino production in main-sequence stars and primordial nucleosynthesis.

Relativistic models based on the exchange of mesons between nucleons have also been developed and have been shown to be successful in explaining deuteron form factors (Gross, Schiavilla, Van Orden) and in describing electrodisintegration of few body nuclei (Gross, Jeschonneck, Schiavilla, and Van Orden). Effective field theories (EFT) provide a systematic expansion of the interaction valid at low energies (Goity, Roberts) and work is in progress to develop a relativistic EFT for the NN interaction (Goity, Prezeau, and Lehmann).

3. DEEP INELASTIC SCATTERING AND DUALITY

When electrons are used to probe the structure of hadrons and few-body nuclei in their normal ground state, the energy transferred to the hadronic or nuclear target is kept to a minimum, leaving the target largely undisturbed. Alternatively, the structure of hadrons and nuclei can be studied by explicitly exciting the underlying quark degrees of freedom. This is most effectively done when both the momentum and energy transferred by the electron are large. Under these conditions, known as deep inelastic scattering (DIS), the quarks are "torn" from the initial hadronic/nuclear target, and because they cannot exist in isolation, reform into different hadrons as they leave the target. The DIS Stanford Linear Accelerator (SLAC) experiments of Friedman, Kendall and Taylor, who received the Nobel Prize in 1990, were among the first to tell us of the existence of quarks, and this method continues to be a major source of information about quark structure.

A new theoretical tool, the so-called generalized parton distributions (GPDs), has been recently developed at JLab (Radyushkin) and elsewhere. The GPDs provide an effective tool for the study of quark distributions through deeply virtual Compton scattering and deep exclusive scattering (Balitsky, Radyushkin). This advance is one of the major new campaigns driving the JLab 12 GeV Upgrade proposal. The proton sea can also be studied in DIS (Melnitchouk).

At moderate energies excited states of hadrons appear as resonance "bumps" in DIS, and it has long been observed that the average of the cross section over these bumps reproduces the smooth result one obtains from DIS at very high energies. This phenomenon is known as "duality". New work at JLab is providing a better understanding of how this comes about (Jeschonnek, Melnitchouk, and Van Orden; and Batiz and Gross).

4. EXACT SOLUTIONS OF QCD

QCD can be solved to high precision at very high energies, where the forces between quarks and gluons become vanishingly small (a phenomenon known as "asymptotic freedom"). However, at the moderate energies of quarks in a cool hadronic medium the QCD forces are very strong, the theory is very difficult to solve. Only one way is known to obtain exact solutions of QCD in this region. It is a numerical method known as "lattice gauge theory". Since QCD is believed to be the theoretical foundation of nuclear physics, using lattice gauge theory to obtain exact numerical solutions remains one of the highest priorities of the Theory Group. Only a few results can be obtained on the lattice (masses of low lying states, couplings and decay amplitudes, and some moments of the DIS structure functions), but these provide guidance for the construction of the accurate models and effective theories that will provide a broader understanding.

An exciting development in 2001 was the award of three years of support to Jefferson Laboratory, totaling around $2M, as part of a US effort to create a *National Computational Infrastructure for Lattice QCD*, under the Department of Energy's Scientific Discovery through Advanced Computing (SciDAC) initiative. Historically, the emphasis in lattice QCD research has been on particle physics applications, and in particular on the calculation of the weak-interaction matrix elements and investigations of the finite-temperature transition. The crucial rôle that lattice QCD plays in hadronic physics is now being recognized not only within the nuclear physics community, but also by the lattice community. This recognition has enabled JLab, together with colleagues at MIT, to attain an equal status with Fermilab and Brookhaven as national centers in the SciDAC program.

The goals of this project are to create a unified programming environment for the US lattice community on diverse, multi-architecture machines. The five-year plan is to site three such machines, of ten teraflops/second scale, i.e. capable of 10^{13} floating-point operators per second, at each of the national centers, including JLab. The physics of JLab, and in particular the calculation of the spectrum of hadrons and the calculation of their quark and gluon structure, is accorded similar prominence.

The JLab Theory Group has been pivotal in this national effort. Robert Edwards is a leading member of the National Software subcommittee, coordinated the submission of the successful proposal in March 2001, and has been instrumental in the design and implementation of the QCD API (*Application Program Interface*). Since joining the Theory Group full-time in December, David Richards involvement has increased through his rôle in coordinating the porting of hadronic physics code, and development of new codes, to the emerging QCD-API, and in the maintenance of the national lattice QCD web site hosted at JLab (www.lqcd.org). Chip Watson, of the High-Performance Computing Group, is a PI on the national SciDAC Executive Committee.

While the emphasis of the current grant is on software development, a substantial investment in hardware is being made, with a 256-node cluster, with fast interconnection, expected to be installed by the end of 2002. This cluster will be not only a test-bed for a future terascale facility, but also a substantial resource for lattice hadronic physics; the first projects will include the calculation of the proton and neutron electric and magnetic form factors, the moments of the polarized and unpolarized structure functions, and the spectrum of excited baryons and hybrid mesons.

The LQCD program is very promising, but can only be used to compute a limited number of observables in the simplest cases, and the numerical solutions it yields often do not provide the physical insight needed to generalize the results to more complicated systems. For these reasons it is of critical importance to the JLab program to find alternative ways to solve QCD. Yuri Simonov, last year JLab Distinguished Visiting Fellow, and his collaborators have developed a very promising method for obtaining approximate solutions to QCD. This method was studied and further developed at JLab, resulting in several new collaborations between Simonov and JLab theorists.

The technique exploits the properties of the QCD vacuum that have been extracted from lattice calculations, and allows the effective hamiltonian for two and three quark systems to be derived directly from QCD. In the process, that part of the confining interaction that is independent of the distance (the constant term), and the spin dependence of the confining interaction, both of which are usually treated in a purely phenomenological manner, are completely given in terms of the string tension (which determines the strength of the linear part of the confining force). This allows one to understand quark and gluon confinement and the spectrum of meson and baryons largely in terms of a string tension fixed by lattice calculations. (The quark masses and the quark-gluon coupling also play a role.) The results are very promising; as good as any model calculations, but with parameters obtained entirely from QCD. The method is currently being used to study the baryon spectrum, and meson and baryon decays.

An alternative method for the exact numerical solutions of field theories is also being developed at JLab (Savkli and Gross). This is known as the “Feynman-Schwinger” technique, and has not yet been applied to QCD.

4.2 Description of Current Research

IAN BALITSKY

- Deep Inelastic Scattering from Nucleons and Nuclei at Small x

  In view of the JLab upgrade it is very important to study the behavior of structure functions of deep inelastic scattering (DIS) at small x (i.e. large energies). DIS provides a unique opportunity which allows us to take "snapshots" of the constituents inside a hadron or nucleus at different moments of time with different resolutions. At low x, we probe the high-density domain of QCD where the constituents are small, but their density is so large that the packing factor for partons $\kappa > 1$ and therefore we cannot use ordinary pQCD methods. This high-density regime of QCD may serve as a bridge between the domain of pQCD and the "real" non-perturbative QCD regime governed by the physics of confinement. It turns out that the small-x behavior of structure functions in the high-density regime is governed by the non-linear evolution for the Wilson-line operators suggested in my paper several years ago.

In 2001, I have published several papers related to this topic. Firstly, I have found the solution of this equation in form of a functional integral [Phys. Lett. **B518**, 235 (2001)]. This is the first known example of an effective (2+1)-dimensional field theory formulated in terms of the effective high-energy degrees of freedom (Wilson lines) rather than in terms of original QCD quarks and gluons. Secondly, in collaboration with A. Belitsky we have found the next-to-leading corrections to the non-linear equation in the large N_c limit [Nucl. Phys. **B629**, 290 (2002)].

- Scattering of Color Dipoles at Intermediate Energies in QCD

  At high energies, the hadron-hadron scattering is conveniently described in terms of color dipoles, two-Wilson-line operators corresponding to fast quark-antiquark pairs. However, at the intermediate energies of order of 10 GeV it is not clear whether this high-energy language is adequate. My student A. Babansky and I are calculating the dipole-dipole scattering in the first two orders in pQCD as an exact function of the energy. When completed, this calculation will give us the rate at which the dipole-dipole amplitude approaches the high-energy asymptotics so it will be clear whether the JLab energies of order of few GeV can be described by the small-x methods.

DEIRDRE BLACK

The scalar mesons are a long-standing puzzle in meson spectroscopy since their properties do not fit neatly those expected from the constituent quark model. Experimentally there are too many states to fit into a conventional SU(3) $q\bar{q}$ multiplet and several states, notably the controversial σ and κ mesons as well as the $a_0(980)$ and $f_0(980)$, are significantly lighter than expected. Previously I was involved in developing a non-linear chiral Lagrangian description of low energy meson-meson scattering in which the scalar, as well as the vector, meson fields are included explicitly. Recently I have been looking at other processes from which we may hope to learn more about the scalar mesons.

In collaboration with Harada and Schechter I have come up with a new approach to studying radiative decays involving light scalar mesons. Using an effective Lagrangian and vector meson dominance we have a unified description of various decays which allows us to make various predictions. Of particular current interest are rare radiative decays of the ϕ meson (to $\pi\eta\gamma$ and $\pi\pi\gamma$) which were measured over the past two years at Novosibirsk and Frascati. Results are also expected soon from Jefferson Lab. It had been suggested that these branching fractions could distinguish between different conventional and exotic scenarios for the $a_0(980)$ and $f_0(980)$ states. In fact the experimental results have still not been fully understood. So far we, in agreement with other authors, have found that a resonance-dominated approximation cannot fit the data as had been originally hoped. We are currently extending our calculation to include interference with non-resonant backgrounds and are exploring the effect of mixing in the scalar sector on the ϕ decay rates and in general. The latter involves extension of our previous work on mixing to the isoscalar scalar mesons, including a scalar glueball.

With Abdel-Rahim, Fariborz and Schechter I have also been studying the isospin-violating strong decay $\eta \to 3\pi$. Historically theoretical estimates of this decay rate have been a factor of four or five too small. In the early 1980s Gasser and Leutwyler extended the original current algebra result to next-to-leading order in Chiral Perturbation Theory and later other authors have investigated the effects of final state interactions and violations of Dashen's Theorem which together bring theory into closer agreement with experiment, although the shape of the Dalitz plot is still not fully understood. We have explored the effect of explicitly including scalar mesons, taking into account symmetry breaking, and found that at tree level the scalar contributions also improve the theoretical prediction for the $\eta \to 3\pi$ rate. We are currently making a more detailed study of the spectrum.

In parallel with non-linear chiral Lagrangian descriptions, I have with Schecter *et al.* also studied meson-meson scattering using SU(3) Linear Sigma models. There we found that the scalar mesons emerge with properties consistent with our previous work. In this case the mass of the scalar mesons is shifted from a "bare" value to a "physical" value by the effects of unitarization. With Abdel-Rahim, Nasri and Schechter I am currently applying the analogue of our analysis of low-energy $\pi\pi$ scattering to the Higgs sector. We are exploring the effect of unitarization on the mass of a strongly-coupled Higgs boson.

Also, based on recent indications of large μ-τ neutrino mixing I have with Sher *et. al.* been considering the possibility of large μ-τ lepton mixing. Using effective μ-τ transition operators and results from current algebra and Heavy Quark Effective theory, we have explored existing experimental constraints on such lepton flavor violation.

ROBERT EDWARDS

An exciting advance in lattice QCD has been the solution of the problem of regulating chiral fermions. The method developed–the Overlap/Domain Wall method–allows for the first time, the realization of exact chiral symmetry on the lattice free of doublers and any other approximations. There are exact zero modes related to topology and non-zero modes responsible for chiral symmetry breaking. In the Domain Wall approach, a flavor fifth dimension is introduced that is infinite in extent; once integrated out, a four dimensional Dirac operator with exact chiral symmetry is induced.

This new theoretical development has been a major focus of my research in the last few years. I have investigated how symmetry breaking effects are manifested in the Domain Wall approach with a finite fifth dimensional extent [Phys. Rev. D **63**, 054509 (2001)] and how these chiral symmetry breaking effects are related to an induced four dimensional kernel of the Dirac operator. In work with Heller [Phys. Rev. D **63**, 094505 (2001)], I showed how the Domain Wall operator can be made to have exact chiral symmetry even with finite fifth dimensional extent. Many important properties of the Dirac operator were clarified.

Recently, Isgur proposed an interesting test of the fundamental question: what is the origin of spontaneously induced chiral symmetry breaking ? In collaboration with Heller I used the overlap operator to study in a clean way, free of the systematic errors endemic to other methods, the properties of near-zero fermion modes in gauge backgrounds [Phys. Rev. D **65**, 014505 (2002)]. A certain local chirality operator determines the near locking of chromo-electric and magnetic fields in the vacuum as expected from instantons. Tests in SU(3) show that there indeed appears to be a non-zero contribution to the infinite volume chiral condensate from what could be described as instantons and indeed the effects vanish in U(1) where instantons do not exist. These results show consistency in the expectation of chromo E and B locking. However, previous results of mine showed that the phenomenological prediction in the Instanton-Liquid model of the scaling of the zero-mode size distribution does not hold. Something is causing "lumps" in gauge fields, and it is not what many authors (strictly) call instantons. Studying the QCD vacuum is an active area of investigation.

JOSÈ GOITY

Recently my research activity has focused on the following areas: i) large N_c QCD in baryons, ii) chiral perturbation theory, iii) effective field theory for few nucleons, and iv) heavy mesons.

In the following I give a brief description of the research work carried out in each of these areas, highlighting the chief results in each case.

- Large N_c QCD in Baryons

  The theoretical study of excited hadrons has in general been carried out in the framework of the quark model. The non-perturbative QCD dynamics that determines the physics of hadronic resonances cannot be represented in the standard form of an effective theory as it is the case for the light ground state hadrons where an effective theory, Chiral Perturbation Theory, can be implemented. The quark model has thus provided in a rather simple framework a good level of predictivity that has served as a strong guidance in the understanding of that non-perturbative domain. The quark model is, however, not an effective theory, and therefore it is incomplete at some level. In QCD there is one expansion parameter that can be used to formulate effective theories even in that domain, namely $1/N_c$, where N_c is the number of colors. Some time ago Dashen, Jenkins and Manohar formulated such effective theory for ground state baryons (octet and decouplet) in terms of the $1/N_c$ expansion, and later on we extended this analysis to excited baryons, focusing in particular on the negative parity 70-plet. This work, carried out in a first collaboration with C. Carlson, C. Carone and R. Lebed, was recently extended and refined in a collaboration with C. Schat and N. Scoccola. The large N_c analysis only introduces the assumption that the expansion makes sense for $N_c = 3$; the rest is general enough, so that once the effective couplings of the theory are phenomenologically fixed, the resulting theory should be a faithful representation of QCD to the given order in $1/N_c$. The analysis of the 70-plet shows the following important features: i) The dominant contributions to masses are the same as in the quark model: the constituent quark masses and spin-independent binding energy, and the hyperfine interaction. ii) The subdominant contributions that are crucial to explain effects such as the splittings between spin-orbit partners, mixings, etc., require in general effective operators that the quark model does not include, such as operators that involve flavor exchanges. In particular the so called spin-orbit puzzle can be consistently resolved by one such operator. iii) The approach has a substantial degree of predictivity, leading to novel mass relations across SU(3) multiplets.

  We expect that the $1/N_c$ expansion will eventually provide a well established framework in baryons that will help for a better understanding of the experimental results for masses and transitions, as well as of results stemming from lattice QCD simulations.

- Chiral Perturbation Theory

  Work has been carried out in two different projects, namely, i) the study of the π^0 decay rate into two-photons to next to leading order, and ii) the study of isospin breaking in the π-N couplings through the Goldberger-Treiman relation.

  The $\pi^0 \to \gamma\gamma$ decay is currently of direct importance to Jefferson Lab, as it will be measured to a new level of precision by the PRIMEX experiment. In collaboration with A. Bernstein, J. Donoghue and B. Holstein, I have analyzed this decay beyond the leading order using a combined framework of Chiral Perturbation Theory and the $1/N_c$ expansion. It is shown that there is a correction that increases the rate with respect to the one obtained by using the decay amplitude given by the anomaly induced by the EM field on the isotriplet axial current, which is the proper amplitude in the limit of massless u and d quarks. The dominant correction is driven by the isospin breaking effects stemming from $m_u \neq m_d$ that give an admixture of the pure U(3) states associated with the η and the η' into the physical π^0. This admixture is such that it produces an enhancement of about 4% in the rate. This effect is a definite theoretical prediction that can be tested by the PRIMEX experiment where the expected error will be in the range of 1.5%. The PRIMEX will therefore be able to test the anomaly as well as the corrections induced by quark masses.

  The possibility of predicting isospin breaking on the π-N couplings is being investigated. This is a long standing issue on which we can now shed some light. The study involves the Goldberger-Treiman relations in SU(3) and their discrepancies, where both isospin breaking due to the $m_u - m_d$ mass difference and to EM corrections are considered. This work is being completed in collaboration with one graduate student, J. Saez.

- Effective Field Theory for Few Nucleons

  One important open problem in strong interactions is the construction of an effective field theory for the N-N system. This has proven to be a very difficult problem because to be realistic the one-pion exchange needs to be resummed to all orders in the S-wave channels where the scattering lengths are large. This requirement has proven to be difficult to implement in a rigorous way within an effective theory. Different approaches have been so far attempted, and work is still in progress.

  At a level of perturbation theory, a new regularization was developed for the two-nucleon system. The regularization allows for implementation of a low energy power counting while preserving Lorentz covariance. This work was carried out in collaboration with D. Lehmann, G. Prezeau and J. Saez.

- Heavy Mesons

Heavy mesons are the simplest environment to study the dynamics of light quarks in QCD; they are the "Hydrogen atom"of QCD. In the ongoing project studying heavy mesons and their excited states in collaboration with W. Roberts, I have recently studied the radiative transitions from excited heavy mesons. This work is based on the relativistic quark model, employing the same potential and constituent quark masses as in the case of the chiral quark model used previously to study the strong decays. It was shown that the observed ratios $\Gamma(D^{0*} \to D^0\gamma)/\Gamma(D^{0*} \to D^0\pi^0)$ and $\Gamma(D^{+*} \to D^+\gamma)/\Gamma(D^{+*} \to D^+\pi^0)$ require contributions from the heavy quark component of the EM current as well as a non-vanishing anomalous magnetic moment for the light quark. Although the experimental study of radiative transitions in heavy mesons is in its infancy, it is observed that some of the transitions will indeed be measurable, leading together with the strong transitions to a well constrained picture of the dynamics of light quarks in heavy mesons. Currently we are working on improving a calculation of the so called $B_{\ell 4}$ decays that we had done in a non-relativistic quark model. Th. These decays are important in context of the measurements on B-decays being carried out at CLEO as well as at the B-factories BABAR and Belle. As it had been emphasized in that previous work, the $B_{\ell 4}$ decays provide an indirect access to the excited heavy mesons, in particular the excited B-mesons, and represent one of the few possible ways to obtain empirical information on such excited states.

FRANZ GROSS

- Exact Solutions of Field Theory

  Using the Feynman-Schwinger (FS) path integral formalism, exact numerical solutions to scalar field theories can be found. In this promising approach, integrations over fields are replaced by path integrals over particle trajectories. The method allows a study the effect of particle exchange mechanisms and self-energy corrections *independently*.

  It has long been known (since Baym's proof in 1959) that the scalar $\chi^2\phi$ theory is unstable. The FS technique was used [Phys. Rev. D **64**, 076008 (2001)] to show that this theory is stable in quenched approximation (the approximation in which heavy χ particle loops are neglected), and that the introduction of heavy particle loops produces the instability. This explains why scalar meson exchange theories are a useful model for the study of relativistic equations (which usually neglect heavy particle loops), answering a long standing puzzle and clarifying a recent controversy.

- Quark-Antiquark Bound States

  It was shown how to model confinement in the $q\bar{q}$ system using the covariant Spectator (or Gross) equation [Phys. Rev. C **63**, 035208 (2001)]. In this approach individual quarks can be on their mass shell (i.e. the quark propagator can have real mass poles), but two interacting quarks can never *both* be on mass shell (i.e. there are no elastic cuts). For example, in the treatment of $q\bar{q}$ bound states, the quark is on mass-shell and confinement is realized by the condition that the bound state $q\bar{q}$ vertex function is zero at precisely the kinematic point where the antiquark would also be on mass-shell (kinematically possible if $M_b < m_q + m_{\bar{q}}$, which frequently occurs for confined systems). This condition occurs naturally and automatically whenever a confining interaction is present. One advantage of this approach is that it has a smooth non-relativistic limit, and the vanishing of the vertex function can be shown to also occur in systems described by the Schrödinger equation using a nonrelativistic confining potential.

- Charge Conjugation Invariance of the Spectator Equations

  The Spectator equation was recently criticized for failing to satisfy charge conjugation (C) invariance. This occurs if the equation is not even or odd under change in sign of the external energies W_i. Since the equation was not defined originally for negative energies, this problem is easily eliminated (or, more correctly, would not occur at all) by defining the equation for negative energies in the correct manner. It was shown [Few Body Syst. **30**, 21 (2001)] that this is easily done be defining all external energies to be positive, so that W_i is replaced by $\sqrt{W_i}$. This definition is also consistent with (and even required) by the physics underlying the derivation of the Spectator equations.

WALLY MELNITCHOUK

- Quark-Hadron Duality

  Quark-hadron duality addresses one of the core issues in strong interaction physics–the nature of the transition from quark to hadron degrees of freedom. A classic example of quark-hadron duality is in inclusive electron-hadron scattering (known as Bloom-Gilman duality). Recent experiments at Jefferson Lab have observed a remarkable equivalence between the inclusive structure function in the resonance region, averaged over appropriate W intervals (where W is the mass of the hadronic final state), and the scaling structure function measured in the deep-inelastic region, to low values of Q^2 below 1 GeV^2. The equivalence is also found to hold for each of the low-lying resonance region, so that the resonance-scaling duality exist locally as well as globally.

Building on earlier work with N. Isgur, S. Jeschonnek and J.W. Van Orden [Phys. Rev. D **64**, 054005 (2001)], I am extending the study of duality in structure functions to QCD in 1+1 dimensions in the limit of a large number of colors ('t Hooft model). The model provides exact solutions for the form factors from which the inclusive structure functions are constructed. Because resonances here are infinitely narrow, the model provides a unique opportunity to study the transition from low energy, where the structure function is dominated by resonance spikes, to high energy, where dominance of single quark scattering leads to a smooth function of Bjorken-x.

Following earlier work on the applications of local duality to asymptotic relations between nucleon form factors and deep-inelastic structure functions [Phys. Rev. Lett. **86**, 35 (2001); Nucl. Phys. **A680**, 52 (2001)], I am currently investigating duality relations for the simplest QCD bound state, the pion. This study will aim to test the validity of the relationship between the pion structure function at large x and the pion form factor at high Q^2. The pion form factor is being measured at JLab in Hall C, and there are plans to measure the pion structure function in Hall A at JLab with 12 GeV.

A study is also being carried out (in collaboration with Yu. Simonov) on generalizations of the Veneziano model of s and t channel duality to deep-inelastic structure functions. In addition, a major review of quark-hadron duality is currently being completed with R. Ent and C. Keppel.

- Hadron Spectrum in Lattice QCD

  The hadron spectrum is a defining problem in QCD. At present the only practical method for obtaining hadron masses directly from QCD is a numerical solution on the lattice. With collaborators at the Centre for the Subatomic Structure of Matter (CSSM) at the University of Adelaide, Australia (D. Leinweber *et al.*), I have studied the hadron mass spectrum in lattice QCD using an $\mathcal{O}(a^2)$ improved gluon action and a novel fat-link clover fermion action in which only the irrelevant operators are constructed with fat links. This action exhibits superior scaling behavior compared to mean-field improvement, and a reduced exceptional configuration problem compared with nonperturbative $\mathcal{O}(a)$ improvement [Nucl. Phys. (Proc. Suppl.) **109**, 101 (2002)].

  As an application of this action, masses of positive and negative parity excited baryons have been computed [Nucl. Phys. (Proc. Suppl.) **109**, 96 (2002)]. The results are in agreement with earlier calculations of N^* resonances using improved actions and exhibit a clear mass splitting between the nucleon and its chiral partner, the $N^*(1535)$. However, we find no evidence of overlap with the $1/2^+$ Roper resonance. The study of different Λ interpolating fields reveals a clear mass splitting of ~ 400 MeV between the octet Λ and its parity partner, although again we find no evidence of the empirical mass suppression of the $\Lambda^*(1405)$. This suggests either an important role for the meson cloud of the $\Lambda^*(1405)$ and/or a need for more exotic interpolating fields.

The results of this work have direct bearing on the experimental program at CLAS in Hall B, as well as on other theoretical approaches such as those based on large N_c counting or on QCD-inspired models. The recent progress made in tackling the hadronic mass spectrum in lattice QCD was one of the motivations for the formation of a discussion group on excited hadrons with the Theory Group and JLab experimentalists, in order to assess the interconnections between different theoretical approaches, as well as the impact on the N^* program at JLab.

As part of the Lattice Hadron Physics Collaboration, I plan to continue lattice studies of excited baryon and meson spectra, which will provide an important complement to the experimental program in Hall B, and to the exotic (hybrid) meson spectroscopy program at a future Hall D.

- Chiral Symmetry and Lattice QCD

  The fundamental role played by the dynamically broken chiral symmetry of QCD in nuclear physics is well known. However, the importance of chiral symmetry constraints on the small quark mass (m_q) behavior of observables calculated on the lattice is only now beginning to be fully appreciated [Pramana–Journal of Physics **57**, 251 (2001)]. In particular, it is vital to take into account the correct m_q dependence when extrapolating lattice calculations, which are currently performed at quark masses $m_q > 50$ MeV, to the physical point.

  This was dramatically illustrated for the case of moments of quark distributions calculated on the lattice, which when extrapolated linearly to the physical region overestimates the experimental values by up to 50%. In collaboration with researchers in Adelaide (A.W. Thomas and W. Detmold), and MIT (J. Negele and D. Renner), I reanalyzed moments of the u-d quark distribution, taking into account general constraints imposed by the chiral symmetry of QCD [Phys. Rev. Lett. **87**, 172001 (2001)]. The inclusion of the (model-independent) leading non-analytic behavior of the moments arising from Goldstone boson loops leads to an excellent description of both the lattice data and the experimental values of the moments, and resolves this long-standing discrepancy.

  Subsequently, the x dependence of the valence u-d distribution in the nucleon has been extracted from the lowest few moments calculated on the lattice, using an extrapolation formula which ensures the correct behavior in the chiral and heavy quark limits [Eur. Phys. J. C **13**, 1 (2001)]. This study found important implications for the quark mass dependence of meson masses lying on the $J^{PC} = 1^{--}$ Regge trajectory.

Currently the analysis is being extended to the polarized sector, where the chiral corrections arising from $N\pi$ and $\Delta\pi$ loops are being calculated for moments of the helicity and transversity moments. No empirical information exists on the latter distribution, and future measurements may be possible in Hall A at 12 GeV.

- Nuclear Effects in Few-Nucleon Systems

  Ongoing work on nuclear corrections to bound nucleon structure functions has focussed on the A=3 system. Since the polarization of ^{3}He resides mainly on the neutron, ^{3}He is often used as an effective polarized neutron target. I have calculated the nuclear corrections to the g_1 and g_2 structure functions of the neutron extracted from ^{3}He, which are necessary for the analysis of current and future data from Hall A. The measurement of the g_2 structure function in particular will reveal new information on the structure of higher twists (quark-gluon correlations) in the nucleon.

  In addition, a comprehensive analysis of nuclear corrections to the unpolarized ^{3}He and ^{3}H structure functions is being carried out, in which different theoretical approaches (including those based on the Faddeev and variational methods) are compared, as well as corrections to the standard impulse approximation. A major report on this analysis is currently being prepared.

IGOR MUSATOV

Generalized Parton Distributions (GPDs) are a subject of intensive research, both theoretical and experimental, and a significant part of the JLab research program. Recently, there was significant progress in the theoretical understanding of GPDs in the specific kinematics of vanishing four-momentum transfer.

To establish the relationship between theoretical models for GPDs and experimental observables within currently accessible kinematical regions, one needs to extend the theoretical description of the physical amplitudes to incorporate the momentum transfer dependence. Particularly, the parameterization of the DVCS and hadron annihilation amplitudes beyond the leading twist is required to restore gauge invariance in the case of not-very-small momentum transfers [Musatov and Radyushkin, in progress].

A practical way to build t-dependent GPDS is to relate the GPDs to known physical observables (structure functions and form factors) along with QCD-inspired models of hadron structure. It was found that light cone wave functions with power-law momentum behavior may be used to derive realistic GPDs [Mukherjee, Musatov, Pauli, Radyushkin, to be published].

Another promising approach is to use a Bethe-Salpeter-type equation to study the relation between the Regge behavior and t-dependence of the GPDs. As a first step, this work is being done with the scalar model. The structure of the equations hints that in the QCD case this approach may lead to a unified model, suitable for description of both the Regge behavior and DGLAP evolution [Musatov and Simonov, in progress].

An important task is to provide experimentalists an effective algorithm which will allow the evaluation of observables for DVCS using different theoretical models for GPDs as an input [Kuchina and Musatov, in progress]. The work is being done in cooperation with JLab experimental groups.

ANATOLY RADYUSHKIN

- Studies of Generalized Parton Distributions

  The main focus of my theoretical studies is on the investigation of hadronic structure using hard scattering processes. This structure can be described in terms of various functions: hadronic form factors, parton distribution functions, distribution amplitudes, etc. Recently, it was established that these functions can be treated as limiting cases of so-called Generalized Parton Distributions (GPDs) which provide a unified description of many inclusive and exclusive hard processes. I participated in the development of the GPD formalism, in particular, in its application for calculating the cross section of deeply virtual and wide-angle Compton scattering in quantum chromodynamics.

  The most recent development of the formalism is the incorporation of the kinematical twist-3 contributions to the DVCS amplitude, required to restore electromagnetic gauge invariance of the twist-2 amplitude up to $O(t/Q^2)$ level. In my previous papers (published in 1996-2000) I introduced two types of nonperturbative functions parameterizing such matrix elements: double distributions (DDs) and nonforward (or skewed) distribution functions. I developed simple models for DDs with correct spectral and symmetry properties and established the reduction relations connecting them to the usual parton densities. In 2001, I started a collaboration on this project with German colleagues from Ruhr-Universität in Bochum and University of Regensburg. In collaboration with Weiss (University of Regensburg), we developed a new approach

[Phys. Rev. D **63**, 114012 (2001)] to the analysis of DVCS beyond the leading twist. We parameterize non-forward matrix elements of the elementary twist-2 operators in terms of two-variable spectral functions (double distributions), from which twist-2 and -3 skewed distributions are obtained through reduction formulas. Our approach is equivalent to a Wandzura-Wilczek type approximation for the twist-3 distributions. The resulting Compton amplitude is manifestly transverse up to terms of order t/Q^2. We also demonstrated in [Phys. Rev. D **64**, 097504 (2001)] that the kinematical twist-3 corrections can be understood as a spin rotation applied to the twist-2 quark density matrix in the target. This allows for a compact representation of the twist-3 effects, as well as for a simple physical interpretation. The studies of generalized parton distributions was recently included as one of the major directions of futurergy studies at Jefferson Lab. A review of my work on generalized parton distributions was published as a chapter in the book "At the Frontier of Particle Physics/Handbook of QCD", edited by M. Shifman (World Scientific, 2001).

- Studies of Hadronic Form Factors

  I performed the studies of the basic hard exclusive processes: $\pi\gamma^*\gamma$–transition and pion electromagnetic form factors. I wrote a short review (published in the proceedings of 3rd Workshop on Chiral Dynamics) of calculations of the pion electromagnetic and transition form factors within the framework of quantum chromodynamics. I argued that both the perturbative and nonperturbative aspects of the Q^2 dependence of these form factors are rather well understood in QCD. However, new experimental data at higher Q^2 would be extremely helpful for detailed tests of the transition to the regime where the pQCD hard contribution plays the dominant role.

DAVID RICHARDS

- Spectroscopy of Excited Baryons

  The exploration of the excited baryon spectrum provides a theater to explore many of the central questions in hadronic physics, including the applicability of the quark model, the rôle of excited glue, and the existence of "molecular" states. It is thus a critical component of the Jefferson Lab experimental program. The lattice study of the excited baryon spectrum is a vital complement to this program that can both guide and inform the experiments, and extract the crucial physics from the experimental data.

I computed, within the quenched approximation, the mass of the lowest-lying negative parity baryon state, the $N^{1/2-}$, using the improved fermion action [Nucl. Phys. (Proc. Suppl.) **94**, 269 (2001) and to be published]. By performing the calculation at a variety of lattice spacings and lattice volumes, finite-volume effects could be estimated, and an extrapolation performed to the continuum limit. After this extrapolation, remarkably good consistency was found between the lattice calculation and the physical hadron masses, even in the quenched approximation, encouraging investigation of the higher resonances.

One of the long-standing puzzles of N^* spectroscopy has been the nature of the light Roper resonance at around 1440 MeV. On a subset of the lattices, the mass of the first radial excitation of the nucleon was determined, and found to be around 2 GeV, far higher than the experimental Roper mass [Nucl. Phys. (Proc. Suppl.) to be published]; such an observation is also seen in other lattice calculations. Thus lattice calculations are questioning the interpretation of the Roper as a naive three-quark state, and emphasizing their importance in interpreting the experimental program.

This research program is developing in collaboration with other members of the Lattice Hadron Physics Collaboration, employing a variety of lattice technology to extract higher excitations, such as the use of lattices anisotropic in time and the adoption of Bayesian statistics to analyze the data. An important extension of the work is the calculation of the masses of the light hybrid mesons, where the presence of excited glue can be most clearly identified.

- Weak Interaction Matrix Elements

The experimental determination of the CKM matrix elements requires a quantitative description of the strong interaction effects masking the weak interactions of the quarks. Lattice QCD calculations can provide an *ab initio* description of these effects.

We performed a calculation of the leptonic decay constants of B, D and K mesons in quenched lattice QCD, using a $\mathcal{O}(a)$-improved fermion action [Nucl. Phys. **B619**, 507 (2001)]. The decay constant f_B is profoundly important in phenomenology, since the combination $f_B\sqrt{B_B}$, where the B-parameter is expected to be close to unity, is required in the experimental extraction of CKM matrix elements, and CP violation parameters. However, the phenomenological utility of lattice results depends crucially on careful control of the systematic uncertainties impinging on the calculation. By performing the calculation at two lattice spacings, we were able to demonstrate good scaling of the data, and by careful consideration of the heavy-quark dependence of the results, show that many of the heavy-quark-effective-theory relations satisfied.

WINSTON ROBERTS

All of my research focuses on aspects of hadron spectroscopy using two somewhat different approaches. One of these is the effective Lagrangian approach, such as the heavy quark effective theory (HQET). The other is the use of specific constituent quark models, both relativistic and non-relativistic. Although such models are, for the most part, not rigorously derived from QCD, they are nevertheless very useful in helping us to understand and integrate a wide range of data in hadron phenomenology. As an example of the possible impact of such models, note that HQET grew out of work that had been done in non-relativistic quark models of this type.

- Heavy Quark Effective Theory

  Recently I have used the tensor formalism of HQET to examine the strong decays of heavy hadrons in a manner that allows treatment of decays involving light daughter hadrons other than pions. The formalism reproduces the results of the spin-counting arguments of the late Nathan Isgur and his collaborator Mark Wise, but this formulation, in principle, could allow study of the $1/m$ corrections to ratios of decay rates. As there are not much data on the strong decays of charm and beauty hadrons, with N. Trégourès, a graduate student (M. S. completed in the fall of 1998), I have applied this formalism to hadrons with strangeness to see if we can understand the global features of these decays within this framework. We have found that treating the strange quark as a heavy one leads to surprisingly good results in most cases. This formalism is now being applied to the decays of heavy baryons. However, since data in this sector are even more scarce than in the meson sector, the predictions of HQET will be compared with those of a quark model.

  My most recent work in this area focused on the extraction of V_{ub} from the semileptonic decays of B mesons. Using HQET as it applies to the transitions between heavy mesons and light ones, I found a number of measurements that could be used to extract this important element of the CKM matrix. In particular, I found that the ratio of differences of differential helicity decay rates, measured in the semileptonic decays of B mesons to ρ mesons and D mesons to ρ mesons, denoted $(d\Gamma_+^B/dq^2 - d\Gamma_-^B/dq^2)/(d\Gamma_+^D/dq^2 - d\Gamma_-^D/dq^2)$, was independent of any form factors, in leading order. This may turn out to play a significant role in the extraction of V_{ub}.

- Relativistic Quark Model

We have applied a model of heavy mesons to strong decays of heavy mesons using a chiral quark model to describe the decays (with J.L. Goity). Our results show that relativistic effects are quite large, as some of the results obtained here are very different from those obtained using a non-relativistic model of the mesons, with the same chiral quark model for the decays.

We have also applied this relativistic model of the mesons to their electromagnetic decays. For mesons like the D^*, the electromagnetic decay width is comparable to the strong one, because of the very limited phase space for strong decays. In the case of some excited mesons like D_s^{**} and B_s^{**}, the electromagnetic decays are expected to be dominant, as the only kinematically allowed strong decays are both OZI and isospin violating.

- Hadron Spectroscopy

  In addition to the projects described above, I am also working on quark models for the semileptonic decays of baryons (and mesons), as well as a description of meson photoproduction and electroproduction processes using a phenomenological Lagrangian approach.

ROCCO SCHIAVILLA

In the last few years, a “Standard Nuclear Physics Model” (SNPM) has been emerging, in which nuclei are viewed as assemblies of individual nucleons interacting among themselves via two- and three-body potentials, and with external electro-weak probes via currents consisting of one- and many-body components [for a recent review of the SNPM, see Rev. Mod. Phys. **70**, 743 (1998)]. How these effective potentials and currents arise from the underlying quark and gluon degrees of freedoms, the ultimate building blocks of nuclear matter, is still an open question.

The deceptively simple picture put forward in the SNPM, however, has been shown to provide a quantitatively accurate description of nuclear structure and dynamics over a wide range of energy, from the few keV of astrophysical relevance to the MeV regime of nuclear spectra to the tens to hundreds of MeV measured in nuclear response experiments. In the nuclear astrophysics realm, the SNPM has led to accurate predictions for the cross sections of the $pp \to d\, e^+ \nu_e$, $pd \to ^3\mathrm{He}\, \gamma$ and $p^3\mathrm{He} \to ^4\mathrm{He}\, e^+ \nu_e$ processes occurring in the pp chain, whose network of reactions, converting hydrogen into helium, constitute the principal source of energy and neutrinos in the Sun.

In the few MeV energy region relevant for nuclear structure, the SNPM has successfully predicted the observed energy spectra of low-lying states of nuclei with mass numbers in the range A=2–10 [the Argonne-Los Alamos-Urbana group, Phys. Rev. C **62**, 014001 (2000)], the measured rates of radiative and weak transitions between some of these states, and lastly the experimentally known elastic and inelastic electromagnetic form factors of nuclei with A=2–6 up to momentum transfers of $\simeq 1$ GeV/c.

Finally, in the hundreds of MeV energy regime, the SNPM has produced a quantitative understanding of the electromagnetic response of light nuclei, in particular of the role played by correlations and many-body currents in the distribution of longitudinal and transverse strength in the quasi-elastic region and beyond.

My research interests deal, in general terms, with the development and application of the SNPM and of methods, in particular quantum Monte Carlo techniques, for its practical implementation. Recently, I have been interested in:

- parity-violating effects, due to the weak interaction, on the properties of few-nucleon systems, such as the asymmetry induced by γ-Z interference in deuteron electrodisintegration at quasielastic kinematics [Phys. Rev. C **63**, 044007 (2001)] and the longitudinal asymmetry in pp elastic scattering originating from parity-violating components in the NN interaction [Phys. Rev. **C65**, 035502 (2002)];
- weak transitions, in particular β-decays and electron- and muon-captures in A=3–7 nuclei [nucl-th/0112008 and Phys. Rev. C **65**, 054302 (2002)].

YURI SIMONOV

The main research activity is the development of the nonperturbative QCD based on the method of field correlators, which has a universal character.

The topics include:

- chiral symmetry breaking in the confining vacuum;
- structure of hadrons (mesons, baryons, hybrids, and glueballs);
- nonperturbative theory of scattering and structure functions;

- perturbation theory in the nonperturbative confining background.

WALLY VAN ORDEN

- Duality

  One of the more intriguing experimental results to come from Jefferson Lab has been the verification of Bloom-Gilman duality, in which the inclusive structure function at low W (where W is the mass of the hadronic final state) is found to follow a global scaling curve which describes high W data, to which the resonance structure function averages. The equivalence of the averaged resonance and scaling structure functions was also found to hold for each resonance region, so that the resonance–scaling duality appears to exist locally as well as globally. To help understand the physics of duality, we have constructed a simple, quantum-mechanical model in which qualitatively reproduces the features of Bloom-Gilman duality. The model consists of a light quark bound to an infinitely heavy quark by a relativistic harmonic oscillator potential. The excitation spectrum of this system consists of an infinite number of infinitely narrow resonances. We find that this simple system reproduces the qualitative features Bloom-Gilman duality and illuminates the minimal physical conditions for this phenomenon to occur. An additional finding of this study is that the usual separation of deep inelastic scattering into a "resonance region" at low W and a "scaling region" at high W is totally spurious, and that resonances are an integral part of the scaling structure functions. This has important practical consequences for global analyses of parton distributions, and could open the way to an enormously rich program at Jefferson Lab extending structure functions into previously inaccessible regions of kinematics. The original model contained only scalar particles including a "scalar photon" probe. We have now extended the model to include a vector photon and have shown that the model satisfies the appropriate sum rules and that the scaling and duality of the simpler model are retained.

- Elastic Electron-Deuteron Scattering

  Over the last several years we have developed a relativistic, gauge-invariant model of elastic electron-deuteron scattering. This model is in excellent agreement with the new data for $A(Q^2)$, $B(Q^2)$ and $t_{20}(Q^2)$ obtained at Jefferson Lab. We continue to study the sensitivity of this model to nucleon electromagnetic form factors, and to the $\rho\pi\gamma$ and off-shell form factors. A review of the deuteron related to this work was published during 2001.

A. PUBLICATIONS IN REFEREED JOURNALS
(1/1/01 to 12/31/01)

References

[1] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, Phys. Lett. **B518**, 235 (2001).

[2] **D. Black**, A.H. Fariborz, S. Moussa, S. Nasri, and J. Schechter, *Unitarized Pseudoscalar Meson Scattering Amplitudes from Three Flavor Linear Sigma Models*, Phys. Rev. D **64**, 014031 (2001).

[3] C. Jung, **R.G. Edwards**, V. Gadiyak, and X.J. Ji, *Residual Chiral Symmetry Breaking in Domain-Wall Fermions*, Phys. Rev. D **63**, 054509 (2001).

[4] **R.G. Edwards** and U.M. Heller, *Domain Wall Fermions with Exact Chiral Symmetry*, Phys. Rev. D **63**, 094505 (2001).

[5] **J.L. Goity**, D. Lehmann, G. Prezeau and J. Saez, *Regularization for Effective Field Theory with Two Heavy Particles*, Phys. Lett. **B504**, 21 (2001).

[6] **J.L. Goity** and **W. Roberts**, *Radiative Transitions in Heavy Mesons in a Relativistic Quark Model*, Phys. Rev. D **64**, 094007 (2001).

[7] C. Savkli and **F. Gross**, *Quark-Antiquark Bound States in the Relativistic Spectator Formalism*, Phys. Rev. C **63**, 035208 (2001).

[8] **F. Gross**, *Charge Conjugation Invariance of the Spectator Equations*, Few Body Syst. **30**, 21 (2001).

[9] **F. Gross**, C. Savkli, and J. Tjon, *The Stability of the Scalar $\chi^2\phi$ Interaction*, Phys. Rev. D **64**, 076008 (2001).

[10] **S. Jeschonnek**, *Unfactorized versus Factorized Calculations for $^2H(e,e'p)$ Reactions at GeV Energies*, Phys. Rev. C **63**, 034609 (2001).

[11] **W. Melnitchouk**, *Local Duality Predictions for $x \sim 1$ Structure Functions*, Phys. Rev. Lett. **86**, 35 (2001).

[12] W. Detmold, **W. Melnitchouk**, J.W. Negele, D. Renner, and A.W. Thomas, *Chiral Dynamics and Lattice Moments of Proton Quark Distributions*, Phys. Rev. Lett. **87**, 172001 (2001).

[13] **W. Melnitchouk**, *Local Quark-Hadron Duality in Structure Functions*, Nucl. Phys. **A680**, 52 (2001).

[14] W. Detmold, D.B. Leinweber, **W. Melnitchouk**, A.W. Thomas, and S.V. Wright, *A New Slant on Hadron Structure*, Pramana—Journal of Physics **57**, 251 (2001).

[15] N. Isgur, S. Jeschonnek, **W. Melnitchouk**, and **J.W. Van Orden**, *Quark-Hadron Duality in Structure Functions*, Phys. Rev. D **64**, 054005 (2001).

[16] W. Detmold, **W. Melnitchouk**, and A.W. Thomas, *Parton Distributions from Lattice QCD*, Eur. Phys. J. C **13**, 1 (2001).

[17] **A.V. Radyushkin** and C. Weiss, *DVCS Amplitude at Tree Level: Transversality, Twist-3 and Factorization*, Phys. Rev. D **63**, 114012 (2001).

[18] **A.V. Radyushkin** and C. Weiss, *Kinematical Twist-3 Effects in DVCS as a Quark Spin Rotation*, Phys. Rev. D **64**, 097504 (2001).

[19] K.C. Bowler, L. Del Debbio, J.M. Flynn, G.N. Lacagnina, V.I. Lesk, C.M. Maynard, and **D.G. Richards**, *Decay Constants of B and D Mesons from Nonperturbatively Improved Lattice QCD*, Nucl. Phys. **B619**, 507 (2001).

[20] S. Capstick and **W. Roberts**, *Quark Models of Baryon Masses and Decays*, Prog. Part. Nucl. Phys. **45**, 241 (2001).

[21] L.E. Marcucci, **R. Schiavilla**, M. Viviani, A. Kievsky, S. Rosati, and J.F. Beacom, *Weak Proton Capture on ^3He*, Phys. Rev. C **63**, 015801 (2001).

[22] K.M. Nollett, R.B. Wiringa, and **R. Schiavilla**, *A Six-Body Calculation of the α-d Radiative Capture Cross Section*, Phys. Rev. C **63**, 024003 (2001).

[23] L. Diaconescu, **R. Schiavilla**, and U. van Kolck, *Parity-Violating Electron-Deuteron Scattering*, Phys. Rev. C **63**, 044007 (2001).

[24] **R. Schiavilla** and I. Sick, *Neutron Charge Form Factor at Large q^2*, Phys. Rev. C **64**, 041002 (2001).

[25] M. Garçon and **J.W. Van Orden**, *The Deuteron: Structure and Form Factors*, Adv. Nucl. Phys. **26**, 293 (2001).

B. PUBLICATIONS IN CONFERENCE PROCEEDINGS (Talks published in the period 1/1/01–12/31/01)

[26] **I. Balitsky**, *Small-x Evolution of Wilson Lines*, "Thera Book" (DESY 01-123F, vol. 4), U. Katz, M. Klein, A. Levy, and S. Schlenstedt, eds., DESY, December 2001 (ISSN 0418-9833), Ch. 3.1.

[27] **I. Balitsky**, *High-Energy QCD and Wilson Lines*, Proceedings of the Boris Ioffe Festschrift "At the Frontier of Particle Physics/Handbook of QCD" (World Scientific, Singapore, 2001), Ch. 22.

[28] **D. Black**, *Exploring Pseudoscalar Meson Scattering in Linear Sigma Models*, Proceedings of the MRST 2001 conference, London, Ontario 2001, AIP Conference proceedings, Elias, McKeon and Miransky, Eds.

[29] **R.G. Edwards**, *Topology and Low Lying Fermion Modes*, Proceedings of the International Conference "Lattice 2001", Berlin, Germany, 2001, Nucl. Phys. (Proc. Suppl.) **106**, 38 (2002).

[30] **R.G. Edwards** and U.M. Heller, *Probing the QCD Vacuum with Overlap Fermions*, Proceedings of the Workshop on "Lattice Hadron Physics (LHP 2001)", Cairns, Australia, 2001, Nucl. Phys. (Proc. Suppl.) **109**, 124 (2002).

[31] **J.L. Goity**, $\pi^0 \to \gamma\gamma$ *to NLO in ChPT*, Proceedings of "Baryons 2002", to be published.

[32] **F. Gross** [panel and discussion leader], D. Drechsel, J. Friar, V.R. Pandharipande, and I. Sick, *Conference Discussion of the Nuclear Few-Body Problem: Questions and Issues*, Proceedings of the XVIIth European Conference on "Few-Body Problems in Physics", Nucl. Phys. **A689**, 573c (2001).

[33] **F. Gross** and R. Gilman, *The Deuteron: a Mini Review*, VIIIth Meeting on "Mesons and Light Nuclei", Prague, Czech Republic, July 2001, AIP Conference Proceedings **603**, p. 55.

[34] **W. Melnitchouk**, *Quark Hadron Duality: Resonances and the Onset of Scaling*, International Workshop on "Physics of Excited Nucleons (N^* 2001)", Mainz, Germany, 2001, World Scientific, to be published.

[35] **W. Melnitchouk**, W. Detmold, and A.W. Thomas, *Connecting Structure Functions on the Lattice with Phenomenology*, 3rd Circum-Pan-Pacific Symposium on "High Energy Spin Physics", Beijing, China, 2001, to appear in Int. J. Mod. Phys. A.

[36] **W. Melnitchouk**, *Quark Hadron Duality in Inclusive Electron-Hadron Scattering*, "Lepton Scattering, Hadrons and QCD" (World Scientific, Singapore, 2001), p. 122.

[37] **W. Melnitchouk**, *Quark Hadron Duality: Resonances and the Onset of Scaling*, 3rd International Conference on "Perspectives in Hadronic Physics", ICTP, Trieste, Italy, 2001, to appear in proceedings.

[38] J.M. Zanotti, S. Bilson-Thompson, F.D.R. Bonnet, P. Coddington, D.B. Leinweber, A.G. Williams, J. Zhang, **W. Melnitchouk**, and F.X. Lee, *Novel Fat-Link Fermion Actions*, Workshop on "Lattice Hadron Physics", Cairns, Australia, 2001, Nucl. Phys. (Proc. Suppl.) **109**, 101 (2002).

[39] **W. Melnitchouk**, S. Bilson-Thompson, F.D.R. Bonnet, P. Coddington, D.B. Leinweber, A.G. Williams, J.M. Zanotti, J. Zhang, and F.X. Lee, *Baryon Resonances from a Novel Fat Link Fermion Action*, Workshop on "Lattice Hadron Physics", Cairns, Australia, 2001, Nucl. Phys. (Proc. Suppl.) **109**, 96 (2002).

[40] A.W. Thomas, W. Detmold, and **W. Melnitchouk**, *Progress in the Calculation of Parton Distributions in QCD*, 3rd International Conference on "Perspectives in Hadronic Physics", ICTP, Trieste, Italy, 2001, to appear in proceedings.

[41] J. Haidenbauer, **W. Melnitchouk**, and J. Speth, *A Meson Exchange Model for the YN Interaction*, VIIIth Meeting on "Mesons and Light Nuclei", Prague, Czech Republic, July 2001, AIP Conference Proceedings **603**, p. 421.

[42] **W. Melnitchouk**, *QCD and the Structure of the Nucleon in Electron Scattering*, 14th Annual HUGS at CEBAF on "Hadronic Structure", J. Goity, ed., (World Scientific, Singapore, 2001), p. 202.

[43] J. Bijnens, A. Farilla, R. Miskimen, F. Ambrosino, M. Arenton, P. Cenci, V. Cirigliano, A. Fariborz, A. Gasparian, M. Golterman, R. Kaiser, D. Mack, B. Moussallam, T. Nakano, B. Nefkens, A. Nyffeler, J. Oller, E. Oset, J.R. Pelaez, J. Palomar, **A. Radyushkin**, P. Rubin, J. Sa Borges, J. Schacher, S. Schmidt, J. Stern, and T. Walcher, *Report of the Working Group on Goldstone Bosons*, Proceedings of the workshop on "Chiral Dynamics 2000: Theory and Experiment" (World Scientific, Singapore, 2001), p. 253.

[44] **A.V. Radyushkin**, *QCD Calculations of Form Factors*, Proceedings of the workshop on "Chiral Dynamics 2000: Theory and Experiment" (World Scientific, Singapore, 2001), p. 309.

[45] **D.G. Richards** (UKQCD and LHPC Collaboration), *N^* Spectrum Using an $\mathcal{O}(a)$-Improved Fermion Action*, Nucl. Phys. (Proc. Suppl.) **94**, 269 (2001).

[46] **D.G. Richards**, M. Göckeler, R. Horsley, D. Pleiter, P.E.L. Rakow, G. Schierholz, and C.M. Maynard, *Excited Nucleon Spectrum Using a Non-Perturbatively Improved Clover Fermion Action*, Proceedings of the Workshop on "Lattice Hadron Physics (LHP 2001)", Cairns, Australia, 2001, Nucl. Phys. (Proc. Suppl.) **109**, 89 (2002).

[47] **D.G. Richards**, *Review of NN Interaction from Lattice QCD*, Proceedings of the workshop "Chiral Dynamics 2000: Theory and Experiment", (World Scientific, Singapore, 2001), p. 444.

[48] **R. Schiavilla**, *Electro-Weak Reactions for Astrophysics*, Proceedings of the XVIth International Conference on "Few-Body Problems in Physics", Nucl. Phys. **A684**, 157c (2001).

[49] **R. Schiavilla**, *Interactions, Currents, and the Structure of Few-Nucleon Systems*, Proceedings of the International Conference "Bologna 2000–Structure of the Nucleus at the Dawn of the Century" Vol. "Hadrons, Nuclei, and Applications" (World Scientific, Singapore, 2001), p. 10.

[50] **R. Schiavilla**, *Electromagnetic Structure of Few-Nucleon Systems*, Proceedings of the XVIIth European Conference on "Few-Body Problems in Physics" Nucl. Phys. **A689**, 84c (2001).

[51] **R. Schiavilla**, *The hep Astrophysical Factor*, Proceedings of the 2nd International Workshop "Neutrino Oscillations and their Origin–NOON2000" (World Scientific, Singapore, 2001), p. 23.

[52] **R. Schiavilla**, U. van Kolck, and H.R. Weller, *Summary of Few-Nucleon Working Group*, Proceedings of the workshop "Chiral Dynamics 2000: Theory and Experiment" (World Scientific, Singapore, 2001), p. 401.

[53] M. Viviani, A. Kievsky, L.E. Marcucci, S. Rosati, and **R. Schiavilla**, *Few-Nucleon Reactions of Astrophysical Interest*, Proceedings of the workshop "Selected Few-Body

Problems in Hadronic and Atomic Physics", Bled Workshops in Physics, Ljubljana, 2001, Vol. 2, No. 1, p. 29.

C. UNPUBLISHED INVITED TALKS GIVEN AT CONFERENCES AND WORKSHOPS
(Talks given in the period 1/1/01–12/31/01)

[54] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, 2001 DNP APS meeting, Maui, Hawaii, October 2001.

[55] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, International Workshop on "High-Energy QCD: Beyond the Pomeron", BNL, New York, May 2001.

[56] **I. Balitsky**, *Renormalons as Dilatation Modes in the Functional Space*, 6th International Workshop on "Non-Perturbative QCD", Paris, France, June 2001.

[57] **D. Black**, *Scalar Mesons in Three-Flavor Linear Sigma Models*, International Workshop on "Chiral Fluctuations in Hadronic Matter", IPN, Orsay, France, September 2001.

[58] **R.G. Edwards**, *Quantum Field Theory on the Lattice*, HUGS 2001, Jefferson Lab, Newport News, June 2001.

[59] **R.G. Edwards**, *The QCD-API*, SciDAC Software Workshop, Jefferson Lab, Newport News, November 2001.

[60] **J.L. Goity**, *Large N_c QCD in Mesons and Baryons*, three talks in Theory Group working group, Jefferson Lab, Newport News, December 2001.

[61] **F. Gross**, *Covariant Effective Field Theories*, INT Workshop on "Theories of Nuclear Forces and Few-Nucleon Systems", University of Washington, Seattle, June 2001.

[62] **W. Melnitchouk**, *Quark Hadron Duality, Resonances and the Onset of Scaling*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, May 2001.

[63] **W. Melnitchouk**, *Chiral Extrapolation of Baryon Properties on the Lattice*, INT Workshop on "Lattice QCD and Hadron Phenomenology", University of Washington, Seattle, October 2001.

[64] **W. Melnitchouk**, *Extraction of Hadron Masses in Lattice QCD*, Workshop on "Hamiltonian Lattice Gauge Theories", Adelaide, Australia, April 2001.

[65] **W. Melnitchouk**, *Hadron Spectroscopy in Lattice QCD*, Hall D Collaboration Meeting, Indiana University, Bloomington, November 2001.

[66] **A.V. Radyushkin**, *Hadronic Form Factors in QCD*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, March 2001.

[67] **A.V. Radyushkin**, *Generalized Parton Distributions*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, May 2001.

[68] **A.V. Radyushkin**, *Double Distributions*, Workshop on "Generalized Parton Distributions", Santorini, Greece, October 2001.

[69] **A.V. Radyushkin**, *Spin Structure of the Nucleon in the Resonance Region*, 2001 DNP APS meeting, Maui, Hawaii, October 2001.

[70] **A.V. Radyushkin**, *The Uses of Double Distributions*, WE-HERAEUS-Seminar on "Generalized Parton Distributions", Bad Honnef, Germany, November 2001.

[71] **D.G. Richards**, *Lattice Status Report*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, Washington, March 2001.

[72] **D.G. Richards**, *N* Physics and Lattice QCD*, INT Workshop on " Lattice QCD and Hadron Phenomenology", University of Washington, Seattle, September, 2001.

[73] **D.G. Richards**, *Lattice QCD and Hall D Physics*, Hall D Collaboration Meeting, Indiana University, Bloomington, November 2001.

[74] **R. Schiavilla**, *Standard Nuclear Model versus EFT: a Case Study in Weak Transitions*, INT workshop on "Theories of Nuclear Forces and Few-Nucleon Systems", University of Washington, Seattle, June 2001.

[75] **R. Schiavilla**, *Low-Energy Electro-Weak Reactions in Three- and Four-Nucleon Systems*, ECT* Workshop "Few-Body Systems at Low and Moderate Energies: Open Questions Beyond Computational Problems", Trento, Italy, June 2001.

[76] **R. Schiavilla**, *Open Discussion on $d(e,e'p)n$*, "OOPS Theory Workshop", MIT, Cambridge, July 2001.

[77] **J. W. Van Orden**, *Electron Scattering from Nuclei*, International Meeting on "Electron Scattering from Atoms Nuclei, Molecules and Bulk Matter", Magdalene College, Cambridge, U.K., December 2001.

D. SEMINARS AND COLLOQUIA (Period 1/1/01 to 12/31/01)

[78] **I. Balitsky**, *Renormalons as Dilatation Modes in the Functional Space*, MIT, Cambridge, March 2001.

[79] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, CEA Saclay, Paris, France, June 2001.

[80] **I. Balitsky**, *Small-x Evolution of Wilson Lines*, CERN, Geneva, Switzerland, June 2001.

[81] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, University of Maryland, College Park, November 2001.

[82] **I. Balitsky**, *Small-x Evolution of Wilson Lines*, Penn State University, State College, November 2001.

[83] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, INT, University of Washington, Seattle, January 2001.

[84] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, Jefferson Lab, Newport News, February 2001.

[85] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, Physics Division, ANL, Argonne, February 2001.

[86] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, University of Maryland, College Park, March 2001.

[87] **D. Black**, *Scalar Mesons in Three-Flavor Linear Sigma Models*, Jefferson Lab, Newport News, November 2001.

[88] **J.L. Goity**, *The π^0 width at NLO in Chiral Perturbation Theory*, University of Bern, Switzerland, May 2001.

[89] **J.L. Goity**, *Towards Non Perturbative Pions in the Effective Field Theory for NN Interaction*, University of Bern, Switzerland, June 2001.

[90] **J.L. Goity**, *Towards Non Perturbative Pions in the Effective Field Theory for NN Interaction*, University of Barcelona, Spain, June 2001.

[91] **J.L. Goity**, *The Measurement of a Lifetime.*, Clark Atlanta University, Atlanta, November 2001.

[92] **W. Melnitchouk**, *Nuclear Physics Program at Jefferson Lab*, University of Sao Paulo, Brazil, January 2001.

[93] **W. Melnitchouk**, *Quark-Hadron Duality in Electron Scattering*, Universidade Federal Fluminense, Rio de Janeiro, Brazil, January 2001.

[94] **W. Melnitchouk**, *Duality in Electron Scattering*, University of Kentucky, Lexington, October 2001.

[95] **W. Melnitchouk**, *Chiral Extrapolation of Baryon Properties from Lattice QCD*, University of Pittsburgh, Pittsburgh, November 2001.

[96] **A.V. Radyushkin**, *Generalized Parton Distributions*, University of Rochester, New York, April 2001.

[97] **A.V. Radyushkin**, *Double and Skewed Parton Distribution Functions*, Ruhr University, Bochum, Germany, June 2001.

[98] **A.V. Radyushkin**, *Hadronic Form Factors and QCD in Spacelike and Timelike Regions*, University of Wuppertal, Germany, June 2001.

[99] **D.G. Richards**, *Baryon Spectroscopy from Lattice QCD*, Florida International University, Miami, May 2001.

[100] **D.G. Richards**, *N^* Spectrum Using Lattice QCD*, Hadron Physics Group seminar, University of Maryland, College Park, June 2001.

[101] **R. Schiavilla**, *Electro-Weak Structure, Capture Reactions, Parity Violation, and All That*, Theoretical Division, LANL, Los Alamos, January 2001.

[102] **R. Schiavilla**, *Longitudinal and Transverse Strength in Nuclei*, Kellogg Radiation Laboratory, Caltech, Pasadena, January 2001.

[103] **R. Schiavilla**, *G_{En}, L/T Strength in Nuclei, and More (Maybe)*, Jefferson Lab, Newport News, July 2001.

[104] **R. Schiavilla**, *Structure and Dynamics of Few-Nucleon Systems: a Progress Report*, Department of Physics, University of Helsinki, Helsinki, Finland, August 2001.

[105] **R. Schiavilla**, *A Random Walk in the Physics of Few-Nucleon Systems*, Department of Physics, University of Virginia, Charlottesville, October 2001.

[106] **Yu.A. Simonov**, *QCD Vacuum and Hadrons*, three lectures, Jlab, October 2001.

[107] **Yu.A. Simonov**, *Method of Vacuum Correlators*, six lectures, Jlab, October-December 2001.

[108] **Yu.A. Simonov**, *New Developments in the nonperturbative QCD*, two lectures, Institute of Theoretical Physics, University of Minnesota, December 2001.

E. REVIEWS, EDITORSHIPS, AND MAJOR PROPOSALS (2001)

[109] The U.S. Lattice QCD Collaboration, **R.G. Edwards** and **D.G. Richards**, *National Computational Infrastructure for Lattice Gauge Theory*, funded under the SciDAC Program of the U.S. Dept. of Energy, July 2001.

[110] **J. L. Goity**, A. Bernstein, and U-G. Meissner, Eds., *Chiral Dynamics: Theory and Experiment III* (World Scientific, Singapore, 2001).

[111] **W. Melnitchouk**, A.W. Schreiber, P.C. Tandy, and A.W. Thomas, eds., *Lepton Scattering, Hadrons and QCD* (World Scientific, Singapore, 2001).

[112] A.C. Kalloniatis, D.B. Leinweber, **W. Melnitchouk**, and A.G. Williams, eds., *Lattice Hadron Physics*, Nuclear Physics B–Proceedings Supplement **109** (2002).

[113] **A.V. Radyushkin**, *Generalized Parton Distributions*, "At the Frontier of Particle Physics/Handbook of QCD", M. Shifman, ed., (World Scientific, Singapore, 2001), vol. 2, p. 1037.

[114] M. Garçon and **J.W. Van Orden**, *The Deuteron: Structure and Form Factors*, Adv. Nucl. Phys. **26**, 293 (2001).

F. WORKSHOP AND CONFERENCE ORGANIZATION (2001)

[115] **R.G. Edwards**, Co-organizer for the Workshop on "Lattice Hadron Physics (LHP 2001)", Cairns, Australia, July 9–19, 2001.

[116] **R.G. Edwards**, Organizer for the SciDAC Software Workshop, Jefferson Lab, Newport News, November 8–9, 2001.

APPENDICES

A. WORKSHOPS FUNDED JOINTLY WITH INT

March 12–16, 2001 Correlations in Nucleons and Nuclei

B. LONG TERM VISITORS IN 2001

W. Melnitchouk	University of Adelaide	01/01–31/07
C. Schat	Argentina (CONICET)	01/23–present
A. Stadler	University of Lisbon	02/03–02/18
I. Aznauryan	Yerevan Physics Institute	05/02–09/02
W. Melnitchouk	University of Adelaide	05/12–05/23
J.-M. Laget	Saclay	06/05–06/23
W. Wilcox	Baylor University	06/25–07/07
A. Stadler	University of Lisbon	07/21–09/14
T. Pena	University of Lisbon	07/21–09/14
J. Tjon	University of Utrecht	07/22–08/18
E. Lomon	Massachusetts Institute of Technology	09/09–09/21
J.-M. Laget	Saclay	10/15–11/03
V. Suslov	St. Petersburg State University	12/02–12/15
S. Kulagin	Russian Academy of Science	12/10–12/20

C. SHORT TERM VISITORS IN 2001

V. Mandelzweig	Hebrew University	01/24–01/31
W. Lee	Los Alamos National Laboratory	02/03–02/07
S. Puglia	Ohio State University	02/10–02/13
J. Tjon	University of Utrecht	02/11–02/17
T. Blum	Brookhaven National Laboratory	02/13–02/15
D. Black	Syracuse University	02/15–02/18
A. Williams	University of Adelaide	02/21–02/23
A. Arriaga	University of Lisbon	02/24–03/03
T. Cohen	University of Maryland	02/25–02/26
M. Paris	University of Illinois at Urbana-Champaign	03/07–03/11
V. Pandharipande	University of Illinois at Urbana-Champaign	04/12–04/13
A. Fonseca	University of Lisbon	05/01–05/04
F. Lee	George Washington University	07/02–07/06
S. Mintz	Florida International University	07/16
S. Mintz	Florida International University	08/02–08/09
J. Speth	University of Bonn	09/05–09/08
J. Speth	University of Bonn	09/16–09/22
W. Detmold	University of Adelaide	09/08–09/14
A. Belitsky	University of Maryland	09/23–09/26
S. Beane	University of Washington	10/29–10/30
N. Kalantar	Kernfysisch Versneller Instituut (KVI)	11/02
D. Riska	Helsinki Institute of Physics	11/03–11/11
L. Marcucci	University of Pisa	12/02–12/08
A. Rinat	Weizmann Institute of Science	12/02–12/07
T. Mizutani	Virginia Polytechnic Institute	12/12–12/16

D. THEORY SEMINARS IN 2001

V. Mandelzweig, Hebrew University, 01/29/01
Quasilinearization Method and Its Application to Physical Problems

W. Lee, Los Alamos National Laboratory, 02/05/01
Recent Progress in ϵ'/ϵ *Calculation Using Staggered Fermions*

R. Edwards, Jefferson Laboratory, 02/09/01
From 5D to 4D: Chiral Fermions on the Lattice

S. Puglia, University of Connecticut, 02/12/01
How Well Does the Chiral Expansion for Baryons Converge

T. Blum, Brookhaven National Laboratory, 02/14/01
Lattice QCD Using Domain Wall Fermions

D. Black, Syracuse University, 02/16/01
Chiral Lagrangian Treatment of the Scalar Meson Puzzle

D. Richards, Old Dominion University/Jefferson Laboratory, 02/21/01
Large Baryon Spectroscopy fromLattice QCD

A. Williams, University of Adelaide, 02/23/01
On Triviality, Regularization, and Renormalization in High Precision Studies of Nonperturbative QED

T. Cohen, University of Maryland, 02/26/01
Does the Vafa-Wittne Theorem Rule Out Spontaneous Parity Violation in Finite Temperature QCD ?

I. Musatov, Jefferson Laboratory, 02/28/01
Higher-Twist Skewed Parton Distributions and DVCS

H.-W. Hammer, Ohio State University, 03/05/01
Three-Body Forces in Effective Field Theory

T. Mehen, Ohio State University, 03/07/01
Effective Field Theory for Nuclear Physics

D. THEORY SEMINARS IN 2001 (cont'd)

M. Paris, Univerity of Illinois at Urbana-Champaign, 03/09/01
Quantum Monte Carlo Calculations of Six-Quark States

J.-W. Chen, University of Maryland, 03/12/01
Measuring the Longest Range P-Odd π-N Coupling in π-Photoproduction Near Threshold

W. Roberts, Old Dominion University/Jefferson Laboratory, 04/02/01
Phenomenological Lagrangian Description of Photo- and Electro-Production: Very Preliminary

D. Ernst, Vanderbilt University/Jefferson Laboratory, 04/09/01
Meson Cloud Contribution to the Masses of the Nucleon and Δ

V. Pandharipande, Univerity of Illinois at Urbana-Champaign, 04/13/01
Many-Body Theory Approach to Deep Inelastic Scattering

J. Juge, Fermi National Laboratory, 04/18/01
Heavy Hybrid Mesons

C. Jung, University of Maryland, 04/20/01
Hadronic Structure of the Photon in Lattice QCD

P. Bedaque, Lawrence Berkeley Laboratory, 04/23/01
Nonperturbative Effective Theories

W. Wilcox, Baylor University, 06/28/01
Lattice Methods

S. Mintz, Florida International University, 07/16/01
Neutrino Reactions in ^{56}Fe and an Interesting Relation

I. Balitsky, Old Dominion University/Jefferson Laboratory, 07/23/01
Effective Field Theory for the Small x-Evolution

C. Schat, Hampton University, 07/30/01
The Negative Parity 70-plet in Large N_C QCD

D. THEORY SEMINARS IN 2001 (cont'd)

T. Peña, University of Lisbon, 08/13/01
Learning About the $N\eta$ Interaction from the $Np \rightarrow \eta d$ Reaction Close to Threshold

W. Melnitchouk, Jefferson Laboratory, 08/27/01
Lattice QCD and Chiral Extrapolation

A. Freund, University of Regensburg, 09/05/01
Deeply Virtual Compton Scattering in Next-to-Leading Order

W. Detmold, University of Adelaide, 09/10/01
Chiral Behavior of Quark Distributions from Lattice QCD

E. Lomon, Massachusetts Institute of Technology, 09/19/01
Physical Nucleon Electromagnetic Form Factor Models Fitted to Old and New Data

J. Speth, University of Bonn, 09/21/01
Pion-Nucleon Reactions (Two-Pion Production)

A. Belitsky, Univerity of Maryland, 09/24/01
Theory and Phenomenology of Generalized Parton Distributions

S. Beane, University of Washington, 10/29/01
Quark-Hadron Duality at Large N_c

D. Riska, Helsinki Institute of Physics, 11/05/01
Pion Decay of Charm Mesons

D. Black, Jefferson Laboratory, 11/19/01
Scalar Mesons in Three-Flavor Linear Sigma Models

A. Rinat, Weizmann Institute of Science, 12/03/01
Extraction of the Neutron $F_2^n(x, Q^2)$ on Inclusive Electron Scattering from D, C and Fe

E. THEORY MINI-LECTURE SERIES IN 2001

I. Aznauryan, Yerevan Physics Institute, 08/20–08/24/01
Pion Electroproduction on the Nucleons in the Resonance Region:Unitary Isobar Model and Dispersion Relations

J.-M. Laget, Saclay, 10/22–10/29/01
Meson Photo-Production: a Window on the Quark-Gluon Structure of Hadronic Matter

Yu. Simonov, ITEP-Moscow, 11/12–11/16/01
Microscopic Structure of the QCD Vacuum and How it is Revealed in Normal (Mesons and Baryons) and Unusual (Hybrids, Glueballs, and Hybrid Baryons) Hadrons