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Progress Report
for the period June 1, 1992 through May 31, 1993

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I. INTRODUCTION

The University of Massachusetts (UMass) Nuclear Physics Program continues to concentrate upon the use of the electromagnetic interaction in a joint experimental and theoretical approach to the study of nucleon and nuclear properties. During the past year the activities of the group involved data analysis, design and construction of equipment, planning for new experiments, completion of papers and review articles for publication, writing of proposals for experiments, but very little actual data acquisition. The reason for the lack of data acquisition has to do with the status of electron accelerators at this juncture in time. The M.I.T.-Bates South Hall Ring is not yet completed and its construction precluded running the accelerator, the NIKHEF pulse stretcher ring in Amsterdam (AmPS) has had some unanticipated problems, and the CLAS detector in Hall B at CEBAF will not be operational for at least three years. Our group was not currently active in experiments at SLAC, where beams have been available, but we have very recently decided to join the spin structure of the nucleon experimental collaboration E-153. Notwithstanding this lack of beam time, there has been a great deal of work necessary for completion of past activities and preparation for future experiments.

In Part II.A. of this report we describe our work related to the M.I.T.-Bates Linear Accelerator Center. Our major project in this regard involves the construction of high-pressure cryogenic ^3He and hydrogen target loops for use in Experiment 89-09, which involves the measurement of ^3He elastic magnetic scattering to a momentum transfer squared of 54 fm^{-2} . In the same spectrometer momentum bite we will get information on the threshold breakup of ^3He . Two graduate students are working on this experiment: one has the primary responsibility for the ^3He target loop, and the other for the hydrogen loop. One will analyze the elastic magnetic scattering data and the other the threshold data. Both are involved in the design, construction, and testing of equipment for this complicated experiment. They both have become experts in computer aided design. The components of both loops are about 90% complete, they have been leak tested and cold tested at liquid nitrogen temperatures. About two-person years of machine

shop time has been necessary up to now with more time projected. A gas handling system has been designed and is being assembled, and a "thermal pump" with no moving parts has been designed for transferring the gas to and from the target. In the accompanying proposal, plans for executing this experiment are discussed, and preceding the budget section of the proposal a short summary of expenditures for this expensive experiment is given.

A second experiment 89-15 at Bates involves the use of the continuous beam from the South Hall Ring in an out-of-plane (e,e'p) electron-proton coincidence measurement of the threshold breakup of the deuteron at high momentum transfers. This experiment is a collaboration between Japanese, UMass, and Bates physicists. Tadaaki Tamae of Tohoku University in Sendai, Japan will come to the U.S. to participate in the R.P.I.-Illinois $^3\text{He}(e,e'd)$ experiment which involves the use of the South Hall MEPS and OHIPS spectrometers, which will also be used in 89-15. Two other Japanese physicists are planning to come to UMass in September in order to prepare for this experiment and to help with the UMass ^3He experiment.

Papers have been published or are about to be published for three experiments completed several years ago at Bates: the threshold electrodisintegration of the deuteron, elastic magnetic scattering from ^{89}Y , and a measurement of transverse form factors of low-lying states of ^{117}Sn .

As is pointed out in Section II.B., several papers have been published related to work completed at the Stanford Linear Accelerator Center (SLAC) largely in collaboration with American University physicists. Our major project involving SLAC has been the analysis of data largely acquired as background over many years by the TPC/ 2γ collaboration. This background came from the scattering of 14.5 GeV electrons and positrons from residual gas in the PEP storage ring's vacuum chamber. These scattered electrons and positrons, as well as pions, kaons, protons, deuterons, etc., were detected in forward calorimeters and in the Time Projection Chamber (TPC). This TPC analysis work was undertaken for three central reasons: (1) the 14.5-GeV beam energy is considerably higher than is planned for CEBAF, (2) the data

are unique in the entire world at this time, and (3) the experience gained in analyzing these final state multiparticle data acquired with a very large detector having a large solid angle should prepare us for data analysis for the CLAS detector at CEBAF when it becomes operational in 1996. The type of physics involved in the TPC analysis, e.g., nucleon resonance excitation, was new to our group, and thus has led us in new directions. This work has required a major effort on our part as both of our postdoctoral research associates, a graduate student, two Russian undergraduate students, two senior Russian visitors, as well as Professor Miskimen, have all been involved in this analysis. We expect to draw this project to completion before the year's end. Although we do not have high statistical accuracy, we think that several interesting conclusions can be drawn from these exclusive data which simply could not have been obtained from single-arm, or small solid-angle coincidence studies.

In Section II.C. a long-term study of the ^{10}B nucleus is described. This nucleus has been examined by us with a variety of techniques and probes. For example, elastic and inelastic magnetic scattering of electrons has been used in single-arm experiments at Bates and NIKHEF, as well as $(e,e'p)$ coincidence studies at NIKHEF and (γ,p) reactions at Lund. By virtue of these measurements the ground state and the 1.74 MeV first-excited state of ^{10}B are among the best understood states of all nuclei.

Another project that has involved our group in a significant way is the design of the signal and high-voltage translator boards in electronics development for the innermost drift chamber of the CLAS detector at CEBAF. This is described in section II.D. During the past year considerable progress has been made with this project. Since the first beams are expected in very late 1993 from the CEBAF accelerator, and the CLAS detector is not expected to be operational until 1996, and since we have approved experiments which involve the use of the CLAS detector, it is clear that no data will be acquired until at least 1996 on the two approved CEBAF experiments proposed by UMass.

In part III theoretical work on parity-violating electron scattering and nuclear structure are described. The final two sections of this progress report lists publications by our group and the various seminars and colloquia given at UMass in the past year.

In each of the subsections that follow, references and figures pertaining to that particular subsection are placed immediately after it.

II. Experimental Work

A. Experiments at the Bates Linear Accelerator Center

1. Experiment 87-02: Measurement of Deuteron Threshold Electrodisintegration

In conventional models, the nucleon-nucleon force is mediated by meson exchange. One of the most striking examples for the validity of the meson exchange representation of the nucleon-nucleon (NN) force is found in the threshold electrodisintegration of the deuteron at backward electron scattering angles. At low excitation energy in the neutron-proton center of mass (E_{np}), this reaction is dominated by an M1 spin-flip transition between the deuteron ground state and the unbound 1S_0 $T = 1$ scattering state. At a four-momentum transfer squared (Q^2) of approximately 12 fm^{-2} , the consideration of meson exchange currents (MEC) is essential in explaining the absence of a minimum predicted to exist in the cross section due to the destructive interference between $^3S_1 \rightarrow ^1S_0$ and $^3D_1 \rightarrow ^1S_0$ transitions.¹

At higher momentum transfers, where Q^2 equals or exceeds M_N^2 , the reaction becomes sensitive to factors that include relativistic effects, the NN potential model, and the nucleon electromagnetic form factors.² The availability of data at high Q^2 not only serves as a test of these effects, but also probes MEC with a spatial resolution where mesonic theories may no longer be valid. In particular, for $Q^2 > 40 \text{ fm}^{-2}$, the spatial resolution of the virtual photon probe is less than the typical hadronic size of 1 fm. Indeed, several exploratory calculations have been made of threshold electrodisintegration which treat the deuteron as a six-quark cluster at short distances. As the simplest nucleus, the deuteron can provide the most unambiguous test of such concepts.

Previous measurements of the threshold electrodisintegration lack either the Q^2 range or the energy resolution required to comprehensively examine non-nucleonic effects in the kinematic region where these are expected to be dominant. Data from Saclay³ have good resolution, $\Delta E_{np} = 1.7 \text{ MeV}$ full-width at half-maximum (FWHM) but only extend to $Q^2 = 28$

fm^{-2} . Data from SLAC extend to $Q^2 = 71 \text{ fm}^{-2}$ but have coarse resolution, $\Delta E_{np} = 10$ to 20 MeV FWHM, and are discussed in the section entitled "Experiments at the Stanford Linear Accelerator". Coarse resolution complicates the interpretation of the data and may obscure features such as the possible presence of a minimum in the differential cross section near threshold. Moreover, theoretical calculations predict considerably different shapes for the differential cross section: some models predict cross sections that rise monotonically with E_{np} and others give sharp cusps just above threshold. Such features cannot be resolved in poor resolution experiments.

A measurement of the threshold electrodisintegration of the deuteron at high Q^2 with good energy resolution, $\Delta E_{np} \approx 2.5 \text{ MeV}$ FWHM, was performed at the MIT-Bates Linear Accelerator using the Energy Loss Spectrometer System⁵ in the spring of 1990. This experiment was a collaborative effort involving the University of Massachusetts, M.I.T., American University, Saclay, University of Illinois, and Shizuoka University, and served as the Ph.D. thesis experiment for Kyong Sei Lee of the University of Massachusetts and William Schmitt of M.I.T. Data were taken at beam energies of 347, 574, 750, 813, and 903 MeV at a scattering angle of 160° , corresponding to momentum transfers squared of 8.7, 20.5, 31.3, 35.5, and 41.7 fm^{-2} , respectively, using a liquid deuterium (LD_2) target cell.⁴

Because the anticipated count rate at the highest Q^2 was only a few counts per day, the spectrometer focal plane and data acquisition software were optimized for background rejection. Transverse array drift chambers made at UMass were placed in the spectrometer focal plane and were used to restrict the range of acceptable track angles, greatly reducing cosmic ray backgrounds. The remaining cosmic ray muons were rejected with a 12 radiation length lead glass shower counter array borrowed from SLAC. Pions were rejected with a Cerenkov counter made at Saclay that used isobutane at atmospheric pressure as the light-producing medium.

Radiative corrections to the data were assessed for each value of E_{np} by means of a Monte Carlo simulation that included Landau straggling and bremsstrahlung. Figure 1 shows the 750 MeV cross sections corrected for radiative effects as a function of E_{np} . The resolution function resulting from the Monte Carlo simulation and normalized to the same elastic cross section is also shown. The systematic errors in the cross sections, estimated at approximately $\pm 3\%$ and dominated by uncertainties in target thickness and density, are negligible compared to the statistical errors for all but the 347 MeV data point. However, uncertainties of elastic peak positions caused additional systematic errors in the threshold cross sections. For the 750 and 813 MeV data, they were 13% and 25%, respectively. For the rest of the data, they were less than 10%. The elastic scattering data are in agreement with previously measured values for the deuterium elastic cross section⁶ at 347 MeV and the hydrogen elastic cross section⁷ at 903 MeV.

Figure 2 shows the Q^2 dependence of the threshold data averaged over the range $E_{np} = 0$ to 3 MeV, along with previous results from Saclay³ that had comparable energy resolution. Figure 2 also compares these data sets with coarse resolution data⁴ from SLAC that were averaged over a range $E_{np} = 0$ to 10 MeV. These new data averaged over $E_{np} = 0$ to 3 MeV show that the cross section departs from a pure exponential slope at $Q^2 \approx 25 \text{ fm}^{-2}$, with perhaps some evidence for a minimum near $Q^2 \approx 35 \text{ fm}^{-2}$. The difference between the SLAC and Bates results may be due to the significant participation of multipole transitions associated with P-wave states at higher excitation energy in the coarse resolution SLAC data.

Calculations by Schiavilla and Riska⁸ are shown in Fig. 2. They use the Argonne v_{14} potential⁹ and sum over all partial waves up to $J \leq 2$. This figure shows the results for both F_1^v and G_E^v for the exchange current, as well as for nucleon EM form factors given by either the dipole or Gari and Krümpelmann¹⁰(GK) expressions. The results of calculations shown in Fig. 2 show a large sensitivity to the choice of the nucleon EM form factors. For the v_{14} calculation the deviation between the dipole and GK predictions is as great as that between

prediction using F_1^V and G_E^V . This is caused primarily by the large difference in the dipole and GK parameterizations of the neutron electric form factor.

Excitation energy spectra at $Q^2 = 31.3, 35.5$, and 41.7 fm^{-2} are shown in Fig. 3. At $Q^2 = 31.3 \text{ fm}^{-2}$ the data may show the persistence of the threshold cusp that has been widely observed at much lower values of Q^2 . However, this threshold cusp is completely diminished at $Q^2 = 35.5 \text{ fm}^{-2}$. Figure 3 also shows predictions by Arenhövel et al.¹¹ that use the Bonn and Paris potentials¹² and sum over all multipole transitions $L \leq 6$. The dashed curves and dash-dotted curves are Bonn potential calculations for F_1^V and G_E^V , respectively, and solid curves are Paris potential calculations for F_1^V . All of the calculations use the dipole expression for the nucleon form factors. In these calculations, Arenhövel et al. have added relativistic corrections to their non-relativistic calculations. The large deviations between the v_{14} calculations (Schiavilla et al.) using F_1^V and G_E^V in Fig. 2 seem to be somewhat diminished. This indicates that the relativistic effect becomes more significant as the speed of the recoiling n-p system increases. Hence, the large deviations between the predictions using F_1^V and G_E^V partially result from a difference in relativistic order between these two types of form factors. However, comparing the two Bonn potential calculations (dashed curves and dash-dotted curves in Fig. 3), it is shown that the deviation becomes severe again for the 903 MeV data ($Q^2 = 41.7 \text{ fm}^{-2}$). Figure 3 also shows the sensitivity of the predictions to the potential model. This is attributed to differences between potential models for the predicted D-state admixture in the deuteron and for the radial forms of the S and D waves.

The non-relativistic calculations in Fig. 2 are similar in that they use a current operator that is consistent with the interaction model.¹³ To ensure current conservation, their calculations use the single universal isovector nucleon EM form factor to describe the structure of the MEC. In these calculations there is an ambiguity as to whether the isovector Dirac (F_1^V) or the isovector Sachs form factor (G_E^V) should be used for the exchange current. This approach differs from that of Gross et al.¹⁴ who have shown that a single universal form factor, such as

F_1^V or G_E^V is not required by current conservation and that a conserved current can be constructed using different EM form factors for the pion, nucleon, and contact contributions.

The results of quark cluster calculations by Cheng and Kisslinger¹⁵ and by Yamauchi et al.¹⁶ are also shown in Fig. 4. In Cheng and Kisslinger's model the deuteron is treated as a six-quark state within a 1 fm matching radius and as a two-baryon state outside the radius. Yamauchi et al. use resonating group methods to connect the short distance six-quark configuration of the deuteron smoothly with the long-distance two-nucleon configuration. These models incorporate not only quark- and gluon-exchange mechanisms at short distance but also MEC at long and intermediate distances. Figure 4 shows that both of these calculations predict a second maximum in the cross section. While other quark cluster calculations, such as those by Chemtob and Furui¹⁷ and Glozman et al.¹⁸ may not show a second maximum, in Cheng and Kisslinger's model this structure cannot be avoided.

Two advances are required for better understanding of this fundamental M1 spin-flip transition in the deuteron: first, a reliable estimate of relativistic effects; and second, incorporation of more accurate experimental data for the electric and magnetic form factors of the proton and neutron, such as those discussed under our SLAC activities. When these form factors are better established, the data presented here will provide an important test for relativistic theories and for models of the NN interaction. Even with spatial resolutions of less than 1 fm, there is no evidence for the breakdown of nucleon-meson theories and no explicit evidence that quark degrees of freedom play a significant role in this Q^2 range.

In November 1991 a Physical Review Letter was published for this experiment, and we are now working on a longer paper to be submitted to Physical Review C which will contain some of the recent results given in this section.

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Figure 1

Figure 2

Figure 3

Figure 4

2. Experiment 89-03: Measurement of the Elastic Magnetic Form Factor of ^3He at High Momentum Transfer

The elastic magnetic form factor of ^3He is one of the few observables in all of nuclear physics in which non-nucleonic degrees of freedom are clearly manifest. Figure 1 shows magnetic form factors calculated by Hadjimichael et al.¹ and by Schiavilla et al.², as well as impulse approximation calculations (IA). Clearly the IA cannot explain the existing data of Cavedon et al.³ and of Dunn et al.⁴ In the region of $Q^2 = 8 \text{ fm}^{-2}$, the cross section is almost entirely due to non-nucleonic processes because of the suppression of the IA amplitude due to destructive interference between the S and D state matrix elements of the single nucleon current operator. However, reasonable agreement is obtained when the effects of Δ -isobar and meson exchange currents (MEC) are included. The existing data only go to a momentum transfer squared of about $Q^2 = 31 \text{ fm}^{-2}$.

We plan to make measurements at higher Q^2 , up to 54 fm^{-2} . Since the anticipated cross sections for these momentum transfers may be of the order of $10^{-40} \text{ cm}^2/\text{sr}$, a dense target and a high beam current must be used in order to obtain reasonable counting rates. Consequently a high luminosity target system is being built and tested for this approved experiment. It uses cooled ^3He at high pressure from which heat deposited by the beam is continually removed. The target will be viewed by the ELSSY spectrometer set at a 160° scattering angle in the Bates North Hall. The scattered electrons will be detected in the ELSSY focal plane with the same detection system used in the deuteron threshold electrodisintegration experiment⁵ carried out in April and May of 1990. For that experiment new drift chambers were built at UMass for measurements in the transverse direction, a lead-glass shower counter borrowed from SLAC, and a compact Cerenkov counter was made by the Saclay group. The combination of this equipment gave greatly improved tracking and background rejection compared to the former system. Plans call for 2500 liters of ^3He to be pressurized to 50 atmospheres and reduced in temperature to 22K. The gas will be driven by a fan around a closed circulation loop containing

a heat exchanger to remove the heat deposited by the beam, as shown in Fig. 2. The heat exchanger will be connected to the Bates 200 W ^4He refrigerator, which in turn will be connected to both the Bates compressor, and to an identical second compressor obtained from SLAC. The use of two compressors in parallel should permit more reliable operation of the refrigerator. Temperature and pressure will be continuously monitored by a dedicated PC, which will also control heaters in the circulation loop in order to maintain a constant temperature and pressure. The 19.6 cm long target cell consists of two thin aluminum cylinders with non-concentric parallel axes in the horizontal plane. Gas flows down the inner cylinder, strikes an end cap and returns through the outer cylinder to be recirculated through the cooling loop as shown in Fig. 3. For cross section normalization purposes a separate hydrogen target loop with an identical cell will be assembled below the ^3He loop together with an empty target cell, a viewing screen, and a CH_2 target. A remotely controlled linear actuator will be used to move the targets in and out of the beam. All coordinate degrees of freedom are adjustable for this target changer while the targets are under vacuum in the scattering chamber, thus permitting accurate positioning with respect to the beam. The target changer is mounted on a larger flange above a new spool piece which fits above the Bates standard scattering chamber.

Most of the equipment specific to this experiment has been built at UMass. Various high pressure components, such as the target cells and the heat exchanger, have been vacuum leak checked and pressure tested at liquid nitrogen temperatures. About 90% of the components shown in Fig. 2 have been completed and individually tested, but await assembly as a complete unit. A gas-handling system has been designed, the components acquired, and is being assembled at this time. After the complete system is assembled and tested at UMass this summer, it will be moved to Bates for further tests with the refrigerator and compressors. Two University of Massachusetts students will base their Ph.D. theses upon the experiment. One will concentrate upon the elastic magnetic scattering and the other upon the threshold electrodisintegration data which will be obtained in the same spectrometer momentum bite as the

elastic scattering. After the experiment is completed, most of the equipment will remain at Bates and will be available to others for their use. Cryogenic engineer John Mark of SLAC is assisting in all aspects of this project.

The anticipated data shown in Fig. 1 is based on the following assumptions: An allocation of 480 hours of beam time, an average beam current of 25 μA , a target pressure of 50 atmospheres, and a target temperature of 22K. There is substantial difference between the theories in the Q^2 region above about 46 fm^{-2} . It should be possible to differentiate between the existing theories.

Approximately 4400 STP liters of 99.99% pure ^3He will be transferred this month from the Department of Energy Savannah River Facility to the Bates Laboratory to be used for this experiment and for the R.P.I.-Illinois experiment 88-22 $^3\text{He}(\text{e},\text{e}'\text{d})$. Other aspects of this experiment are discussed in the accompanying proposal.

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Figure 1

Figure 2

Figure 3

**3. Experiment 89-15: Coincidence Out-of-Plane Measurement
of the $D(e,e'p)$ Cross Section at Low Excitation Energy
and High Momentum Transfer**

This experiment is being carried out in collaboration with physicists from Japan as well as from Bates. The spokesman for the experiment is Tadaaki Tamae of Tohoku University who made the first out-of-plane coincidence measurements on a nucleus at the Tohoku 150 MeV pulse stretcher, the first pulse stretcher storage ring.

This experiment does not require the OOPS spectrometer system because of the kinematic boost near threshold breakup which "compresses" the center-of-mass angle in the laboratory frame. Instead the OHIPS spectrometer will be used for electron detection, and the MEPS spectrometer for the relatively low energy protons. A very thin target is necessary in order that the low energy protons can exit the target without very large ionization energy losses.

During the past year the target cell has been developed in Japan with 0.4 mil Havar walls. In August several members of the collaboration from Japan met with Bates and UMass personnel at the Gordon Photonuclear Reactions Conference. A discussion ensued of necessary running conditions and other experimental details. The existing target cell at that time was taken to UMass for pressure tests. In late May of 1993, Akio Hotta, a collaborator from Shizuoka University visited UMass and Bates for two weeks in order to make further plans for this experiment. These are discussed in the accompanying proposal.

4. Experiment 84-28: Transverse Form Factors of ^{117}Sn

Transverse form factors for low-lying states in ^{117}Sn were measured at Bates by 180° electron scattering in the momentum transfer range $q_{\text{eff}} = 1.1 - 2.4 \text{ fm}^{-1}$. Motivation for this experiment came from (e,e') measurements¹ of the elastic M1 form factors of ^{207}Pb and ^{205}Tl , which revealed a deep minimum in the M1 form factor of ^{205}Tl near $q_{\text{eff}} = 1.5 \text{ fm}^{-1}$. According to the independent particle model (IPM), the $J^\pi = 1/2^+$ ground state of ^{205}Tl arises from an unpaired proton hole in the $3s_{1/2}$ valence orbit of the ^{208}Pb core. However, at $q_{\text{eff}} = 1.5 \text{ fm}^{-1}$ the form factor predicted by the IPM exceeds the measurements by more than one order-of-magnitude. Remarkably, the strong suppression of the M1 form factor had been predicted by two prior theoretical evaluations^{2,3} of first-order core polarization (CP). In these calculations the minimum results from almost complete destructive interference between the IPM matrix element and CP terms associated primarily with the tensor force in the effective interaction. The size of the CP effect in ^{205}Tl subsequently attracted much attention as evidence for the underlying validity of the CP treatment.

Results from particle-transfer reactions suggest that the dominant configuration in the $J^\pi = 1/2^+$ ^{117}Sn ground state also has an unpaired nucleon in the $3s_{1/2}$ orbit. *A priori*, however, it was not clear that the CP effects in the M1 form factor of ^{117}Sn should necessarily resemble those seen in ^{205}Tl . In ^{205}Tl the $3s_{1/2}$ valence particle is a proton, and both the proton and neutron shells are almost full. Moreover, whereas the ^{117}Sn proton shell is closed, the valence $3s_{1/2}$ neutron orbit lies midway between the $N=50$ and $N=82$ major shell closures. Nevertheless, the elastic M1 form factor of ^{117}Sn indicated in Fig. 1, turned out to be remarkably similar to that of ^{205}Tl . Again CP proved to be the crucial ingredient required to reach an understanding of the data. With its half-occupied valence neutron shell, ^{117}Sn poses a particular challenge for CP evaluations, which are normally confined to nuclei near the doubly-magic shell closures. We treated this problem using a method which combined $O\hbar\omega$ configuration mixing, evaluated by means of a shell-model calculation, with first-order CP to

configurations having excitation energies of $\geq 2\hbar\omega$. In this procedure the occupancies of the j -shells in the $0\hbar\omega$ shell-model neutron space were used to weight the CP contributions for particle excitation into the higher empty shells, as well as to determine the blocking of transitions from the closed neutron core into the $0\hbar\omega$ space. While this composite calculations is not entirely rigorous, it merges the key features of the shell model and CP.

As shown in Fig. 1, while these calculations account for the deep diffraction minimum near $q_{\text{eff}} = 1.5 \text{ fm}^{-1}$, the magnitude of the form factor maximum at $q_{\text{eff}} = 2.2 \text{ fm}^{-1}$ is still overestimated by a factor of approximately 2. Similar disagreements, seen in ^{205}Tl and ^{207}Pb have been interpreted⁴ as evidence for the need to include further depletion of the occupation probability near the Fermi surface. Confirmation of this conclusion for ^{117}Sn requires more complete and consistent calculations that include not only first-order CP, but also the effects of multi-particle-hole excitations outside the $0\hbar\omega$ space.

In addition to the elastic M1 form factor of ^{117}Sn , form factors were also obtained for transverse excitations of states at 0.159 MeV ($J^\pi = 3/2^+$), 0.317 MeV ($J^\pi = 11/2^-$), 0.712 MeV ($J^\pi = 7/2^+$), 1.01 MeV ($J^\pi = 3/2^+, 5/2^+$ doublet), 1.18 MeV ($J^\pi = 5/2^+$), as well as for excitations to multiplets at 1.45 and 1.57 MeV. These transitions appear to have appreciable single-particle character, and therefore provide additional tests for the various structure models. A paper reporting all our results will soon be published.⁵

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Fig. 1. Elastic M1 form factor of ^{117}Sn . The dotted and dashed curves represent the results of IPM calculations employing harmonic oscillator and Woods-Saxon radial wave functions. The dash-double-dotted curve shows the IPM harmonic oscillator result when MEC are included. Also shown are two core polarization calculations, both of which use harmonic oscillator wave functions. The dash-dot curve includes first-order CP, whereas the solid curve combines $0\hbar\omega$ shell-model configuration mixing with first-order CP to configurations with $2\hbar\omega$ or greater excitation energy.

5. Experiments 84-22 and 84-30: Ground state magnetization density of ^{89}Y

In collaboration with the University of New Hampshire group we have used the Bates 180° facility to measure elastic electron scattering from ^{89}Y in the momentum transfer range $0.72 < q < 2.67$ fm $^{-1}$. The M1 form factor was isolated and the ground state magnetization density extracted by means of a Fourier-Bessel analysis. The results were compared with calculations based on Migdal's self-consistent theory of finite Fermi systems¹. The phenomenological effective forces of this theory were made density-dependent using parameters fixed from properties of other nuclei², and core polarization configurations were introduced by means of a RPA-like expansion of the effective field. In this form only qualified agreement was obtained with the M1 form factor, excessively large polarization effects being the main cause for the discrepancy. This problem can be alleviated by weakening the strong repulsion in the spin-isospin term of the effective interaction. A paper reporting the above measurements and our interpretations has been accepted³ for publication in Physical Review C.

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6. Experiment 89-10: First Measurement of the Fifth Structure

Function in the $^{12}\text{C} (\vec{e} e, 'p)$ and $^2\text{H} (\vec{e} e, 'p)$ Reactions

Recently University of Massachusetts group members R. Miskimen and K. Wang participated in an experiment at the Bates Linac to measure a new observable f'_{01} - the so-called fifth structure function which corresponds to the imaginary part of the transverse-longitudinal interference response. Its observation in coincident electron scattering requires a longitudinally polarized beam and out-of-plane detection. The experiment was performed in the North Hall using a 560 MeV electron beam with 34% polarization. Electrons were detected in the ELSSY spectrometer and the protons were detected in the recently constructed Out-of-Plane Spectrometers (OOPS). The experiment was performed by the OOPS collaboration, and the University of Massachusetts participants were responsible for the ELSSY electronics and detectors.

In the $^{12}\text{C} (\vec{e} e'p)$ measurement f'_{01} was confirmed to be primarily sensitive to final state interactions (FSI) and therefore to the proton-nucleus optical potential. Model calculations that include meson exchange and isobar currents show almost no sensitivity to these currents. Relative to elastic (p,p') , a measurement of f'_{01} is more sensitive to the potential and to the FSI in the nuclear interior. It should therefore offer strong constraints to the proton-nucleus optical potential models.

A Physical Review Letter is being prepared on the ^{12}C measurement, and the deuterium results will be presented in another publication.

B. Experiments at the Stanford Linear Accelerator Center

1. Experiment NE-4: Deuteron Threshold Electrodisintegration

As was pointed out in the discussion of the Bates deuteron threshold electrodisintegration experiment, an earlier measurement was carried out at SLAC as part of the NE-4 experiment for which the central objective was the measurement of elastic magnetic scattering to high momentum transfers. The threshold data were necessarily of very coarse resolution (10 to 20 MeV FWHM), but were carried out at momentum transfers as high as 71 fm^{-2} . These results have been published first in an abbreviated form¹, and very recently in a more comprehensive article.² This work constituted the Ph.D. thesis subject of Marc Frodyma.

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2. Experiment NE11: Separation of the Charge and Magnetic Form Factors of the Neutron and Proton at Large Momentum Transfer

The charge and magnetic form factors of nucleons are determined by the internal distributions of charge and current, and hence are of fundamental interest. Moreover, a knowledge of these form factors is an essential ingredient for the understanding of electronuclear cross sections in general. An example of the latter is the electrodisintegration of the deuteron near threshold, identified as perhaps the best experimental test of the meson exchange representation of the strong interaction. In this case the understanding of the deuteron electrodisintegration cross section at large Q^2 has been impeded by uncertainties in the neutron electric form factor¹, G_{En} . SLAC experiment NE11 was proposed to not only improve the precision of data on the nucleon form factors, but also to extend the Q^2 -range of the available data. The experiment was performed at the SLAC end station A

using two detectors, the 8 GeV/c spectrometer at angles of 15° to 90°, and the 1.6 GeV/c spectrometer which was fixed at 90°

The proton form factors were determined by performing Rosenbluth separations of data obtained using a hydrogen target. The results, divided by the dipole fit $G_D(Q^2) = (1 + Q^2 / 0.71)^{-2}$ are shown in Fig. 1. For $Q^2 < 4$ (GeV/c)² these are in reasonable agreement with data from previous measurements. Also shown in Fig.1 are curves representing various theoretical predictions and fits. A full discussion of these curves can be found in our published paper². Although most of these theoretical interpretations adequately describe the decrease in G_{Mp}/G_D at large Q^2 , the models fare worse with G_{Ep} . In particular, the Gari and Krümpelmann³ (solid curve) and Iachello, Jackson and Lande⁴ VMD (dotted curve) fail badly at large Q^2 . The elastic cross section can alternatively be expressed in terms of the Dirac and Pauli form factors given by $G_{Ep} = F_1 - \tau(\mu_p - 1)F_2$ and $G_{Mp} = F_1 + \tau(\mu_p - 1)F_2$. According to PQCD, at large Q^2 the helicity nonconserving term F_2 should be suppressed by a factor of Q^2 compared to the helicity conserving term F_1 , so that the ratio $Q^2 F_2 / F_1$ should approach a constant. As indicated in Fig. 1c, this expectation is supported by our results.

The neutron form factors were determined by measuring quasielastic *ed* cross sections. The isolation of the neutron form factors from this reaction is model-dependent, requiring not only the subtraction of the proton and inelastic contributions, but also consideration of kinematic smearing due to Fermi motion. There could also be some sensitivity to final-state interactions, meson exchange currents, and a possible modification of nucleon properties inside the deuteron. Furthermore, at low Q^2 the neutron electric form factor G_{En} is inherently small. The results of our analysis, already published⁵, are shown in Fig. 2. The information on both G_{En} and G_{Mn} is markedly improved, especially at large Q^2 . The results of our analyses showed little dependence on either the choice of deuteron

wave function or the representation of the inelastic background. Greater sensitivity was found to proposed relativistic corrections⁵ for quasielastic scattering.

Both G_{En} and G_{Mn} were observed to be remarkably consistent with the simple dipole form. Fig. 2 shows, in particular, that the divergent theoretical treatments of Gari and Krümpelmann³ and Chung and Coester⁶, who used a relativistic constituent quark model, are both inappropriate. A fully detailed report on both the neutron and proton determinations is in preparation.

In order to assess the background due to the aluminum target cell used in NE11, additional measurements were made on an empty target cell. These data proved to be worthwhile in their own right, as we were able to extract publishable⁷ values for the deep inelastic structure function W_2 and the ratio of the longitudinal and transverse cross sections, $R = \sigma_L / \sigma_T$. These results span the kinematic range $1.75 < Q^2 < 7 \text{ (GeV/c)}^2$, and extend to $x = 1.37$. As shown in Fig. 3, they are well described by a microscopic calculation of Liuti⁸, which incorporates parameterizations of elastic and deep inelastic scattering as well as resonance excitation.

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Figure Captions

- Fig. 1. Results for proton form factors. Inner errors are statistical only; outer errors include point-to-point systematic errors.
- Fig. 2. Results for neutron form factors, extracted using a nonrelativistic quasielastic model and Paris deuteron wave function. Inner errors are statistical only; outer errors include point-to-point systematic errors.
- Fig. 3. Ratio of cross sections per nucleon for scattering from aluminum compared to deuterium. The indicated Q^2 values are for $x = 1$. Solid curves represent the results of calculations by Liuti.⁸

Figure 1

Figure 2

Figure 3

3. Experiment E140: Measurement of the x , Q^2 , and A dependences of $R = \sigma_L/\sigma_T$

The ratio of the longitudinal to transverse cross sections R for deep inelastic scattering (DIS), is a fundamental parameter for high energy leptonic interactions. Because R is sensitive to the spin and transverse momenta carried by the struck partons in DIS, measurements of its dependence on the kinematic parameters x and Q^2 provide important tests of the theory of QCD. Nevertheless, this potential had never been fully exploited because R is difficult to measure, and hence determined only imprecisely. Additional motivation for a precise measurement of R came from the practical need to reconcile a vast amount of data taken in a whole generation of experiments at laboratories such as SLAC, Fermilab, CERN, DESY and Cornell. Further interest in R came out of the suggestion that it may have an A -dependence which accounts for the classic EMC effect.

The first phase of what was to be experiment E140 was completed at SLAC during 1987, using the 8 GeV spectrometer of End Station A. Largely due to the intensive efforts to measure and improve the properties of this spectrometer, R was determined to an unprecedented precision of ± 0.03 throughout the range $1 \leq Q^2 \leq 10$ (GeV/c)² and $0.2 \leq x \leq 0.5$. These results showed, for the first time, a clear decrease of R with increasing Q^2 . Agreement with QCD predictions was obtained only if target mass effects and some higher-twist terms were considered. No A -dependence of R was found. These results were first published in 1988¹. A complete description of the experiment and analysis will soon be submitted for publication.

As a byproduct of experiment E140, data were also obtained on the elastic form factors of the proton in the range $1 \leq Q^2 \leq 3$ (GeV/c)². The preparation of a detailed paper on this work, also previously published as a letter², is close to finalization.

While the experiment E140 was successful, it did not fulfill all our objectives. In particular, poor linac performance prevented us from obtaining all the data sought in our original proposal. As a result, a request was submitted for additional beam time. This was approved and in the summer of 1991 further measurements were made, broadening the x -range of the data to $0.1 \leq x \leq 0.7$ and thereby affording increased sensitivity to possible higher-twist and diquark contributions. In addition, data

were obtained on both hydrogen and deuterium, enabling us to investigate if there was any evidence for difference between R_p and R_n , the longitudinal-to-transverse cross section ratios for the proton and neutron.

Preliminary results for the second E140 measurements were presented^{3,4} at the APS spring meeting in Washington this year. Within errors, it was found that $R_p = R_d = R_n$. Values measured for R at $x = 0.6$ and 0.7 appear to be somewhat larger than second-order QCD predictions that include target mass effects. Measurements were also made at a low Q^2 value of 0.5 (GeV/c)^2 in order to search for the onset of the decrease to zero that R must make as the photoproduction limit $Q^2 = 0$ is approached. This decrease was not seen. For $Q^2 = 4.2 \text{ (GeV/c)}^2$ a measurement was made at the energy of the $\Delta_{3,3}$ resonance. The value obtained for R was consistent with zero. The analysis of these data is continuing at SLAC by two graduate students from American University. Numerous checks remain to be made, but final results should begin to emerge during 1994.

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4. Analysis of 14.5 GeV Electrons and Positrons Scattering from Gases in the PEP Storage Ring Using the TPC Detector

a. Characteristics of the Produced Hadrons

The understanding of highly excited nuclear matter presents a challenge to the modern physics of strong interactions. Cumulative particle production from nuclei,¹ the EMC effect,² and other experimental evidence indicates that nuclei may not be considered to be simply sets of quasi-free nucleons, and/or that the properties of nucleons inside nuclei, such as their structure functions, are different from those of free nucleons. On the other hand, experimental observations of interactions at energies above approximately 1 GeV show several regularities such as the independence of secondary particle spectra on projectile energy, the atomic number of the target nucleus, the type of the projectile (proton, pion, electron, neutrino, etc.), and the saturation of yields of the secondary particles from nuclei at some critical incident energy varying approximately as $A^{1/3}$ ("limiting fragmentation"), and others.¹ Theoretical approaches to understand these effects based upon QCD seem to be difficult. On the other hand, phenomenological models using "fluctons" (multi-quark bags, or droplets of quark-gluon plasma), or projectile interactions with close groups of nucleons ("short range correlations"³), are available.

In order to clarify the situation phenomenologically, a series of experiments have been proposed using electron beams. The electromagnetic vertex is known very well, and if the scattered electron is detected, then the energy-momentum transfer to a nucleus may be measured in the interaction. This may simplify theoretical analysis. Two proposals,⁴ one for the CLAS detector at CEBAF, and one for the PEP storage ring at SLAC,⁵ were submitted by the authors. The CEBAF proposal was approved and we are taking part in the CLAS detector construction, and hopefully in the future, in the collection and analysis of the data.

As a part of the preparations for the CLAS experiments, we decided to analyze available electron-nucleus interaction data taken at 14.5 GeV with the TPC/two-gamma detector⁶ at the

PEP electron-positron storage ring at SLAC. Advantages of the detector are large acceptance, large kinematic coverage in momentum transfer squared Q^2 and in energy transfer ν , and the ability to detect many-body final states.

The TPC/two-gamma facility is shown in Fig. 1. The time-projection chamber (TPC) tracks particles in a 13.25 kG solenoidal magnetic field, using dE/dx measurement for particle identification as shown in Fig. 2. The solid angle coverage of the TPC is approximately 80% of 4π steradians. Neutral particles are identified with the gas-lead-laminate barrel and pole-tip calorimeters that surround the TPC. Electrons and positrons scattered at small angles (22 mr to 180 mr) were tagged in the forward "two-gamma" spectrometers⁷ located at each end of the TPC. The data were obtained from the analysis of the electron or positron interactions with the nuclei of residual gas in the beam pipe, and also from the dedicated runs⁸ in which deuterium, argon, and xenon gases were injected into the PEP ring. The residual gas in the PEP ring consisted of hydrogen and carbon-monoxide (CO). The detector trigger required at least one charged hadron in the TPC and an electron or positron tag in one of the forward spectrometers with $E > 2$ GeV. The selection of the interactions with the nuclear target required at least two charged tracks in the TPC with a common vertex at least 5 cm, but no more than 25 cm from the e^+e^- interaction region. An example of an event is shown in Fig. 3. The number of tagged events selected was 22,700 for (HCO) beam-gas, 4,700 for deuterium, 2,500 for argon, and 1,000 for xenon.

The schematic diagram of the process is shown in Fig. 4, together with a standard set of reaction variables from the kinematics of electron scattering and inclusive particle production. Figure 5 shows experimental distributions of the events on a Q^2 versus ν plot. The distribution is peaked at low Q^2 ($0.2 \text{ GeV}^2/c^2$) and relatively low ν (1 GeV). But ranges in Q^2 and ν are rather wide ($0.1 - 5 \text{ GeV}^2/c^2$) and ($0.1 - 12 \text{ GeV}$). Various model approaches to electron scattering, for example, nucleon resonance, deep inelastic scattering (DIS), vector meson

dominance (VMD), etc., apply to different regions in the Q^2 versus ν diagram. The regions are not defined rigorously, but qualitatively one may say that the resonance part may dominate at $W \sim < 2$ GeV, DIS at high $Q^2 > \sim 0.5-1.0$ GeV²/c² and $x_b > \sim 0.1$ where $x_b = Q^2/2M\nu$, and VMD at low Q^2 and high ν , as defined in Fig. 4. We may say that the data cover a transition region between VMD and DIS, and that a sufficient part of the data lie in the region of ν where nucleon resonance production in nuclei may be studied. The data could represent a reference point for the future higher Q^2 experiments at CEBAF.

Figure 6 shows the dependence of the invariant inclusive cross-section on the transverse mass for protons and charged pions produced in e-(beam-gas) interactions in different intervals of rapidity y . The data have been corrected for the detector acceptance. In this form the inclusive spectra are comparable with the results obtained from proton interactions with nuclei⁹ at 14.6 GeV/c as indicated by the solid lines in the figures. The overall normalization is arbitrary, but the relative normalization between protons and positive and negative pions is kept. We may conclude from this figure that the "nuclear scaling" regularities are fulfilled: The spectra and relative yields of secondary hadrons do not depend on the type of incident particle at this energy.

Figure 7 shows that within the limits of statistical errors, there are no changes in the spectra when we choose events with high Q^2 in the reaction. Assuming now that the spectra and the relative yields of the secondary hadrons do not depend on Q^2 and ν , and integrating the yields of protons and charged pions with $y < 1$ (target fragmentation region) we can study the nuclear response (the mean multiplicity of such hadrons) as a function of ν of the electron. We believe that the efficiency and acceptance of the forward calorimeters and the efficiency and acceptance of the TPC detector are independent, and that the TPC acceptance does not depend on ν . Figure 8 shows the dependence of the mean multiplicity on ν . The "saturation" of the nuclear response at $\nu = \sim 2$ GeV seen in the figure is also characteristic of "nuclear scaling."

The large acceptance of the TPC detector together with its relatively high neutral particle detection efficiency permitted the investigation of resonance production in electro-nucleus interactions. The resonance vector mesons ρ and ω are of particular interest. There are several considerations on possible nuclear medium effects which could influence the position and width of vector mesons production and decay in the nuclear medium.¹⁰ From an experimental point of view the detection of ω mesons seems to be most effective because of its narrow resonance width. Figure 11 shows the mass distribution of the π^+ , π^- , and π^0 combinations of the events with small combinatorial background (number of pions of each kind equals to 1) for the case when at least one additional proton is observed in the event. The missing momentum and energy distributions clearly indicate interaction on a nuclear target. The position of the ω peak is shifted by 45 MeV with respect to the accepted value. This cannot be attributed to systematic errors. This result requires more detailed Monte-Carlo study.

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Figure Captions

- Fig. 1. Diagram of the TPC/Two-gamma facility at SLAC.
- Fig. 2. Distribution of tracks measured in the TPC detector on $\ln(dE/dx)$ versus $\ln p$ where dE/dx is the specific energy deposition in the TPC volume in arbitrary units and p is the momentum of the particle in GeV/c. The values of dE/dx and p were used for particle identification. Arrows show the limits on momentum used to identify unambiguously protons and charged pions.
- Fig. 3. The output picture of the event-display program showing a 3-prong event with a vertex outside electron-positron interaction region.
- Fig. 4. Schematic diagram of electron-nucleus interaction. A list of common reaction variables is given.
- Fig. 5. Experimental distributions of the events on a $Q^2 \nu$ plot. The size of boxes in each bin in the upper plot correspond to the logarithm of the number of events in the bin. The lines correspond approximately to the angular acceptances of the two sensitive detectors in the forward direction: the NaI calorimeter and the shower counter, respectively. The lower figures show the dependence of the distribution of events on ν and Q^2 .
- Fig. 6. Particle production in e-(CO) interactions. Invariant cross sections are shown as a function of $m_t - m_0$. There are three panels in the figure for the identified π^+ and π^- and protons. In each panel, spectra are binned in rapidity intervals $\Delta y = 0.8$ for pions and $\Delta y = 0.4$ for protons. The spectra are displaced vertically by multiplying each by powers of 10 for each rapidity step $\Delta y = 0.2$ (the proton spectra are displaced by a factor of 100 and pion spectra by a factor of 10,000). The notation is the same as in Ref. 9 except that our data have arbitrary overall normalization. The solid lines show the spectra of protons and charged pions measured in (p,Be) interactions at 14.6 GeV/c, which may be compared to our data in the rapidity interval for which $\bar{y} =$

1.1 for pions and $\bar{y} = 0.7$ for protons. The slopes of the spectra and relative yields of protons and pions show good coincidence between the two experiments.

- Fig. 7. Invariant cross sections of charged pion and proton production in e-(CO) interactions in the region of $Q^2 > 1$ (points). The notation is the same as in Fig. 6. The solid lines are taken again from Ref. 9. The dashed lines indicate e-(CO) data at $Q^2 \leq 1$. (Overall normalization is arbitrary).
- Fig. 8. The multiplicity of the identified protons and charged mesons in the nuclear fragmentation region ($y < 1$) as a function of transferred energy ν for (e-CO) interactions.
- Fig. 9. x_F distributions of protons and charged pions produced on different targets: D, Ar and Xe (points) compared with x_F distributions measured on CO. Since the statistics on CO are much higher than on the other targets, the distribution is shown as a curve without statistical errors. The normalization is on the total number of entries in each distribution.
- Fig. 10. x_F distributions (points) corrected by the detector acceptance, for protons produced in e-(CO), e-Ar and e-Xe interactions at $W > 2$ (outside resonance region) compared with different models: LUND (dash-dotted line, present only for e-(CO) data), VENUS (dashed line) and DINREG (dotted line).
- Fig. 11. The experimental distribution of the effective mass of π^+ , π^- , π^0 combinations for e-(CO) interactions with at least one proton present in the event (upper panel); the same distribution with subtracted estimated background and ω resonance fitting curve.

PEP-9 2γ Detector

XBL 845-2033

Figure 1

Figure 2

Figure 3

Reaction Variables

Electron

$$\nu = E_0 - E'$$

$$q = k - k'$$

$$Q^2 = -q^2 = 4E_0E' \sin^2(\theta/2)$$

$$W^2 = M_N^2 + 2M_N\nu - Q^2$$

$$x_B = Q^2/(2M_N\nu) \quad (\text{Bjorken } x)$$

Figure 4

Secondary hadrons

Invariant inclusive cross-section in the form:

$$\sigma_{\text{incl}} = E d^3\sigma / (d^3p) = d^3\sigma / (dy d^2p_t), \text{ or}$$

$$\sigma_{\text{incl}}(y, m_t) = (1/m_t) d^2\sigma / (dy dm_t), \text{ where}$$

$$m_t^2 = m_0^2 + p_t^2 = \text{transverse mass, and}$$

$$y = (1/2) \ln((E + p_z)/(E - p_z)) = \text{rapidity}$$

$$x_F = (p_z/p_{z, \text{max}})_{\text{cm}} = (\text{Feynman } x)$$

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

**b. Electroproduction of Nucleon Resonances in Nuclei and the
(e,e'p π^-) and (e,e'pp) Reactions**

Since the advent of multi-GeV electron accelerators it has been known that electroproduction and photoproduction cross sections on the nucleon exhibit a series of three maxima corresponding to the excitation of nucleon resonances (N*'s), of which the first and most prominent is due to the $\Delta(1232)$ resonance.¹ While N* properties have been extensively studied in inclusive and exclusive reactions on the nucleon,² much less is known about the excitation of nucleon resonances in nuclei. Because of Fermi motion and N*-nucleus interactions, modifications of the resonances by the medium might be expected. For example, the nuclear resonance peak widths and centroids as well as the resonance decay modes and angular distributions might differ from those of the nucleon. The presence or absence of these effects can help to constrain models for the N*-nucleus interaction and possibly models for nucleon resonance structure.

The electron can be used as a precise probe of resonance excitation in nuclei. In the Δ resonance region several electron scattering inclusive and exclusive measurements have been performed. An analysis of inclusive electron scattering data on p-shell nuclei at low four-momentum transfer ($Q^2 \approx 0.1 \text{ GeV}^2/c^2$) indicates that the integrated Δ peak is enhanced by approximately 34% and is broadened by an additional 185 MeV, compared to the proton,³ although at higher Q^2 there is no enhancement.⁴ These analyses also show a Q^2 dependent shift of the Δ peak. At $Q^2 \approx 0.35 \text{ GeV}^2/c^2$ the fitted peak position is 1.250 GeV instead of 1.232 GeV at the photon point. The Q^2 dependent shift has been interpreted as evidence that the real part of the Δ -nucleus potential is more than twice as deep as the nucleon-nucleus potential.⁵ The ambiguity with these analyses is that channels unrelated to resonance production, such as quasi-deuteron absorption, may bias the results in an unknown way. This is seen in the exclusive $^{12}\text{C}(e,e'p)$,⁶ $^3\text{He}(\gamma,p)$,⁷ and (γ,pn,pp) ⁸ experiments in the Δ region, which have shown that multi-nucleon emission is a significant fraction of the inclusive cross

section. Medium effects have also been observed at a forward angle in the pion angular distribution for the $^{16}\text{O}(\gamma, p\pi^-)$ reaction in the Δ region,⁹ although additional data over a wide range of pion angles are needed to confirm this.

Much less is known about the second and third resonance regions in nuclei than the Δ region, although total photoproduction cross sections¹⁰ on Be, C, and ^{238}U and inclusive electron scattering¹¹ on Be and Al show no evidence for maxima in these regions, but nevertheless an enhanced smooth cross section. If confirmed, the absence of these resonances would indicate that the N^* -nucleus interaction in the second and third resonance regions is more absorptive than the Δ -nucleus interaction, causing the resonance width to broaden in the medium. The increased absorption could result from the large size of the N^* 's, and in the Isgur-Karl model the radial size of the $D_{13}(1520)$ and $F_{15}(1680)$ resonances are approximately 60% larger than the Δ . While the above measurements demonstrate the importance of the medium, they lack large solid angle acceptance, kinematic coverage in Q^2 and energy transfer, and the ability to detect many-body final states. To date there have been no exclusive measurements in the second and third resonance region for nuclear targets.

Using data taken at the TPC/ 2γ detector at the PEP electron positron storage ring¹² at Stanford, we are completing an analysis of the first measurements of $(e, e'p\pi^-)$ and $(e, e'pp)$ reactions in the nucleon resonance region taken with this nearly 4π solid angle detector. Our collaborators in this project are P. Degtyarenko, V. Gavrilov, and S. Shuvalov from the Institute of Theoretical and Experimental Physics, Moscow, Russia, and F. Dietrich and K. Van Bibber from Lawrence Livermore National Laboratory. The targets were the residual gases carbon monoxide (CO) and hydrogen (H_2) which were present in the storage ring, and Ar, D_2 , and Xe which were injected into the ring. The photon-nucleon invariant mass (W) range for these data is from 1 to 2 GeV, and the Q^2 range is from 0.1 to approximately 1 GeV^2/c^2 , with an average $Q^2 \approx 0.35 \text{ GeV}^2/c^2$.

The data were taken for both 14.5 GeV electrons and 14.5 GeV positrons circulating in the PEP ring. The time-projection-chamber (TPC) tracked particles in a 13.25 kG solenoidal magnetic field, using dE/dx for particle identification. The solid angle coverage of the TPC was approximately 80% of 4π . Neutral particles were identified with a gas-lead laminate barrel and with pole-tip calorimeters that surrounded the TPC. Electrons and positrons scattered at small angles ($22 \text{ mr} < \theta_e < 180 \text{ mr}$) were tagged in the forward 2γ spectrometers¹³ located at each end of the TPC, where the resolution was approximately 3.5% FWHM. Data were obtained both in dedicated runs and from an analysis of beam-gas interactions. In the dedicated runs,¹⁴ the gases D_2 , Ar, and Xe were injected into the PEP ring while electron and positron bunches were circulating. The detector trigger required at least one charged hadron in the TPC and an electron or positron tag in one of the forward spectrometers with $E > 4 \text{ GeV}$. Data were also obtained from interactions of the beam with the residual gas (beam-gas) in the PEP ring, which vacuum analysis indicates is hydrogen and carbon-monoxide (CO). The beam-gas data were extracted from previously recorded two-photon interaction data¹³ by requiring at least two charged tracks in the TPC with a common vertex located at least 5 cm, but no more than 25 cm from the e^+e^- interaction region. In the event selection, only events with the correct number and type of hadrons contained in a single vertex were considered. Events with neutral hits in the TPC calorimeters, possibly indicating π^0 production, were rejected.

For the $(e,e'\rho\pi^-)$ reaction cuts were placed on missing energy ($|E_m| < 0.4 \text{ GeV}$), missing momentum parallel to the beam axis ($|p_{mz}| < 0.4 \text{ GeV}/c$), and missing transverse momentum ($|p_{mx}|, |p_{my}| < 0.25 \text{ GeV}/c$). Figure 1a shows the p_{mx} distribution for the pp^- beam-gas events, where the total detector resolution including electrons and produced particles is approximately 0.07 GeV/c FWHM. The curves are Monte Carlo calculations scaled to the data using harmonic-oscillator momentum densities for ^{12}C and ^{16}O . The calculations indicate that quasi-free production from CO (solid curve) is dominant, with a smaller background

consistent with a $p\pi^-N$ final state (dashed curve). The p_{mx} distribution for the $(e,e'pp)$ data is shown in Fig. 1b with cuts $|E_m| < 0.4$ GeV and $|p_{mx}| < 0.4$ GeV. The distribution is significantly broader than that for the $p\pi^-$ data and the calculations shown in the figure for a pp final state (solid curve) and a ppn final state (dashed curve) indicate that n -body emission, where $n \geq 3$, is the dominant nucleon emission process in the resonance region. Because a four-body final state gives nearly the same p_{mx} distribution as a three-body final state, modeled here as n -body phase-space, the data cannot distinguish between a three-body or four-body final state.

To facilitate the comparison of the data with real photon and inclusive electron scattering cross sections, the $(e,e'x)$ cross section was modeled as,

$$\frac{d^2\sigma}{dE_f d\Omega} = \Gamma_V \sigma(W, Q^2),$$

where Γ_V is the virtual photon flux factor and $\sigma(W, Q^2)$ is the virtual photoproduction cross section. The dependence on virtual photon polarization was neglected. The variation of s with Q^2 was taken from the parameterizations of Brasse et al.¹ for $p(e,e')$, and W was calculated from $W^2 = (q + p)^2$ where q and p are the photon and Fermi-smeared nucleon four-vectors, respectively. Using the TPC/ 2γ Monte Carlo calculations, the W dependence of $\sigma(W, Q^2)$ at fixed $Q^2 = 0.35$ GeV²/c² was varied to agree with the experimental W and p_{mx} (for the pp data) distributions. The particle momentum and angular distributions predicted by the Monte Carlo calculations were in good agreement with the data. Normalized $p\pi^-$ cross sections on CO were obtained by using known observables for electro- and photo-reactions on the proton and neutron at the Δ peak.^{1,15} To normalize the data it was also necessary to estimate the ratio of quasi-free pp^- production per target neutron on $A = 14$ to deuterium, which has been measured⁸ with real photons as $0.56 \pm x$. The ratio can also be estimated from this data if it is assumed that the total number of events is proportional to the integrated luminosity times atomic mass number, giving 0.430 ± 0.047 . For cross section normalization a ratio of 0.5 was

assumed, and the same normalization factor from the pp^- data was applied to the pp data. The normalization error is estimated at $\pm 20\%$.

The preliminary $p\pi^-$ and pp cross sections for CO as a function of invariant mass are shown in Fig. 2a and 2b. The mass resolution is estimated at approximately 0.014 GeV FWHM. The figure also shows total cross sections for $\gamma n \rightarrow p\pi^-$ and inclusive $p(e,e')$ at $Q^2 = 0.35 \text{ GeV}^2/c^2$, where both distributions were scaled to fit the measured cross sections at the Δ peak. The figure shows that the shape of the quasi-free $p\pi^-$ cross section corresponds closely to the shape of the $\gamma n \rightarrow p\pi^-$ cross section in the Δ region. Assuming a Breit-Wigner line shape with fixed width 0.12 GeV and $(M_{pp^-} - M_p - M_{p^-})^{1/2}$ for the form of the non-resonant background, Δ peak positions were fitted for the ^2H , CO, and Ar + Xe data. The fitted peak positions, $1.214 \pm 0.014 \text{ GeV}$ for ^2H , $1.206 \pm 0.007 \text{ GeV}$ for CO, and $1.213 \pm 0.019 \text{ GeV}$ for Ar + Xe, are in agreement with the $p(e,e')$,¹ and $\gamma n \rightarrow p\pi^-$ results.¹⁵ However, they do not agree with the $A(e,e')$ results in this Q^2 region, where the fitted Δ position is 1.25 GeV.⁴ Figure 3 shows the Δ centroids from this analysis along with results from fits to inclusive (e,e') on ^{12}C and ^{16}O as a function of Q^2 .

Figure 2a shows that at higher excitation energy, $M_{p\pi^-} \approx 1.5 \text{ GeV}$, the second resonance is clearly observed in the quasi-free data and the correspondence with the γn data is quite good. In the third resonance, $M_{p\pi^-} \approx 1.7 \text{ GeV}$, the quasi-free data shows evidence for a maximum in this region, which appears more pronounced than in the γn data.

Preliminary data for the pion angular distribution relative to the three-momentum transfer for $M_{p\pi^-} < 1.4 \text{ GeV}$ are shown in Fig. 4. The angular distribution was acceptance corrected and normalized using the virtual photon cross section at $W = 1.210 \text{ GeV}$, and the virtual photon flux factor at $Q^2 = 0.35 \text{ GeV}^2/c^2$. Model studies indicate that the kinematic sensitivity of the angular distribution to the conditions $W = 1.210 \text{ GeV}$ and $Q^2 = 0.35 \text{ GeV}^2/c^2$ versus the actual W and Q^2 distributions of the data is small. The solid curve in the figure is a plane wave impulse approximation (PWIA) calculation for $(e,e'p\pi^-)$ at $W = 1.210 \text{ GeV}$ and Q^2

$= 0.35 \text{ GeV}^2/c^2$, where the cross section has been integrated over proton momentum and direction, summed over s-shell and p-shell knockout, and averaged for ^{12}C and ^{16}O .¹⁷ Because distorted waves were not used in the calculation, the data fall considerably below the calculations in magnitude. Nevertheless, since the effect of distorted waves is generally to decrease the cross section without changing the shape of the angular distribution,^{9,16,17} it is interesting to compare the shape of the PWIA and experimental angular distributions. The figure shows that the experimental data in the forward direction are suppressed relative to PWIA to a greater extent than the data in the backward direction by a factor of approximately three. This is similar to the results for a $^{16}\text{O}(\gamma, pp)$ experiment,⁹ where the cross sections at a backward angle were in good agreement with distorted wave impulse approximation (DWIA) calculations and delta-hole calculations,¹⁶ and at a forward angle the calculations were approximately three times larger than the data. This discrepancy was found to persist despite including the Δ -nucleon interaction, and may indicate an incomplete understanding of the reaction mechanism for this data.¹⁶ DWIA calculations are in progress for the electron scattering data.¹⁷

Preliminary pp cross sections for CO are shown in Fig. 2b as a function of W . The corrected resolution in W is estimated at 0.1 GeV FWHM. Figure 2b shows that pp emission is approximately 50% of $p\pi^-$ production in the region of the Δ peak. The acceptance corrected fraction of many-body ($n \geq 3$) knockout to the total pp yield is estimated at $88 \pm 3\%$. These results are similar to the observation of pion absorption measurements where the total pion absorption cross section appears to have a three-nucleon component in the 30-40% range.¹⁸ The W dependence of the pp data, while showing some correlation with the Δ peak, is broader than the Δ and appears to extend with significant strength into the dip region between the quasi-elastic and Δ peaks. A many-body effect was also seen in a $^{12}\text{C}(e, e'p)$ measurement in the dip region,¹⁹ where it was necessary to invoke a three-body mechanism to explain the excess strength at high missing energy.²⁰

The nature of the many-body process is not understood at present,^{18,21} although it has been suggested that in the resonance region the reaction proceeds through pion electroproduction followed by the absorption of the pion on a nucleon pair.^{22,20} However, pion absorption experiments do not support a two-step process and indicate that the multi-nucleon emission results from true three-nucleon absorption.²³ If the former interpretation is correct, and if final-state-interactions (FSI) are insensitive to variations in Q^2 , then the Q^2 dependence of the many-body process should follow that of single pion electroproduction. The Q^2 dependence of the pp and $p\pi^-$ data does not contradict this hypothesis, and Fig. 5a shows that the ratio of $p\pi^-$ yield divided by the inclusive electron scattering cross section is nearly constant as a function of Q^2 . Figure 5b shows the same ratio for the pp data. The constancy of the pp^- ratio indicates that FSI are nearly constant over this Q^2 range.

To summarize our preliminary results, the $A(e,e'p\pi^-)$ data show that at $Q^2 \approx 0.35$ GeV^2/c^2 the position of the $\Delta(1232)$ peak is consistent with free production. The second resonance region is clearly seen in the data, and the data show evidence for the presence of the third resonance region. The pion angular distribution shows evidence for suppression relative to a PWIA calculation in the forward direction, similar to that observed in a $^{16}\text{O}(\gamma, p\pi^-)$ measurement. While detailed DWIA calculations are needed to interpret this result, the apparent confirmation of the real photon data may indicate serious shortcomings in theoretical descriptions of this reaction. Models for the many-body absorption process observed in the $(e,e'pp)$ reaction should account for the identical Q^2 dependence of the multi-nucleon reaction and the $p(e,e')$ cross section for Q^2 up to 1 GeV^2/c^2 . It seems probable that some of the phenomena observed in inclusive electron and photon measurements, such as shifts of the Δ centroid and its increased width, and the absence of the second and third resonance regions, may be due to accompanying many-body processes rather than processes involving the Δ or the other resonances. This points out the importance of doing coincidence experiments with large acceptance detectors to study N^* electroproduction in nuclei.

There will be a good opportunity to extend this investigation to higher Q^2 and with many orders of magnitude greater statistics at CEBAF with the CLAS detector in Hall B. Using the CLAS calorimeters it should also be possible to examine the $(e,e'p\pi^0)$ and $(e,e'p\eta)$ channels on nuclear targets by observing the 2γ decay of these particles. The $(e,e'p\pi^0)$ reaction is interesting because the non-resonant backgrounds are much smaller than in the $(e,e'p\pi^-)$ reaction. The $(e,e'p\eta)$ reaction is interesting because of its large coupling to the $S_{11}(1535)$ resonance (50% branching ratio) with small non-resonant backgrounds. Approximately 800 hours of beam time have been approved for nuclear targets on CLAS (^3He , ^4He , ^{12}C , and W). The University of Massachusetts is one of the collaborating groups that have been assigned this beam time.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

c. Hadronization and Target Fragmentation

An exploratory effort is being made to categorize our TPC data in an attempt to develop some understanding of how hadrons develop from quarks. The data have been sorted into kinematic regions according to hadron type and target nucleus. It is generally assumed that various models of hadron electroproduction are valid in certain kinematic regimes with rather vaguely defined boundaries. For example in the vector meson dominance (VDM) model the virtual photon is represented by a superposition of vector mesons thus giving the photon a hadron-like nature at high energy loss ν and low momentum transfer squared Q^2 . On the other hand in deep inelastic scattering (DIS) the virtual photon interacts with a single quark at high Q^2 . In DIS hadrons are produced in quark (or current) fragmentation as modeled by string breaking. In this process the energetic leading quark moves in the forward current direction in the center-of-mass system, whereas the remaining two spectator quarks of the nucleon move relatively slowly backward in the center-of-mass system as a diquark. The spectator quarks then "fragment" into hadrons, the process being referred to as "spectator or target fragmentation". The forward-going current quark also undergoes hadronization. But for our experimental situation, because there is little magnetic field near the beam axis for the solenoidal TPC detector, forward-going hadrons from current fragmentation go down the beam pipe and miss the detector. Hence mostly those hadrons resulting from target fragmentation are available for our study.

Figure 1 shows some yields plotted as a function of the Feynman x_F variable, where $x_F = (p_L/p_{Lmax})_{cm}$ and p_{Lmax} is the maximum kinematically allowed longitudinal momentum of the hadron in the center-of-mass system of the virtual photon and the target nucleus. The dominant values of the yield occur for negative x_F , which means that the target remnants are moving opposite to the direction of the leading quark in the center-of-mass. In the figure the solid curve is the result obtained for the residual CO gas in the vacuum chamber of the PEP storage ring. It should be noted that the data showing emitted protons for the injected deuterium, argon, and

xenon gases are shifted to more negative x_F relative to the CO data as their nuclear mass increases. This clearly shows a nuclear effect on target fragmentation which in some respects resembles an EMC-like behavior for emitted protons, but not for pions. Clearly more work is needed on our part in categorizing and understanding these results.

Data have also been compared to the Lund string model¹ which applies to the proton, the VENUS string model² which takes into account nuclear effects, and DINREG³ which is based upon a quark phase space formulation. All three of these codes are operational on the UMass computer system.

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Figure 1

C. Experiments at NIKHEF and Lund, and Other Results

1. Complementary studies of single-nucleon knockout and single-nucleon wave functions using electromagnetic interactions.

a. Inelastic Electron Scattering

Motivation for this program derives from the existence of a distinctive and well-understood 1.740 MeV M3 excitation in the nucleus ^{10}B . The interpretation of this excitation is especially illuminating because in all $1p$ -shell models it can only arise from a '*stretched*' spin-flip transition of a $p_{3/2}$ nucleon. In these models the (e,e') form factor is thereby given solely in terms of the $p_{3/2}$ wave function $R_{p_{3/2}}(r)$:

$$F_{M3}(q) = q \int_0^{\infty} \left| R_{p_{3/2}}(r) \right|^2 j_2(qr) r^2 dr$$

This relation can be transformed to yield the shape of the $p_{3/2}$ single-particle wave function orbit within the nuclear interior, not merely the rms orbital size as has been the case with previous magnetic (e,e') results. Our first measurements of the form factor¹ at the MIT-Bates accelerator¹ provided an almost unique opportunity to test the understanding of single-nucleon knockout processes, particularly the $(e,e'p)$ reaction, which in recent years has emerged as the most general and powerful method for studying the single-nucleon properties of nuclei. According to the quasi-free knockout picture, cross sections measured in $(e,e'p)$ experiments are directly proportional to the square of the wave function of the ejected proton. Thus, in principle, the $p_{3/2}$ wave function of ^{10}B ($J_0^\pi = 3^-$) can be also be obtained from measurements of the $^{10}\text{B}(e,e'p)$ reaction in which the residual ^9Be nucleus is left in its $J_0^\pi = 3/2^-$ ground state. Unfortunately, however, the interpretation of $(e,e'p)$ results is compromised by uncertainties in the description of effects such as final state interactions, multi-step processes, and meson exchange currents (MEC). Increased understanding of such processes will permit the potential of the $(e,e'p)$ reaction to be realized more fully. This motivated us to propose a measurement the $^{10}\text{B}(e,e'p)$ reaction at NIKHEF, the facility best suited for such investigations.

Before undertaking this investigation it was first necessary, however, to improve the quality of the (e,e') data for the 1.74 MeV M3 transition: the $\geq 20\%$ uncertainties of prior measurements² at $q < 2 \text{ fm}^{-1}$ restricted the information on the wave function at large r , corresponding to small nucleon momentum, the region to which present $(e,e'p)$ techniques are most sensitive. The results of these

additional (e,e') measurements, also made at NIKHEF, are included in Fig. 1. These data are poorly represented by harmonic oscillator wave functions; Woods-Saxon wave functions give much better agreement. In relative core-particle coordinates, the best-fit Woods-Saxon radius $R = 0.99(A-1)^{1/3}$ and diffuseness $a = 0.73$ fm correspond to an rms size for the $p_{3/2}$ orbit of 2.76 ± 0.02 fm. A Fourier-Bessel (FB) analysis yields a rms size equal to 2.79 ± 0.11 fm. In our FB analysis only very weak constraints were placed on the shape of the radial wave function at large r ; accounting for the much larger error in the rms size compared to that obtained from the more constrained Woods-Saxon fit. (This result has implications for previous determinations of orbital sizes in odd- A nuclei from elastic magnetic (e,e') form factors. Due to the superimposed contributions of smaller magnetic multipoles at $q \leq 2$ fm $^{-1}$, these orbital sizes are obtained from just the high- q part of data belonging to the largest ΔJ multipole. Very precise values have been published; however, these rely upon specific model assumptions, e.g., usually Woods-Saxon radial wave functions.) Nevertheless, as shown in Fig. 1, FB analysis yields a $p_{3/2}$ radial dependence that is precisely defined for $r < 4$ fm. Indeed, this result represents the most precise information ever obtained on the dependence of a single-nucleon wave function within the nuclear interior. It has been utilized to assist in the interpretation of $^{10}\text{B}(p,p')$, $^{10}\text{B}(p,n)$, and $^{10}\text{B}(\vec{p},\vec{p}')$ measurements³⁻⁵. In the latter case⁵, for example, this constraint permitted the inference to be drawn that the ratio of transverse to longitudinal spin couplings in the effective NN interaction was larger than for free NN scattering.

b. The $(e,e'p)$ Reaction

Figure 2 shows an excitation energy spectrum measured at NIKHEF in the subsequent $^{10}\text{B}(e,e'p)$ experiment. The ≈ 250 keV FWHM energy resolution of this spectrum was more than adequate to separate the $J^\pi = 3/2^-$ ground state and $5/2^-$ state at 2.429 MeV. Above 5 MeV ^9Be has many broad and overlapped levels. Dominant in our measurements are excitations to states at 6.67 ($7/2^-$), 11.28, and 14.5 MeV. The last of these states is probably the isobaric analog of the 14.7 MeV $5/2^-$ state in ^9B . As shown in Fig. 3, notwithstanding the even-parity assignment tentatively given to the 11.28 MeV state, all these excitations have dependences on missing momentum p_m that are consistent with $1p$ -shell knock-out; in this experiment the only evidence for $1s$ -shell knock-out came from excitations above 19 MeV.

A variety of fits were made to these data in order to determine the $1p$ and $1s$ orbital sizes as well as the spectroscopic factors S of final states in ${}^9\text{Be}$. These fits relied upon two different optical model potentials, one spherical and the other deformed. In addition, the effects of channel-couplings in the final state and a possible anomalous ratio for the longitudinal and transverse quasielastic response functions were investigated. Shown in Table 1 are the mean values obtained for the rms orbital sizes and spectroscopic factors, with the indicated uncertainties being linear sums of the statistical uncertainties and the spreads arising from the different analysis assumptions.

$\Delta\ell$	E_x (MeV)	r_{rms} (fm)	S
1	0.000	3.21 ± 0.06	0.37 ± 0.02
	2.429	3.13 ± 0.07	0.35 ± 0.02
	5.0–9.0	2.96 ± 0.09	0.25 ± 0.03
	9.0–13.0	2.93 ± 0.08	0.51 ± 0.08
	13.0–16.0	2.99 ± 0.17	0.12 ± 0.03
	16.0–19.0	3.06 ± 0.41	0.05 ± 0.02
0	19.0–25.0	2.02 ± 0.18	0.23 ± 0.07

Table 1: Results of fits in the relative core-particle coordinate system to ${}^{10}\text{B}(e,e'p)$ data.

All these results for the size of the $1p$ orbit exceed the value of 2.79 ± 0.11 fm obtained from the (e,e') data for the M3 transition. However, most of the $\Delta\ell = 1$ final states are also accessible by knock-out from the $p_{1/2}$ orbit, which could have a larger size than the $p_{3/2}$ orbit. On the other hand, as previously noted, the $p_{3/2}$ wave function is isolated when the ${}^{10}\text{B}(e,e'p)$ reaction leaves the residual ${}^9\text{Be}$ nucleus in its $J^\pi = 3/2^-$ ground state. For this final state the discrepancy with the rms size deduced from (e,e') is 4 standard deviations! In Fig. 4, which shows the deduced radial densities, the difference is even more striking. A disagreement of this magnitude casts grave doubts on the ability to determine precise values of orbital sizes using electron scattering.

We have considered several factors which may influence the determination of the $p_{3/2}$ orbital distribution from (e,e') . The data shown in Fig. 1 have been corrected for MEC contributions. These

provide less than a 2% correction to the rms size. Unlike the $(e,e'p)$ data, the (e,e') measurements also depend on the neutron distribution. However, because the one-body interaction of the electron is with the nucleon magnetic moment, the (e,e') results are primarily sensitive to $p_{3/2}$ protons. In any case, calculations using Woods-Saxon potential wells suggest that the size difference between the $p_{3/2}$ proton and neutron orbits should be only 2–3%. Admixtures of higher-lying orbits in the ^{10}B ground-state wave function may also modify the apparent size of the $p_{3/2}$ orbit. However, our calculations¹ in an extended $2\hbar\omega$ shell model space indicate that the effect of these admixtures is less than 2%. Thus, even combined, it is unlikely that these effects could account for the 15% difference between the orbital sizes deduced from (e,e') and $(e,e'p)$.

A clue to the resolution of this problem perhaps comes from a comparison of the kinematic ranges of the (e,e') and $(e,e'p)$ data: Whereas the single-arm data span a momentum transfer range of about 700 MeV/c, the coincidence results extend only to $p_m = 270$ MeV/c, barely up to the Fermi momentum. In analyses of the $(e,e'p)$ data, a Woods-Saxon dependence was assumed for the radial wave function, with conventional choices being made for the diffuseness and non-locality parameters, as well as the single-nucleon binding energies. The radius of the Woods-Saxon well was then varied to obtain a best fit to the data. To assess the extent to which the limited kinematic range of $(e,e'p)$ data compromised this analysis, we extended the $^{10}\text{B}(e,e'p)$ beyond 270 MeV/c by adding concocted “pseudo-data”, similar to what is often done in FB analyses of (e,e') form factors. Of course, because the high-momentum part of the single-nucleon momentum distribution is not well known, this procedure is necessarily quite *ad hoc*. Nevertheless, the results demonstrated a considerable potential sensitivity of $(e,e'p)$ analyses to the unmeasured large p_m region.

The result of this investigation led us to seek a Woods-Saxon wave function that would give a good simultaneous fit to both the (e,e') and $(e,e'p)$ data sets. One result, shown in Fig. 5, has a χ^2 per-degree-of-freedom equal to 2.45, with the χ^2 for $(e,e'p)$ being about twice that of the (e,e') fit. The rms $p_{3/2}$ size obtained from this analysis was 2.78 fm, essentially equal to the values deduced from the (e,e') data alone. With this orbital size, the spectroscopic factor found for the $^{10}\text{B}(e,e'p)^9\text{Be}_{g.s.}$ data was 0.46, a value considerably larger than 0.37 ± 0.02 obtained by fitting just the $(e,e'p)$ measurements. This is a provocative result in view of the long-standing difficulty in understanding the small

spectroscopic strengths deduced from analyses of $(e,e'p)$ data. Additional comparisons of the $^{10}\text{B}(e,e')$ and $(e,e'p)$ results have been made by transforming to momentum space the wave function obtained from the FB analysis of the (e,e') data. Nevertheless, none of analyses led to a wholly satisfying reconciliation of the (e,e') and $(e,e'p)$ results. On the other hand, the extent of the remaining disagreement may not lie beyond what could be explained by improving the treatment of several aspects of the $(e,e'p)$ reaction. For example, the optical model potential, coupled-channel effects, meson-exchange currents, and the ratio of longitudinal-to-transverse quasielastic responses are all issues still under debate. Of course, our complementary results on ^{10}B provide a unique opportunity to explore these issues theoretically, and indeed, Chris Arabadjis, a UMass graduate student working under the supervision of Dr. Dubach, will soon submit a Ph.D. thesis on this topic. An important practical outcome of our findings is the caution given against attempts to determine orbital sizes by fitting $(e,e'p)$ data constrained to a relatively narrow kinematic range.

c. The (γ,p) Reaction

The evident importance of the high p_m dependence of single-nucleon knock-out led us to submit a proposal to perform a $^{10}\text{B}(\gamma,p)$ measurement at the University of Lund, in Sweden, where the availability of a continuous beam of *tagged* photons permits measurements to be made at larger values of p_m than accessible at NIKHEF. Unlike the $(e,e'p)$ reaction however, where the dominant reaction mechanism is quasi-free knock-out, the mechanism for (γ,p) is less well understood. While two-nucleon processes such as the interactions with quasi-deuterons are known⁶ to be important for photon energies $E_\gamma > 40$ MeV, there is also evidence⁷ that quasi-free knock-out may be the dominant reaction mechanism for (γ,p) . For this experiment our collaboration was expanded to include Bent Schröder of the University of Lund and a group from Edinburgh University who have developed a proton spectrometer system consisting of hyper-pure germanium crystals with silicon-strip arrays for trajectory information. The large-area ^{10}B target for this experiment was constructed by the UMass group.

The analysis of the (γ,p) data was performed as part of the Ph.D. dissertation of Laurens de Bever, a NIKHEF graduate student. The excitation spectra of Fig. 6, are remarkably similar to the $(e,e'p)$ spectrum shown in Fig. 2. Figure 7 compares momentum densities deduced from $(e,e'p)$ and (γ,p) . Because of the similarity of the excitation spectra, these distributions have been obtained by

integrating all p -shell knock-out strength in the 0–19 MeV excitation region of the residual ${}^9\text{Be}$. The smooth transition observed between the $(e,e'p)$ and (γ,p) results is in fact unanticipated due to the rather different kinetic energies of the ejected protons in these reactions: for $(e,e'p)$ $T_p \approx 120$ MeV; for (γ,p) $T_p \approx 50$ MeV. The extent of the expected discontinuity is indicated in Fig. 7 by curves which show the results of DWIA calculations using the same radial wave functions and optical model parameters. De Bever preformed an exploratory study of the possible sources for the enhancement of the (γ,p) data, effects such as the orthogonality of the initial- and final-state proton wave functions, antisymmetrization, final state interactions including channel couplings, and MEC. Meson exchange effects are of particular interest in view of the long-standing difficulty of seeing clear manifestations of their presence in complex nuclei. For the kinematics of our (γ,p) measurements the knocked-out proton has roughly 300 MeV/c more momentum than the incident photon. According to the simplest interpretation, such protons must have been in high-momentum components of the initial state wave function, which, in principle, are constrained by the (e,e') and $(e,e'p)$ results. In addition, however, the momentum imbalance between the incoming photon and ejected proton can also be eased if the photon is absorbed on an interacting NN pair. Hence (γ,p) measurements should be sensitive to MEC. This sensitivity is enhanced because isovector MEC are favored in purely transverse interactions, such as the absorption of real photons. In contrast, the ${}^{10}\text{B}(e,e'p)$ cross sections measured at NIKHEF were mediated primarily by longitudinal interactions. Although de Bever was unable to fully explain the enhancement of the (γ,p) cross sections over the DWIA predictions, his analyses nonetheless suggested that the major contribution may indeed come from MEC.

d. Additional Results

In addition to the information obtained on reaction mechanisms for single-nucleon knock-out and the ${}^{10}\text{B}$ radial wave functions, these experiments have also provided much data on other properties of ${}^{10}\text{B}$. For example, Fig. 8 shows just one of the (e,e') spectra measured at NIKHEF. Although the M3 excitation of the $J^\pi = 0^+$ state at 1.74 MeV was the main focus of this measurement, at least 12 other excitations were resolved, many for the first time. Spectra were obtained at both forward and backward scattering angles, enabling separation of the longitudinal and transverse form factor components. Most of the longitudinal excitation strength belongs to the C2 multipole. Examples are shown in Fig. 9. An

immense amount of theoretical effort that has been devoted to the understanding of low-energy C2 excitations in nuclei. These excitations are known to have much collective character, their form factors often exceeding shell model predictions by factors of 2 or more. Quantitative explanations of enhanced C2 transition strength have been sought in mixing with collective giant resonances or $2\hbar\omega$ single-particle excitations, as well as core polarization involving many high-lying shells. Nevertheless, the understanding of these transitions remains only approximate.

All C2 form factors in ^{10}B should have identical q -dependences according to harmonic oscillator p -shell models. The curves shown in Fig. 9 indicate that this prediction is only slightly modified when the calculations are extended to a $2\hbar\omega$ model space. These $2\hbar\omega$ shell-model calculations, which use Millener-Kurath potentials for the sd and $2p$ interactions, fail to account for the magnitudes of the form factors. More striking perhaps is the variation between the observed C2 form factor shapes, particularly that of the 4.774 MeV excitation. This observation provides a detailed test of our understanding of the collectivity of C2 transitions.

Data were also obtained on the Coulomb form factor of the ^{10}B ground state. The kinematic range of our data is comparable to results from the only previous measurement⁸, however the experimental precision was considerably improved. Although the presence of a C2 component in the ground state form factor prevents a detailed determination of the ^{10}B charge density, some ground state properties can be established. Using the harmonic oscillator model, Stovall *et al.* obtained an rms size for the charge density of 2.45 ± 0.12 fm, with the error primarily governed by the uncertainty in the C2 contribution. Because our studies of the 1.74 MeV M3 transition revealed that the harmonic oscillator model provides an inexact representation of single-particle wave functions in ^{10}B , we chose to fit the elastic form factor using a C0 component calculated using a simple 2-parameter Fermi distribution. When this is done, we obtained an rms size of 2.57 fm for the data of Stovall *et al.*, in agreement with the 2.58 fm deduced from the new NIKHEF results. The error in this value, which again derives largely from the model dependence, is about ± 0.10 fm.

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Figure Captions:

Fig. 1 Left: M3 form factor for the 1.74 MeV transition in ^{10}B . The curves represent the results of fits employing harmonic oscillator (dotted curve) and Woods-Saxon (dashed curve) wave functions. The solid curve is a Fourier-Bessel fit. Calculated MEC contributions have been removed from the data. Right: $p_{3/2}$ wave function deduced from Fourier-Bessel analysis. The width of the band indicates the error due to the statistical uncertainties and incompleteness of the measured data.

Fig. 2 Excitation energy spectrum for $^{10}\text{B}(e,e'p)$.

Fig. 3 Momentum distributions for protons from the $^{10}\text{B}(e,e'p)$ reaction, shown as a function of excitation energy in the residual ^9Be . The curves show fits obtained with a $1p$ Woods-Saxon wave function and various optical potentials.

Fig. 4 Comparison of radial wave functions obtained by fits to (e,e') and $(e,e'p)$ data. The FB analysis of the (e,e') data used a radius cut-off of 7.5 MeV. Three fits, based on slightly different assumptions, are shown for $(e,e'p)$.

Fig. 5 Result of simultaneous $1p$ wave-function fit to distortion-corrected (e,e') form factor, shown on left, and the $(e,e'p)$ momentum density, on the right.

Fig. 6 Excitation energy spectra obtained from the $^{10}\text{B}(\gamma p)$ measurements at Lund. The four spectra correspond to average photon energies and proton angles of (a) $\langle E_\gamma \rangle = 57.6$ MeV, $\langle \theta_p \rangle = 70^\circ$; (b)

$\langle E_\gamma \rangle = 57.6$ MeV, $\langle \theta_p \rangle = 110^\circ$; (c) $\langle E_\gamma \rangle = 72.9$ MeV, $\langle \theta_p \rangle = 70^\circ$; and (d) $\langle E_\gamma \rangle = 72.9$ MeV, $\langle \theta_p \rangle = 110^\circ$. Dashed curves represent (γnp) contributions calculated using a quasideuteron model.

Fig. 7 Reduced cross sections for the $^{10}\text{B}(e, e'p)$ (solid circles) and $^{10}\text{B}(\gamma, p)$ (triangles and squares) reactions, integrated over all observed $1p$ shell knock-out. The curves represent DWIA calculations, with the (γp) results including two-nucleon knockout calculated using a quasideuteron model.

Fig. 8 $^{10}\text{B}(e, e')$ spectrum measured at NIKHEF. The curves were obtained by means of a peak-fitting procedure, used to determine cross sections for individual excitations. Apparent in the spectrum are peaks due to ^{11}B and ^{12}C contaminants in the target.

Fig. 9 Longitudinal form factors obtained for six C2-dominated excitations in $^{10}\text{B}(e, e')$. The curves depict the results of $2\hbar\omega$ shell-model calculations for the C2 multipole only.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

F_{C2}^2

Figure 9

2. Single-Particle Densities of *sd*-Shell Nuclei

For nuclei near the middle of the *sd*-shell, there exists little evidence for the abrupt filling of the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ subshells. Instead, these subshells all have partial occupancies, filling only gradually with increasing A . With its sensitivity to single-particle densities, elastic electron scattering represents a good means of learning about this progressive filling of the subshells, as well as the radial sizes of the single-particle wave functions. Accordingly, extensive electron scattering measurements have been made at the University of Mainz and at the Bates Electron Accelerator of the elastic Coulomb and magnetic form factors of the $J^\pi = 5/2^+$ nucleus ^{27}Al . Much is known regarding the Coulomb and magnetic form factors of other nuclei in this region. For example, similar data exists for ^{25}Mg , ^{29}Si and ^{31}P , and the Coulomb form factors have been determined for the $J=0$ nuclei ^{28}Si , ^{30}S , and ^{32}P , for which magnetic scattering is forbidden.

Nuclear magnetism is largely governed by a relatively small number of nucleons in valence orbits, and hence magnetic scattering has obvious sensitivity to single-particle properties. Of the various magnetic multipole components possible in the *sd*-shell, the highest $M5$ multipole relies, to a good approximation, only on nucleons in $1d_{5/2}$ orbits. This dependence makes it possible to obtain a precise measure of the radial size of this orbit. However, because protons in all shell-model orbits contribute to Coulomb elastic scattering, the extraction of single-particle information from Coulomb form factors is less direct. By Fourier-transforming Coulomb monopole ($C0$) form factors, precise results have been obtained on ground-state charge distributions for nuclei throughout the entire periodic table. In principle, information on single-particle properties can be derived from differences between the charge distributions of neighbouring nuclei. But these differences also depend on core polarization and changes in nuclear size parameters, so that uncertainties in these properties can hamper interpretations of charge density differences in terms of single-particle densities. On the other hand, these effects appear to be less important for nuclei in the middle of the *sd*-shell, and because the single-particle orbit parameters are further constrained by the available magnetic scattering data, these nuclei are good candidates for instructive tests of our understanding of configuration mixing in valence shell-model orbits.

Analyses of C0 form factors are normally confined to those nuclei having ground state spin $J=0$ or $1/2$. For $J \geq 1$ nuclei other even Coulomb multipoles enter, beginning with the quadrupole C2 form factor. Because the cross sections measured in such cases are comprised of an incoherent sum of the various multipole components, the C0 form factor is not isolated for transformation. One method of overcoming this difficulty would be to measure the additional form factors which characterize the scattering of polarized electrons from spin-aligned targets. Although facilities for such experiments are currently being developed, the relative complexity of these measurements will likely limit investigations to a relatively small number of cases. For the present, however, the only recourse is to use observed systematics and results from nuclear models to eliminate the contributions of the C2 and higher multipole components. It is this approach that we have taken to extract the charge distribution of ^{27}Al . The reliability of this procedure is supported by comparisons with cross sections measured for inelastic transitions where the higher multipoles are more clearly manifested.

In this way we have been able to deduce the ^{28}Si – ^{27}Al charge density difference, to go along with the ^{29}Si – ^{28}Si and ^{30}Si – ^{29}Si charge density differences. A detailed study is being made to examine the extent to which these results can be interpreted in terms of single-particle densities. Specifically, together with the magnetic scattering data, these results are presently being compared with configuration-mixed calculations made in an expanded shell-model basis.

D. Preparations for Future Work at CEBAF: Electronics for the CLAS Region 1 Drift Chamber

1. Overview

The UMass group is responsible for the design, construction, and testing of the chamber-mounted electronics for the CLAS Region 1 drift chamber, the innermost drift chamber (DC) for CLAS, consisting of six identical sectors arranged around the beam axis. The mechanical construction of this chamber is the responsibility of Carnegie Mellon University and the University of Pittsburgh. Altogether, there will be approximately 7,500 signal wires in the Region 1 detector.

Our group is designing the signal translator boards and the high voltage (HV) translator boards which fit in the approximately 2 inch gap between sectors of the Region 1 chamber. Space constraints in the detector, together with the mixed high and low voltages that these boards must provide, make the Region 1 electronics one of the most difficult design problems for CLAS. The signal translator boards connect signal wires to chamber-mounted preamps, which in turn drive twisted pair cables connected to TDCs in the front-end electronics. It is intended that the pre-amplifier will be a single-in-line-package (SIP) that has been designed by CEBAF engineers¹. The signal translator board must carry high voltage from the signal wires ($\approx +1.3$ kV), low voltage for the SIPs (+5 V), and a ground plane for isolation, making the possibility of high voltage breakdown on the board a serious concern. The HV translator boards provide HV biasing for the signal wires, field wires (≈ -1.5 kV), and guard wires (≈ -1.5 kV). The HV segmentation of the drift chamber is provided for in the HV translator board.

2. Design

A design objective for the Region 1 DCs was to provide as close to full 2π azimuthal coverage as possible. Hence the inactive space between DCs in adjacent sectors was made to be only 2.00 inches wide. Into this small space must fit not only the two DC end-plates, but also extensions of the feed-throughs and crimp-pins for the wires. Additional space is required for the high-voltage and signal translator boards and by HV blocking capacitors and resistors.

Our proposed solution² is shown in Fig. 1. The view shown transverse to the plane of the DC end-plates includes all components listed above. Although some of the details of the feed-throughs and

crimp pins are given only approximately, important distances, such as the extensions of these components beyond the end-plates, are correctly drawn. This design incorporates standard pig-tail capacitors and resistors on the signal wires. Surface-mount resistors are much thinner and hence could be accommodated with comparative ease, however, the mounting of these components requires special instruments and procedures. Furthermore, we have encountered problems with leakage currents on surface-mount capacitors. The plan view, shown on the bottom, shows the signal wire resistors to be aligned in "channels" between pairs of adjacent sense wire crimp pins. Alternate channels would then be clear for high-voltage cable which has ample flexibility for threading between the hexagonal crimp pin lattice. A workable assembly procedure has been devised for this design.

The signal translator boards (STBs) have various functions. They capacitively couple the signal wires to the SIPs, and provide low voltage and test pulse inputs to the SIPs. The boards also make connections to multi-pin connectors where twisted pair signal cables are attached. The medium that best satisfies these design requirements is a multiple-layer printed circuit (PC) board. In our STB design we tried to satisfy several criteria. The traces were routed assuming a high voltage stay-clear distance of 130 mil. By commonly used HV engineering standards, the STBs should then be able to hold off sense wire voltages of at least +1.3 kV. We also attempted to minimize the number of signal cables, maximize the overlap between axial and stereo regions of the STB, and keep the length of the PC boards less than 24 inches. Figure 2 shows a side view of a Region 1 sector and the STB segmentation scheme we plan to use. There will be 10 STBs per sector, with typically 126 channels per STB. As the figure shows, due to the forward curvature of the drift chamber no two STBs will be physically identical, although several share the same SIP and connector pattern. The uniqueness of each STB in a given sector is another feature of the Region 1 electronics design that increases the complexity of the task. In total, 60 STBs will be needed to cover all six sectors of the Region 1 chamber.

Figure 3 is a detailed view of one PC layer in STB #8. Traces run from the capacitively coupled signal wires to the rows of SIPs, and then to multi-pin connectors. Groups of 16 signal wires are connected to 34 conductor twisted-pair cables. In our design the 17th twisted pair on the cable is

used as a test pulse for the SIPs. To minimize cross talk, the ground plane is extensively used in the design and a ground trace is placed between every pair of adjacent signal traces. The traces themselves are 10 mil thick, a fairly common design standard. In total the STBs will have 10 PC layers, and will be 0.25 in. thick.

HV cables for the signal wires are mounted on the HV translator boards (HVTB) and bias the signal wires through a large resistance, $\approx 1 \text{ M}\Omega$. HV cables for the field and sense wires are also mounted to the HVTB, although these wires are biased by a wire network attached to the crimp pins between the HVTB and the end plate (see Fig. 1b). The HVTBs also provide for HV segmentation in the drift chamber. While details of the HV segmentation remain to be worked out, we expect to have approximately four times as many signal wires per HV cable in the backward region ($\theta > 45^\circ$) than in the forward region.

3. Tests and Prototypes

Due to the novel design aspects of the CLAS DCs, an extensive program of prototyping and testing is in progress. One of the first tests we participated in used a small hexagonal-lattice chamber inside a large-gap dipole magnet at Brookhaven. The primary goal of these tests was to study the deterioration in spatial resolution of a hexagonal-cell DC when subjected to large non-axial magnetic fields. Good spatial resolution requires a sound understanding of the drift-time versus drift-distance correlation on magnetic field strength and direction, as well as track entrance angle. For these tests we used cosmic rays and a 50:50 (by weight) argon-ethane gas mixture. Except for the longest drift paths, it was established³ that spatial resolutions of better than $200 \text{ }\mu\text{m}$ could be achieved for magnetic field strengths up to 1.5 T and angles between the wire and field direction ranging from 0° to 30° . Additional tests using an argon-ethane mixture diluted with 60% helium showed less sensitivity to magnetic field effects and only slightly worse resolution.

Following the design of the the preamplifier circuit by Barbosa¹, a number of these SIPs were fabricated and mounted on a prototype STB that we designed for a 6×8 hexagonal array of drift-cells. The first round of tests to be performed on the prototype STB and preamps used pulser-generated signals to examine signal linearity, pulse-width broadening, and crosstalk. In each case the properties

of the STB and preamps were found to be entirely satisfactory⁴. Prior to these tests, most concern centered on possible problems due to crosstalk. Two potential areas of difficulty had been identified. The first was between the pairs of closely-separated signal traces having the longest paths from the anode wires to the preamps. The other region for concern on the STB was where unamplified signals follow traces parallel to paths for signals that have already been amplified. Fortunately, no problems were encountered in either of these instances. Indeed, based on our tests we expect $\leq 1\%$ crosstalk between signals from different drift cells.

We then sought to test the performance of the prototype STB when mounted on a DC we constructed to mimic a section of the Region 1 chambers. The UMass chamber contains a 6×8 lattice of hexagonal cells with wire lengths of about 65 cm, corresponding roughly to the maximum lengths of wires in the Region 1 chambers. Cosmic rays were used for this test, with the trigger being provided by coincident pulses from two scintillator paddles, one above and the other below the DC. As shown in Fig. 4, the high voltage plateau for these chambers begins near an anode-field wire voltage difference of about 2.8 kV. At 3.0 kV, the DC had begun to go into streamer mode operation. The high voltage plateau was observed to be unaffected by a 100 V change in the absolute field wire potential, indicating that at this level, the response of the DC is relatively insensitive to charge induced elsewhere in the DC. We are continuing these studies of the DC and prototype electronics boards, planning to make measurements of drift time and pulse height spectra.

References:

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2. R.S. Hicks, UMass memorandum: proposed spatial layout for electronics in vicinity of end plates of Region 1 drift chambers (1992).
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4. R.S. Hicks, UMass Memorandum: Tests of Prototype Signal Translator Board (STB) for Region 1 Drift Chambers (1992).

Fig. 1: Proposed design for electronics boards and connectors between end-plates of Region 1 drift chambers

Figure 2

Figure 3

Fig. 4 Count rate for two central drift cells as a function of the anode-field wire voltage difference for two different field wire voltages.

2 of 2

III. Theoretical Work

A. Parity-Violating Electron Scattering

One focus of the theoretical effort this past year has been the completion of a large review article (with T.W. Donnelly, M. Musolf, S. Pollock, E. Beise, and S. Kowalski) on the present theoretical and experimental status of parity-violating (PV) electron scattering and its use as a probe of nucleon (strangeness) content, of nuclear structure, and of possible physics beyond the Standard Model. In addition to a discussion of the physics issues which can be addressed by a parity-violating electron scattering program and development of the necessary theoretical framework, the review addresses a large variety of specific cases where PV (e,e') may have an impact and emphasizes the interrelationships and interdependences between the various cases. For example, PV electron scattering can be used to extract the strangeness content in the vector current of the nucleon by measuring back-angle polarized electron scattering from the proton (the Bates "Sample" experiment). However, such an experiment cannot be extended to determine the strange magnetic form factor of the proton to arbitrary precision since one quickly encounters a theoretical limit imposed by our inability to calculate (beyond an estimate) a certain class of radiative corrections to the axial-vector contribution to the PV asymmetry. Other experiments, in particular PV quasielastic electron scattering from the deuteron are more sensitive to this term and so can be used to provide experimental limits better than those that can be obtained from theoretical estimates. Similarly, attempts to use forward-angle $p(\vec{e},e)$ to determine the strange electric form factor of the proton are limited by the uncertainty in the strange magnetic form factor and one turns to PV electron scattering from a light ($J^\pi T) = (0^+0)$ nucleus such as ^4He to obtain a second probe of strangeness in the electric form factor, but one must then cope with the additional complexities introduced by nuclear structure. As a final example, use of atomic parity violation as a test of the Standard Model requires knowledge of the nuclear neutron distribution; PV ($\vec{e},e$) should be able to provide such information. Topics covered in this way in the review include: elastic scattering from the

proton, elastic scattering from spin-0 nuclei, elastic scattering from the deuteron, other discrete nuclear transitions, the axial-vector hadronic response, quasielastic scattering, the nucleon to Δ transition, deep inelastic scattering, atomic parity violation, and neutrino scattering from nucleons and nuclei.

B. Nuclear Structure

In the area of nuclear structure, graduate student J. Gallant has completed development of the formalism and a first computer code to merge perturbation expansions ("core polarization") with the large-basis shell model techniques we have used over the last few years. The problem is to expand perturbatively the shell model basis space beyond that which can be exactly diagonalized and to be able to do so with any choice of diagonalized space (i.e., both closed and open shells). In general, n^{th} order perturbation theory contributions outside the exactly diagonalized space can be treated as an $(n + 1)$ -body operator within the diagonalized space. Mr. Gallant will limit his applications to first-order perturbations and so has modified existing two-body density matrix codes to produce the "segmented" two-body density needed for the perturbation theory calculations. The first goal of this work is to establish the validity of previous core polarization approximations by comparing results obtained for different divisions of the basis space between that which is fully diagonalized and that which is treated in perturbation theory. At least preliminary efforts in this regard will comprise the remainder of Mr. Gallant's Ph.D. work with a thesis expected by early Fall. We will also then use this technique as appropriate for nuclear structure studies per se (such as the cases of ^{10}B and ^{117}Sn discussed elsewhere in this report) and in other areas of research, particularly the electroweak sector, where extensive nuclear structure calculations may be required.

Another student, C. Arabadjis, has completed the theoretical formalism and essentially all the programming for a description of the $^{10}\text{B}(\text{e},\text{e}'\text{p})$ reaction. The object of this project is to explore the effects of electroexcitation of intermediate states in ^9Be followed by deexcitation through final-state interactions with the outgoing ejected proton and to examine the influence of

such processes on the determination of the single-particle wave function(s) in ^{10}B via the (e,e') reaction. ^{10}B is a nearly unique case where the $p_{3/2}$ wave function can be well-determined by inelastic electron scattering and thus provides an important calibration of the validity of the more generally applicable (e,e'p) reaction as a means of determining single-particle wave functions. Unfortunately, this project has been beset with numerical and computational difficulties and reliable results and conclusions are still not yet available for the full calculations. Once these problems are ironed out, a thesis should quickly follow.

Finally, a third student, T. Hennert, has been working on a project (in collaboration with B. Holstein) using chiral symmetry techniques to describe the transition form factor of the nucleon to Δ excitation. The specific interest is a test of a generalized Goldberger-Treiman relation in this sector. Such a relation is a consequence of chiral symmetry and relates form factors of the axial-vector current to form factors of the strong interaction. The final step of this project, to estimate the size of several of the relevant form factors in a quark model and to compare with both previous work and recent experimental results, is now underway.

IV. Publications and Presentations by Members of the University of Massachusetts Medium Energy Physics Group in the Period June 1, 1992 to May 31, 1993

A. Journal Publications:

1. "Measurements of Transverse Electron Scattering from the Deuteron in the Threshold Region at High Momentum Transfers", M. Frodyma, R.G. Arnold, D. Benton, P.E. Bosted, L. Clogher, G. Dechambrier, A.T. Katramatou, J. Lambert, A. Lung, G.G. Petratos, A. Rahbar, S.E. Rock, Z.M. Szalata, B. Debebe, R.S. Hicks, A. Hotta, G.A. Peterson, R.A. Gearhart, J. Alster, J. Lichtenstadt, F. Dietrich, and K. van Bibber, Phys. Rev. C **47**, 1599 (1993).
2. "Measurements of νW_2 and $R = \sigma_L/\sigma_T$ from Inelastic Electron-Aluminum Scattering Near $x = 1$ ", P.E. Bosted, A. Lung, L. Andivahis, L.M. Stuart, J. Alster, R.G. Arnold, C.C. Chang, F.S. Dietrich, W. Dodge, R. Gearhart, J. Gomez, K.A. Griffioen, R.S. Hicks, C.E. Hyde-Wright, C. Keppel, S.E. Kuhn, J. Lichtenstadt, R.A. Miskimen, G.A. Peterson, G.G. Petratos, S.E. Rock, S. Rokni, W.K. Sakumoto, M. Spengos, K. Swartz, Z. Szalata, and L.H. Tao, Phys. Rev. C **46**, 2505 (1992).
3. "Measurements of the Electric and Magnetic Form Factors of the Neutron from $Q^2 = 1.75$ to 4.00 (GeV/c)²", A. Lung, L.M. Stuart, P.E. Bosted, L. Andivahis, J. Alster, R.G. Arnold, C.C. Chang, F.S. Dietrich, W.R. Dodge, R. Gearhart, J. Gomez, K.A. Griffioen, R.S. Hicks, C.E. Hyde-Wright, C. Keppel, S.E. Kuhn, J. Lichtenstadt, R.A. Miskimen, G.A. Peterson, G.G. Petratos, S.E. Rock, S.H. Rokni, W.K. Sakumoto, M. Spengos, K. Swartz, Z. Szalata, and L.H. Tao, Phys. Rev. Lett. **70**, 718 (1993).
4. "Measurements of the Electric and Magnetic Form Factors of the Proton from $Q^2 = 1.75$ to 8.83 (GeV/c)²", P.E. Bosted, L. Andivahis, A. Lung, L.M. Stuart, J. Alster, R.G. Arnold, C.C. Chang, F.S. Dietrich, W. Dodge, R. Gearhart, J. Gomez, K.A. Griffioen, R.S. Hicks, C.E. Hyde-Wright, C. Keppel, S.E. Kuhn, J. Lichtenstadt, R.A. Miskimen, G.A. Peterson, G.G. Petratos, S.E. Rock, S. Rokni, W.K. Sakumoto, M. Spengos, K. Swartz, Z. Szalata, and L.H. Tao, Phys. Rev. Lett. **68**, 3841 (1992).
5. "Effects of Non-Parallel Magnetic Fields on Hexagonal Cell Drift Chambers", M.D. Mestayer, C.L. Tam, K. Wang, H. Baghaei, S. Christo, S.A. Dytman, G.P. Gilfoyle, J.D. Hewitt, F.W. Hersman, R.S. Hicks, R.A. Miskimen, R. Schumacher, and M.F. Vineyard, IEEE Trans. Nucl. Sci. **39**, 690 (1992).

B. Articles Accepted for Publication:

1. "Ground State Magnetization Density of ⁸⁹Y", J.E. Wise, J.R. Calarco, J.P. Connelly, S.A. Fayans, F.W. Hersman, J.H. Heisenberg, R.S. Hicks, W. Kim, T.E. Milliman, R.A. Miskimen, G.A. Peterson, A.P. Platanov, E.E. Saperstein, and R.P. Singhal, Accepted for Publication in Phys. Rev. C.

2. "Transverse Form Factors of ^{117}Sn ", H. Baghaei, M.B. Frodyma, R.S. Hicks, A. Hotta, R.A. Miskimen, G.A. Peterson, S.H. Rokni, J. Dubach, and T. Suzuki, Accepted for Publication in Phys. Rev. C.

C. Articles Submitted for Publication:

1. "Intermediate-Energy Semileptonic Probes of the Hadronic Neutral Current", M.J. Musolf, J. Dubach, T.W. Donnelly, S.J. Pollock, S. Kowalski, and E. Beise, Review Article Submitted to Physics Reports.

D. Articles Soon to be Submitted for Publication:

1. "Electroproduction of Nucleon Resonances in Nuclei with the $(e,e'p\pi^-)$ and $(e,e'pp)$ Reactions", L. Elouadrhiri, R.A. Miskimen, G.A. Peterson, J. Button-Shafer, K. Wang, P. Degtyarenko, V. Gavrilov, S. Shuvalov, F. Dietrich, and K. Van Bibber, To be Submitted to Phys. Rev. Letters.
2. "Measurements of the Proton Elastic Form Factors for $1 \leq Q^2 \leq 3 \text{ (GeV/c)}^2$ at SLAC", R.C. Walker, B.W. Filippone, J. Jourdan, R. Milner, R. McKeown, D. Potterveld, L. Andivahis, R. Arnold, D. Benton, P. Bosted, G. de Chambrier, A. Lung, S.E. Rock, Z.M. Szalata, A. Para, F. Dietrich, K. Van Bibber, J. Button-Shafer, B. Debebe, P. de Barbaro, A. Bodek, S. Dasu, H. Harada, M.W. Krasny, K. Lang, E.M. Riordan, R. Gearhart, L.W. Whitlow, and J. Alster, To be Submitted to Phys. Rev. D.
3. "Weak Hypernuclear Decay", J. Dubach, G.B. Feldman, B.R. Holstein, and L. de la Torre, To be Submitted to Phys. Rev. C.
4. "Measurement of Kinematic and Nuclear Dependence of $R = \sigma_L/\sigma_T$ in Deep Inelastic Electron Scattering", S. Dasu, P. de Barbaro, A. Bodek, H. Harada, M.W. Krasny, K. Lang, E.M. Riordan, L. Andivahis, R. Arnold, D. Benton, P. Bosted, G. de Chambrier, A. Lung, S.E. Rock, Z.M. Szalata, R.C. Walker, B.W. Filippone, J. Jourdan, R. Milner, R. McKeown, D. Potterveld, A. Para, F. Dietrich, K. Van Bibber, J. Button-Shafer, B. Debebe, R.S. Hicks, R. Gearhart, L.W. Whitlow, and J. Alster, To be Submitted to Phys. Rev. D.

E. Articles in Preparation:

1. "Comparison of $^{10}\text{B}(e,e'p)$ and $^{10}\text{B}(e,e')$: A Study of Radial Densities", R.S. Hicks, G.A. Peterson, R.A. Miskimen, A. Cichocki, C.W. deJager, H. deVries, L. de Bever, G. van der Steenhoven, N. Kalantar, and L. Lapikas, To be Submitted to Phys. Rev. C.
2. "Elastic and Inelastic Electron Scattering from ^{10}B ", R.S. Hicks, G.A. Peterson, R.A. Miskimen, A. Cichocki, C.W. deJager, H. deVries, N. Kalantar, and L. Lapikas, To be Submitted to Phys. Rev. C.

3. "Comparison of $^{10}\text{B}(\gamma, p)$ and $^{10}\text{B}(e, e'p)$ Reactions: Evidence for Meson Exchange Currents", R.S. Hicks, G.A. Peterson, K. Wang, G. van der Steenhoven, L. de Bever, C.W. deJager, I. Bobeldijk, B. Schröder, D. Branford, and D.G. Ireland, To be Submitted to Phys. Rev. C.
4. "Various Exclusive Electron-Nucleus Reactions Observed with the TPC/2 γ Detection at SLAC", L. Elouadrhiri, R.A. Miskimen, G.A. Peterson, J. Button-Shafer, K. Wang, P. Degtyarenko, V. Gavrilov, S. Shuvalov, F. Dietrich, and K. Van Bibber, To be Submitted to Phys. Rev. C.
5. "Hadron Production in the Target Fragmentation Region from Electro-nuclear Reactions at 14.5 GeV", P. Degtyarenko, V. Gavrilov, S. Shuvalov, K. Wang, L. Elouadrhiri, R.A. Miskimen, G.A. Peterson, J. Button-Shafer, F. Dietrich, and K. Van Bibber, To be Submitted to Phys. Rev. C.
6. " ω Meson Production from Electronuclear Reactions at 14.5 GeV", P. Degtyarenko, V. Gavrilov, S. Shuvalov, L. Elouadrhiri, R.A. Miskimen, G.A. Peterson, J. Button-Shafer, K. Wang, F. Dietrich, and K. Van Bibber, To be Submitted to Phys. Rev. C.

F. Abstracts of Contributed Papers:

1. "New Results for the $\gamma, N \rightarrow N\pi^+\pi^-$ Reaction in the N^* Region", R.A. Miskimen, J. Button-Shafer, L. Elouadrhiri, D. Olivieri, G.A. Peterson, K. Wang, P. Degtyarenko, V. Gavrilov, S. Shuvalov, F. Dietrich, and K. van Bibber, International Conf. on the Structure of Baryons and Related Mesons, Yale Univ., June 1-4, 1992, World Scientific.
2. "Progress and Status of an Experiment to Measure the Transition Quadrupole Moment of the $N \rightarrow \Delta$ Reaction", J. Mandeville, R. Beck, S. Dolfini, J. Harrop, W. Kim, R. Laszewski, E. Offerman, C. Papanicolas, S. Williamson, A. Bernstein, W. Bertozzi, V. Bhushan, W. Boeglin, D. Dale, S. Gilad, M. Holtrup, D. Jordan, S. Kowalski, T. McIlvain, L. Weinstein, K. Dow, G. Dodson, M. Farkhondeh, W. Sapp, D. Tieger, C. Tschalaer, W. Turchinets, J. Zumbro, R. Alarcon, J. Comfort, J. Görgen, D. Martinez, M. Epstein, D. Margaziotis, R. Miskimen, S. Wood, and D. Mack, International Conf. on the Structure of Baryons and Related Mesons, Yale Univ., June 1-4, 1992, World Scientific.
3. "Measurement of the $\Delta(1232)$ Transition Form Factor in the Range $1.6 < Q^2 < 6.8 \text{ (GeV/c)}^2$ ", International Conf. on the Structure of Baryons and Related Mesons, Yale Univ., June 1-4, 1992, World Scientific.

4. "Electromagnetic Form Factors of the Nucleon at High Q^2 ", P.E. Bosted, L. Andivahis, A. Lung, L.M. Stuart, J. Alster, R.G. Arnold, C.C. Chang, F.S. Dietrich, W. Dodge, R. Gearhart, J. Gomez, K.A. Griffioen, R.S. Hicks, C.E. Hyde-Wright, C. Keppel, S.E. Kuhn, J. Lichtenstadt, R.A. Miskimen, G.A. Peterson, G.G. Petratos, S.E. Rock, S. Rokni, W.K. Sakumoto, M. Spengos, K. Swartz, Z. Szalata, and L.H. Tao, International Conf. on the Structure of Baryons and Related Mesons, Yale Univ., June 1-4, 1992, World Scientific.
5. "Study of $(\gamma N \rightarrow p\pi^-)$ in the N^* Region", L. Elouadrhiri, J. Button-Shafer, R.A. Miskimen, D. Olivieri, G.A. Peterson, K. Wang, P. Degtyarenko, V. Gavrilov, S. Shuvalov, F. Dietrich, and K. van Bibber, International Conf. on the Structure of Baryons and Related Mesons, Yale Univ., June 1-4, 1992, World Scientific.
6. "Performance of an Out-of-Plane Spectrometer for Studying $(e,e'x)$ Reactions", J. Mandeville, R. Beck, S. Dolfini, J. Harrop, R. Laszewski, E. Offerman, C. Papanicolas, S. Williamson, A. Bernstein, W. Bertozzi, V. Bhushan, W. Boeglin, D. Dale, S. Gilad, M. Holtrop, D. Jordan, S. Kowalski, T. McIlvain, L. Weinstein, K. Dow, G. Dodson, M. Farkhondeh, W. Sapp, D. Tieger, T. Schalaer, W. Turchinets, J. Zumbro, R. Alarcon, J. Comfort, J. G3rgen, D. Martinez, M. Epstein, D. Margaziotis, R. Miskimen, S. Wood, and D. Mack, Bull. Am. Phys. Soc. **37**, 885 (1992).
7. " ^{10}B : A Test of $(e,e'p)$ as a Structure Tool", C.J. Arabadjis, Bull. Am. Phys. Soc. **38**, 1035 (1993).
8. "Exclusive Electronuclear Reactions in the Nucleon Resonance Region", D. Olivieri, R. Miskimen, L. Elouadrhiri, K. Wang, J. Button-Shafer, G. Peterson, P. Degtyarenko, S. Shuvalov, V. Gavrilov, F. Dietrich, and K. van Bibber, Bull. Am. Phys. Soc. **38**, 1034 (1993).
9. "Target Fragmentation in Deep Inelastic Scattering of 14.5 GeV Electrons From Nuclei", P. Degtyarenko, V. Gavrilov, S. Shuvalov, J. Button-Shafer, L. Elouadrhiri, R.A. Miskimen, D. Olivieri, G.A. Peterson, K. Wang, F. Dietrich, and K. Van Bibber, Bull. Am. Phys. Soc. **38**, 1034 (1993).
10. "Resonance Electroproduction at High Momentum Transfers", C. Keppel, L. Andivahis, R. Arnold, P. Bosted, J. Dunne, A. Lung, S. Rock, M. Spengos, Z. Szalata, L.H. Tao, J. White, J. Gomez, P. Anthony, F. Dietrich, L. Stuart, K. Van Bibber, J. Button-Shafer, R. Hicks, G. Peterson, K. Wang, A. Banerjee, K. Griffioen, A. Bodek, P. deBarbaro, R. Walker, S. Kuhn, S. Dasu, R. Gearhart, G. Petratos, M. Riordan, S. Rokni, M. Frodyma, and C. Hyde-Wright, Bull. Am. Phys. Soc. **38**, 1034 (1993).

11. "Measurement of x , Q^2 and Hydrogen- Deuterium Dependence of $R = \sigma_L/\sigma_T$ ", L.H. Tao, L. Andivahis, R. Arnold, P. Bosted, J. Dunne, A. Lung, S. Rock, M. Spengos, Z. Szalata, J. White, J. Gomez, P. Anthony, F. Dietrich, L. Stuart, K. Van Bibber, J. Button-Shafer, R. Hicks, G. Peterson, K. Wang, A. Banerjee, K. Griffioen, A. Bodek, P. deBarbaro, R. Walker, S. Kuhn, S. Dasu, R. Gearhart, G. Petratos, M. Riordan, S. Rokni, M. Frodyma, and C. Hyde-Wright, Bull. Am. Phys. Soc. **38**, 1034 (1993).
12. "Measurements of Threshold Electrodisintegration of the Deuteron at High Momentum Transfers", K. Lee, S. Churchwell, R. Hicks, R. Miskimen, G. Peterson, K. Wang, W. Schmitt, W. Turchinets, C. Williamson, T. Yates, J. Zumbro, P. Bosted, M. Spengos, D. Beck, B. Frois, S. Martino, S. Platchkov, H. Baghaei, and A. Hotta, Bull. Am. Phys. Soc. **38**, 1935 (1993).
13. "Addition of Core Polarization to Large Basis Shell Model Calculations", J. Gallant, Bull. Am. Phys. Soc. **38**, 962 (1993).
14. "New Form Factor Results for the Giant Dipole Resonance", J.R. Marinelli, F.F. DeSouza Cruz, M.M. W. deMoraes, L.I. Weiss, and M. Barbi, Bull. Am. Phys. Soc. **38**, 1052 (1993).
15. "Measurements of the Nucleon Form Factors at Large Momentum Transfers", L. Andivahis, P. Bosted, A. Lung, L. Stuart, J. Alster, R. Arnold, C. Chang, F. Dietrich, W. Dodge, R. Gearhart, J. Gomez, K. Griffioen, R. Hicks, C. Hyde-Wright, C. Keppel, S. Kuhn, J. Lichtenstadt, R. Miskimen, G. Peterson, G. Petratos, S. Rock, S. Rokni, W. Sakumoto, M. Spengos, K. Swartz, Z. Szalata, and L. Tao, International Nuclear Physics Conference, Weisbaden, Germany, July 26-August 1, 1992.

G. Invited Talks:

1. "Electroweak Probes of Strangeness: Theory", J. Dubach, CEBAF Users Group Retreat, May 21-25, 1993, Snowshoe, West Virginia.

V. An Incomplete List of Nuclear Physics Seminars and Colloquia Given at the University of Massachusetts at Amherst from June 1, 1992 through May 31, 1993

- June 5: Joachim Kambor, Munich, "Chiral corrections and the $1/m$ expansion for photon-nucleon processes"
- June 10: Pavel Degtyarenko, Institute of Theoretical and Experimental Physics, Moscow, Russia, "Data organization, analysis, and presentation using PAW"
- June 22: Pavel Degtyarenko, Institute of Theoretical and Experimental Physics, Moscow, Russia, "Multihadron electroproduction on nuclei using the ARGUS detector at DESY"
- Sept. 10: Eugene Golowich & John Donoghue, University of Massachusetts, "News from the XXVI International Conference on HEP", SSC Lab, Dallas, TX
- Sept. 22: Ross Hicks, University of Massachusetts, "Outlook for electromagnetic nuclear physics in Europe"
- Sept. 29: Larry Hunter, Amherst College, "A measurement of the electron electric dipole moment"
- Sept. 29: Thomas Hemmert, Xiaodong Jiang, David Olivieri, University of Massachusetts, "Summer research at CEBAF"
- Sept. 30: Edward P. Hartouni, University of Massachusetts, "Soft physics, hard detectors"
- October 6: Xiangdong Ji, Massachusetts Institute of Technology, "Transverse polarization in high energy scattering"
- October 13: Kurt Haller, University of Connecticut, "Perturbative and non-perturbative implications of Gauss' Law in QCD"
- October 14: Gary Adams, Rensselaer Polytechnic Institute, "Photon absorption in ^3He with polarized photons"
- October 20: Kandula Sastry, University of Massachusetts, "In vivo radioprotection by chemicals: Vitamin C?"
- October 20: Paul E. Karchin, Yale University, "Hadro-production of charm in Fermilab experiment E691"
- October 27: David A. Garelick, Northeastern University, "At least four highly speculative experiments"
- October 29: Richard Kofler, University of Massachusetts, "Performance and results: SLAC's SLC and SLD"
- Nov. 3: Bruce Schumm, Lawrence Berkeley Laboratory, "Perturbative QCD and the charge multiplicity of events containing heavy quarks in e^+ and e^- annihilation"
- Nov. 3: George Rawitscher, University of Connecticut, "Effect of exchange non-locality on elastic neutron- ^{16}O scattering"

- Nov. 4: Thomas Ludlam, Brookhaven National Laboratory, "The relativistic heavy-ion collider"
- Nov. 5: Arthur Swift, University of Massachusetts, "QCD: Tome for a Nobel Prize? Qualitative and quantitative successes of QCD"
- Nov. 9: Sekhar Chivukula, Boston University, "Hiding the electroweak symmetry breaking sector"
- Nov. 10: Janice B. Shafer, University of Massachusetts, "SLAC experiment E143 and the spin structure of the nucleon"
- Nov. 19: Gustavo Burdman, University of Massachusetts, "Union of heavy quark and chiral symmetries"
- Nov. 24: Michael F. Lauterback, LeCroy Corporation, "Advances in digital technology"
- Dec. 1: Ricardo Marinelli, University of Santa Caterina, Brazil, "Giant dipole resonance within the GCM approach"
- Dec. 8: Andrew M.J. Sandoz, Brookhaven National Laboratory, "Photonuclear physics at LEGS - How round is the proton?"
- Dec. 15: Edward Hartouni, University of Massachusetts, "A high statistics study of like-paired pion pair correlations"
- Jan. 29: John Calarco, University of New Hampshire, "Giant resonance studies by inelastic electron scattering coincidence measurements"
- Feb. 4: John Donoghue, University of Massachusetts, "Report on Santa Cruz conference on the Higgs boson"
- Feb. 5: Keith Griffioen, University of Pennsylvania, "Shadowing, the sea, and the nuclear medium in deep inelastic scattering"
- Feb. 10: Barry R. Holstein, University of Massachusetts, "Symmetry breaking in nuclear and particle physics"
- Feb. 11: Thomas Hemmert, University of Massachusetts, "Color transparency"
- Feb. 12: Barry Holstein, University of Massachusetts, "How large is the d-u quark mass splitting difference?"
- Feb. 18: Eugene Golowich, University of Massachusetts, "How do particles put on weight?"
- Feb. 25: Barry Holstein, University of Massachusetts, "A polarizability primer"

- Feb. 26: Jim Napolitano, Rensselaer Polytechnic Institute, "Deuteron photodisintegration at high energy"
- March 4: Antonio Perez, University of Massachusetts, "Neutral kaon mischief: First CP, now quantum mechanics?"
- March 10: Stanley Hertzbach, University of Massachusetts, "Electron-positron collisions at the Z-boson mass: First results from SLD at the Stanford Linear Collider"
- March 11: Iris Abt, University of California at Davis, "First Results from H1"
- March 11: Janice Button Shafer, University of Massachusetts, "Upcoming SLAC experiments on the spin structure of the nucleons"
- March 12: Ross S. Hicks, University of Massachusetts, "Is there such a thing as a simple single-nucleon knockout reaction?"
- March 22: Mikhail Kozlov, Amherst College, "Parity non-conservation effects in rare earth atoms"
- March 25: Juan Jose Gomez Cadenas, CERN, "Highlights in tau physics"
- March 26: Thomas Cohen, University of Maryland, "Current status of QCD sum rule calculations for baryons in nuclear matter"
- March 30: David Williams, Los Alamos National Laboratory, "Particle astrophysics with the CYGNUS air shower array"
- April 1: Edward Hartouni, University of Massachusetts, "What I did on my spring break: Thoughts on the B hadron"
- April 1: Robert Tshirhart, Fermilab, "Kaon physics and CP violation at Fermilab"
- April 2: Pavel Degtyarenko, Institute of Theoretical and Experimental Physics, Moscow, Russia, "Target fragmentation in deep inelastic scattering of 14.5 GeV electrons from nuclei"
- April 8: Prasad Venugopal, University of Massachusetts, "Looking for Some Axion"
- April 8: Harry Cheung, University of Colorado, "Charm Hadron Lifetimes"
- April 9: Pavel Degtyarenko, Christopher Arabadjis, Latifa Elouadrhiri, Joseph Gallant, Ricardo Marinelli, and Kyong Sei Lee, University of Massachusetts, "Practice Talks for APS Washington Meeting"
- April 13: Milind Purohit, Princeton University, "Fixed Target Charm Physics"
- May 7: Joe Mandeville, University of Illinois, "Measurement of the 5th structure function in ^{12}C "
- May 14: Dr. Mikhail Kossov, ITEP, Moscow, and CEBAF, "Electroproduction of Light Quark Mesons"
- May 20: Sarah Yoffa, University of Massachusetts, "Design Automation with AutoLISP", and Kebin Wang, University of Massachusetts, "Target Fragmentation and the TPC Data"

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