A PROGRAM IN MEDIUM ENERGY NUCLEAR PHYSICS

DOE/ER/40285--1-Pt. 3

Renewal Proposal and Progress Report
August 1, 1994

Professor B.L. Berman, Principal Investigator
Associate Professor K.S. Dhuga, Co-Principal Investigator
Center for Nuclear Studies
Department of Physics
The George Washington University
Washington, DC

ABSTRACT

This renewal proposal requests continued funding for our program in experimental medium-energy nuclear physics. The focus of our program remains the understanding of the short-range part of the strong interaction in the nuclear medium. In the past three years we have focused our attention ever more sharply on experiments with real tagged photons at CEBAF. We are part of the Hall-B Collaboration at CEBAF. We are co-spokespersons on two approved CEBAF experiments, *Photoreactions on ^3He* and *Photoabsorption and Photofission of Nuclei*, and we are preparing another, *Nondiffractive Photoproduction of the ρ Meson with Linearly Polarized Photons*, for presentation to the next CEBAF PAC. We are part of the team that is instrumenting the Photon Tagger and a high-energy tagged polarized-photon beam for Hall B; some of the instrumentation for these projects is being built at our Nuclear Detector Laboratory, under the auspices of The George Washington University Center for Nuclear Studies. Our recent measurements of pion scattering from ^{3}H and ^{3}He at LAMPF and of cluster knockout from few-body nuclei at NIKHEF have yielded very provocative results, showing the importance of the very light nuclei as a laboratory for quantifying important aspects of the nuclear many-body force. We look forward to expanding our studies of short-range forces in nuclei, particularly the very light nuclei, using electromagnetic probes and employing the extraordinary power of CEBAF and the CLAS.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

I. OVERVIEW AND PERSPECTIVE

A. RESEARCH GOALS

Of the various properties and symmetries that are most commonly used in the description of both nuclear structure and reaction dynamics, the ones that we think are most intriguing are those that relate to the spin, isospin, and strangeness structure of the constituent particles and their interactions. At low energies, using these very properties, models based on constituent particles that include only nucleons and mesons have successfully provided a good description of a great variety of electromagnetic and hadronic scattering processes. At sufficiently high energies we expect these models to fail. Thus, a transition is expected as one increases the energy (or shortens the wavelength) such that the behavior of a given process can no longer be fully described by these models. It is widely anticipated that in this transition-energy region and beyond, QCD-inspired models based on quark-gluon degrees of freedom will provide the basic framework for describing the interaction of strongly interacting particles.

The central theme of our experimental program is the delineation of the properties and symmetries of the many-body nuclear force. In particular, we wish to explore and understand the nature of the short-range part of the strong interaction in the nuclear environment. Thus, one of the main thrusts of our effort continues to be the investigation of the leading term beyond the much-studied two-body part of the nuclear force--the three-body component, i.e., the additional force that exists only when three or more nucleons are present. The investigation of this short-range phenomenon is hampered by the fact that the effects usually are small compared to those due to the ever-present two-body force. Furthermore, the extraction of these small effects requires not only the suppression of two-body effects but also the detection of multiparticle events, often including neutral particles, in the final state. However, with the advent of CEBAF, the exciting prospect of identifying, and indeed, quantifying the nature of the many-body part of the nuclear force is made much more feasible, especially when we have at our disposal the combined power of a well-understood short-wavelength electromagnetic probe and an efficient large-acceptance detector, such as the CLAS. Accordingly, we plan to study the nuclear three-body force in its most elementary manifestation, the three-body photodisintegration of ^{3}He.

Elucidation of the various mechanisms by which the strong interaction is modified by the nuclear medium is also central to our program. We plan to perform a systematic study of the photoexcitation, propagation, and decay of nucleon resonances in light-to-heavy nuclei (ranging from ^{3}He to ^{238}U). Resonances of particular interest include the D_{13} and F_{15}, for which there is existing evidence that indicates considerable damping of strength--an observation which is very puzzling, especially in light of the fact that in the region of the Δ (P_{33}) resonance the strength is conserved. This study not only will provide a measure of the density-dependence of the γN and NN interactions, but also will provide valuable information on both the role of shadowing and on the A-dependence of the photoabsorption and photofission processes as a function of photon energy.

Low-energy studies involving the exchange of light mesons have produced a wealth of information on the long-range part of the nuclear force. Clearly, high-energy studies involving more massive mesons are required to probe the short-range nucleon dynamics in the nuclear medium. We have joined collaborations planning to measure the photoproduction of pseudoscalar mesons (η and η'), first from nucleons and then from nuclei; strange (K^{+} and K^{0}) mesons from ^{3}He, ^{4}He, and ^{12}C; and vector mesons (ρ, ω, and ϕ) at high t, first from nucleons and then from ^{3}He. As an important next step, we are in the latter stages of preparing a proposal to measure the photoproduction of vector mesons (ρ^{+} and ρ^{0}) with linearly polarized photons in order to observe the spin dependence of the decay of nucleon resonances, first from nucleons and then from nuclei.

In summary, our proposed research program for the next three years centers around three major projects:

- Photoreactions on ^{3}He
- Photoabsorption and Photofission of Nuclei
- Photoproduction of Pseudoscalar, Strange, and Vector Mesons

We are co-spokespersons on the first two projects; on the experiments approved to date that make up the third, we are collaborators.

B. Experiments

One of the main highlights of our current effort has been the approval by the CEBAF PAC of both of the proposals that we have submitted. These are *Photoreactions on ^{3}He*, CEBAF proposal 93-044 (B.L. Berman, P. Corvisiero, and G. Audit, Co-spokespersons) and *Photoabsorption and Photofission of Nuclei*, CEBAF proposal 93-019 (N. Bianchi, V. Muccifora, and B.L. Berman, Co-spokespersons). We are also preparing a proposal to measure photofission cross sections at lower energies at the Saskatchewan Accelerator Laboratory. The salient features of these proposals are delineated in Section IIA below, and the approved proposals are reproduced in full in Appendix A.

We are collaborators on several other approved proposals at CEBAF. These include *Photoproduction of η and η' Mesons*, CEBAF proposal 91-008 (B.G. Ritchie, Spokesperson), *Quasifree Strangeness Production in Nuclei*, CEBAF proposal 91-014 (C. Hyde-Wright, Spokesperson), and *Photoproduction of Vector Mesons at High t*, CEBAF proposal 93-031 (J.-M. Laget and M. Anghinolfi, Co-spokespersons). Brief descriptions of these proposals are given in Section IIB.

We are currently preparing another proposal, for the next CEBAF PAC, *Nondiffractive Photoproduction of the ρ Meson with Linearly Polarized Photons* (P.L. Cole, J.P. Connelly, and R.R. Whitney, Co-spokespersons). This proposed experiment is described in some detail in Section IIB.

Because GW has withdrawn from the HARP Collaboration (see Section VI), we shall not perform our approved experiment at NIKHEF, proposal 93-09, *Recoil Polarization of the Neutron in the Reactions $^3He(e,e'\vec{n})$ and $^4He(e,e'\vec{n})$* (K.S. Dhuga, Spokesperson). This gives us the opportunity to focus and strengthen our research program by concentrating essentially all of our efforts on our Hall-B CEBAF program, particularly those of K.S. Dhuga and P.L. Cole, who have previously spent much of their efforts on the HARP project.

C. Instrumentation

Currently, we are involved in the instrumentation of the focal-plane detector array of the Photon Tagger for Hall B at CEBAF. For the CEBAF tagger project, the GW group (particularly W.J. Briscoe and J.P. Connelly) is responsible for the design and construction of the 11-m long 436-scintillator focal-plane detector array. Most of the design work is complete, much of the prototype testing has been done, and construction is in progress at our new Virginia-Campus Laboratory. We (particularly S.L. Rugari, P.L. Cole, and B.L. Berman) are also involved with the design and eventual instrumentation of a polarized tagged photon beam for Hall B by means of coherent bremsstrahlung produced on a crystal target, and with the design and construction of parallel-plate avalanche detectors for our photofission measurements. These projects are described in more detail in Section IIC.

D. HIGHLIGHTS OF RECENT RESEARCH

Our recent research includes measurements of electron scattering at NIKHEF and of pion scattering at LAMPF. We report some of our results here.

In a series of cluster-knockout (e,e'X) measurements on ^{6}Li and ^{12}C at NIKHEF, where X = d, α, ^{3}H, or ^{3}He, we have nearly completed the analysis of the last in the series, namely, ^{6}Li(e,e'^{3}He)^{3}H. These results, when combined with those for ^{6}Li(e,e'^{3}H)^{3}He, will elucidate the reaction mechanism, since the final-state interactions are the same for these mirror reactions. The results show that the q-dependence for the (e,e'^{3}H) reaction deviates markedly from that which would be expected from a system in which the trinucleon clusters were the same as they are in free space, which was expected, while that for the (e,e'^{3}He) reaction does not, which was *not* expected. The ratio of these cross sections, instead of being roughly constant and equal to four (the Z^2 ratio), deviates from that value by more than a factor of three at low q. A paper describing these striking results is in preparation. The (e,e'd) and (e,e'α) results have already been published or are in press. More details on this subject are given in Section IIIA.

The aim of our series of pion-scattering measurements from the isospin doublet ^{3}H and ^{3}He has been twofold: (a) to probe the matter distributions of the nucleons in these mirror nuclei, since they are complementary to the charge and magnetization distributions measured by electron scattering--the neutron distribution in ^{3}H in particular, to which electron scattering is insensitive because the neutrons in this nucleus carry neither the charge nor the magnetic moment; and (b) to test the magnitude and nature of charge-symmetry breaking in the strong interaction by measuring charge-symmetric cross-section ratios and their product, the superratio. The energy and angle behavior of these ratios provide the signature for charge-symmetry breaking--in its absence, these ratios are unity. Most of our measurements (at 180 MeV incident pion energy) have yielded values for the superratio substantially greater than unity, indicating a breaking of charge symmetry beyond that arising from Coulomb effects alone. Even more striking, our measurements at 256 MeV have uncovered values for the superratio substantially *smaller* than unity. Such a negative deviation from unity cannot be explained even qualitatively by Coulomb effects alone. Although a number of models can explain the qualitative behavior of the superratio at 180 MeV, none is able to describe the data at all angles, and so far, none has simultaneously explained the superratios at *both* energies. The need for a second-order isospin-dependent potential to explain these results has been echoed recently by several theorists. The analysis of our most recent large-angle elastic-scattering data on these nuclei is now complete, and two papers are being prepared for publication (one has been submitted). A number of articles detailing the early results have already been published. Some of these results have been the subject of invited talks by the P.I. at national and international conferences, including "Pion Scattering from ^{3}H and ^{3}He" in 1991 at Peniscola, Spain and "Pion Scattering from Light Nuclei" at the 1993 APS meeting in Washington. Our work at LAMPF is described in more detail in Section IIIB.

A tabular summary of all of our recent work in nuclear physics is given in Section IV. Our nuclear physics publications for 1991 to 1994 are listed in Section VII. Papers currently submitted or in press are reproduced in Appendix B.

E. Institutional Support

We have benefited considerably through substantial institutional support by the University, through several faculty appointments, substantial cost-sharing, and the chartering and funding of the Center for Nuclear Studies, which has been designated as one of only six Centers of Excellence at GW. In the last several years the University has spent over $400,000 towards the creation of our Nuclear Detector Laboratory at our Foggy Bottom Campus, and more recently, approximately an additional $300,000 for its sister Laboratory at our new Virginia Campus. We use these Laboratories not only to fulfill our obligations to the Hall-B Collaboration, but also as our primary training facilities for both graduate and undergraduate students. We also benefit greatly from the close ties that exist between GW and CEBAF; our research program there is supported strongly by this close institutional relationship. Further elaboration of our institutional support and personnel can be found in Section V. Our resumes and complete publication lists for 1989 to 1994 are given in Appendix C.

II. CURRENT RESEARCH PROGRAM

A. PHOTONUCLEAR REACTIONS AT CEBAF

1. Photoreactions on ^{3}He

This experiment will use real photons to study three different physical phenomena in ^{3}He: three-body-force effects, the Δ-isobar part of the nuclear wavefunction, and the formation and propagation of nucleon resonances in the nuclear medium. With the Hall-B Photon Tagger and the CLAS, each of these phenomena will be studied in exclusive reaction channels. The three-body part is primarily our responsibility. The particular channels of interest are (γ,ppn) and (γ,NNΔ), studied in the "star" configuration (see below). The probability for a small ΔNN component in the ^{3}He ground-state wave function will be studied via direct Δ^{++} knockout [the (γ,pπ^+) and (γ,pπ^+n) channels]. This part is primarily the responsibility of our collaborators from Saclay, and has also been the subject of an invited talk, "Delta Knockout from ^{3}He" at the CEBAF Retreat at Snowshoe (Ber93). The modification of the properties of nucleon resonances, principally the D_{13}(1520) and the F_{15}(1680), in the ^{3}He nucleus will be studied via the (γ,π3N) and (γ,2π3N) channels, which then can be summed to give an excellent approximation to the total resonance production. This last topic is primarily the responsibility of our collaborators from Genoa.

The study of the interaction of nucleons in the presence of other nucleons is a fundamental problem of nuclear physics. In ^{3}He, the two-body N-N force dominates the wave function at low energies (and hence long distances) to such a degree that the very existence of a three-body component is still a subject of debate (Wei90). Some intriguing three-body photodisintegration data exist at lower energies, which exhibit some evidence for the existence of three-body effects in ^{3}He (Aud91, Sar93, Emu94, Kol94, Rut94, Ted94). We will look for manifestations of the three-body force at higher photon energies, up to 1.5 GeV, corresponding to a reduced photon wavelength of about 0.1 fm. The main difficulty of this measurement will be to distinguish the effects of true three-body forces from effects of sequential two-body processes. The most likely signature is the "star" configuration in the reaction channel in which the three nucleons are emitted 120° apart with equal momenta in the center-of-mass frame, and no additional particles are produced, as shown in Fig. 1. The star configuration occupies the central region of a triangular Dalitz plot, shown in Fig. 2, while the dominant two-body channels populate the

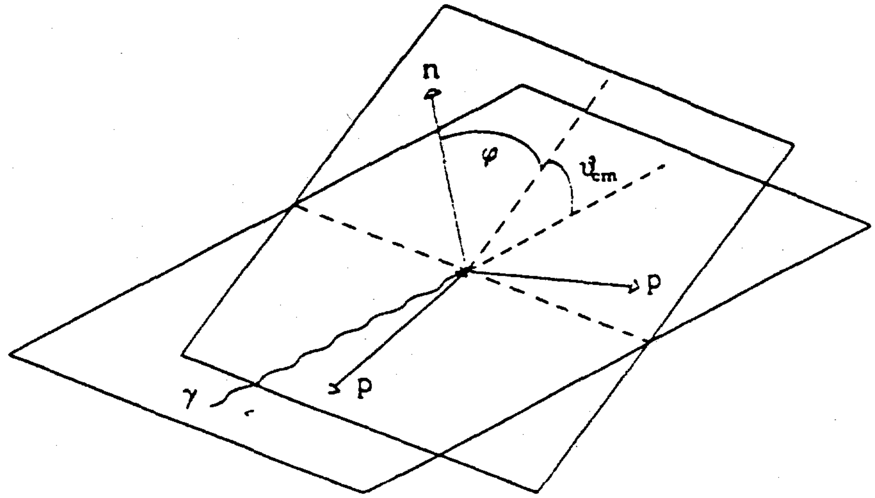

Fig. 1 Schematic representation of the star configuration.

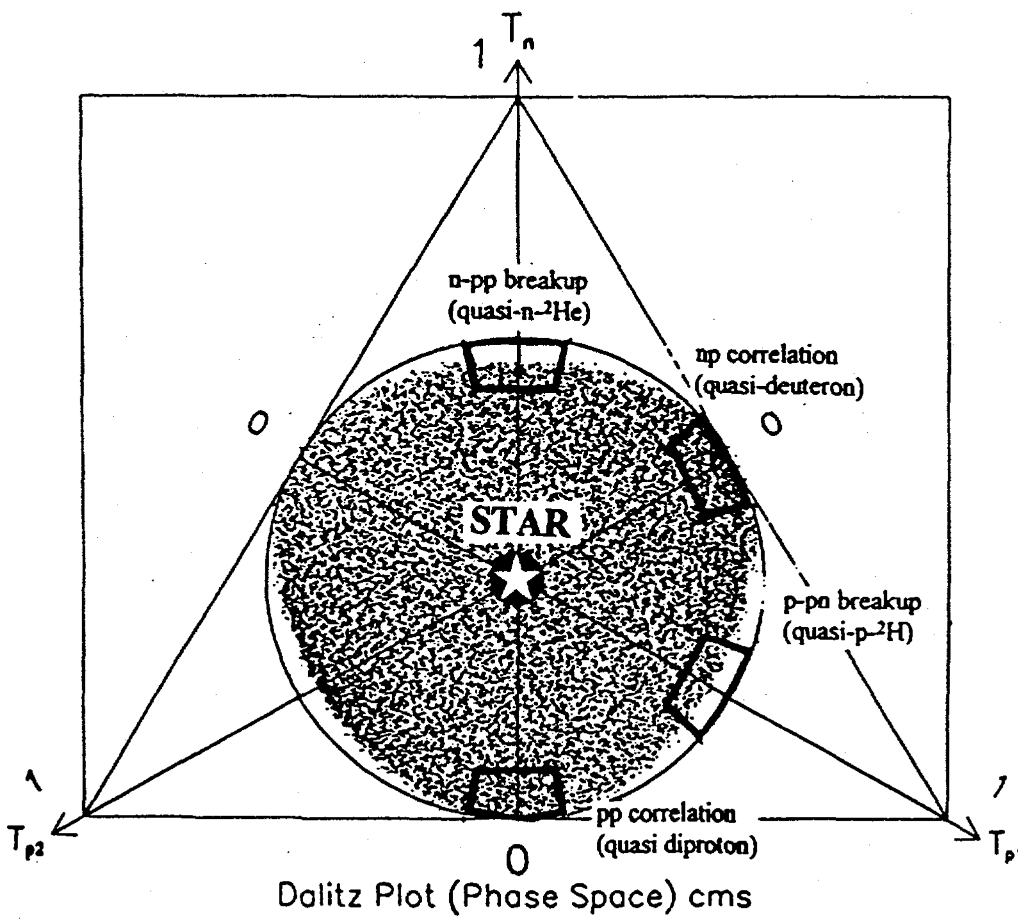

Fig. 2 Triangular Dalitz plot of ^3He breakup in the center-of-mass frame for an incident photon energy of 0.8 GeV. Star event candidates are located in the center.

periphery. Additionally, the plane of the nucleon momenta need not include the direction of the incident photon. In this way the background from two-body processes is minimized. Laget has calculated the effect of the three-body contribution with the star configuration in certain kinematics, for incident photon energies of 500, 800, and 1100 MeV (Lag93). The diagrams used are shown in Fig. 3, and the results of this calculation for 800 MeV (the best case) are shown in Fig. 4. It can readily be seen that for the kinematical region near an azimuthal angle ϕ of 30°, three-body effects are predicted to play the dominant role--so much so (by a factor of 20), that good statistics for this effect can be obtained in a relatively modest amount of running time.

The second objective of this experiment is to look for the small Δ-isobar part of the nuclear wave function. At low energies, the ^{3}He wave function is dominated by the NNN configuration; however, at higher energies the contribution of the ΔNN configuration has been predicted to be between a few tenths (Abd90) and several percent (Str87). The clearest signature of such a configuration is the direct knockout of a Δ. To minimize contributions from the much more probable Δ-production events, we will look for Δ^{++} knockout events (Δ photoproduction from nucleons will contribute directly only to Δ^0 and Δ^+ production). These events will be identified by an invariant-mass reconstruction analysis of p-π^+ events in the CLAS detector, both with and without detection of the recoil neutron. Using the diagrams shown in Fig. 5, Laget has calculated (Lag92) the cross section for Δ knockout [parts (c) and (d)] as a function of the momentum of the Δ in the nucleus, and has found that it is much larger than competing background processes [parts (a) and (b)], as shown in Fig. 6.

The third objective is to determine the amount of damping of nucleon resonances in ^{3}He. Recent total photoabsorption data on Be, C, and U for photon energies from 0.2 to 1.1 GeV (Ang93, Bia93a) show strong suppression of the cross section ($\sim$35%) in the region of the D_{13} and F_{15} resonances, when compared with data from the free proton and the deuteron, as shown in Fig. 7. However, the Δ resonance shows only Fermi-broadening effects. Because ^{3}He is intermediate in nuclear density and binding between the free nucleon (or the deuteron) and heavier nuclei, it constitutes an ideal case for studying the effect of the nuclear medium on the propagation of these resonances. We will study the degree of suppression (or "damping") of the D_{13} and F_{15} resonances in the photoabsorption cross section of ^{3}He by detecting and summing the *exclusive* N-π and N-π-π reaction channels. A prediction of this total cross section, with Fermi broadening but no suppression (Cio93), is shown in Fig. 8. Some data up to 800 MeV exist,

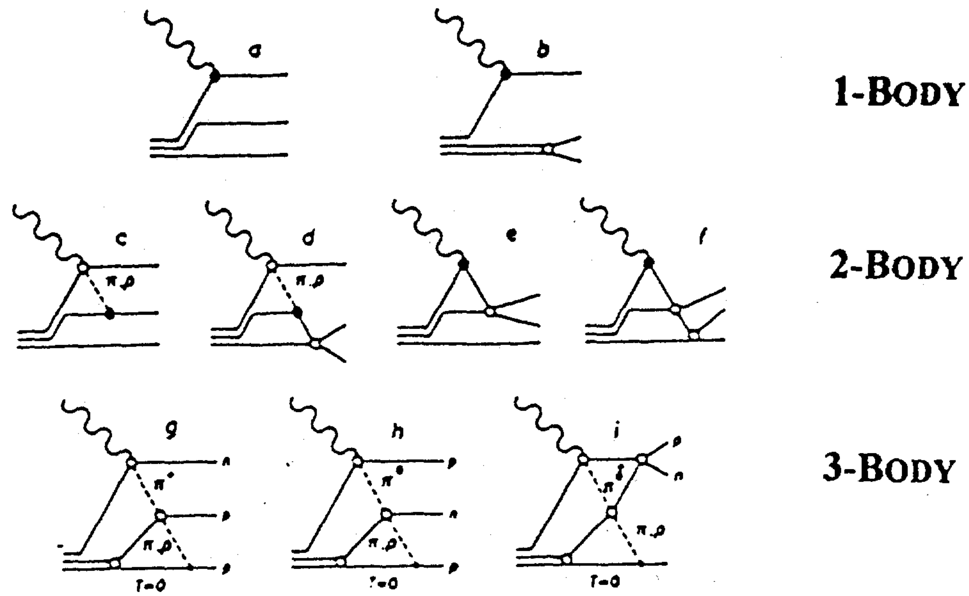

Fig. 3 Diagrams used in the calculation of the ^{3}He(γ,ppn) cross section.

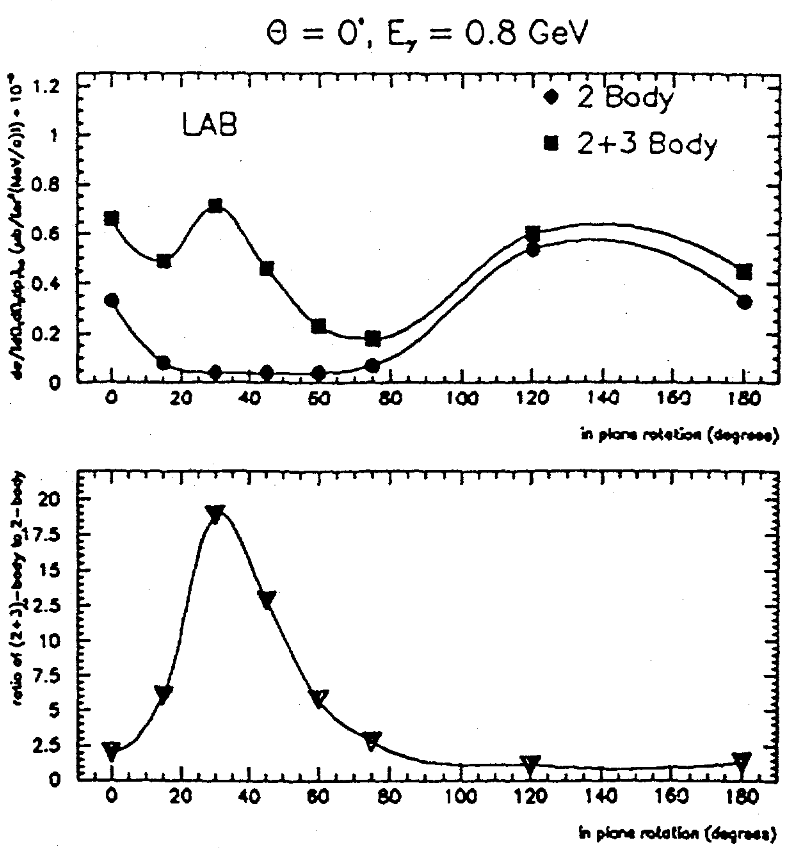

Fig. 4 Calculated (2+3)-body and 2-body cross sections (top) and their ratio (bottom) for $\theta = 0°$ as a function of ϕ in the star configuration (see text). Note the enhancement of the 3-body cross section at $\phi = 30°$

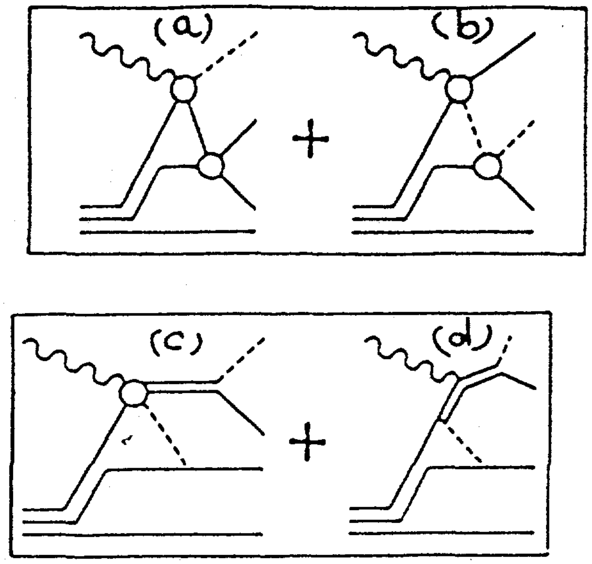

Fig. 5 The processes (a) and (b) depict the multiple-scattering mechanisms which contribute to the background of the $^3He(\gamma,\Delta^{++})$ reaction. The mechanisms which lead to a Δ component in the wave function of ^3He and the associated meson-exchange currents are shown by diagrams (c) and (d).

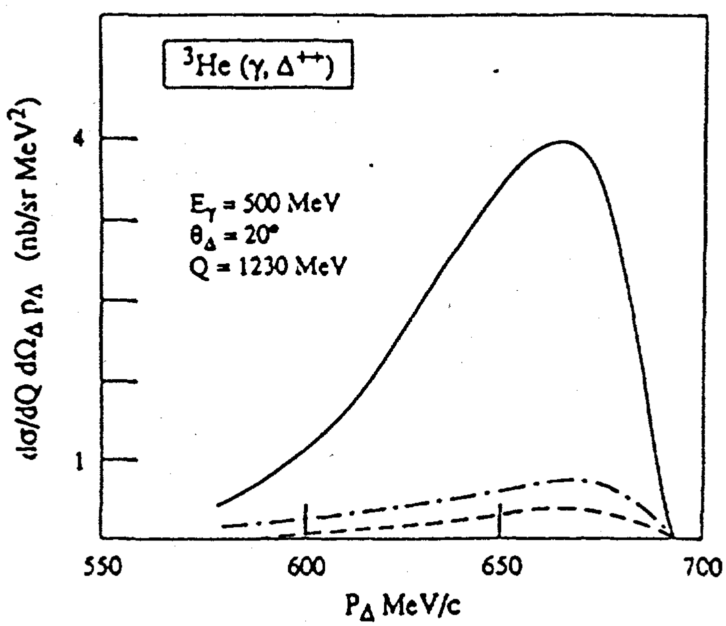

Fig. 6 The predicted spectrum of the Δ^{++} emitted in the $^3He(\gamma,\Delta^{++})$ reaction. The dashed curve includes only N-N rescattering mechanisms, while the dot-dashed curve includes π-N rescattering terms as well. The full curve takes into account the contributions of the Δ component in the ground state and the associated exchange currents.

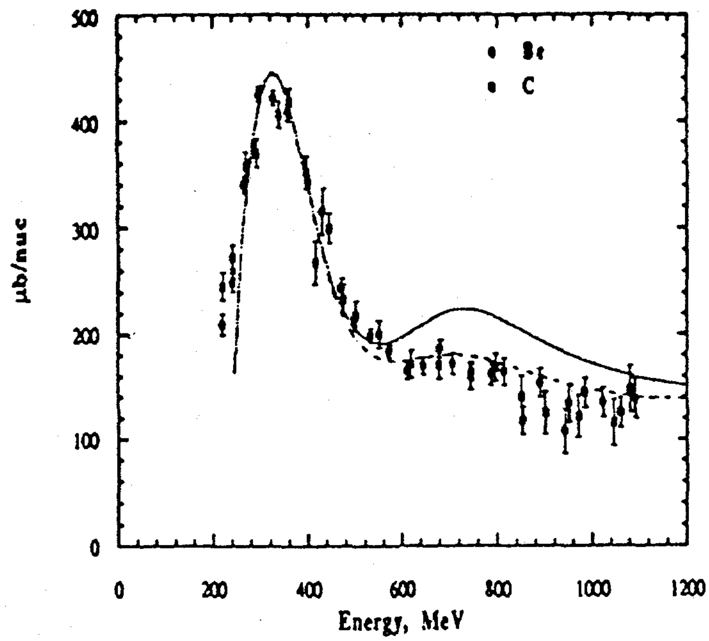

Fig. 7 Total photon absorption cross section per nucleon for Be (circles) and C (squares). The solid curve is a fit to the average of the free proton and neutron cross sections, broadened by the Fermi momentum for C. The dashed curve results from attenuating the D_{13} and F_{15} amplitudes each by 20%.

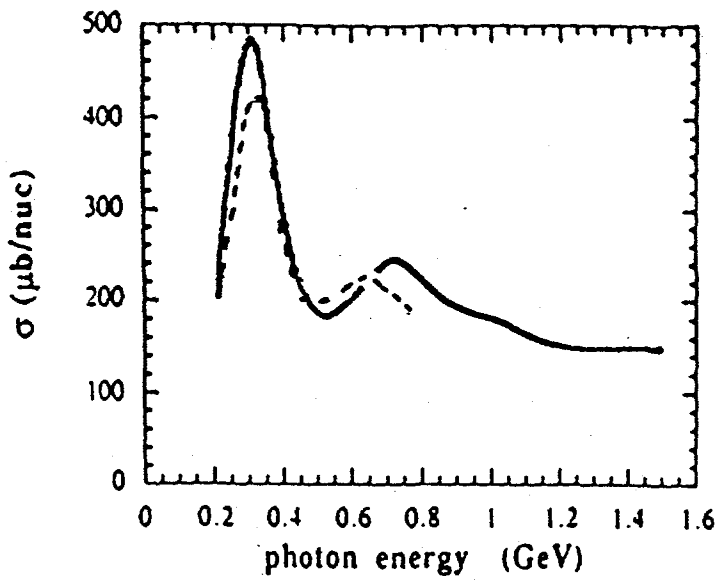

Fig. 8 Total photon absorption cross section for ^{3}He. The solid line is a theoretical prediction from the free-nucleon cross sections that have been broadened by Fermi motion; the dashed line is a representation of the data from DAPHNE at Mainz.

obtained at Mainz with the DAPHNE detector (Aud94), which also are shown in Fig. 8. These data exhibit some indication of the D_{13} resonance, neither as prominent as in the deuteron nor as damped as in Be and C. More remarkably, in these data the Δ peak is shifted upward in energy relative to the prediction, while the D_{13} peak is shifted downward. Clearly, we need to examine the exclusive channels to determine the cause of this unexpected result.

This experiment will require a tagged-photon beam in the energy range from 0.5 to 1.5 GeV, a cryogenic ^3He target, and the CLAS detector system. The target system is being built by our colleagues at Saclay, and the ^3He will be supplied by our colleagues at Los Alamos. This experiment will run for 300 hours, of which 150 hours will be concurrent with Experiment 91-014.

2. Photoabsorption and Photofission of Nuclei

In this experiment, we shall investigate the nuclear-medium effects on the photon interaction with bound nucleons, as a function of A, from carbon to uranium. Also, we shall explore the onset of the shadowing effect as a function of E_γ. For the actinide nuclei, the fission channel is expected to incorporate nearly all of the photon absorption strength; if so, this part of the experiment will provide an alternative and very efficient way, with parallel-plate avalanche detectors (PPADs) to measure the total photonuclear cross section. Thus, this experiment will serve as a definitive study of the damping of the nucleon resonances in nuclei (except for the lightest nuclei--which is one of the objectives of the ^3He experiment discussed above).

The interaction of baryon resonances in the nuclear medium has not been studied extensively. Although the Δ-resonance strength appears to be conserved over a wide range in mass number, the higher-lying baryon resonances at E_γ = 0.7 GeV and 1.0 GeV (mainly the D_{13} and F_{15} resonances) are clearly seen only in the photon absorption spectra of free protons and deuterons. Figure 9 shows that recent results for ^{238}U from Frascati up to 1.2 GeV (Bia93a) follow the trend of the carbon data shown in Fig. 7, as do recent data from Mainz (Kne94) up to 800 MeV. This unexpected phenomenon might result from the shadowing effect, or possibly from the damping of the excitation or propagation of certain resonances in the nuclear medium. The general idea is that a resonance whose excitation involves a change in *orbital* angular momentum *or* whose spatial extent is large

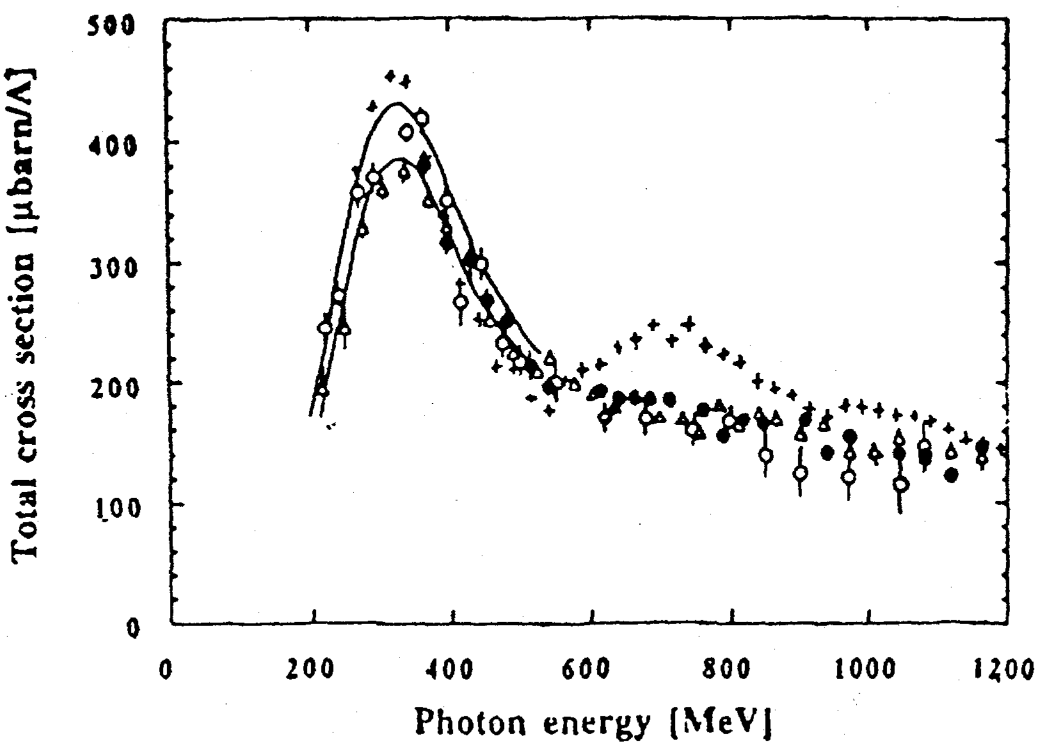

Fig. 9 The Frascati data on C, obtained both with the photo-hadronic method (solid circles) and the transmission method (open circles), and on ^{238}U (open triangles), compared with deuterium data (crosses) and with the universal nuclear behavior in the Δ region.

by virtue of its large intrinsic angular momentum has a range of interaction comparable to the internucleon spacing in a tightly bound nucleus (unlike deuterium and possibly ^{3}He), and hence interacts strongly with the nucleons in such a nucleus.

This experiment will measure the total photoabsorption cross section for C, Al, Cu, Sn, and Pb nuclei to study the interaction of baryon resonances in the nuclear medium. These measurements will be performed with photons in the energy range from 0.4 to 1.9 GeV using the Hall-B Photon Tagger. The total absorption cross section will be measured using the photo-hadronic method. A cylindrical shell of NaI detectors will be used to measure the photoproduction rate of (large-angle) hadronic events, and a lead-glass shower detector downstream will provide a veto for the vast preponderance of (small-angle) purely electromagnetic events. This measurement does not require the CLAS detector and is expected to run with the Photon Tagger prior to final commissioning of the CLAS. The NaI and lead-glass detectors will be provided by our colleagues at Frascati.

For nuclei in the actinide region with fissility nearly equal to one, specifically ^{238}U, measurement of the photofission cross section is a useful technique to measure the total photoabsorption cross section. This experiment will measure the photofission cross sections in the same energy range, from 0.4 to 1.9 GeV, for the nuclei ^{238}U, ^{232}Th, and ^{237}Np.

Data on ^{238}U show that the photofissility has a constant value consistent with one over a large energy region, from the quasideuteron region well into the resonance region, up to 1.2 GeV (Bia93a). This is expected to be valid at higher energy as well. We shall obtain data that overlap those from Frascati and extend the energy range to 1.9 GeV.

The photofission of ^{232}Th shows a behavior different from the heavier actinide nuclei. This nucleus appears to have a photofissility which is smaller than that for ^{238}U by 20-40%, and which increases somewhat with energy from 0.25 GeV to 1.2 GeV (Bia93b). [There is a gap in the data for ^{232}Th between about 0.1 GeV (Lep87) and 0.25 GeV.] This behavior has been attributed to a smaller transparency of ^{232}Th (Arr93), although the explanation could be that the fissionability Z^2/A is simply too small. We shall obtain data that explore the expected increase in fissility of this nucleus up to 1.9 GeV.

For ^{237}Np, recent photofission experiments at Novosibirsk (Ilj92), in the energy range from 0.06 to 0.24 GeV, indicate a photofissility for ^{237}Np of about 20-40% *larger* than that for ^{238}U. If these ^{237}Np results are confirmed, it would cast doubt on all the other measurements for ^{235}U and ^{238}U, and would also be a difficult anomaly to incorporate within the current theoretical framework. Clearly, this behavior needs to be explored further. We shall measure the (relative) fissility of ^{237}Np, to see if this anomalous behavior persists to higher energies.

The fission products will be detected in parallel-plate avalanche detectors (PPADs) in which the nuclear target is internal, forming one of the electrode planes. This measurement does not require the CLAS and can be performed prior to CLAS commissioning as well. In fact, this experiment, which is approved for eight days, would constitute an ideal commissioning experiment for the Photon Tagger.

We also propose to use the photon-tagging facility at the Saskatchewan Accelerator Laboratory (SAL) to measure the total photofission cross sections up to 0.25 GeV and to extract the photofissilities of ^{232}Th and ^{237}Np relative to ^{238}U. These measurements will complement our approved experiment at CEBAF and will use the same PPAD system that will be implemented for the CEBAF measurements. Not only will this experiment fill in the gap for ^{232}Th and directly check the Novosibirsk results for ^{237}Np, but it will also serve as an extremely valuable prelude to our CEBAF experiment, as a training experience for our students and as a shakedown of the detector system under experimental conditions. Finally, we plan for it to be done in 1995, prior to the availability of beam in Hall B, thus decreasing the waiting time of our students.

However, no matter what the situation is for other nuclei, what if the fissility of the apparently well-behaved ^{238}U nucleus is not unity at high energies? Several interesting questions would then be raised (Ber92a): What is the branching ratio of non-fission events? What curious kinds of processes can leave the residual nucleus so cold? Are these surface events on a very heavy nucleus? Are strong many-body forces important? How can we quantify them? There is no question that further study, by measurement of *other* emitted particles, *with* the CLAS, in *anticoincidence* with a fission fragment, is highly desirable, in order to determine the character of the non-fission events. We plan to propose, in due course, such a follow-on experiment using the CLAS, and we are designing our PPAD system (see Section IIC) to fit inside the CLAS.

B. Meson Photoproduction at CEBAF

1. Photoproduction of η and η' Mesons

This experiment will make high-precision measurements of the differential cross sections for η(549) and η'(958) photoproduction on the proton, with tagged photons of energies from 0.65 to 2.25 GeV. These measurements will provide much-needed data for the delineation of the elementary amplitudes for these processes, and will provide the first photoproduction data for the η'. Moreover, future investigations of η and η' photoproduction from the neutron (in deuterium) and from nuclei (particularly ^{3}He and ^{4}He) will require for their interpretation the detailed understanding of this process on the proton that this experiment will provide. Finally, these data will be useful in identifying baryon resonances, because the isospin selectivity of these processes results in an isospin filter for the resonances that decay via these pseudoscalar mesons.

2. Quasifree Strangeness Production in Nuclei

This experiment will use tagged photons (up to 2 GeV) in the CLAS to measure the differential A(γ,K)Y and A(γ,KY) cross sections for ^{3}He, ^{4}He, and ^{12}C, in quasifree kinematics. Both K^+ and K^0, as well as Y = Λ and Σ production will be measured. This experiment is designed to study the relative importance of one-nucleon and two-nucleon currents in kaon photoproduction, as well as to investigate the magnitude of kaon and hyperon final-state interactions in the nucleus. The acceptance studies for this experiment were performed by P.L. Cole, and are the subject of a CLAS Note (Col92; also see Col93).

We will use three nuclear targets, ^{3}He, ^{4}He, and ^{12}C. Data for the ^{3}He nucleus will provide an important comparison with the elementary amplitudes that will be extracted from proton (Sch89) and deuterium data (Mec89). The differential ^{3}He(γ,K) data might constitute a test of the quasifree model, in a context where the (e,e') data suggest the nuclear medium effects are small. Because for self-conjugate nuclei, such as ^{4}He and ^{12}C, the neutron and proton amplitudes can be weighted equally, the K^+/K^0 ratio should be insensitive to the details of the quasifree mechanism. Hence, this ratio should be a sensitive probe for either two-nucleon currents or charge-exchange final-state interactions.

3. Photoproduction of Vector Mesons at High t

As part of our program to study the small parts of the wave functions for few-body nuclei, we shall explore the probability for two-gluon exchange from the proton in the photoproduction of the ϕ meson using the Photon Tagger and the CLAS. The ultimate objective is to search for a (small) hidden-color component of the ^{3}He wave function, measured by detection of a high-t ϕ meson (manifested as a K^+-K^- pair) recoiling against *two* protons–this kind of event can be produced only by one-gluon exchange from *each* of the two colored three-quark objects within ^{3}He that are thereby transformed into the measured recoil protons. The CEBAF PAC has approved the first part of this program, namely, the photoproduction of vector mesons at high t from the proton.

At low t, the photoproduction of the ϕ meson is purely diffractive and is well described by the Vector Dominance Model. At high t, hard scattering processes are expected to dominate the cross section; assuming the strangeness content of the proton is small, two-gluon exchange, as shown in Fig. 10 is expected to dominate ϕ photoproduction. Figure 11 shows the data for the $\gamma p \rightarrow \phi p$ reaction at 3.5 GeV; the data are confined to the diffractive regime, since $|t| < 1.0$ (GeV/c)^2. The purely gluonic process, calculated (Cud90) as the dot-dashed curve in Fig. 11, exhibits a node at a $|t|$ of about 2.4 (GeV/c)^2. This node, if seen in the experimental data, would provide evidence for a two-gluon exchange mechanism. A more detailed calculation (the solid curve) merely shifts the minimum somewhat.

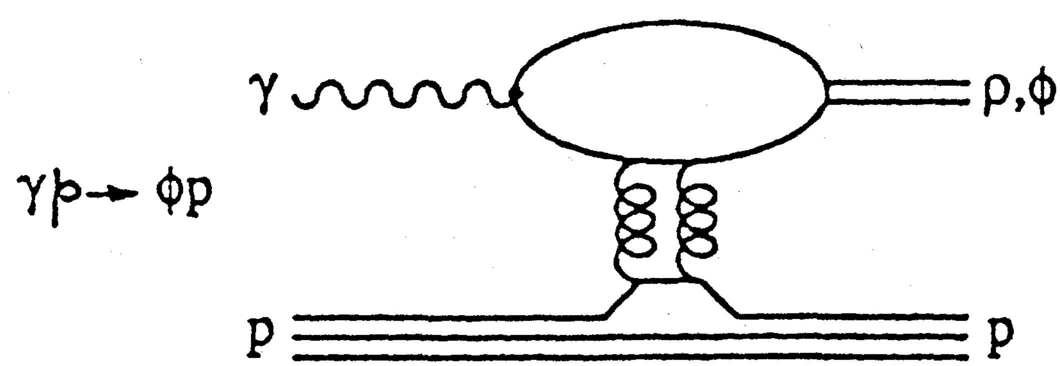

Fig. 10 Conceptual diagram of two-gluon exchange on the nucleon. Between the gluon exchanges, the three-quark object has "hidden" color.

In addition to the ϕ meson, we will also measure high-t cross-sections for the ρ and ω mesons. Again, we hope to see the onset of hard scattering from point-like quarks both in the nucleon and in few-body nuclei. For all three vector mesons we will measure the three decay matrix elements one obtains using unpolarized photons; the polar- and azimuthal-angle dependence of the scalar meson decay of the vector mesons will provide a clear method of determining the onset of processes other than purely diffractive photoproduction. In all cases (ρ,ω,ϕ), there are no data for $|t| > 1.5$ (GeV/c)^2 in the energy range below 4 GeV; and in all cases, this experiment will benefit greatly from the planned extension of the CEBAF beam energy up to 6 GeV.

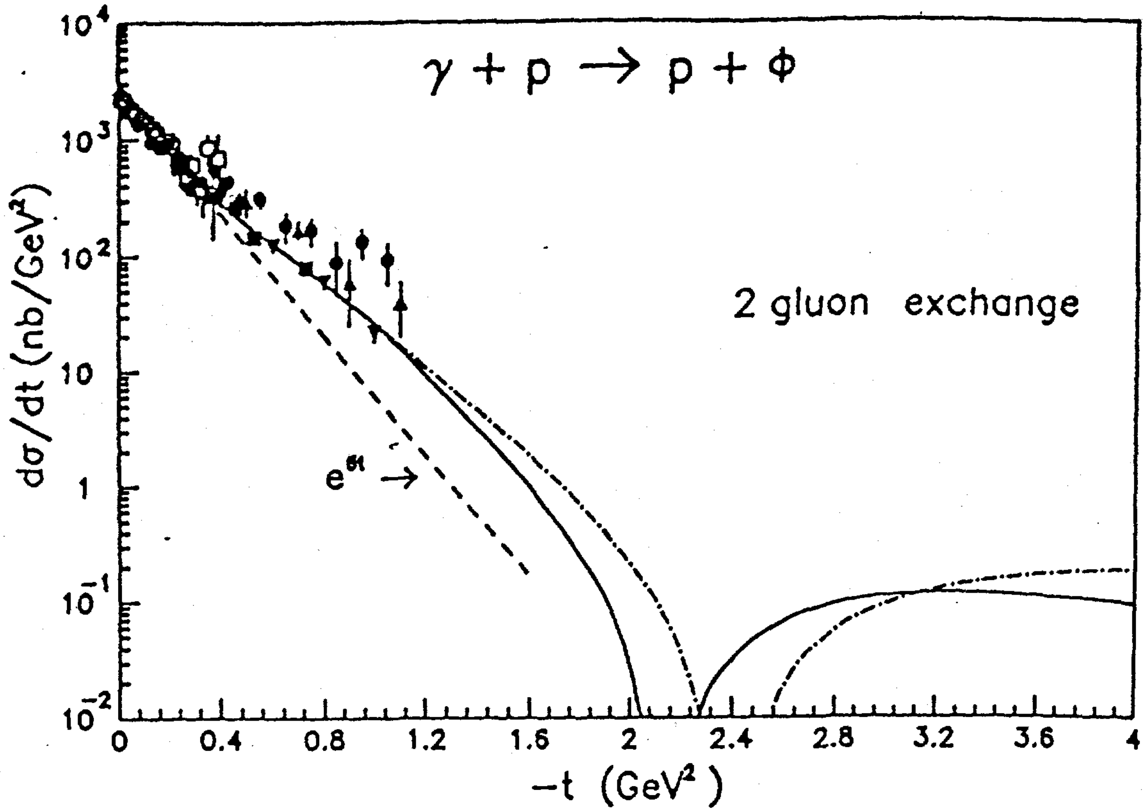

Fig. 11 The cross section of the $\gamma p \rightarrow \phi p$ reaction is plotted against $-t$. The dashed line corresponds to the parametrization of the existing experimental data below $|t| < 0.4$ $(GeV/c)^2$ in the framework of the Vector Dominance Model. The dot-dashed line includes two-gluon exchange mechanisms. The solid line includes full amplitude calculations.

4. Nondiffractive Photoproduction of the ρ Meson with Linearly Polarized Photons

We are presently preparing a proposal to study baryon resonances that decay primarily into a nucleon and a ρ meson, using linearly polarized photons. We expect that the beam polarization will play a crucial role in identifying and extracting the properties of each of these baryon resonances. The large acceptance of the CLAS will afford us the means to access all vector-meson decay angular distributions simultaneously, and will allow us to measure to higher four-momentum transfers, t, than have been measured previously. This is the first step in our program to examine the modification of the properties of these resonances in the nuclear medium. In the future we intend to expand this work, first to the neutron in ^2H, and then to more tightly bound nuclei, such as ^4He.

Microscopic models based on quark-gluon degrees of freedom, such as the Koniuk-Isgur nonrelativistic model (Kon80), have had considerable success in describing baryon spectroscopy and in calculating the masses of the known resonances. But this model predicts the existence of far more resonances than have been observed. This is not surprising, since baryon spectroscopy has been studied primarily with pion probes, and these "missing" resonances are predicted to couple only very weakly to the πN channel and to decay mainly via the ρN channel.

The t-dependence of the resonance production will depend on the spin of the resonance. However, at any t, disentangling the resonance contribution from the background processes is difficult. The three processes that are involved in ρ meson photoproduction are shown in Fig. 12.

In addition to the diffractive and t-channel exchange terms, the resonance strength in the ρN channel is smeared by the nonresonant two-pion background. Using linearly polarized photons, it is possible to differentiate between these processes and to separate the resonances more cleanly than with unpolarized photoproduction (Sch70). In diffraction, the polarization vector does not change, and the decay plane of the ρ^0 will be parallel to the polarization plane of the photon (Bal70). In resonant ρ^0 photoproduction, however, the distribution of the decay pions need not emerge preferentially in the plane of the photon polarization, and in general the decay plane of the ρ will be determined from the spin and parity of the resonance itself. For example, in the $\gamma p \rightarrow \Delta(1950) \rightarrow \rho^0 p$ process, (Sch71) showed that one is maximally sensitive to the $\Delta(1950)$ resonance when the photon polarization is at a 45-degree angle to the production plane, and the π^+ decay angles are determined uniquely.

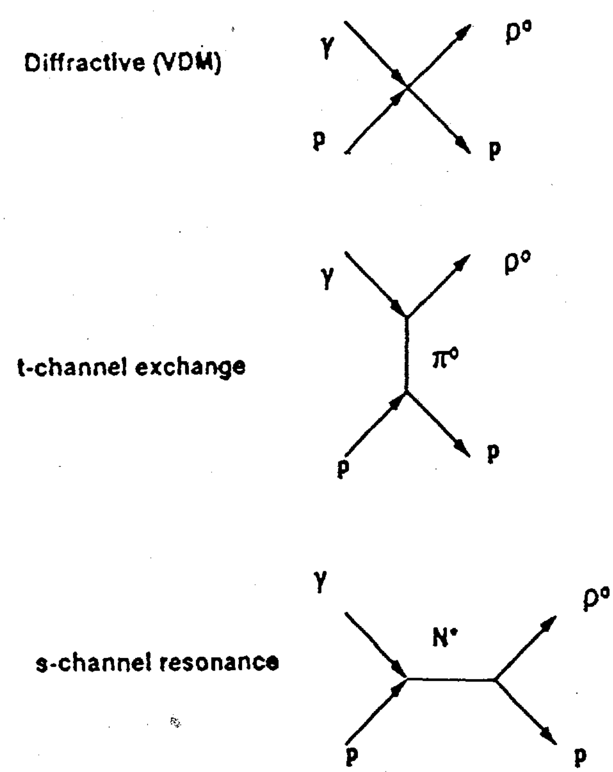

Fig. 12 Processes in ρ photoproduction.

The reactions we will measure are:

$$\vec{\gamma}p \rightarrow \rho^0 p \rightarrow \pi^+\pi^- p$$

$$\vec{\gamma}p \rightarrow \rho^+ n \rightarrow \pi^+\pi^0 n$$

We are now performing simulations based on the calculations made by Roberts (Rob94) of several predicted resonances with spins $J = 1/2$, $3/2$, and $5/2$ in the energy range $1.35 < \sqrt{s} < 2.10$ GeV, to determine (a) the sensitivity to the pion-decay angular distributions for each resonance and (b) our ability to separate the resonance contributions from other effects. We have recently concluded our Monte-Carlo acceptance studies of photoproduced ρ mesons in the CLAS detector. The study was undertaken to determine the feasibility of measuring and reconstructing the four-momentum of the ρ meson from the two-pion decay products and the efficiency of measuring all final-state particles in the reaction $\vec{\gamma} + p \rightarrow N^* \rightarrow \rho + N$. We have found that the acceptance for $|t| > 1$ $(GeV/c)^2$ for the exclusive reaction $p(\vec{\gamma},\rho^0 p)$ ranges from 10 to 20% ($1.7 < E_\gamma < 2.1$ GeV). The acceptance for the $p(\vec{\gamma},\rho^+ n)$ channel is 2%.

In order to extract the signals for resonance production, we must first understand our background (see Fig. 12). Diffractive scattering is associated with the elastic scattering of the hadronic component of the isovector part of the photon, and is described by the Vector Dominance Model. The cross section for diffractive vector meson photoproduction peaks at forward angles, with a four-momentum transfer dependence given by $d\sigma/dt = Ae^{-B|t|}$. At low t, the dominant contribution to $\vec{\gamma}p \rightarrow \rho^0 p$ is diffractive, whereas for charged ρ production the cross section is strictly nondiffractive, since the quantum numbers of the γ and the ρ are no longer identical. The second process shown in Fig. 12 is the t-channel exchange term and contributes to both ρ^0 and ρ^+ photoproduction. However, the t-channel exchange cross section is expected to be predominantly one-pion exchange at $E_\gamma = 2$ GeV and has been shown to be only about 10% of the diffractive cross section in ρ^0 photoproduction (Bal70). As with the diffractive cross section, t-channel exchange contributions peak at $|t| < 1$ $(GeV/c)^2$.

The ABBHHM collaboration (ABB68) has measured the differential cross section $d\sigma/dt$ as a function of t for the reaction $\gamma p \rightarrow \rho^0 p$ with unpolarized photons. These data are plotted in Fig. 13. There is evidence for an excess of cross section for $|t| > 0.6$ $(GeV/c)^2$ over that expected for purely diffractive and one-pion-exchange events. One explanation for the excess at high t is a resonance contribution, and a calculation by (Rip93) which includes contributions from the D_{13} and F_{15} resonances accounts for most of this excess.

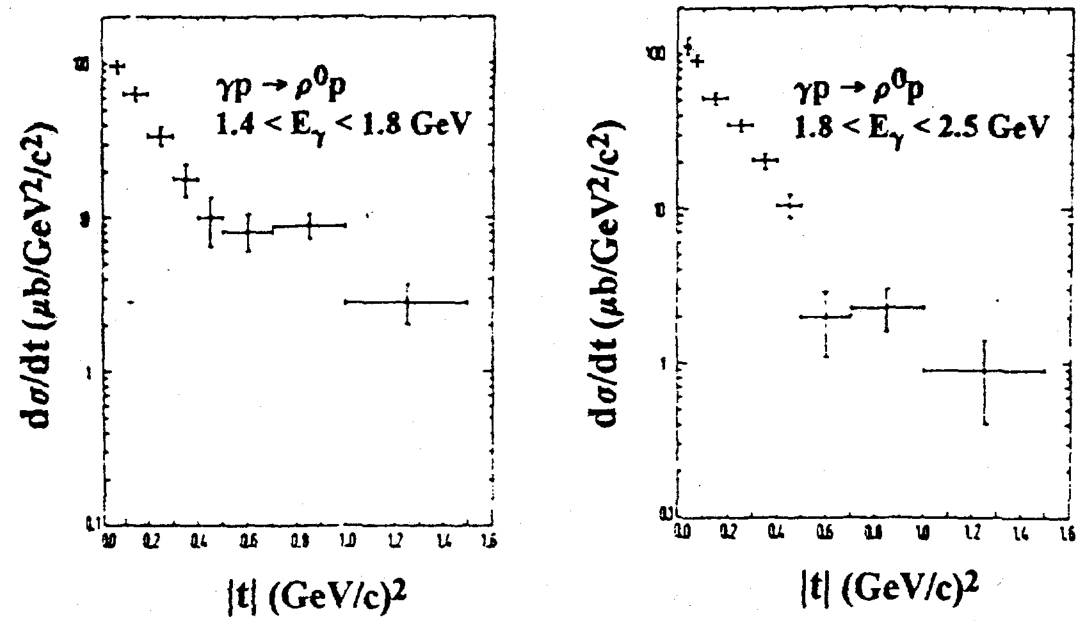

Fig 13 Unpolarized photoproduction data from the ABBHHM collaboration for the reaction $\gamma p \rightarrow \rho^0 p$ for two photon energy intervals.

There are even fewer data for charged-ρ photoproduction than for ρ^0 photoproduction, and no experiments at all have been performed with polarized photons. The photoproduction of the ρ^+ from the proton has been studied by (Bar79) using unpolarized photons in the energy range from 2.8 to 4.8 GeV. They find that the one-pion-exchange mechanism does not adequately describe the helicity-flip contributions in the angular distribution of the ρ^+. The cross section peaks at low t and has been described by a decaying exponential function of t for $|t| < 0.5$ (GeV/c)^2, but given the size of the error bars, an exponential fit is not the only function that fits the data [see Fig. 6 of (Bar79)]. In fact, for $0.5 < |t| < 0.7$ (GeV/c)^2, there is an indication of some enhancement of the differential cross section. Given the current state of the data, delineation of the nature of ρ^+ photoproduction is not possible. With the CLAS, our proposed experiment will increase the world's data set by two orders of magnitude, and will extend the t range by at least a factor of two. Furthermore, polarized photons will allow us to measure the decay angular distributions of the ρ^+, and thereby provide important information in determining the role played by resonance production.

Our data sample will also contain $\gamma p \rightarrow \Delta^{++}\rho^-$ events, since the threshold photon energy for this reaction is only 1.66 GeV. It appears from (Bar79) that the differential cross section for this reaction is similar in both magnitude and slope to that for the ρ^+ channel. After we study the photoproduction of ρ^- from the neutron using a deuteron target (see above), we can compare the two.

C. INSTRUMENTATION

1. The Photon Tagger

The experimental nuclear physics group at GW is participating in the construction of the tagged photon facility at CEBAF. This device will produce a high quality tagged photon beam to be used mainly in conjunction with the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B. The primary responsibility of the GW group is the design, construction, and installation of the detector array at the focal plane of the tagger magnet. This effort is led by W.J. Briscoe, and the detailed design of the detector array and the accompanying support structure has been performed by J.P. Connelly; together they are now supervising the construction phase of the project. We are supporting three additional graduate students this summer to help with the various construction tasks.

The apparatus being constructed at GW consists of two arrays of plastic scintillators, the support structure for precision positioning of the scintillators, and the light-tight outer box. The complete tagger assembly is shown in Fig. 14. The magnet, vacuum extension box, and gantry were installed in Hall B this Spring.

Shown in Fig. 15 are the Energy-Counter and Timing-Counter arrays. The E-Counter array consists of 384 thin (4-mm) plastic scintillators, of varying widths. The sole purpose of the E Counters is to produce a signal above threshold from an electron which has radiated a bremsstrahlung photon. The momentum (and hence the energy) of the electron is determined from its position along the momentum axis of the magnet focal plane. The E Counters are positioned in a "Venetian-blind" orientation so that every other energy bin will be either a coincidence between two counters or a single counter hit. This arrangement results in 768 energy bins, spread between 20% and 95% of the incident electron beam energy, thus giving an energy resolution of 0.1%. The E counters are read out through optical fibers to fast one-inch photomultiplier tubes.

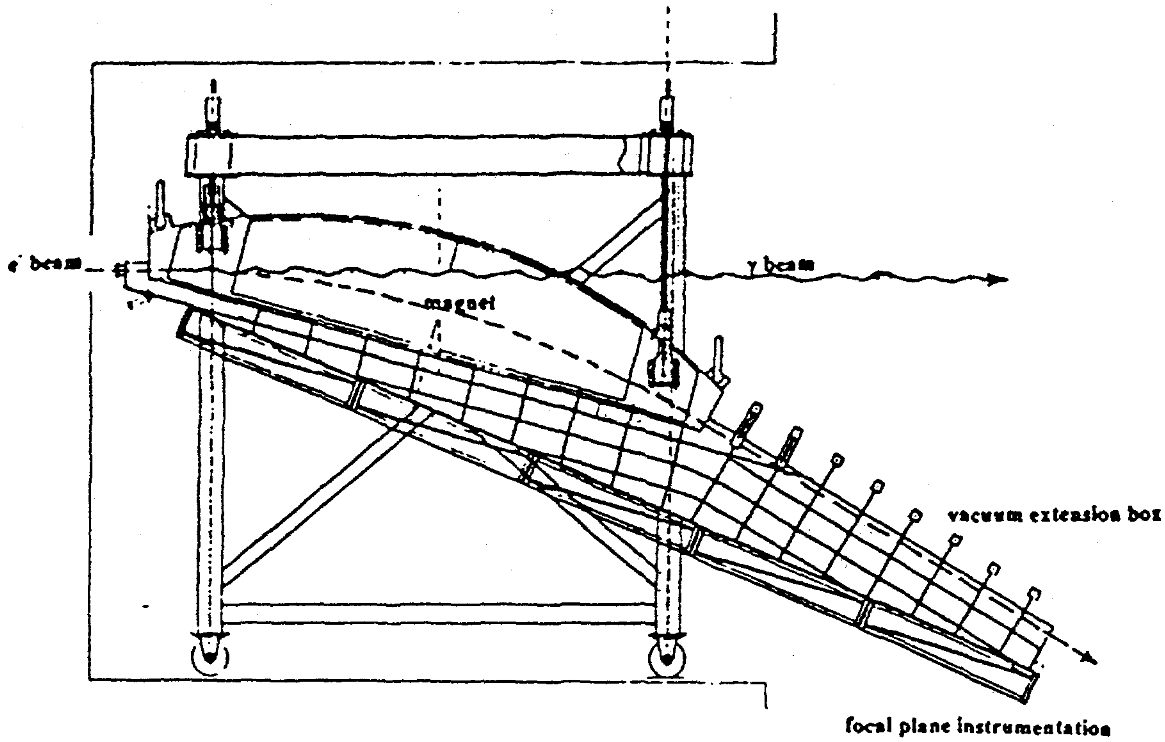

Fig. 14 Photon tagger for Hall B at CEBAF.

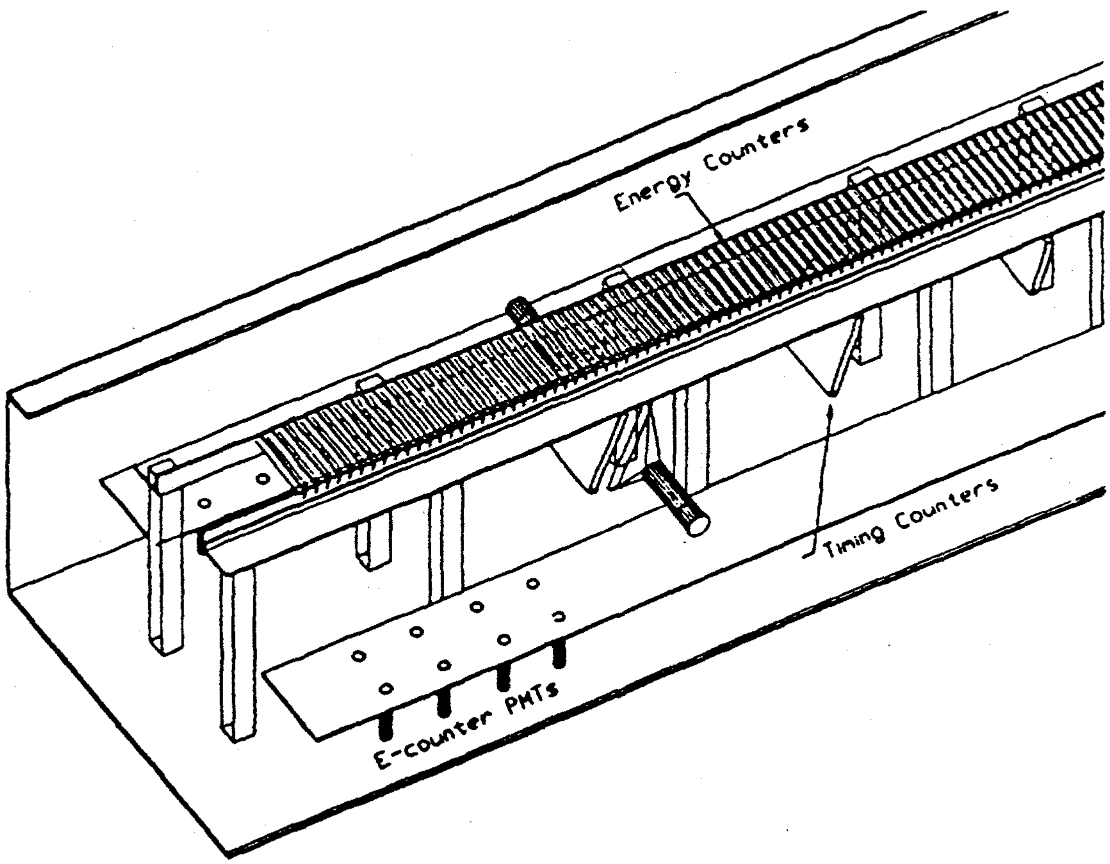

Fig 15 Detail of the focal plane detector array for the Photon Tagger.

The T-Counter array consists of 52 thick (3/4-inch) backing scintillators, used to establish the timing of the event relative to the CLAS trigger. The rate expected through the entire focal plane will be a few times 10^7 Hz; the T Counters have been designed so that each sees approximately the same number of electrons--hence, the typical rate seen by each T Counter will be less than 1 MHz.

The rail system holding the scintillator array and the support structure of the light-tight box was designed jointly by GW and CEBAF engineers. This structure was sent out for bids in mid-June and delivery to GW is expected in early Fall. The scintillators and read-out components are now being prepared. The entire device is scheduled to be assembled and tested by early 1995, and is scheduled to be shipped from GW in the Spring. Installation, final testing, and calibration at CEBAF will be completed by Summer 1995. Our experiment on total photoabsorption and photofission is currently planned to be the first Hall-B experiment, and will serve as the commissioning experiment for the Photon Tagger.

2. Linearly Polarized Photon Production at CEBAF

We propose to implement a coherent-bremsstrahlung facility to be integrated with the CEBAF Hall-B Photon Tagger.

As nuclear physics measurements progress, more sophisticated probes, with controllable degrees of freedom, are required. The use of linearly polarized photons as a probe is a particularly powerful and elegant method to delineate these details. For example, linearly polarized photons are necessary for our proposal to study baryon resonances which decay through vector-meson channels, described in Section IIB above.

There are three well known methods for producing linearly polarized photons using an incident electron beam: Compton backscattering of a linearly polarized laser beam, off-axis tagging of bremsstrahlung photons, and coherent bremsstrahlung from a crystal radiator. Implementation of the first two methods at CEBAF have been studied by B.E. Norum (University of Virginia) and D.I. Sober (Catholic University), respectively. The Compton-backscattering method can produce a photon beam of high polarization and low background, but it is limited in energy. The off-axis tagging of bremsstrahlung photons can produce a continuous linearly polarized photon beam up to about half the incident beam energy, but the degree of polarization is lower. Additionally, both of these methods are technically difficult to implement and relatively expensive. Therefore, we have elected to use the third method, coherent bremsstrahlung, for our planned vector-meson photoproduction experiment (Section IIIB) at CEBAF. Using this method, polarizations up to 60% are achievable at about half of the incident electron energy. Moreover, the spectrum is discrete--only a narrow range of photon energies (approximately 10% wide in energy) is produced at a time; this enables the experimenter to select the desired energy range without flooding the CLAS with unwanted photons at other energies. Finally, the cost of implementing coherent bremsstrahlung is much more modest than for either of the other two methods. The detailed results of our study will be reported shortly as a CLAS Note (Rug94a).

Coherent bremsstrahlung is an interference effect in the radiative interaction of electrons with the periodic structure of a crystal. This interference results in a photon-energy spectrum which is peaked at discrete energies, dependent only on the crystal orientation. The polarization of the resultant spectrum can be controlled and is maximized by choosing a crystal with a well isolated reciprocal lattice vector (Dia68, Tim69). The best crystal for coherent-bremsstrahlung production of linearly polarized photons is a diamond, $<100\ \mu m$ thick for incident electrons in the GeV region. The diamond can be oriented such that only one symmetry plane produces the coherent effect, and the resulting photon-energy spectrum contains a single dominant peak. In addition, the angular distribution of the radiated photons is correlated with their energy, and thus the width of the peak can be controlled by collimation of the photons. Collimation not only minimizes the photon energy spread, but has the added desirable effect of reducing uniformly the incoherent bremsstrahlung background, thus increasing the polarization of the photon beam. The degree of linear polarization varies with the peak energy of the photon beam and with the incident electron energy.

A coherent-bremsstrahlung spectrum from SLAC (Kau75) is shown in Fig. 16. The solid line represents the results of a Monte-Carlo program that we have written to model the spectrum that we plan to generate; one sees that the agreement with the data is very good.

Use of the Photon Tagger will greatly enhance the effectiveness of this method. As noted above, the cost of implementing a coherent-bremsstrahlung facility is modest, and the necessary hardware is commercially obtainable. Additionally, linearly polarized photons have been produced using coherent bremsstrahlung at several electron accelerator facilities, over a wide range of energies, from a few MeV up to 20 GeV; and we have had previous experimental experience in this area (Wal75). We also are participating in the instrumentation of a coherent-radiation facility at a newly-acquired linac at the MIRF Laboratory at NIST. This facility will enable us to test the goniometer and related equipment needed for the coherent-bremsstrahlung facility at CEBAF, and will give our students hands-on experience at an operating accelerator.

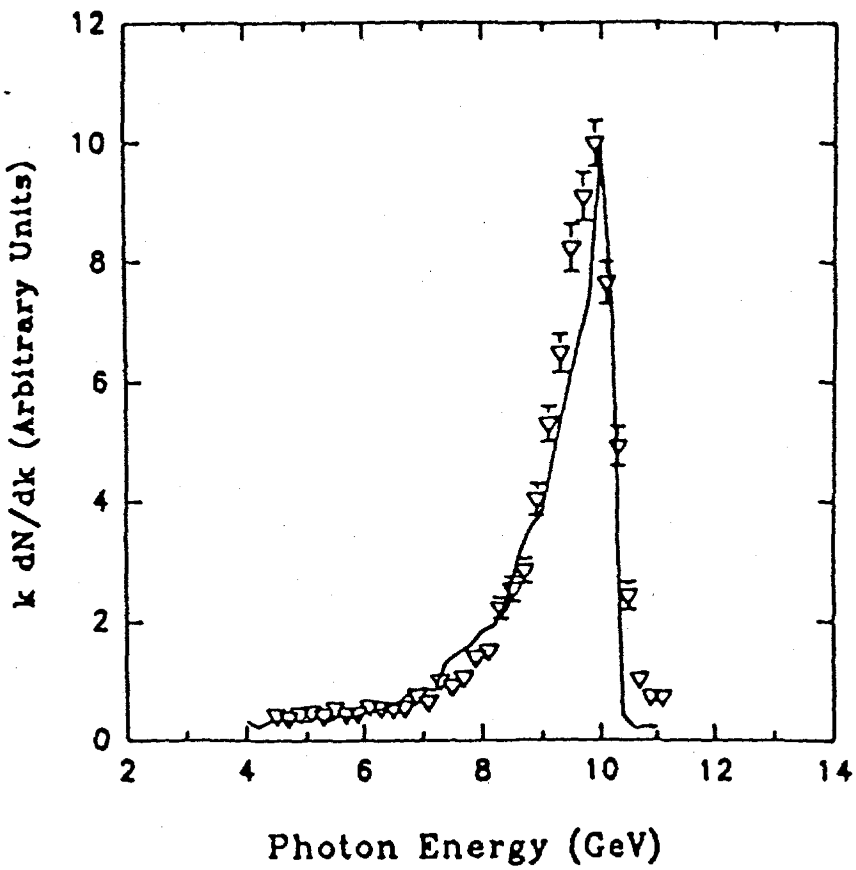

Fig. 16 Coherent-bremsstrahlung data from SLAC obtained with $E_e = 20$ GeV. The solid line represents the result of our Monte-Carlo calculation.

3. Parallel-Plate Avalanche Detectors

We are designing a parallel-plate avalanche detector system for use in our approved photofission experiment at CEBAF and in measurements to be proposed at SAL. The detectors will be built and tested in our Nuclear Detector Laboratory.

Since the fission process liberates about 200 MeV in addition to the energy of the incident photon, a fission event is easy to detect with a PPAD. The detectors will incorporate the fission foil mounted on a substrate as the cathode. Simultaneous measurements on ^{238}U, ^{237}Np, and ^{232}Th will be possible with multiple PPADs because the thin target foils do not noticeably attenuate the photon beam. PPADs have been used to detect the fission fragments in many photo- and electrofission experiments; except for problems associated with a pulsed, high-current electron beam, these detectors have performed extremely well, and certainly are the detectors of choice for the experiments proposed here. The PPAD detector system that we are designing will make use of a sample foil thickness of 0.2 mg/cm^2, a voltage of about 500 V between the foil and the board of the PPAD, and an equal mixture of argon and isobutane as the filling gas; the pressure and the voltage will be optimized for a maximum signal from the fission fragments as well as to inhibit avalanche formation from alpha activity in the foil. The total solid angle subtended at the target foils by the PPADs will be nearly 50% of 4π (since the two fission fragments are emitted nearly back-to-back in the laboratory).

The simplest scheme for performing these measurements is illustrated in Fig. 17(a). Three PPADs, each containing a fission foil for one of the three nuclei under study, are arranged as three independent detectors, with the foils perpendicular to the incident photon beam. This minimizes the foil size, and hence the amount of fissionable material, but also maximizes the amount of necessary beam time. The sample foils can be tilted at a small angle with respect to the incident photon beam, as shown in Fig. 17(b); this makes them thick to photons while keeping them thin to the emerging fission fragments. In this way, a large factor in effective thickness can be readily achieved, resulting in smaller beam-time requirements, at the cost of the need to produce larger fission foils. The arrangement shown in Fig. 17(c) improves on this scheme even more by using more PPADs (and foils), and not only improves the counting rate by another factor of nearly three by brute force, but also opens the possibility of studying more than three nuclear species simultaneously (^{235}U, for example, is another good candidate for study). It should be noted that every one of the experimental arrangements illustrated in Fig. 17 is compact (less than 40 cm long) so that it would fit into the space occupied by the NaI detector in the photoabsorption experiment, and also would easily fit into the target position in the CLAS. It should be noted as well that because of the thick backings of the target foils, there can be no cross-talk between PPADs; and because of the low true counting rate in any given PPAD, there would be no tracking ambiguity for protons or pions that enter the CLAS from a fission event.

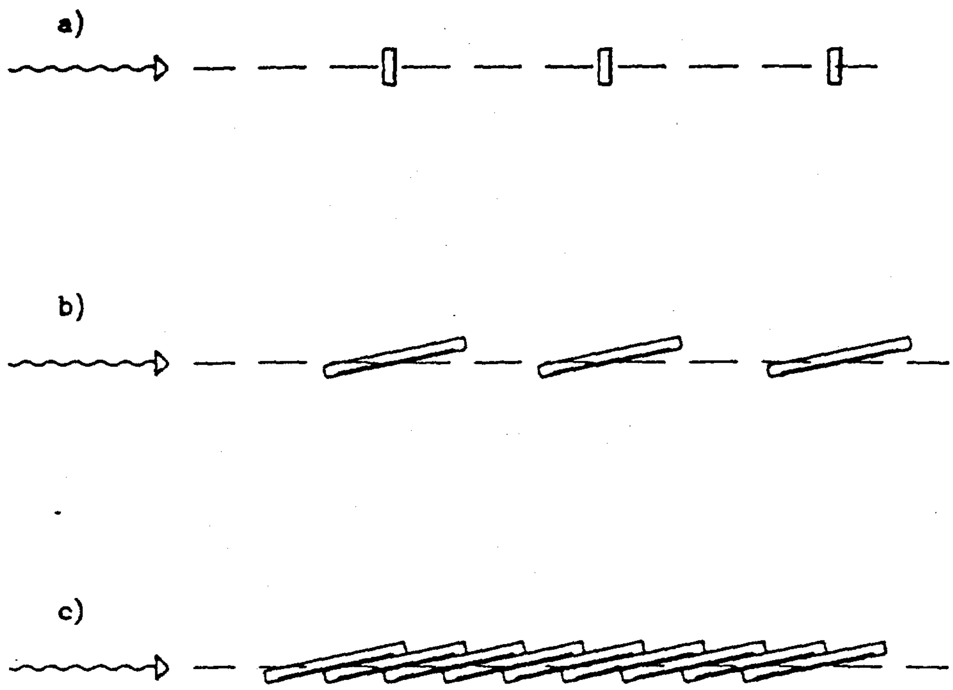

Fig. 17 Three alternative experimental arrangements for the proposed photofission measurements: (a) with fission foils (and PPADs) perpendicular to the direction of the incident photon beam; (b) tilted at an angle of 11.5°; and (c) tilted as in (b) but with three times the number of PPADs and foils.

In addition, we, together with our colleagues from Moscow and Novosibirsk, will be developing similar detectors to be used in the proportional mode, in order to allow measurement of the fission-fragment energy. The detector parameters are now being studied. These detectors will use thin, self-supporting fission foils suspended between wire anode planes, and thus will measure the energy of both fission fragments--information that is needed to study the details of the photofission process. The price to be paid is the loss in counting rate that will result from our inability to fabricate large-area self-supporting foils that can be placed at a small angle with respect to the incident photon beam as shown in Fig. 17(b) and (c).

References to Section II

ABB68 Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Phys. Rev. **175**, 1669 (1968)

Abd90 S.K. Abdullin *et al.*, Sov. J. Nucl. Phys. **51**, 774 (1990)

Ang93 M. Anghinolfi *et al.*, Phys. Rev. C **47**, 922 (1993)

Arr93 J.D.T. Arruda-Neto, private communication

Aud91 G. Audit *et al.*, Phys. Rev. C **44**, R575 (1991)

Aud94 G. Audit, private communication and Jahresbericht 1992-1993, Institut für Kernphysik, Mainz

Bal70 J. Ballam *et al.*, Phys. Rev. Lett. **24**, 960 (1970)

Bar79 D.P. Barber *et al.*, Z. Phys. C **2**, 1 (1979)

Ber92a B.L. Berman *et al.*, CEBAF CLAS Note 92-010 (1992)

Ber93 B.L. Berman, "Delta Knockout from ^{3}He," CEBAF Retreat at Snowshoe, WV, 1993 (unpublished)

Bia93a N. Bianchi *et al.*, Phys. Lett. **299B**, 219 (1993)

Bia93b N. Bianchi *et al.*, Phys. Rev. C **48**, 1785 (1993)

Cio93 C. Ciofi degli Atti, private communication

Col92 P.L. Cole, CEBAF CLAS Note 92-002 (1992)

Col93 P.L. Cole, CEBAF CLAS Note 93-006 (1993)

Cud90 J.R. Cudell *et al.*, Nucl. Phys. **B336**, 1 (1990)

Dia68 G. Diambrini-Palazzi, Rev. Mod. Phys. **40**, 611 (1968)

Emu94 T. Emura *et al.*, Phys. Rev. Lett. **73**, 404 (1994)

Ilj92 S.D. Iljinov *et al.*, Nucl. Phys. **A539**, 263 (1992)

Kau75 W. Kaune *et al.*, Phys. Rev. D **11**, 478 (1975)

Kne94 U. Kneissel, private communication and Jahresbericht 1992-1993, Institut für Kernphysik, Mainz

Kol94 N.R. Kolb *et al.*, Phys. Rev. C (to be submitted); also see Phys. Rev. C **49**, 2586 (1994)

Kon80 R. Koniuk and N. Isgur, Phys. Rev. D **21**, 1868 (1980)

Lag92 J.-M. Laget, in Electronuclear Physics with Internal Targets and the BLAST Detector (eds. R. Alarcon and M. Butler, World Scientific, 1992)

Lag93 J.-M. Laget, private communication

Lep87 A. Leprêtre *et al.*, Nucl. Phys. **A472**, 533 (1987)

Mec89 B. Mecking *et al.*, CEBAF Proposal 89-045

Rip93 M. Ripani *et al.*, CEBAF Proposal 93-006

Rob94 W. Roberts, "Report to the GRAAL Group on Photoproduction of Baryon Resonances Using Polarized Photons," (1994)

Rug94a S.L. Rugari, CEBAF CLAS Note 94-xxx (1994)

Rut94 C. Ruth *et al.*, Phys. Rev. Lett. **72**, 617 (1994)

Sar93 A.J. Sarty *et al.*, Phys. Rev. C **47**, 459 (1993)

Sch70 K. Schilling *et al.*, Nucl. Phys. **B15**, 397 (1970)

Sch71 D. Schildknecht and B. Schrempp-Otto, Nuovo Cim. **5A**, 103 (1971)

Sch89 R. Schumacher *et al.*, CEBAF Proposal 89-004

Str87 W. Strüve *et al.*, Nucl. Phys. **A465**, 651 (1987)

Ted94 D.J. Tedeschi *et al.*, Phys. Rev. Lett. **73**, 408 (1994)

Tim69 U. Timm, Fortschritte der Physik **17**, 765 (1969)

Wal75 R.L. Walker, B.L. Berman, and S.D. Bloom, Phys. Rev. A **11**, 736 (1975)

Wei90 S. Weinberg, Phys. Lett. **251B**, 288 (1990); also see Nucl. Phys. **B363**, 3 (1991) and Univ. of Texas Preprint UTTG-11-92

III. RESULTS OF RECENT RESEARCH

A. ELECTROMAGNETIC REACTIONS AT NIKHEF

1. The (e,e'd) and (e,e'α) Reactions

We have performed a series of (e,e'd) and (e,e'α) cluster-knockout experiments on ^{6}Li and ^{12}C in collaboration with the group of H.P. Blok at NIKHEF and others, first to test the α-p-n three-body model of ^{6}Li proposed by our theory colleagues at GW, W.C. Parke and D.R. Lehman (Par84), and then to compare this kind of reaction on the loosely bound ^{6}Li nucleus with the case for tightly bound closed-shell nuclei. These measurements were carried out over a period of several years, and all of the results are now published or in press.

In the distorted-wave impulse approximation, the six-fold differential cross section for an exclusive electron-scattering measurement is given by

$$\frac{d^6\sigma}{dE_e d\Omega_e dE_X d\Omega_X} = K\sigma_{eX} S^D(E_m, \mathbf{p_m}, \mathbf{p})$$

where K is a kinematical factor, σ_{ex} is the off-shell electron-cluster cross section, and $S^D(E_m,\mathbf{p}_m,\mathbf{p})$ is the distorted spectral function, which is equal to the probability that a bound cluster with missing energy E_m and missing momentum $\mathbf{p}_m$ exists in the nucleus. The dependence of S^D on the momentum of the detected cluster $\mathbf{p}$ arises from the introduction of an optical model to account for final-state interactions. One can then define the momentum distribution $\rho_m(\mathbf{p}_m)$ as the integral of the spectral function over a specified missing-energy range; it can be shown to be the Fourier transform of the relative $X-(A-X)$ wave function, where X is the cluster knocked out. One can also investigate the dependence of the (e,e'X) coincidence cross section on the momentum transfer $\mathbf{q}$. The measured six-fold cross section is integrated over a discrete peak or energy region (often the elastic peak) in the missing-energy spectrum, and the resulting five-fold cross section is expressed as a function of q^2.

Results for ^{6}Li(e,e'd)^{4}He, ^{6}Li(e,e'α)^{2}H, and ^{6}Li(e,e'α)pn (Ent86, Mit91) can be described adequately by a quasielastic approach. Figure 18 shows the excellent agreement of the results of the calculation (Par84) with our $^{6}Li(e,e'd)^{4}He$ data. Figure 19 compares the q-dependence of the (e,e'd) cross section for ^{6}Li with those for ^{4}He and ^{12}C (Ent94). One sees that the quasielastic approach is not adequate for the latter two cases,. owing to the existence of larger higher-momentum components in their ground-state wave functions, and thus a microscopic approach, at least for ^{4}He and ^{12}C, is needed. In fact, we suspect that ^{6}Li is one of only very few nuclei for which the quasielastic approach is adequate, because it is one of only very few nuclei for which the average spacing of the proton and neutron in the valence shell is comparable to that in the free deuteron.

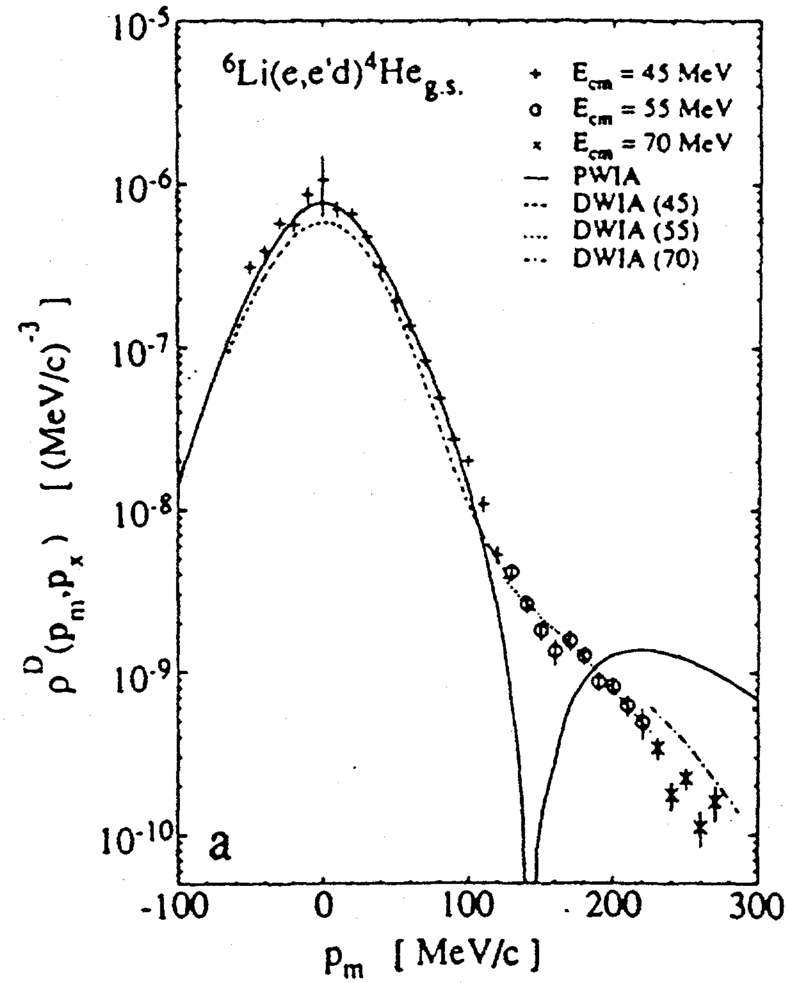

Fig. 18 Measured reduced cross section for the reaction $^{6}Li(e,e'd)^{4}He_{g.s.}$ compared with the results of the DWIA calculation of Parke and Lehman.

The excitation of a T = 1 state in the $^{12}C(e,e'd)^{10}B$ reaction (the second excited state of ^{10}B) can be described in the microscopic approach as a transition from a $^{1}S_{0}$ p-n cluster to a $^{3}S_{1}$ deuteron (Ent89). This reaction, which we showed to be purely transverse, shows the sensitivity of cluster-knockout measurements to certain kinds of two-body correlations in the nuclear ground state.

Many details of these measurements and their interpretation can be found in (Ent94), which is reproduced in Appendix B.

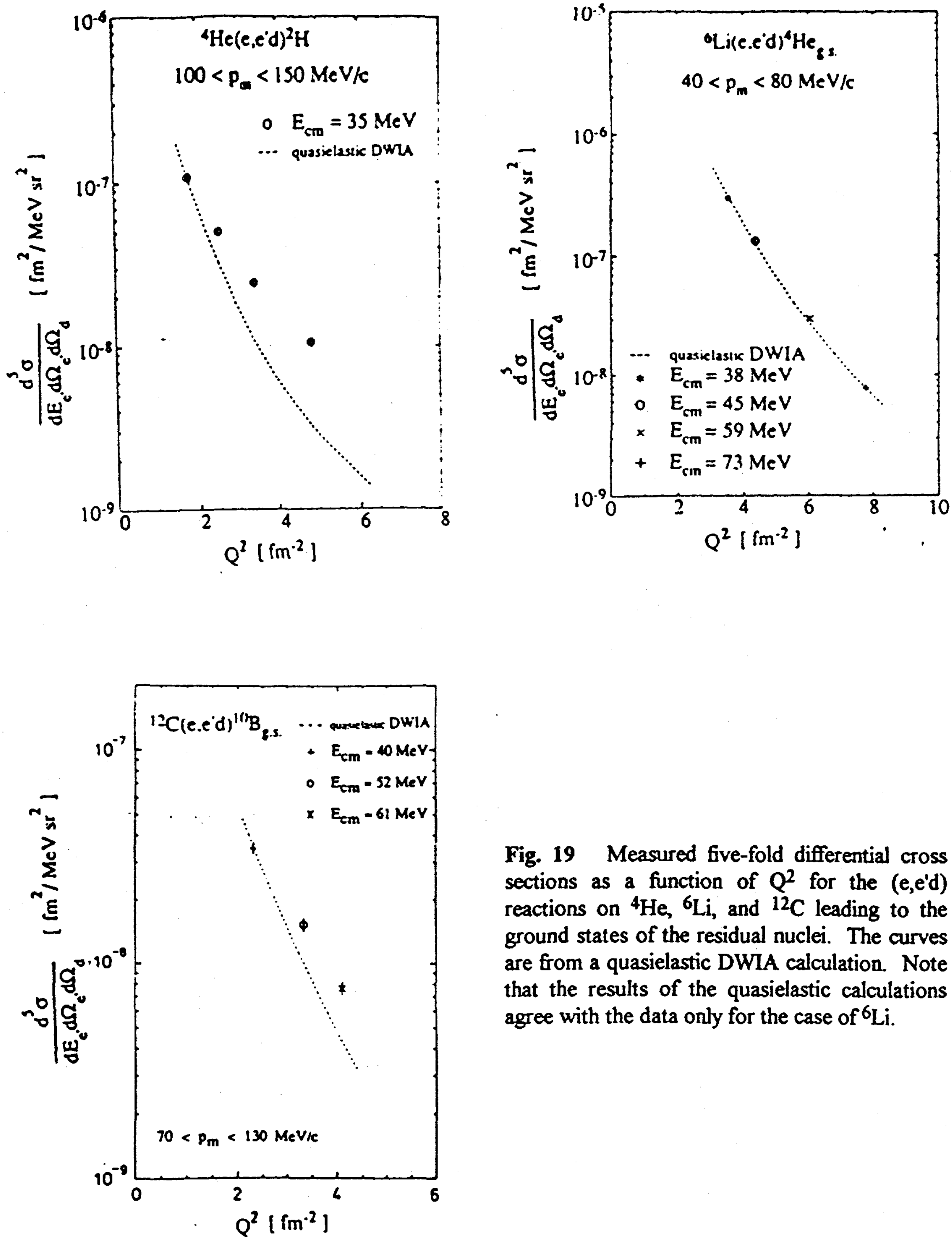

Fig. 19 Measured five-fold differential cross sections as a function of Q^2 for the (e,e'd) reactions on ^4He, ^6Li, and ^{12}C leading to the ground states of the residual nuclei. The curves are from a quasielastic DWIA calculation. Note that the results of the quasielastic calculations agree with the data only for the case of ^6Li.

2. The $^6Li(e,e'^3H)^3He$ and $^6Li(e,e'^3He)^3H$ Reactions

The mirror reactions $^6Li(e,e'^3H)^3He$ and $^6Li(e,e'^3He)^3H$ have been measured to study the remaining cluster-knockout processes in ^6Li. A direct comparison of the momentum-transfer dependence has been performed (see below), and just as we did for the deuteron and alpha clusters (see the preceding section), we are in the process of extracting the momentum distributions of the ^3H and ^3He clusters in the ^6Li nucleus.

The measured six-fold cross section was integrated over the elastic peak, in the missing-momentum range from 60 to 100 MeV/c for both reactions, and the q-dependence can now be compared. In Fig. 20 we show the q-dependence for both the ^3H and ^3He knockout reactions from ^6Li.

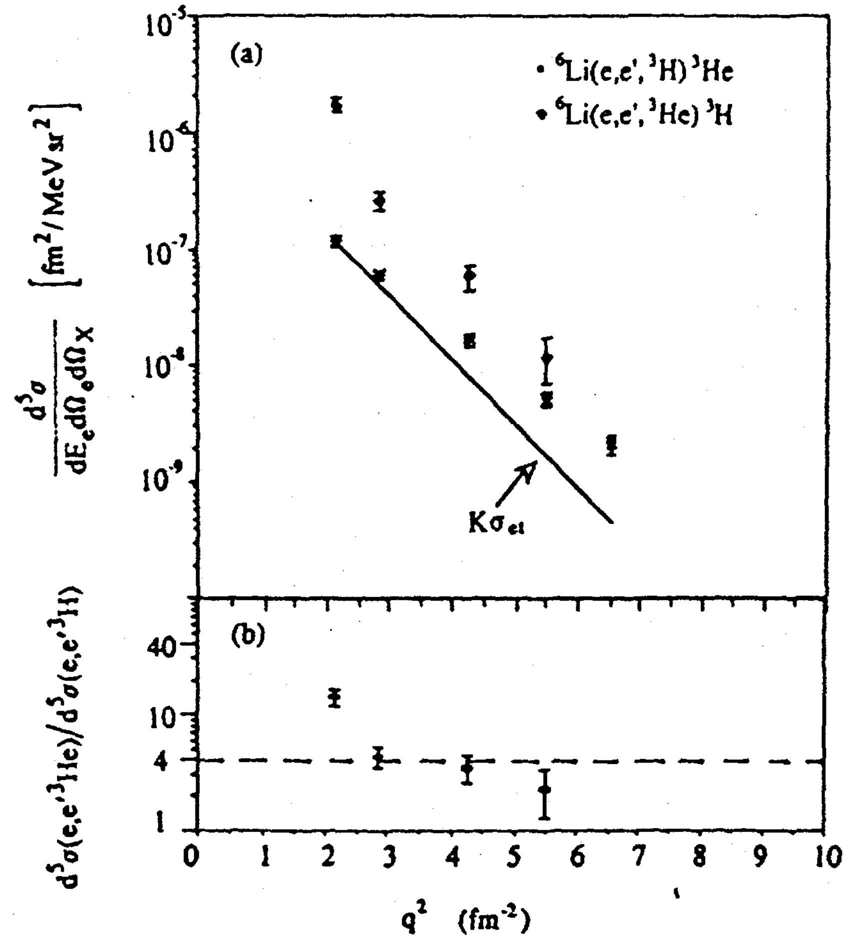

Fig. 20 (a) Measured five-fold differential cross sections as a function of q^2 for the reactions $^6Li(e,e'^3H)^3He$ and $^6Li(e,e'^3He)^3H$, compared with the predicted quasielastic cross section on a triton in ^6Li, normalized at the lowest q data point. (b) Ratio of the (e,e'^{3}He) and (e,e'^{3}H) cross sections, compared with the predicted value of 4.

Because of the isospin symmetry of the ^{3}H and ^{3}He clusters, the ^{6}Li nucleus presents us with a unique opportunity to examine the cluster-knockout reaction. One expects that the spectral functions and final-state interactions will cancel in the cross-section ratio. If the only contribution to the cross section is from the virtual photon coupling directly to the cluster inside the ^{6}Li nucleus, then one should see only a factor of $Z^2_{^3He}/Z^2_{^3H} = 4$ between the ^{3}He and ^{3}H knockout cross sections, and they should exhibit a very similar q-dependence. Any manifestations of two-step formation of the three-nucleon cluster will be evident in the deviation of the q-dependence in this simple picture.

As can be seen in Fig. 20, the q-dependence of the two mirror reactions is indeed quite different. The ^{3}H knockout is compared to a curve given by $K\sigma_{et}$, where σ_{et} is the free electron-^{3}H off-shell cross section (normalized to the lowest-momentum-transfer data point). That the higher-q data deviates from this curve is not surprising, since the ^{3}H cluster is bound inside the ^{6}Li nucleus. However, the slope of the ^{3}He knockout data more closely resembles that of the free electron-^{3}H off-shell cross section. We also show in Fig. 20 the ratio of the ^{3}He and ^{3}H knockout cross sections. The deviation from the value of 4 is striking--more than a factor of three at low momentum transfer. We are presently studying the implications of this result and preparing a paper on this comparative investigation for publication (Con94).

B. Hadronic Reactions at LAMPF

1. Pion Scattering from ^{3}H and ^{3}He

Over a period of several years, in collaboration with the UCLA group of B.M.K. Nefkens and others, we have carried out an extensive and systematic program of pion-scattering measurements (Ber88, Pil88, Pil91, Ber94) on the A=3 nuclei. The primary purpose of these measurements was to probe the matter distributions of nucleons in these few-body nuclei, particularly the neutron distribution in ^{3}H (which cannot be accessed with electron scattering), and to investigate the extent to which charge symmetry is broken in the strong pion-nucleus interaction.

The measurements were performed over the energy range spanning the Δ resonance. The data set includes, in addition to earlier survey cross-section measurements (experiment 905) at several energies and at forward angles, cross-section measurements in the non-spin-flip (NSF) dip region near 75-80° at these energies (experiment 1032), a large-angle excitation function (experiment 1064), and an angular distribution for backward angles (from 114° to 168°) near the peak of the Δ at 180 MeV (experiment 1155). The analysis of the entire data set is now complete; we provide here a brief summary of the more notable features that have emerged.

We discuss the results in terms of a number of charge-symmetric ratios, namely, r_1, r_2, and the superratio R, which is the product of r_1 and r_2. These ratios are defined as

$$r_1 = d\sigma(\pi^{+3}H) / d\sigma(\pi^{-3}He)$$
$$r_2 = d\sigma(\pi^{-3}H) / d\sigma(\pi^{+3}He)$$
$$R = r_1 \times r_2.$$

The cross sections and ratios are determined from the measured pion-nucleus elastic-scattering yields. The charge-symmetric prediction for each of these ratios is unity. Thus, a sizable deviation from unity of any one of these ratios (particularly of R, which is independent of the systematic uncertainties in the monitoring of the pion beam) as a function of energy and angle can be interpreted as evidence for charge-symmetry breaking in the strong interaction. Such deviations also can be thought of as arising from (small) differences in the neutron and proton distributions in these mirror nuclei. Of course, the Coulomb interaction must be taken into account properly.

For resonance-energy pions, single-scattering models based on the impulse approximation predict that the scattering in and around the NSF dip is dominated by the spin-flip part of the total pion-nucleon amplitude, and that the ratio r_1 is primarily proportional to the squared ratio of the *odd-nucleon* matter form factors in the A=3 nuclei (i.e., the proton in ^3H and the neutron in ^3He). These same models show that the scattering at angles approaching 180° is dominated by the non-spin-flip amplitude, and that r_2 is proportional to the squared ratio of the *even-nucleon* matter form factors of the A=3 nuclei (i.e., the neutrons in ^3H and the protons in ^3He). Thus, pion-scattering measurements, under the favorable kinematic conditions described, are a very sensitive way of studying neutron and proton distributions in these nuclei, in addition to allowing one to isolate the contributions of the spin-flip and the non-spin-flip amplitudes in pion-nucleus interactions without the need for polarized targets.

At the peak of the Δ resonance, the superratio R is significantly greater than unity in the angular region spanning the NSF dip, as shown in Fig. 21. These same data (Nef90, Pil91) show that r_1, on the other hand, is consistent with unity throughout this angular region, and that the observed magnitude and the angular behavior of R is a reflection of the behavior of the ratio r_2, since $R = r_1 \times r_2$.

A detailed theoretical analysis of these early data by Gibbs and Gibson (Gib91) concluded that the magnitude and the angular behavior of these ratios, particularly that of the superratio R, is indicative of a significant charge-symmetry-breaking effect above and beyond that which is expected from the Coulomb interaction. It also allows one to determine the differences between the odd- and even-nucleon matter radii in ^3H and ^3He (quantities equal to 0.030-0.040 fm) with a precision of a few times 10^{-18} m.

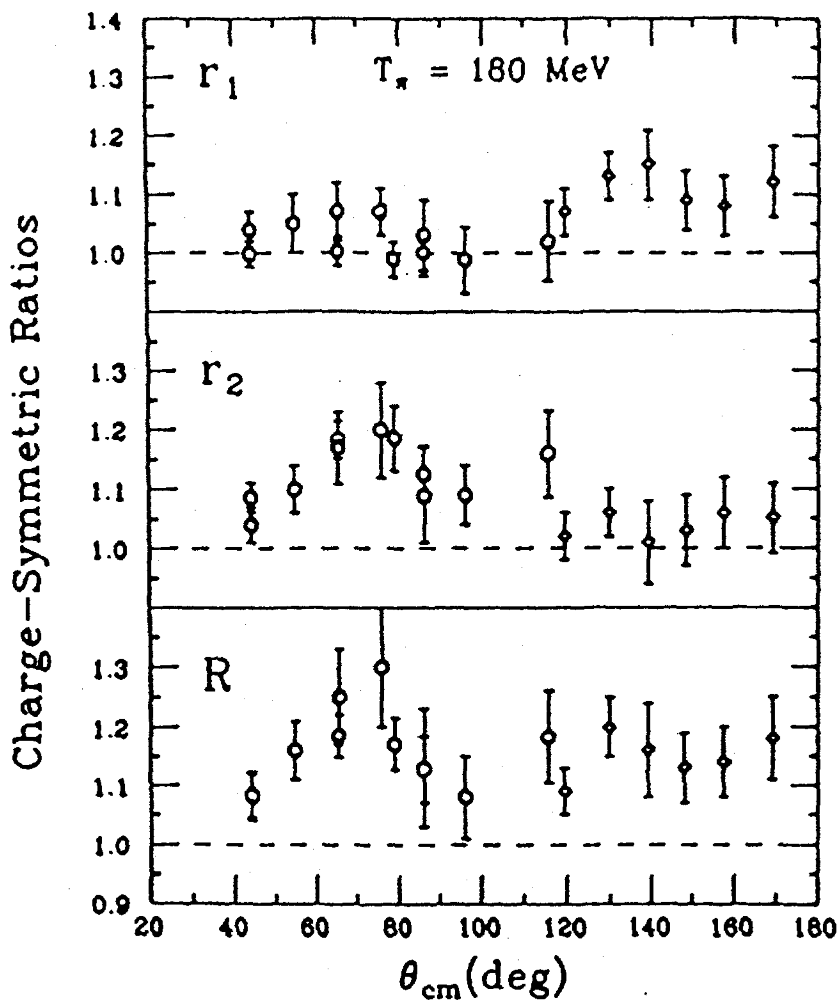

Fig. 21 Charge-symmetric ratios at T_π = 180 MeV. Data are from (Nef90) and (Pil91) (open circles) and (Mat94) (diamonds). Note that the superratio is greater than one for all angles at this energy. For definitions of r_1, r_2, and R, see text.

Results of our latest angular-distribution measurements (Mat94), at 180 MeV, also show that the superratio R is greater than unity for all the measured angles in the range 114° to 168°, as shown in Fig. 21. However, we find that a remarkable role-reversal occurs for the ratios r_1 and r_2 in this angular range: r_2 is now consistent with unity, and it is r_1 that deviates significantly from this value. Perhaps even more remarkable, this role-reversal was predicted by Gibbs and Gibson solely from their analysis of the forward-angle data at this energy. We note, however, that although the cross-section ratios are well described by the Gibbs and Gibson calculation, some of the individual cross sections are predicted to be too small, by a factor of two at the largest angles. This apparent enhancement of the large-angle pion-nucleus scattering cross section has been noted a number of times before [(Dhu87) and references therein]; as far as we are aware, it has yet to receive a satisfactory explanation.

Another very interesting feature of the new results is the observation of a steep rise in the cross sections (for angles greater than 140°) for the reactions $^3He(\pi^+,\pi^+)^3He$ and $^3H(\pi^-,\pi^-)^3H$, i.e., for the *even-nucleon* cases, as shown in Fig. 22 (Mat94). No such rise is seen in the reactions for the *odd-nucleon* cases, $^3He(\pi^-,\pi^-)^3He$ and $^3H(\pi^+,\pi^+)^3H$. We note that $\pi^+ + {}^3He$ and $\pi^- + {}^3H$ both couple to form isospin I = 3/2, whereas, $\pi^- + {}^3He$ and $\pi^+ + {}^3H$ couple to produce isospin I = 1/2. One possible explanation is the existence of a second-order isospin-dependent scattering process. This possibility is currently being investigated by one of our theory colleagues at GW (C. Bennhold). In a recently published calculation (Kam93) (based on multiple-scattering theory) of pion elastic-scattering cross sections for the trinucleon system, the authors employed correlated three-body wave functions obtained from the solution of the Faddeev equations with the use of the Reid potential for the NN interaction. Also included in the calculation is a phenomenological second-order term (a ρ^2 scalar term obtained by fitting angular-distribution data for heavy nuclei) to allow for absorption and other higher-order processes. As was the case with the (Gib91) calculation, the (Kam93) calculation also does a good job of describing the angular distributions for all four (pion + trinucleon) cases up to about 110°, the extent of the old data. For the new measurements in the backward hemisphere, however, the results of the (Kam93) calculation are mixed: the *odd-nucleon* cross sections are reasonably well described, but again, the *even-nucleon* cross sections, as with the (Gib91) calculation, are smaller, this time by a factor of three.

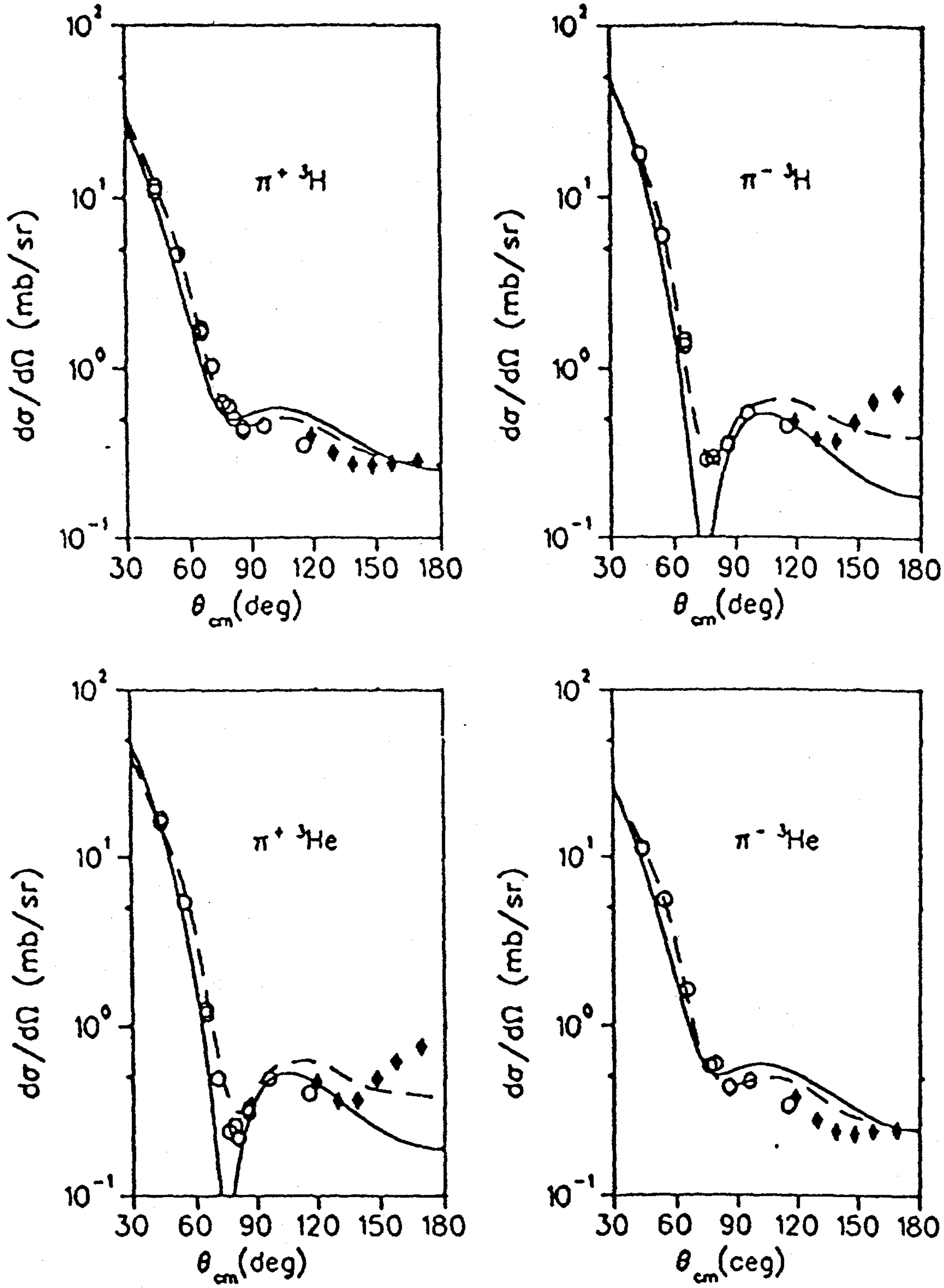

Fig. 22 Pion elastic angular distributions at T_π = 180 MeV. The large-angle data (diamonds) are from (Mat94), the forward-angle data (open circles), from (Pil91). The solid curves are from (Kam93), and the dashed curves are from (Gib91).

The investigation of this large-angle scattering region (dominated by the non-spin-flip scattering amplitude) was the main focus our experiment #1064, in which we measured the energy dependence from 142 to 256 MeV of the cross sections at an angle of 168° in the laboratory. As can be seen in Fig. 23, the measured *even-nucleon* cross sections (at all energies) are considerably larger (by a factor of three in most cases) than those calculated. For the *odd-nucleon* cases, a similar statement can be made for most of the energies, with the exception of the 180-MeV data, where it would seem that the calculations and the data agree very well. We note that Bennhold and his collaborators point out that part of the large-angle cross-section discrepancy may be resolved once they have fully implemented the spin and isospin structure of the second-order potential. Our new cross-section results at 180 MeV and the large-angle excitation data have recently been submitted for publication (Mat94).

In experiment #1032, we again focused our attention on the NSF region, but this time the measurements were carried out mostly with 256-MeV incident pions. Again, we extracted the charge-symmetric ratios r_1 and r_2 and the superratio R (see Ber92b). This experiment also yielded a very surprising result: for the first time, the measured superratio turned out to be substantially *smaller* than unity, as seen in Fig. 24, in complete contrast to the results at 180 MeV. Interestingly, the behavior of the individual ratios r_1 and r_2 at the two energies is qualitatively the same; r_1 is consistent with unity across the NSF dip, and r_2 deviates quite significantly from unity, leading to the observed behavior in R.

In the recent past, several models (Kim86, Kim87, Gib91) have appeared in the literature that attempt to explain the behavior of the superratio. For example, (Kim87) use as input for their (optical-model) calculation the measured electromagnetic form factors of the three-body nuclei, along with the argument that the Coulomb force distorts the nuclear force sufficiently to cause the observed deviation of R from unity. However, all preliminary calculations with this model indicate that it is going to be very difficult, if not impossible with the limited physics contained in the model thus far, to obtain a good simultaneous description of both the cross sections and the superratio at 180 and 256 MeV. Indeed, both the (Kam93) and the (Gib91) models fail to reproduce even qualitatively the behavior of R at 256 MeV. We strongly suspect that the radically different behavior of the superratio at 180 and 256 MeV is an indication of scattering and/or absorption processes that have not yet been implemented in the models.

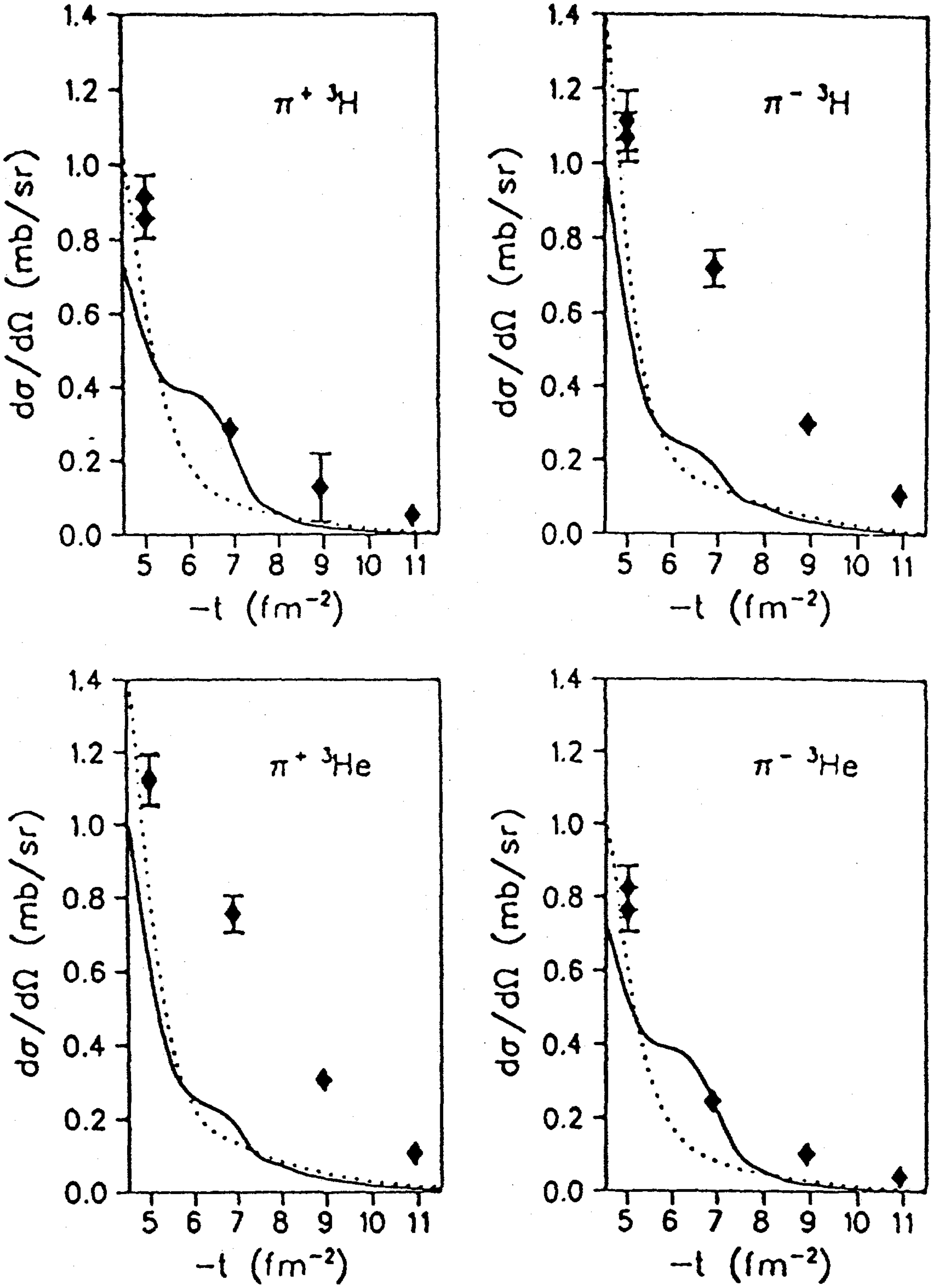

Fig. 23 Large-angle pion elastic cross sections plotted as a function of the square of the momentum transfer. The curves are the results of optical-model calculations (Kam93); the solid curve represents a second-order calculation and the dotted one is from a first-order calculation.

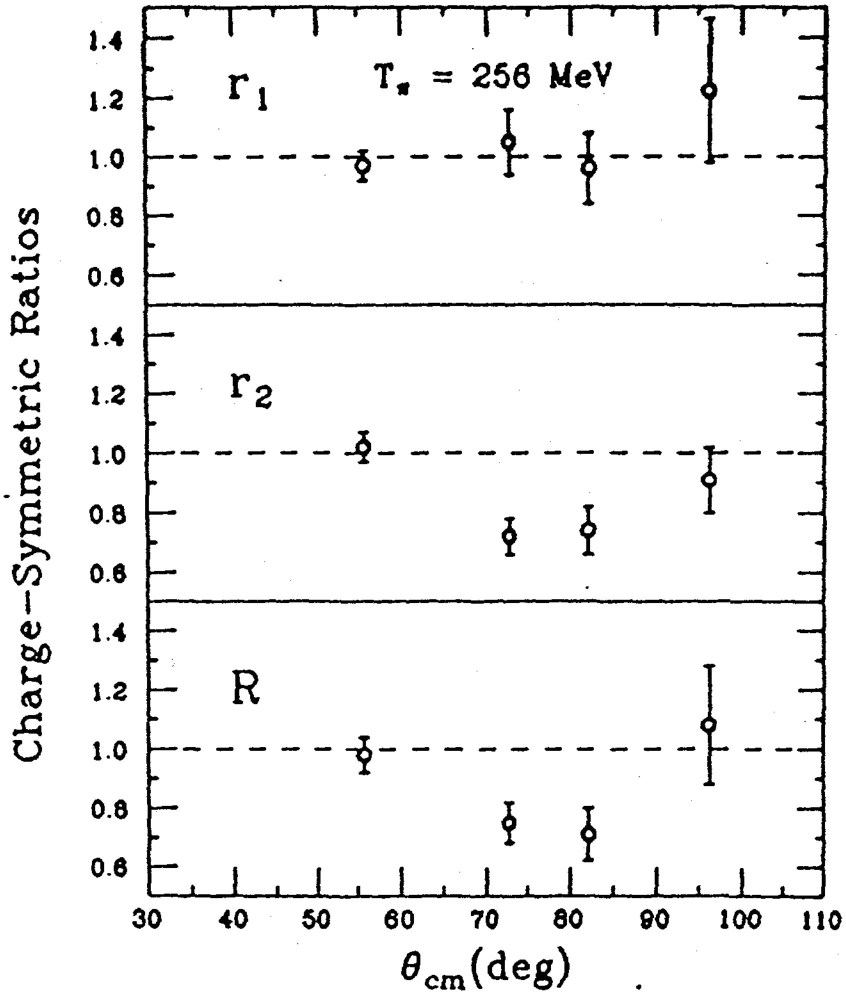

Fig. 24 Charge-symmetric ratios at T_π = 256 MeV, showing values below unity in the NSF-dip region.

Our 180-MeV data establish that R is greater than unity. However, the 256-MeV measurements show R to be substantially less than unity in the NSF-dip region. Clearly, a transition must occur as a function of energy. As a part of our experiment #1032, we also obtained data (in the NSF-dip region) at 220 MeV and 295 MeV, in order to locate the transition energy and to shed more light on our results at 256 MeV. These data are now also fully analyzed and confirm the transition in behavior of the superratio in which it is substantially larger than unity for energies below 180 MeV and significantly smaller than unity for higher energies, with the transition occurring at around 210 MeV, as shown in Fig. 25. For the 295-MeV point, we were only able to establish a limit on the superratio because of the very small π^{-3}He cross section at this energy. However, the downward trend of the superratio as a function of incident pion energy is evident. The reproduction of this behavior of the superratio is a major challenge to all the theoretical models considered so far. Our investigation of the NSF-dip region is currently being prepared for publication (Dhu94a).

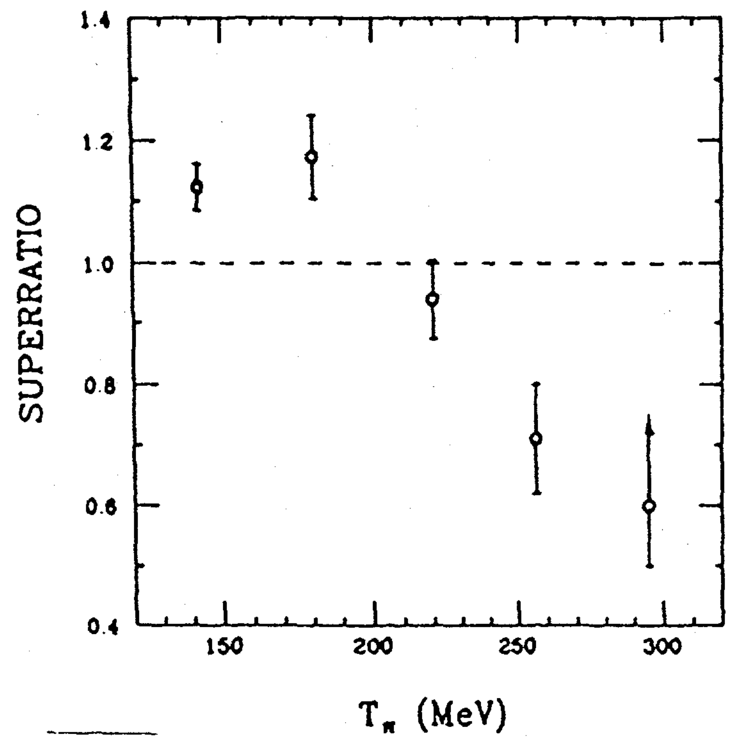

Fig. 25 The superratio is plotted as a function of the incident pion kinetic energy, showing that it decreases with energy and passes through the transition region at around $T_\pi = 210$ MeV.

2. Pion Scattering from Shell-Model Nuclei

Over the last few years, we have amassed a considerable volume of pion elastic-scattering data for a number of shell-model nuclei. One of the prime kinematic regions of interest is that of large-angle scattering in and around the Δ resonance. As noted above, the large-angle scattering region is of considerable interest because of the apparent enhancement that is observed in the measured cross sections as compared to those calculated with the best available optical-potential models.

The data set includes differential cross sections out to nearly 175° (in the center of mass) for π^+ scattering on ^{12}C, ^{16}O, ^{28}Si, and ^{40}Ca at energies on, below, and above the Δ resonance. In particular, we have completed the analysis of the 148-MeV angular distribution for ^{12}C and the 240-MeV angular distribution for ^{16}O.

We recently completed the analysis of the much more extensive large-angle data set on ^{28}Si. These data include π^+ angular distributions for 130, 180, and 226 MeV, shown in Fig. 26, along with a large-angle excitation function spanning the energy range of 100 to 240 MeV. The analysis of the data on ^{40}Ca (π^+ and π^- angular distributions at 116 MeV, along with a large-angle excitation function) is in progress, and should be completed this summer. Two papers summarizing these results are currently in preparation (Bur94, Dhu94b).

We have also made extensive measurements of pion-elastic scattering from these and other (heavier) nuclei in the region well above the Δ resonance. The data include forward-angle elastic differential cross sections for π^+ (and some for π^-) on ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr, and ^{208}Pb at 400 and 500 MeV. The purpose of these measurements was to investigate the effects on pion-nuclear scattering of relativity, higher partial waves (including D and F waves), and, if present, the onset of higher-lying resonances.

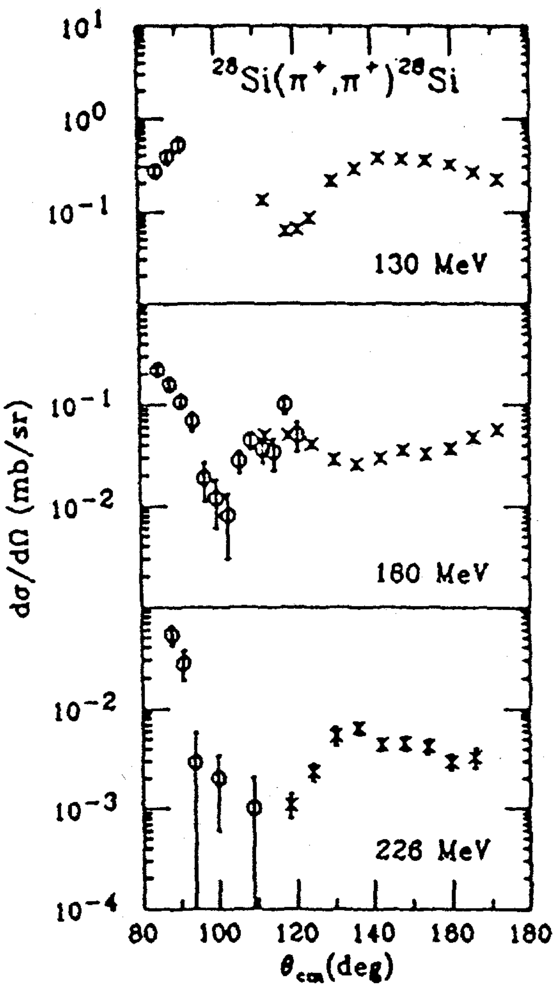

Fig. 26 Pion elastic differential cross sections for ^{28}Si at T_π = 130, 180, and 226 MeV. The forward-angle data (open circles) come from (Pre79); the backward-angle data are from (Dhu94b).

From the outset, the analysis of these data suffered from curious inconsistencies between π^+ and π^- flux normalizations. Several data points were re-measured in order to resolve this normalization problem. A new analysis indicates that the situation is now much improved for the data on ^{12}C, ^{16}O, and ^{40}Ca. The analysis of the remaining data is still in progress. Meanwhile, a paper summarizing the results on carbon, oxygen and calcium is being prepared for publication (Kah94).

3. (n,p) Reactions at WNR

We have performed measurements utilizing the "white" neutron source at the WNR facility at LAMPF to study the large-angle production of protons from a natural carbon and a composite CH_2 target. The purpose of this experiment was to measure the inclusive (n,p) cross sections because they are important in the design of high-energy neutron polarimeters. Remarkably few data exist for carbon--none for large-angle scattering (>30°) at neutron energies above 60 MeV.

There are two main methods of measuring the polarization of neutrons: (a) detecting the recoil proton at large angles from (n,p) scattering on hydrogen, and (b) double scattering, where two scintillators are used and the asymmetry of the neutron elastically scattered from hydrogen or carbon is measured at small angles. In the first method, the neutron scatterer is inactive and composed either of liquid hydrogen or of a hydrogen-rich material such as CH_2 (this method has been employed in the design of the HARP detector, for example). In the second method, the neutron scatterer is an active plastic scintillator, having approximately equal numbers of hydrogen and carbon nuclei. In either type of neutron polarimeter, the cross sections for (n,p) reactions for high neutron energies and large proton angles from hydrogen and natural carbon are needed for the design and modeling of the detector.

The neutron beam for these measurements was continuous in energy up to a maximum energy of 800 MeV. The energy of the neutrons was extracted from their flight time over an 89-meter flight path. The neutron beam flux was monitored using a ^{238}U fission foil in a drift chamber. The flux is calculated from the known cross section for neutron-induced fission of ^{238}U. The flux calculations give the absolute normalization for the measurement and are checked by comparing the extracted $^{1}H(n,p)$ differential cross sections at the smaller angles with their literature values.

The scattering target, one meter in length, was positioned at an angle of 6° with respect to the incident neutron beam. The proton detector consisted of two multiwire drift chambers, a thin plastic scintillator (the ΔE detector) and an array of CsI crystal scintillators (the E detector). The proton angle is determined from the drift chambers, and the charged particles are identified by the fraction of their total energy deposited in the ΔE detector. The CsI scintillators are capable of detecting protons up to a maximum energy of 260 MeV and cross sections are being extracted for neutron energies up to 300 MeV.

The angular range of the detector was approximately 20-100°, including the effect of the extended target.

The data, an example of which is shown in Fig. 27, are extracted in bins of 20 MeV in neutron energy and 2° in scattering angle. The data from the carbon and CH_2 targets are summed separately, and their normalization is obtained from the fission-chamber data. Background events obtained with no target in place have been subtracted. At the largest angles, the yields from the two targets should be identical within statistical uncertainties, since the scattering from hydrogen produces below-threshold protons at angles larger than about 70° for incident neutron energies of 300 MeV. This effect can be seen in Fig. 27, in which we show data for incident neutrons between 80 and 100 MeV, corresponding to an angular cutoff of approximately 55° for the detected protons. The results of this experiment will be submitted for publication later this summer (Rug94b).

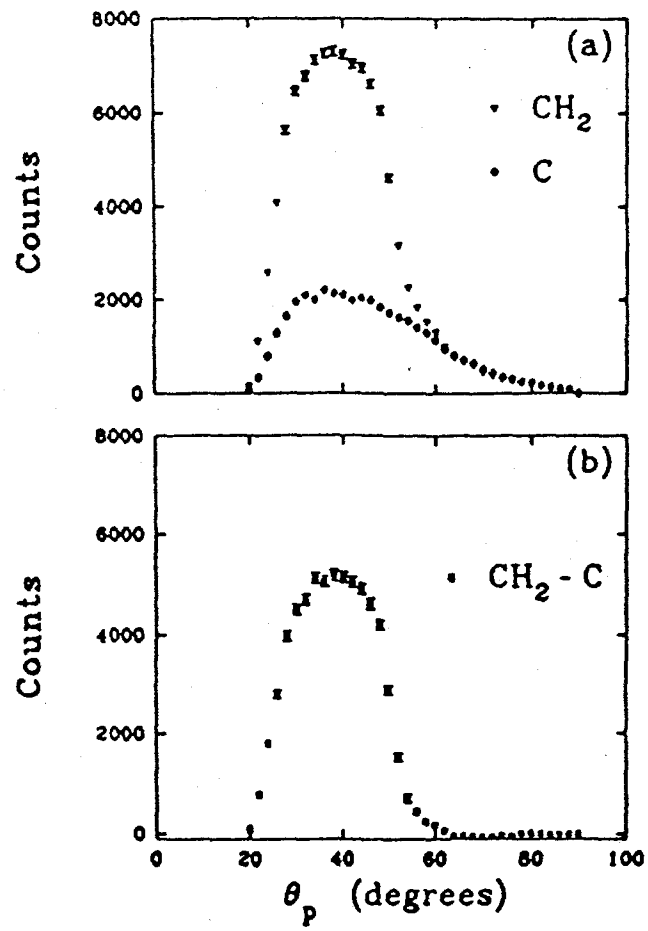

Fig. 27 Proton angular distributions from neutron bombardment of CH_2 and carbon for incident neutron energies between 80 and 100 MeV: (a) normalized data; (b) subtracted data. Note the cutoff at $\theta_p \cong 55°$ (see text).

REFERENCES TO SECTION III

Ber88 B.L. Berman *et al.*, in **Medium and High-Energy Nuclear Physics** (eds. W-Y.P. Hwang *et al.*, World Scientific, Singapore, 1988), p. 549

Ber92b B.L. Berman *et al.*, in **Pions in Nuclei** (eds. E. Oset *et al.*, World Scientific, Singapore, 1992), p. 161

Ber94 B.L. Berman *et al.*, Phys. Rev. C (submitted)

Bur94 G.R. Burleson *et al.*, Phys. Rev. C (to be submitted)

Con94 J.P. Connelly *et al.*, Phys. Rev. C (to be submitted)

Dhu87 K.S. Dhuga *et al.*, Phys. Rev. C **35**, 1148 (1987)

Dhu94a K.S. Dhuga *et al.*, Phys. Rev. C (to be submitted)

Dhu94b K.S. Dhuga *et al.*, Phys. Rev. C (to be submitted)

Ent86 R. Ent *et al.*, Phys. Rev. Lett. **57**, 2367 (1986)

Ent89 R. Ent *et al.*, Phys. Rev. Lett. **62**, 24 (1989)

Ent94 R. Ent *et al.*, Phys. Rev. C (in press)

Gib91 W.R. Gibbs and B.F. Gibson, Phys. Rev. C **43**, 1012 (1991)

Kah94 G.P. Kahrimanis *et al.*, Phys. Rev. C (to be submitted)

Kam93 S.S. Kamalov, L. Tiator, and C. Bennhold, Phys. Rev. C **47**, 941 (1993)

Kim86 Y.E. Kim, M. Krell, and L. Tiator, Phys. Lett. **B172**, 287 (1986)

Kim87 K.T. Kim, Y.E. Kim, and R.H. Landau, Phys. Rev. C **36**, 2155 (1987)

Mat94 S.K. Matthews *et al.*, Phys. Rev. C (submitted); also see Proc. XIV Int. Conf. on Few-Body Problems in Physics (Williamsburg, 1994)

Mit91 J.H. Mitchell *et al.*, Phys. Rev. C **44**, 2002 (1991)

Nef90 B.M.K. Nefkens *et al.*, Phys. Rev. C **41**, 2770 (1990)

Par84 W.C. Parke and D.R. Lehman, Phys. Rev. C **29**, 2319 (1984); also see C.T. Christou *et al.*, Phys. Rev. C **31**, 250 (1985)

Pil88 C. Pillai *et al.*, Phys. Lett. **207B**, 389 (1988)

Pil91 C. Pillai *et al.*, Phys. Rev. C **43**, 1838 (1991)

Pre79 B.M. Preedom *et al.*, Nucl. Phys. **A326**, 385 (1979)

Rug94b S.L. Rugari *et al.*, Phys. Rev. C (to be submitted); also see S.M. Wennersten and B.L. Berman, Proc. 7th Natl. Conf. on Undergraduate Research (Salt Lake City, 1993)

IV. RELATION OF PAST AND CURRENT RESEARCH

We list here, in tabular form, with references, the current status of previous experiments for which data collection has been completed. Some, but not all, of these measurements have been referred to in the previous sections. We are making good progress towards the documentation of the results and the publication of these papers in the pipeline. A complete listing of our nuclear physics publications for 1991-94 is given in Section VII. Papers in press or submitted for publication are reproduced in Appendix B.

We note here that several of our recent publications, on electron and proton scattering from the isotopes of oxygen and beryllium, report the results of measurements that some years ago constituted a major part of our research program. The electron experiments were carried out at the MIT Bates Accelerator and the proton experiments at the Indiana University Cyclotron Facility and at the High-Resolution Spectrometer at LAMPF. It is important to keep in mind that these experiments had as their primary goal the elucidation of the nuclear many-body force in these light (but not very light) nuclei, via the quantification of the *density dependence* of the nuclear force. Once the structure of a nucleus (its static shape parameters and electromagnetic transition strengths to excited states) has been specified from elastic and inelastic electron-scattering form factors, measurement of the proton-scattering form factors for the same nuclear states can be used to quantify the reaction mechanism. Especially for the spin observables measured with polarized-proton beams, we found that significant density dependence and/or relativistic effects were necessary to account for the large-angle results.

As detailed in Section III, we then moved on to coincidence electron-induced cluster knockout measurements on light nuclei at NIKHEF and pion-scattering measurements, particularly on ^{3}H and ^{3}He, at LAMPF. The former throw light on two-step or multiparticle-absorption processes, the latter on charge-symmetry breaking and on differences in nucleon-matter distributions. Now, as detailed in Section II, our program has evolved into the study of short-range forces and reaction mechanisms at CEBAF.

Thus, the focus of our program remains the understanding of the strong interaction in the nuclear medium, even though our emphasis has by now shifted almost completely from nuclear-structure studies on shell-model nuclei to studies of few-body nuclei, from measurements with hadronic probes to measurements with electromagnetic probes, and from singles to multiparticle-coincidence measurements.

Table I. Recent Studies of Few-Body Nuclei with Electromagnetic and Hadronic Probes

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^{1}H(n,p)$	LAMPF-WNR*	Application to neutron polarimeters	Data analyzed, paper in preparation	1
^{3}H, $^{3}He(\pi^{\pm},\pi^{\pm})$, $(\pi^{\pm},\pi^{\pm\prime})$	LAMPF-EPICS	142- to 220-MeV cross sections, form factors, charge asymmetry	Two papers published, one submitted	2
^{3}H, $^{3}He(\pi^{\pm},\pi^{\pm})$	LAMPF-EPICS*	180- to 295-MeV cross sections, form factors, charge asymmetry, spin-flip amplitudes	Data analyzed, paper in preparation	3
^{3}H, $^{3}He(\pi^{\pm},\pi^{\pm})$	LAMPF-EPICS*	180° cross sections, 142 to 256 MeV, form factors, non-spin-flip amplitudes	Data analyzed, one paper submitted, one to be submitted	4
^{3}H, $^{3}He(\pi^{\pm},\pi^{\pm})$	LAMPF-EPICS*	180-MeV cross sections and angular distribution, charge asymmetry	Data analyzed, one paper submitted, one to be submitted	4
$^{6}Li(e,e'd)$	NIKHEF	Spectral functions, q-dependence	One paper published, one in press	5
$^{6}Li(e,e'^{3}H)$	NIKHEF*	Momentum distributions, reaction mechanism, q-dependence	Data analyzed, paper in preparation	6
$^{6}Li(e,e'^{3}He)$	NIKHEF*	Momentum distributions, reaction mechanism, validity of 2-body model	Data being analyzed, paper in preparation	6

* Spokesperson or co-spokesperson

Table II. Recent Studies of Selected Shell-Model Nuclei with Electromagnetic and Hadronic Probes

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^{12}C(e,e'd)$	NIKHEF	Spectral functions, q-dependence	One paper published, one in press	7
$^{12}C(n,p)$	LAMPF-WNR*	Application to neutron polarimeters	Data analyzed, paper in preparation	1
^{12}C, ^{16}O, ^{28}Si, $^{40}Ca(\pi^{\pm},\pi^{\pm})$	LAMPF-EPICS*	Excitation functions at large angles, medium modifications	Two papers published, two in preparation	8
^{12}C, ^{16}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, ^{208}Pb $(\pi^{\pm},\pi^{\pm}),(\pi^{\pm},\pi^{\pm'})$	LAMPF-P^3*	Exploratory (300-500 MeV); test of optical models	Data being analyzed, invited paper presented, paper in preparation	9
$^{16}O(e,e')$	Bates	High-excitation, isovector states	Data analyzed, paper in preparation	10
$^{18}O(e,e')$	Bates	Stretched-spin states; isospin structure	Data analyzed, paper in preparation	11
$^{30}Si(e,e')$	Bates*	Stretched-spin states	Data analyzed, paper in preparation	12

* Spokesperson or co-spokesperson

References to Tables

1. S.L. Rugari *et al.*, to be submitted to Phys. Rev. C; also see S.M. Wennersten and B.L. Berman, Proc. 7th Natl. Conf. Undergrad. Res., Salt Lake City, 1993 and B.L. Berman *et al.*, LAMPF Proposals 4N0041 (1991and 1992)

2. C. Pillai *et al.*, Phys. Lett. **207B**, 389 (1988); C. Pillai *et al.*, Phys. Rev. C **43**, 1838 (1991); B.L. Berman *et al.*, submitted to Phys. Rev. C

3. K.S. Dhuga *et al.*, to be submitted to Phys. Rev. C; also see K.S. Dhuga *et al.*, Proc. Particles and Nuclei Int. Conf. (1990) and B.L. Berman *et al.*, Proc. Int. Workshop on Pions in Nuclei (1991)

4. S.K. Matthews *et al.*, submitted to Phys. Rev. C; W.J. Briscoe *et al.*, to be submitted to Phys. Rev. C; also see S.K. Matthews *et al.*, Proc. XIV Int. Conf. on Few-Body Problems in Physics, (Williamsburg, 1994), S.K. Matthews *et al.*, Bull. Am. Phys. Soc. **35**, 945 (1990), and S.K. Matthews *et al.*, S.J.Greene *et al.*, and W.J. Briscoe *et al.*, Proc. Int. Conf. on Nuclear Physics (1992)

5. R. Ent *et al.*, Phys. Rev. Lett. **57**, 2367 (1986); R. Ent *et al.*, Phys. Rev. C (in press); also see R. Ent *et al.*, Proc. Particles and Nuclei Int. Conf. (1990) and Verhandl. Deutsche Phys. Ges. (1990)

6. J.P. Connelly *et al.*, to be submitted to Phys. Rev. C; also see D. Zubanov *et al.*, Bull. Am. Phys. Soc. **35**, 927 (1990) and B.L. Berman *et al.*, NIKHEF Proposal 88-E1 (1987)

7. R. Ent *et al.*, Phys. Rev. Lett. **62**, 24 (1989); R. Ent *et al.*, Phys. Rev. C (in press); also see R. Ent *et al.*, in Proc. CEBAF 1988 Summer Workshop

8. K.S. Dhuga *et al.*, Phys. Rev. C **32**, 2208 (1985); K.S. Dhuga *et al.*, Phys. Rev. C **35**, 1148 (1987); K.S. Dhuga *et al.* and G.R. Burleson *et al.*, to be submitted to Phys. Rev. C; also see K.S. Dhuga *et al.*, LAMPF Proposal 1018 (1986)

9. K.S. Dhuga *et al.*, invited paper at Workshop on Pion Scattering above the Delta Resonance (KEK, Japan, 1990); G.P. Kahrimanis *et al.*, to be submitted to Phys. Rev. C; also see M.W. Rawool-Sullivan et al., Bull. Am. Phys. Soc. **37**, 916 (1992) and K.S. Dhuga *et al.*, LAMPF Proposal 1106 (1987)

10. J. Ruthenberg *et al.*, to be submitted to Phys. Rev. C

11. R.M. Sellers *et al.*, Bull. Am. Phys. Soc. **35**, 927 (1990) and to be submitted to Phys. Rev. C; also see D.M. Manley *et al.*, Bull. Am. Phys. Soc. **38**, 1820 (1993)

12. L. Knox *et al.*, Bull. Am. Phys. Soc. **34**, 1812 (1989) and to be submitted to Phys. Rev. C

V. INSTITUTIONAL SUPPORT

A. THE GW CENTER FOR NUCLEAR STUDIES

The George Washington University Center for Nuclear Studies provides the organizational umbrella for the research efforts in nuclear physics in the Department of Physics. Currently thirteen faculty members (one emeritus) and two postdoctoral research associates are members of the Center, about equally split between experiment and theory. The Center is administered by an executive committee, now consisting of L.C. Maximon (Acting Chair, while H. Haberzettl is on sabbatical leave), B.L. Berman, and W.J. Briscoe. Financial support for the Center is borne entirely by GW, as one of only six Centers of Excellence within the University. An electro-mechanical technician and two graduate research assistants (currently one in experiment and one in theory) are supported under its auspices (including tuition benefits for the GRAs). This support has been increased to $83K, effective this July, so that the research grants would no longer need to share the cost of the salaries for the GRAs and so that the GRA appointments could be expanded to twelve months. [This amount of support, if funded by our research grants, would cost the DOE $125K per year.] The Center helps us in our research efforts in other, less tangible but quite important, ways as well. The relatively large number of nuclear physicists at GW--one of the largest groups in the country--makes the Center a very congenial work environment, with a high degree of interaction between experimentalists and theorists. Many visitors, from this country and abroad, enrich our program and broaden our horizons. And our Friday Bag-Lunch Seminars in Nuclear Physics have become a popular fixture of the Washington-area nuclear physics community.

B. THE GW NUCLEAR DETECTOR LABORATORY

The GW Nuclear Detector Laboratory now has two branches, one in the basement of the Physics Building at the main (Foggy Bottom) campus, which was newly renovated about seven years ago, and the other at our new Virginia Campus near Dulles Airport. The construction and furnishing costs for these laboratory facilities have been borne by the University, at a cost of about $700K to date. Our new laboratory in particular is spacious and well appointed, and has comfortable offices and excellent shop facilities, including a modern lapper and lathe and a computer-controlled milling machine. Our activities connected with the CEBAF Photon Tagger project are centered at this laboratory, and our

Virginia Campus was the site of the Hall-B Collaboration Meeting last summer. At both laboratories we carry out a variety of teaching activities, so that our students at both graduate and undergraduate levels can become involved in internationally recognized research at an early stage, giving them a hands-on learning experience at the forefront of nuclear physics research.

C. Relationship with SURA and CEBAF

The George Washington University has had a special relationship with CEBAF since its inception. GW is a Charter Member of the Southeastern Universities Research Association (SURA), and has supported CEBAF in many ways, both institutionally and in the form of the research efforts of its faculty. Since 1983, GW has created nine CEBAF-oriented faculty positions. Among these are the present P.I. and co-P.I. Professor B.L. Berman has been active on a variety of CEBAF working groups and committees since before he came to GW in 1985; he has been on the Advisory Board of HUGS since its inception, the Users' Group Board of Directors during 1989-91, spent his 1991-92 sabbatical year mostly at CEBAF, and chaired the Hall B Real-Photon Physics Working Group for 1991-93 and the Users' Group Nominating Committee this year. Associate Professor K.S. Dhuga will leave shortly to spend his 1994-95 sabbatical year at CEBAF, working on the implementation of the CLAS. Four of our graduate students last year and three this year attended HUGS. Last year, in addition to the Hall-B Collaboration Meeting that we hosted, we had a GW Day at CEBAF, in which some 25 GW nuclear physics faculty and students spent a busy day with the CEBAF theoretical and experimental physics staff, listening to lectures and touring the facilities.

D. Personnel

The grant currently supports three faculty, two postdoctoral associates, and six graduate students. Resumes and publication lists for the past five years (1989-94) for the faculty and postdoctoral associates are given in Appendix C. We list here some of the research activities of the non-permanent staff. Dr. P.L. Cole is engaged primarily in the physics of high-energy photoreactions and a variety of calculations of event generators and acceptance functions for the CLAS, and has modified and updated some of the standard CLAS Monte-Carlo programs. Assistant Research Professor J.P. Connelly plays a principal role in the design and construction of the focal-plane detector array for the Photon Tagger and is analyzing the (e,e'^{3}He) data from NIKHEF. Cole and Connelly are primarily responsible for producing our upcoming vector-meson photoproduction proposal. Dr. S.L. Rugari is primarily responsible for our upcoming photofission proposal at SAL, the PPAD design and construction for our photofission experiments there and at CEBAF, the generation of a linearly polarized tagged-photon beam by coherent bremsstrahlung at CEBAF, and the analysis of our (n,p) data from LAMPF. Of the graduate students, three are primarily engaged in activities leading to CEBAF-related dissertation experiments, and the other three are being supported for the summer only, primarily working on the construction of the Photon Tagger focal-plane detector array.

This current half-year (July-December 1994) we have received a special supplementary grant from DOE to continue the progress of the GW group in the construction of the Photon Tagger for CEBAF. Dr. Connelly is now being supported by this supplementary grant; he was supported by the University for the previous year (July 1993-June 1994), since the [NSF] grant under which he had been supported prior to July 1993 was terminated. For the first eight months of our renewal period, during this time of transition, we need to retain Dr. Connelly in order that the Photon Tagger be completed and installed most efficiently and on schedule. Therefore, our budget request for 1995 is higher than those for 1996 and 1997.

In our proposed budget (see below), we request funds to change the mix somewhat from that which we have had in the recent past. We look towards a steady-state group consisting (in addition to the P.I. and co-P.I.) of an Assistant Research Professor, only one postdoctoral associate, and four Ph.D. students. We feel that this represents the minimum mix of new and experienced personnel needed to carry out our ambitious research program. Moreover, the University has agreed to cost-share 50% of the cost of the Assistant Research Professor (whereas it will no longer agree to cost-share indirect costs for the postdoctoral associates), so that the more senior person will actually cost the DOE over 40% less than a new postdoc. This clearly represents an opportunity to upgrade our level of personnel that is extremely cost-effective.

VI. WITHDRAWAL OF GW FROM THE HARP COLLABORATION

On March 31 of this year, the GW group withdrew from the HARP Collaboration. This withdrawal came about as a result of what began as a minor dispute concerning a funding proposal submitted by the GW group to the W.M. Keck Foundation, but which was quickly escalated by certain members of the HARP Coordinating Committee, including its Chair, into a major confrontation.

In what follows, we briefly describe the events that led up to the point where the GW group was left with no alternative but to withdraw from the collaboration.

The HARP Collaboration came into being in 1990. The GW group was a founding member of the collaboration. The purpose of the collaboration was to construct an advanced neutron detector and polarimeter system with which to perform experiments at NIKHEF and at CEBAF. The idea for the detector was conceived by B.L. Berman in the early 1980s, and GW students worked on a prototype model in 1985 and 1986 at Los Alamos. Other founding members included groups from Utrecht, Grenoble, and Regina; groups from Maryland and NIKHEF joined the collaboration at a later date.

A Memorandum Of Understanding (MOU), detailing the various HARP-related responsibilities of each member-group, was signed by representatives from each institution. K.S. Dhuga signed for the GW group, and was, from the outset, the GW representative on the HARP Coordinating Committee (CC). The primary (HARP) task for the GW group was to design and build, in collaboration with the group from Grenoble, a number of large-active-area multiwire proportional chambers. This part of the GW effort was led by P.L. Cole, who devoted the main part of his research effort since 1992 to this task. These chambers would have been employed in Phase 1 of the detector, which was scheduled to be commissioned at NIKHEF in late 1994.

From the outset, we at GW had envisioned the HARP program to be a two-stage project, Phase 1 at NIKHEF and Phase 2 at CEBAF. At NIKHEF, we would commission the detector and perform the first (e,e'n) measurements with it; in particular, we would use the detector to extract the recoil polarization of the outgoing neutron. At CEBAF, however, our experiments would be technically more challenging, in that they would involve higher energies, higher luminosities, and polarized beams, and would require the maximum possible efficiency of the detector, along with its full polarimetric and out-of-plane capabilities. The collaboration was fully aware that these added features would require a substantial and costly upgrade of the Phase-1 detector--an upgrade for which the funds had yet to be realized.

Our funding contribution towards the establishment of the first phase of the program was significant ($100K). This was made possible in part by a DOE University Instrumentation Program Award (P.I., Dhuga), which provided funds for the establishment of a multiwire proportional chamber-based nuclear detector facility at GW. Our contribution to the physics program was also substantial. In fact, among the entire collaboration, our group had the only approved experiment that intended to use the detector as a polarimeter--its designated purpose (NIKHEF proposal 93-09--Spokesperson, Dhuga).

Having established ourselves as one of the leading groups in the collaboration, we began our preparations for the much anticipated CEBAF phase of the HARP program, and in particular, began exploring various sources of funding. On March 14 of this year, we submitted a funding proposal (for $362K) for Phase 2 of the HARP to the W.M. Keck Foundation. We note that the award of a grant from the Keck Foundation was a goal that we, with the enthusiastic backing of the GW administration, had been pursuing for the last three years. As part of this effort our President, S.J. Trachtenberg, visited the Keck Foundation in California; considerable additional groundwork was done by Vice President M.J. Worth (Development), by Associate Vice President D.R. Lehman (Research and Graduate Studies, and former Chairman of the Physics Department), and by others.

Based on the strength of the required pre-proposal letter (submitted by Dhuga and Berman last July), we were invited by S. A. Glass, the Program Vice President of the Keck Foundation, to submit the full proposal at the beginning of this year. The proposal was enthusiastically endorsed by our President. We felt very confident of the outcome because not only had our preliminary application received good reviews, but we had also received considerable encouragement and support from Dr. Glass, who, in fact, visited GW this January. Unfortunately, it was not to be.

Having some objections to some parts of the proposal, certain members of the HARP CC, in particular the Chair, decided to force the GW group (and the GW President) to withdraw (rather than merely to modify) the proposal. Their mode of operation was both uncompromising and unprofessional. They voted to prohibit GW from submitting the proposal, in spite of the fact that the MOU did not give the CC jurisdiction over funding proposals. They voted to expel Dhuga from the CC, again with no authority from the MOU. No meeting of the full CC was ever convened. All charges were conveyed via a blizzard of E-mail messages--messages that on several occasions contained crude and slanderous personal attacks. All of our attempts at mediation were rebuffed; at no time was the GW group given a realistic opportunity for clarification of the claims or rectification of the grievances of these members of the CC. The Chair of the CC was escalating a minor dispute, that should have been easy to resolve with simple modifications of the proposal, into a major confrontation. The Chair of the CC pursued his unwarranted actions until he broke all bounds of ethical behavior by sending a message, full of inaccuracies, directly to the President of GW. This message, sent on Friday night, March 25, not only demanded a complete revision of the proposal, but also laid down a deadline of the following Monday morning at 3 A.M. Then, just 21 minutes after he sent this message, he sent a similarly unethical message to the Keck Foundation. It was for these thoughtless and unacceptable actions by the Chair of the HARP CC that the Directors of the three European member-institutions of the collaboration, namely, Utrecht, Grenoble, and NIKHEF, later sent a letter of apology to the Keck Foundation and to the President of GW. By this time, however, the damage had been done, and the proposal had been withdrawn.

Our decision to withdraw from the collaboration was not taken lightly. We each had a lot to lose. However, given the circumstances, and the atmosphere of ill feeling and mistrust that had been created, it was clear that we had no other option but to withdraw.

Professor Lehman, who tried his best to serve as mediator in the dispute, oversaw the official withdrawal of the GW group from the HARP Collaboration. His Office retains all pertinent records and documentation of this affair.

With the exception of one junior person not supported by this grant, the GW group is no longer associated with the HARP Collaboration. In our view, all parties lost.

VII. NUCLEAR PHYSICS PUBLICATIONS, 1991-1994

A. EXPERIMENTAL PROPOSALS (Spokespersons only listed)
(#--Reproduced in Appendix A)

1. B.L. Berman and J.L. Ullmann
Large-Angle Protons from Neutron Bombardment of Carbon
LAMPF/WNR Proposal 4N0041 (Continuation) (1992)

2. K.S. Dhuga
Recoil Polarization of the Neutron in the Reactions ^{3}He(e,e'n) and ^{4}He(e,e'n)
NIKHEF Proposal 93-09

3.# B.L. Berman, P. Corvisiero, and G. Audit
Photoreactions on ^{3}He
CEBAF Proposal 93-044

4.# N. Bianchi, V. Muccifora, and B. L. Berman
Photoabsorption and Photofission of Nuclei
CEBAF Proposal 93-019

5. P.L. Cole, J.P. Connelly, and R.R. Whitney
Non-Diffractive Photoproduction of the ρ Meson with Linearly Polarized Photons
CEBAF Proposal (to be submitted, 1994)

6. S.L. Rugari and B.L. Berman
Photofission of Actinide Nuclei
SAL Proposal (to be submitted, 1994)

B. JOURNAL ARTICLES PUBLISHED OR SUBMITTED FOR PUBLICATION
(#--Reproduced in Appendix B)
(†--Not directly supported by this grant)

1. K.G. McNeill, J.W. Jury, M.N. Thompson, B.L. Berman, and R.E. Pywell
^{18}O(γ,pn+np) Cross Section
Phys. Rev. C **43**, 489 (1991)

2. J.J. Kelly, A.E. Feldman, B.S. Flanders, H. Seifert, D. Lopiano, B. Aas, A. Azizi, G. Igo, G. Weston, C. Whitten, A. Wong, M.V. Hynes, J. McClelland, W. Bertozzi, J.M. Finn, C.E. Hyde-Wright, R.W. Lourie, P.E. Ulmer, B.E. Norum, and B.L. Berman
Effective Interaction for ^{16}O(p,p') at E_p = 318 MeV
Phys. Rev. C **43**, 1272 (1991)

3. J.P. Glickman, W. Bertozzi, T.N. Buti, S. Dixit, F.W. Hersman, C.E. Hyde-Wright, M.V. Hynes, R.W. Lourie, B.E. Norum, J.J. Kelly, B.L. Berman, and D.J. Millener
Electron Scattering from ^{9}Be
Phys. Rev. C **43**, 1740 (1991)

4. S. Dixit, W. Bertozzi, T.N. Buti, J.M. Finn, F.W. Hersman, C.E. Hyde-Wright, M.V. Hynes, M.A. Kovash, B.E. Norum, J.J. Kelly, A.D. Bacher, G.T. Emery, C.C. Foster, W.P. Jones, D.W. Miller, B.L. Berman, and D.J. Millener
Structure of ^{9}Be from Proton Scattering at 180 MeV
Phys. Rev. C **43**, 1758 (1991)

5. C. Pillai, D.B. Barlow, B.L. Berman, W.J. Briscoe, A. Mokhtari, B.M.K. Nefkens, and M.E. Sadler
Angle and Energy Dependence of the Superratio for π^+ and π^- Elastic Scattering from ^{3}H and ^{3}He: Evidence for Charge-Symmetry Violation
Phys. Rev. C **43**, 1838 (1991)

6. B.S. Flanders, J.J. Kelly, H. Seifert, D. Lopiano, B. Aas, A. Azizi, G. Igo, G. Weston, C. Whitten, A. Wong, M.V. Hynes, J. McClelland, W. Bertozzi, J.M. Finn, C.E. Hyde-Wright, R.W. Lourie, B.E. Norum, P. Ulmer, and B.L. Berman
Empirical Density-Dependent Effective Interaction for Nucleon-Nucleus Scattering at 500 MeV
Phys. Rev. C **43**, 2103 (1991)

7. D.M. Manley, B.L. Berman, W. Bertozzi, T.N. Buti, J.M. Finn, F.W. Hersman, C.E. Hyde-Wright, M.V. Hynes, J.J. Kelly, M.A. Kovash, S. Kowalski, R.W. Lourie, B. Murdock, B.E. Norum, B. Pugh, C.P. Sargent, and D.J. Millener
Electroexcitation of Negative-Parity States in ^{18}O
Phys. Rev. C **43**, 2147 (1991)

8. D. McLean, M.N. Thompson, D. Zubanov, K.G. McNeill, J.W. Jury, and B.L. Berman
^{14}C Photoproton Cross Section
Phys. Rev. C **44**, 1137 (1991)

9. †D.L. Olson, M. Baumgartner, D.E. Greiner, P.J. Lindstrom, T.J.M. Symons, R. Wada, M.L. Webb, B.L. Berman, H.J. Crawford, and J.M. Engelage
Direct Observation of the Giant Dipole Resonance of ^{16}O via Electromagnetic Dissociation
Phys. Rev. C **44**, 1862 (1991)

10. J.H. Mitchell, H.P. Blok, B.L. Berman, W.J. Briscoe, M.A. Daman, R. Ent, E. Jans, L. Lapikas, and J.J.M. Steijger
Mechanism of the ^{6}Li(e,e'α) Reaction
Phys. Rev. C **44**, 2002 (1991)

11. B. Brinkmöller, C.L. Blilie, D. Dehnhard, M.K. Jones, G.M. Martinez, S.K. Nanda, S.M. Sterbenz, Yi-Fen Yen, L.G. Atencio, S.J. Greene, C.L. Morris, S.J. Seestrom, G.R. Burleson, K.S. Dhuga, J.A. Faucett, R.W. Garnett, K. Maeda, C.F. Moore, S. Mordechai, A. Williams, S.H. Yoo, and L.C. Bland
Elastic Scattering of π^{+} and π^{-} from ^{4}He between 90 and 240 MeV
Phys. Rev. C **44**, 2031 (1991)

12. D. Zubanov, M.N. Thompson, B.L. Berman, J.W. Jury, R.E. Pywell, and K.G. McNeill
Giant Dipole Resonance in ^{17}O Observed with the (γ,p) Reaction
Phys. Rev. C **45**, 174 (1992)

13. †J.T. O'Brien, D.I. Sober, L.W. Fagg, H. Crannell, M. Petraitis, J.P. Connelly, J.R. Deininger, and S.E. Williamson
Design and Testing of Apparatus for 180° Electron Scattering at Low Momentum Transfer
Nucl. Instrum. Methods **A312**, 531 (1992)

14. †J.P. Connelly, H. Crannell, L.W. Fagg, J.T. O'Brien, M. Petraitis, D.I. Sober, J.R. Deininger, and S.E. Williamson
Magnetic Dipole Strength in ^{46}Ca Observed with 180-Degree Electron Scattering
Phys. Lett. **B277**, 383 (1992)

15. †W. Kim, B.L. Miller, J.R. Calarco, L.S. Cardman, J.P. Connelly, S.A. Fayans, B. Frois, D. Goutte, J.H. Heisenberg, F.W. Hersman, V. Meot, T.E. Milliman, P. Mueller, C.N. Papanicolas, A.P. Platonov, V.Yu. Ponomarev, and J.E. Wise
Interplay between Single-Particle and Collective Degrees of Freedom in the Excitation of Low-Lying States in ^{140}Ce
Phys. Rev. C **45**, 2290 (1992)

16. †J.P. Connelly, H. Crannell, L.W. Fagg, J.T. O'Brien, M. Petraitis, D.I. Sober, J.R. Deininger, and S.E. Williamson
Magnetic Transition Strengths from the 3.68-MeV 3/2^{-} State and the 3.85-MeV 5/2^{+} State in ^{13}C
Phys. Rev. C **45**, 2494 (1992)

17. †J.P. Connelly, D.E. DeAngelis, J.H. Heisenberg, F.W. Hersman, M. Leuschner, W. Kim, T.E. Milliman, J.E. Wise, and C.N. Papanicolas
High-Resolution Electron Scattering from High Spin States in ^{208}Pb
Phys. Rev. C **45**, 2711 (1992)

18. K.G. McNeill, M.N. Thompson, A.D. Bates, J.W. Jury, and B.L. Berman
Isospin Effects in the Photodisintegration of Light Nuclei
Phys. Rev. C **47**, 1108 (1993)

19. †J.J. Kelly, B.S. Flanders, F.W. Hersman, J.H. Heisenberg, J.R. Calarco, J.P. Connelly, T.E. Milliman, A. Scott, F.T. Baker, V. Penumetcha, W.P. Jones, G.T. Emory, A.D. Bacher, C. Olmer, M.A. Grimm, and M.L. Whitten
Neutron Transition Densities from ^{88}Sr at $E_p = 200$ MeV
Phys. Rev. C **47**, 2146 (1993)

20. †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. Platonov, E.E. Saperstein, and R.P. Singhal
Ground-State Magnetization Density of ^{89}Y
Phys. Rev. C **47**, 2539 (1993)

21. †Z. Zhao, R.H. France III, K.S. Lai, S.L. Rugari, M. Gai, and E.L. Wilds
Astrophysical S-Factor of $^{12}C(\alpha,\gamma)^{16}O$ from the Beta Delayed Alpha-Particle Emission of ^{16}N
Phys. Rev. Lett. **70**, 2066 (1993); Erratum, **70**, 3524 (1993)

22. †S.L. Rugari, R.H. France III, B.J. Lund, Z. Zhao, M. Gai, P.A. Butler, V.A. Holliday, A.N. James, G.D. Jones, R.J. Poynter, R.J. Tanner, K.L. Ying, and J. Simpson
Broken Reflection Symmetry in ^{114}Xe
Phys. Rev. C **48**, 2078 (1993)

23. †M. Petraitis, J.P. Connelly, H. Crannell, L.W. Fagg, J.T. O'Brien, D.I. Sober, J.R. Deiniger, S.E. Williamson, R. Lindgren, and S. Raman
Low-Multipolarity Magnetic Transitions in ^{30}Si, ^{32}S, and ^{34}S Studied by 180° Electron Scattering
Phys. Rev. C **49**, 3000 (1994)

24.# R. Ent, B.L. Berman, H.P. Blok, J.F.J. van den Brand, W.J. Briscoe, M.N. Harakeh, E. Jans, P.D. Kunz, and L. Lapikás
The (e,e'd) Reaction on ^{4}He, ^{6}Li, and ^{12}C
Phys. Rev. C (in press)

25.# B.L. Berman, G.C. Anderson, W.J. Briscoe, A. Mokhtari, A.M. Petrov, M.E. Sadler, D.B. Barlow, B.M.K. Nefkens, and C. Pillai
Inelastic Pion Scattering from ^{3}H and ^{3}He
Phys. Rev. C (submitted)

26.# S.K. Matthews, W.J. Briscoe, C. Bennhold, B.L. Berman, R.W. Caress, K.S. Dhuga, S.N. Dragic, N.J. Nicholas, M.F. Taragin, S.J. Greene, D.B. Barlow, B.M.K. Nefkens, C. Pillai, J.W. Price, L.D. Isenhower, M.E. Sadler, I. Slaus, and I. Supek
Elastic Scattering of Pions from ^{3}H and ^{3}He into the Backward Hemisphere
Phys. Rev. C (submitted)

27. †M. Petraitis, J.P. Connelly, H. Crannell, L.W. Fagg, J.T. O'Brien, D.I. Sober, J.R. Deiniger, S.E. Williamson, R. Lindgren, and S. Raman
Low-Multipolarity Magnetic Transitions in ^{40}Ca Excited by 180° Electron Scattering
Phys. Rev. C (submitted)

C. Journal Articles in Preparation

1. K.S. Dhuga, B.L. Berman, W.J. Briscoe, R.W. Caress, D.A. Hanson, S.K. Matthews, C.S. Smith, D.B. Barlow, R.S. Kessler, B.M.K. Nefkens, C. Pillai, J.W. Price, S.J. Greene, and I. Slaus
Investigation of the Non-Spin-Flip Dip in Pion Elastic Scattering on ^{3}H and ^{3}He
Phys. Rev. C (to be submitted)

2. R.M.Sellers, D.M. Manley, M.M. Niboh, R.A. Lindgren, B.L. Clausen, M. Farkhondeh, B.E. Norum, and B.L. Berman
Inelastic Electron Scattering from ^{18}O at Backward Angles
Phys. Rev. C (to be submitted)

3. J. Ruthenberg, D.M. Manley, R.M. Sellers, R.A. Lindgren, B.L. Clausen, M. Farkhondeh, B.E. Norum and B.L. Berman
Inelastic Electron Scattering from ^{16}O at Backward Angles
Phys. Rev. C (to be submitted)

4. S.L. Rugari, B.L. Berman, W.J. Briscoe, K.S. Dhuga, A. Ling, D.S. Sorenson, and J. Ullmann
Large-Angle Protons from Neutron Bombardment of Carbon
Phys. Rev. C (to be submitted)

5. K.S. Dhuga, G.R. Burleson, R.L. Boudrie, J.A. Faucett, R.W. Garnett, S.J. Greene, M.K. Jones, K.W. Johnson, J.W. McDonald, S. Mordechai, D.S. Oakley, B. Park, M.W. Rawool-Sullivan, J.C. Sanabria, M.J. Smithson, and A.L. Williams
Large-Angle Pion Elastic Scattering off ^{28}Si
Phys. Rev. C (to be submitted)

6. G.P. Kahrimanis, G.R. Burleson, K.S. Dhuga, D.J. Ernst, J.A. Faucett, H.T. Fortune, E. Insko, K.W. Johnson, C.F. Moore, J.A. McGill, C.L. Morris, J.M. O'Donnell, M.W. Rawool-Sullivan, A.L. Williams, and C. Whitley
Pion-Nucleus Elastic Scattering at the Energies above the $\Delta(1232)$
Phys. Rev. C (to be submitted)

7. W.J. Briscoe, C. Bennhold, B.L. Berman, R.W. Caress, K.S. Dhuga, S.N. Dragic, S.K. Matthews, N.J. Nicholas, M.F. Taragin, S.J. Greene, D.B. Barlow, B.M.K. Nefkens, C. Pillai, J.W. Price, L.D. Isenhower, M.E. Sadler, I. Slaus, and I. Supek
Large-Angle Cross-Section Ratios for Pion Scattering from ^3H and ^3He
Phys. Rev. C (to be submitted)

8. G.R. Burleson, R.L. Boudrie, K.S. Dhuga, J.A. Faucett, R.W. Garnett, S.J. Greene, M.K. Jones, K.W. Johnson, J.W. McDonald, S. Mordechai, D.S. Oakley, B. Park, M.W. Rawool-Sullivan, J.C. Sanabria, M.J. Smithson, and A.L. Williams
Large-Angle Pion Elastic Scattering
Phys. Rev. C (to be submitted)

9. J.P. Connelly, B.L. Berman, H.P. Blok, W.J. Briscoe, K.S. Dhuga, R. Ent, E. Jans, L. Lapikás, A. Mokhtari, and D. Zubanov
The $^6Li(e,e'^3H)^3He$ and $^6Li(e,e'^3He)^3H$ Reactions
Phys. Rev. C (to be submitted)

D. Papers Published in Conference Proceedings

(*--Invited Papers)
(†--Not directly supported by this grant)

1.* B.L. Berman, W.J. Briscoe, K.S. Dhuga, D.A. Hanson, S.K. Matthews, A. Mokhtari, C.S. Smith, D.B. Barlow, B.M.K. Nefkens, C. Pillai, J.W. Price, S.J. Greene, and I. Slaus
Pion Scattering from ^3H and ^3He
Pions in Nuclei (Proc. Int. Workshop, eds. E. Oset, M.J. Vicente Vacas, and C. Garcia Recio, World Scientific, Singapore, 1992), p. 161

2.* †B.L. Berman, D.L. Olson, D.E. Greiner, P.J. Lindstrom, and H.J. Crawford
Electromagnetic Dissociation of Heavy Ions
Dynamical Aspects of Nuclear Fission (Proc. Int. Workshop, eds. J. Kristiak and B.I. Pustylnik, JINR, Dubna, 1992), p. 269

3. †S.L. Rugari, R.H. France III, Z. Zhao, and M. Gai
Broken Reflection Symmetry and Isospin Dependence of Enhanced E1 Decays in ^{114}Xe
Proc. 6th Int. Conf. on Nuclei Far from Stability (Bernkastel-Kues, Germany, 1992), p. PE26

4.* W.J. Briscoe, D.B. Barlow, B.L. Berman, R.W. Caress, K.S. Dhuga, S.N. Dragic, S.J. Greene, D. Isenhower, D. Knowles, D. Macek, S.K. Matthews, A. Mokhtari, B.M.K. Nefkens, N.J. Nicholas, C. Pillai, J.W. Price, M.E. Sadler, I. Slaus, I. Supek, and M.F. Taragin
$\pi^{\pm}$ Elastic and Inelastic Scattering from ^{3}H and ^{3}He
Proc. Int. Conf. Nucl. Phys. (Wiesbaden, 1992)

5.* S.M. Wennersten and B.L. Berman
Large-Angle Protons from Neutron Bombardment of Carbon
7th Natl. Conf. on Undergraduate Research (Salt Lake City, 1993)

6.* S.K. Matthews, W.J. Briscoe, D.B. Barlow, C. Bennhold, B.L. Berman, R.W. Caress, K.S. Dhuga, S.N. Dragic, S.J. Greene, L.D. Isenhower, B.M.K. Nefkins, N.J. Nicholas, C. Pillai, J.W. Price, M.E. Sadler, I. Slaus, I. Supek, and M.F. Taragin
Elastic Scattering of Pions from ^{3}H and ^{3}He into the Backwards Hemisphere
Proc. XIV Int. Conf. on Few-Body Problems in Physics (Williamsburg, 1994)

E. Reports

1. B.L. Berman, W.J. Briscoe, K.S. Dhuga, W.R. Dodge, A. Mokhtari, and M.F. Taragin
A Large, Novel, Neutron Detector for Basic Nuclear Physics Studies
George Washington University Center for Nuclear Studies Report (1991)

2. P.L. Cole
Hyperon Acceptance Studies with the CLAS
CEBAF CLAS Note 92-002 (1992)

3. B.L. Berman, K.S. Dhuga, W.R. Dodge, and B. G. Ritchie
Photofission at CEBAF Energies
CEBAF CLAS Note 92-010 (1992)

4. P.L. Cole and J.C. Sanabria
Feasibility Studies for a Proposed MWPC Design for the HARP
George Washington University HARP Note (1992)

5. P.L. Cole and J.C. Sanabria
Feasibility Studies for a Proposed Design for a Drift Chamber for the HARP
George Washington University Center for Nuclear Studies Note (1992)

6. P.L. Cole
Effects of Multiple Scattering for the HARP
George Washington University Center for Nuclear Studies Note (1992)

7. P.L. Cole
A Generalized FASTMC for the CLAS
CEBAF CLAS Note 93-006 (1993)

8. J. Ballon, K. Grüner, G. Laborie, A. Pelissier, F. Vezzu, E. Voutier, P.L. Cole, and J.C. Sanabria
The Design and Construction of the HARP MWPCs
HARP Note (1993)

9. E. Voutier, K. Grüner, and P.L. Cole
Optimization of the HARP MWPC Design
HARP Internal Report (1993)

10. R.W. Caress
Application of Monte-Carlo Techniques to the Design of a High-Acceptance Recoil Polarimeter
M.S. Thesis, The George Washington University (1993)

11. S.L. Rugari
Monte Carlo Simulation of Coherent Bremsstrahlung
CEBAF CLAS Note 94-xxx (1994)

12. D. Pang
Electron Scattering
George Washington University Center for Nuclear Studies Report (1994)