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A PROGRAM IN MEDIUM-ENERGY NUCLEAR PHYSICS
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TECHNICAL PROGRESS REPORT -- SEPTEMBER, 1989 - SEPTEMBER, 1990

# I. OVERVIEW

## A. Overall Scope

This report contains a description of our research activities in Medium-Energy Nuclear Physics for the past year, with brief projections of our planned activities for the future.

Our present activities are centered about four experimental programs (see Sec. II). Two of these programs, on nuclear structure, are contracting, since we have no plans (at present) to propose further extensions of this work, while the other two, on few-body nuclei, are occupying a greater fraction of our efforts, mainly because of our conviction that the physics is crucial to our understanding of nuclear forces, but also because of the parallel interests of our theoretical and experimental colleagues at GWU. Other experimental efforts have been completed and are being phased out (Sec. III).

Our current experimental programs, and their future extensions at CEBAF and elsewhere, are supported by our new GWU Nuclear Detector Laboratory, now a vital element of the newly-organized GWU Center for Nuclear Studies (see Sec. IV). The University has contributed generously to the NDL, both in terms of building renovation and fixtures and furnishings; it also is providing strong support, both financial and institutional, to the CNS, and this support, including technical manpower, will be devoted exclusively to research activities in experimental and theoretical nuclear physics. In addition, we recently have been awarded a sizable equipment grant for development of MWPC-based neutron detectors by DOE, 20% of which is cost-shared by the University.

We look forward to the advent of CEBAF, towards which we are devoting an increasing fraction of our efforts. We, together with our NSF-supported colleagues, are full participants in the planning and construction of CLAS, in particular its tagged-photon facility; together we are designing and shall build the focal-plane detector array, and together we shall propose and participate in experiments using real photons at CLAS (see Sec. V). One of us (Berman) plans to spend his upcoming sabbatical year (1991-92) at CEBAF.

Our publications since the date of our last progress report (September, 1989) are listed in Sec. VI, and tables of details concerning our recent, pending, and planned experiments constitute Sec. VII. Copies of our recent reprints and preprints are reproduced in the Appendix.

## B. Scope of Experimental Programs on Few-Body Nuclei

### Coincidence Electrodisintegration of Light Nuclei

Until CEBAF and the Bates stretcher ring become operational, the NIKHEF machine MEA (Medium-Energy Accelerator) offers the best combination of electron energy (>500 MeV) and duty factor (>1%) for performing (e,e'x) coincidence experiments. Therefore, both experimental groups at GWU, strongly supported by the theoretical group at GWU as well, have participated in a very active collaboration with scientists at NIKHEF and the Free University of Amsterdam to perform such measurements there. To date, we have completed (e,e'd) measurements on $^{6}Li$ and $^{12}C$, and (e, e' alpha) and (e, e't) measurements on $^{6}Li$. We are currently engaged (Fall, 1990) in $^{3}He$-knockout measurements on $^{6}Li$, and we have plans for pursuing a program of (e,e'n) experiments on several light nuclei, including $^{3}He$ and $^{4}He$ as well as $^{6}Li$. Since (e,e'n) measurements require the use of a neutron detector in the high-background environment of an electron beam, we have proposed to build a novel wire-chamber-based neutron detector with the desired characteristics at our Nuclear Detector Laboratory. This proposal has now grown into a collaboration with Dr. Thomas Bauer and his group at the University of Utrecht. Should such detectors prove feasible, they will have widespread application at CEBAF and elsewhere. Finally, the upgraded MEA will, upon completion in late 1992, constitute an accelerator facility which will complement CEBAF on the low-energy side (as will the Bates upgrade as well). Our collaboration then can serve to facilitate experiments at both laboratories.

## Pion Studies of the A=3 Nuclei

A number of fundamental issues in nuclear structure can be addressed by pion scattering and reactions on the A=3 nuclei, not only because the nuclear systems are light, and therefore amenable to calculation, but because of the mirror nature both of $pi^+$ and $pi^-$ and of $^3H$ and $^3He$. Elastic scattering probes the proton and neutron matter distributions of these nuclei, including the neutron distribution in $^3H$, to which electron scattering is blind. Measurement and comparison of the charge-symmetric mirror ratios $r_1$ (the ratio of the $pi^+$-$^3H$ and $pi^-$-$^3He$ cross sections) and $r_2$ (the ratio of the $pi^-$-$^3H$ and pi+-$^3He$ cross sections) and their product, the superratio $R=r_1r_2$, establish the surprisingly large extent of charge-symmetry breaking and the fact that it is caused by the like nucleons, and not the unlike nucleons, in the A=3 nuclei. Curious and unexpected structure in R has appeared at energies above the delta resonance (at $T_{pi}$ = 220-290 MeV) which merits further study. Inelastic scattering explores the two- and three-body breakup channels of these nuclei. Single-charge exchange at 50 MeV is an even cleaner probe of the p and n distributions. All reactions at energies above the delta resonance are largely independent of internal Coulomb corrections. Angular distributions, particularly comparison of the cross sections in the non-spin-flip dip (90° in the pi-N center-of-mass system) and at 180°, will yield the spin-flip and non-spin-flip amplitudes separately, without the need for polarized targets. Finally, comparisons with both single-arm and coincidence electron-scattering studies can result in a much better understanding of nuclear forces, particularly their three-body component. We have performed or are proposing experimental studies of all of the above; our data for elastic scattering at 256 MeV in particular show large excursions of R from unity on the low side, for which there is no (at present) theoretical explanation.

## II. ACTIVE EXPERIMENTAL PROGRAMS

A. Electron-Scattering Nuclear-Structure Studies

B. Coincidence Electrodisintegration Studies of Light Nuclei

C. Pion Scattering and Reactions on the Three-Body Nuclei

D. Pion Scattering from Shell-Model Nuclei

### A. Electron-Scattering Nuclear-Structure Studies

**$^{17}$O: High-q Magnetic Elastic Scattering (Bates 83-23)**

Spokesman: Bertozzi

GWU participation: Berman

Collaboration: MIT, Virginia, Maryland, Free University, GWU

Lead physicist: Kalantar-Nayestanaki (Free University)

Status: Beam time approved, not yet scheduled. The background-rejection capability at ELSSY now is good enough to perform this experiment.

**$^{18}$O: Stretched M4 and M6 Excitations (Bates 86-11)**

Co-spokesmen: Lindgren, Manley, Peterson

GWU participation: Berman

Collaboration: Kent State, Virginia, Colorado, Washington, GWU

Lead physicist: Manley (Kent State)

Status: Data-taking completed in November, 1988. Data analyzed at Kent State; paper in preparation.

The primary motivation for this experiment was to locate and study high-spin magnetic excitations in $^{18}$O. In particular, we sought to identify T=2 $4^-$ states and T=1 $6^-$ states; the excitation of T=2 $4^-$ states proceeds through a stretched $1p_{3/2}$-$1f_{7/2}$ transition. These states were identified by their characteristic, completely transverse, form factors. The results are being compared with measurements for similar transitions in $^{16}$O, with theoretical structure calculations, and (for the $6^-$ states) with results obtained from the $^{17}$O(alpha,$^{3}$He)$^{18}$O reaction.

**$^{30}$Si: Stretched M6 Excitations (Bates 82-08)**

Co-spokesmen: Lindgren, Berman, Fagg

GWU participation: Berman, Zubanov

Collaboration: Virginia, GWU, Kent State, Catholic

Lead physicist: Lindgren (Virginia)

Status: Data-taking completed in January, 1989. Data being analyzed at Virginia. Contributed paper presented at Asilomar APS Meeting, October, 1989.

The primary motivation of this experiment was to identify the isovector stretched M6 strength in $^{30}$Si and to study the systematics of the quenching and fragmentation of the strength across the closing of the $d_{5/2}$ shell. This region is of particular interest because realistic large-basis shell-model calculations can be performed and compared with experiment. Moreover, the observed strong variation in M6 strength from $^{28}$Si, where only one transition has been observed, to $^{32}$S, where our results indicate quite a few moderately strong transitions, is provocative. The study of these transition strengths as a function of the occupation of the $2s_{1/2}$ spectator orbit should provide constraints on parameters describing the shell-model calculations.

**$^{32}$S: Stretched M6 Excitations (NIKHEF 88-E5)**

Co-spokesmen: Fagg, Berman, Lindgren

GWU participation: Berman, Dhuga

Collaboration: Virginia, Catholic, NIKHEF, GWU

Lead physicist: Clausen (Virginia)

Status: Data-taking completed in November, 1988. Data analyzed at Virginia. Paper published in Phys. Rev. Lett.

Nine possible isovector M6 transitions were identified in $^{32}$S, exhausting 40-51% of the sum-rule strength. This is the first observation of substantially fragmented isovector electromagnetic stretched strength in a self-conjugate nucleus. A recent shell-model study indicates increased fragmentation of isovector M6 strength for $^{32}S$, but fails to give a detailed reproduction of the new data.

Figure 1 shows a sample $^{32}S(e,e')$ spectrum at $q_{eff} = 2.1\ fm^{-1}$, showing eight of the nine $6^-$ states identified. Figure 2 shows the (transverse) form factors for these states.

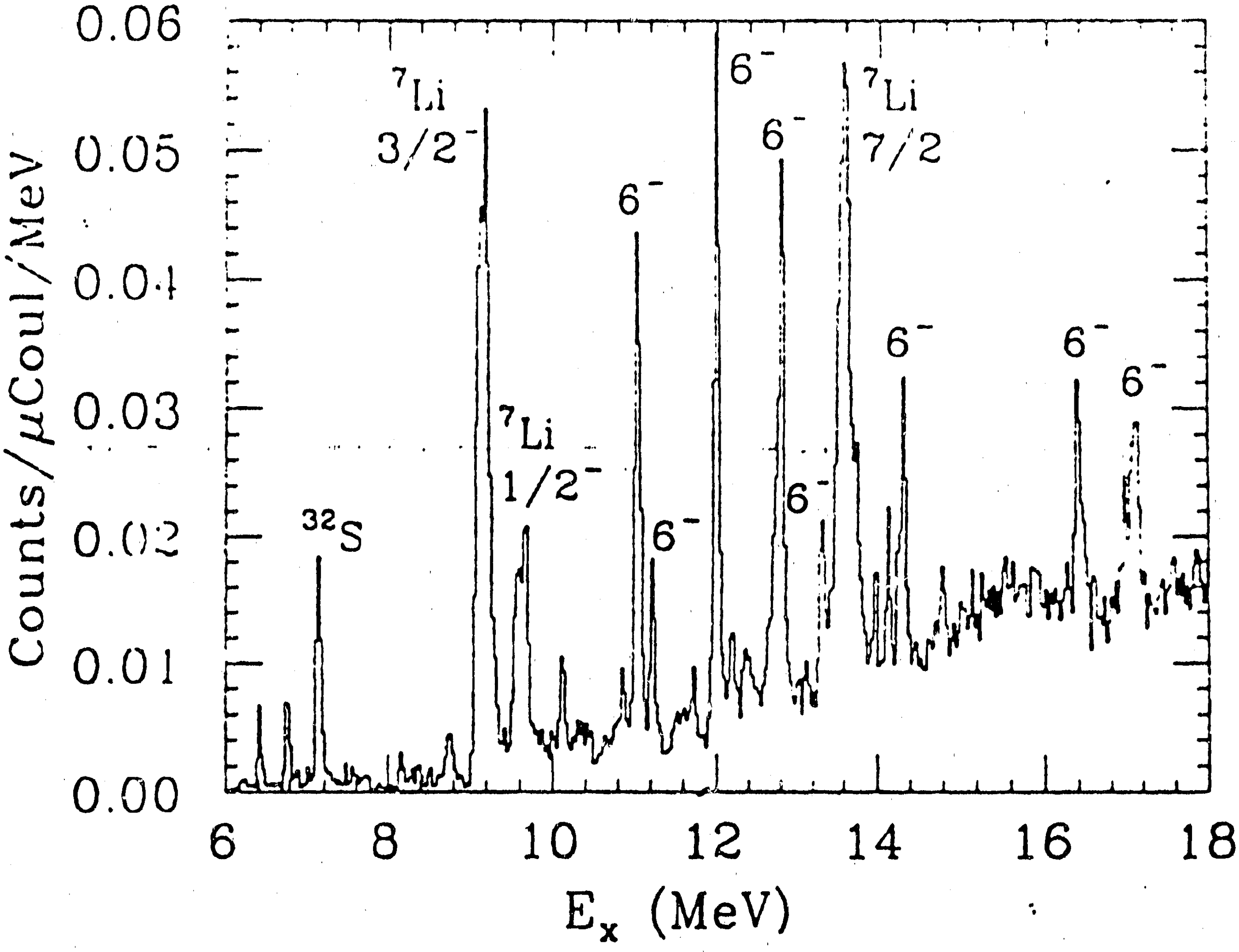



FIG. 1. A sample $^{32}S(e,e')$ spectrum taken at NIKHEF using a $Li_2S$ target. The scattering angle is $\theta = 154°$ and the incident electron energy is $E_0 = 207$ MeV ($q = 2.0$ fm$^{-1}$).

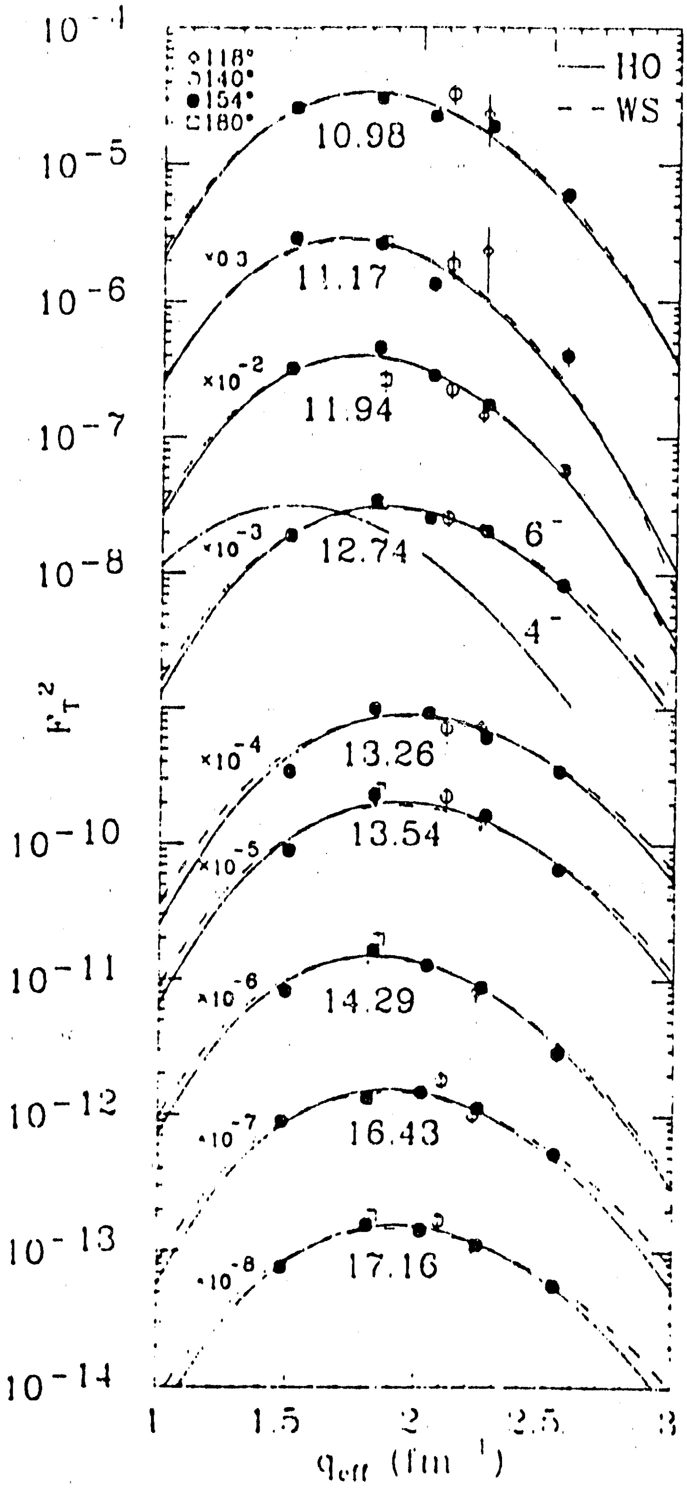



FIG. 2. Form factors as defined in Ref. 1 for the $^{32}S(e,e')$ $6^-$ stretched states (with excitation energies in MeV), where the HO $b$ and the WS $r_0$ were varied independently for each state. A form factor calculated for a $4^-$ excitation is shown to illustrate the basis for rejecting the $4^-$ spin assignment.

**$^{21}$Ne, $^{23}$Na: Ground-State Rotational-Band Transitions (Bates 88-18)**

Co-spokesmen: Manley, Lindgren, Berman

GWU participation: Berman, Dhuga

Collaboration: Kent State, Virginia, GWU, New Hampshire, BNL

Lead physicist: Manley (Kent State)

Status: Beam time approved with highest priority (chosen to be one of only six experiments to be done if running time at Bates were to be cut back to 1500 hours for the next three years). We plan to perform both parts of this experiment ($^{23}$Na and $^{21}$Ne) in 1991.

Measurements of electromagnetic form factors will be performed to excite members of the $3/2^+$ ground-state rotational bands in $^{21}$Ne and $^{23}$Na. The measurements will utilize ELSSY, the high-resolution energy-loss spectrometer system. The kinematics will span the excitation region up to about 10 MeV and the momentum-transfer region between 0.5 and 2.3 fm$^{-1}$ at forward angles and between 1.0 and 2.3 fm$^{-1}$ at backward angles. The chosen kinematics will allow a Rosenbluth separation of the longitudinal and transverse form factors.

The primary interest for performing these measurements is to investigate the distribution of C2 and C4 strengths in $^{21}$Ne and $^{23}$Na, two rather similar light, deformed nuclei. The results obtained will allow comparisons to be made with existing data for neighboring even-A nuclei, such as $^{20}$Ne, $^{22}$Ne, and $^{24}$Mg. The planned experiments for $^{21}$Ne and $^{23}$Na will include measurements of both elastic charge and magnetic scattering from both nuclei; only very limited measurements presently exist for the elastic magnetic form factor of $^{23}$Na and no measurements at all (to our knowledge) exist for the elastic charge or magnetic form factors of $^{21}$Ne.

B. Coincidence Electrodisintegration Studies of Light Nuclei

**$^{6}$Li(e,e'alpha) and the Alpha Knockout Process (NIKHEF 86-E)**

Spokesman: Ent

GWU participation: Berman, Zubanov, Briscoe, Taragin
Collaboration: Free University, NIKHEF, GWU
Lead Physicist: Mitchell (NIKHEF, now Virginia)
Status: Data-taking completed in November, 1988. Data analyzed at NIKHEF and Virginia. Paper being prepared for publication.

This experiment was performed at the electron-scattering facility of NIKHEF-K using the high-resolution electron and hadron spectrometers. Alpha particles were knocked out by 550-MeV incident electrons and were detected with resolution sufficient to separate, for the first time, the $^2H$ final state from the pn breakup, which opens at an excitation energy of 2.2 MeV. The measured cross section for the (e,e'alpha) reaction leading to the $^2H$ final state, as a function of momentum transfer, follows the electron-alpha cross section, after correcting the latter for distortions. This implies that the reaction process is consistent with a quasielastic mechanism. The cross section for the pn breakup, on the other hand, does not follow the electron-alpha cross section, indicating that the quasielastic scattering mechanism for the $^6Li$(e,e'alpha)pn reaction is not an appropriate description. Two-step processes might be more important for this reaction than for the reaction leading to the $^2H$ final state, or else the overlap of $^6Li$ and the pn pair might not correspond to a free alpha. It also is possible that the alpha-d optical potential used in the calculation of final-state interactions between the knocked-out alpha and the pn pair in the continuum is not valid.

The alpha-d momentum distribution in the ground state of $^6Li$, measured in the momentum range $30 < p_m < 140$ MeV/c, is in reasonable agreement with the results from the study of the $^6Li(e,e'd)^4He$ reaction, performed previously. This agreement is encouraging with regard to future studies of alpha clusters in nuclei using the (e,e'alpha) reaction.

**$^{6}$Li(e,e't) and the $^{3}$H-$^{3}$He Cluster Model of $^{6}$Li (NIKHEF 88-E1, part 1)**

Spokesman: Berman

GWU participation: Berman, Zubanov, Briscoe, Taragin

Collaboration: GWU, Free University, NIKHEF

Lead physicist: Zubanov

Status: Data-taking completed in April, 1989. Data analyzed by Zubanov at NIKHEF and GWU. Contributed paper given at Washington APS Meeting (April, 1990).

Data for the $^{6}$Li(e,e't)$^{3}$He reaction were taken in parallel kinematics at an incident electron energy of 523 MeV. Knock-out tritons were detected using the standard detection system (4 wire chambers and E-delta E scin tillators) of the hadron spectrometer. For the q-dependence study, five points were obtained keeping the missing momentum $p_m$ fixed at 75 MeV/c and varying the t-$^{3}$He center-of-mass energy $E_{cm}$ from 16.5 to 33 MeV. For the measurement of the t-$^{3}$He momentum distribution, the range in missing momentum covered was $30<p_m<180$ MeV, taken mostly at $E_{cm}$=33 MeV. Also, about 20 MeV of transitions to the pd and p2n breakup states were recorded; these channels open at 5.5 and 7.7 MeV, respectively.

The results show that the q-dependence for the $^{6}$Li(e,e't)$^{3}$He$_{gs}$ reaction is the same as that for the $^{6}$Li(e,e't)pd/$^{6}$Li(e,e't)n2p breakup reactions. It is not yet clear whether this dependence follows the electron-triton off-shell cross section, since the calculation of final-state interactions between the knock-out triton and the $^{3}$He final state has not yet been carried out. The reason for this is that a good set of optical-model parameters for the t-$^{3}$He system is not available from experiment. In the very near future, we intend to derive an optical-model parameter set from a realistic nucleon-nucleon interaction. We expect to then learn if the quasielastic mechanism is the appropriate description for the transitions to the $^{3}$He final state and the breakup states. We then can derive the distorted momentum distribution from the data by dividing the six-fold cross sections that we have now by the electron-triton cross section, which finally can be compared with model predictions and data from other studies of $^{6}Li$.

Figure 3 shows the q-dependence of the $^{6}Li(e,e't)^{3}He_{gs}$ reaction, compared with that for the free e-$^{3}H$ cross section (solid line) and with that for bound $^{3}H$ and $^{3}He$ clusters (dashed line).

**$^{6}Li(e,e'^{3}He)$ and the $^{3}H$-$^{3}He$ Cluster Model of $^{6}Li$ (NIKHEF 88-E1, part 2)**

Spokesman: Berman

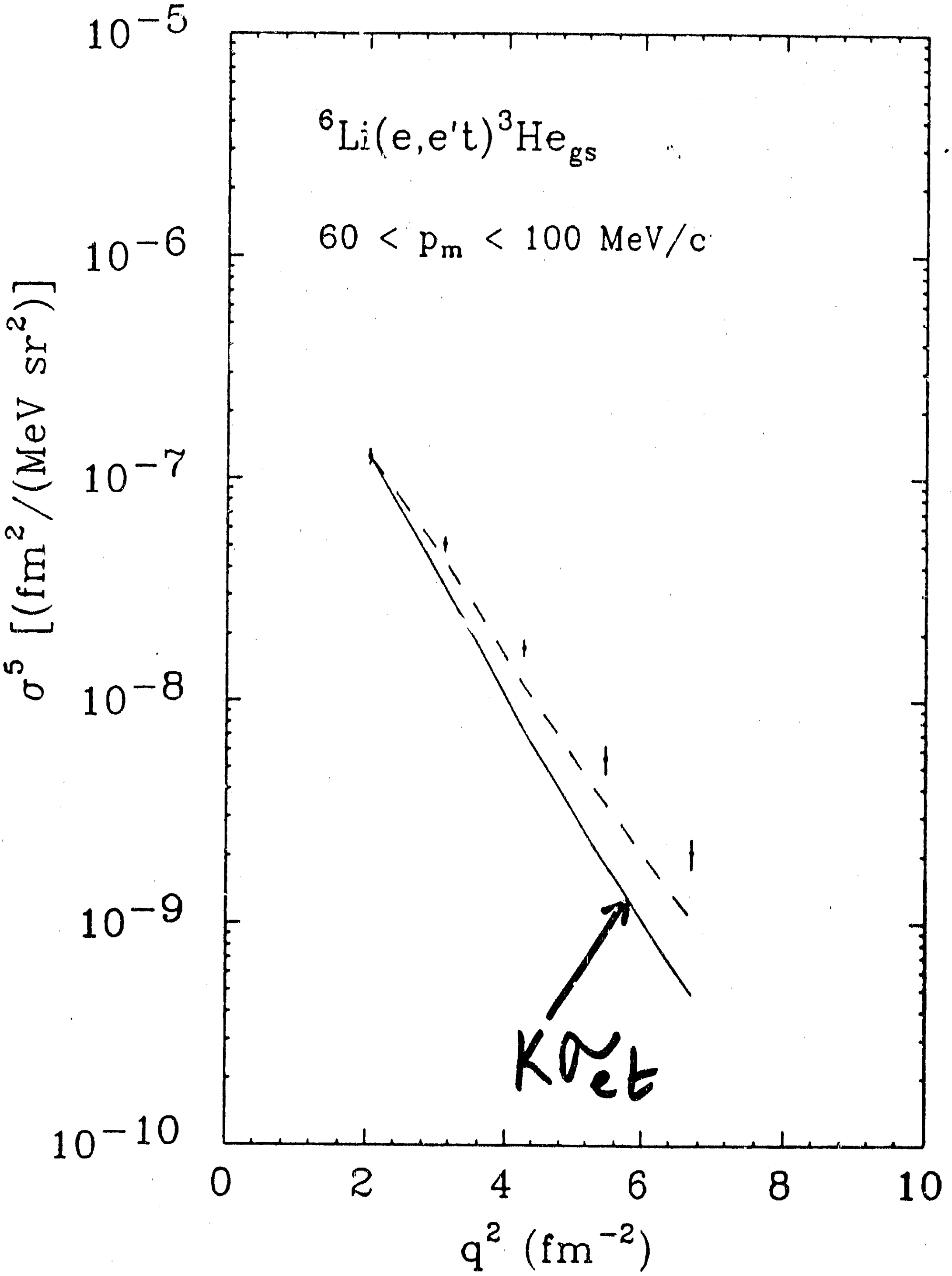
GWU participation: Berman, Dhuga, students

Collaboration: GWU, Free University, NIKHEF

Lead physicist: Berman

Status: Beam time approved, scheduled for Oct-Nov, 1990. Data will be analyzed by S.N. Dragic, a GWU student, as part of his Ph.D. research.

This experiment will explore the behavior of the charge-symmetric $^{6}Li(e,e'^{3}He)$ reaction. Since distortions and final-state interactions should cancel in the ratio of the $(e,e'^{3}He)$ and (e,e't) cross sections, we should be able to infer directly the momentum distributions and hence the cluster probability for the two-body "heavy-deuteron" cluster configuration of $^{6}Li$ (first suggested by Berman in 1965).



$^6Li(e,e't)^3He_{gs}$
60 < $p_m$ < 100 MeV/c
$\sigma^5$ [(fm$^2$/(MeV sr$^2$))]
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
0
2
4
6
8
10
$q^2$ (fm$^{-2}$)


Figure 3

**$^3$He(e,e't)pi$^+$ and $^3$He(e,e'$^3$He)pi$^0$ (NIKHEF, to be proposed)**

Intended spokesman: Berman

Intended GWU participation: Both experimental groups

This experiment will be part of a combined attack on the pion-trinucleon amplitudes which includes those for the neutral pion, together with the single-charge-exchange reactions $^3$H,$^3$He(pi$^{+-}$,pi$^0$) (see Sec. IIC below). Here, the well-understood electro-magnetic interaction in the initial-state channel will be exploited to yield the pi$^+$-$^3$H and pi$^0$-$^3$He final-state amplitudes.

**The (e,e'n) Reaction on $^3$He, $^4$He, $^6$Li, and $^{12}$C (NIKHEF or Bates, to be proposed)**

Intended spokesmen: Berman, Bauer (Utrecht)

Intended GWU participation: Both experimental groups

This series of experiments will be complementary to the body of data already existing on the (e,e'p) reaction and will explore, among other things, the neutron distribution in these nuclei and the importance of two-step processes. These measurements are planned to be the first to utilize the novel MWPC-based neutron detectors which we shall design and construct in our new Nuclear Detector Laboratory (see Sec. IV below).

## C. Pion Scattering and Reactions on the Three-Body Nuclei

**Pion Scattering on $^3$H and $^3$He in the Non-Spin-Flip Dip Region (LAMPF 1032)**

Co-spokesmen: Nefkens, Berman, Briscoe

GWU participation: Berman, Dhuga, Briscoe, students

Collaboration: UCLA, GWU, Abilene Christian, LANL

Lead physicist: Dhuga

Status: Data-taking completed in August, 1988. Data analyzed at GWU. Contributed papers presented at Santa Fe APS Meeting, Vancouver Few-Body Conference, and PANIC; paper being prepared for publication.

**Pion Scattering on $^3H$ and $^3He$ near 180° (LAMPF 1064)**

Co-spokesmen: Briscoe, Berman, Nefkens

GWU participation: Berman, Dhuga, Briscoe, Taragin, students

Collaboration: GWU, UCLA, Abilene Christian, LANL

Lead physicist: Briscoe

Status: Data-taking completed Summer, 1989. Data being analyzed at LANL by S.K. Matthews, a GWU student, as part of his Ph.D. research.

**Pion Scattering on $^3H$ and $^3He$ at 180 MeV at Backward Angles (LAMPF 1155)**

Co-spokesmen: Dhuga, Briscoe, Pillai

GWU participation: Berman, Dhuga, Briscoe, Taragin, students

Collaboration: GWU, UCLA, Abilene Christian, LANL

Lead physicist: Dhuga

Status: Data-taking completed Summer, 1989. Data being analyzed at LANL by S.K. Matthews, a GWU student, as part of his Ph.D. research.

Following our 1985 survey measurements (LAMPF Expt. 905) at three incident pion energies and five angles, all of which yielded values greater than unity for the superratio R, we mounted a series of three additional experiments of the same type, each exploring in depth a particularly sensitive kinematic region: The angular (momentum-transfer) region of the non-spin-flip dip at several energies, where Coulomb-nuclear interference should be largest; the back-angle region (near 180°), where the spin-flip amplitude should be negligible and one can measure the non-spin-flip amplitude without the need for polarized targets; and on resonance (180 MeV) for the entire angular region between the forward-angle measurements of Expt. 905 and the near-180° point of Expt. 1064. The first of these experiments (1032) uncovered values for R <u>smaller</u> than unity at 256 MeV coupled with <u>nuclear</u> interference effects. The values for the superratio R for $T_{pi}$ = 256 MeV are shown in Fig. 4. Results of the other two experiments (1064 and 1155) amplify the interference phenomenon and extend the clearly charge-asymmetric result $R \neq 1$ to backward angles, far from the non-spin-flip dip. These combined data have enabled us to extract both the unlike-nucleon and paired-nucleon matter form factors for $^3H$ and $^3He$ over a wide range of energy and momentum transfer, which then can be compared with the charge and magnetization form-factor data from the recent electron-scattering measurements at Bates and Saclay. Further, it has enabled us to obtain the information on the crucial neutron-matter distribution in $^3H$, to which electron scattering is blind.

In fact Gibbs and Gibson, using an optical potential formalism, have analyzed the measured elastic differential cross sections, and have extracted the difference between $r_p(^3H)$ and $r_n(^3H)$ with a precision that exceeds the uncertainty in the electron scattering measurements of the charge radii of $^3H$ and $^3He$. They conclude from this radius difference that there is a significant charge-symmetry-breaking effect beyond the Coulomb interaction.

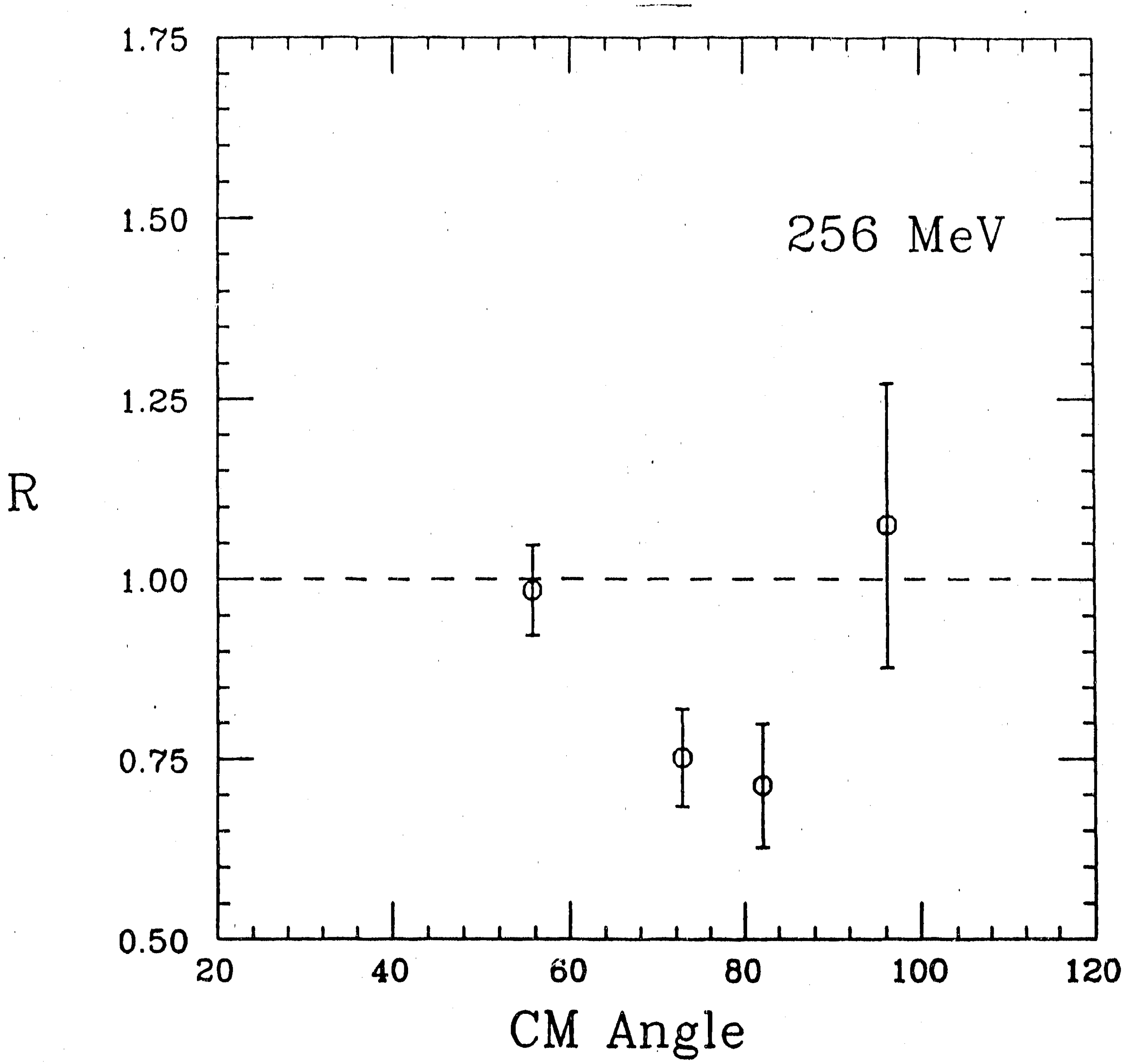



Figure 4

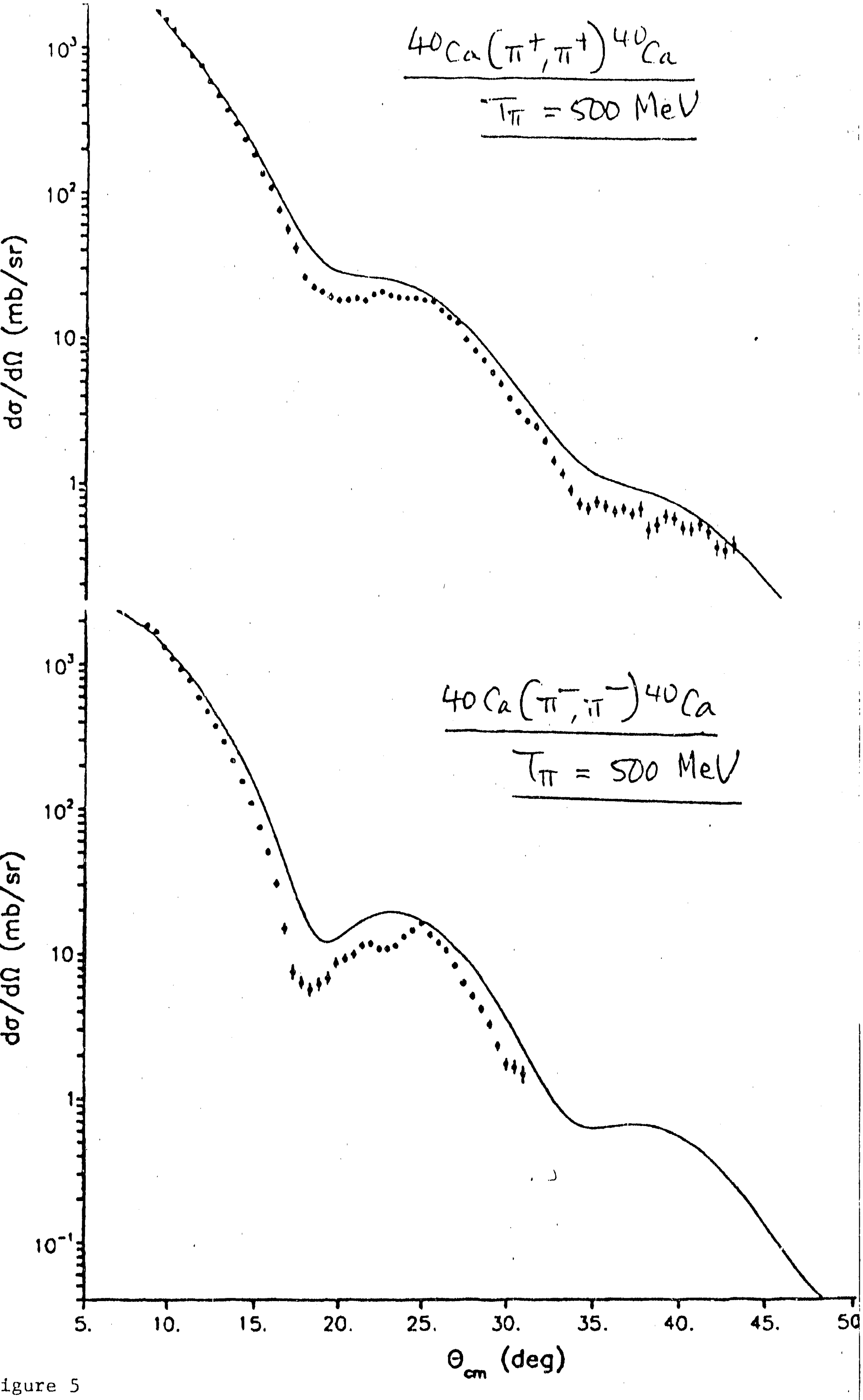
**Pion Single Charge Exchange on $^3H$ and $^3He$**
**(LAMPF, to be proposed)**
Intended spokesman: Dhuga
Intended GWU participation: Both experimental groups

The $^3H$-$^3He$ isospin doublet provides a natural laboratory for testing charge symmetry through comparison of the differential cross sections for mirror reactions, such as $^3H(pi^+,pi^0)^3He$ and $^3He(pi^-,pi^0)^3H$. In order to improve our understanding of the pi-trinucleon cross sections, and in particular to obtain a better handle on the question of charge-symmetry violation in the pi-nucleon interaction, we propose to carry out a series of single-charge-exchange measurements on $^3H$ and $^3He$ at 50 and 180 MeV. This experiment will use the new Neutral Meson Spectrometer, being built at LAMPF with participation by GWU and other universities. With these measurements, we hope to quantify and distinguish between the two most plausible explanations of the reported charge-symmetry breaking, i.e., Coulomb interactions and neutron-proton distribution differences in $^3H$ and $^3He$.

Moreover, $^3H(pi^+,pi^0)^3He$ is complementary to the $^3He(e,e't)$ and $^3He(e,e'^3He)$ reactions to be studied with coincidence electro-disintegration measurements (Sec. II B above), and $^3He(pi^-,pi^0)^3H$ would be complementary to similar studies, if and when they are done, on $^3H$.

D. Pion Scattering from Shell-Model Nuclei
Co-spokesmen: Dhuga, McGill
GWU participation: Dhuga
Collaboration: GWU, LANL, New Mexico State, Pennsylvania, Texas, Texas A. & M.
Lead physicist: Kirmanos (Texas)
Status: Data-taking completed in August, 1988. Data being analyzed at Texas; theoretical analysis being carried out at GWU and Texas A. & M. Invited paper presented at KEK (Japan), 1990.

The cross sections for pi$^+$- elastic scattering on $^{12}C$, $^{16}O$, $^{40}Ca$, $^{90}Zr$, and $^{208}Pb$ were measured at 400 and 500 MeV, in the angular range 15 to 60 degrees. The measurements were carried out at the $P^3$ channel of LAMPF using the large acceptance spectrometer (LAS). Most of these data now have been analyzed. The theoretical analysis, being carried out both at GWU (Dhuga) and Texas A & M (Ernst), is based on the momentum-space optical-potential model of Ernst and Giebink. Shown in Fig. 5 are the differential cross-section data on $^{40}Ca$ along with the results of a first-order optical-potential calculation which includes the effect of D-waves in the pi-nucleon t-matrix. The theory, while in qualitative agreement with the data, overestimates the cross sections, particularly around the diffraction minima. This indicates the probable need for higher-order terms, such as Fermi motion and Pauli blocking. The contributions of these terms are being investigated.



40Ca(π+,π+)40Ca
Tπ = 500 MeV
40Ca(π−,π−)40Ca
Tπ = 500 MeV
dσ/dΩ (mb/sr)
Θcm (deg)


Figure 5

## III. COMPLETED EXPERIMENTAL PROGRAMS

### Proton Scattering (Berman)

A series of experiments on polarized and unpolarized proton-scattering measurements on the oxygen isotopes and beryllium was performed at IUCF and LAMPF, in collaboration with the MIT group of W. Bertozzi. The analysis of all of these data has been completed, and all are being prepared for publication under the direction of J.J. Kelly at Maryland. This year one paper was published and three others submitted for publication, all in Phys. Rev. C.

### Photonuclear Reactions (Berman, Zubanov)

A series of measurements of the photoneutron and photoproton cross sections for the C-N-O nuclei, one or two nucleons removed from a closed shell or subshell, was performed at LLNL and Melbourne, in collaboration with colleagues from Toronto, Trent, Saskatchewan, and Melbourne. The analysis of these data has been completed. The last three papers in this long series, on $^{14}$C(gamma,p), $^{17}$O(gamma,p), and $^{18}$O(gamma,pn), have been submitted to Phys. Rev. C.

### Pion Scattering and Reactions (Dhuga)

Several experiments on pion elastic scattering, (pi,2p) reactions, and charge exchange have been performed at LAMPF, in collaboration with physicists at Pennsylvania, New Mexico State, and elsewhere. The analysis of these data is complete. One paper has been accepted for publication in Phys. Rev. C. this year, another has been submitted, and a third is in preparation.

### Other Nuclear Physics (Berman)

A number of low-energy nuclear physics experiments have been performed on radiative capture and electrofission reactions. This year, three papers on these topics have been published, and the last (on coincidence electromagnetic dissociation of 2-GeV/nucleon $^{16}$O nuclei) is in preparation.

## IV. THE GWU NUCLEAR DETECTOR LABORATORY AND CENTER FOR NUCLEAR STUDIES

### The GWU Nuclear Detector Laboratory (NDL)

In the last two years the University has spent over $400,000 on the reconstruction and furnishing of the basement of Corcoran Hall for our new Nuclear Detector Laboratory (NDL). The NDL consists of a computer room, a test laboratory, a machine shop, a special room to house a wire-winding machine, and an electronics shop, along with two small offices for graduate students. The work was completed in May 1989, and the GWU Nuclear Physics Group finally moved into the NDL in the summer of 1989.

During the last year, we have relocated our MicroVax computer along with peripherals (such as a tape drive, a laser printer, and two terminals) to the NDL, and we have set up the test laboratory and the electronics shop. One student has already completed her M.S. thesis and another is doing so this year.

The main activities in the NDL will center around two major experimental projects:

a) The MWPC-based neutron detector, and

b) The focal-plane detector array for the Photon Tagger facility at CEBAF.

The DOE University Research Instrumentation Program has provided funding for the dedicated start-up instrumentation needed for the development and construction of a MWPC-based neutron detection system. (The principal investigator is Dhuga.) The DOE awarded the total requested amount of $146,041, to which GWU added $36,510, for a total of $182,551, to be spent over a period of two years towards the development and construction of the neutron detector.

We are currently planning a program of (e,e'n) measurements on few-body nuclei, to be mounted at NIKHEF (Amsterdam), or possibly at MIT (Bates). For these measurements we intend to employ a hydrogen-recoil detection system which will detect knockout protons having energies between 30 and 150 MeV. The detector will consist of an array of slabs or cylinders of hydrogenic material, or possibly liquid hydrogen, for neutron-to-proton conversion, and MWPC planes for detection and tracking of the recoil protons. The group leader for this project is Dhuga; significant contributions are expected from all GWU experimental faculty, namely, Berman, Briscoe, Dodge, Mokhtari, and Taragin, along with contributions from several graduate students, including Dragic and Caress (this will be the subject of her M.S. thesis). We have set up a collaboration with Dr. Thomas Bauer and his group at the University of Utrecht for all phases of the detector design and construction. His group is funded at a level comparable to ours.

The initial stage of this project, consisting of kinematic and Monte-Carlo studies of the (e,e'n) reaction, using computer codes MCNP and GEANT to ascertain the overall parameters of the detection system, has already begun, and several designs are being evaluated. We have made some progress along the hardware front as well. A gas-handling system has been designed and is being implemented by one of our graduate students, Dalong Pang. Also, we have acquired a MWPC (from LAMPF) with the aim of evaluating it as a possible prototype for the neutron detector. This project will form part of the Master's thesis of Rebecca Caress.

The other major experimental project is the focal-plane detector array for the Photon Tagger facility at CEBAF. This project is being led by Briscoe, but again significant contribution of time and effort is expected from all experimental faculty, along with contributions from graduate and undergraduate students.

The GWU group has formed a large collaboration which includes physicists at Catholic University, Arizona State University, the Universities of Virginia and South Carolina, and CEBAF to undertake a program of measurements of the photoproduction of vector mesons on nucleons and few-body nuclei. These measurements will utilize the CEBAF Large-Acceptance Spectrometer (CLAS), in conjunction with the monochromatic photon beam from tagged bremsstrahlung. In connection with this proposal, the task of the GWU group is to design, develop, and build the focal-plane detector array for the photon tagger. Initial design considerations call for a 256-channel overlapping scintillator array. Details concerning the choice of phototubes, bases, light pipes, discriminators, and associated electronics are being determined at present. A number of preliminary laboratory tests have been carried out at the NDL.

The New GWU Center for Nuclear Studies (CNS)

As part of its continuing strong commitment to nuclear physics research, the GWU administration has agreed to the proposal (put forward by the Physics Department) to establish on campus a Center for Nuclear Studies (CNS). In fact, the proposal has reached the stage of a line item in the budget, and has been funded at the level of $67,000 for the first year (1990-91). This is sufficient to hire a technician, as well as to support two Graduate Research Assistants in experimental nuclear physics (Pang and Nagata).

It is understood at the outset that the technician would devote all of his time to nuclear research projects. In fact, the first project that the technician would tackle is the wire-winding machine for which we recently received funding.

Moreover, the expected growth of the CNS over the next few years, in addition to providing a framework and infrastructure for our nuclear physics research program, will add considerable institutional weight to that effort.

## V. LOOKING TOWARDS CEBAF

Although CEBAF-related activities have not yet had a major impact in terms of time spent away from our other research programs, this is progressively becoming less so. This year, we attended several meetings and workshops, especially those related to CLAS and the photon tagger. We have spent some time, and will spend considerably more, on the design, construction, and testing of the photon-tagger detector system at our NDL. One of us (Berman) has served on the advisory committee for the HUGS at CEBAF Summer School since its inception four years ago, last year was elected to the Board of Directors of the CEBAF Users' Group, and will spend his sabbatical year (1991-92) at CEBAF. Very likely a postdoctoral research scientist and possibly a student will join him there.

## VI Publications, 1989-90

### A. Medium-Energy Nuclear Structure

1. D.M. Manley, D.J. Milliner, 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, and C.P. Sargent
   Electroexcitation of Rotational Bands in $^{18}O$
   Phys. Rev. C 41, 448 (1990)

2. J.J. Kelly, J.M. Finn, W. Bertozzi, T.N. Buti, F.W. Hersman, C.E. Hyde-Wright, M.V. Hynes, M.A. Kovash, B. Murdock, P. Ulmer, A.D. Bacher, G.T. Emery, C.C. Foster, W.P. Jones, D.W. Miller, and B.L. Berman
   Effective Interactions and Nuclear Structure Using 180-MeV Protons. I: $^{16}O(p,p')$
   Phys. Rev. C 41, 2504 (1990)

3. B.L. Clausen, R.A. Lindgren, M. Farkondeh, L.W. Fagg, D.I. Sober, C.W. de Jager, H. de Vries, N. Kalantar-Nayestanaki, B.L. Berman, K.S. Dhuga, J.A. Carr, F. Petrovich, and P.E. Burt
   Electroexcitation of $6^-$ States in $^{32}S$
   Phys. Rev. Lett. 65, 547 (1990)

4. P.A. Seidl, M.A. Bryan, M. Burlein, G.R. Burleson, K.S. Dhuga, H.T. Fortune, R. Gilman, S.J. Greene, M.A. Machuca, C.F. Moore, S. Mordechai, C.L. Morris, D.S. Oakley, M.A. Plum, G. Rai, M.J. Smithson, Z.F. Wang, D.L. Watson, and J.D. Zumbro.
   Pion double charge exchange on T = 2 nuclei in the $\Delta$ resonance region
   Phys. Rev. C (in press)

5. 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 (submitted)

6. 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. Milliner
   Electroexcitation of Negative-Parity States in $^{18}O$
   Phys. Rev. C (submitted)

Abstracts

7. R.M. Sellers, D.M. Manley, R.A. Lindgren, B.L. Clausen, M. Farkhondeh, B.E. Norum, R.J. Peterson, B.L. Berman, and C.E.Hyde-Wright
Electroexcitation of $4^-$ and $6^-$ States in $^{18}O$
Bull. Am. Phys. Soc. 35, 927 (1990)

B. Few-Body Nuclei

1. G.M. Hale, D.C. Dodder, J.D. Seagrave, B.L. Berman, and T.W. Phillips
Neutron-Triton Cross Sections and Scattering Lengths Obtained from p-$^3$He Scattering
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2. K. Maeda, C.L. Blilie, R.L. Boudrie, G.R. Burleson, W.B. Cottingame, D. Dehnhard, K.S. Dhuga, J.A. Faucett, M. Garakhani, S.J. Greene, N. Hiroshige, M.K. Jones, L-P. Lung, C.F. Moore, C.L. Morris, S. Mordechai, H. Ohnuma, A.L. Williams, J.W. McDonald, P.A. Seidl, S. Nanda, S.J. Seestrom-Morris, and J.D. Zumbro
Pion Elastic Scattering from Deuterium at Large Angles
Phys. Rev. C (submitted)

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Electron Scattering from $^9$Be
Phys. Rev. C (submitted)

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
Spectrum of $^9$Be from Proton Scattering
Phys. Rev. C (submitted)

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 $\pi^+$ and $\pi^-$ Elastic Scattering from $^3$H and $^3$He: Evidence for Charge-Symmetry Violation
Phys. Rev. C (submitted)

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Reaction Mechanism and Spectroscopic Results of the (e,e'd) Reaction
Proc. Particles and Nuclei Int. Conf. (Cambridge, MA, 1990)

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Charge-Symmetry Breaking in $\pi^+$ and $\pi^-$ Elastic Scattering from $^3H$ and $^3He$
Proc. Particles and Nuclei Int. Conf. (Cambridge, MA, 1990)

<u>Abstracts</u>

8. D. Zubanov, B.L. Berman, W.J. Briscoe, K.S. Dhuga, A. Mokhtari, M.F. Taragin, H.P. Blok, R. Ent, T.S. Bauer, E. Jans, L. Lapikas, and P.K.A. de Witt Huberts
The $^6Li(e,e't)^3He$ Reaction
Bull. Am. Phys. Soc. <u>35</u>, 927 (1990)

9. S.K. Matthews, B.L. Berman, W.J. Briscoe, R.W. Caress, K.S. Dhuga, S.N. Dragic, D. Knowles, D. Macek, A. Mokhtari, N.J. Nicholas, M.F. Taragin, A. Donley, L.D. Isenhower, K. Powell, M.E. Sadler, D.B. Barlow, B.M.K. Nefkens, J. Price, W.R. Gibbs, B.F. Gibson, S. Greene, and I. Supek
Elastic Pion Scattering from $^3H$ and $^3He$ at Backward Angles
Bull. Am. Phys. Soc. <u>35</u>, 945 (1990)

10. D. Zhang, H. Breuer, N.S. Chant, B.S. Flanders, S.D. Hyman, M.A. Khandaker, D.J. Mack, P.G. Roos, J.D. Silk, K.S. Dhuga, G.S. Kyle, M. Wang, P.A. Amaudruz, C.H.Q Ingram, R.A. Schumacher, U. Sennhauser, J. Jacob, B.G. Ritchie, D. Rothenberger, J. McDonald, and A. Williams.
Study of Energy Dependence of the $^6Li(\pi^+,2p)$ Reaction around the $\Delta(1232)$ Resonance Region.
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Reaction Mechanism and Spectroscopic Results of the (e,e'd) Reaction
Verhandl. Deutsche Phys. Ges. (1990)

C. Low-Energy Nuclear Physics

1. J.D.T. Arruda-Neto, S. Simionatto, S.B. Herdade, Z. Carvalheiro, M.L. Yoneama, and B.L. Berman
Electrofission of $^{233}U$
Physica Scripta 40, 735 (1989)

2. D. Vartsky, M.B. Goldberg, G. Engler, A. Goldschmidt, A. Breskin, R.E. Morgado, C. Hollas, L. Ussery, B.L. Berman and C. Moss
The Total Width of the 9.17-MeV Level in $^{14}N$
Nucl. Phys. A505, 328 (1989)

3. D. Zubanov, M.N. Thompson, B.L. Berman, J.W. Jury, R.E. Pywell, and K.G. McNeill
Photoproton Cross Section for $^{17}O$
Phys. Rev. C (submitted)

4. K.G. McNeill, J.W. Jury, M.N. Thompson, B.L. Berman, and R.E. Pywell
The $^{18}O(\gamma,pn+np)$ Cross Section
Phys. Rev. C (submitted)

5. D. McLean, M.N. Thompson, D. Zubanov, K.G. McNeill, J.W. Jury, and B.L. Berman
Photoproton Cross Section for $^{14}C$
Phys. Rev. C (submitted)

## VII. TABLES

A. Shell-Model Nuclei

1. Recent Experiments: Table I
2. Pending and Planned Experiments: Table II

B. Few-Body Nuclei

1. Recent Experiments: Table III
2. Pending and Planned Experiments: Table IV

C. References to Tables

Table I. 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 | Data analyzed, one paper published, one in preparation | 1 |
| $^{12}C$, $^{16}O$, $^{40}Ca$ (pi+-,pi+-) | LAMPF-EPICS* | Excitation functions at large angles, medium modifications | Data analyzed, two papers published, one in preparation | 2 |
| $^{12}C$, $^{16}O$, $^{40}Ca$, $^{48}Ca$, $^{90}Zr$, $^{208}Pb$ (pi+-,pi+-), (pi+-,pi+-') | LAMPF-P$^3$* | Exploratory (300-500 MeV); test of optical models | Data analyzed invited paper presented, paper in preparation | 3 |
| $^{13}C(p,gamma)$ | LANL | Resonance width | Published | 4 |
| $^{14}C(gamma,p)$ | Melbourne | Isospin structure | Submitted for publication | 5 |
| $^{16}O(e,e')$ | Bates | High-excitation, isovector states | Data analyzed | 6 |
| $^{16}O(\vec{p},p')$ | IUCF | 180-MeV cross sections and analyzing powers, comparison with (e,e') | Published | 7 |
| $^{16}O(\vec{p},p')$ | LAMPF-HRS | 318-MeV excited-state cross sections, analyzing powers | Submitted for publication | 8 |
| $^{16}O(\vec{p},\vec{p}')$ | LAMPF-HRS | 498-MeV excited-state cross sections, spin-rotation parameters | Data analyzed, paper in preparation | 9 |
| $^{16}O$ Dissociation | Bevalac* | Electromagnetic dissociation into $^{15}N$+p (coincidence experiment) | Data analyzed, paper in preparation | 10 |
| $^{17}O(gamma,p)$ | LLNL* | Isospin structure | Submitted for publication | 11 |
| $^{17,18}O(p,p')$ | IUCF | 135-MeV cross sections, comparison with (e,e') | Data analyzed, two papers in preparation | 12 |

* Spokesman or co-spokesman

Table I. Recent Studies of Selected Shell-Model Nuclei with Electromagnetic and Hadronic Probes (continued)

| Reaction | Laboratory | Physics Emphasis | Status | Reference |
|---|---|---|---|---|
| $^{18}O$(gamma, pn) | LLNL* | Isospin structure | Submitted for publication | 13 |
| $^{18}O$(e,e') | Bates | States up to 15 MeV, validity of weak-coupling model | One paper published, one submitted for publication | 14 |
| $^{18}O$(e,e') | Bates | Stretched-spin states; isospin structure | Data analyzed, paper in preparation | 15 |
| $^{28,29,30}Si$,$^{31}P$(e,e) | Mainz | Charge distributions | Data analyzed | 16 |
| $^{30}Si$(e,e') | Bates* | Stretched-spin states | Data analyzed | 17 |
| $^{32}S$(e,e') | NIKHEF* | $6^-$ states, stretched-spin strength | Published | 18 |

* Spokesman or co-spokesman

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

| Reaction | Laboratory | Physics Emphasis | Status | Reference |
|---|---|---|---|---|
| $^{16}O(pi^+,pi^-)^{16}Ne$ | LAMPF-EPICS* | Interference effects in double charge exchange | Approved, not yet scheduled | 19 |
| $^{17}O(e,e)$ | Bates | Magnetization distribution at very high q, meson-exchange currents | Approved, not yet scheduled | 20 |
| $^{21}Ne,^{23}Na(e,e')$ | Bates* | Low-lying states, collective bands | Approved, to be performed in 1991 | 21 |

* Spokesman or co-spokesman

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

| Reaction | Laboratory | Physics Emphasis | Status | Reference |
|---|---|---|---|---|
| $^{3}H$,$^{3}He$(pi+-,pi+-), (pi+-,pi+-') | LAMPF-EPICS | 142- to 220-MeV cross sections, form factors, charge asymmetry | One paper published, one submitted for publication, one in preparation | 22 |
| $^{3}H$,$^{3}He$(pi+-,pi+-) | LAMPF-EPICS* | 180- to 295-MeV cross sections, form factors, charge asymmetry, spin-flip amplitudes | Data analyzed, paper in preparation | 23 |
| $^{3}H$,$^{3}He$(pi+-,pi+-) | LAMPF-EPICS* | 180° cross sections, 142 to 256 MeV, form factors, non-spin-flip amplitudes | Data being analyzed | 24 |
| $^{3}H$,$^{3}He$(pi+-,pi+-) | LAMPF-EPICS* | 180-MeV cross sections and angular distribution, charge asymmetry | Data being analyzed | 25 |
| $^{3}H$(n,tot) | LLNL* | Comparison with $^{3}He$(p,tot), charge asymmetry, scattering lengths | Published | 26 |
| $^{6}Li$(e,e'd) | NIKHEF | Spectral functions, q-dependence | Data analyzed, one paper published, one in preparation | 27 |
| $^{6}Li$(e,e'alpha) | NIKHEF | n-p momentum distributions, validity of three-body model | Data analyzed, paper in preparation | 28 |
| $^{6}Li$(e,e't) | NIKHEF* | Momentum distributions, reaction mechanism, q-dependence | Data analyzed, paper in preparation | 29 |
| $^{6}Li$(pi+,2p) | PSI | Energy dependence near the delta resonance | Data analyzed, paper in preparation | 30 |
| $^{9}Be$(e,e') | Bates | Broad low-excitation states, discovery of new state | Submitted for publication | 31 |
| $^{9}Be$($\vec{p}$,p') | IUCF | 135- and 180-MeV cross sections and analyzing powers, comparison with (e,e') | Submitted for publication | 32 |

* Spokesman or co-spokesman

Table III. Recent Studies of Few-Body Nuclei with Electromagnetic and Hadronic Probes (continued)

| Reaction | Laboratory | Physics Emphasis | Status | Reference |
|---|---|---|---|---|
| $^{9}Be(\vec{p},p'),(\vec{p},\vec{p}')$ | LAMPF-HRS | 318- and 498-MeV cross sections and spin observables, comparison with (e,e') | Data analyzed | 33 |

Table IV. Pending and Planned Studies of Few-Body Nuclei with Electromagnetic and Hadronic Probes

| Reaction | Laboratory | Physics Emphasis | Status | Reference |
|---|---|---|---|---|
| $^{3}$He, $^{4}$He $(\gamma,\rho)$, $(\gamma,\omega)$, $(\gamma,\phi)$ | CEBAF* | Modification of elementary amplitudes in the nuclear medium | Letters of Intent submitted, proposal being prepared | |
| $^{3}$H, $^{3}$He(pi+-,pi$^{0}$) | LAMPF-LEP* | Charge exchange, $T_{pi}$=50 MeV | Proposal being prepared | |
| $^{3}$He(e,e't), (e,e'$^{3}$He) | NIKHEF | Virtual-photon production of pi$^{+}$, pi$^{0}$ | Proposal to be prepared | |
| $^{3}$He(e,e'n) | NIKHEF* | Reaction mechanism, three-body breakup | Proposal to be prepared | |
| $^{4}$He(e,e'n) | NIKHEF* | Reaction mechanism, charge asymmetry | Proposal to be prepared | |
| $^{6}$Li(e,e'$^{3}$He) | NIKHEF* | Momentum distributions, reaction mechanism, validity of two-body model | Approved, to be performed in 1990 | 34 |
| $^{6}$Li(e,e'n) | NIHKEF* | Reaction mechanism(s), validity of three-body model | Proposal to be prepared | |

* Spokesman or co-spokesman

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15. R.M. Sellers et al., to be submitted to Phys. Rev. C; see R.M. Sellers et al., Bull. Am. Phys. Soc. 35, 927 (1990).

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## Appendix: Reprints and Preprints, 1989-90


Reprints:

1. D.M. Manley et al., Phys. Rev. C 41, 448 (1990)
2. J.J. Kelly et al., Phys. Rev. C 41, 2504 (1990)
3. B.L. Clausen et al., Phys. Rev. Lett. 65, 547 (1990)
4. G.M. Hale et al., Phys. Rev. C. 42, 438 (1990)

Preprints:

1. P.A. Seidl et al., Phys. Rev. C (in press)
2. J.J. Kelly et al., submitted to Phys. Rev. C
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6. C. Pillai et al., submitted to Phys. Rev. C
7. K.S. Dhuga et al., Proc. Particles and Nuclei Int. Conf.

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