A PROGRAM IN MEDIUM-ENERGY NUCLEAR PHYSICS

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I. OVERVIEW

Since the beginning of this program in Medium-Energy Nuclear Physics in 1986, as well as throughout the duration of the program of Electron and Proton Scattering from Nuclei conducted by the present principal investigator that preceded it (1978-85), we have attempted to perform nuclear-physics measurements that would throw light on the understanding of the strong interaction in the nuclear medium, whatever the language used to describe it--medium modifications, density dependence, or many-body (specifically, three-body) forces. We continue to believe that this is arguably the most fundamental problem in nuclear physics, shy of the understanding of the (well-studied) strong two-body force itself. Now, the roots of this problem seem to lie deeper, in the quark-gluon substructure of the nucleons and mesons. But whether or not it is necessary to invoke QCD to explain the low-energy behavior of nucleons in nuclei, it has become increasingly clear that the nuclear three-body force is of shorter range than the two-body force, and that in order to enhance its effects in the laboratory, it is necessary to use shorter-range probes than were available just a few years ago. We need to use shorter-wavelength photons, both real and virtual, we need to study short-range correlations of strongly interacting particles in the nucleus, and we need to produce and to scatter mesons more massive than the pion. Thus, we need to combine higher-energy and longer-duty-factor accelerators with efficient, large-acceptance detectors capable of viewing multiparticle final states,

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including neutral particles. Finally, in the light of recent experimental evidence, the spin and strangeness quantum numbers have taken on increased importance, and appropriate polarization and associated-production measurements are necessary to elucidate their effects in nuclei.

In keeping with these general considerations, we are continuing to focus on nuclear-medium effects, while our emphasis continues to shift 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 coincidence and to multiparticle measurements. In particular, we are greatly increasing our efforts on coincidence electron-scattering studies, notably $(e,e'n)$ measurements at NIKHEF, and on CEBAF-related studies, notably those with real photons at the CEBAF Large-Acceptance Spectrometer. For the former, we are collaborating in the design and construction of a novel type of neutron detector and polarimeter based on proton recoil and tracking, and for the latter, of the Photon Tagger and the polarized-photon beam for the CLAS. During the next three years, we are planning to place most of our effort into measurements of the $(e,e'n)$ and $(e,e'pn)$ processes on ^3He and ^4He at NIKHEF and in the experimental design and instrumentation for the photoproduction of strange particles and vector mesons on ^1H and ^2H at CEBAF, to be followed in future years by key photoproduction experiments on ^4He and ^3He , eventually on ^3H , and possibly on ^{238}U (as a means of approximating nuclear matter). Our proposed program is presented in detail in Sec. II.

Our future program builds upon our past and present research in medium-energy nuclear physics, which is discussed in some detail in Sec. III. Since 1989 we have published 18 papers and 11 abstracts on our work on electron, proton, and pion scattering, including eight articles and two abstracts since our last progress report

ten months ago. Section V lists our nuclear-physics publications since 1989, Appendix A consists of the eight reprints and four preprints that have appeared since our last progress report, Appendix B consists of five experimental proposals submitted in 1991, and all of our publications for the last five years are listed following our curricula vitae in Appendix C. We have participated in 11 experiments at Bates, LAMPF, and NIKHEF during this period (as spokesmen or co-spokesmen for all but two), and will continue with six more currently approved experiments at these facilities (as co-spokesmen for three). For the longer term, we are part of the Hall B Collaboration at CEBAF, and we plan to participate in many of the experiments to be conducted at that facility during the first few years of its operation.

We continue to enjoy firm institutional backing and generous financial support from The George Washington University (discussed, along with related matters, in Sec. IV) as well as the stimulating collaboration of our colleagues in experimental and theoretical nuclear physics at GWU. These fruitful associations enable us to look forward together to becoming major contributors to the new and exciting nuclear physics to be learned at the new accelerator facilities in the coming years.

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III. PRESENT RESEARCH PROGRAM

In keeping with our greatly increased emphasis on coincidence measurements on few-body nuclei with electromagnetic probes, we are phasing out our previous and present programs on singles measurements on shell-model nuclei (with both hadronic and electromagnetic probes).

Table I, which appears at the end of this section, lists three measurements on shell-model nuclei that are still pending. The first of these, the study of large-angle proton emission from medium-energy neutrons incident on carbon, is being done primarily to provide information necessary for the design of the neutron detector: can it be made from polyethylene, or must liquid hydrogen be used for the neutron-to-proton converter (see the proposal, in Appendix B). Remarkably, no data exist for large angles, and very few data of any kind have been obtained for neutron energies above 60 MeV. Clearly, it is essential to know whether the large-angle interference from carbon would preclude the use of CH₂ for the converter, and soon--the experiment is scheduled to run at LAMPF-WNR in August, 1991.

The second entry in Table I, elastic electron scattering from ¹⁷O, is a holdover from long ago, and consists of the measurement of a single, high-q data point.

The third, inelastic electron scattering from ²¹Ne and ²³Na, is a high-priority nuclear-structure experiment which should have been performed this year, but because of limited running time and scheduling problems at Bates will not be performed until 1992.

Tables II and III, which also appear at the end of this section, list our recent studies of shell-model and few-body nuclei, respectively. These tables update our research activities since our last progress report (October, 1990). Details of many of the entries in these tables are described below.

A. MEASUREMENTS WITH ELECTROMAGNETIC PROBES

1. Singles Electron Scattering at Bates and NIKHEF

Our program of high-resolution single-arm electron-scattering measurements at the Bates accelerator, performed in collaboration with the MIT group of W. Bertozzi, dates from 1976, when ELSSY was first commissioned. Over a period of several years, the longitudinal and transverse form factors for all of the narrow states up to about 20 MeV in all of the oxygen isotopes and beryllium were measured in great detail. Three of the long series of papers describing this work were published within the last year, and the last is in preparation. This program led to a more specialized series of measurements of the transverse form factors for stretched magnetic transitions for selected nuclei in the 2s-1d shell, namely, ^{18}O , ^{30}Si , and ^{32}S . These are described below.

A. STRETCHED M4 AND M6 EXCITATIONS IN ^{18}O (BATES 86-11)

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 $^{17}\text{O}(\alpha, ^3\text{He})^{18}\text{O}$ reaction. These results were reported at an APS meeting last year (Sep90) and are being prepared for publication.

B. STRETCHED M6 EXCITATIONS IN ^{30}Si (BATES 82-08)

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 (see below) 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. Unfortunately, although the data we have obtained to date are of high quality, they are insufficient to determine the spins unambiguously--data at another value of momentum transfer are needed. We would like to complete this experiment in the very near future.

C. STRETCHED M6 EXCITATIONS IN ^{32}S (NIKHEF 88-E5)

Nine possible isovector M6 transitions were identified in ^{32}S , exhausting 40-51% of the sum-rule strength (Cla90). Figure 5 shows the transverse form factors of the nine 6^- states identified. This is the first observation of substantially fragmented isovector electromagnetic stretched strength in a self-conjugate nucleus. A recent shell-model study (Car89) indicates increased fragmentation of isovector M6 strength for ^{32}S , but fails to give a detailed reproduction of the new data.

D. GROUND-STATE ROTATIONAL-BAND TRANSITIONS IN ^{21}Ne AND ^{23}Na (BATES 88-18)

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

Figure 5 M6 form factors for ^{32}S .

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 .

2. Coincidence Electron Scattering at NIKHEF

We have participated for a number of years in high-resolution inelastic electron-scattering measurements at the NIKHEF accelerator, where a charged particle (or cluster) is detected in coincidence with the scattered electron. In particular, we have collaborated with the coincidence group at NIKHEF in a series of $(e, e'd)$ measurements on ^6Li and ^{12}C (Ent86, Ent89). More recently, we have collaborated in $(e, e'^3\text{H})$ and $(e, e'^3\text{He})$ coincidence experiments on ^6Li . This program of measurements addresses several issues, including the cluster-knockout reaction mechanism, the strength of final-state interactions, and most importantly, testing the cluster model of ^6Li formulated by the GWU theory group (see, e.g., Leh82 and Chr88).

A. $^6\text{Li}(e, e'\alpha)$ AND THE α -KNOCKOUT PROCESS (NIKHEF 86-E)

This experiment was performed at the electron-scattering facility of NIKHEF-K using the high-resolution electron and hadron spectrometers (Mit91). The α particles

were knocked out by 537-MeV incident electrons and were detected with resolution sufficient to separate, for the first time, the ${}^2\text{H}$ 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 bound ${}^2\text{H}$ final state, as a function of momentum transfer, follows the $e\text{-}\alpha$ cross section, after correcting the latter for distortions. This implies that the reaction process is consistent with a quasielastic mechanism. Moreover, the cross section for the pn breakup follows the free $e\text{-}\alpha$ cross section as well, indicating that the quasielastic scattering mechanism for the ${}^6\text{Li}(e, e'\alpha)\text{pn}$ reaction also is an appropriate description, as predicted by the calculation of Lehman and Rajan (Leh82), using a repulsive $\alpha\text{-d}$ wave function. One might think that two-step processes might be more important for this reaction than for the reaction leading to the bound ${}^2\text{H}$ final state, but our results show that these, as well as any other rescattering mechanisms are unimportant.

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

B. ${}^6\text{Li}(e, e't)$ AND THE ${}^3\text{H}\text{-}{}^3\text{He}$ CLUSTER MODEL OF ${}^6\text{Li}$ (NIKHEF 88-E1, PART 1)

Data for the ${}^6\text{Li}(e, e't){}^3\text{He}$ reaction were taken in parallel kinematics at an incident electron energy of 523 MeV. Knockout tritons were detected using the standard detection system (four wire chambers and $\Delta E\text{-}E$ scintillators) 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 $t\text{-}{}^3\text{He}$ center-of-mass energy T_{cm} from 16.5 to 33 MeV. For the measurement of the

Figure 6 The alpha-d momentum distribution extracted from the ${}^6Li(e,e'\alpha)$ reaction compared with that extracted from the complementary ${}^6Li(e,e'd)$ reaction.

t - ^3He momentum distribution, the range in missing momentum covered was $30 < p_m < 180$ MeV/c, taken mostly at $T_{\text{cm}} = 33$ MeV. Also, transitions to the pd and n2p breakup states were recorded over a 20-MeV interval; these channels open at 5.5 and 7.7 MeV, respectively.

The results show that the q -dependence for the $^6\text{Li}(e, e't)^3\text{He}_{\text{gs}}$ reaction is the same as that for the $^6\text{Li}(e, e't)\text{pd}/^6\text{Li}(e, e't)\text{n2p}$ breakup reactions. It is not yet clear whether this dependence follows the e - t off-shell cross section, since the calculation of final-state interactions between the knockout triton and the ^3He final state has not yet been carried out. The reason for this is that a good set of optical-model parameters for the t - ^3He system is not available from experiment. In the 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 ^3He 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 e - t cross section, which finally can be compared with model predictions and data from other studies of ^6Li . Figure 7 shows the q -dependence of the $^6\text{Li}(e, e't)^3\text{He}_{\text{gs}}$ reaction, compared with that for the free e - ^3H cross section.

c. $^6\text{Li}(e, e'^3\text{He})$ AND THE ^3H - ^3He CLUSTER MODEL OF ^6Li (NIKHEF 88-E1, PART 2)

This experiment explores the behavior of the charge-symmetric $^6\text{Li}(e, e'^3\text{He})$ reaction. Since distortions and final-state interactions should cancel in the ratio of the $(e, e'^3\text{He})$ 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 ^6Li first suggested in (Ber65).

Figure 7 The q -dependence of the ${}^6\text{Li}(e,e't){}^3\text{He}(\text{gs})$ reaction, compared with that for the free e - t cross section (solid line) and with that for bound ${}^3\text{H}$ and ${}^3\text{He}$ clusters (dashed line).

This experiment involved the detection of ^3He particles under circumstances where each ^3He was accompanied by about 10^5 protons (and lesser, but still large, numbers of deuterons, tritons, and α particles), and arguably was the most difficult measurement ever carried out successfully at NIKHEF. The data were obtained last year, and have been analyzed to the point where they are ready to be reduced to cross sections. The data were taken at an incident electron energy of 484.5 MeV, in parallel kinematics. The scattered electrons were detected in the QDD spectrometer with its standard focal-plane detector. The knockout ^3He 's were detected in the QDQ spectrometer with a low-pressure position-sensitive detector. This detector consists of a time-projection chamber and a thin scintillator. Particle identification is accomplished by an ΔE -E technique, where ΔE comes from the grid and E comes from the scintillator.

The calibrations for ΔE and E were performed via overconstrained $^3\text{He}(e, e'^3\text{He})$ elastic-scattering measurements at $T_{^3\text{He}} = 17, 27, 37, \text{ and } 47 \text{ MeV}$. For the q-dependence studies of the $^6\text{Li}(e, e'^3\text{He})$ reaction, data were taken at fixed missing momentum $P_m = 75 \text{ MeV}/c$ and $^3\text{H}-^3\text{He}$ center-of-mass energy $T_{\text{cm}} = 16.5, 22, 27.5, \text{ and } 33 \text{ MeV}$. For the $^3\text{H}-^3\text{He}$ missing-momentum distribution, two additional measurements were made, at $P_m \approx 25 \text{ MeV}/c$, $T_{\text{cm}} = 16.5 \text{ MeV}$ and $P_m = 125 \text{ MeV}/c$, $T_{\text{cm}} = 27.5 \text{ MeV}$. At each kinematic point every particle whose ratio of momentum divided by its electric charge is the same as the ratio for ^3He will also traverse the QDQ spectrometer. However, the kinetic energies of these particles, compared with that of the protons, must be $T_d = T_p/2$, $T_t = T_p/3$, $T_\tau = 4T_p/3$, and $T_\alpha = T_p$. The ionization energy losses are proportional to Z^2/β^2 , and, compared with that for the proton, are then $I_d = 4I_p$, $I_t = I_\tau = 9I_p$, and $I_\alpha = 16I_p$. Thus, a T-I correlation plot can be used for particle identification. This plot, for $P_m = 25 \text{ MeV}/c$, $T_{\text{cm}} = 16.5 \text{ MeV}$ is shown in Fig. 8.

Clearly, one can select the ^3He 's by setting an appropriate ΔE - E window around them. The effect of the window on the excitation-energy spectrum is shown in Fig. 9. As can be seen, use of the ΔE - E technique allows us to separate the ^3He 's from the deuterons, tritons, and α particles, and we are left with a clean peak, shown in Fig. 9b, on top of a smooth accidentals background, shown in Fig. 9a.

3. Photonuclear Reactions

The photoproton cross section for ^{18}O , measured at LLNL over 15 years ago (Ber76), provided one of the first clear indications of a nuclear-medium effect--that was later called core polarization. (This experiment in fact was the progenitor of the electron-scattering measurements on the oxygen isotopes performed at Bates.) In the following decade, a long 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 series, on $^{14}\text{C}(\gamma, p)$, $^{17}\text{O}(\gamma, p)$, and $^{18}\text{O}(\gamma, pn+np)$, were submitted to Phys. Rev. C this year; at the time of this writing, one has been published, and one is in press.

Figure 9 Missing-energy spectra for sample ${}^6\text{Li}$ ($e, e' {}^3\text{He}$) data:
 (a) accidental spectrum; (b) coincidence spectrum.

B. MEASUREMENTS WITH HADRONIC PROBES

There no longer is any question that one can learn more about a nuclear process by studying it in a coordinated way with two or more kinds of probes than by trying to interpret the data obtained with individual probes in isolation, as we have believed, and promoted, for many years. In keeping with this belief, we have attempted, over the years, to perform coordinated measurements with both electromagnetic and hadronic probes on certain selected nuclei, notably the trinucleons and the oxygen isotopes. Our recent work with hadronic probes is described below.

1. Pion Scattering at LAMPF

A. PION SCATTERING FROM FEW-BODY NUCLEI

We have concentrated our efforts mainly on pion elastic scattering from the $A=3$ nuclei. Essentially, the main aims of this program have been:

- a) To provide a basic and self-consistent data set on these fundamental cross sections, since they clearly are crucial for our understanding of pion interactions with more complex nuclei;
- b) To probe the matter distributions (or form factors) of the nucleons in these nuclei, since they are complementary to the charge and magnetization distributions measured by electron scattering, and to probe the neutron distribution in ^3H in particular, to which electron scattering is insensitive because the neutrons carry neither the charge nor the magnetic moment of ^3H ; and
- c) To test the magnitude and nature of charge-symmetry breaking (CSB) in these nuclei by measuring the charge-symmetric ratios

$$r_1 = \frac{d\sigma(\pi^+{}^3\text{H})}{d\sigma(\pi^+{}^3\text{He})}$$

$$r_2 = \frac{d\sigma(\pi^-{}^3\text{H})}{d\sigma(\pi^-{}^3\text{He})}$$

and their product, the "superratio" $R = r_1 r_2$. The energy and angle behavior of these ratios provides the signature for charge-symmetry breaking. The CS prediction for these ratios is unity.

In its simplest interpretation (barring the Coulomb force), CS implies the equality of the pp and nn interactions. In the formal language of isospin invariance, CS is associated with the sign change of the third component of isospin I_3 , as the multiplet is rotated through 180° about the I_2 axis in isospin space (Wil69, Mil90). Over the years ample evidence has been gathered demonstrating that the electromagnetic interaction alone is not sufficient to explain CSB, such as isospin-multiplet mass splittings, the binding-energy difference between ${}^3\text{H}$ and ${}^3\text{He}$, and the inequality of the nucleon-nucleon scattering lengths.

At the nucleon-nucleon level, CSB is interpreted in terms of meson mixing, i.e., ρ - ω and π^0 - η . However, at the more fundamental level of quarks and quantum chromodynamics, CSB is thought to arise directly from the mass difference between the up and down quarks and the electromagnetic interaction between them.

One of the main aims of the study of CSB is to relate the measured hadronic cross sections directly to the properties and interactions of the light quarks, in particular to their mass difference. This link should be possible through a systematic study (under favorable kinematic conditions) of light systems which can be characterized by the interchange of one or a few light quarks. The isomirror combinations $\pi^+{}^3\text{H}$ and $\pi^+{}^3\text{He}$ are good candidates for such a system. Of course, there are reservations to the simple interpretation of a deviation in

R from unity as an absolute indication of CSB in the hadronic process. At resonance energies the Δ plays a major role, specifically the Δ^- in $\pi^3\text{H}$ scattering and the Δ^{++} in $\pi^3\text{He}$. Quark-model calculations (Isg80, Bic82) give a mass difference of about 5 MeV between the two isobars, leading to a value of R not equal to one. If one believes that this mass difference is entirely due to Coulomb effects, then a deviation of R from unity also could be considered to be electromagnetic in nature.

The choice of the $A=3$ nuclei is further justified because of the considerable interest in the extraction and comparison of neutron and proton form factors via pion and electron scattering, theoretical interest in three-body forces (Fri84, Ber86), and the availability of good wave functions which can be used as input for realistic optical-potential calculations.

Particular kinematic regions of interest include the non-spin-flip (NSF) dip (about 78° in the lab on resonance) and large-angle scattering (up to and including 180°). In a rather simple single-scattering model that employs the impulse approximation, one can show that in the region of the NSF dip the spin-flip amplitude dominates the scattering, and that the ratio r_1 is proportional to the squared ratio of the odd-nucleon matter form factors of the trinucleons.

At angles far from the NSF dip (but still on resonance) the same model (coupled with isospin arguments) leads to the statement that r_2 is proportional to the squared ratio of the like-nucleon matter form factors of the trinucleons. Also, at angles near 180° , the spin-flip amplitude tends to zero and consequently the scattering is dominated by the non-spin-flip amplitude. Thus, by comparing the scattering in the NSF dip region (spin-flip dominated), with scattering near 180° (non-spin-flip dominated), one can extract meaningful information on the two scattering amplitudes without the use of a polarized target.

Following survey measurements (LAMPF 905) at three incident pion energies and five angles, all of which yielded values greater than unity for the superratio (Pil91), we mounted a series of three additional experiments of the same type, each exploring in depth a particularly sensitive kinematic region: the NSF dip (LAMPF 1032), the large-angle region (near 180°) (LAMPF 1064), and on resonance for the entire angular distribution (LAMPF 1155). The first of these experiments (at 256 MeV incident pion energy) uncovered values for R substantially smaller than unity. The final values for the "charge-symmetric" ratios r_1 , r_2 , and the superratio R for this case are shown in Fig. 10. Preliminary analysis of the other two experiments indicates that the charge-asymmetric result $R \neq 1$ continues to backward angles, far from the NSF dip.

Over the last several years a number of models have been put forward to explain the deviation of R from unity. For example, Kim, Krell, and Tiator (Kim86) predict that the observed CSB is mainly the result of Coulomb repulsion between the protons in ^3He . Werntz and Cannata (Wer86) suggest that the observed effect is due to the binding-energy difference of the paired nucleons in ^3H and ^3He . Kim, Kim, and Landau (Kim87) use the Coulomb distortion of the nuclear force to explain the qualitative behavior of R at 180 MeV. However, none of these theories fits the data at all angles.

Recently, Gibbs and Gibson (Gib90), using an optical-potential formalism, have analyzed the measured elastic differential cross sections at 180 MeV, and have extracted the difference between $r_p(^3\text{He})$ and $r_n(^3\text{H})$ 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 CSB effect beyond the Coulomb interaction. However, this same model does not predict correctly the behavior of R at 256 MeV.

Figure 10 Charge-symmetry ratios at 256 MeV.

B. PION SCATTERING FROM SHELL-MODEL NUCLEI

We have concentrated our efforts mainly in two kinematic regions: 300-500 MeV (i.e., above the Δ -resonance) and large-angle scattering at and around the Δ -resonance.

In the region above the Δ -resonance, we have measured differential cross sections for π^+ (and π^-) elastic scattering on ^{12}C , ^{16}O , ^{40}Ca , ^{90}Zr , and ^{208}Pb at 400 and 500 MeV, in the angular range from 15 to 60 degrees (LAMPF 1106). The measurements were carried out at the P^3 channel of LAMPF using a large-acceptance spectrometer. Some of these data have been analyzed at the University of Texas and the remainder are currently being analyzed at New Mexico State University and GWU. The theoretical analysis is being carried out mainly at GWU. Results of the preliminary analysis were presented by Dhuga in an invited paper at a recent pion-nucleus scattering workshop held at KEK (Japan).

The theoretical analysis is based on the momentum-space optical-potential model of Ernst and Giebink (Gie88). Shown in Fig. 11 are the elastic differential cross-section data on ^{40}Ca at 400 MeV, along with the results of a first-order relativistic optical-potential calculation which includes the effect of D-waves in the pion-nucleon t-matrix. The theory, while in qualitative agreement with the data, overestimates the cross sections, particularly around the diffraction minimum. The calculations include the effects of binding; also, the fermi-averaging procedure is carried out exactly. The nuclear structure of the ^{40}Ca ground state is parametrized in the form of a nuclear charge density obtained from the work of Negele (Neg70). The contributions from higher-order terms such as true pion absorption and Pauli blocking are currently under investigation.

We have explored another kind of nuclear-medium effect in our pion-scattering program on the shell-model nuclei at large angles. We have measured differential cross sections out to nearly 180° for π^+ scattering on ^{12}C , ^{16}O , ^{28}Si , and

Figure 11 Preliminary pion-elastic differential cross-section data on ^{40}Ca at 400 MeV, compared with the results of a first-order optical-potential calculation.

^{40}Ca at energies on, below, and above the Δ -resonance. Figure 12 shows the large-angle differential cross sections for ^{28}Si , together with the results of an optical-model calculation based on the delta-hole model in the local density approximation (Ern88). From these large-angle pion-scattering data we expect to extract the strength and the density dependence of the Δ -nucleus interaction, i.e., the spreading potential. Preliminary analysis indicates that the imaginary component of the spreading potential is substantially weaker than that found in previous work (Kar86). Were this result to persist for all the nuclei (and energies) under investigation, this work then would have considerable impact on the interpretation of the Δ -nucleus spreading potential--in particular, the relation of the imaginary component to true pion absorption on two nucleons.

2. Proton Scattering at IUCF and LAMPF

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. This series of experiments also had as its focus the delineation of the effects of the nuclear medium on the N-N interaction--in this case called the density dependence of the effective interaction (Kel80). By performing proton-scattering measurements on many states whose nuclear structure had already been defined by the electron-scattering measurements done at Bates, we have been able to parametrize in surprisingly simple terms this nuclear-medium effect (Kel89). The analysis of all of these data has been completed under the direction of J.J. Kelly at Maryland, and most have now been published. This year four papers were published, all in Phys. Rev. C.

Figure 12 Large-angle pion elastic data on ^{28}Si at 180 MeV, compared with a first-order optical-potential calculation.

References for Section III

- (Ber65) B.L. Berman et al., Phys. Rev. Lett. 15, 727 (1965)
- (Ber76) B.L. Berman et al., Phys. Rev. Lett. 36, 1441 (1976)
- (Ber86) The Three-Body Force in the Three-Nucleon System, eds. B.L. Berman and B.F. Gibson (Springer-Verlag, Heidelberg, 1986)
- (Bic82) R. Bickerstaff and A.W. Thomas, Phys. Rev D 25, 1869 (1982)
- (Car89) J.A. Carr et al., Phys. Rev. Lett. 62, 2249 (1989)
- (Chr88) C.T. Christou, D.R. Lehman, and W.C. Parke, Phys. Rev. C 37, 445 (1988)
- (Cla90) B.L. Clausen et al., Phys. Rev. Lett. 65, 547 (1990)
- (Ent86) R. Ent et al., Phys. Rev. Lett. 57, 2367 (1986)
- (Ent89) R. Ent et al., Phys. Rev. Lett. 62, 24 (1989)
- (Ern88) D.J. Ernst and K.S. Dhuga, Phys. Rev. C 37, 2651 (1988)
- (Fri84) J.L. Friar, B.F. Gibson, and G. Payne, Ann. Rev. Nucl. Part. Sci. 34, 4032 (1984)
- (Gib90) W.R. Gibbs and B.F. Gibson, Phys. Rev. C 43, 1012 (1991)
- (Gie88) D.R. Giebink and D.J. Ernst, Comp. Phys. Comm. 48, 407 (1988)
- (Isg80) N. Isgur, Phys. Rev. D 21, 779 (1980)
- (Kar86) B. Karaoglu and E.J. Moniz, Phys. Rev. C 33, 974 (1986)
- (Kel80) J. Kelly et al., Phys. Rev. Lett. 45, 2012 (1980)
- (Kel89) J.J. Kelly et al., Phys. Rev. C 39, 1222 (1989)
- (Kim86) Y.E. Kim, M. Krell, and L. Tiator, Phys. Lett. B172, 287 (1986)
- (Kim87) Kr.T. Kim, Y.E. Kim, and R.H. Landau, Phys. Rev. C 36, 2155 (1987)

- (Leh82) D.R. Lehman and Mamta Rajan, Phys. Rev. C 25, 2743 (1982)
- (Mil90) G. Miller, B.M.K. Nefkens, and I. Slaus, Phys. Rep. 194, 1 (1990)
- (Mit91) J.H. Mitchell et al., Phys. Rev. C (submitted)
- (Neg70) J.W. Negele, Phys. Rev. C 30, 1260 (1970)
- (Pil91) C.Pillai et al., Phys. Rev. C 43, 1838 (1991)
- (Sel90) R.M. Sellers et al., Bull. Am. Phys. Soc. 35, 927 (1990)
- (Wer86) C. Werntz and F. Cannata, in (Ber86), p. 391
- (Wil69) Isospin in Nuclear Physics, ed. D.H. Wilkinson (North-Holland, Amsterdam, 1969)

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^{12}\text{C}(n,p)$	LAMPF-MUR*	Large-angle proton emission	Scheduled for 1991	1
$^{17}\text{O}(e,e)$	Bates	Magnetization distribution at very high q , meson-exchange currents	Approved, not yet scheduled	2
$^{21}\text{Ne}, ^{21}\text{Ne}(e,e')$	Bates*	Low-lying states, collective bands	Approved, to be performed in 1992	3

* Spokesman or co-spokesman

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^{12}\text{C}(\text{e},\text{e}')^*$	NIKHEF	Spectral functions, q-dependence	Data analyzed, one paper published, one in preparation	4
$^{12}\text{C}, ^{16}\text{O}, ^{40}\text{Ca}$ (π^2, π^2)	LAMPF-EPICS*	Excitation functions at large angles, medium modifications	Data analyzed, two papers published, one in preparation	5
$^{12}\text{C}, ^{16}\text{O}, ^{40}\text{Ca},$ $^{48}\text{Ca}, ^{90}\text{Zr}, ^{208}\text{Pb}$ $(\pi^2, \pi^2), (\pi^2, \pi^2')$	LAMPF- p^3 *	Exploratory (300-500 MeV); test of optical models	Data analyzed, invited paper presented, paper in preparation	6
$^{14}\text{C}(\text{gamma}, \text{p})$	Melbourne	Isospin structure	Paper in press	7
$^{16}\text{O}(\text{e}, \text{e}')$	Bates	High-excitation, isovector states	Data analyzed	8
$^{16}\text{O}(\pi^+, \pi^-)^{16}\text{Ne}$	LAMPF-EPICS*	Interference effects in double charge exchange	Data being analyzed	9
$^{16}\text{O}(\text{p}, \text{p}')$	LAMPF-HRS	$^{318}\text{-MeV}$ excited-state cross sections, analyzing powers	Published	10
$^{16}\text{O}(\text{p}, \text{p}')$	LAMPF-HRS	$^{498}\text{-MeV}$ excited-state cross sections, spin-rotation parameters	Published	11
^{16}O Dissociation	Bevalac*	Electromagnetic dissociation into $^{15}\text{N}+\text{p}$ (coincidence experiment)	Submitted for publication	12
$^{17}\text{O}(\text{gamma}, \text{p})$	LLNL*	Isospin structure	Submitted for publication	13
$^{17}, ^{18}\text{O}(\text{p}, \text{p}')$	IUCF	$^{135}\text{-MeV}$ cross sections, comparison with (e, e')	Data analyzed, two papers in preparation	14

* Spokesman or co-spokesman

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^{18}\text{O}(\gamma, pn)$	LLNL*	Isospin structure	Published	15
$^{18}\text{O}(e, e')$	Bates	States up to 15 MeV, validity of weak-coupling model	Two papers published	16
$^{18}\text{O}(e, e')$	Bates	Stretched-spin states; isospin structure	Data analyzed, paper in preparation	17
$^{28,29,30}\text{Si}, ^{31}\text{P}(e, e)$	Mainz	Charge distributions	Data analyzed	18
$^{30}\text{Si}(e, e')$	Bates*	Stretched-spin states	Data analyzed, more data needed	19

* Spokesman or co-spokesman

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^3\text{H}, ^3\text{He}(\pi^{\pm}, \pi^{\pm}), (\pi^{\pm}, \pi^{\pm'})$	LAMPF-EPICS	142- to 220-MeV cross sections, form factors, charge asymmetry	Two papers published, one in preparation	20
$^3\text{H}, ^3\text{He}(\pi^{\pm}, \pi^{\pm})$	LAMPF-EPICS*	180- to 295-MeV cross sections, form factors, charge asymmetry, spin-flip amplitudes	Data analyzed, paper in preparation	21
$^3\text{H}, ^3\text{He}(\pi^{\pm}, \pi^{\pm})$	LAMPF-EPICS*	180° cross sections, 142 to 256 MeV, form factors, non-spin-flip amplitudes	Data being analyzed	22
$^3\text{H}, ^3\text{He}(\pi^{\pm}, \pi^{\pm})$	LAMPF-EPICS*	180-MeV cross sections and angular distribution, charge asymmetry	Data being analyzed	23
$^4\text{He}(\pi^{\pm}, \pi^{\pm})$	LAMPF-EPICS	Large-angle scattering, partial-wave analysis	Submitted for publication	24
$^6\text{Li}(e, e'd)$	NIKHEF	Spectral functions, q-dependence	One paper published, one in preparation	25
$^6\text{Li}(e, e'a)$	NIKHEF	n-p momentum distributions, validity of three-body model	Submitted for publication	26
$^6\text{Li}(e, e't)$	NIKHEF*	Momentum distributions, reaction mechanism, q-dependence	Data analyzed, paper in preparation	27
$^6\text{Li}(e, e'^3\text{He})$	NIKHEF*	Momentum distributions, reaction mechanism, validity of 2-body model	Data being analyzed	28
$^6\text{Li}(\pi^+, 2p)$	PSI	Energy dependence near the delta resonance	Data analyzed, paper in preparation	29

* Spokesman or co-spokesman

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
${}^9\text{Be}(e,e')$	Bates	Broad low-excitation states, discovery of new state	Published	30
${}^9\text{Be}(\vec{p},p')$	IUCF	135- and 180-MeV cross sections and analyzing powers, comparison with (e,e')	Published	31
${}^9\text{Be}(\vec{p},p'), \vec{p}, \vec{p}'$	LAMPF-HRS	318- and 498-MeV cross sections and spin observables, comparison with (e,e')	Data analyzed	32

References to Tables I-III

1. B. L. Berman et al., LAMPF-WNR Proposal (1991)
2. W. Bertozzi et al., Bates Proposal 83-23 (1983)
3. D.M. Manley et al., Bates Proposal 88-18 (1988)
4. R. Ent et al., Phys. Rev. Lett. 62, 24 (1989); R. Ent et al., to be submitted to Phys. Rev. C; also see R. Ent et al., in Proc. CEBAF 1988 Summer Workshop
5. K.S. Dhuga et al., Phys. Rev. C 32, 2208 (1985); K.S. Dhuga et al., Phys. Rev. C 35, 1148 (1987); also see K.S. Dhuga et al., LAMPF Proposal 1018 (1986)
6. K.S. Dhuga et al., LAMPF Proposal 1106 (1987); K.S. Dhuga et al., invited paper at Workshop on Pion Scattering above the Delta Resonance (KEK, Japan, 1990)
7. D. McLean et al., Phys. Rev. C (in press)
8. C. Hyde-Wright et al., to be submitted to Phys. Rev. C
9. K.S. Dhuga et al., LAMPF Proposal 1017 (1986)
10. J.J. Kelly et al., Phys. Rev. C 43, 1272 (1991)
11. B.S. Flanders et al., Phys. Rev. C 43, 2103 (1991)
12. D.L. Olson et al., submitted to Phys. Rev. C
13. D. Zubanov et al., submitted to Phys. Rev. C
14. J. Kelly et al., Proc. Workshop Nuclear Structure with Intermediate Energy Probes (Los Alamos, 1980), p. 461 and to be submitted to Phys. Rev. C
15. K.G. McNeill et al., Phys. Rev. C 43, 489 (1991)
16. D.M. Manley et al., Phys. Rev. C 41, 448 (1990); D.M. Manley et al., Phys. Rev. C 43, 2147 (1991); D.M. Manley et al., Bull. Am. Phys. Soc. 36, 1241 (1991)
17. R.M. Sellers et al., Bull. Am. Phys. Soc. 35, 927 (1990) and to be submitted to Phys. Rev. C
18. H. Rothhaas, H. Miessen, and B.L. Berman, to be submitted to Nucl. Phys. A
19. L.Knox et al., Bull. Am. Phys. Soc. 34, 1812 (1989) and to be submitted to Phys. Rev. C

20. C. Pillai et al., Phys. Lett. 207B, 389 (1988);
C. Pillai et al., Phys. Rev. C 43, 1838 (1991);
B.L. Berman et al., to be submitted to Phys. Rev. C
21. K.S. Dhuga et al., to be submitted to Phys. Rev. C; 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)
22. S.K. Matthews et al., Bull. Am. Phys. Soc. 35, 945
(1990) and to be submitted to Phys. Rev. C
23. S.K. Matthews et al., to be submitted to Phys. Rev. C
24. B. Brinkmoeller et al., submitted to Phys. Rev. C
25. R. Ent et al., Phys. Rev. Lett. 57, 2367 (1986); R. Ent
et al., Proc. Particles and Nuclei Int. Conf. and
Verhandl. Deutsche Phys. Ges. (1990), and to be
submitted to Phys. Rev. C
26. J.H. Mitchell et al., submitted to Phys. Rev. C
27. D. Zubanov et al., Bull. Am. Phys. Soc. 35, 927 (1990)
and to be submitted to Phys. Rev. C
28. B.L. Berman et al., NIKHEF Proposal 88-E1 (1987)
29. D. Zhang et al., Bull. Am. Phys. Soc. 35, 946 (1990)
and to be submitted to Phys. Rev. C
30. J.P. Glickman et al., Phys. Rev. C 43, 1740 (1991)
31. S. Dixit et al., Phys. Rev. C 43, 1758 (1991)
32. C.A. Whitten et al., to be submitted to Phys. Rev. C

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

For the last several years, The George Washington University has provided a great deal of support for research in nuclear physics, particularly that oriented towards CEBAF. This section provides some of the details of that support, together with personnel and other matters related to the present grant proposal.

A. THE GWU NUCLEAR DETECTOR LABORATORY

In the last three years the University has spent well 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/counting room, a test laboratory, a machine shop, a plastics shop, an electronics shop, and a small storage area, along with two small offices for graduate students. The renovation work was completed in May 1989, and the GWU Nuclear Physics Group moved into the NDL in the summer of 1989.

During the last two years, we have relocated our MicroVax computer along with peripherals (such as a tape drive, a laser printer, and several terminals) to the NDL, and we have set up the test laboratory and the shops. In the plastics shop, scintillators and light guides are polished and mounted on phototubes for a variety of uses, including prototyping the focal-plane detectors for the CEBAF photon tagger and construction of detectors for use in our experiments at major accelerator laboratories elsewhere, such as the thin ΔE paddle for our upcoming experiment at Los Alamos.

The main activities in the NDL are centered around two major experimental projects, the MWPC-based neutron detector/polarimeter and 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 the MWPC-based neutron detection system. 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. 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, or possibly cylinders, for detection and tracking of the knockout protons. This project is led at GWU by Prof. Dhuga, with the active participation of all of the nuclear experimentalists at GWU, namely Profs. Berman, Briscoe, Mokhtari, and Taragin, Drs. Cole, Dodge, and Rugari, and several students.

The initial stage of the project, consisting of kinematic and Monte-Carlo studies of the $(e, e'n)$ reaction, using the computer codes MCNP, LAHET, and GEANT to ascertain the overall parameters of the detection system, already has begun, and several designs are being evaluated. A MWPC has been acquired (from LAMPF), and is being used for test purposes, with the gas-handling system built last year in the NDL.

The other major experimental project is the focal-plane detector array for the Photon-Tagger facility at CEBAF. This project is being led by Prof. Briscoe, also with the active participation of the rest of the experimental staff, including significant contributions from both graduate and undergraduate students. The GWU group is part of a larger collaboration which includes physicists at Catholic University, Arizona State University, the Universities of Virginia and South Carolina, and CEBAF to undertake the design, construction, and testing of the Photon Tagger, in support of the extensive program of measurements of the photoproduction of strange particles and resonances and of

vector mesons on nucleons and few-body nuclei, as well as other photodisintegration and photoabsorption experiments at CEBAF. These measurements will utilize the CEBAF Large-Acceptance Spectrometer, in conjunction with the monochromatic photon beam from tagged bremsstrahlung (possibly tagged coherent 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 tagger. Initial design considerations call for a 384-channel energy-determining-scintillator array, backed by a 48-channel timing-scintillator array. Details concerning the choice of phototubes, bases, light pipes, discriminators, and associated electronics are being determined at present. Extensive laboratory tests of these components are being carried out in the NDL, mostly by Dr. Dodge and several students under his supervision. The effort on tagged coherent bremsstrahlung is being led by Prof. Berman, and will be done mostly at CEBAF by him and Dr. Cole.

Much of the electronic and counting equipment with which the NDL was furnished initially came from Los Alamos National Laboratory on long-term loan agreements. Another valuable source of borrowed equipment has been the National Institute of Standards and Technology, which has contributed some fast electronics, several Nimbins, and a MicroVax. General laboratory equipment not available otherwise, notably fast oscilloscopes and PCs, has been furnished by the present grant and by GWU--last year this amounted to \$19,810, shared equally.

B. THE GWU CENTER FOR NUCLEAR STUDIES

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. This has been used to hire a technician, as well as to support two Graduate Research Assistants.

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. Among other benefits, we hope to be successful in our request for additional laboratory (and office) space at the new GWU Virginia Campus, located in Loudon County near Dulles Airport, scheduled to open this Fall. This will make it possible to move the Photon-Tagger project there and consequently to make much more room available to the neutron-detector project in the present NDL. Since the Center for Nuclear Studies has been recognized as one of only eight "Centers of Excellence" by the GWU administration, we are very hopeful of the outcome.

C. RELATIONS WITH SURA AND CEBAF

The George Washington University is one of the charter members of SURA, and has from the outset given SURA a high priority in its research plans. There is no better measure of this commitment than the fact that GWU has created more new faculty positions in support of CEBAF than any other SURA university. We continue to benefit from this commitment in many ways. Two are mentioned above--the NDL, including cost-sharing of laboratory equipment not available from other sources, and the CNS; another that plays a key role specifically in the present proposal is the new agreement by GWU to cost-share the entire indirect-cost charge on the salaries and fringe benefits of both postdoctoral associates for all three years of the grant period, at a projected cost to the University of \$138,523.

The present principal investigator also has participated from the outset in the planning for CEBAF, even prior to his arrival at GWU in 1985, in several ways: as a

participant and working-group leader in many of the CEBAF Summer Workshops, as a member of the advisory committee to the HUGS AT CEBAF Summer School since its inception, as one of the organizers of the Photon-Tagger Group, as a member of the CEBAF Users Board of Directors (1989-91), and now (1991-92) as chairman of the CLAS Real Photon Physics Working Group while on sabbatical leave at CEBAF. One of our new postdoctoral associates, Dr. Cole, already has spent some time at CEBAF and will spend much of his time there after October, 1991. Prof. Briscoe, principal investigator of the NSF-funded Nuclear Physics Group at GWU, is the GWU Coordinator with CEBAF and leads our design-and-construction project for the focal-plane detector array for the Photon Tagger. Prof. Taragin is one of the three co-principal investigators for SURANET. Res. Prof. Maximon, of the Nuclear Theory Group (led by Prof. D.R. Lehman), has a joint appointment with CEBAF and is an active participant there.

The two experimental groups and the theory group at GWU consist together of 12 faculty and three postdoctoral associates and thus constitute one of the largest concentrations of physicists working primarily in medium-energy electromagnetic few-body nuclear physics. It is particularly noteworthy that not only do we talk to each other (in itself somewhat unusual), but we collaborate on physics problems [e.g., the ${}^6\text{Li}(e, e'd)$ work]; clearly we all benefit from the resulting cross-fertilization.

D. NOTE ON PERSONNEL SUPPORTED BY THIS GRANT

Two faculty members at GWU, Prof. Barry L. Berman and Asst. Prof. Kalvir S. Dhuga, lead this program; their resumes and publications (last five years only) constitute Appendix C. Two postdoctoral associates, Steven L. Rugari and Philip L. Cole, have been appointed recently, Dr. Rugari to begin in August, 1991 and Dr. Cole to begin in October, 1991. Dr. Rugari, from Yale, has a background in low-energy nuclear physics and neutron detectors, and will play a major

role in the neutron-detector project and the (e,e'n) program at NIKHEF. Dr. Cole, from Purdue and Fermilab, has a background in high-energy nuclear and particle physics, and will play a major role in the Photon-Tagger project and the photoproduction program at CEBAF.

At the moment, three graduate students are associated with the program. Sinisa Dragic (G.S. II) is engaged in the neutron-detector project and, together with Dr. Rugari, will analyze the data from the upcoming $^{12}\text{C}(\text{n},\text{p})$ experiment at LAMPF-WNR; Rebecca Caress (G.S. I) is performing Monte-Carlo calculations for the neutron detector and also will participate in the Los Alamos experiment. Both of these students have participated in a previous experiment at LAMPF (pion scattering on ^3H and ^3He), and Mr. Dragic in the $^6\text{Li}(\text{e},\text{e}'^3\text{He})$ experiment at NIKHEF. Miss Caress expects to receive her M.S. degree in December, 1991. Dalong Pang (G.S. I) currently is analyzing high-energy pion-scattering data and previously has designed and built phototube bases in support of the Photon-Tagger project as well as the NDL's gas-handling system.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

V. NUCLEAR-PHYSICS PUBLICATIONS, 1989-91

A. MEDIUM-ENERGY NUCLEAR STRUCTURE

1. J.J. Kelly, W. Bertozzi, T.N. Buti, J.M. Finn, F.W. Hersman, C. Hyde-Wright, M.V. Hynes, M.A. Kovash, B. Murdock, B.E. Norum, B. Pugh, F.N. Rad, A.D. Bacher, G.T. Emery, C.C. Foster, W.P. Jones, D.W. Miller, B.L. Berman, W.G. Love, J.A. Carr, and F. Petrovich
Density Dependence in the Two-Nucleon Effective Interaction at 135 MeV
Phys. Rev. C 39, 1222 (1989)
2. M. Burlein, H.T. Fortune, W.M. Amos, T.L. Ekenberg, A. Kotwal, P.H. Kutt, J.M. O'Donnell, J.D. Silk, B. Boyer, A. Fuentes, K. Johnson, C.F. Moore, S.H. Yoo, S. Mordechai, C.L. Morris, J.D. Zumbro, D.L. Watson, and K.S. Dhuga
Pion Inelastic Scattering to the Low-Lying Broad 2^+ in ^{20}Ne
Phys. Rev. C 40, 785 (1989)
3. R. Ent, B.L. Berman, H.P. Blok, J.F.J. van den Brand, W.J. Briscoe, J.F.A. van Hienen, E. Jans, G.J. Kramer, J.B.J.M. Lanen, L. Lapikas, B.E. Norum, E.N.M. Quint, A. Saha, G. van der Steenhoven, and P.K.A. de Witt Huberts
Deuteron Formation in the Reaction $^{12}\text{C}(e, e'd)^{10}\text{B}_{T=1}$
Phys. Rev. Lett. 62, 24 (1989)
4. Allen Williams, L. Agnew, L.G. Atencio, H.W. Baer, M.G. Burlein, G.R. Burleson, K.S. Dhuga, H.T. Fortune, G.S. Kyle, J.A. McGill, C. Fred Moore, C.L. Morris, S. Mordechai, J.M. O'Donnell, M.W. Rawool, S. Schilling, J.D. Silk, J.D. Zumbro
Pion Double Charge Exchange above the $\Delta(1232)$ Resonance
Phys. Lett. B216, 11 (1989)
5. D.M. Manley, D.J. Millener, 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)

6. 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: $^{16}\text{O}(\text{p},\text{p}')$
Phys. Rev. C 41, 2504 (1990)
7. P.A. Seidl, M.A. Bryan, M. Burlein, G.R. Burleson,
Kalvir S. Dhuga, H.T. Fortune, R. Gilman,
S.J. Greene, M.A. Machuca, C. Fred 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
 $\Delta_{3/2,3/2}$ Resonance Region
Phys. Rev. C 42, 1929 (1990)
8. 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)
9. 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 $^{16}\text{O}(\text{p},\text{p}')$ at $E_p=318$ MeV
Phys. Rev. C 43, 1272 (1991)
10. 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)
11. 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)

Abstracts

1. M. Burlein, W.M. Amos, T.L. Ekenberg, H.T. Fortune, A.V. Kotwal, P.H. Kutt, J.M. O'Donnell, J.D. Silk, C.L. Morris, J.D. Zumbro, D.L. Watson, C.F. Moore, B. Boyer, A. Fuentes, K. Johnson, S.H. Yoo, and K.S. Dhuga
Pion Inelastic Scattering to the Low-Lying Broad 2^+ in ^{20}Ne
Bull. Am. Phys. Soc. 34, 1204 (1989)
2. L. Knox, R.A. Lindgren, B.L. Clausen, B.L. Berman, D. Zubanov, M. Farkhondeh, L.W. Fagg, and M. Manley
Electroexcitation of 6^- States in ^{30}Si
Bull. Am. Phys. Soc. 34, 1812 (1989)
3. 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)
4. 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 Low-Lying 1^- , 3^- , and 5^- States in ^{18}O
Bull. Am. Phys. Soc. 36, 1241 (1991)

B. FEW-BODY NUCLEI

1. K.S. Dhuga, B.L. Berman, W.J. Briscoe, D.A. Hanson, S. Matthews, A. Mokhtari, C.E. Smith, D. Barlow, B.M.K. Nefkens, C. Pillai, J. Price, S.J. Greene, and I. Slaus
Charge-Symmetry Violation in π^+ and π^- Elastic Scattering from ^3H and ^3He
Proc. 12th Int. Conf. on Few Body Problems in Physics (Vancouver, 1989)
2. 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 $p\text{-}^3\text{He}$ Scattering
Phys. Rev. C 42, 438 (1990)

3. R. Ent, H.P. Blok, J.F.J. van den Brand, E. Jans,
L. Lapikas, B.L. Berman, W.J. Briscoe, P.D. Kunz,
and H. Morita
Reaction Mechanism and Spectroscopic Results of the
(e,e'd) Reaction
Proc. Particles and Nuclei Int. Conf. (Cambridge, MA,
1990)
4. K.S. Dhuga, B.L. Berman, W.J. Briscoe, D.A. Hanson,
S.K. Matthews, A. Mokhtari, C.E. Smith,
B.M.K. Nefkens, J. Price, D.B. Barlow,
S.J. Greene, C. Pillai, and I. Slaus
Charge-Symmetry Breaking in π^+ and π^- Elastic
Scattering from ^3H and ^3He
Ibid.
5. 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 ^9Be
Phys. Rev. C 43, 1740 (1991)
6. 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 ^9Be from Proton Scattering at 180 MeV
Phys. Rev. C 43, 1758 (1991)
7. 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 ^3H and ^3He :
Evidence for Charge-Symmetry Violation
Phys. Rev. C 43, 1838 (1991)
8. 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 $^6\text{Li}(e,e'\alpha)$ Reaction
Phys. Rev. C (submitted)
9. B. Brinkmoeller, C.L. Blilie, D. Dehnhard, M.K. Jones,
G.M. Martinez, S.K. Nanda, S.M. Sterben,
Yi-Fen Yen, J. Faucett, S.J. Greene, C.L. Morris,
S.J. Seestrom, G.R. Burleson, K.S. Dhuga,
R.W. Garnett, K. Maeda, C.F. Moore, S. Mordechai,
A. Williams, S.H. Yoo, and L.C. Bland
Systematic Study of Elastic Scattering of p^+ and p^-
from ^4He between 90 and 240 MeV
Phys. Rev. C (submitted)

Abstracts

1. B. Brinkmoeller, D. Dehnhard, M.K. Jones,
S.M. Sterbenz, Yi-Fen Yen, C.L. Morris,
S.J. Seestrom-Morris, S.J. Greene, G.R. Burleson,
K.S. Dhuga, J.A. Faucett, R. Garnett, C.F. Moore,
S. Mordechai, D. Oakley, M. Smithson, A. Williams,
and S. Yoo
 π^+ He Elastic Scattering at Far Forward and Far
Backward Angles
Bull. Am. Phys. Soc. 34, 1203 (1989)
2. D. Zhang, H. Breuer, N.S. Chant, B.S. Flanders,
S.D. Hyman, D.J. Mack, P.G. Roos, J.D. Silk,
K.S. Dhuga, G.S. Kyle, M. Wang, P.A. Amandruz,
C.H.Q. Ingram, R.A. Schumacher, U. Sennhauser,
J. Jacob, B.G. Ritchie, D. Rothenberger,
J. McDonald, and A. Williams
Energy Dependence of the ${}^6\text{Li}(\pi^+, 2p)$ Reaction
Bull. Am. Phys. Soc. 34, 1205 (1989)
3. 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 ${}^6\text{Li}(e, e't){}^3\text{He}$ Reaction
Bull. Am. Phys. Soc. 35, 927 (1990)
4. 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 ${}^3\text{H}$ and ${}^3\text{He}$ at Backward
Angles
Bull. Am. Phys. Soc. 35, 945 (1990)
5. 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. Amandruz, 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 ${}^6\text{Li}(\pi^+, 2p)$ Reaction
around the $\Delta(1232)$ Resonance Region
Bull. Am. Phys. Soc. 35, 946 (1990)
6. R. Ent, H.P. Blok, J.F.J. van den Brand, E. Jans,
L. Lapikas, B.L. Berman, W.J. Briscoe, P.D. Kunz,
and H. Morita
Reaction Mechanism and Spectroscopic Results of the
($e, e'd$) Reaction
Verhandl. Deutsche Phys. Ges. (1990)

7. B.L. Berman, W.J. Briscoe, K.S. Dhuga, D.A. Hanson, S.K. Mathews, A. Mokhtari, C.S. Smith, B.M.K. Nefkens, J. Price, D.B. Barlow, S.J. Greene, C. Pillai, and I. Slaus
Pion Scattering from ^3H and ^3He
Proc. Int. Workshop on Pions in Nuclei (Peniscola, Spain, 1991), p.3

C. OTHER NUCLEAR PHYSICS

1. 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)
2. J. Engelage, M.E. Baumgartner, E. Beleal, B.L. Berman, F. Bieser, F.P. Brady, M. Bronson, J.B. Carroll, H.J. Crawford, I. Flores, D.E. Greiner, L. Greiner, O. Hashimoto, G. Igo, S. Kadota, P.N. Kirk, P.J. Lindstrom, C. McParland, S. Nagamiya, D.L. Olson, J. Porter, J.L. Romero, C.L. Ruiz, T.J.M. Symons, I. Tanihata, R. Wada, M.L. Webb, J. Yamada, and H. Yee
Design of the Bevalac Heavy Ion Spectrometer System and Its Performance in Studying ^{12}C Fragmentation
Nucl. Instrum. Methods A277, 431 (1989)
3. 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)
4. K.G. McNeill, J.W. Jury, M.N. Thompson, B.L. Berman, and R.E. Pywell
 $^{18}\text{O}(\gamma, \text{pn}+\text{np})$ Cross Section
Phys. Rev. C 43, 489 (1991)
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 (in press)
6. 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 (submitted)

7. 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)

APPENDICES

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