

A PROGRAM IN MEDIUM ENERGY NUCLEAR PHYSICS

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Progress Report and Continuation Proposal

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OVERVIEW

This progress report and continuation proposal summarizes our achievements for the period from July 1, 1994 to September 30, 1995 and requests continued funding for our program in experimental medium-energy nuclear physics. The focus of our program remains the understanding of the short-range part of the strong interaction in the nuclear medium. In the past year we have focused our attention ever more sharply on experiments with real tagged photons, and we have successfully defended two new experimental proposals: *Photofission of Actinide and Preactinide Nuclei* at SAL and *Photoproduction of the ρ Meson from the Proton with Linearly Polarized Photons* at CEBAF. (We are co-speakersons on two previously approved Hall-B experiments at CEBAF, *Photoreactions on ^3He* and *Photoabsorption and Photofission of Nuclei*.) As part of the team that is instrumenting the Photon Tagger for Hall B; we report excellent progress on the focal-plane detector array that is being built at our Nuclear Detector Laboratory, as well as progress on our plans for instrumentation of a tagged polarized-photon beam using coherent bremsstrahlung. Also, we shall soon receive a large computer system (from the SSC) which will form the basis for our new Data Analysis Center, which, like the Nuclear Detector Laboratory, will be operated under the auspices of The George Washington University Center for Nuclear Studies. Finally, during the past year we have published six more papers on the results of our measurements of pion scattering at LAMPF and of electron scattering at NIKHEF and Bates, and we can report that nearly all of the remaining papers documenting this long series of measurements are in the pipeline.

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I. RESEARCH PROGRAM

During the past year we have made great progress on our research program in medium-energy nuclear physics. We have had two more experiments approved at major electron accelerators, published six more papers on our previous results on pion and electron scattering, and made considerable headway in the analysis and documentation of our remaining data. A brief description follows below, and copies of our new proposals, updates of the older ones, and publications constitute the appendices to this report.

A. Photofission at Medium Energies

Our proposal, *Photofission of Actinide and Preactinide Nuclei* (B.L. Berman, Spokesperson; reproduced in Appendix A), was approved this year by the Saskatchewan Accelerator Laboratory (SAL) PAC and was awarded 280 hours of beamtime. We intend to measure the photofission cross sections of ^{232}Th , ^{235}U , ^{238}U , ^{237}Np , and ^{208}Pb from 60 to 270 MeV, spanning the quasideuteron region and up the leading edge of the delta resonance. We shall use parallel-plate avalanche detectors (PPADs) for the fission fragments, designed and being built at our Nuclear Detector Laboratory. Not only will this be an extremely useful preliminary experiment for our CEBAF experiment *Photoabsorption and Photofission of Nuclei* (N. Bianchi, V. Muccifora, and B.L. Berman, Co-Spokespersons; Update reproduced in Appendix A), but it will resolve several important discrepancies in the literature regarding the validity of the "universal" curve for photon absorption above the giant-resonance region and will also probe the nature of pion absorption in heavy nuclei.

B. Photodisintegration of Three-Body Nuclei

We have joined Dr. G. Feldman of SAL (Spokesperson) in *Two-Body Photodisintegration of the $A = 3$ Systems* (reproduced in Appendix A), which was approved this year to run for 280 hours at SAL at relatively low energies (up to about 50 MeV). This experiment will use multiple solid-state telescopes for coincidence detection of the breakup deuteron and nucleons from both ^3H and ^3He simultaneously. This experiment, too, in addition to resolving discrepancies in the literature for these fundamental nuclear reactions, will serve as an excellent forerunner to our CEBAF experiment *Photoreactions on ^3He* (B.L. Berman, P. Corvisiero, and G. Audit, Co-Spokespersons; Update reproduced in Appendix A).

C. Vector Mesons with Polarized Photons

Our proposal, *Photoproduction of the ρ Meson from the Proton with Linearly Polarized Photons* (P.L. Cole, J.P. Connelly, and R.R. Whitney, Co-Spokespersons; reproduced in

Appendix A), was approved this year by the CEBAF PAC and was awarded 20 days of new beamtime. This is the only experiment employing linearly polarized photons that has been approved to run in the CLAS to date. We will be investigating the angular distributions of the ρ^0 and ρ^+ mesons in the baryon resonance region ranging from 1.66 to 2.22 GeV. The ρN channel is known to be a significant decay branch for established resonances in this energy regime. It also has been predicted by symmetric quark models to be a primary decay channel for hitherto unestablished resonances that do not couple strongly to the πN system. The measurement will use a linearly polarized photon beam produced by coherent bremsstrahlung from a diamond crystal radiator (see below) to measure the beam asymmetry and the spin-density matrix elements of the two-pion decay of the ρ mesons. The spin-density matrix elements and the polarization asymmetry of the ρ decay will be extracted as functions of the Mandelstam variables, t and s . This will afford a clean separation, for intermediate polar angles, of resonance decay processes from those arising from the diffractive scattering of the hadronic component of the isovector part of the photon. Our experiment, moreover, will increase the world's data set by at least two orders of magnitude, and will extend its range in t by a factor of two.

D. Pion-Scattering Studies

We continue to make good progress in analyzing and publishing our pion scattering data from our experiments at LAMPF. From our series of pion-scattering measurements on the $A = 3$ nuclei, two more articles, *Inelastic Pion Scattering from 3H and 3He* (Berman *et al.*) and *Elastic Scattering of Pions from 3H and 3He into the Backward Hemisphere* (Matthews *et al.*), and a conference report, *Recent Pion-Scattering Measurements on 3H and 3He* (Berman *et al.*), have been published this year. Another paper, *Investigation of Nuclear Charge Symmetry by Pion Scattering from 3H and 3He* (Dhuga *et al.*), is ready for submission. One final article, on the backward-angle cross-section ratios, but also summarizing all of our measurements on the $A = 3$ nuclei is currently being prepared.

We continue to make progress in the analysis of our large data set on pion scattering from shell-model nuclei. One article, *Pion Inelastic Scattering to Low-Lying Positive-Parity States in ^{20}Ne* (Burlein *et al.*), has been published this year. Two more articles, one describing large-angle pion elastic scattering from ^{28}Si and the other high-energy pion elastic scattering from ^{12}C , ^{16}O , and ^{40}Ca , are being prepared.

The four published papers on pion scattering are reproduced in Appendix B.

E. Electron-Scattering Studies

In concluding publication of the results of our large body of data on inclusive electron scattering at Bates, one paper, *Inelastic Electron Scattering from ^{18}O at Backward Angles* (Sellers *et al.*), has been published this year, and the last two, on ^{16}O and ^{30}Si , are in preparation.

Analysis of the data from our series of cluster-knockout measurements on light nuclei at NIKHEF has been completed, our comprehensive paper on deuteron knockout, *The $(e,e'd)$ Reaction on ^4He , ^6Li , and ^{12}C* (Ent *et al.*), was published last year, and the last paper in the series, on ^3H and ^3He knockout from ^6Li (Connelly *et al.*), is in preparation.

The two published papers on electron scattering also are reproduced in Appendix B.

F. Summary of Recent Work

Our recent work is summarized in Tables I and II. In addition to the work referred to in Sections D and E above, our (n,p) data on the proton and ^{12}C from LAMPF-WNR are now analyzed, and a paper (Rugari *et al.*) is being prepared for publication.

Comparison of these tables with their counterparts in past years shows that we have nearly completed the publication of a very large body of previous data (over 70 published papers), so that our current backlog is clearly of manageable proportions.

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^1\text{H}(n,p)$	LAMPF-WNR*	Fundamental cross section, angular distribution	Data analyzed, paper in preparation	1
$^3\text{H}, ^3\text{He}(\pi^\pm, \pi^\pm),$ (π^\pm, π^\pm')	LAMPF-EPICS	142- to 220-MeV cross sections, form factors, charge asymmetry	Three papers published	2
$^3\text{H}, ^3\text{He}(\pi^\pm, \pi^\pm)$	LAMPF-EPICS*	180- to 295-MeV non-spin-flip-dip cross sections, charge asymmetry	Data analyzed, paper to be submitted	3
$^3\text{H}, ^3\text{He}(\pi^\pm, \pi^\pm)$	LAMPF-EPICS*	180° cross sections, 142 to 256 MeV, non-spin-flip amplitudes	Data analyzed, one paper published, one in preparation	4
$^3\text{H}, ^3\text{He}(\pi^\pm, \pi^\pm)$	LAMPF-EPICS*	180-MeV large-angle cross sections, charge asymmetry	Data analyzed, one paper published, one in preparation	4
$^6\text{Li}(e, e'd)$	NIKHEF	Spectral functions, q-dependence	Two papers published	5
$^6\text{Li}(e, e^3\text{H}), (e, e^3\text{He})$	NIKHEF*	Momentum distributions, reaction mechanism, q-dependence	Data analyzed, paper in preparation	6

* Spokesperson or co-spokesperson

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

Reaction	Laboratory	Physics Emphasis	Status	Reference
$^{12}\text{C}(e,e'd)$	NIKHEF	Spectral functions, q-dependence	Two papers published	7
$^{12}\text{C}(n,p)$	LAMPF-WNR*	Application to neutron polarimeters	Data analyzed, paper in preparation	1
$^{12}\text{C}, ^{16}\text{O}, ^{20}\text{Ne}, ^{28}\text{Si},$ $^{40}\text{Ca}(\pi^\pm, \pi^\pm)$	LAMPF-EPICS*	Excitation functions at large angles, medium modifications	Three papers published, one in preparation	8
$^{12}\text{C}, ^{16}\text{O}, ^{40}\text{Ca}, ^{48}\text{Ca},$ $^{90}\text{Zr}, ^{208}\text{Pb}$ $(\pi^\pm, \pi^\pm), (\pi^\pm, \pi^\pm')$	LAMPF-P ³ *	Exploratory (300-500 MeV); test of optical models	Data analyzed, paper in preparation	9
$^{16}\text{O}(e,e')$	Bates	High-excitation, isovector states	Data analyzed, paper in preparation	10
$^{18}\text{O}(e,e')$	Bates	Stretched-spin states; isospin structure	Published	11
$^{30}\text{Si}(e,e')$	Bates*	Stretched-spin states	Data analyzed, paper in preparation	12

* Spokesperson or co-spokesperson

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9. G.P. Kahirmanis *et al.*, to be submitted to Phys. Rev. C; also see M.W. Rawool-Sullivan *et al.*, Bull. Am. Phys. Soc. **37**, 916 (1992) and K.S. Dhuga *et al.*, LAMPF Proposal 1106 (1987)
10. J. Ruthenberg *et al.*, to be submitted to Phys. Rev. C
11. R.M. Sellers *et al.*, Phys. Rev. C **51**, 1926 (1995)
12. L. Knox *et al.*, Bull. Am. Phys. Soc. **34**, 1812 (1989), and to be submitted to Phys. Rev. C

II. INSTRUMENTATION FOR CEBAF

As the date for the delivery of beam to Hall B approaches, we have been devoting more attention to the instrumentation that will be needed to perform our experiments there. These efforts are outlined below.

A. The Photon-Tagger Hodoscope

The George Washington University experimental nuclear physics group, in collaboration with Catholic University, Arizona State University and Georgetown University, is responsible for the construction, installation and calibration of the CEBAF Hall-B photon tagger. The photon tagger is designed to deliver a high rate (5×10^7 Hz) of tagged photons to the CEBAF Large Acceptance Spectrometer (CLAS), over an energy range of 20% to 95% of the incident electron energy ($E_e < 6$ GeV). The primary component of GW's contribution to this enterprise has been the design and construction of the focal-plane detector array (hodoscope) used to determine the energy and timing information of the electrons responsible for the bremsstrahlung photons.

The tagger hodoscope is comprised of a two-tiered detector array. The first level the electron encounters is the energy-counter array, composed of 386 thin plastic scintillators in a "Venetian-blind" configuration, spread over a 10-meter momentum axis. This configuration will enable the tagger to attain an energy resolution of 0.1% of the incident electron energy. The second layer consists of 52 timing counters, 3/4"-thick plastic scintillators designed to generate a large signal for determining the timing of the electron relative to a CLAS photon event to within 350 picoseconds. Both sets of counters are contained in a light-tight 11-meter-long box that will be installed underneath the tagger magnet.

The construction of the hodoscope, which has taken place at our Nuclear Detector Laboratory under the supervision of Assoc. Prof. W.J. Briscoe, is nearly complete; the shipment of the hodoscope box to CEBAF will occur on October 16, 1995. Once shipped, we and our collaborators will begin the surveying, installation and calibration procedures. We expect this effort to be finished by the summer of 1996, comfortably prior to the scheduled turn-on time for Hall B next Fall.

B. Coherent-Bremsstrahlung Facility

Early this year, the CEBAF Program Advisory Committee approved our proposal, *Photoproduction of the ρ Meson from the Proton with Linearly Polarized Photons*. The main goal of this experiment is to identify and extract information on baryon resonances that have a significant decay probability in the ρN channel. A critical requirement of the experiment is that the tagged photons be linearly polarized. Although a high-quality tagged photon beam will be available in Hall B at turn-on, there is as yet no facility at CEBAF to produce a linearly polarized photon beam. In support of our approved experiment (and our anticipated polarization studies involving few-body nuclei), we have taken on the responsibility of the design and installation of such a facility.

There are three well known methods for producing linearly polarized photons using an incident electron beam: Compton backscattering from a linearly polarized laser beam, off-axis tagging of incoherent bremsstrahlung, and coherent bremsstrahlung from a crystal radiator. Of these methods, we at GW are pursuing the coherent-bremsstrahlung option. It is a well tested technique, and has been used for many years at a number of international laboratories. It is by far the simplest to install and easily the most cost-effective. For CEBAF energies and beam conditions, polarizations in the range of 40-60% can be expected in the coherent peak of the photon spectrum. Even higher polarizations might be achievable with tight collimation of the photon beam.

The proposed coherent-bremsstrahlung facility has modest physical space and device requirements. In order to implement the facility, approximately 1 m of beamline space is required near or somewhat upstream from the bremsstrahlung radiator position. This space has already been specifically allocated for the necessary equipment. The primary piece of equipment that comprises the facility is an accurate, computer-controlled, multi-axis goniometer. Such devices, which are used extensively in x-ray diffraction research and surface studies of crystalline structures, are available commercially. Additional essential equipment includes stepping motors and controllers (one per axis, about or along which motion of the crystal is desired), as well as a device to locate the absolute position of the stepping motors. The entire goniometer-stepping-motor assembly will be housed in a medium-sized multiport vacuum chamber coupled directly to the main electron beamline entering Hall B. A funding proposal to purchase the necessary equipment is currently being prepared.

C. Slow Controls

An integral part of our proposal to install a coherent-bremsstrahlung facility at CEBAF is the development and installation of the software to control and monitor the necessary hardware. Specifically, the stepping motors that control the motion of the goniometer will need to be controlled and monitored by the host data-acquisition system. This link between the controlling software and the hardware will be made via some fast local-area network. PC-based motion-control software is readily available from commercial vendors. However, it is almost certain that any of these software packages will require considerable modification before it can be fully integrated into the standard controls software that has already been adopted at CEBAF. This standard is based on the Experimental Physics and Industrial Control Systems (EPICS)--an extensive set of controls software developed primarily at the Los Alamos National Laboratory.

In light of these compatibility issues, the GW group has entered into an agreement with the Hall-B management to supply EPICS-based controls software for the coherent-bremsstrahlung facility. As part of this agreement, CEBAF has supplied us with appropriate controls-related computational equipment, whose value totals approximately \$19,000. This equipment, which includes a UNIX-based host machine (a Sun workstation), a VME crate with an on-board single (Motorola 162) CPU chip, and a crate power supply, was only recently installed at GW. Currently, we have one graduate student working (part-time) on the controls software.

D. Fission-Fragment Detectors

As part of our commitment to our photofission experiments at SAL and CEBAF, we have undertaken the design and construction of the PPADs to detect the fission fragments. The design of both the PPADs and the reaction chamber in which they are to be mounted is now essentially complete; construction of the former is ready to begin at our Nuclear Detector Laboratory, and preliminary bids have been received for the latter.

III. ACQUISITION OF A LARGE COMPUTER FROM THE SSC

Earlier this year the DOE initiated and supervised a program to distribute (to DOE Grantees) equipment that had been originally procured for the SSC project. In response, we submitted (in late April of this year) a request for a powerful VAX computer system capable of supporting a UNIX operating system (a necessary requirement to be compatible with the computers at CEBAF), along with sufficient peripherals to allow for mass storage and backup facilities. In our justification for such a system, we noted that members of our group were co-spokespersons on four approved experiments to be carried out in Hall B at CEBAF. Three of these experiments will be carried out using the CLAS detector, currently under construction. This detector, when fully operational, is expected produce data at unprecedented rates. Indeed, so much data is likely to be produced that the CEBAF management is actively encouraging university groups to create on-campus data-analysis centers in order to prevent crippling demands on CEBAF's own computational facilities. Needless to say, we were absolutely delighted to learn in late June that we had been awarded the VAX system, which will become the centerpiece (for the next few years) of our GW Data Analysis Center.

Specifically, the VAX consists of an array of 4 CPUs with a total memory of 512 Megabytes, and 2 disk drives with a net capacity of 68 Gigabytes. Indeed, it is a large, multi-user, multiprocessor system capable of supporting both the VMS and UNIX environments. In order to be compatible with CEBAF, we will install the most modern Digital UNIX operating system.

When installed and fully operational later this year, we anticipate that the VAX system will enhance our current computing capability by an order of magnitude, and thus will fulfill the immediate (and for some years to come) computing needs of our research programs in experimental and theoretical nuclear physics. Moreover, we are making plans for the VAX to serve as a valuable facility for the training of our graduate students in computational skills.

IV. PERSONNEL

During the past year, the grant has supported the following personnel:

Prof. B.L. Berman, PI
Assoc. Prof. K.S. Dhuga, Co-PI
Assoc. Prof. W.J. Briscoe (summer 1994)
Asst. Res. Prof. J.P. Connelly (until Aug. 31, 1995, now Vis. Asst. Prof.)
Dr. P.L. Cole, Postdoc. Assoc., now Asst. Res. Prof.
Dr. S.L. Rugari, Postdoc. Assoc. (until Dec. 31, 1994)
Mr. D. Pang, Grad. Stud. (until Dec. 31, 1994)
Mr. J.C. Sanabria, Grad. Stud. II
Ms. C. Cetina, Grad. Stud. II
Mr. S. Philips, Grad. Stud. II (summer 1994 and since Jun. 1, 1995)
Mr. H. Ayvazian, Grad. Stud. I (summers 1994 and 1995)
Mr. A. Shafi, Grad. Stud. I (summer 1994)
Mr. E. Anciant, Grad. Stud., will join the group on Oct. 1, 1995
Dr. L.Y. Murphy, Postdoc. Assoc., will join the group on Nov. 15, 1995

Thus, the steady-state group consists of (in addition to the P.I. and co-P.I.) of an Assistant Research Professor, (only) one Postdoctoral Associate, and four Ph.D. students. We feel that this represents the minimum mix of new and experienced personnel needed to carry out our ambitious research program.

Professor Dhuga spent his sabbatical year (1994-95) part-time at CEBAF, working on slow controls and coherent bremsstrahlung. Professor Connelly concentrated his efforts on the Photon Tagger. Professor Cole spent several months this past year working with our CEBAF collaborators in Genoa and Saclay, where he wrote a CLAS-Note on calibration procedures for the CLAS (reproduced in Appendix B). Our photofission experiment at SAL will constitute the Ph.D. thesis experiment of Mr. Sanabria; our photofission experiment at CEBAF that of Ms. Cetina; and our ^3He experiment at CEBAF will provide the data for the Ph.D. theses of Mr. Philips and Mr. Anciant (who will join us shortly). Dr. Murphy, who also will join us shortly, brings to the group extensive experience with the photon tagger and the large-acceptance spectrometer DAPHNE at Mainz.

V. UNIVERSITY SUPPORT

The George Washington University has continued to provide us with superb support, in many forms. The charter of the Center for Nuclear Studies as one of only six Centers of Excellence at GW has been renewed for another four years, and its funding has been continued at a level of about \$75K/year, enough to fund our Electro-Mechanical Technician (Dr. W.R. Dodge) and a graduate student in nuclear theory. The Nuclear Detector Laboratory likewise continues to be supported, and will expand to become the site of our new Data Analysis Center built around the large VAX computer that we shall receive from the SSC in a few weeks (the University also has agreed to underwrite its shipping and set-up costs).

In support of the present grant, the University has agreed to cost-share no less than \$164K over the three-year life of the grant, including \$69K in direct personnel costs, \$43K in indirect costs, and \$52K in tuition costs for our graduate students. This includes cost-sharing of 50% of the cost of the Assistant Research Professor, so that the more senior person actually costs the DOE over 40% less than a new postdoc. Now, because we are asking DOE for additional support for the upcoming year (see Section VII below), the University has offered to cost-share an additional \$5K for equipment (the reaction chamber for the photofission experiments) and \$2.4K in indirect costs for personnel (see Section VII below for details).

VI. PUBLICATIONS

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