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Submitted by

J. H. Heisenberg, *Co-Principal Investigator*

J. R. Calarco, *Co-Principal Investigator*

F. W. Hersman, *Co-Principal Investigator*

J. F. Dawson, *Investigator*

Department of Physics
University of New Hampshire, Durham, NH 03824

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NUCLEAR PHYSICS GROUP-1993

J. H. Heisenberg, *Professor*
J. R. Calarco, *Professor*
F. W. Hersman, *Associate Professor*
J. F. Dawson, *Professor*
F. Cooper, *Visiting Professor*
L. C. Balling, *Professor*
J. Wright, *Professor*
J. Distelbrink, *Research Scientist*
I. The, *Research Scientist*
T. Smith, *Postdoctoral Scientist*
D. DeAngelis, *Postdoctoral Scientist*
L. Gelinas, *Research Assistant*
V. Pomeroy, *Research Assistant*
V. Boykin, *Research Assistant*
M. Kennedy, *Research Assistant*
A. Tutein, *Research Assistant*
B. Mihaila, *Research Assistant*
T. Li, *Research Assistant*
P. Green, *Research Assistant*
S. Taylor, *Research Assistant*
B. Ball, *Research Assistant*
B. St. Hilaire, *Research Assistant*
K. MacArthur, *Research Technician*
M. Chevalier, *Undergraduate Student*
L. Ravila, *Undergraduate Student*
O. Kremzier, *Undergraduate Student*
A. Birch, *Undergraduate Student*
S. Cox, *Undergraduate Student*
T. Nadeau, *Undergraduate Student*

TABLE OF CONTENTS

	Page
A. Introduction	1
B. Progress Summary for July 1990--July 1993	3
B.1 Direct reactions	4
B.1.1 Completion of $^{16}\text{O}(\text{e},\text{e}'\text{p})$	4
B.1.2 $^{12}\text{C}(\text{e},\text{e}'\text{pp})$ in the dip region	7
B.1.3 $^{12}\text{C}(\text{e},\text{e}'\text{pp})$ in the Δ region	8
B.1.4 CEBAF physics program	9
B.1.5 Study of the $P_{11}(1440)$ Roper resonance	10
B.1.6 Large acceptance detector physics simulations	11
B.2 Giant resonance studies	13
B.2.1 The Mainz program	14
B.2.2 Measurements of $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ at Bates	14
B.2.3 The third response function in $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_0)$	17
B.2.4 Comparison of the $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_3)$ reactions	22
B.2.5 Quadrupole strength in the ^{12}C and $^{16}\text{O}(\text{e},\text{e}'\alpha)$ reactions	24
B.2.6 Analysis of the $^{12}\text{C}(\text{e},\text{e}'\text{p}_1)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_3)$ angular distributions	25
B.2.7 Quadrupole strength in the $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_0)$ reactions	26
B.2.8 Summary and status of publications	26
B.3 Models of nuclear structure	28
B.3.1 Hartree-Fock calculations	28
B.3.2 TDA calculations	31
B.3.3 Phonon coupling	33
B.3.4 Analysis of experiments	33
B.3.5 Relativistic nuclear model	33

TABLE OF CONTENTS

	Page
A. Introduction	1
B. Progress Summary for July 1990–July 1993	3
B.1 Direct reactions	4
B.1.1 Completion of $^{16}\text{O}(\text{e},\text{e}'\text{p})$	4
B.1.2 $^{12}\text{C}(\text{e},\text{e}'\text{pp})$ in the dip region	7
B.1.3 $^{12}\text{C}(\text{e},\text{e}'\text{pp})$ in the Δ region	8
B.1.4 CEBAF physics program	9
B.1.5 Study of the $P_{11}(1440)$ Roper resonance	10
B.1.6 Large acceptance detector physics simulations	11
B.2 Giant resonance studies	13
B.2.1 The Mainz program	14
B.2.2 Measurements of $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ at Bates	14
B.2.3 The third response function in $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_0)$	17
B.2.4 Comparison of the $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_3)$ reactions	22
B.2.5 Quadrupole strength in the ^{12}C and $^{16}\text{O}(\text{e},\text{e}'\alpha)$ reactions	24
B.2.6 Analysis of the $^{12}\text{C}(\text{e},\text{e}'\text{p}_1)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_3)$ angular distributions	25
B.2.7 Quadrupole strength in the $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_0)$ reactions	26
B.2.8 Summary and status of publications	26
B.3 Models of nuclear structure	28
B.3.1 Hartree-Fock calculations	28
B.3.2 TDA calculations	31
B.3.3 Phonon coupling	33
B.3.4 Analysis of experiments	33
B.3.5 Relativistic nuclear model	33

ii *University of New Hampshire*

B.3.6	Variational methods for QHD	34
B.3.7	Two proton knockout ($e,e'pp$)	34
B.3.8	Chiral anomaly	36
B.3.9	Sub-nucleon degrees of freedom	36
B.4	Instrumentation development	39
B.4.1	CLAS contracts	40
B.4.2	Scintillators	41
B.4.3	CEBAF Hall A event trigger electronics	45
B.4.4	CLAS event tracking	46
B.4.5	Multiwire drift chamber development	47
B.4.6	Polarized target development	48
B.4.7	BLAST detector design	50
B.4.8	BLAST Čerenkov detectors	52
B.4.9	BLAST wire chambers	56
B.4.10	BLAST event trigger logic and electronics	60
B.4.11	BLAST Collaboration developments	61
B.5	Publications, talks, abstracts	63
B.5.1	Refereed journal articles	63
B.5.2	Papers submitted	88
B.5.3	New proposals with UNH spokespersons	88
B.5.4	Invited talks	88
B.5.5	Departmental talks	90
B.5.6	Contributed talks, abstracts, and posters	91
C.	Planned Project for July 1993–July 1996	94
C.1	Direct reactions	95
C.1.1	Neutron electric form factor	95
C.1.2	Neutron magnetic form factor	101

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A. Introduction

This document reports on the progress of the University of New Hampshire Nuclear Physics group on our present three year program, "*Electromagnetic Studies of Nuclear Structure and Reactions*," for the period between July 1990 and July 1993, and describes our plan for the next three years. The primary objectives of our group continue to be the study of subatomic structure through experimental measurements at accelerator laboratories, the interpretation of the data through modeling, and the education and training of new physicists. The focus of our interest is evolving, however, from one primarily devoted to the study of the structure of complex nuclei to one aimed at understanding the structure of nucleons and light nuclei. Also the nature of our contribution has expanded to include instrumentation development, supported in part by companion contracts with the CEBAF accelerator laboratory and in part by supplemental funds from DOE.

The common theme that unifies our studies of strong interactions and hadronic systems is an effort to experimentally determine the electromagnetic response as completely and exclusively as possible, and interpret the results. This comes from our recognition that many dynamical processes combine in the observables in a complicated way, and that developing a complete description of the system offers the best opportunity for significant advancement.

Our general approach to pursuing these goals is through coincidence detection of exclusive final states and by determining the dependence on the spin variables using polarized beams, targets, and outgoing nucleon polarimetry. Specifically, our past accomplishments include providing several complete descriptions of low-lying nuclear bound state spectra using high resolution inelastic electron scattering, decomposing much of the giant resonance region of several nuclei into their separate multipole matrix elements using coincident measurements of hadron emission, isolating correlations by exclusive, high resolution measurements of proton knockout to weak states, and initiatives in triple coincidence ($e, e'pp$) reactions. This approach led to our origination of the Bates Large Acceptance Spectrometer Toroid (BLAST) program, and guides our involvement in the CEBAF Large Acceptance Spectrometer (CLAS) and Hall A Collaborations. Within the time period considered in this proposal, we will embark upon major new programs of kinematically complete coincidence measurements of the unpolarized and polarization dependent electromagnetic responses of nucleons and nuclei.

Our nuclear modeling objectives are to organize and interpret these data through

a consistent description of a broad spectrum of reaction observables and to make predictions for our forthcoming program. Our structure calculations currently achieve world-class agreement with energy levels and transition densities starting from a single two-body interaction. We also seek consistent relativistic models to interpret multi-GeV reactions, based on both nucleon-meson and quark-gluon degrees of freedom.

Our instrumentation development is devoted to achieving the physics objectives discussed above: increasing the specificity of reaction variables using higher resolution, larger acceptance devices, with coincidence detection, particle identification, and spin definition. In addition, this work also satisfies the now accepted general requirement for participation in collaborations.

In Section B we summarize our initiatives, accomplishments, and progress towards our goals over the past three years. We also review the current status of our active projects and what is planned for the remainder of this year. In Section C we present our program for the next three years. In Section D we discuss the resources required to execute the plan.

B. Progress Summary for July 1990–July 1993

The shift in electromagnetic physics from execution of ongoing programs to preparations for new facilities is reflected in our own accomplishments for the past three years. In general, our extensive activities supporting development of programs at new laboratories partially replaced data acquisition with existing facilities, while analysis and publishing of former results remained roughly constant.

Our major contributions towards preparation for new facilities include defining the physics programs, providing leadership in the collaborations, and developing the instrumentation. We developed and defended proposals for three physics programs, now approved for Bates, Novosibirsk, and CLAS, with three others pending. We served several terms in elected office in the leadership in the BLAST and CLAS collaborations. In our instrumentation development program, we have designed, developed, tested, and delivered the forward angle time-of-flight scintillators for the CLAS, and are committed to building the complete scintillator system. With the award of separate CEBAF contracts, the UNH Nuclear Instrumentation Laboratory efforts led to several substantial improvements to this system, including the design of compact, low power, gain stabilized photomultiplier assemblies with improved time resolution. We have led the design of the trigger electronics for the CEBAF Hall A spectrometers. We developed many of the major BLAST subsystems, and are committed to trigger implementation and wire chamber fabrication once funding is forthcoming. We have begun developing a polarized ^3He target, partially supported internally by UNH, for use at Bates and CEBAF.

On the experimental side, we planned and helped execute an experiment at NIKHEF on $^{12}\text{C}(e,e'pp)$ in the dip region. A new set of giant resonance data, obtained at Bates immediately prior to the time period being reviewed here, was analyzed and led to two Ph.D. theses. We have also analyzed and published several sets of existing data from Mainz, NIKHEF, and Bates, producing another Ph.D. Our participation in collaborations included one of the first measurements of polarized electron scattering from polarized ^3He at Bates. We are presently shipping equipment to Saskatoon for our tagged photon experiment to be run this summer, under the present grant, and we are collaborating on two upcoming Bates runs.

Our data interpretation efforts have been extended and enhanced through state of the art modeling of spherical nuclei. New results to provide a consistent framework for describing multi-GeV reactions on nuclei were completed. Calculations are also underway to assist in the interpretation of the $(e,e'pp)$ data and planning for CEBAF.

B.1 DIRECT REACTIONS

Nucleon-nucleon correlations resulting from tensor forces and short range repulsion lead to high momentum components in the nuclear wave-function. Exclusive direct knockout measurements are sensitive to these components by identifying spectator nucleons in orbits above the Fermi level or in the continuum. Our studies of direct exclusive one and two nucleon knockout have the following physics objectives:

1. Measure spectroscopic factors for $(e,e'p)$ to final states with particles above the Fermi level to provide a quantitative result for correlations leading to occupation of these levels.
2. Measure the first two nucleon knockout $(e,e'pp)$ cross section to provide a benchmark constraint on estimates of the short range interaction in the medium.
3. Demonstrate proof of method for more ambitious studies to map out the momentum dependence of the correlation function in the nuclear medium.

During the period 1991-1993 our initiative at NIKHEF to study short-range correlations in nuclei by the triple coincidence reaction $(e,e'pp)$ became our main experimental activity in direct reactions. Our earlier measurement of long-range correlations in oxygen by $(e,e'p)$ moved through analysis to publication. We began also to contribute to studies of fundamental neutron form factors by participation in an inclusive scattering measurement of polarized electrons from polarized ^3He . This area will become an increasingly important part of our program.

B.1.1 Completion of $^{16}\text{O}(e,e'p)$

$^{16}\text{O}(e,e'p)$ was the Ph.D. thesis project of Mark Leuschner. The data analysis, performed at UNH, was a very thorough and refined study of systematic effects in $(e,e'p)$, including both instrumental and theoretical sources. On the instrumental side, we were the first to explore and adjust the geometrical relationships between the beam on target and the spectrometer jaw locations using the shape of the two-dimensional randoms spectrum. On the theoretical side, we explored the sensitivity to different optical potentials for final state interactions, and adjustments in the potential consistent with the proton scattering data.

Mark also included in his analysis the new density dependent interactions of Jim Kelly¹⁾ that provide a successful description of the inelastic proton scattering. The coupled channels code CHUCK was installed on the UNIX workstations to explore the influence of multistep processes. An expanded method for angular momentum

Fig. 1. Missing energy spectrum of ^{16}O .

Fig. 2. Momentum distribution of weak states.

decomposition of the continuum into an incoherent sum of l -orbitals was implemented. Acquisition of our RISC workstations was essential to the timely completion of this analysis.

Spectroscopic strengths to the weak states measure occupation of the $2s_{1/2}$ and $1d_{5/2}$ orbitals above the Fermi level in ^{16}O . The cross sections were extracted with high precision due to the good energy resolution (Fig. 1) of the two spectrometer system, and the purity that comes from using water and heavy water targets. The individual contributions are separated by the different momentum content of the $L=0$ and $L=2$ orbitals (Fig. 2). Examination of the extracted spectroscopic strength of the $1p_{3/2}$ and $1p_{1/2}$ orbitals for different choices of the optical potential revealed large sensitivity of the $1p_{3/2}$ spectroscopic factor on the choice of optical potential, while the $1p_{1/2}$ was relatively insensitive. (Fig. 3) Constraining the optical potential used in the final state interactions was identified as the largest source of systematic uncertainty in $(e,e'p)$. An analysis of the continuum (Fig. 4) clearly revealed strength from the $1s$ and $2s$ orbitals,

as well as p- and d-state strength. No evidence for $L=3$ strength was observed. Mark finished his thesis last year. He submitted a paper on his results to *Physical Review*, and is preparing a letter comparing the experimental results to our nuclear structure calculations.

Fig. 3. Momentum distribution of the p-shell states compared with calculations using various optical models. Although good agreement is achieved for all fits, the extracted spectroscopic factor of the $1p_{3/2}$ depends on the choice of potential.

Fig. 4. Multipole decomposition of the continuum shows substantial localized strength in the p-shell, with some distributed strength in s-, p-, and d-shells. Agreement is excellent between the integrated decomposition (histogram) and fitting discrete states when they can be separated (dots).

B.1.2 $^{12}\text{C}(e,e'pp)$ in the dip region

Fig. 5. Missing energy spectrum of two-nucleon knockout.

The $^{12}\text{C}(e,e'pp)$ experiment to decompose the quasielastic dip region into its various channels received four weeks of beam time during September and October 1990 at NIKHEF. Triple coincidences were measured in the EMIN Hall, using the QDQ spectrometer, and two specially designed hadron detectors. The reaction was measured at fixed inelasticity in the dip region, but with several proton angles in the reaction plane. Counting rates for true triple coincidence events were approximately one per hour. These data complement earlier data taken by the same NIKHEF/VU/UNH/Lecce collaboration in the delta excitation region, and complete the existing triple coincidence program. Analysis is proceeding at NIKHEF and VU. Initial results reveal knockout associated with two protons in the s-shell and two protons in the p-shell, but very little strength associated with one proton in each shell. (Fig. 5) The measurement of $^{12}\text{C}(e,e'pp)$ in the dip region is being analyzed at the Free University as the Ph.D. topic of Leon Kester.

B.1.3 $^{12}\text{C}(e,e'pp)$ in the Δ region

Fig. 6. Two-dimensional timing spectrum of events from the $^{12}\text{C}(e,e'pp)$ triple coincidence measurement.

Fig. 7. Best fit functional form used to extract cross sections in the central peak corresponding to true triple coincidences.

We contributed to the analysis of the $^{12}\text{C}(e,e'pp)$ in the Δ region. We developed new techniques for handling data with high kinematic dimensionality that is acquired with large acceptance spectrometers. Typically the data points are sparsely distributed throughout the kinematic space (Fig. 6). Our sparse data fitting routines can extract multidimensional cross sections from these data sets. Tim Smith applied these techniques to our $(e,e'pp)$ data and extracted cross sections (Fig. 7). He also explored the properties of the technique, finding formulas for the most probable value of the likelihood function and its probability distribution. He connected these distributions with the curvature matrix to extract uncertainties in the traditional way. All statistical formulae were checked with Monte Carlo simulations. The physics has led to a Ph.D. thesis of Albert Zondervan at NIKHEF. We have written a publication on the fitting technique that has been accepted for publication in *Nuclear Instruments and Methods*.

In addition, since we had been involved in the design and development of the electronics for the hadron detectors, in particular the voltage dividers for the calorimeter layers, we helped in the writing of a publication on the hardware. This paper was

submitted to *Nuclear Instruments and Methods* this past spring. In addition, this experience led to the design which was incorporated into the PMT assemblies of the CLAS TOF scintillators.

B.1.4 CEBAF physics program

We received approval from PAC5 for our experiment at CLAS to measure two and more nucleons emitted from the three nuclei, helium three and four and carbon, in an effort to disentangle the reactions contributing to the continuum. We also joined a proposal, conditionally approved by PAC5, to measure response functions with polarized helium three. For PAC6 we have developed two proposals, both are extensions of our studies on ^3He to exclusive measurements.

We are shifting our emphasis to carrying out this program. We are working on the theory of multihadron currents, Monte Carlo event simulation and cross section extraction, on-line event software, and scintillator and wire chamber hardware efforts. Our theory efforts (described below) are focussed on deriving cross sections from fundamental assumptions about the nature of the two-body current, with the goal of eventually doing the inverse problem, that is, extracting the nature of the current from the measurement. Our simulations allow us to determine the accuracy needed to extract certain features from the cross sections. On-line event software improvements we have accomplished will allow us to accumulate the needed statistics in all kinematic dimensions, and replay the data more than once. Scintillator timing improvements will help in particle identification. Wire chamber operation with helium gas mixtures will drastically improve momentum resolution for highly ionizing particles, particularly important for experiments on nuclei involving detection of slow protons.

Representing UNH involvement in the physics program at CLAS, Bill Hersman served three terms as elected chairman of the Nuclear Multihadron Reactions Physics Working Group and served concurrently on the CLAS Coordinating Committee. His and Jan Distelbrink's service as elected chairman of the time-of-flight technical working group is discussed below in the context of our technical contributions.

B.1.5 Study of the $P_{11}(1440)$ Roper resonance

Fig. 8. Cross section and target asymmetry in the invariant mass region of the Roper calculated with and without including the resonance shows strong sensitivity.

Fig. 9. Experimental arrangement at the INP storage ring VEPP-3, including the internal target storage cell, the wire chambers and the calorimeters.

During his visit to UNH in January 1992, Stas Popov suggested that we consider doing experiments in Novosibirsk. We proposed a coincidence measurement of target asymmetries of proton inelastic states, with an emphasis on the Roper $P_{11}(1440)$. The present configuration of the detectors include the Roper in the middle of their acceptance with their 2.0 GeV electron beam. Model calculations indicate that target asymmetries are very sensitive to the scalar amplitude through an interference with the magnetic Born terms and other resonances (Fig. 8). Theoretical studies indicate that a quark transition should have a large scalar amplitude, while a quark-gluon hybrid should have little or no scalar amplitude.

During the March 1992 BLAST workshop in Tempe, Arizona, an agreement was reached between the members of the deuterium T_{20} collaboration (NIKHEF and Argonne) that study of proton excitations should be approved. Bill Hersman traveled to

Novosibirsk in July to examine the details for the measurement (Fig. 9). The acceptances, stopping power, and efficiencies of the existing detectors were calculated and, unfortunately, found to be marginal, especially for the kinematics most sensitive to the longitudinal-transverse interference amplitude. Extending the detectors seemed not to be practical. Also modification of the target holding field magnet without breaking vacuum posed a challenge. The experiment is not planned for the immediate future.

B.1.6 Large acceptance detector physics simulations

At the beginning of this funding period, we developed a capability of performing simulations to determine detector acceptances and counting rates. Our Monte Carlo code, written by Mark Leuschner, can utilize cross sections for a variety of reactions. Jean-Marc Laget provided calculations of the multidimensional plane wave longitudinal response for the reaction ${}^3\text{He}(e,e'pp)$. We also included a model of the $d(e,e'p\pi^-)p$ reaction. We used the dominant M1 excitation amplitude for the $p(e,e'p)\pi^0$ response. This reaction was kinematically smeared by folding with the deuteron momentum distribution. These calculations were used to define the multiparticle capabilities of the BLAST detector, served in optimizing the BLAST acceptance, and defining its capability to accomplish the physics program. (Fig. 10)

Acceptances and count rates can be calculated by applying a probability correction factor, usually the cross section, to a uniformly populated distribution. Extracting events whose probability of occurrence is equal to the cross section is more difficult. Mark has extended MPMC to produce events according to their real probability. He has further extended the program to fit these data as though they were an actual data set and extract response functions and their uncertainties. We can now model the accuracy of extracting certain response functions with specific detector geometry and integrated luminosity. Winfried Leidemann²⁾ recently sent us his polarization response functions for the $d(e,e'p)$ reaction. We plan to incorporate these predictions into our simulations. Mark performed simulations using a subset of the new deuteron distributions, used the events to fit response functions, and presented the results at the Washington APS meeting in 1992.

Activities over the past year were concentrated on conversion of the source code from PASCAL to FORTRAN, and acquiring reaction models. (It was originally written in PASCAL as a contribution to the NIKHEF-K program on $(e,e'pp)$.) The conversion was necessary for three reasons. First, since the program is compute-intensive it is important that the code be portable and run on the fastest machine. FORTRAN

Fig. 10. Count rates expected for the $^2\text{H}(e,e'p\pi^-)$ reaction as measured by the BLAST. The count rate is plotted against the angle of the proton (left) and the angle of the pion (right).

compilers are more readily available on the latest advanced workstations than PASCAL compilers. Secondly, memory limitations are relaxed in FORTRAN. Finally, source codes to calculate nuclear model cross sections are more readily available in FORTRAN. This conversion was completed by Mark and Irwan The. Two new reaction models, one for nucleon resonances and one for deuteron quasielastic scattering, have been acquired and are being incorporated into the code for simulations. These activities are discussed in the context of our plan for the next three years.

1. J. J. Kelly, *Phys. Rev. C* **39** (1989) 2120.
2. W. Leidemann, E. L. Tomusiak, and H. Arenhövel, *Phys. Rev. C* **43** (1991) 1022, and W. Leidemann, private communication.

B.2 GIANT RESONANCE STUDIES

In 1983, a program of experiments was initiated at Mainz using the MAMI-A 183 MeV electron microtron to study nuclear giant resonances with the $(e,e'c)$ reaction, where c is a charged particle, by a collaboration of researchers from the Max Planck Institute in Heidelberg, the University of New Hampshire, the Jožef Stefan Institute in Ljubljana, and Mainz. When the Mainz experimental program ended, the UNH group continued the experiments in collaboration with Stanford, the University of Virginia, and MIT at the Bates accelerator, and more are planned. In this section, we will discuss the primary motivation for this program of experiments, an overview of the experiments themselves, and the present status of the analysis.

The goal of these experiments is a kinematically complete description of the charged particle decay of the giant resonances in the $1p$ -shell nuclei ^{12}C and ^{16}O to all open channels. These two nuclei have long been testing grounds for microscopic models of the giant resonances. Yet, until now, data have been limited. All previous electron scattering experiments were inclusive single arm measurements, and almost all photonuclear and capture experiments were sensitive only to ground state transitions. In these microscopic models, the giant resonances of $J^\pi = 1^-, 2^-, 3^-$, and 4^- in both nuclei are composed of the same basic $1p$ - $1h$ configurations. By mapping out, and comparing for both these nuclei, the excitation and decay to all channels as a function of transferred momentum and energy, we will be able to perform the most sensitive test of these models.

The electrons are scattered into a conventional magnetic spectrometer. The charged reaction products are detected in an array of silicon solid state detector telescopes in order to perform charged particle identification and measure the complete angular correlations for the various particle types. The use of these telescopes in the environment of an electron beam was pioneered by John Calarco at Stanford and installed by him at Mainz. This technique allowed the first complete studies of the decay by charged particle emission from giant resonances excited by the electromagnetic interaction. To date, we have performed measurements up to 0.95 fm^{-1} . The analysis allows one to decompose the cross sections into multipole form factors for the various allowed decay channels and for the different electromagnetic response functions.

In particular, we have measured the electric dipole and quadrupole form factors for proton emission from the giant resonances of ^{12}C and ^{16}O for various final states in ^{11}B and ^{15}N respectively. We have investigated the electromagnetic longitudinal/transverse interference response function and its sensitivity to the relative phases of these nuclear

currents. We have measured the monopole, quadrupole, and octupole contributions to alpha emission and extracted the corresponding form factors. The $^{12}\text{C}(e,e'\alpha)$ measurements at Bates and Mainz constituted the thesis project of Dave DeAngelis. Dave and John Calarco have recently published some of these results in *Physical Review Letters* and are preparing a larger publication. All the proton decay results are presently in draft form.

B.2.1 The Mainz program

The Mainz program provided the first high quality complete angular correlations for proton and alpha emission (as well as other charged ions) from giant resonances leaving the residual nuclei in all available final states, for a full range of excitation energy spanning the resonance, and for a range of transferred momentum from 0.24 to 0.74 fm^{-1} . Although the Mainz program ended in 1989, it has taken several years to completely analyze and interpret the enormous amount of data. Part of the delay was due to the concentration of the original analysis on fitting the angular correlations to the formalism of Kleppinger and Walecka¹⁾ which is applicable to some but certainly not all of the data. During this past three years, considerable progress was made towards completing the analysis of $^{12}\text{C}(e,e'x)$ and $^{16}\text{O}(e,e'x)$ data from Mainz and preparing them for publication. We have reanalyzed much of the original data after discovering some errors in the original analyses at Mainz. We have made doorway model calculations for comparison with the analyzed data and are now receiving continuum RPA results from some of the world's experts. In the sections to follow, we present the status of the analysis of various cuts on the data.

B.2.2 Measurements of $^{12}\text{C}(e,e'p_0)$ at Bates

In June 1990, we completed our first long data run on $^{12}\text{C}(e,e'x)$ in the giant resonance region at Bates. Data were collected for both $x=p,\alpha$ for transferred momenta of 0.75 and 0.95 fm^{-1} . We will discuss the proton data here and the α data later. The $^{12}\text{C}(e,e'p)$ Bates data and analysis were the thesis work of Gail Dodge from Stanford for whom John Calarco served on a thesis committee. Final normalizations are in progress in preparation for publication. In this section, we review this work.

Protons were detected in four-detector telescopes (see Fig. 11) capable of stopping them with energies up to about 20 MeV in order to obtain information on a possible isovector quadrupole resonance at excitation energies above the dipole state. However, to date, the analysis has been concentrated on protons of $E_p \leq 12\text{ MeV}$ due to some

Fig. 11. Top view of telescope with 4 silicon detectors. Permanent magnets sweep away electrons with less than 2 MeV.

Fig. 12. Schematic arrangement of telescopes rotated to $\phi_x = 135^\circ$ about v_q .

calibration problems with the last detectors in each telescope. This proton energy range still overlaps that available for the Mainz data and the combined data sets from both laboratories allow the angular correlation coefficients for the dipole resonance region to be observed as continuous functions of q from 0.24 to 0.95 fm⁻¹.

At the out-of-plane angle used in the Mainz and Bates measurements, 135°, as shown in Fig. 12, the proton angular correlations can be fit to an expression of the form¹⁾

$$\sigma(\vartheta_p) = \sum_k A_k P_k(\cos\vartheta_p) - 0.707 \sum_k B_k P_k^1(\cos\vartheta_p)$$

where the sums over k run to twice the highest significant multipolarity, the first sum is a multipole expansion of the longitudinal and transverse response functions R_L and R_T , and the second sum is a multipole expansion of the longitudinal/transverse interference function R_{LT} .

The next four figures display the coefficients A_0 (where $4\pi A_0$ is the cross section integrated over proton angle), A_1/A_0 , A_2/A_0 , and B_2/A_0 for $^{12}\text{C}(e,e'p_0)$ as functions of excitation energy for all measured values of q from 0.24 to 0.95 fm⁻¹ and thus includes both the Mainz and Bates data sets. A_0 clearly shows that the familiar shape of the dipole resonance observed in photonuclear reactions dominates the cross section for most of this range of q . (Fig. 13) We see a structure around 19 MeV growing with increasing q . This is the well known 2^- , 4^- doublet. In the measurements at the highest two values of q , this structure becomes comparable to the dipole resonance. The fact that all structure becomes washed out is in large part due to the energy resolution of the Bates beam of 0.3% which amounts to 1 MeV at the 315 MeV used for the highest q measurements. However, the other coefficients in ratio to A_0 show an excellent consistency which lends confidence to the measurements. A_1/A_0 is due to interference of the dominant dipole resonance with underlying E_0 and E_2 strength. (Fig. 14) A_2/A_0 is the basic "shape" coefficient and is more or less consistent with unity near the peak of the dipole resonance and with that expected from photonuclear results. (Fig. 15) Off-resonance, other multipole contributions are clearly becoming increasingly important as q increases. We discuss B_2/A_0 (Fig. 16) in detail in the next section.

Fig. 13. Fitted A_0 coefficient for the Mainz and Bates $^{12}\text{C}(e,e'p_0)$ measurements.

$$A_1/A_0$$

Fig. 14. Fitted A_1 normalized to A_0 .

$$A_2/A_0$$

Fig. 15. Fitted A_2 normalized to A_0 .

Fig. 16. Fitted B_2 normalized to A_0 .

B.2.3 The third response function in $^{12}\text{C}(e,e'p_0)$ and $^{16}\text{O}(e,e'p_0)$

In the course of the measurements at Mainz and Bates, we have made the first determination of the third response function R_{LT} for excitation and decay of giant resonances. We are completing the analysis of the measured R_{LT} for the reactions $^{12}\text{C}(e,e'p_0)$ and $^{16}\text{O}(e,e'p_0)$, combining the Mainz and Bates data sets for ^{12}C and incorporating a recent analysis of higher q Mainz data for ^{16}O . Furthermore, from our data analysis, we have (partially) decomposed R_{LT} into its multipole contributions.

Fig. 17. Fitted B_2/A_0 integrated from 20 to 26 MeV and plotted vs. q .

To the extent that the cross sections are dipole dominated, B_2 constitutes a measurement of the dipole component of the third response function. The last figure in

the previous section shows the quantity B_2/A_0 vs. excitation energy where $4\pi A_0$ is the cross section integrated over ϑ_p . Dividing by A_0 removes the q -dependence due to the overall cross section and leaves the q -dependence due to the change in *shape* of the correlation. It is clear from these measurements that B_2/A_0 decreases in magnitude as q increases, eventually passing through zero and changing sign.

We implemented Bill Donnelly's shell model code SHOWME²⁾ on our system. Using SHOWME to generate form factors and coupling these with decay amplitudes for the ^{12}C and ^{16}O giant resonances from a Stanford thesis by Dave Mavis,³⁾ we have now calculated the third response for the two reactions for a range of kinematics covering both the Mainz and Bates measurements for models involving interfering dipole doorways. The results confirm our expectation that the third response is very sensitive to the relative phases of interfering doorway configurations and that the measurements clearly show the effects of such interference. At the present time, Sabine Kopp in Jülich and Giampaolo C in Lecce are both carrying out RPA calculations for comparison with these results, Kopp using a G-matrix approach and C a Landau-Migdal parametrization of the residual interaction.

Fig. 17 displays B_2/A_0 for $^{12}\text{C}(e,e'p_0)$, integrated over excitation energy from 20 to 26 MeV (encompassing the GDR), vs. q , compared to our doorway calculations and Kopp's preliminary RPA results. The data clearly show a change in sign occurs near $q=0.7 \text{ fm}^{-1}$. Our calculations show that this is primarily due to a change in sign of the collective transverse form factor, predicted by the p-h model but not by the Goldhaber-Teller (GT) model. The GT form factors do not change sign in this range of q and are clearly in disagreement with observation. There is also a contribution from the spin-flip transition form factor, which is of opposite phase to the collective transverse contribution at low q . The preliminary RPA results are not in agreement with the trend of the data. This is not presently understood.

The draft of a *Physical Review Letter* discussing these results is essentially complete. We are only awaiting the final RPA calculations.

B.2.4 Comparison of the $^{12}\text{C}(e,e'p_0)$ and $^{16}\text{O}(e,e'p_3)$ reactions

In any model of the giant dipole resonance incorporating 1p-1h excitations from the 1p-shell, one would naively suspect that comparing the $^{12}\text{C}(e,e'p_0)$ and $^{16}\text{O}(e,e'p_3)$ reactions would show them to have similar angular correlations since both reactions leave the residual nuclei with one hole in the $p_{3/2}$ orbit. Our doorway calculations confirmed this suspicion. However, the experimental observations are at odds with

Fig. 18. Comparison of A_0 and A_2/A_0 for $^{12}\text{C}(e,e'p_0)$ (triangles) and $^{16}\text{O}(e,e'p_3)$ (circles) along with our doorway calculations, dashed for ^{12}C and dot-dashed for ^{16}O . The solid line is the experimental photonuclear value⁴⁾ extrapolated to our q using Kleppinger and Walecka.¹⁾

this expectation. Fig. 18 shows the A_0 and A_2/A_0 for these two reactions. While the theoretical predictions for A_2/A_0 are similar, the experimental values are quite different. We recently reanalyzed the data and obtained the same fitted coefficients.

We are presently awaiting the RPA results of Kopp and C6 to see if a less naive theoretical approach leads to predictions more consistent with observation. However, we expect the RPA results to be reasonably consistent with the doorway calculations since the shape of the correlations is primarily dependent on the partial waves of the outgoing proton and their relative phase. The partial waves are constrained to be d and s by the 1^- identity of the resonance, and while the phases may be somewhat dependent on internal structure, they are in large part determined by the proton kinetic energy and potential well depth which are essentially the same if the calculation puts the resonance at the observed energy. Nevertheless, when we submitted these results for publication, a referee demanded we compare to more modern calculations rather

than our doorway results.

Therefore, the draft of this Letter remains essentially complete. When the final calculations arrive, we will include those results.

B.2.5 Quadrupole strength in the ^{12}C and $^{16}\text{O}(\text{e},\text{e}'\alpha)$ reactions

Last year, a Letter was submitted and published on the analysis of the isoscalar $E2$ strength observed in the $^{16}\text{O}(\text{e},\text{e}'\alpha)$ reaction which resolves a long standing discrepancy. The observations confirm the strength seen in earlier work at the real photon limit in the $^{12}\text{C}(\alpha, \gamma_0)^{16}\text{O}$ reaction and disagree with the earlier observations from $^{16}\text{O}(\alpha, \alpha'\alpha)$, which claimed about three times as much strength. Our measurements also include the first information on the form factors associated with this strength.

This past year, we completed the analysis of the $^{12}\text{C}(\text{e},\text{e}'\alpha)$ reaction. This was facilitated by implementing and debugging the Mainz analysis code EUMEL, which was accomplished by Dave DeAngelis. We again find $E2$ strength in disagreement with that seen in exclusive hadron induced reactions on ^{12}C . However, in the case of ^{12}C , the disagreement is in the opposite direction from that observed for ^{16}O ; we find more $E2$ strength in $^{12}\text{C}(\text{e},\text{e}'\alpha)$ than seen in $^{12}\text{C}(\alpha, \alpha'\alpha)^{5)}$ by a factor of about three and slightly more than claimed from $(\text{p},\text{p}'\alpha)^{6)}$. The disagreement is further aggravated by the fact that in both $(\alpha, \alpha'\alpha)$ and $(\text{p},\text{p}'\alpha)$ the total exclusive cross section was *assumed* to be $E2$ in nature, whereas our multipole decomposition shows significant contributions from both $E0$ and $E3$. Fig. 19 displays our cross sections and $E2$ contribution in comparison to the hadron reactions for both α_0 and α_1 emission channels. This work constituted the Ph.D. thesis of Dave DeAngelis and recently appeared in *Physical Review Letters*.⁷⁾

The question has often been raised as to the existence or non existence of giant quadrupole resonances in light nuclei. In both ^{12}C and ^{16}O , we see substantial fractions of the isoscalar quadrupole sum rule, approximately 37% and 19% respectively. However, this strength is not concentrated in any single large resonance but, rather, in a combination of isolated, narrow ($\sim 1\text{-}2$ MeV) resonances on top of a more or less monotonic continuum. So the strength exists but does not appear to be contained within any kind of coherent collective structure. It is interesting to note that, since the sum rule for ^{16}O is larger than that for ^{12}C by a factor of about 1.6, the fractions just quoted imply that the absolute strengths are approximately equal in these two almost neighboring nuclei.

Fig. 19. Comparison of our cross sections and $E2$ contribution with those from $(p,p'\alpha)^{6)}$ and $(\alpha,\alpha'\alpha)^{5)}$

B.2.6 Analysis of the $^{12}\text{C}(e,e'p_1)$ and $^{16}\text{O}(e,e'p_3)$ angular distributions

While the $(e,e'p_0)$ angular correlations have been analyzed using both unconstrained Legendre fits as well as those with coefficients constrained using the Kleppinger and

Walecka formalism, angular distributions of the $^{12}\text{C}(\text{e,e}'\text{p}_1)$ and $^{16}\text{O}(\text{e,e}'\text{p}_3)$ reactions have recently been reanalyzed at UNH using only the unconstrained Legendre polynomial fit. When we attempt to use the constrained fits, interpretation is hindered due to an ambiguity between two solutions with equal χ^2 , which can only be resolved by eliminating either the transverse or longitudinal response. The source of this ambiguity is that, while we know the coefficient of the P_2 Legendre polynomial for p_0 emission at the real photon limit from photonuclear and capture data, the same is not true of emission leaving the residual nuclei in excited states. The result is that the data can be fit with drastically different sets of coefficients each giving the same χ^2 .

The practical solution is a measurement at the real photon point, which is purely due to the transverse response. To this end, we made count rate calculations and submitted a proposal to carry out these measurements at Saskatoon using their tagged photon facility. This proposal was approved for 240 hours in January of 1992, and beam time has been scheduled for the forthcoming July. We will discuss this in more detail in the section on our proposed activities for the forthcoming year.

B.2.7 Quadrupole strength in the $^{12}\text{C}(\text{e,e}'\text{p}_0)$ and $^{16}\text{O}(\text{e,e}'\text{p}_0)$ reactions

We observe $E2$ strength in the GDR regions in both $^{12}\text{C}(\text{e,e}'\text{p})$ and $^{16}\text{O}(\text{e,e}'\text{p})$, at least in the $(\text{e,e}'\text{p}_0)$ channels (we see the effect of $E2$ in the higher channels but cannot quantify it until the ambiguity discussed above is resolved). The primary effect of $E2$ is to interfere with the dominant $E1$ and produce significant forward-backward asymmetries. Mathematically, this shows up as fairly large coefficients for the P_1 and P_3 Legendre polynomials. We have already shown the P_1 coefficient, A_1/A_0 for $^{12}\text{C}(\text{e,e}'\text{p}_0)$. For the $(\text{e,e}'\text{p}_0)$ channels, there is some inconsistency between the coefficients of the P_1 and P_3 Legendre polynomials, indicating possible $E0$ strength, which may contribute to the former but not the latter by interfering with the dominant GDR. This effect is still being pursued by one of our collaborators, Milan Potokar in Ljubljana, Slovenia, who is performing some calculations.

B.2.8 Summary and status of publications

The $(\alpha, \alpha'\alpha)$ results for both ^{12}C and ^{16}O have recently been published in *Physical Review Letters (PRL)*. Both of these reported on isoscalar quadrupole strength. A larger paper is presently being submitted to *Physical Review C (PRC)* describing the complete multipole decomposition for $^{12}\text{C}(\text{e,e}'\alpha)$. The results on the third response function in ^{12}C and $^{16}\text{O}(\text{e,e}'\text{p}_0)$ are in final draft form for submission to *PRL* pending

final RPA calculations. The comparison of $^{12}\text{C}(\text{e},\text{e}'\text{p}_0)$ and $^{16}\text{O}(\text{e},\text{e}'\text{p}_3)$ has been submitted and revised for submission to *PRL* also pending final RPA results. Two large papers are in preparation for *PRC* describing the Mainz experiments on $^{12}\text{C}(\text{e},\text{e}'\text{p})$ and $^{16}\text{O}(\text{e},\text{e}'\text{p})$. When the final normalizations are completed for the Bates $^{12}\text{C}(\text{e},\text{e}'\text{p})$, those results will be submitted to *PRC*.

1. W. E. Kleppinger and J. D. Walecka, *Ann. Phys. (N.Y.)* **146** (1983) 349.
2. T. W. Donnelly, *Phys. Rev.* **C1** (1970) 883.
3. D. G. Mavis, Ph.D. Thesis, Stanford University (1977), unpublished.
4. R. G. Allas, *et al.*, *Nucl. Phys.* **58** (1964) 122.
5. H. Riedesel, *et al.*, *Phys. Rev. Lett.* **41** (1978) 377.
6. G. D'Erasmo, *et al.*, *Z. Phys.* **A299** (1981) 41.
7. D. DeAngelis, *et al.*, *Phys. Rev. Lett* **70** (1993) 2872.

B.3 MODELS OF NUCLEAR STRUCTURE

Over the last twenty years a large amount of data has been collected on (e,e') cross sections for elastic scattering and for the excitation of discrete nuclear levels resulting in the determination of nuclear ground state densities or transition densities between the ground state and the excited nuclear state. The UNH group has contributed significantly in the past to this collection of data through experiments at Bates, Saclay or NIKHEF-K. The goal of this program has been to provide precise data for the testing of quantitative descriptions of the nuclear many body system, and by doing so to stimulate new methods to solve for the nuclear many body system.

This data has helped us to understand the importance of modeling in the analysis of the data. The modeling has been in the form of very detailed non-relativistic Hartree-Fock and shell model descriptions of nuclei, and in studies of the relativistic nuclear model, and sub-nucleon degrees of freedom. The non-relativistic modeling provides a description of nuclei consisting of protons and neutrons, and based on two body forces. These calculations start from realistic soft-core interactions. They avoid the intermediate step of computing a G-matrix by including multi-particle correlation energies in a finite nucleus description. The relativistic modeling work includes some meson degrees of freedom in addition to the nucleons in a mean-field description. This work has a more fundamental theoretical foundation, but lacks the ability to treat low-lying nuclear states in detail.

In addition, we have started an investigation of sub-nucleon degrees of freedom, and in a related development, we have begun a study of a semi-classical description of QCD and time-dependent problems in field theory. Application so far has been to the time evolution of a quark-gluon plasma created by the collision of heavy ions.

B.3.1 Hartree-Fock calculations

In the past, the emphasis of our group has mostly been on collecting (e,e') data and providing an analysis that yielded densities for comparisons with theoretical predictions; however, we have become increasingly active in improving the methods and foundations for the calculation of these quantities. Our efforts have gone mainly towards developing approximations that go beyond the effective interaction Hartree-Fock description for the ground state and RPA for the excited states. This change in emphasis has been assisted by the fact that already a huge body of data does exist and that the high resolution (e,e') facilities had been mostly unavailable for high resolution scattering experiments due to the development of stretcher rings at these facilities. As a result,

only one high resolution experiment on ^{138}Ba has been carried out by our group in the past three years. However, we have continued with the interpretation of the data collected earlier.

During the past five years we have worked and collaborated with theorists from the former Soviet Union, employing an improved treatment over the RPA by constructing from the RPA phonons a basis of one-, two- and three-phonon states. As in shell model calculations, mixed states are calculated as eigenstates of the effective hamiltonian in that basis. This results in a more realistic description of the nuclear structure as the collective strength is more fragmented due to mixing with two- or three-phonon states which otherwise would carry no strength at all. This treatment has been applied to the Ce-nuclei where we had taken a large number of data.

Our own developments have been based on our earlier treatment of effective operators in shell model calculations. In this treatment the effective interaction as well as any other effective operator is calculated via a transformation $\mathbf{T}$ in the full Hilbert space as $\mathbf{O}^{eff} = \mathbf{T} \mathbf{O} \mathbf{T}^\dagger$. This transformation $\mathbf{T}$ was generated by the condition that any further corrections to the effective interaction in the truncated shell model space vanish as calculated using the Feshbach projection operator formalism. By dealing with this, we had shown also previously that this condition is equivalent to the generalized Hartree-Fock assumption namely that the shell model ground state with its correlations is the state of minimum energy.

With this result it seemed proper to turn our attention to the Hartree-Fock treatment of spherical nuclei first. During the last three years we have developed a software package that allows us to generate wave functions including correlations for spherical nuclei. In particular we have been applying this to ^{16}O . These calculations had been carried out in a space of $\approx 20 \hbar\omega$.

During the fall of 1992, J. Heisenberg participated in the INT workshop on nuclear structure and reported on our nuclear structure modeling. This workshop was extremely helpful. There were two significant results from this workshop impacting on our developments:

- (1) It was found that our method of generating the effective interaction for shell model calculations was first published by Lee and Suzuki¹⁰⁾. It had been generally agreed at this workshop that this procedure is likely the most effective way for generating the effective interaction as it avoids all the convergence problems of the perturbation treatments. While this was a welcome confirmation of our methods, it pointed out the need to get away from phenomenologically adjusted

interactions for which the relationship to real nucleon-nucleon interactions is not determined and incorrect treatments can be masked by meaningless adjustments of parameters.

- (2) Estimates indicated that our Hartree-Fock calculations may be carried out in a large enough space so that we can use realistic nucleon-nucleon interactions.

To implement these conclusions we obtained from R. Wiringa (Argonne) the program for the Argonne-V8 potential. At the root of all our calculations is a computer code that calculates two-body matrix elements for realistic finite range nucleon-nucleon interactions. Such a program has been available to us from previous work with S. Krewald in Jülich. This program, however, did not contain a finite range spin-orbit interaction and it failed for large n orbitals due to numerical instabilities. During the last six months we have solved those problems, and presently we are debugging the new program that includes the spin-orbit force and is accurate up to $40 \hbar\omega$ orbits and above. Also, recently we have increased the size of the basis for the actual calculations in ^{16}O to $\approx 20 \hbar\omega$. This basis already appears to be sufficiently large for the use of real interactions without any prior renormalizations which include a repulsive core and fit the nucleon-nucleon phase shifts. Furthermore, all the programs have been modified such that they can be adjusted without substantial work to handle even larger bases. Thus it appears to be possible to perform a direct calculation of the nuclear structure with its correlations rather than renormalizing the interaction in infinite nuclear matter and subsequently using this renormalized interaction for the calculation of finite nuclei.

The present package of programs allows for a calculation of the Hartree-Fock ground state as well as for the calculation of phonons by means of TDA. Furthermore, we have developed two new programs. The first computes the two-body density for the nuclear ground state from the generated wave functions, and the second program calculates cross sections for the $(e,e'2p)$ reaction based on the correlated ground state alone.

We have worked out many details for the calculation of the nuclear ground state by means of a variational Hartree-Fock calculation. These details are:

- (a) development of the equations that establish the size of the correlations based on the variational principle such that the ground state with its correlations minimizes the energy expectation value.
- (b) establishment of a consistent approach to Hartree-Fock single particle energies and single particle wave functions.
- (c) working out the transformation to natural orbits and their occupation numbers.

- (d) development of the program to calculate the two-body density.
- (e) development of a $1/A$ -expansion for the center of mass corrections in the one- and two-body density operators which does not rely on harmonic oscillator wave functions and thus can be applied to the Hartree-Fock wave functions.

We have generated a Hartree-Fock computer code in which the ground state for the nucleus is represented by a Slater determinant on which multi-particle-hole correlations are built. The amplitudes for the 2p2h correlations are explicitly calculated as these dominantly modify the two-body density in the ground state and thus are needed to handle a short range repulsion in the nucleon-nucleon force. Higher order correlations such as 3p3h or 4p4h are included implicitly, as they influence the amplitudes of the 2p2h-correlations. These correlations for ^{16}O are calculated presently in a space of $20\hbar\omega$. This space can easily be expanded to $40\hbar\omega$ and beyond.

The Hartree-Fock principle is equivalent to the condition that the expectation value of any ph-operator in the ground state vanishes. This alone, however, is not sufficient to establish the single particle wave functions as this condition is not affected by any unitary transformation within the particle-space alone or a unitary transformation within the hole-space alone. Thus one has to introduce additional constraints. We have chosen the constraint that the one-body part of the full hamiltonian be as diagonal as possible for ph-excitations. However, since for ph-excitations the shape of the p-orbit is not independent of the energy of the hole-orbit we have chosen an energy weighted ph-energy for the diagonalization. This procedure fully determines some Hartree-Fock single particle orbits and their energies, however, one has to keep in mind that ph-excitations are not exactly diagonal with respect to the one-body part of the hamiltonian. At the present time we make the assumption that the non diagonal terms are small enough to be neglected.

In our description of the ground state the 2p2h correlations take the form

$$\mathbf{T}_2 = \sum_{p_1 h_1, p_2 h_2, \lambda} Z_{p_1 h_1, p_2 h_2}^\lambda (\mathbf{p}_1 \mathbf{h}_1^{-1})_\lambda \otimes (\mathbf{p}_2 \mathbf{h}_2^{-1})_\lambda$$

This 2p2h correlation causes the major contribution to the two-body density. We find that the dominant correction to the HF two-body density takes the form:

$$\Delta\rho(r_1, r_2, \theta_{12}) = 2 \sum_{p_1 h_1, p_2 h_2, \lambda} (2\lambda + 1) Z_{p_1 h_1, p_2 h_2}^\lambda \rho_{p_1 h_1}^\lambda(r_1) \rho_{p_2 h_2}^\lambda(r_2) P_\lambda(\cos\theta_{12})$$

Correspondingly we can associate the 3p3h correlation as the major contributor to the three-body density.

B.3.2 TDA calculations

In our approach ground state correlations are not calculated as a dynamical property of transitions but as a static property of the nuclear ground state similar to the large scale shell model calculations. Thus we can write the correlated ground state as

$$|\tilde{0}\rangle = (\mathbf{1} + \mathbf{T}^\dagger)|0\rangle,$$

where the operator $\mathbf{T}^\dagger$ creates the *nph* excitations. As a consequence, the elementary excitations from the correlated ground state that are orthogonal to the ground state can be written as quasi-particle-hole excitations given by

$$\mathbf{O}_{p,h_i}^\dagger |\tilde{0}\rangle = (\mathbf{1} + \mathbf{T})^{-1} \mathbf{a}_{p_i}^\dagger \mathbf{a}_{h_i} |\tilde{0}\rangle \approx (1 - T) \mathbf{a}_{p_i}^\dagger \mathbf{a}_{h_i} |\tilde{0}\rangle$$

The general form of the one-phonon states can be written as

$$|1 - phonon\rangle = \boldsymbol{\Omega}_n^\dagger |\tilde{0}\rangle = \sum_i X_i^n (\mathbf{O}_{p_i,h_i}^\dagger + \sum_{j,k} \alpha_{jk}^i \mathbf{O}_{p_j,h_j}^\dagger \mathbf{O}_{p_k,h_k}^\dagger) |\tilde{0}\rangle$$

Here the coefficients α_{jk}^i describe the coupling to two-quasi-particle-hole excitations. These coefficients are calculated such that the one-phonon excitations no longer couple to the two-quasi particle-hole excitations. The amplitudes X_i^n that describe the one phonon states are calculated using the Tamm Dancoff Approximation.

In this description there are two significant elements that account for the quenching of the transverse scattering amplitude in the excitation of nuclear levels in electron scattering: The transformation to quasi-ph excitations, which admix the backward going amplitudes, and the coupling to two-quasi-ph excitations, which accounts for missing strength both in the longitudinal and transverse scattering. While in RPA the backward amplitudes in a transition of multipolarity λ depend only on the ph-hp matrix element of multipolarity λ and thus is small for large λ , in our treatment these amplitudes are much larger due to exchange terms from low multipolarity contributions.

A computer code handling these TDA calculations has been written and is working.

B.3.3 Phonon coupling

Two-phonon states can be created from the solutions of the TDA calculation as

$$|2 - \text{phonon}\rangle = \Omega_n^\dagger \Omega_k^\dagger |\tilde{0}\rangle$$

By construction of the operator Ω the coupling between one- and two-phonon states is largely eliminated except for small terms not included in the calculation of the coefficients α^i_i . However, there is a significant cross-coupling between the two phonons in the two-phonon excitation, which shifts the energy of the two-phonon excitations down. For example, in ^{16}O , one-phonon excitations are the negative parity states such as 1^- , 3^- , 2^- , etc. Two-phonon states can be constructed as e.g. $(3^- \otimes 3^-)_{0+}$. While without the cross coupling the energy would be twice the one-phonon energy, i.e. 12.2 MeV, the coupling shifts the energy down by several MeV so that we can assign to the 0^+ state at 6.03 MeV a structure that is mostly two-phonon.

The computer code has been working for smaller spaces. At the present time, using the codes for a space of $40\hbar\omega$ appears not possible.

B.3.4 Analysis of experiments

Most of our projects of high resolution (e,e') experiments have been completed with reports on the results published. These publications are shown in section B.5.1.

Recently we have exchanged information with K. H. Maier from the Hahn-Meitner Institut at Berlin, Germany, on the identification of excited states in ^{208}Pb . Their assignments are in rather close agreement with our assignments as published in the thesis of J. Connelly. We expect that combining this information with our data may make it easier to publish the remaining results from our experiment on ^{208}Pb .

B.3.5 Relativistic nuclear model

During the past few years, J. Dawson has been working on various aspects of the relativistic nuclear model, or quantum hadrodynamics (QHD), developed by Dirk Walecka and Brian Serot. This theory is a relativistic mean-field theory of baryons and mesons that uses a scalar sigma meson to represent the intermediate range nucleon-nucleon attraction, and a vector meson for the repulsion. It leads to a model of nuclei which relies on relativistic effects to describe the average nuclear potential and the spin-orbit force. The model has met with considerable success for the consistent description of

spin-dependent scattering and ground state properties. J. Dawson has been very active in the development of this model. Along with R. J. Furnstahl, he was one of the first to show how to describe nuclear excitations as a linear RPA response of the relativistic mean-field model ground state. We showed¹⁾ how to construct an RPA theory using the analytic structure of the ground state Hartree green's functions for finite nuclei, and, for the first time, showed that by using a large enough basis, we could extract the spurious center-of-mass motion from the spectrum, and that we could maintain current conservation. The relativistic RPA theory has been extended by J. R. Shepard, E. Rost, and J. A. McNeil²⁾ using a non-spectral approach, and by J. Piekariewicz³⁾ to include vacuum polarization effects at the one-loop level.

In the relativistic mean-field nuclear model, the pseudoscalar isovector mesons, such as the pion, play a minor role. However, in order to obtain a reasonable picture of isovector excited states, such mesons must be included. In a first step towards understanding pion dynamics, we studied the pion self-energy for a pion propagating in a nuclear matter ground state obtained in a mean field approximation to the Walecka model⁴⁾ We found that (unexpected) relativistic effects, due to the reduced nucleon mass, weakened the transition to pion condensation, and that it would be unlikely that one could find condensation at high nuclear densities. These results were preliminary and used a non-chiral lagrangian. Effects of the Δ were not included. It seems that much more work needs to be done to include isovector mesons. This difficulty has prevented detailed application of the relativistic model to low energy nuclear structure.

B.3.6 Variational methods for QHD

It was found early on⁵⁾ that the two-loop corrections to QHD for nuclear matter were large and that the loop expansion for QHD was not convergent. In an effort to find an alternative expansion method, J. Dawson and a graduate student, B. Doyle, attempted a variational calculation of the vacuum state for QHD based on the Schrödinger representation in quantum field theory. This attempt has, so far, failed because of renormalization difficulties. Several model field theories were tried. Finally, following a suggestion from Dirk Walecka, and with the help of Fred Cooper, we are attempting to apply Schrödinger methods to a gauge theory with asymptotic freedom, where we can use scaling. We have also changed the nature of the problem somewhat by looking at initial value problems in quantum field theory. This change in emphasis has proved to be quite fruitful, and we are now using these methods to find equations of motion for the time development of the quark-gluon plasma (see below). It is hoped that the lessons learned can be applied to other strong coupling problems, such as QHD.

Fig. 20. The $(e,e'pp)$ longitudinal response function plotted as a function of the energy loss ω , and the angle between the photon and the center-of-mass decay angle.

B.3.7 Two proton knockout $(e,e'pp)$

We have started a program to find out what can be measured in planned $(e,e'pp)$ studies at CEBAF and NIKHEF-K, and to discover where and how, in the five-dimensional kinematic region, to look for the interesting physics. In light nuclei, such studies have been done, for example, by Laget and Ciofi degli Atti. We have been concentrating on heavy nuclei, such as ^{12}C and ^{16}O , and have been trying to find out if useful information about nuclear structure and dynamics can be obtained by experimental investigations in these nuclei. In general, $(e,e'pp)$ measures directly the two-particle correlations in nuclei. We did a preliminary calculation of the cross section using pair wave functions based on an old calculation by Dawson, Talmi, and Walecka. (Fig. 20) This pair wave function included short range correlations due to a hard core interaction between the particles, and was included in a talk by J. D. Walecka at the 1992 summer workshop at CEBAF. The cross section shows dramatic effects due to the hard core.

B.3.8 Chiral anomaly

Following a suggestion by Barry Holstein,⁶⁾ we attempted to find out if we could test the $\gamma \rightarrow \pi^+ + \pi^- + \pi^0$ chiral anomaly in QCD by an electron scattering experiment at CEBAF. The amplitude for the process is related to the number of colors in QCD, N_c and is given by $\frac{e N_c}{12\pi^2 f_\pi^3}$ where f_π is the pion decay constant. Earlier results by Antipov, *et al.*⁷⁾ taken in conjunction with more recent values of the pion decay constant imply the existence of a fourth color. This is a clear discrepancy with our present understanding of QCD. Using amplitudes given by Holstein, we estimated cross sections for the reaction, $p(e, e' \pi^+ \pi^-) p'$. The experiment depends on the ability to surmise that a π^0 is, in fact, exchanged with the struck proton. The cross sections turned out to have a small phase space and were on the order of 10^{-16} barns/MeV², which gave a count rate of about 30 counts/hr for CEBAF beams. In view of the low count rates, the experiment may be difficult to do. Melissa Kennedy presented these results at the New England sectional meeting in April, 1993.

B.3.9 Sub-nucleon degrees of freedom

In a supplemental proposal to this grant, we were able to bring Fred Cooper, from Los Alamos National Laboratory, and John Dawson and Harvey Shepard, from UNH, together to begin a collaboration in an effort to formulate a time-dependent mean field theory for the creation and evolution of a quark-gluon plasma; such as what is expected to be made in heavy ion collisions at RHIC. This is a very ambitious program. We intend to calculate particle distribution functions for quarks and gluons as a function of time after such collisions. These distribution functions can be used to calculate lepton pair production, and would be the most important signal for the creation of a new form of matter. Dr. Cooper has been working on initial value field theory problems for a long time and is familiar with QCD and hydrodynamical models of the quark-gluon plasma.

We followed previous work on scalar and spinor QED, and on the static QCD problem in strong color fields. We extended this work to the case of a (pure glue) non-abelian $SU(2)$ Yang-Mills gauge field theory, and applied a $1/N$ expansion to the path integral to find mean-field equations of motion for the time-development of the gluon phase, starting from an initial classical color field, and for the back-reaction of the gluons on the field. The process proceeds through the well-known Schwinger mechanism.⁸⁾ There were many technical questions to be solved in this analysis — the correct gauge to choose, the question of the ghost fields, definitions of interpolating field

operators, BRS charge conservation, renormalization and asymptotic freedom, etc. We went through these questions one by one and finally came up with a set of equations that do maintain conservation laws and asymptotic freedom, and we understand how to scale our results so that we can write a computer code to obtain numerical answers. F. Cooper talked about preliminary work on this problem at the HIPAGS '93 conference at MIT in January, 1993, at a Brown University Seminar in February, 1993, and at Dartmouth in March, 1993. J. Dawson also reported on this work⁹⁾ in an invited paper at the Quark Matter '93 conference in Borlänge, Sweden, in June 1993, and a paper is currently being written about our work, and will be submitted for publication. We will report further on this work at the Santa Fe workshop on QCD and Quark Matter to be held July, 1993.

This work is a first step in understanding the time-evolution of the full $SU(3)$ quark-gluon plasma, and is the *only* method that proceeds directly from the complete QCD gauge field theory, which has both gluons and quarks.

It made a tremendous difference to our theoretical efforts at UNH to have Fred Cooper visiting for the past six months. Fred provided expertise in particle physics which we have needed for some time — it was an exciting time for all involved.

J. Dawson has visited the Nuclear Theory Center at Indiana University, CEBAF, and the Institute for Nuclear Theory at the University of Washington, where he took part in the program on Mesons and Fields in Nuclei during 1991-92. He has given talks at Indiana, INT, Saskatoon, and QM93, and has been invited to talk at the NSERC/CAP Summer Institute on "Current Issues in Lepton Scattering in Nuclei," in Kingston, Ontario, Canada.

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B.4 INSTRUMENTATION DEVELOPMENT

The new electron facilities offering continuous beams and polarization open new areas of nuclear physics for investigation. These beam properties need to be matched by conceptually new detector devices that maximize the opportunities for new physics offered by these facilities. A few years ago, the nuclear physics group at UNH made the commitment to play an active and leading role in these detector developments as these detectors will drive the new physics. UNH has made commitments to CEBAF to participate in the CEBAF Large Acceptance Spectrometer (CLAS) development and in the instrumentation for the Hall A high resolution spectrometers. At Bates, Bill Hersman had a leading role in initiating the BLAST project (Bates Large Acceptance Spectrometer Toroid), modeled after the CLAS. Much of our energy and creativity was invested in the design of BLAST, the management of the collaboration, and the development of the proposal. Although the proposal has not yet been funded, the scientific and technological studies are finding applications in planning for the CLAS. Because of many similarities in these detectors they share many design and development challenges.

We have supported our initiatives and collaborative efforts with technical contributions. We provided design and development of stabilized voltage dividers for photomultipliers in the NIKHEF hadron detector. We designed several BLAST components, and tested helium dominated wire chamber gas, critical for high resolution tracking of lower momentum particle trajectories. We developed and published a new data analysis technique for treatment of the sparsely distributed multidimensional NIKHEF data. We contributed a solution of the inverse tracking problem, an algorithm for determining wire chamber tracks from wire chamber information. Our general purpose multiparticle Monte Carlo code, developed over these years, filled a need for BLAST and CLAS reaction studies.

UNH developments for CEBAF have led to three new funding awards two years ago. Our group proposed and performed an engineering design study for compact photomultiplier tube voltage dividers for the CLAS. Our second award, also from CEBAF, was for the fabrication of the forward angle time-of-flight system. The third was a supplemental award from DOE to provide the "missing manpower" we so badly needed to maintain our technical contributions while continuing some physics. We describe our technical efforts and contributions below.

B.4.1 CLAS contracts

In our CEBAF Memorandum of Understanding, UNH took responsibility for scintillator development, wire chamber gas tests, and software improvements. With the award of a CEBAF contract, major developments occurred over the past two years in scintillator development and software contributions. We have also completed our prototype drift chamber to explore the use of helium-dominated wire chamber gas mixtures.

Last year we hired a research technician, Korac MacArthur, and an electrical engineer, Lauchlan Gordon, under contract from CEBAF. Three additional students have joined our project. While these individuals are supported primarily by the CEBAF contract, we discuss their contribution here because it fulfills our material commitment to the scientific collaboration. With a supplemental award, we recently added a new Research Scientist, Jan Distelbrink, directly responsible to help lead the group.

We have performed a complete engineering design of a low-profile voltage divider with high rate capability, under contract with CEBAF. Components are assembled on two sides of a single circuit board and potted, due to space constraints. Gain stability is maintained at high rates by using FETs on the last four stages as low impedance voltage sources, in an upgrade of a design developed by our group in residence at the NIKHEF laboratory, and successfully applied in the $^{12}\text{C}(e,e'pp)$ experiments. Extensive tests have been performed to optimize the high frequency performance for improved timing. Various physical configurations for PM tube sockets, components and connectors were engineered and built by Lauchlan Gordon, our engineer. A nitrogen laser, designed and built in our laboratory by Lauchlan and Jack Wright, was optimized for short reproducible pulses. We also made several improvements to the support structure design and to the scintillator wrapping materials.

The additional contracts required laboratory space. We acquired temporary use of a new room in the Science and Engineering Research Building, and established the UNH Nuclear Instrumentation Laboratory there. We invited the CLAS Scintillator Technical Working Group to UNH for a workshop and site visit in May, 1992. Colleagues from CEBAF, College of William and Mary, Virginia Polytechnic Institute, and Boston University attended. Many design and fabrication issues were discussed, and tours were conducted through our lab and workshop. The group expressed confidence in the abilities of our team. We are currently negotiating for permanent laboratory space.

B.4.2 Scintillators

Fig. 21. Plan of a sector of the forward angle time-of-flight scintillator system for CLAS.

Last year we made several important contributions to the CLAS project. First and foremost, we have nearly completed fabrication of the forward angle time of flight scintillator system, support structure, and PM tube voltage dividers under a contract with CEBAF. (Fig. 21) Particular care was taken in the design of the compact voltage divider. Students developed an extremely compact design, and optimized timing by adjusting resistor values and paying careful attention to distributed inductances and capacitances. Our voltage divider is likely to become the CEBAF standard. (Fig. 22)

Fig. 22. Schematic of the voltage divider.

Fig. 23. Ray tracing in a scintillator and light guide.

The constrained space of the region in the shadow of the CLAS coils required that the light guides be short and stubby. We performed extensive Monte Carlo studies of the pulse shape as a function of the design of the light guide using the code GUIDE7, modified by Tim Smith to provide graphical output (Fig. 23). These studies indicated that the additional photons collected in the PM tube after reflecting from the angled faces of the stubby light guide were essentially all late arrivals, many of them having reflected off the opposite end of the scintillator (Fig. 24). As a consequence we have blackened these surfaces of the light guide to remove late signals due to multiply reflected photons (Fig. 25).

New materials were incorporated into the scintillator design. A steel and foam sandwich support structure locates and supports each scintillator. A thin lead foil provides a low energy photon shield. Rugged black kapton and two aluminum layers

Fig. 24. The pulse in one PM tube of the CLAS time-of-flight scintillator with all surfaces of the stubby light guide polished.

Fig. 25. The pulse with some surfaces of the light guide blackened.

will provide a long lasting light barrier. (Fig. 26) A thermoformed boot provides an integrated light seal and high voltage isolation at the PM tubes. Dark current is measured and recorded for all scintillators. We test and document the timing of each assembled scintillator by injecting laser pulses into the fiber optic as well as with cosmic rays.

Fig. 26. Detail of the scintillator wrapping.

We have begun development of the rear scintillators. The timing performance of the prototypes existing at CEBAF is poor due to the limited photostatistics from these large scintillators. We performed test measurements with two increased diameter (3") PM tubes per scintillator end to convert more photons. By converting twice as many photons we can improve the timing performance by as much as 40% while increasing the cost only 15%. That cost could be recovered in other areas with a minimal impact on performance. The alternative plan, to recover most of the direct photons with a conventional adiabatic light guide has been simulated, but remains to be tested. The status of these plans is discussed in our proposal in Chapter C.

In addition to his directing day-to-day progress on the CEBAF contract at UNH, Jan Distelbrink has CLAS collaboration responsibilities. As chairman of the CLAS scintillator time-of-flight technical working group, he helps plan and lead working group meetings, and he represents this part of the detector at the CLAS Technical Group Meetings at CEBAF every second month. He will also coordinate the integration of this system into the CLAS detector.

B.4.3 CEBAF Hall A event trigger electronics

The UNH nuclear physics group has accepted responsibility for the design and implementation of the event trigger logic electronics for the two Hall A high resolution spectrometers (HRS²). During the past three years, the trigger design has been developed and defended before a technical review committee. In this section, we describe the trigger and its operation.

The basic philosophy underlying the trigger design is that the hardware should be remote (*i.e.*, localized at the HRS²) but controlled from the experimental counting house. This has led a design utilizing currently available emitter-coupled-logic (ECL) modules with remotely programmable parameters.

In the electron arm, signals from the scintillators, Čerenkov detectors, and shower counters are processed in front-end logic to provide a reduced set of signals to the single arm coincidence logic. A similar sequence is followed in the hadron arm, with the exceptions that the shower counters are replaced by the focal plane polarimeter (FPP) and that the number and arrangement of scintillators are different. Electron-hadron coincidence logic is performed in parallel in each spectrometer to provide gates for ADCs and starts for TDCs which are housed locally.

The basic philosophy of the coincidence logic is that a "double handshake" insures clean coincidences with the leading edge timing of that coincidence preserving the prompt trigger timing individually for each arm. Preservation of this leading edge guarantees that ADC gates are opened appropriately for the individual analogue inputs. The double handshake appears to be superfluous, and a single handshake would suffice if each HRS were to be dedicated to the detection of only one type of particle. We have designed the electronics to allow for "second generation" experiments such as (e,pp) and (e,p π) which requires that the electronics be maintained as symmetric as possible.

The data acquisition utilizes sparse readout ADCs and TDCs which are currently available. The advantages of this method are that it is cheap and fast. The disadvantage is that ADC and TDC upper and lower limits must be set to closely match those in the logic to prevent triggers with empty ADCs and TDCs or triggers with spurious ADCs and TDCs.

B.4.4 CLAS event tracking

We have long recognized that a leading technical obstacle for the CLAS project, and the high rate high multiplicity multihadron program in particular, is event reconstruction. The traditional technique of reconstructing the track of an ionizing particle is to start with a guess of the momentum and trajectory of the particle, and integrate it through the magnetic field. A comparison of the calculated signals with the observed signals, provides a correction to the guess for the next iteration (Fig. 27). There are two major resources required by the existing code and technique: computer cycles and computer memory. Reconstruction can take tens of millions of instructions and field maps are several megabytes in size.

Fig. 27. The track of an electron through CLAS.

Fig. 28. Histogram of the difference between an electron's momentum and its reconstructed momentum.

We developed a new tracking method, based on high order interpolation. A small number of analytical formulae are used to represent wire chamber hit information for tracks of different kinematics. Rather than perform an integration of the equations of motion through the field to determine geometry parameters, the code only needs to

evaluate an analytic formula that has been adjusted beforehand to provide the correct answer. Tim Smith implemented a prototype version of this method.

The CLAS collaboration has begun writing the code for the Standard Event Analysis/Distributed Event Processing System (SEA/DEPS). Tim Smith has become integrally involved in this effort. He traveled to CEBAF and the Florida State University to install his prototype algorithm in SEA, improving tracking computational speed by a factor of six, and reducing storage requirements by an even larger factor.

With the early success of our parametrized event tracking method, we have decided to contribute to solving the 'inverse problem': given a set of wire chamber sub-tracks, determine the particle's momentum and emission direction. Tim has developed a prototype solution of the inverse problem based on the previous algorithm. It was able to reconstruct the momentum of the particle with 3% resolution if the sub-tracks are well known (Fig. 28). This reconstruction routine was a factor of over one hundred times faster than the technique of 'swimming' the particle through the magnetic field. The prototype code used a single parametrization with only 18 parameters to describe the entire CLAS. With this speed and resolution this routine can perform the first pass analysis for SEA. Resolution improvements can be achieved by subdividing the momentum space, with no change in CPU requirements.

B.4.5 Multiwire drift chamber development

We originally proposed the use of helium dominated drift chamber gas to minimize multiple scattering and improve momentum. More recently we have recognized that the principal limitation on the luminosity of the CLAS is the rate of photo-ionization of the vertex drift chamber gas. Replacing the argon with helium will reduce this background in the vertex chamber. In addition to these certain advantages, recent work indicates the disadvantages are minimal.

Jyuji Hewitt, our recent Masters student supported by the Army, conducted a study of helium-dominated wire chamber gas mixtures. Measurements were performed at Brookhaven National Laboratory using a large magnet and a small drift chamber. We identified a mixture that provides insensitivity to magnetic fields and low multiple scattering, while retaining stable operation. He also demonstrated that helium dominated mixtures are not substantially slower than the traditional fast gases if the chamber is in a strong magnetic field. Finally researchers elsewhere¹⁾ recently reported that energy loss resolution is not seriously degraded in helium mixtures. Helium mixtures provide substantial improvements in the two most important detector parameters

with no drawbacks. The wire chamber gas mixture studies resulted in a Master's Thesis for Jyuji. We recently completed additional tests of operating parameters with several different gas mixtures to convince the collaboration to switch to helium as the main drift chamber gas component.

We also worked on the development of a wire feedthrough treatment that would reduce noise and corona. Our plan was centered on applying a conductive coating around the tip to eliminate the localized high electric field, and a prototype was made by Vance Pomeroy. He demonstrated at CEBAF the effectiveness of our design. That effort has resulted in the adoption by CLAS of a conductive insert into the feedthrough, eliminating the noise, corona, and wire breaks.

B.4.6 Polarized target development

We have developed a new plan for installing a polarized ^3He target in the CLAS (Fig. 29) for exclusive measurements.²⁾ (An existing program to install a polarized metastability exchange ^3He target and emphasizing inclusive measurements³⁾ is discussed elsewhere.) The key features of the new plan are:

1. Cancellation of field gradients produced by the CLAS inner toroid.
2. Fabrication of a thin, surface-wound magnet for establishing an arbitrary quantization axis.
3. Use of a high density spin-exchange target for minimal sensitivity to remaining magnetic field gradients.
4. Development of thin target windows to eliminate their dominance of the data rate.
5. Achieving maximum CLAS luminosity with the low current, high polarization beam permitted by the high density target.

The CLAS inner toroid sweeps Moller electrons from the vertex drift chamber. The location of the conductors as close as 17 cm from the beam axis leads to gradients within the volume of the pumping cell. Calculations show that a single winding with current flowing in the opposite direction located 4-5 cm closer to the target cancels the leading term in the gradient.

The standard use of Helmholtz coils to provide the target quantization axis can not be adopted for CLAS without substantial modifications. We have designed a surface wound magnet that produces a uniform field. Independent currents in the two

Fig. 29. Views of the spin exchange ^3He target installed in the CLAS inner toroid, including the surface wound magnet, the target and pumping cells, the optics path, and utilities.

perpendicular coils will provide a uniform target field in an arbitrary direction. An orthogonal dipolar winding will provide RF perpendicular to the main field for adiabatic fast passage.

Choice of a high density target offers the best possibility for low sensitivity to magnetic field gradients.⁴⁾ The rubidium spin exchange target has operated at pressures of up to 10 bar.⁵⁾ A 15 cm long target achieves the limiting CLAS luminosity of 10^{34} electrons-nucleons/cm²/sec at a beam current of 100 nA. At this current we can use the high polarization strained crystal source with 75% polarization.

We have developed a glass cell configuration that allows use of thin windows for beam entry and exit from the target cell. It is based on a concave spherical window supported by a hoop on a thicker convex cell. Since the thin window is in compression the full yield modulus of aluminosilicate glass ($\sigma_y=1000$ MPa) can be used in the formula for pressure vessels: $\Delta P_{\max} = 4\sigma_y(t/d)$, where t/d is the ratio of window thickness to diameter. A prototype window 6 mm in diameter with $t=15$ μm has held 5 bar pressure without rupture (Fig. 30). Although scattering from these windows is

Fig. 30. A thin aluminosilicate glass window was successfully blown and tested at UNH.

significant, it does not dominate the luminosity, and can be removed by tracking in the vertex detector.

B.4.7 BLAST detector design

Over the past three years we played a strong role in the development of a physics program to exploit the internal target capability of the new Bates South Hall Ring. The requirements of the program determined the properties of a new detector:

- a) Ability to determine the trajectories of 1 to 3 charged particles emerging on either side of the beam.
- b) Coverage of θ (scattering angle) from forward angles (about 15°) to 90° .
- c) 60° coverage of the azimuthal angle ϕ , i.e. a 30° coverage on either side of the beam.
- d) Particle identification, in particular separation of electrons, protons, and pions in the range of 300 MeV/c to 1 GeV/c.

Fig. 31. The BLAST detector was developed to serve a program of polarized internal target physics at the Bates South Hall Ring.

- e) Good momentum resolution for electrons, protons and pions in the range of 300 MeV/c to 1 GeV/c.
- f) Ability to handle luminosities up to 3×10^{33} nucleons-cm⁻²s⁻¹.
- g) An appropriate space along the axis of the beam line to place polarized gas targets. This means a clear radius of 50 cm and magnetic field gradients less than 0.05 gauss/cm in the central region.

Bill Hersman developed an initial design for the Bates Large Acceptance Spectrometer Toroid (BLAST). (Fig. 31) Subsequently, detailed designs for several subsystems, including the Čerenkov detectors, the wire chambers and the trigger, were prepared by

the UNH group for the BLAST proposal(s).

B.4.8 BLAST Čerenkov detectors

Čerenkov detectors are used as the principal detector in the BLAST for identifying electrons. They play a central role in the event trigger: the presence of a signal above threshold in the Čerenkov being the unique element in an electron reaction. The role requires that they have a well understood, high efficiency for signaling the presence of electrons. They must also discriminate electrons from pions, requiring very low index of refraction.

The Čerenkov design uses gas as the radiating medium, in a specular reflecting enclosure. The magnetic optics of BLAST provide a unique angle in the ϕ -direction for each transverse position y across the entrance face. A particular choice of mirror curvature can image the center axis of each Čerenkov cone to a line at the edge of the detector where the phototubes are placed. The mixture of scattering angles θ with momentum curvatures produces a range of angles for each position x across the entrance face, preventing transverse imaging. The transverse focusing must, therefore be optimized around a central ray. The optical image at the photomultiplier tubes is spread by the Čerenkov cone angle. Winston cones gather the light onto the photomultiplier tube surface.

All reflecting surfaces are aluminum. The reflectivity of aluminum of 85% to 90% extends deep into the ultraviolet spectrum where most of the Čerenkov light is produced. The two-angled flat sides consist of a single thickness of Everbright to minimize the inactive region between detector elements. The bottom flat mirror is also Everbright, reinforced with a fiberglass honeycomb structural plate. The doubly-curved primary mirror surface is aluminized film, either mylar or nylon, reinforced with a fiberglass honeycomb. The Winston cones are molded plexiglass with a vacuum-deposited aluminum surface. Photons can be reflected in three to five bounces to the photomultiplier tube surface.

The end-plates provide the structural support for the photomultiplier tubes and the reflecting surfaces and the attachment points to the outside structure. They are designed to be common to all segments. The attachment will be at a single point on each end to allow for alignment of the segment around its local central ray. This scheme allows for optimizing Čerenkov acceptance for vastly different experimental configurations, especially different target locations, or beam energies.

Fig. 32. The Čerenkov detector system covers electron emission angles from 20° to 90° with five modules.

Segmentation of the Čerenkov detectors is required to discriminate two tracks when one is the electron and the other a pion. Also the angular coverage of a single unit determines the relative angle between the two side faces, being equal to the angular span. Segmentation should not be so fine such that some tracks distribute their light over more than two modules. We have selected a Čerenkov width of 80 cm at the entrance face, corresponding to a 15° angular coverage. The depth of the Čerenkov is 1 m at the sides (by the PM tubes) increasing to 1.4 m in the center. Four photomultiplier tubes with 5" photocathodes receive the Čerenkov light on each side. Fig. 32 shows that five modules cover scattering angles from 20° to 90° with some overlap at the ends.

The Winston cone design determines the angular acceptance of the photon collection. The geometry of a Winston cone is simply a parabola tilted by the desired acceptance angle rotated about the center of the collection surface. This parameter

plays a significant role in the Čerenkov acceptance. Tracks with different momenta receive different amounts of ϕ -focusing, moving their trajectory away from the central trajectory. Photons striking the inclined sides of the module are deflected out of the image line. Tracks originating from different target origins will follow different trajectories. Finally the Čerenkov cone itself contributes to spreading. We have selected a Winston cone acceptance angle of 24° .

The BLAST collaboration and the CLAS collaboration have combined efforts to develop a unified approach to Čerenkov detector development. Researchers at RPI have constructed a prototype detector using a geometry similar to that described here, and using UV transmitting photomultiplier tubes. Tests for three detector orientations were performed in a beam at Brookhaven Laboratory. Efficiency peaked at over 99 %, but varied with orientation. This variation was traced to imperfections in the Winston cones, which have recently been repolished. A detector testing area has been developed jointly by the BLAST and CLAS Collaborations in the Bates 14° area, and initial tests were performed.

Performance of Čerenkov designs can now be simulated using a new Monte Carlo code developed at RPI. This program will model a gas Čerenkov detector that contains flat and elliptical (singly curved) mirrors or ellipsoidal (doubly curved) mirrors, and focusing Winston cones. At present the program allows for

- a) losses of photons due to absorption in the gas,
- b) losses of photons due to absorption by the mirrors,
- c) consideration of the quantum efficiency of the phototubes for detection of photons of varying wavelengths.

The program yields information on the wavelengths of the photons produced, the angle of incidence to the phototube face, the mirrors hit by the photons and the pulse height produced by the event. The UNH group has modified this program to simulate ellipsoidal (doubly-curved) mirrors. The additional degree of freedom in the curvature can be used to maximize the acceptance angles of each Čerenkov detector in both the θ and ϕ directions.

Simulations for a particular chosen geometry have been performed to explore the expected efficiency of the Čerenkov detector over a range of possible trajectories. The ellipsoidal mirror parameters were chosen with vertices at the target origin and the photomultiplier tube face reflected in the plane surface front mirror (a preferred choice would probably be closer to the center of the Winston cone entrance circle). This choice

Fig. 33. The Čerenkov reflector geometry. An ellipsoidal primary mirror directs light to an inclined planar secondary mirror, before the light is collected by Winston cones.

Fig. 34. Inefficiency of the Čerenkov detector is plotted as a function of the two photon entry coordinates. Trajectories are oriented (top) along the central ray, and (bottom) at an angle of 7° with respect to the central ray along the momentum bending direction.

provides perfect imaging for all rays projected through the front face of the Čerenkov detector, called local central rays. (Fig. 33) The local central rays of real particles traced through the magnetic field will have slightly different trajectories, requiring a slightly different choice of mirror curvature for each detector. The geometrical coverage of the primary mirror used in the Monte Carlo (Fig. 34) covers an azimuthal acceptance angle at the target of $\pm 12.5^\circ$. The actual Čerenkov detectors will cover a wider angle, out to about 16° .

B.4.9 BLAST wire chambers

The BLAST drift chambers are similar, in principle, to the drift chambers that are being built for CLAS. Anode wires are 20 μm gold plated tungsten, positioned at the center of a hexagonal field cage of 140 μm gold plated aluminum, as in the CLAS chamber. The distance between sense wires along a wire plane in the center of each of the three regions is 3.0, 4.0 and 5.0 cm. Included in the pattern is one additional field wire on each side of the sense wire, raising the number of cathode wires per anode wire from 2 to 3. (Fig. 35) This wire offers three advantages. It reduces the field strength on the cathode wire surfaces by 2/3 to below 20 kV/cm, it increases the field strength at the edge of the cell reducing the angle dependence of the drift, and it reduces sense wire crosstalk.

The chamber is designed to operate at a gas gain of 10^6 . The inner chamber with a 3.0 cm cell operates at 2600 V. The outer chambers with correspondingly larger cells have higher voltages. The voltage gradient at the anode and cathode wires is 330 kV/cm and 16 kV/cm. The side wires disrupt the symmetry of the cell cathode cage. The six wires in the field cage are repelled from the side wires and attracted to the sense wires. This force per unit length is one tenth that of gravity, but will dominate in our vertically oriented chambers. (Fig. 36) The deflection will be 50 μm for two meter wires under 50 g tension (4.9×10^4 dynes).

The field wires will have 50 g tension, while the sense wires will be at 20 g, far above the electrostatic instability limit. If the tensions are chosen 85 g and 12 g, inversely proportional to their mass per unit length as in CLAS, they deflect equally in gravity. This is not a concern for the vertically oriented BLAST wires. The force on the end plates per cell is 140 g.

Cells are not perfect hexagons aligned on a regular grid. They are oriented along circles centered at the nominal target position. Arcs of these circles included inside the wire chamber regions provide the layout pattern for the superlayers. (Fig. 37) The repeating pattern is terminated at the edges with a collection of guard wires located at the nominal position where the next sense wire would have been located. These guard wires are held at a potential intermediate between the sense and field wires, to optimize the regularity of the fields at the sense wires.

The wires are grouped into superlayers, and the superlayers are grouped into regions. The vertex region has two superlayers with wires oriented at 6 degrees with respect to each other, each with a thickness of 5 wires. The central region has only one superlayer of 5 wires to determine the midpoint on the curved trajectory. Its position

Fig. 35. A comparison of electric field lines for 6 wire and 8 wire hexagonal cells. Fields at the cathode wires are 50% higher on the 6 cell design. Symbols indicate isochrones for drifting electrons.

Fig. 36. Calculated electrostatic force per unit length as a function of position for the hexcell corner cathode wires. The direction of the force is toward the anode wire, away from the side wire. The gravitational force (for horizontal orientation) is also indicated.

Fig. 37. Wire chamber dimensions along the midplane. Wires are laid out along circles centered at the nominal target position. Three distinct regions, the vertex region, central region, and outer region are evident.

He-CH₄ mixtures resp. 95/5, 85/15, 70/30 and 55/44%

Fig. 38. Pulse height measurements in the UNH prototype chamber versus chamber voltage for several gases.

is optimized in the center of the bent trajectory to provide maximum resolution. The outer region has two superlayers with four wires each, again with a 6 degree angle between the directions of the wires.

The gas mixture must provide sufficient ionization, avalanche multiplication and quenching, and resistance to polymerization, with the minimum of multiple scattering. The study of the low scattering wire chamber gas has been the subject of considerable prototyping effort. Mixtures dominated by helium and hydrogen quenched by methane have been investigated. Measured parameters include drift velocity v_d , gain versus voltage, and spatial resolution σ_r , with some relative information on efficiency. Properties of gases tested are listed in Table 1.

Table 1. *Drift Chamber Gas Properties.*

He (%)	CH ₄ (%)	H ₂ (%)	Voltage	v_d (mm/ μ s)	σ_r (μ m)
55	45	0	2700	17	460
85	15	0	2300	23	330
95	5	0	1700	17	330
70	15	15	2600	20	420

The stability of operation of a particular gas mixture is determined by the range over which the gain was exponential, without sparking. (Fig. 38) All gases indicated satisfied that criterion over some voltage range.

The UNH prototype wire chamber was operated with each of these gases using cosmic rays. Drift times from various wires were recorded. A drift-time-to-drift-distance function was determined by adjusting the parameters of the function to provide the straightest reconstructed tracks from the drift times. This adjustment was performed by the standard technique of plotting the distance of closest approach of a fitted straight line against the drift time and extracting a distance to time relation. (Fig. 39) The straight line track can then be plotted as the tangent to circles representing the drift distance (Fig. 40). The wire chamber fit residuals give an estimate of the position accuracy.

Simulations indicate that multiple scattering in the gas is far more important than intrinsic cell resolution for much of the momentum range for electrons and essentially

Fig. 39. The distance of closest approach of a best fit line is plotted against time measured by the TDCs. The extracted drift time to drift distance function is indicated.

Fig. 40. A reconstructed straight line track through the UNH prototype wire chamber. Drift distances are indicated by circles around the sense wires.

all the momentum range for protons. The gas that is ultimately selected for use will be the thinnest gas that allows stable operation. We have specified 85% helium and 15% methane as a leading candidate. An additional component, water, ethanol, or methylal, will be added to suppress polymer growth on the wires.

B.4.10 BLAST event trigger logic and electronics

We have accepted the responsibility for designing and constructing the trigger hardware for the BLAST detector. This design was reviewed by a technical advisory panel and accepted with suggestions for modifications which have subsequently been incorporated.

The trigger logic configuration for BLAST has been designed with the following philosophy: a *first level* trigger will be in place for the BLAST detector at the time of completion of the instrument for initial testing and commissioning; a *second level* trigger will exist in design but will only be implemented if the initial testing indicates its necessity. Accordingly, in this section, we separately describe the designs for the two trigger levels and their costs.

The first level trigger logic configuration for BLAST has been designed assuming

that, while the data acquisition will be done via FASTBUS for the sake of speed, the TRIGGER LOGIC can be done via a CAMAC-based ECL system. The advantages provided by such a logic system are

- (1) compactness,
- (2) full programmability of the logic configuration providing maximum flexibility, and
- (3) immediate off-the-shelf commercial availability of the appropriate modules.

Since the logic configuration output need not be read for each event, there is no loss of data acquisition speed by going to such a hybrid system.

The model chosen for the first level trigger is the loosest possible: an event is defined by any electron in coincidence with any hadron, where a hadron is defined as any non-electron-generated event in a scintillator. An electron is defined by a scintillator signal in coincidence with a physically adjacent Čerenkov. Since essentially all inelastically scattered electrons result in the emission of at least one hadron, the only events lost, within the geometrical acceptance, by this trigger definition are those in which all emitted hadrons are neutral (and there will be some lower but non-zero efficiency for these).

A second level trigger has been designed which incorporates fast wire chamber logic outputs in order to coarsely determine that the event was initiated in the region of the target in order to eliminate background from external sources. This configuration is also based on ECL for all the same reasons as given for the first level logic design as well as to render it compatible with that system.

B.4.11 BLAST Collaboration developments

During the academic year 90/91 F. W. Hersman was on sabbatical leave, giving him the opportunity to spend a large fraction of his time and energy on the BLAST project. As chairman of the BLAST steering committee he helped to develop a coherent physics program, refine the conceptual design of BLAST, and solidify the collaboration.

During March, 1991, a Technical Advisory Panel appointed by the Bates director reviewed the BLAST design and gave it a strong recommendation. In April, the Bates PAC recommended 3200 beam hours for experiments using BLAST, including the UNH proposal to study two nucleon and nucleon-pion knockout. With this recommendation the PAC has strongly endorsed the new physics to be done with BLAST. Also, the BLAST collaboration has grown from approximately 60 physicists from 7 institutions to roughly 80 physicists from 11 institutions.

In September 1991, the BLAST proposal was completed and submitted to the funding agencies. After that time our efforts for the BLAST project shifted from design to preparations for the physics program. We aided in the planning for the BLAST workshop in Tempe and made several contributions. On the technical side, we have participated in the efforts to study injection flash at Bates, both in the planning and preparations and the beam studies. We have interacted numerous times with the funding agencies, laboratory management, and the BLAST collaboration on aspects of the project. Many of the contributions we undertake for the CLAS, including large acceptance Monte Carlo, event reconstruction, and helium dominated gas mixtures, are vital to the BLAST project as well.

During the fall 1992, the BLAST proposal was revised and updated. Commitments were adjusted to reflect a real opportunity for substantial NSF funding involvement. UNH accepted responsibility for the wire chambers, and offered the Cerenkov detectors to Arizona State.

1. Zimmerman *et al.*, *Nucl. Instr. Meth.* **A243** (1986) 86.
2. CEBAF Proposal 93-037, F. W. Hersman, Timothy P. Smith, co-spokesmen.
3. CEBAF Proposal 89-007 and updates, R. McKeown, spokesman.
4. T. Chupp, *et al.*, *Phys. Rev.* **C45** (1992) 915, and references therein.
5. H. Middleton, International Workshop on Polarized Ion Sources and Polarized Gas Targets, Madison, WI, May, 1993.

END

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