

Nuclear Structure at Intermediate Energies

Progress Report

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T. W. Bonner Nuclear Laboratories

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Project Abstract

The year has seen a continuation of experimental and theoretical studies of intermediate energy physics and an extension of development of required instrumentation and applications to medical problems. Experiments have been carried out at the Space Radiation Effects Laboratory (SREL) in the areas of small angle proton and pion multiple scattering, Coulomb-nuclear interference total cross section measurements, and pion therapy dosimetry. Experiments were started in multi-particle final state measurements. These experiments are all preparatory to approved experiments at the Los Alamos Meson Physics Facility (LAMPF). During the year a portable laboratory was constructed in a Fruehauf trailer and an on-line computer system installed that is especially designed for use with many multi-wire proportional counters at LAMPF at high data rates. The principal collaborators in this work were the University of Houston group.

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Progress Report on Contract No. AT-(40-1)-1316, Task C
 Rice University, Nuclear Structure at Intermediate Energies
 Houston, Texas

Personnel working on the project during the year to
 March 31, 1973, includes the following:

G. C. Phillips, Professor and Director of the T. W. Bonner
 Nuclear Laboratories

I. M. Duck, Professor of Physics

V. Valkovic, Associate Professor of Physics

R. F. Guertin, Assistant Professor of Physics

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L. V. Coulson (Ph.D., Univ. of Virginia) Research Associate

C. R. Fletcher (Ph.D., Univ. of Illinois) Research Associate

D. B. Mann (Ph.D., Rensselaer Poly. Inst.) Research Associate

G. S. Mutchler (Ph.D., M.I.T.) Senior Research Associate

T. R. Witten (Ph.D., Virginia Poly. Tech.) Research Associate

B. Chang (B.A., St. John's University) Research Assistant

J. B. Cone (B.S., Arkansas Poly. College) Research Assistant

N. D. Gabitzsch (M.A., Rice University) Research Assistant

K. Hogstrom (M.A., Univ. of Houston) Research Assistant

G. Pfeufer (M.A., University of Maryland) Research Assistant

T. M. Williams (B.S., Texas A & M University) Research Assistant

J. A. Buchanan (B.S., Univ. of Houston) Research Engineer

W. P. Madigan (Georgia Tech - no degree) Research Engineer

R. L. Hopper, Technician

J. Windish, Technician

Physics Shop Personnel

Genevieve Wright, Secretary

1. Background for the Work

This report marks the fourth year for this task and is submitted after 45 months of operation. Considerable progress has been attained and has resulted in the publication of 10 papers, and the granting of 5 M.A. and 3 Ph.D. degrees to date.

In the original proposal (December, 1968) four activities were contemplated: a) continued collaboration with Palevsky's BNL group; b) collaboration with the University of Houston group for studies using protons and pions at intermediate energies; c) development of experimental systems, especially multiwire proportional counters and on-line computer systems; and d) collaboration with LAMPF.

Additionally, there has developed interests in applying intermediate energy technologies to problems in bio-medicine and other fields.

Progress in these areas is given below.

2. Collaboration with Brookhaven National Laboratory

The earlier collaboration of Rice with Palevsky's group has been finished for some time except for publication of the results. During this past year the last of this series of papers was published.¹⁾

3. Experiments in Intermediate Energy Physics at the Space Radiation Effects Laboratory (SREL) (Rice-University of Houston)

This collaboration is now about three years old and continues to be satisfactory. The collaboration continued to carry out experiments at SREL on the 600 MeV Synchrocyclotron using beams of protons and charged pions, and considerable progress was made. This work is preparatory to the work during the coming years at L.A.M.P.F. where four approved experiments are planned to start during 1973. The areas of research during the year have been: 1) studies of small angle proton and charged pion Coulomb multiple scattering; 2) studies of small angle Coulomb-nuclear interference scattering of pions; 3) studies of π^{\pm} total cross sections for nuclei; 4) studies of three-particle final states in such reactions as $pd \rightarrow ppn$. The progress on these experiments is given below.

3.1 Studies of Small Angle Proton and Pion Coulomb Multiple Scattering. Since the nuclear force may interfere with the Coulomb force it is possible that current theories (such as Molière's) of small angle multiple scattering may be inaccurate. Two experiments have tested these theories.

3.1.1 Proton Multiple Scattering. 600 MeV protons were used for several elemental targets. Multi-wire proportional counters and scintillators were used for trajectory measurements. The

results show deviations from Molière Scattering and a paper presenting the data has been accepted for publication.

3.1.2 Pion Multiple Scattering. π^{\pm} were used at a series of energies across the 3/2-3/2 resonance for a series of target elements, and systematic deviations from Molière scattering were observed. The data have been compared to all available electron, pion, muon, and proton data in a paper that will be shortly submitted for publication.

3.2 Studies of Coulomb-Nuclear Interference Scattering.

Pions of a few hundred MeV, in scattering from nuclei at small angles (5° - 15°), experience nearly equal Coulomb and nuclear forces which may interfere either constructively or destructively. Most theories of pion-nuclear scattering suppose that the strong nuclear ($T=3/2$) interaction of π^+p and π^-n are the same while the interaction ($T=1/2$ or $3/2$) of π^-p and π^+n are supposed to be the same. Thus, if either charged pion scatters from a self-conjugate ($N=Z$) nucleus, the nuclear force is expected to be the same and can be represented by an amplitude f_N that is independent of the charge on the pion. The Coulomb amplitude, of course, obeys

$$f_c^+ = -(f_c^-)^*.$$

Thus if the total amplitude f^{\pm} can be written as the sum of f_N^{\pm} and f_c^{\pm}

$$f^{\pm} = f_N^{\pm} + f_c^{\pm}$$

since the differential cross section is just

$$\frac{d\sigma^{\pm}}{d\Omega} = |f^{\pm}|^2$$

it follows that

$$\frac{d\sigma^{+}}{d\Omega} - \frac{d\sigma^{-}}{d\Omega} = 4 \operatorname{Re}(f_N^{+}) \operatorname{Re}(f_C^{+}).$$

Since f_C^{+} is known (calculable) this formula allows the difference of the π^{+} and π^{-} cross sections for a $N=Z$ nucleus to give the real part of the nuclear amplitude.

This real part should vanish at resonance (which for π -nucleon scattering is near 190 MeV). Several experiments have been carried out to test these ideas.

3.2.1 Small Angle $\pi^{\pm}-^{12}\text{C}$ Scattering from 115 to 240 MeV.

This project has been completed and the results have been published.²⁾

3.2.2 Coulomb-Nuclear Interference in $\pi^{\pm}-^{16}\text{O}$ Elastic Scattering.

The previous $\pi^{\pm}-^{16}\text{O}$ differential cross section measurements at 120, 155, and 185 MeV have been extended to 215 MeV. In addition $\pi^{-}-^{16}\text{O}$ data at 155, 185, and 215 MeV were collected. The measurements covered the Coulomb-nuclear interference region from $4-12^{\circ}$ around the (3,3) pion nucleon resonance. In this angular region the difference of the π^{+} and π^{-} data directly determines the sign and magnitude of the real part of the forward nuclear scattering amplitude ($\operatorname{Re} f_N(0^{\circ})$). This information plus

the the imaginary part ($\text{Im } f_N(0^\circ)$) obtained from total cross section data (see below) via the optical theorem, will completely determine the nuclear scattering amplitude at 0° . Such information provides an important constraint for pion-nucleus scattering models and allows an experimental test of forward nuclear dispersion relations.

The data clearly show constructive interference for π^+ (and destructive interference for π^-) at 215 MeV. The interference disappears between 155 and 185 MeV. This confirms the downward shift of the (3/2,3/2) pion-nucleus resonance with respect to the pion-nucleon resonance previously reported in $\pi^\pm -^{12}\text{C}$ scattering. (Figure 1) The LAMPF Program Advisory Committee has allotted beam time for a systematic study of this effect during 1973.

Progress reports on this work have been presented at the Washington and Seattle APS meeting.^{3,4)}

3.3 Studies of Pion-Nucleus Total Cross-Sections. Pion nucleus total cross-sections are fundamental to studies of pion-intermediate physics. The optical theorem relates the imaginary part of the forward scattering amplitude to the total cross-section by

$$\sigma_{\text{total}} = (4\pi/k) \text{Im} \left[f_N(0^\circ) \right] \quad \text{and}$$

in combination with Coulomb-nuclear interference data allows the amplitude f_N to be determined.

Figure Caption: Comparison of experimental results obtained for $\text{Re } f_N(0^0)$ in $\pi^{\pm-12}\text{C}$ and $\pi^{\pm-16}\text{O}$ scattering with the predictions of pion-nucleon forward dispersion relations. The open circles are $\pi^{-12}\text{C}$ scattering,¹⁾ closed circles are $\pi^{+12}\text{C}$ scattering,²⁾ and x's are $\pi^{\pm-16}\text{O}$ scattering.³⁾ The curve labelled "old" is the $\text{Re } f_N(0^0)$ versus E for $\pi^{-12}\text{C}$ scattering calculated from forward dispersion relations by Locher.⁴⁾ The curve labelled "new" is a calculation made by Landau and Locher⁵⁾ on the basis of more recent results for the $\pi^{-12}\text{C}$ total cross sections.⁶⁾

1) F. Binon et al., Nucl. Phys. B33 (1971) 42

2) M. L. Scott et al., Phys. Rev. Lett. 28 (1972) 1209

3) Present results

4) M. P. Locher, Nucl. Phys. B2 (1967) 525

5) see Figure 7 in Reference 1)

6. F. Binon et al., Nucl. Phys. B17 (1970) 168

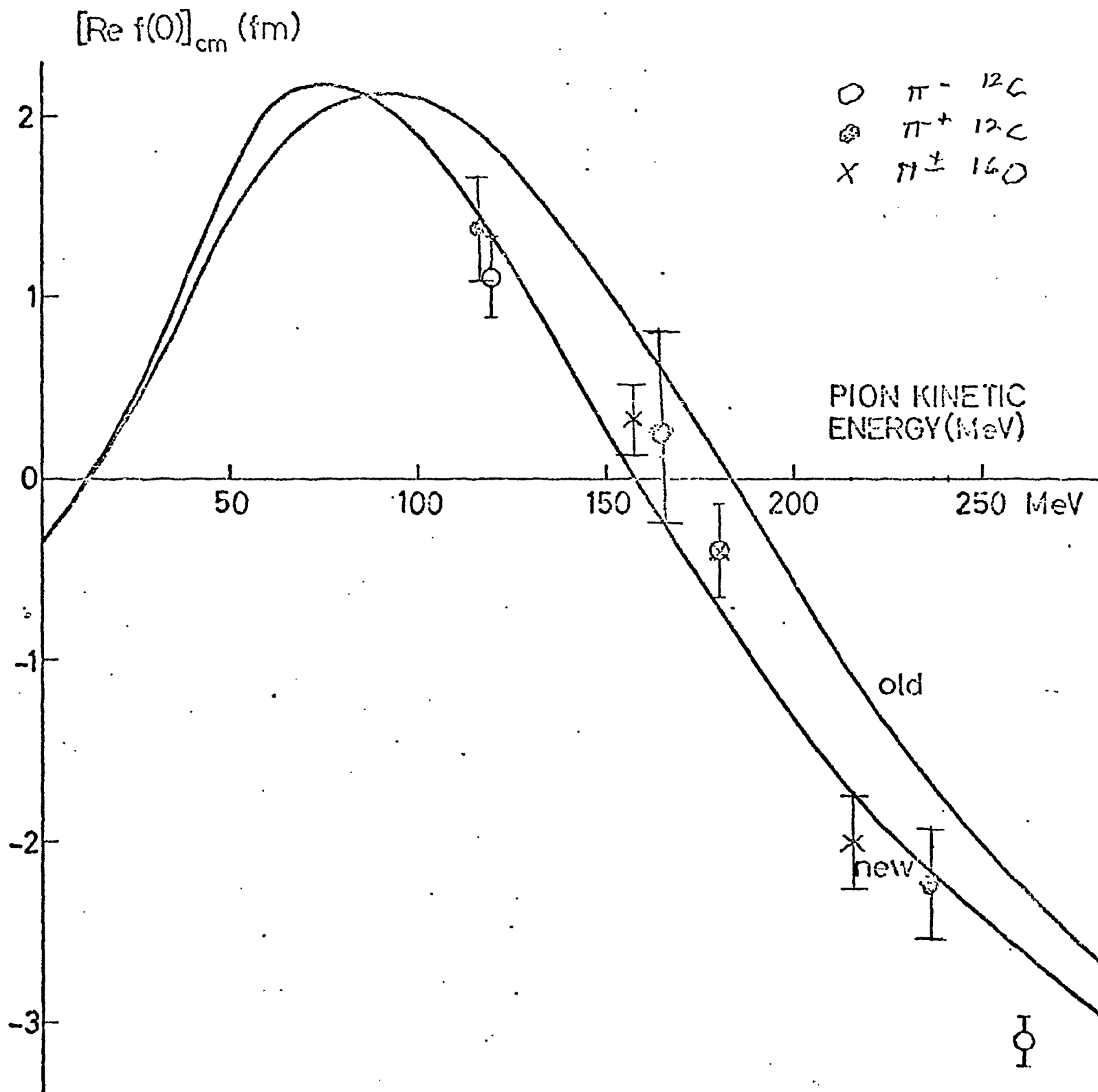


Fig. 1

3.3.1 Survey of π^{\pm} Total Cross Section and Small Angle Scattering Around the $(3/2, 3/2)$ Resonance. Total cross section and small angle scattering data have been collected for π^+ on ^{12}C , ^{27}Al , H_2O , and ^9Be at energies 120, 140, 155, 180, 200, 215, and π^- at energies 155 and 215 MeV. Preliminary analyses of $\pi^+ - ^{12}\text{C}$ at 180 MeV and 215 MeV are consistent with CERN $\pi^- - ^{12}\text{C}$ data. Analyses of the remainder of the data are now in progress.

3.4 Multi-Particle Final State Reactions at Intermediate Energies. A fundamental type of study in all strong-interaction physics involves measurements of multi-particle final states. Such studies give information on reaction mechanisms, final state interactions, quasi-free scattering, rescattering effects, off-energy shell effects, etc. Approved experiments at LAMPF call for our carrying out both proton and π^{\pm} induced multi-particle break-up experiments. Preparatory work to these experiments has been underway during the past year at SREL.

3.4.1 p+d Break-up at 600 MeV. Equipment and techniques have been tested to determine the optimum conditions to perform a kinematically complete three-body experiment in the intermediate energy range using MWPC, scintillators, and magnetic spectrographs. Preliminary data have been taken on p-d break-up at the angle pairs $41^\circ - 41^\circ$, $41^\circ - 55^\circ$, and $41^\circ - 61^\circ$ to survey the quasi-free scattering and final state interaction mechanisms at 600 MeV. Analysis of the data and a critical

study of the data collection system are now in progress.

3.5 Nuclear Activation by Pions. An interest has developed in nuclear chemistry, especially nuclear activities induced by intermediate energy beams.

3.5.1 Pion Activation Measurements. Carbon and fluorine targets were bombarded with a positive pion beam at SREL in April, 1972. The method of activation analysis was employed to measure the sum of the (π^+, π^+n) and (π^+, π^0p) reaction cross sections in the region of the $3/2, 3/2$ resonance. Results for the $^{12}\text{C}(\pi^+, \pi n)^{11}\text{C}$ reaction differ from previous measurements,⁵⁾ being 20% lower, and such differences cannot be explained. Preparation of a publication to summarize the experimental methods and results is now in progress.

4. Application of Intermediate Energy Physics

The interest in applications (principally medical) of intermediate energy physics has continued to develop during the year and some progress has been attained. The principal collaboration with the Rice-University of Houston group has been from Drs. George Oliver and Walter Grant of the M.D. Anderson Hospital and Tumor Institute, and Dr. Morris Taylor of Columbia Scientific Industries.

4.1 Elemental Analysis of Bone and Tissue by μ^- -X-rays.

This work has been continuing with improvements in

instrumentation, and a paper has been submitted for publication.

4.2 Dosimetry for Pion-Therapy. This work has been continued during the year at SREL in preparation for an approved experiment at LAMPF.

5. Intermediate Energy Theory.

5.1 Zitterbewegung in Relativistic Spin 0 and Spin 1/2

Hamiltonian Theories. The previous work of one of the authors (Guth) has been extended to investigate the role of Zitterbewegung in the "doubling" of Hamiltonian equation such as the Dirac equation. The results have been applied to the recent spin $\frac{1}{2}$ equation of Biedenharn, Han, and Van Dan (submitted to Physical Review).

5.2 Hamiltonian Theory for Arbitrary Spins. A Hamiltonian

which is of second order in the three-momenta and which factorized the Klein-Gordon equation has been found for a particle of arbitrary spin. The theory is Poincare invariant, but not manifestly covariant, and appears to require Bose statistics for second quantization, regardless of the spin.

5.3 Spin $\frac{1}{2}$ Boson in an External Electromagnetic Field. An

external electromagnetic field has been introduced into the Guertin-Guth Hamiltonian for spin $\frac{1}{2}$ particles in the usual gauge-invariant manner. The energy levels in a Coulomb field and in a constant homogeneous magnetic field have been calculated, but it remains to be demonstrated that the equation

is relativistically invariant in form.

5.4 Coupled-Channel Bootstrap Model for Regge Trajectories.

A bootstrap model is under investigation in which the n^{th} particle on the 0 -meson Regge trajectory is a resonance in the two-particle channel consisting of a π -meson and the n^{th} particle on the π Regge trajectory. The static approximation is being employed for each channel with $n \geq 2$.

6. Instrument Development for Intermediate Energy Physics.

Instrument development has continued to be emphasized strongly because of the new types of experiments that are contemplated for LAMPF. A report on "An In Flight Pion Beam Flux Monitor" has been published.⁶⁾

6.1 Development of Multi-wire Proportional Counters. Develop-

ment of MWPC's has continued:⁷⁾ a clean room has been built to improve quality control in the construction of the wire counters. Engineering techniques have been developed to allow for the construction of large (0.5 x 0.5) MWPC. A large counter (0.5m x 0.5m) has been built and preliminary tests have been performed.

6.2 On-Line PDP-11/MIOP/CAMAC System. During the year this system became operational in most fundamental aspects and a paper describing the system has been given.^{8,9)}

6.2.1 PDP-11/20 and PDP-11/45 Computers. During the year the 11/20 was accepted and operated and an 11/45 modification was ordered as AEC-owned capital equipment for delivery in 1973.

6.2.2 MIOP and CAMAC. The Multi-Programmed and Multi-plexed Input-Output Processor (MIOP) was completed and became operational as an interactive interface between CAMAC and the PDP-11/20. This Rice invention has had a patent applied for (Patent Case S-42,345) through the Oak Ridge Operations Office. Basic CAMAC modules were acquired.

6.2.3 Systems Development. During the year considerable effort was spent in developing the System for use in 1973 at LAMPF.

6.2.3.1 Software Development. The command list structure has been finalized and implements with assembling, linking, and loading capabilities. Command lists can be stored on the disk or read in from cards or from the keyboard. A hardware diagnostic package is now being used regularly as a part of our system maintenance. A program to allow rapid check-out of peripherals such as Mag tapes is currently being written. The following new MIOP microprograms are now operational.

INIT - a short initialize channel program

Return - calls next micro-program via a command list

Branch - alter order in which command list is processed

Loop - directs iterative processing of a portion of a command list

Control - performs CAMAC control operations

Read - performs CAMAC read operations

Write - performs CAMAC write operations

Trans - computer core memory to memory transfer

RLOAD - load MIOP file registers from a command list

XMI, XSI, XCR - a series of sub-programs allowing for various
types of exits
DISPL - displays a computer buffer and labels with an
arbitrary scale factor

Several other special purpose programs are operational.

6.2.3.2 CAMAC Device Driver Development. A "C2" CAMAC device driver is now operational. It has been tested with the proposed final hardware arrangement. So far event lengths up to seventeen words have been used. Partial analysis in the background, automatic streaming of data to tape, and MIOP background displays have been tested simultaneously with the operation of three separate "C2" data channels. Begin, End, Print, Alter, and Display buttons have been implemented into the system. A publication describing the "Rice" system is nearly completed.

6.3 Portable Laboratory. During the year a 40' Fruehauf trailer was purchased from operating funds and outfitted for use as a portable laboratory. It is equipped with a hydraulic tail-gate, 6 tons of airconditioning, electrical wiring and lighting, accoustical ceiling and walls, and an approved fire extinguisher system. The on-line computer system and relay racks for electronic modules were installed. It is planned to take this portable laboratory to LAMPF in 1973.

6.4 Construction of Cerenkov Counters for Pion Physics and Pion Dosimetry Experiments. Gas and liquid Cerenkov counters which can identify pions, muons, and electrons in a low energy negative pion beam were constructed. Particle identification is required, for example, to measure the LET in a tissue equivalent phantom as a function of depth and type of particle.

Recent tests of such counters at SREL in November, 1972 indicate the feasibility of particle by particle identification. This project is based on the needs of LAMPF proposal #84.

7. Collaboration with LAMPF

During the year close collaboration with the staff of LAMPF and with the LAMPF Users Group continued and consisted of: 1) the principal investigator serving as a member of the LAMPF Policy Board, 2) the principal investigator serving as a founding Director of the LAMPF Users Group, Inc., and 3) preparations, in collaboration with Dr. Robert Macek, for tuning up the P^3 meson channel early in 1973.

References

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3. Small Angle $\pi^+ - ^{16}\text{O}$ Scattering from 117 to 185 MeV.
G. S. Mutchler, C. R. Fletcher, L.V. Coulson, D. Mann,
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7. A Multi-Wire Proportional Counter System for Use in Low
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J. A. Buchanan, L. Coulson, N. Gabitzsch, E.V.
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Nucl. Instru. & Meth. 99, 159 (1972).
8. Rice - A Multi-Processor Acquisition and Analysis System
Incorporating CAMAC
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IEEE, Nuclear Science Symposium Proceedings,
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9. CAMAC Multi-Microprogrammed IO Processor

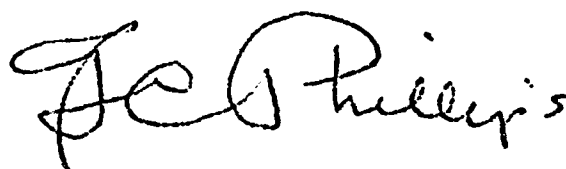
James A. Buchanan and Hugh V. Jones
IEEE Transactions on Nuclear Science 19,#1, 682 (1972)

Changes in Personnel

During this period Mr. William P. Madigan, formerly on the staff at the Space Radiation Effects Laboratory, Newport News, joined our staff as research engineer. Dr. Larry Coulson, Research Associate, resigned to accept a permanent position at the National Accelerator Laboratory, Batavia, Illinois.

Incident Report

No incident such as those outlined in attachment "A" have occurred during the contract year.



G. C. Phillips, Director
T. W. Bonner Nuclear Laboratories
and Principal Investigator

December 22, 1972

Publications since last report (1971 and 1972)

1. An In-Flight Pion Beam Flux Monitor

L. V. Coulson, C. R. Fletcher, E. V. Hungerford, G. S. Mutchler, G. C. Phillips, and M. L. Scott, Nucl. Instr. & Meth. 101, 247 (1972).

2. Nuclear-Coulomb Interference in $\pi^+{}^{-12}\text{C}$ Scattering

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3. CAMAC Multi-Microprogrammed IO Processor

James A. Buchanan and Hugh V. Jones,
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4. A Multi-Wire Proportional Counter System for Use in Low, Medium, and High Energy Physics

J. Buchanan, L. Coulson, N. Gabitzsch, E. V. Hungerford, G. S. Mutchler, R. Persson, M. L. Scott, J. Windish, and G. C. Phillips,
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