SUMMARIES OF FY 1978 RESEARCH IN NUCLEAR PHYSICS

December 1978

U.S. Department of Energy
Office of Energy Research
Division of Nuclear Physics

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Division of Nuclear Physics
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INTRODUCTION

This report contains summaries of programs funded in Fiscal Year 1978 by the Division of Nuclear Physics, Office of High Energy and Nuclear Physics, U. S. Department of Energy. All dollar figures refer to operating funds only and do not include capital equipment (equipment whose title vests in the United States Government) or construction funds. The long range goal and objectives of Nuclear Physics are as follows:

Long range goal: To attain deeper understanding of the structure and properties of atomic nuclei and the laws governing their motions and interactions through experimental medium energy and heavy ion nuclear research and theoretical studies. Nuclear Physics-supported basic research provides underlying scientific knowledge which is essential for the development of advanced nuclear energy technologies.

Major objectives:

1. To pursue frontier nuclear research studies of the interactions of nuclei with probes of heavy ions and of medium energy primary and secondary particles;
2. To operate the national accelerator facilities (Clinton P. Anderson Meson Physics Facility (LAMPF), William H. Bates Electron Facility, Brookhaven Double MP Tandem Facility, SuperHILAC/Bevalac, and Holifield Heavy Ion Research Facility) and other accelerator facilities as justified by scientific demand and technical feasibility;
3. To equip experimental areas at these facilities in order to exploit fully the research capabilities offered by the available beams of nuclear projectiles. Requirements include magnetic spectrometers, beam transport lines, high resolution detectors and off-line and on-line computer-based data systems;
4. To advance research capability in this area by developing improved accelerator beams. These improvements would be in the energy, intensity, resolution and variety of beams.
5. To develop physical theories able to describe and to predict properties of nuclei and nuclear interactions. To guide experimental research along those lines that will best test theory and will be most likely to provide new insight into nuclear phenomena;
6. To establish a position of leadership in nuclear research for the United States; and
7. To identify practical applications, particularly those which relate to energy technology, resulting from medium energy and heavy ion research studies and to transfer these results to the appropriate scientific discipline or technology.

It should be noted that an appreciable program of nuclear research (low energy, light ion research; isotope separation and preparation for research use; heavy element chemistry research; data compilation and evaluation; and neutron and fission research) is also supported by the Department of Energy in the Division of Nuclear Sciences, Office of Basic Energy Sciences.

MEDIUM ENERGY NUCLEAR PHYSICS

(HK 03 01)

Includes all costs associated with experimental Nuclear Physics activities carried out at facilities with maximum primary beam energy (per nucleon or electron) in excess of the pion production threshold and with primary beam particle not more massive than helium-4.

MEDIUM ENERGY NUCLEAR PHYSICS - RESEARCH

(HK 03 01 01)

Includes all costs of nuclear and subnuclear research carried out with light ions at facilities having a maximum primary beam energy (per nucleon or electron) in excess of the pion production threshold but not exceeding 10,000 MeV. Also includes all costs of experimental nuclear and subnuclear research carried out at facilities having primary beam energies beyond 10,000 MeV (per nucleon or electron) where the interest is more for nuclear structure study than for elementary particle study.

ARGONNE NATIONAL LABORATORY.....\$255,000
Chemistry Division

**"Mechanisms of Nuclear Reactions Induced by Mesons, Light Charged Particles,
and Relativistic Heavy Ions"**

E. P. Steinberg, S. B. Kaufman, B. D. Wilkins

The main objective of this program is to characterize the mechanisms of the interactions of high energy projectiles with complex nuclei and to assess the applicability of current theoretical models in the interpretation of the results. Radiochemical and multiparameter, on-line (event-by-event) counting techniques are utilized in studies of the reaction cross sections, the energy and momentum transfer to the products, their angular and energy distributions, and the correlations in angle and energy between products of binary events. Experiments with 1-400 GeV protons at the ZGS and Fermilab accelerators have established the major features of a new reaction mechanism which becomes important above about 3 GeV bombarding energy. Current experiments utilize relativistic heavy ions at the LBL Bevalac as projectiles for comparison of the characteristics of the energy and momentum transfer processes with those initiated by protons. The nature of the pion-nucleus interaction and the effect of the nuclear environment on the free pion-nucleon resonance are being investigated in experiments at LAMPF. In addition to its inherent interest, an understanding of the pion-nucleus interaction is important for the interpretation of the role of pions and the Δ -isobar in the mechanisms of reactions induced by other projectiles with energy above the pion-production threshold. Experiments with high-energy electrons are planned at SLAC to extend the study of energy and momentum transfer in high-energy interactions.

Recent results have shown that: (1) fission is primarily a low-excitation energy process which takes place toward the end of the deexcitation chain of the highly-excited nuclei formed in the bombardment of heavy targets with GeV protons; (2) products in the mass range 30-70 (the so-called "fragmentation" products) are formed in events with the highest deposition energies; (3) many of the fragmentation products are formed in binary events and have kinetic energies greater than that expected from a normal fission mechanism; (4) with increasing deposition energy in the interaction, the forward momentum transfer initially increases, reaches a maximum and then decreases; (5) the forward momentum transfer with complex projectiles is related to the total projectile energy rather than the energy per nucleon; and (6) current theories of pion interactions have serious deficiencies. The interpretation of these data in terms of several models proposed for the interpretation of results in particle physics and heavy-ion reaction studies is being investigated.

Major collaborators:

G. W. Butler, Los Alamos Scientific Laboratory
N. T. Porile, Purdue University
N. Sugarman, The University of Chicago
L. Winsberg, University of Illinois at Chicago Circle

ARGONNE NATIONAL LABORATORY \$416,000
Physics Division

"Experimental Studies of Pion-Nucleus Interactions and Pion-Propagation in Nuclear Matter"

H. E. Jackson, J. P. Schiffer, S. B. Kaufman, L. Meyer-Schützmeister,
R. J. Holt, B. Zeidman, R. E. Holland, D. S. Gemmell, and T. P. Wangler

One of the basic challenges of medium energy physics is the development of a clear picture of the manner in which pions propagate in nuclear matter. Since the pion is a basic quantum of the nuclear force, understanding its propagation in nuclei will certainly contribute to our understanding of the basic nature of nuclear forces. The key to such a study is a comprehensive and precise experimental description of pion-interactions with complex nuclei. This is a major objective of the ANL effort in medium energy physics.

Efforts of the Argonne group have focussed on measurements of "inclusive" spectra of charged particles, neutral pions from nuclear charge exchange reactions, and nuclear-decay γ -rays. Recently, the Argonne group demonstrated and easily implemented a simple new technique for direct observation of neutral pions. These (π^+ , π^0) measurements provided a body of qualitatively new data; and the trends displayed in the first results suggest, quite unexpectedly, that the bulk of this reaction proceeds through a quasi-free scattering process favoring large momentum transfer.

The elastic scattering of pions has been studied by the ANL group in a survey of targets of varying mass over the region of the (3,3) resonance. The measurements are made with the EPICS facility at Los Alamos. The first spectra demonstrate experimental sensitivity and angular resolution which is unexcelled. The results, together with data from other laboratories at lower energies will provide a complete picture of pion elastic scattering for representative nuclei, and will be of major importance in the development of precise optical model descriptions of pion-nucleus interactions.

A LAMPF experiment which takes advantage of expertise in the physics of ion channeling has been performed at the EPICS channel. Our study of transmission of positive and negative pions in single crystals was the first time in which channeling has been studied for otherwise identical positive and negatively charged classically behaving particles. Steering of the pions by the channeling crystal as well as anomalies in the energy loss was observed.

Major collaborators: R. E. Segel, Northwestern University; R. L. Burman, R. P. Redwine, M. A. Yates-Williams, J. F. Amman, C. L. Morris, and H. A. Thiessen, Los Alamos Scientific Laboratory; G. R. Burleson and M. J. Devereux, New Mexico State University

BROOKHAVEN NATIONAL LABORATORY \$ 413,000
Chemistry Department

"Studies of Light Fragment Production and of Pion Interactions"

Y. Y. Chu, J. B. Cumming, P. E. Haustein, J. Hudis, S. Katcoff, and
L. Remsberg

The aim of this work is to understand the fundamental processes involved in the interactions of high energy projectiles with complex nuclei. Studies of these reactions lie at the interface between nuclear physics and elementary particle physics, and they often involve using knowledge from one area to learn something new in the other. Various target elements of low, medium, and high Z are bombarded with protons (800 MeV at LAMPF, 28 GeV at the AGS, and 400 GeV at FNAL), and with mesons (50-500 MeV at LAMPF, greater than 500 MeV at the AGS). Measurements are made of the charges and masses of the particles produced, and their production cross sections, energy spectra, and angular distributions. As a follow-up to the previous observation that light fragments were ejected from heavy elements preferentially at sideward angles, a two counter-telescope experiment was initiated at the AGS to measure masses of the partners of these fragments. The observed mass distribution--nearly flat from $A \approx 20$ to 120--when considered together with the energy spectrum and broad angular correlation, provides strong evidence that many of the light fragments result from multifragment break-up of the target nucleus. Radiochemical studies were also performed which showed that the sideward peaking persists to products with mass $A \approx 100$. A study of the spallation of copper by 50- to 350-MeV $\pi^\pm$ mesons at LAMPF was completed. The experimental results are in good overall agreement with predictions of a theoretical model (the VEGAS code, developed initially at BNL) which assumes that the production and decay of nucleon isobars are important in determining the energy transferred between an incident pion and a nucleus in this energy region. Similar spallation measurements have been performed with π^- mesons from the AGS at higher energies (500- to 1570-MeV) which are well above the $T = 3/2$ resonance and which encompass the first $T = 1/2$ resonances in the π^- -nucleon cross section. These studies when combined with the LAMPF work reveal smooth gradual changes of spallation yields toward asymptotic behavior of the type previously observed in proton and heavy-ion reactions. Specific effects of the higher resonances were not observed. Other pion studies seek to obtain cross sections for double charge exchange reactions such as $^{209}\text{Bi}(\pi^+, \pi^- \text{xn})^{209-\text{x}}\text{At}$. The unique properties of the LAMPF proton beam--its fine time-structure and high current--continue to be exploited to produce, detect, and identify new nuclides in a collaborative experiment. Following the discovery of several new neutron-rich nuclides, both the target and detector system have been changed in order to search for new proton-rich nuclides.

Major collaborators: Carnegie-Mellon Univ., LASL, LBL, ORNL, and Texas A&M Univ.

BROOKHAVEN NATIONAL LABORATORY.....\$382,000
Physics Department

"Medium Energy Nuclear Structure Probes"

H. Palevsky, R. E. Chrien, Morgan May, Rossanna Regge, and Richard Sutter

Two major efforts are underway. First, a spectrometer has been fabricated at BNL to take advantage of the intense separated K^- beam available at the Alternating Gradient Synchrotron (AGS) to study "hypernuclei". The "hypernucleus" is a new nuclear species created by transforming one of the constituent nucleons into a lambda hyperon, through the (K^-, π^-) interaction. The novel features of this new nuclear species come about because the Λ introduces one unit of the strangeness quantum number into the nucleon orbit. The Λ thus moves within the nuclear volume free of the restrictions imposed by the Pauli principle in a normal nucleus. Considerable theoretical interest arises in this because of the possibility of the strangeness-exchange reactions producing analog states built on the strangeness quantum number much as the isobaric analogs are based on the isospin quantum number. Approximately one half of the approved experiment #646 at the AGS has been completed. This work is concerned with the interactions of K^- 's with ^{12}C and the emission of π^- 's associated with formation of the carbon hypernucleus. This first measurement verified that we obtained the expected counting rates and that they were at least an order of magnitude greater than originally published by the Heidelberg Group at CERN. The results also showed that the so-called analog state in carbon is more than a single state and may be a combination of two or three states. We also obtained angular distributions for the states formed. One of the original aims of doing angular distributions of the emitted π^- 's was to identify the orbit in which the Λ is formed. From our data we can already see that the so-called analog state at 10 MeV excitation is formed by the ingoing K^- interacting with p-wave neutrons to form p-wave Λ hypernucleus, whereas the ground state is formed when the K^- interacts with a p-wave neutron to form a s-wave hypernucleus. We are now in the process of completing the second half of our experiment which concerns the formation of Σ hypernuclei in deuterium.

In the second effort, the BNL group is a supporter and user of the high resolution proton spectrometer at Los Alamos. The High Resolution Spectrometer (HRS) uses 800-MeV protons to probe nuclear structure by elastic, quasi-elastic, and inelastic scattering of these protons. The first measurement with the HRS spectrometer at Los Alamos was started in FY 1978. This was the measurement of the quasi-free scattering of protons from a series of elements in ascending mass number from Li to Pb. At the high energy end of the spectrum we see evidence of heavier clusters in the nucleus. In particular we identify mass 2 and mass 4 clusters.

Major collaborators: Princeton, MIT, Univ. of Houston, Carnegie-Mellon Univ., Vassar, LASL, UCLA, and Univ. of Texas.

UNIVERSITY OF CALIFORNIA AT LOS ANGELES..... \$269,245
 Physics Department

"Studies In Particle Physics"

R. P. Haddock and B. M. K. Nefkens

Research under this contract continues to emphasize: (1) experimental tests of time reversal invariance and charge symmetry; (2) experimental determination of electromagnetic properties of low-lying nucleon resonances; and (3) measurement of fundamental nucleon-nucleon and pion-nucleon interaction parameters. Priority has been given to analysis and partial publication of results from two 184-inch Cyclotron experiments ($pp \rightarrow pp\gamma$ at $T_p=730$ MeV and $\pi^\pm p \rightarrow \pi^\pm p\gamma$ in the Δ (1232) region) and to analysis for LAMPF Expt. #90 "A Test of Time Reversal Invariance In Single Pion Photo-Production Through A Study of Reciprocity In the Reactions $\pi^- \text{He}^3 \rightarrow \gamma T$ and $\pi^+ T \rightarrow \text{He}^3 \gamma$." Objective of the pp bremsstrahlung experiment is information on N-N scattering amplitudes in a region where the total cross section has a very strong inelastic component. For photon energies below 80 MeV the UCLA data are in quantitative agreement with external emission dominance models. πp bremsstrahlung results covering 18 photon angles (over 100 photon spectra) for incident pion energies of 269, 298, and 324 MeV have been submitted to Phys. Rev. Objectives of this experiment include test of external emission dominance and soft photon approximation models, measurement of πp off-mass-shell amplitudes, and determination of the Δ^{++} magnetic dipole moment. After some difficulties with theoretical interpretation, this third result has been achieved! In particular, this UCLA experiment finds $4.7 < \mu_{\Delta^{++}} < 6.7 \mu_N$ in good agreement with SU (6) predictions based on the model of P. Pascual and R. Tarrach (Nucl. Phys. B134, 133 (1978)). Objectives of LAMPF Expt. #90 are: (1) measurement of $\pi^-^3\text{H}$ and $\pi^-^3\text{He}$ elastic scattering, charge exchange, and radiative capture cross sections in the (3,3) resonance region; (2) test of multiple scattering theories for the three nucleon system; and (3) test of time reversal invariance and charge independence symmetries.

In terms of new experiments, a substantial portion of this user group's efforts are being devoted to LAMPF Expt. #363 "Measurement of $\pi^\pm p$ Elastic Scattering." Expt. #363 is designed to obtain a complete set of $\pi^\pm p$ charge exchange, radiative capture, and elastic scattering measurements over the 300 to 600 MeV incident pion energy range with both polarized and unpolarized targets. Central objective is a reliable set of energy independent and dependent phase shifts. Also, this group is working on TRIUMF Expt. 109 -- a measurement of $pd \rightarrow ^3\text{He}\gamma$ for 400 to 500 MeV incident protons to test time reversal invariance. Recent Bonn work on the inverse reaction ($\gamma + ^3\text{He} \rightarrow p+d$) are in significant disagreement with previously accepted Cal. Tech data. The Cal Tech data agree with existing $p+d \rightarrow ^3\text{He}+\gamma$ data; thus the new, more accurate results raise the possibility of a violation of time reversal invariance.

Major collaborators:

UNIVERSITY OF CALIFORNIA AT LOS ANGELES \$190,000
Physics Department

"Intermediate Energy Nuclear Physics"

G. J. Igo, C. A. Whitten, Jr., and J. B. Carroll

Recent research has emphasized medium energy p,d, and alpha beam investigations at LAMPF, Bevatron, and ZGS of few nucleon systems, reaction mechanisms, and multiple scattering theory. Recent work has also included very active collaboration in HRS turn-on experiments #139 "Preliminary Proton Scattering Survey with HRS: and #311 "Elastic scattering Survey Using Polarized Protons." These p-nucleus nuclear structure experiments at HRS have been continued with #117 "High Resolution Study of the Neutron Pick-Up Reaction," #204 "Excitation and Symmetry Measurement of T=1, High Spin, Non-Normal Parity 'Particle-Hole' State by (p,p') Scattering in the Intermediate Energy Range," HRS Exp't. #376 "Large Angle Elastic Scattering on ^{40}Ca by Medium Energy Protons" and the first phase of HRS Exp't. #15 "Small Angle Elastic p-p, p-d, and p- ^4He Elastic Scattering." Experiment #117 will investigate neutron separation energies across neutron shell closures; the objective of #204 is detailed information on wavefunctions of high spin nuclear states. The objective of Exp't. #376 is to determine the large momentum transfer behavior of elastic scattering (as well as inelastic scattering up to about 15 MeV excitation); the objective of the first phase of Exp't. #15 is to determine the ratio of the real to imaginary part of the p-p and p- ^{12}C scattering amplitudes at 800 MeV for $q = 0$.

Recently, at the Bevalac, the excitation functions for the reaction $d + ^4\text{He} \rightarrow p + \pi +$ anything has been studied over the momentum range capability of the Bevalac to search for quark matter. A range of rapidity was investigated in this experiment in which competing processes had been found to be minimal in earlier experiments. No resonance-like behavior with width ≥ 100 MeV/c was observed in the excitation function. Recent elastic scattering experiments at the Bevalac have focussed on two 4-nucleon systems: d-d and p- ^3He elastic scattering at 2.65 GeV/c. The objective of this work is to measure the additional multiple scattering amplitudes which are predicted for d-d elastic scattering. In an experiment at the ZGS, large angle p-d elastic scattering using polarized protons has been studied between 600 MeV and 1.2 GeV bombarding energy. With recent TRIUMF data spanning the 250-500 MeV range, the variation of the asymmetry $A(\theta)$ at large angles and particularly near $\theta = 180^\circ$ (through the striking "shoulder" region seen in the 180° excitation function for elastic scattering of unpolarized protons) has been thoroughly delineated. In a companion experiment at the ZGS, small angle p-p elastic polarization in the GeV range has been measured.

Major collaborators: Lawrence Berkeley Laboratory, Rice University, University of Minnesota, Argonne National Laboratory, and University of Colorado.

CALIFORNIA INSTITUTE OF TECHNOLOGY..... \$348,000
Norman Bridge Laboratory of Physics

"Research In Nuclear Physics at Low and Intermediate Energies, Neutrinos, and X-Rays"

F. Boehm, P. Vogel, and R. J. Powers

A. NEUTRINO CROSS SECTIONS AND NEUTRINO OSCILLATIONS

We will continue the build-up of this complex experiment which will be conducted in Grenoble at the high flux reactor of the Laue-Langevin Institute (ILL). Immediate objectives include:
1.) To test a novel neutrino counter system with the help of the reaction $\bar{\nu}_e + d \rightarrow e^+ + n + n$. This charge current reaction has been measured with 50% accuracy by Reines' group in 1969.
2.) To study the energy spectrum of fission antineutrinos, as a prerequisite for the oscillation experiment. 3.) To search for oscillations of electron antineutrinos.

B. TIME REVERSAL AND FINAL STATE EFFECTS

In light of the disparate values of the experimentally measured $\sin(\eta + \xi)$ in ^{191}Ir (η and ξ being the time reversal and final state phases, respectively) and the theoretically calculated $\sin \xi$, an improvement in the limit on time reversal invariance must be obtained by investigating a transition for which the T-odd term proportional to $\sin \eta$ is large and for which $\sin \xi$ is small. An intensive search yielded the 364 keV transition in ^{131}Xe from the decay of ^{131}I as the most favorable transition for our polarimeter technique of measuring T-odd observables. For this higher energy transition, $\sin \xi < 2 \times 10^{-4}$. The measured T-odd asymmetry is $A \approx 0.035 \sin \eta$ at 20 mK, compared to $A \approx 0.013 \sin \eta$ for ^{57}Fe .

C. MEDIUM ENERGY PHYSICS AT LAMPF

1. Pionic x ray measurements with the crystal spectrometer at the East leg of the LAMPF muon channel will be carried out with the goal to determine the fine structure splitting of the $n = 5-4$ transition in Ti as a fundamental test of the Klein-Gordon equation.
2. As a continuation of the muonic x ray work, we plan to study the nuclear moments in ^{185}Re and ^{201}Hg . We also plan to pursue our strong interaction studies (matter radii) with pionic atoms.
3. Feasibility studies with a new curved graphite single crystal diffraction spectrometer for very low energy pionic x-rays will be conducted. The goal is to perform precision measurements of the K x-rays of H, ^2H , ^3He , and ^4He as a source of information on the pion-nucleon potential.

D. X RAYS

The x-ray shift following electron capture first observed by us and recently confirmed by experiments at CERN is still evading a quantitative interpretation.

Major collaborators: C. Cavaignac and B. Vignon, Laue-Langevin Institute (France); R. Mossbauer, TU Munich (Germany); and R. Kunselman, University of Wyoming.

CARNEGIE-MELLON UNIVERSITY..... \$299,800
Physics Department

"Experimental Nuclear Physics at Medium Energies with Pions and Kaons"

P. D. Barnes, R. A. Eisenstein, and W. R. Wharton

At the present time research work under this contract emphasizes experimental investigations of the reaction mechanisms through which pions and kaons interact with nuclei. However, it remains the long-term goal of this group also to use meson probes to extract new and unique information on nuclear structure. Current activities include:

LAMPF Expt. #246 " π^+ Scattering at 50 MeV from Light Nuclei". All results have been submitted for publication. These angular differential cross section data clearly indicate that some of the more simple theoretical descriptions using free π -nucleon amplitudes are inadequate to describe quantitatively π -nucleus scattering.

LAMPF Expt. #191 " π^+ -Nucleus Inelastic Scattering to Giant Resonances". The objective is to search for excitation of giant nuclear resonances in pion-nucleus scattering. The relatively low mass and high isospin of the pion, as compared to more conventional p and α probes of giant resonances, promises interesting results. Large bumps in the energy spectra of Mg, Ca, Ni, and Cu between 10 and 20 MeV have been observed as a function of scattering angle for incident pion energies of 67 MeV.

LAMPF Expt. #23 "A Survey of Pion-Nucleus Elastic and Inelastic Scattering at 180 MeV". Angular distributions for elastic and inelastic π^+ and π^- scattering have been accumulated for targets of ^{89}Y , ^{92}Mo and ^{118}Sn . The angular range studied was $15^\circ \leq \theta \leq 100^\circ$. Careful examination of the π^+/π^- ratios for inelastic scattering hopefully will lead to information about the extent to which low-lying inelastic excitations in these nuclei can be described in terms of valence neutrons or protons.

AGS Expt. #646 "Studies of the (K^-,π^-) Reaction". The kaon spectrometer at BNL has been completed and successfully tested on-line. CMU-developed wire chambers are a part of this apparatus. Useful data for the $^{12}\text{C}(K^-,\pi^-)^{12}\text{C}$ reaction has been accumulated and is being analyzed. In addition, the reaction $K^-+d \rightarrow \Sigma^+\pi+n$ (spectator) has been examined. Further work on both of these studies will take place in the near future.

AGS Expt. #692 "Measurement of $K^\pm$ Elastic Scattering From Selected Nuclei at 650 to 1000 MeV/c". The objective is determination of kaon-nucleus elastic scattering parameters. These data will be the first precision measurements of this type and will include angular distributions.

Major collaborators: Univ. of Colorado, New Mexico State Univ., LASL, College of William and Mary, Univ. of Wyoming, Cal Tech, Univ. of Washington, Univ. of Wisconsin, BNL, and Univ. of Houston.

CARNEGIE-MELLON UNIVERSITY.....\$ 33,000
Chemistry Department

"Experimental Nuclear and Radiochemistry"

P. J. Karol

This endeavor entails the investigation of deep nuclear spallation reactions induced by high-energy light particles on complex nuclei. Experimental studies involve activation of various medium to heavy mass targets bombarded by pi-mesons, protons and alpha particles. A variety of radiochemical and radiometric techniques are employed to quantify the product yield spectrum with particular emphasis being placed on spallation products far from yield maxima. Necessarily these involve radioisotopes of short half-life and low yield so that rapid radiochemical techniques are being developed and employed. Irradiations are performed predominantly at the Clinton P. Anderson Los Alamos Meson Physics Facility although occasional use of other facilities such as Argonne, Brookhaven, Bevelac or SREL prove valuable. Bombardments of several medium mass target elements with 190 MeV π^- , 800 MeV protons and 28 GeV protons have been executed. Theoretical modifications to the cascade and evaporation phases of the high-energy nuclear reaction mechanism will be examined at a fairly fundamental level. The initial theoretical thrust will be directed at the evaporative behavior of very high-temperature nuclei and how such behavior might become evident in spallation processes.

Major collaborators: No major collaborators to date.

CASE WESTERN RESERVE UNIVERSITY \$165,000
Physics Department

"Studies of the Spin Dependence of Proton-Proton Interactions"

H. B. Willard, P. R. Bevington, and H. W. Baer

Our LAMPF Users group is continuing the investigation of the proton-proton interaction by the method of polarized beams and polarized targets. Triple scattering and initial state spin correlation parameters are being measured. This series of experiments is intended to shed light on the strong nuclear force, the spin dependence of the interaction, and symmetries involved. Polarization in p-D elastic scattering is under study. Asymmetries in pion production produced by a polarized proton beam and liquid hydrogen target are planned to be investigated. In addition, we plan to investigate few nucleon systems by observing π^0 particles in the final state. Supporting instrumentation and techniques are part of the program. Single and double pion momentum spectra have been observed for pp collisions at 800 MeV. Total reaction cross sections on carbon, three calcium isotopes, and lead have been measured. The polarization analyzing power of proton-proton elastic scattering at 428, 643, and 796 MeV has been studied. Results for the $A_{yy}(\theta)$ spin correlation parameter in p-p elastic scattering have been obtained at 643 and 796 MeV. Progress on the π^0 spectrometer continues.

Major collaborators: Los Alamos Scientific Laboratory
University of Idaho

UNIVERSITY OF CHICAGO..... \$195,000
Enrico Fermi Institute

"Nuclear Chemistry Research"

N. Sugarman and A. Turkevich

The objective of this investigation is to obtain information on the nature of the interactions of elementary particles (protons, pions and muons) with nuclear matter. Although some features of these interactions, particularly in the case of relativistic protons, can be understood on the basis of free nucleon-elementary particle interactions, other features are already suspected to be related to the short-time scale of phenomena at these energies inside nuclear matter. Nuclear chemical techniques are to be used at the Fermilab and Los Alamos accelerators to study: a) the mechanism of 400 GeV proton reactions with complex nuclei via the determination of yields and kinematic properties of products; b) the yields of pion induced reactions in the 100 GeV range and their relationship to the known yields in proton reactions; c) the yields of products that reflect the participation of mesons; d) the production of products that might be formed via relatively well defined reaction paths; e) the production of new particles (e.g. Han-Nambu quarks) and reactions that test the limits of currently accepted conservation laws (e.g. μ^- , e^+ reactions). ^{238}U target foils have been bombarded with 400 GeV protons at FNAL. One complete angular distribution in the 15° to 175° (lab) range was determined for $^{32,33}\text{P}$ and $^{105, 106\text{m}}, ^{111}\text{Ag}$ reaction products. In each case, evidence of sideward peaking was observed. Also, energy distributions of $^{32, 33}\text{P}$, $^{64, 67}\text{Cu}$, and $^{105, 106\text{m}}, ^{111}\text{Ag}$ fragments were determined at selected angles. Work has also included $p + ^{27}\text{Al}$ bombardments at 400 GeV and $p + ^{181}\text{Ta}$ and ^{238}U runs at ZGS energies. These yield, angular distribution, and energy distribution measurements are interpreted in terms of a two step -- cascade followed by evaporation -- reaction model. At LAMPF, Professor Turkevich's search for polynucleons (particle stable systems of five or more neutrons) is now complete. Sufficiently low limits on production cross-sections were set so as to provide strong evidence that such bound neutral nuclear systems do not exist. At FNAL three experiments are in progress -- (1) a study of $\pi + \text{Cu}$ spallation for incident pions in the 100 to 300 GeV range; (2) a study of (p, X) reactions for 400 GeV protons incident on ^{65}Cu and ^{197}Au targets (X is any assemblage of hadrons whose baryon number totals +1) using radiochemical techniques to identify the specific residual nucleus; and (3) a search for Han-Nambu quarks produced in 400 GeV proton reactions on a Ca CO_3 target using sensitive mass spectrometer techniques to identify any such quarks which have been produced and become attached to a normal nucleus.

Major collaborators:

UNIVERSITY OF COLORADO. \$109,000
Department of Physics and Astrophysics

"Nuclear Structure Studies and Nuclear Reaction Mechanism at Intermediate Energies"

R. J. Peterson, J. J. Kraushaar, D. A. Lind, R. A. Ristinen, and C. D. Zafiratos

Reactions induced by pi mesons and intermediate energy protons have been studied with the HRS and EPICS systems at LAMPF, and with the proton beam from the IUCF. Completed work includes a comprehensive study of pion-induced nucleon removal from light nuclei, studied with gamma-ray detectors. Elastic and inelastic scattering data for (pp') at 800 MeV have been analyzed by optical model and DWBA calculations, demonstrating that at this energy the scattering is strongly dominated by effects at the nuclear surface. The (p,d) reaction has been studied at 800 MeV and at 120 MeV on several targets. These results probe bound neutron distributions at very large momentum transfers. These data are being compared to (π^+ ,p) and (^3He , ^4He) data at equivalent momentum transfers. The latter reaction is studied with the University of Colorado AVF cyclotron. The (p,t) double-pickup reaction has been studied at 80 MeV at Indiana, and preliminary (p,n) runs have been performed at 120 MeV. All the necessary calculations--one-step, two-step, zero-range and finite range--are performed in close conjunction with the data reduction for all these reactions. Future experimental studies, based on approved experiments, include the (π^+ ,p) reaction on ^6Li , ^{13}C and ^{40}Ca , inelastic π^+ and π^- scattering to unbound states in ^{12}C and to the highly collective states of ^7Li , and further (p,n) charge exchange studies.

Major collaborators:

C. Fred Moore, University of Texas
C. L. Morris, LAMPF
H. A. Thiessen, LAMPF
Bo Hoistad, LAMPF
G. J. Igo, UCLA
C. A. Whitten, UCLA
A. D. Bacher, University of Indiana
W. Jacobs, University of Indiana
C. D. Goodman, ORNL

UNIVERSITY OF HOUSTON..... \$160,000
Physics Department

"Meson Production and Reactions at Medium Energies"

B. W. Mayes II, E. V. Hungerford III, and J. C. Allred

This group has been conducting experimental investigations of pion-nucleus interactions in the (3,3) resonance region and of pion production in proton-(few nucleon system) collisions. These studies are being extended to kaon-nucleus interactions. Data taking is complete, and analysis and journal publication work is underway for:

LAMPF Expt. #80 "Forward Elastic Scattering of π^+ and π^- from ^{12}C , ^{13}C , ^{16}O , ^{40}Ca , ^{208}Pb ". These studies emphasize amplitudes from Coulomb-nuclear interference data and total cross-section data. Also, $\pi^\pm$ data on ^{40}Ca and ^{48}Ca were taken to examine differences in neutron and proton matter radii.

LAMPF Expt. #81 "Study of Neutron-Proton and Proton-Proton Coincidence Spectra from $p+d \rightarrow n+p+p$ Reaction". These kinematically complete experiments provide both quasi-free scattering data and final state interaction data to test Simple Impulse Approximation, Spectator Model, and Final State Interaction theoretical descriptions of $p+d$ scattering as well as to provide basic nucleon-nucleon interaction data.

LAMPF Expt. #197 "Investigation of the Charge Symmetric Reactions $p+d \rightarrow {}^3\text{He}+\pi^0$ and $p+d \rightarrow {}^3\text{H}+\pi^+$ ". This work provides kinematically complete data on the important (p,π) reaction in a relatively simple nuclear system.

Current work emphasizes pion production research at LAMPF and initiation of kaon-nucleus data taking at AGS. In particular, work at the AGS will include:

AGS Expt. #646 "Hypernuclear Spectroscopy of States Formed by the Coherent Interaction of K^- with Nuclei". Angular distributions for the (K^-, π^-) reaction will be taken with Palevsky's energy loss spectrometer system.

AGS Expt. #728 Search for a ΣN bound state by observing the (K^-, π^-) reaction on ${}^2\text{H}$.

AGS Expt. #692 "The Measurement of the $K^\pm$ Elastic Scattering From Selected Nuclei At ~ 800 MeV/c". The objective is data on global optical potential parameters for K-nucleus scattering; tentative targets are C and Ca.

Major collaborators: Rice University, Case Western Reserve University, LASL, BNL, Princeton, Vassar, MIT, and Carnegie-Mellon.

IDAHO NUCLEAR ENGINEERING LABORATORY.....\$ 15,000

"Nuclear Level-Schemes Studies Utilizing LAMPF and UNISOR"

R. L. Heath, R. C. Greenwood, R. G. Helmer and C. W. Reich

This program has as objectives the generation of new nuclear-structure data on nuclides far off the line of stability and the characterization and interpretation of these data to test current theories and develop new concepts. These are implemented through study of the radiations emitted in the decay of neutron-deficient nuclides. The primary means for producing these nuclides are proton-induced reactions on LAMPF. Work has continued on the decay schemes of ^{150}Tb and ^{151}Tb , near the $N \sim 90$ region where the transition to strongly deformed equilibrium nuclear shapes takes place. The analysis of extensive γ - γ coincidence data on ^{150}Tb was completed and the major features of this complex ($Q_\beta \sim 4.7$ MeV) decay scheme were established. Particular attention was focused on that portion of the ^{150}Gd level scheme lying within ~ 0.6 MeV of the Q -value. The lack of suitable precise γ -ray energy-calibration standards in the energy region near 4.5 MeV hampered this study. To help alleviate this deficiency, precise energy values were measured for the 4742- and the 4852- keV γ rays from the decay of ^{88}Rb . In addition, involvement in the proposed effort to produce radioactive samples in the LAMPF beam dump to serve as targets for charged-particle-induced reaction spectroscopy continued this fiscal year. A number of discussions were held with interested personnel from LASL and other laboratories in order to determine the scope of such a program.

Major collaborators:

Los Alamos Scientific Laboratory (M. E. Bunker)

JOHNS HOPKINS UNIVERSITY \$50,000

"Nuclear Moments and Nuclear Structure"

L. Madansky, Y. K. Lee, and J. C. Walker

We have undertaken a project to measure accurately (to about 5 ppm) the pionic x-ray energies of light elements such as Si, P, Ti in order to determine the pionic mass to equal precision. In the course of work, we are also exploring the questions of the correctness of the calculations of the vacuum polarization, the strong interaction effects and the electron screening corrections in the pionic x-ray line energies. We also are pursuing a study of high spin nuclear states induced by pion capture. Our work on neutron-gamma coincidence studies following negative pion capture in tantalum and holmium were partially completed at Nevis Synchrotron. The results show a striking correlation between neutron energy and neutron multiplicity. We propose to continue the program at other suitable accelerators. Some future experiments are also being planned for nuclear excitation studies following K-meson capture.

Major collaborators:

J. Dugan, C. S. Wu Columbia University

D. Lu Yale University

LAWRENCE BERKELEY LABORATORY..... \$ 70,000
Nuclear Science Division

"High Energy Nuclear Reactions"

A. M. Poskanzer and H. H. Gutbrod

The project is concerned with understanding the mechanisms of nuclear reactions induced by high energy protons and in discovering isotopes far from beta stability produced in these reactions. The accelerators used are the Bevatron and LAMPF for high energy protons. Spallation, target fragmentation, and fission are studied. The analysis of some old data on the energy spectra of nuclear fragments produced by high energy protons was completed and published. The time-zero detectors which we developed at LBL have been combined with a gas ΔE counter for phase III of the LAMPF experiment. At LAMPF, a search is being made for new neutron deficient nuclei in the region below calcium. Then we will try to make use of our excellent time-of-flight mass resolution to attempt to make direct atomic mass measurements of neutron excess nuclei to an accuracy of 100 keV.

Major collaborators: LASL, Texas A&M University, ORNL, and BNL.

LAWRENCE BERKELEY LABORATORY..... \$610,000
Physics Division

"Medium Energy Nuclear Physics"

K. Crowe, V. Perez-Mendez, C. Wiegand, S. Kaplan, and P. Nemethy

The study of mesonic atoms has provided the most accurate measurement of the mass of pions and kaons. Valuable information on the π^- nucleus and K^- nucleus interaction has also been obtained, but the physics of the meso-atomic system is still not well understood. There is a striking dependence of the x-ray intensities on the atomic number that was unexpected and remains unexplained.

Much recent effort has been devoted to probing the wave functions of light nuclei. A series of experiments has been devoted to the measurement of elastic scattering cross sections and polarization in a number of systems involving nucleons and light nuclei in the energy range from a few hundred MeV up to several GeV. A pion double-charge-exchange experiment at LAMPF is studying many body forces in the 3- and 4-nucleon system. The nuclear structure program will continue with experiments to measure N-N correlations in light nuclei and to measure off-shell effects in the N-N interaction. We have recently begun a program to search for possible resonances in many-quark systems. The investigation of the interaction of muons with fissile nuclei has moved to TRIUMF and is using the high intensity, high duty-factor muon beam.

Radiative pion capture, i.e., the measurement of the high energy gamma ray spectrum produced when pions are captured in nuclei, has been studied from several different points of view. First, the understanding of basic quantitative structure of the photo-pion transition operator has been accurately fixed by a comparison of theory with measurements on a series of light nuclei. Second, these results may be compared with those from electron scattering and photo-pion production near threshold and muon capture processes on the same nuclei. Only recently have these comparisons led to a consistent set of constants. Third, a new set of reactions has been chosen to use pion capture to study the excited states of nuclei. The new phenomena which have been seen are giant dipole states, possible quadrupole excitations and other more complex states. Fourth, since radiative pion capture has been shown to induce the same Gamow-Teller transitions to bound states (e.g., $\pi^-{}^6\text{Li} \rightarrow {}^6\text{He}\gamma$, $\pi^-{}^3\text{He} \rightarrow {}^3\text{T}\gamma$, $\pi^-{}^{12}\text{C} \rightarrow {}^{12}\text{B}\gamma$) as weak forces, the rates from pion capture can be combined with information from weak and electromagnetic processes to test predictions from CVC, PCAC, etc., as for example, the Goldberger-Treiman relation for the nuclear case.

Considerable instrumentation work is carried out, including efforts on Multiwire Proportional Chambers and associated readout techniques, tests of micro-channel plate photo-multipliers for fast timing applications, and development of multiplicity counters for fragment detection.

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Recent accomplishments include:

1. Mesonic Atoms

The absorption coefficient of kaonic potassium x-rays has been measured in erbium for the transition $n = 6 \rightarrow 5$. These x-rays fall on the erbium K-edge which allows us to accurately determine their energy. The negative kaon mass can be calculated from the x-ray energy. In cooperation with the University of Victoria group at TRIUMF, the pionic x-ray intensities of 60 chemical elements have been measured.

2. Investigations on the Structure of Light Nuclei

Work has continued on data analysis and publication of results from our earlier measurements of forward elastic scattering in the $p\text{-}^4\text{He}$ system at (equivalent) proton energies of 0.4, 1.05, 2.68, and 4.89 GeV. The study of forward elastic scattering has been extended to include measurements of $p\text{-}^3\text{He}$ at 2.68 GeV. ($0.1 < t < 0.76$), and $d\text{-}d$ at 4.18 GeV ($0.08 < t < 2.09$ (GeV/c^2)). In a collaborative experiment at ANL, measurements were made of: 1) polarization in elastic $p\text{-}p$ and $p\text{-}n$ scattering at 1.03 GeV. The $p\text{-}n$ measurements are the first to be done in this energy range, and 2) polarization in backward elastic $p\text{-}d$ scattering at 0.68, 1.03, and 1.53 GeV. An extension of this program will permit measurement of forward and backward elastic $p\text{-}d$ scattering using ANL's polarized deuteron beam to study the D-state and N^* components of the deuteron wave function.

3. Radiative Pion Capture, Pion Scattering and Muon Decay

With an improved, high resolution, pair-spectrometer the tritium γ -spectrum resulting from pion capture has been determined with greatly improved accuracy. Preliminary results, with a factor of 10 more good events than earlier work, are in basic agreement with the earlier effort. However, we see no evidence for a possible bound state of 3 neutrons. Complete analysis of the data will allow much more accurate nucleon structure constants to be extracted for comparison with theory of the three-body system.

4. A Neutrino Experiment to Test Muon Conservation

An experimental study of the nature of neutrinos from muon decay is underway at LAMPF. The experiment is designed to distinguish between an additive and a multiplicative muon conservation law.

Major collaborators:

UCLA (G. Igo), University of Minnesota (M. Marshak), ANL (R. Klem), University of Victoria (R. Pearce), CERN (C. Sabev), Central Washington University (W. C. Sperry), Oregon State University (A. Stetz), University of Tokyo (M. Koike), IKO Amsterdam (A. Wapstra), LASL (H. Baer), University of Zurich (P. Truol), SIN (G. Strassner).

LAWRENCE LIVERMORE LABORATORY..... \$ 25,000

"Precision, High-Resolution Electron Scattering at the Bates Linac"

B. L. Berman

The availability of the Bates linac and the energy-loss spectrometer there makes possible electron-scattering measurements of a precision not possible heretofore, and thus opens new vistas in the field and creates the opportunity for obtaining and exploiting a new generation of electron-scattering data. LLL and MIT have begun a series of collaborative experiments which involve the use of the chemical and metallurgical capabilities of LLL to manufacture thin precision scattering targets for use at the Bates facility. We have performed such measurements on the important rare isotopes of oxygen. We hope to continue these studies, and to extend them to the rare silicon isotopes. Thin targets of BeO, enriched in ^{17}O and/or ^{18}O , were manufactured at LLL (from H_2O samples), and electron-scattering data have been obtained at Bates in 1976 and 1977. Also, new BeO targets, synthesized from highly enriched ($\sim 90\%$) ^{17}O gas, have been manufactured at LLL for use in several measurements scheduled for 1978-79, including 180° electron scattering at Bates with the new magnet system there. Thin SiO_2 targets, using material enriched to 95% in the rare isotopes ^{29}Si and ^{30}Si , are now being manufactured at LLL.

The first important results on the oxygen isotopes now have been submitted for publication. These include (a) the precision measurement of the charge distributions for ^{17}O and ^{18}O which showed that, whereas the charge distribution for ^{17}O is almost identical to that for ^{16}O , the charge distribution for ^{18}O is substantially larger; that is, adding a single valence neutron to a ^{16}O core hardly perturbs the proton distribution therein, but adding a pair of (valence) neutrons causes a strong rearrangement of the protons - a result which was foreshadowed by our earlier proton-scattering measurements at Indiana; and (b) the discovery, via the back-angle electron-scattering measurements at Bates of the magnetization-density distribution for ^{17}O , that the M3 component was suppressed to a degree far beyond the ability of any theory to explain, and that the high-momentum-transfer side of the M5 component was similarly enhanced; this result is completely new and as yet we know of no physical mechanism capable of producing such effects, thus showing that more theoretical effort is needed on a subject heretofore thought to be well understood.

Major collaborators: MIT

LOS ALAMOS SCIENTIFIC LABORATORY \$2,060,000
MP Division

"Nuclear and Particle Physics Research"

L. Rosen, D. Nagle, L. Agnew, J. Amann, D. Bowman, R. Burman, D. Cochran, P. Chamberlain, M. Cooper, J. Frank, P. Gram, C. Hoffman, G. Hoffman, R. Macek, R. Mischke, C. Morris, J. Potter, R. Redwine, J. Spencer, N. Tanaka, and H. Thiessen

This task covers the basic research activities of the Medium-Energy Physics Division personnel at LAMPF, namely, investigating the properties of nuclei and particles and their structure and interactions, particularly in the medium-energy region. This is the scientific basis of the LAMPF project. There are very few user groups which are completely self-sufficient. Many of them have resident graduate students and postdoctoral fellows who need some help and guidance. The LAMPF resident staff provides guidance and support for these activities. They also carry out their own research program.

LASL in collaboration with University of Chicago and Stanford University has completed a new search for the rare decay $\mu \rightarrow e\gamma$. The scientific interest in this search is connected with the extraordinary recent successes of gauge theories in unifying the weak and electromagnetic interactions, in predicting weak neutral currents, etc. A prediction which has not been verified is that the physical muon will not be a pure quantum state, but will have an admixture of muon and electron number; and hence the decay $\mu \rightarrow e\gamma$ can proceed at some (very small) rate. Interest was also heightened by a premature report from the Swiss Institute for Nuclear Studies a year ago that the decay had actually been observed at a level of two parts in a billion. LASL thereupon undertook to repeat the experiment with ten times more sensitivity, namely, one part in ten billion, and has by now achieved this goal. As such, it is the most sensitive μ decay experiment ever completed. The improvement was made possible by the intense beams at LAMPF, which provided more decays to examine, plus more precise methods of rejecting spurious events. No such decays have been observed. (The Swiss have now published their result, and see no bona fide events, but at a level twenty times less sensitive than the LASL-Chicago-Stanford result.) The present result rules out certain classes of gauge models, but most models still predict the effect at some level. LAMPF and Stanford are considering how a further improvement of a hundred in sensitivity may be achieved. This appears to be possible.

Approximately 100 events from the reaction $\nu_e + D \rightarrow p + p + e^-$ have been observed in an experiment using the neutrinos created in the LAMPF beam stop. This result was part of an on-going study of lepton-number conservation by a group of physicists from LASL, Yale and Bern Universities, LBL, NRC-Ottawa, and Saclay. In the lepton-number conservation experiment, the type of neutrino omitted in muon-decay is determined from neutrino interactions in a large water Cerenkov detector. For the measurement of the $\nu_e + D$ reaction--the inverse of the "pep" reaction that occurs in the solar energy cycle--the Cerenkov detector was filled with 6.6 tons of heavy water. Completely surrounding the detector was a cosmic ray anti-coincidence shield, composed of a sandwich of plastic scintillators, lead shielding, and drift chambers, which reduced cosmic ray events by a

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factor of 10^4 . Events from the neutrino absorption on a deuteron were signaled by the emergence of an approximately 40 MeV electron. The cross section measured is in good agreement with the theoretical value used in astrophysical calculations. This represents the first direct check on the proton-proton reactions presumed responsible for energy production in the sun.

The 800 MeV H^- beam at LAMPF provides a unique opportunity to study the structure of the H^- ion and its excited states which are difficult or impossible to measure using any other method. The most sophisticated current theories predict two different types of resonances or short lived autodetaching excited states in the H^- ion. One is an especially prominent feature just above the threshold for the reaction which yields an electron and a neutral hydrogen atom in its first excited state ($n=2$); this is known as the "shape resonance." The other is a set of very narrow "Feshbach resonances" which lie just below the $n=2$ threshold. Similar narrow resonances are predicted for the $n=3,4,5...$ levels as well. A collaboration involving LASL, UNM, U. of Conn., and ILC has been using a novel colliding beam technique to measure the cross section for photo-detachment of the extra electron from threshold (0.75 eV) through the first few excited states. Light from a laser shines through a rotating mirror system through the H^- beam and into a beam catcher. The detached electrons continue forward with an energy of 435 keV (corresponding to the same velocity as the 800 MeV H^- beam) and are swept with a weak magnetic field into a solid state electron detector. The center of mass energy of the photon is varied via Doppler shifting by rotating the mirror system about the interaction region to change the angle of incidence between the two beams. A range of photon energies from 1.8 to 12.8 eV has been achieved. This extends into the vacuum ultraviolet, a region unattainable with conventional photon sources. The angle is varied precisely in steps of $30 \mu r$ corresponding to 0.1 meV. This unusually fine resolution allowed the detailed mapping of the $n=2$ Feshbach resonance as well as the shape resonance. Also the effect of a barycentric electric field on these resonances has been well characterized. In particular, the linear Stark splitting of the Feshbach resonance into specific m states has been identified.

The next phase of the experiment involves the complete mapping of the higher energy resonances and a detailed study of two electron photo-detachment.

An interesting spinoff from this work has developed from the fact that the dependence on Doppler shifting in the colliding beams allows the accurate absolute measurement of the H^- beam energy. The precision on this has been shown to be 250 keV out of 800 MeV.

An exploratory survey with polarized protons was undertaken with the high resolution spectrometer (HRS), by LASL and most of the groups active on the HRS facility.

This experiment provided a set of 800 MeV proton-nucleus elastic scattering

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differential cross section and analyzing power data for target nuclei ^{12}C , $^{40,42,44,48}\text{Ca}$, ^{54}Fe , $^{58,64}\text{Ni}$, ^{90}Zr , $^{116,124}\text{Sn}$, and ^{208}Pb . The data were analyzed using the optical model and the KMT microscopic optical potential to determine the neutron density distributions of these nuclei. Approximately model-independent neutron densities were used in the analysis and a complete study of the sources of error which affect the deduced neutron densities was made. The results of the complete error analysis is that the rms neutron radii for the 12 nuclei studied are reliably determined to ± 0.08 fm, while differences between neutron radii for the isotopic sequences are determined to ± 0.04 fm. In all cases both deduced neutron rms radii and the approximately model-independent density distributions themselves are found to be in basic agreement with Hartree-Fock predictions.

One of the motivations for doing pion nucleus scattering is that it is possible to obtain information about neutron and proton distributions in nuclei by comparing π^+ and π^- scattering. This information is expected to be cleaner than that obtained with other methods involving two or more different hadronic probes. An experiment with this goal, which was the first to use the new EPICS spectrometer, measured the cross section for inelastic scattering to the first 2^+ state of ^{180}O . A ratio of π^-/π^+ of 1.66(.13) was obtained for the excitation of the 2^+ state. A similar experiment at SIN reported at the Zurich meeting obtained a ratio of 1.27(.04). This EPICS result means that pions are useful for measurement of neutron deformation parameters, whereas the SIN result indicates that pions are not useful. The EPICS experiment was repeated with an improved target and scattering chamber, and the result was 1.75(.10), completely verifying the accuracy of the initial result. Shell model calculations are underway at Michigan State to make use of this result to improve our understanding of the wave functions of ^{180}O .

A precision double gamma-ray spectrometer; i.e., π^0 spectrometer, has been assembled and installed on the LEP channel. The spectrometer is designed for studying nuclear reactions where the final products include a neutral pion. Studies of single-charge exchange reactions of pions on light nuclei were begun. An extensive program is planned for this instrument.

Major collaborators: R. Hofstadter (Stanford University), H. Anderson (University of Chicago), J. Schiffer (Argonne National Laboratory), A. Yavin (Tel Aviv University), J. Alster (Tel Aviv University), P. Nemethy (Lawrence Berkeley Laboratory), F. Reines (University of California at Irvine), G. Igo (University of California at Los Angeles), N. Hintz (University of Minnesota), H. Frauenfelder (University of Illinois), C. Barnes (California Institute of Technology), F. Boehm (California Institute of Technology).

LOS ALAMOS SCIENTIFIC LABORATORY.....\$453,000
MP Division

"Practical Applications Research at LAMPF"

J. Bradbury, K. Hanson, A. Harvey, R. Heffner, M. Leon, and M. Schillaci

Current applied research programs at LAMPF include: solid-state physics and materials analysis (muons, protons, neutrons), chemical effects on meson capture (muons), radioisotope production (beam stop protons), radiation biology and cancer therapy (pi mesons), radiation damage studies (protons, neutrons), DOD-related studies (pulsed neutrons), and electronuclear fuel breeding feasibility experiments.

Muon-Spin Rotation (μ SR) Research

Muon depolarization measurements as a function of temperature have been made for a number of samples including Al, Cu, V, and Nb, some doped with known quantities of impurities. The results indicate that at low temperatures in Cu the muons are clearly localized at octahedral interstitial sites but surprisingly, this behavior is not observed in Al. By varying impurity concentrations in V and Nb, it was ascertained that even at low temperature (10°K) muon depolarization is dominated by traps associated with impurities. Diffusion studies using μ SR are underway which may improve our understanding of hydrogen diffusion in metals.

Proton Computed Tomography

Residual energy measurements on a nearly monochromatic 200 MeV proton beam passing through an inhomogeneous sample from a number of directions have been used to obtain the density distribution within the sample. The same sample was investigated with a commercial x-ray CT scanner. For the same density resolution ($\sim 0.5\%$), the proton scan delivered about 5 times less dose to the sample than the x-ray scan. An experiment now being planned will determine whether in addition to this dose advantage, protons possess a significant advantage in improving contrast.

Muonic X-Ray Analysis (μ XR)

The cascade x-ray spectra produced when negative muons are captured in a sample have been shown to provide information on the elemental composition of the sample and also the chemical environment in the capture region. Recent effort has been directed toward elucidating chemical effects and applying the technique to selected practical analytical problems.

Radiation Damage

Several electrical components, including cables and connectors, have received neutron irradiations at the beam stop radiation effects facility (REF) as part of a program to investigate damage effects on critical components used at LAMPF. Ceramic vacuum tube sections were exposed to 100 MeV proton pulses at the request of Rutherford Laboratory to determine cracking and shattering thresholds.

Major collaborators: J. Reidy (University of Mississippi), A. Coulter (University of Alabama), M. Rickey (Indiana University), H. Knowles (Washington State University), M. Kligerman et al. (University of New Mexico), A. Denison (University of Wyoming), W. Cooke (Memphis State University), W. Kossler (College of William and Mary), W. Gauster (Sandia Laboratories), T. Blewett (Argonne National Laboratory), A. Fiory (Bell Laboratories).

LOS ALAMOS SCIENTIFIC LABORATORY..... \$300,000
P Division

"Medium Energy Neutron Physics Research and Muonic X-ray Studies of Nuclear Structure"

J. E. Simmons, B. E. Bonner, E. B. Shera, H. D. Wohlfahrt, and M. V. Hoehn

Neutron Physics

The primary scientific objective is the experimental study of the nucleon-nucleon (N-N) force with emphasis on the isospin-zero interaction as manifested in neutron-proton scattering. The eventual result will be a quantitative measure of the scattering amplitudes at energies that are feasible to obtain at LAMPF. The experimental program includes inelastic as well as elastic interactions and extends to neutron scattering from light nuclear targets. In recent experiments the energy dependence of scattering phenomena has been pursued by a time-of-flight method which has added important new information on n-p and n-d scattering. The complexity of the N-N force is such that spin polarization experiments are necessary for full understanding. A polarized target system has been developed that will enable measurements to be made on the scattering of polarized neutrons from polarized protons. Such experiments have not yet been performed at medium energy and are expected to provide important new information. Recent investigations have included: np differential cross sections at 800 MeV; np and nd back-angle scattering from 200 to 800 MeV; studies of np pion production leading to a final-state deuteron; np analyzing power from 400 to 800 MeV.

Muonic X-ray Studies

The experimental program centers around the use of the intense stopped muon beam of LAMPF to study a variety of stable nuclei, with the goal of obtaining new information on nuclear charge distributions. Emphasis is placed on the development and exploitation of novel ways in which muons can be used to study nuclear properties and upon systematic studies of sequences of nuclei known from other work to exhibit interesting variations of nuclear parameters. Precise values of radial charge distribution parameters are being determined for essentially all stable isotopes in the $1f_{7/2}$, $2p_{1/2}$, $2p_{3/2}$, and $1f_{5/2}$ shells. The muonic x-ray data, when combined with electron scattering results, yield a highly precise and model-independent description of the charge distributions of these nuclei. A second area of study centers on the deformed and transition-region nuclei. Here the high intensity of the LAMPF accelerator is especially significant since the amount of available target material is often very limited. In the transition nuclei, muonic x-ray measurements can reveal in detail how the charge distribution changes in progressing from spherical to deformed nuclei. For example, in our recent muonic study of the Os isotopes we have been able to show that the electric multipole moments of these nuclei are not accurately predicted by the best existing microscopic theory.

Major collaborators: University of Texas, Texas A&M University, Case Western Reserve University, Purdue University, Florida State University, University of Mainz (Germany), and University of Fribourg (Switzerland).

LOS ALAMOS SCIENTIFIC LABORATORY\$390,000
CNC Division

"Nuclear Chemistry Research at LAMPF"

B. J. Dropesky, J.D. Knight, C.J. Orth, and G.W. Butler

The nuclear chemistry research program at LAMPF is national in scope and presently consists of 19 experiments. These involve the participation of some 64 scientists, two-thirds of whom are from 17 different U.S. institutions, while the remaining are LASL researchers. The interactions of both fast and stopped pions resulting in proton and neutron knock-out, single and double charge exchange, spallation, fragmentation, and fission are under investigation. The establishment of good pion-beam monitor cross sections has enable reaction probabilities to be put on an absolute basis. Fortunately, a sophisticated model, the ISOBAR version of the VEGAS intranuclear cascade code, has been available for testing against observed pion-induced phenomena. The variety of pion activation experiments can be expected to increase still further as the beam intensities approach their maxima. Plans are also being made to explore several in-beam counter-telescope techniques to complement the activation studies by examining selected aspects of pion interactions. Measurements of prompt γ -rays following fast pion interactions are being made. The investigation of the complex extra-nuclear phenomena (chemical effects) associated with the stopping of negative muons in matter is being vigorously pursued in order to obtain insights and data leading to quantitative models in terms of known chemical structure and with the hope of developing techniques to obtain new information on chemical systems. Measurement of the mean muon life-time in interactions with actinide elements has been extended from looking at decay electrons to include observing neutron emission and fission-fragment emission. Also, neutron and proton knock-out reactions induced by the electromagnetic interaction of fast muons have recently been investigated. Advantage is also being taken of the proton beam to study intermediate energy reactions with complex nuclei to an extent not possible before. At the Thin Target Facility, on the main proton beam, important use is made of both the uniquely high intensity and the microstructure of the beam to measure the yields of light fragments (to $A \sim 40$) emitted from uranium and some lower Z targets to identify new, particle-stable nuclides, and, hopefully, to measure directly some nuclear masses. Nuclear spectroscopy, radiochemistry, and isotope separation expertise continue to be brought to bear on studies of an important neutron-deficient region of the nuclear mass surface by construction of the decay schemes of many radionuclides produced through proton-induced spallation. The intense flux of energetic neutrons from the LAMPF beam stop is being exploited to produce new neutron-rich, short-lived nuclides for characterization.

Major collaborators:

Brookhaven National Laboratory (Hudis, Haustein, Remsberg)
Purdue University (Porile)
Princeton University (Naumann)
Lawrence Berkeley Laboratory (Poskanzer)
Idaho National Engineering Laboratory (Reich, Heath)
Iowa State University (Hill)
University of Rochester (Huizenga)
Texas A&M University (Natowitz)
University of Oklahoma (Petty)

LOS ALAMOS SCIENTIFIC LABORATORY..... \$ 27,000
E Division

"Study of Resolution Limitations In Liquid Ionization Chambers"

C. R. Gruhn

This task is concerned with experimental determination of those physical parameters which limit resolution of liquid ionization chambers. The controlling parameters of the charge transport and production of electron-ion pairs are being measured for liquid argon and a liquid argon-xenon mixture. Detectors having larger volumes (our test chamber uses volumes $\sim 3000 \text{ cm}^3$) and higher Z (Xe) and near Ge detector resolution can be expected as a result of an improved understanding and control of those statistical and nonstatistical factors which contribute to the liquid ion chamber resolution. A resolution of 26 keV FWHM for 480 keV electrons and 34 keV FWHM for 976 keV electrons has been achieved. This is the best resolution obtained by any laboratory in the world to date. The limiting factors contributing to this resolution are being studied.

Major collaborators: M. Edmiston, D. Drake, R. deVries, E. Flynn,
and S. Orbeson - LASL
D. Hendrie and K. Vanbibber - LBL

UNIVERSITY OF MASSACHUSETTS..... \$75,000
Department of Physics and Astronomy

"Nuclear Structure Studies By The Scattering of Medium-Energy Electrons"

G.A. Peterson, R.A. Lindgren, and R.S. Hicks

The new apparatus for 180° electron scattering at the Bates Accelerator has been used to study elastic and inelastic scattering of 50 to 260 MeV electrons in order to obtain exchange, convection, and spin magnetization current data. Magnetic scattering from ^{25}Mg and ^{93}Nb has been measured between 0.8 and 1.9 fm^{-1} so as to obtain the M3 and M5 form factors. Agreement with Nilsson and shell model calculations was found. Magnetic elastic scattering from ^{13}C is being measured so as to obtain information on the magnetic dipole moment distribution, and hence the valence neutron distribution, and possibly exchange currents. The levels of ^{12}C are being investigated by 180° electron scattering. Transverse excitation of the collective $T=0$ and $T=1$, 1^+ , 2^+ , 2^- , and 3^- levels have yielded transverse convection and spin current form factors. Nuclear theory calculations must simultaneously account for both longitudinal form factors and our measured transverse form factors so as to meet the demands of the continuity equation. Exchange currents must be evoked to account for the form factor of the 15.11 MeV, $T=1$, 1^+ excitation. Searches for high multipolarity (8^-) transitions in ^{58}Ni and ^{54}Fe are underway in order to identify strong single particle-hole excitations. An analysis of the form factors of ^{27}Al states up to 8 MeV in excitation is near completion. A liquid-nitrogen cooled gas target is being constructed for a deuteron electro-disintegration experiment in which it is hoped to obtain information on magnetic exchange currents and/or the deuteron wave function.

Major collaborators: Instituut voor Kernfysisch Onderzoek, (Amsterdam, The Netherlands); Universitat Mainz, (Mainz, Germany); Massachusetts Institute of Technology; Catholic University of America

MASSACHUSETTS INSTITUTE OF TECHNOLOGY..... \$1,140,000

"Experimental Research: Electromagnetic Interactions and Nuclear Structure Physics"

P. Demos, J. Heisenberg, W. C. Barber, A. Bernstein, W. Bertozzi, I. Blomqvist, D. Ingham, S. Kowalski, J. Matthews, F. N. Rad, W. Sapp, C. P. Sargent, W. Turchinets, C. Williamson

This report covers the experimental research program in medium energy nuclear structure physics at MIT. The major part of the program is carried out at the Bates Linear Accelerator and involves the study of electromagnetically-induced phenomena in nuclei. Some work is carried out at other accelerator facilities and includes programs in hadronic scattering and hadron-induced reactions. Of the research at Bates, some is carried out independently by MIT physicists, and some in collaboration with scientists from other institutions. A large component of the research at Bates is carried out independently by users from other institutions.

The experiments at Bates are concerned with the two broad categories of electron scattering and electro- and photo-induced reactions. The electron scattering program encompasses elastic scattering and inelastic scattering to discrete states, and deeply inelastic scattering in the quasi-elastic region, involving nucleon knock-out and pion production. The photoreaction program thus far has involved mostly studies of the (γ, π) and the (γ, p) processes, although some (γ, XN) studies of multinucleon emission are underway using induced radioactivity as the reaction indicator and some exploratory measurements have been made in (γ, d) and (γ, t) spectra.

The electron, as an electromagnetic probe, possesses the advantage of employing an interaction which is well understood compared to the strong interaction of the hadronic probes. Used in electron scattering experiments on nuclei, it carries the additional flexibility of allowing the transferred momentum to be varied independently of the transferred energy. Also, due to the weakness of the electromagnetic interaction, the process and its representation are relatively uncomplicated. The spatial structure of the nuclear one-body charge, current and magnetization densities responsible for the scattering may be determined from the measured elastic and inelastic cross-sections with good precision.

Electron Scattering Research

The high resolution ($\Delta p/p \sim 10^{-4}$) and high electron beam currents ($\sim 100 \mu\text{a}$) available with the MIT energy-loss spectrometer at Bates have permitted the measurement of many new or previously unobservable states in nuclei. The recent inclusion of specialized magnets designed by the University of Massachusetts group for 180° scattering allows greatly increased sensitivity in the measurement of the magnetic and electric current properties of the nucleus, in particular for the nuclear ground state, for which measurements of these effects are usually overpowered at low momentum transfer and at angles forward of 180° by scattering from the static charge of the nucleus.

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The measurements of nuclear ground state magnetization densities include work on ^9Be , ^{17}O and ^{181}Ta , by an MIT group; work on ^{27}Al , ^{93}Nb and ^{25}Mg by a group from the University of Massachusetts; work on ^{115}In and ^{39}K by a group including personnel from MIT and IKO Amsterdam; and work on ^6Li by a Mainz, Saskatoon, MIT group. The Be results agree well with previous measurements from Amsterdam and Stanford (HEPL), and serve to confirm the capability and excellent quality of the 180° magnet system.

The ^{17}O data, which span the momentum transfer range $0.5 \leq q \leq 2.8 \text{ fm}^{-1}$ show unexpected behaviour. The shape of the M1 form factor differs considerably from that expected for a single $d5/2$ neutron model; the M3 form factor is greatly suppressed; and the data reveal a surplus of cross-section at the higher momentum transfers, where none of the magnetic multipolarities are predicted to contribute significantly.

The measurements on ^{17}O are part of a broader program underway to understand better the unusual electric and magnetic properties of the oxygen isotopes. The work on ^{181}Ta , similarly, is part of the MIT program of study on the rotational nuclei. Taken together with the 180° scattering measurements from even-even rotational nuclei, the scattering from tantalum at 180° is shown to be entirely magnetic at $q > 1 \text{ fm}^{-1}$. Presuming this to be due to the magnetization produced by the valence nucleon of ^{181}Ta , the data are in rough agreement with a theoretical treatment using a deformed density-dependent Hartree-Fock model, but disagree (factor > 10) with a calculation which assumes the valence nucleon to move in a spherical potential. There appears to be good sensitivity in the measurements, which are being extended in this and similar nuclei, to the details of the nuclear deformation.

In further studies of magnetic scattering, transitions of high multipolarity have been observed in ^{24}Mg , ^{28}Si , ^{58}Ni , ^{54}Fe and ^{208}Pb . In ^{24}Mg and ^{28}Si these have been seen as single strong transitions to 6^- states (University of Toronto and MIT measurements), in ^{58}Ni and ^{54}Fe to groups of 8^- states (University of Massachusetts and MIT), and to states clearly identified for the first time as 12^- and 14^- states in ^{208}Pb (University of New Hampshire, University of Virginia, MIT). Except for the ^{208}Pb nucleus, which shows its expected strong shell model behaviour, the measured strengths of the other states observed in the rest of the above nuclei disagree with shell model predictions, possibly because of fragmentation of the strengths among many weak states, which are not included in the available theory.

Electron scattering measurements have been completed by an MIT group of the ground state rotational bands of the deformed even-even nuclei ^{150}Nd , ^{156}Gd , ^{166}Er , ^{176}Yb , ^{232}Th and ^{238}U . Comparisons of the cross-section data with density-dependent Hartree-Fock calculations show generally good agreement for the 0^+ and 2^+ states. The 4^+ state measurements are not as well predicted by this theory, and agreement with the 6^+ state cross sections is poor.

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Certain vibrational levels observed in this work have been found to be represented successfully by small amplitude surface oscillations about a deformed nuclear core. In particular, calculations based on this model were in good agreement with the measured form factors of the three observed members of the $K^\pi = 0^-$ octupole band in ^{238}U . A Physical Review Letter describing this result has been published.

A comparison of data from the above work (2^+ states in ^{150}Nd) was made also with calculations based on the interacting boson approximation model (IBA). These showed a discrepancy which has been interpreted as due to an unknown 1^- state unresolved from one of the 2^+ levels. A picture consistent with the data following this interpretation has been published (Phys. Rev. Letters).

Measurements made on the odd-even deformed nuclei ^{167}Er , ^{175}Lu and ^{181}Ta have shown features similar to those of the even-even nuclei. The form factors of these nuclei, additionally, exhibit differences when compared with those of their even-even partners which seem to show the polarizing effects of the odd nucleon upon the nuclear core.

Rotational bands are under study also in ^{24}Mg (University of Toronto and MIT), in ^{40}Ca (Northwestern University, University of Lowell and MIT), and in ^{19}F (Catholic University, Chalk River Laboratory, MIT). The ground state rotational band in ^{24}Mg is of particular interest, showing properties in the form factor of its 4^+ member which require an intrinsic spin ($K=0$ and $K=2$ mixing) of the Hartree-Fock model. The focus of interest in ^{40}Ca is the rotational band built on the 3.353 MeV 0^+ level, using detailed shell model calculations to examine its particle-hole structure. The ^{19}F measurements, which have been completed and published, show good agreement of the ground-state rotational band form factors with theory, (variation-after-projection Hartree-Fock) for $q \leq 1.7 \text{ fm}^{-1}$.

In other work, extended experiments on ^{207}Pb and ^{208}Pb have resolved more than 100 levels in these nuclei (University of New Hampshire et al). In ^{207}Pb analysis has been made and published (Phys. Rev. Letters) of specific neutron-hole and neutron-particle transitions which display strong longitudinal form factors due to core polarization induced by the neutron in transition. It is hoped that the data may give information on the neutron-proton interaction. Some thirty levels observed in ^{208}Pb have shown mainly longitudinal form factors. The weak states among these are of particular interest, clearly exhibiting a single particle-hole nature.

Many other experiments are currently underway in the electron-scattering program. Examples are: the charge-density comparisons of ^{16}O , ^{17}O , and ^{18}O (Lawrence Livermore Laboratory and MIT); the transverse form factor of the first 2^+ state in ^{12}C (University of Massachusetts); the single particle and collective

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structure of ^{13}C (Catholic University and MIT); quasi-elastic scattering from ^{40}Ca (Louisiana State University, University of Virginia and MIT); a study of the silicon isotopes (Lawrence Livermore Laboratory, University of Massachusetts, University of Toronto and MIT).

Photonuclear Reaction Experiments

Photo-induced reactions leading to the emission of nucleons are under study in the photon energy range 50 to 400 MeV. Work includes a study of the $^3\text{He}(\gamma, 2p)n$ reaction in the p-p final state interactive region. An experiment by an MIT-University of Montreal collaboration has been completed recently to study the ^3He breakup process, completely determining the reaction kinematics by detecting the two protons in coincidence. The measurements were made at emitted proton angles of $\sim 90^\circ$ to examine specifically the role of the p-p final state interaction. The strong expected enhancement in the cross-section due to the final state interaction was observed, and a detailed comparison with theory is in progress.

Preparations are underway to make accurate absolute measurements of the differential cross section for the photodisintegration of the deuteron over a wide energy and angular range ($E_\gamma = 50\text{-}400$ MeV; $\theta_p = 20^\circ\text{-}160^\circ$). Existing data on this most basic reaction contain discrepancies and do not agree well with theory.

Nuclear structure and reaction mechanisms are being examined by an MIT-University of Glasgow collaboration in which emphasis is placed on good energy resolution for both the photon and the emitted particle, so that the nuclear states involved may be determined. Included here are $^{16}\text{O}(\gamma, p)$ and $^{40}\text{Ca}(\gamma, p)$ reactions leading to low-lying final nuclear states, for $E_\gamma = 100\text{-}400$ MeV. The object of these experiments has been to measure the photon energy dependence and angular distribution of these reactions where there is large momentum mismatch between incoming photon and outgoing proton, thus probing the high momentum components of the nuclear wave function. A fairly complete set of data exists on both reactions at emitted proton angles of 45° , 90° and 135° , and some preliminary results have been published. In the energy region $E_\gamma = 300 \pm 100$ MeV, where the $\Delta(1232)$ isobar is expected to play a role, two theoretical calculations have appeared which agree only qualitatively with the data.

Experiments are planned to examine the (γ, d) , (γ, t) and (γ, α) reactions in light nuclei. Cross-sections for these processes in which the incoming photon and outgoing particle energies are well defined are unknown for the $E_\gamma \geq 100$ MeV region, and are expected to be sensitive both to initial state correlations and final state interactions. Some exploratory measurements of the $^9\text{Be}(\gamma, d)$ and (γ, t) reactions have been performed.

These experiments suffer from low cross-sections, and yield particles of very high momentum at the kinematic limits available at Bates

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energies. To date work has been carried out using the high-resolution electron spectrometer. This instrument is deficient for this purpose in solid angle ($< 5\text{msr}$), range ($\sim 6\%$) and maximum momentum (900 MeV/c). Plans have been developed to convert a surplus dipole magnet to a spectrometer system more suited to the hadron detection: solid angle ($\sim 15\text{msr}$) range ($\sim 15\%$) and maximum momentum ($\sim 1500\text{ MeV/c}$). This system will be mounted in the new experimental hall about a common pivot with the new ($\gamma\pi$) spectrometer.

Photopion Research

An extensive group of experiments is being carried out on the (γ, π) reaction in complex nuclei. This is a fundamental reaction since it involves directly the quanta of both the electromagnetic interaction and the nuclear force field. The interest here is to use the precisely understood nature of the electromagnetic interaction to study the pionic properties of nuclei. In electron scattering these properties manifest themselves through virtual pion emission and absorption, and the effects of these upon the electric charge and current distributions in nuclei. In the photo-pion experiments the pions are real, rather than virtual, and may be studied in terms of their propagation and interaction through and with the nucleus. It is clear that there are deep connections between photo-pion physics and electron scattering on the one hand, as well as with pion-induced reactions on the other.

Earlier (γ, π) experiments performed at the Bates Laboratory (Boston University, RPI, University of Massachusetts and MIT) have been reported and published (total cross-section measurements of reactions in ^{12}C , ^{16}O and deuterium in the 1 to 10 MeV meson energy range). These experiments were in good qualitative agreement with theory and provided the basis upon which the further programs now underway and projected were established. In particular a fixed-angle (90°) charged pion spectrometer has been used to detect photopions emitted in the 10 to 50 MeV energy range. This system has sufficient resolution ($\sim 1\%$) to resolve discrete final nuclear states. Measurements are underway with this instrument on the energy dependence of the (γ, π) cross-section, on the identification of states strongly excited in the reaction, on measurements of the π^-/π^+ ratio in isobaric analog transitions, and on the energy loss mechanisms encountered by the emergent pion in the nucleus. Experiments performed in the ($\gamma, \pi^\pm$) reactions in ^{12}C have been analyzed and published which compare favorably with theoretical estimates of the measured cross-sections, and with the excited state spectra observed elsewhere (Berkeley and SIN Laboratories) in the ^{12}C (π^-, γ) radiative capture experiment. A major collaborative effort is currently underway involving principal investigators from several institutions in preparation for experiments in the Bates second experimental area. A jointly designed (RPI-MIT) variable-angle pion spectrometer of large solid angle (35msr) and dynamic range (15%) is under construction which will be capable of $\sim 50\text{ keV}$ energy resolution.

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Construction of that magnet has been undertaken by the RPI physicists of the collaboration. The instrument will permit experiments over a broad range of pion energies, from the near threshold region to beyond the (3,3) resonance and will be used in the measurement of differential-cross sections, for the examination of discrete nuclear excitations and for quasi-free photopion production studies.

Major collaborators: Amsterdam Free Univ. (Netherlands), Boston Univ. Catholic Univ., Chalk River National Laboratory (Canada), Florida State Univ., George Mason Univ., University of Glasgow (United Kingdom), IKO (Netherlands), Univ. of Illinois, Lawrence Livermore Laboratory, Louisiana State Univ., Lowell State Univ., Univ. of Mainz (W. Germany), Univ. of Massachusetts, Univ. of Montreal (Canada), National Bureau of Standards, Univ. of New Hampshire, Northwestern Univ., Naval Research Laboratory, Oak Ridge National Laboratory, Rensselaer Polytechnic Institute, Univ. of Saskatoon (Canada), Univ. of Toronto (Canada), Vanderbilt Univ., Univ. of Virginia, Virginia State Univ., College of William and Mary, Univ. of Wisconsin, Worcester Polytechnic Institute, Univ. of Wyoming, and Yale Univ.

UNIVERSITY OF MINNESOTA..... \$ 80,000
School of Physics and Astronomy

"Nuclear Structure Studies at Intermediate Energies Using Protons and Pions"

N. Hintz and D. Dehnhard

Our efforts emphasize study of nuclear structure using medium energy proton and pion probes. Priority is currently being given to elastic and inelastic scattering with both unpolarized and polarized (proton) beams using the HRS and EPICS spectrometers. Computer programs are being adapted to analyze the data with optical model, KMT, DWBA and coupled channels reaction theories. Current efforts include:

- 1) Analysis of inelastic proton data on four nickel isotopes from LAMPF Exp #139 (completed).
- 2) Analysis of inelastic proton data on six s-d shell nuclei (^{19}F to ^{32}S) from LAMPF Exp #178 (completed Aug. '78).
- 3) Analysis of inelastic proton data on singly closed shell nuclei (5 targets) to search for high spin "orbit flip" states from LAMPF Exp #347 (completed Aug. '78).
- 4) Participation in LAMPF Exps #311 and #355, elastic scattering of polarized protons to large momentum transfer.
- 5) LAMPF Exp #183, Inelastic Proton Scattering from Heavy Deformed Nuclei (Sm to U) to study high multipoles in nuclear shape and to compare neutron deformations with proton deformations (from electron scattering).
- 6) LAMPF Exp #411, to measure spin-flip probabilities in inelastic scattering to collective magnetic states.
- 7) LAMPF Exp #232, "Inelastic Pion Scattering by ^{24}Mg and ^{25}Mg ". This is a study of elastic and inelastic π^+ and π^- scattering to low lying rotational and vibrational states.
- 8) LAMPF Exp #369, "Inelastic Pion Scattering by ^{17}O ". Special emphasis will be placed on a comparison of the inelastic π^+ and π^- cross sections for the first excited state of ^{17}O ($1/2^+$). Thus this experiment allows a study of a transition that involves mainly the promotion of a single neutron from the $1d_{5/2}$ to the $2s_{1/2}$ shells and large differences are expected between inelastic π^+ and π^- cross sections.

Major collaborators: H. A. Thiessen, G. W. Hoffman, C. L. Morris, LASL; G. S. Blanpied, New Mexico State Univ.; J. Moss, Texas A & M; and C. Glasshauser, Rutgers (on exp #411.)

UNIVERSITY OF MONTANA..... \$ 16,704
Department of Physics and Astronomy

"Total Pion Cross Section Measurements"

M. J. Jakobson and R. H. Jeppesen

The objectives of LAMPF Expt. #2 "Total Pion Cross Sections" are:
1) accurate ($\pm 1\%$) determination of $\pi^\pm$ total cross-sections in the (3,3) region and below for a representative sample of nuclides;
2) exploration of the usefulness of such data for extraction of differences in RMS radii for distributions of neutrons bound in nuclei; and 3) extraction of pion-nucleus interaction information (e.g. test of the various versions of optical potentials). Total pion cross section work is to be continued. The total cross section differences for pairs of isotopes of a number of elements have been measured and the significance of the results is being evaluated (^6Li , ^7Li ; ^{10}B , ^{11}B ; ^{12}C , ^{13}C ; ^{16}O , ^{18}O ; ^{40}Ca , ^{44}Ca , ^{48}Ca .) Also, some effort is to be expended on the measurement of elastic cross sections for ^{208}Pb at energies near the Coulomb barrier and on pion stopping power in light and heavy elements for energies up to 100 MeV. The Calcium isotope differences have been published. The Pion Cross section measurements for aligned ^{165}Ho are also published. Targets and energies to be published for $\pi^\pm$ include ^4He 23-90 MeV; ^{12}C , ^{13}C 23-240 MeV. ^6Li , ^7Li ^9Be ^{10}B ^{11}B , 43-215 MeV; ^{16}O , ^{18}O , ^{40}Ca , ^{44}Ca , ^{48}Ca , 43-240 MeV; ^{45}Sc , ^{51}V , ^{27}Al , Cu, Sn, Pb, 60-215 MeV.

Major collaborators: M. Cooper, D. C. Hagerman, and R. Redwine, MP Division, Los Alamos Scientific Laboratory; I. Halpern, University of Washington; G. Burleson, K. Johnson, New Mexico State Univ., H. Meyer, University of Basel; R. Marrs, Indiana University; J. Calarco, Stanford University; S. A. Becker, B. A. Watson, and R. R. Fisher, Lockheed Palo Alto Research Center; and H. Marshak, National Bureau of Standards

UNIVERSITY OF NEW MEXICO..... \$200,000
Department of Physics and Astronomy

"Nucleon Physics Studies at Intermediate Energies"

D. M. Wolfe, B. D. Dieterle, and C. P. Leavitt

"Research work emphasizes experimental investigation of the nucleon-nucleon interaction. Recent work has included:

LAMPF Expt. #124 "Measurement of the Neutron Energy Spectrum in $p+p \rightarrow n+\pi^+p$ " Data analysis has been completed to the point of extraction of cross-sections.

LAMPF Expt. #129 "Pion Production in Neutron-Proton Collisions"

LAMPF Expt. #193 "Measurement of Small Angle Neutron Elastic Scattering from Protons"

LAMPF Expt. #279 "Measurement of Neutron-Neutron Differential Cross-Section and a Test of Charge Independence" Analysis of the $n+d$ data is well underway; analysis of the $p+d$ data is at a much earlier stage.

AGS Expt. #701 "Search for Bound States and Resonances in the $\bar{p}$ -D Interaction" This experiment is running at Brookhaven as of October 1978.

Duality theory and meson exchange potential theories (e.g., Shapiro at ITEP in Moscow and Dover at BNL) predict bound states of the nucleon-antinucleon systems. However, the various theories most certainly do not agree among themselves on the mass spectrum for such bound states. Thus there is strong expectation that experimental data will have direct impact on our understanding of the nucleon-nucleon interaction. Preliminary pp data from CERN (γ spectra only) is encouraging but inconclusive. The present AGS effort will use the two body reaction $\bar{p}+d \rightarrow (\bar{p}p)+n$ and $\bar{p}+d \rightarrow (\bar{p}n)+p$ in a missing mass experiment to determine masses and widths of any bound states or resonances observed. Coincident γ data will also be taken with a 30-inch diameter X 20-inch long NaI system.

Major collaborators: Temple University, University of California at Irvine

NEW MEXICO STATE UNIVERSITY\$ 55,000
Physics Department

"Experimental Studies of Various Pion-Nucleus Interactions"

G.R. Burleson

Using the LEP and EPICS facilities at LAMPF, we are investigating pion-nucleus interactions. Specific current research emphasis includes:

1.) LAMPF Expt. #2 "Pion-Nucleus Total Cross-Sections"

Data taking (20 targets ranging from ${}^4\text{He}$ to ${}^{208}\text{Pb}$ at $\pi^{\pm}$ energies between 25 and 250 MeV) was completed in the spring of 1976. Data analysis, using a new method, is in progress.

2.) LAMPF Expt. #246 "Scattering of 50 MeV π^+ from Light Nuclei"

Elastic scattering angular distributions were measured for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{13}\text{C}$, ${}^{16}\text{O}$, ${}^{28}\text{Si}$, and ${}^{56}\text{Fe}$. Data taking is complete and all results have been published or submitted for publication.

3.) LAMPF Expt. #245 "Study of the (π^-, n) and $(\pi, \pi p)$ Reactions in ${}^3\text{He}$, ${}^4\text{He}$, and Heavier Nuclei"

Differential cross-sections for the (π^-, n) reaction on ${}^3\text{He}$, ${}^4\text{He}$ were measured at six energies over the 50 to 290 MeV range and over an angular range of 25° to 140° . Data on the (π^-, π^0) reaction with ${}^3\text{He}$ were also measured. The results have been submitted for publication.

4.) LAMPF Expt. #14 " π^+ and π^- Elastic Scattering from ${}^{16}\text{O}$ "

The principal results involved the important discovery that inelastic scattering to certain energy levels in ${}^{18}\text{O}$ is different for π^- and π^+ , indicating differences in the neutron and proton structure of such a state.

5.) LAMPF Expt. #9 "Elastic and Inelastic Scattering from the Calcium Isotopes"

Measurements were made on elastic and inelastic scattering from four calcium isotopes at three energies, quasielastic scattering and some double charge exchange scattering to the continuum. Analysis of the data is in progress.

Major collaborators: LASL, ANL, Northwestern University, Carnegie-Mellon University, the University of Texas, the University of Virginia, the University of Colorado, the University of Montana, the University of Washington, Florida A&M University, Oregon State University.

NORTHWESTERN UNIVERSITY..... \$ 85,000
Department of Physics and Astronomy

"Nuclear Structure Studies with Medium Energy Probes"

K. K. Seth

The primary thrust of research under this contract is to use medium energy probes-pions, protons, and electrons to study aspects of nuclear structure which are not accessible to heavier or lower energy projectiles.

A very strong component of our research relates to the delineation of the separate roles of neutrons and protons in the structure of nuclei, both in ground state matter distributions and excited state deformations. Towards this end we have been heavily involved in LAMPF HRS and EPICS experiments--#14: " π^+ and π^- Elastic and Inelastic Scattering from ^{18}O "; #9: " π^+ and π^- Elastic and Inelastic Scattering from ^{42}Ca "; #139: "Proton Scattering Survey with HRS"; and #311: "Elastic Scattering Survey Using Polarized Protons". In conjunction with precision information on proton distributions from electron scattering, the elastic scattering results from the above experiments, particularly #311, have given precision information on neutron distributions in the ground states of nuclei from ^{12}C to ^{208}Pb . Experiment #14 has, in addition, shown that separate deformations of neutron and proton components of excited states of ^{18}O can be obtained by the comparative study of π^+ and π^- inelastic scattering. Similar information on states of ^{42}Ca is expected from the just completed expt. #9.

We are very deeply committed to the study of double charge exchange (DCX) reactions (π^+, π^-) and (π^-, π^+) on nuclei. These reactions have no analogues in classical nuclear physics and they are expected to lead to unique information on correlations in nuclei and on pion dynamics in the nuclear medium. We have just completed LAMPF Expt. #13 "Study of π^+ Induced Double Charge Exchange Reactions". The preliminary results look extremely interesting and will undoubtedly contribute significantly to the theoretical understanding of this complex reaction. We have also succeeded in measuring the mass of the very "exotic" nucleus ^{18}C by the (π^-, π^+) reaction on ^{18}O .

Using the high resolution spectrometer, HRS, we are studying pion production reactions (p, π^+) and (p, π^-) with polarized and unpolarized beams. These involve: Expt. #10/233 combined version of "Search for (p, π) Reactions with HRS" and "Search for Δ -Configurations in Nuclei"; Expt. #395 " (p, π^+) Reaction on ^{16}O and ^{40}Ca "; and Expt. #405 " (p, π^-) Reaction on ^{12}C and ^{13}C ". Only a small part of #10/233, (p, π^+) reaction on hydrogen and deuterium, has been done so far. Quite surprisingly, the asymmetry for $\text{D}(p, \pi^+)$ shows strong structure while that for $\text{H}(p, \pi^+)$ is essentially flat.

Current work also includes two other pion-nucleus experiments at LAMPF and BATES Expt #75-5 "Electron Scattering Studies of Low Lying States of ^{40}Ca , ^{72}Ge , ^{90}Zr , and ^{98}Mo " and BATES Expt. #78-7 "A Comprehensive Study of ^{40}Ca by Inelastic Electron Scattering".

Major collaborators: Los Alamos Scientific Laboratory, UCLA, University of Texas at Austin, New Mexico State University.

OAK RIDGE NATIONAL LABORATORY..... \$ 75,000

"Interactions of Low-Energy Pions with Nuclei"

F. E. Bertrand, E. E. Gross, and C. A. Ludemann

The program consists of three parts: i) investigation of the pion-absorption mechanism using the $\pi^+ + d$ reaction, ii) elastic scattering of π^+ , π^- from complex nuclei, iii) inelastic scattering of π^+ , π^- from nuclei. These experiments are performed using pion beams from the low-energy pion channel at LAMPF.

Absolute differential cross sections have been measured for the $\pi^+ + d \rightarrow p + p$ reaction at pion energies of 40, 50, and 60 MeV. These data have recently been published. The angular distributions of the emitted protons are adequately fitted by the usual functional form $C_0 + C_2 \cos^2\theta$ with the addition of a small $\cos^4\theta$ term yielding only a slight improvement. The integrated cross sections, which are much more accurate than the older data, indicate the possibility of structure in the pion-absorption vs. pion-momentum curve. During CY 1979 we will take additional measurements at lower π^+ energies to investigate this possible structure.

Elastic scattering differential cross sections have been obtained at three π^+ energies (50, 40, and 30 MeV) from five targets (^{12}C , ^{16}O , ^{40}Ca , ^{90}Zr , and ^{208}Pb). The cross sections were determined with an absolute uncertainty of $\pm 7\%$ or less. Measurements were made using an array of ten plastic scintillator detector telescopes. All of these data have now been analyzed. Comparison of the data with a first order optical-model potential yields good fits, provided the strength parameters of the Kisslinger potential are allowed to vary from the free π^+ -nucleus value. Preliminary analysis shows the possible existence of an A-dependence in the real part of the strength parameters. The value of the imaginary parts of the parameters shows little change as a function of target mass. During CY 1979 elastic scattering measurements will be made on the same nuclei using 20-MeV π^+ . In addition, measurements utilizing a magnetic spectrometer will be made of both π^+ and π^- elastic scattering angular distributions for pions of 60 to 80 MeV, incident on several targets.

Using the recently completed "Bicentennial Spectrometer", inelastic scattering measurements have been made on a few nuclei. Measurements of the π^+ nuclear continuum (up to ≈ 25 MeV of excitation energy) were made using 50-MeV π^+ on ^{16}O , ^{40}Ca , ^{60}Ni , and ^{208}Pb . These results have been published. Recently, inelastic π^+ scattering to low-lying 2^+ and 3^- states has been measured. These data are currently under analysis.

Major collaborators:

Los Alamos Scientific Laboratory, University of South Carolina, Virginia Polytechnic Institute and State University.

UNIVERSITY OF PENNSYLVANIA..... \$ 29,300
Physics Department

"Research In Very High Energy Nuclear Physics"

S. Frankel and W. Frati

The object of this research is to obtain experimental information, to carry out phenomenological investigations of the nature of very high momentum components of the nuclear wave function, to develop methods for extracting such information from inclusive cross sections, and to study mechanisms for high energy nuclear collisions.

The most recently completed experiments are:

LAMPF 346 "Study of High Momentum Components in Nuclei Using a Polarized Proton Beam" This experiment was the first measurement of analyzing power in the reaction $\vec{p} + A \rightarrow (p, d, t) + X$ for detected particles in kinematic regions which require high internal nucleon momenta. We observed large negative analyzing powers at low momenta in Li^6 which became very large and positive as the energy of the detected proton increased. Strong A dependent effects were observed. This experiment also measured the first analyzing powers for quasi-free scattering.

FERMILAB 592 "Proposal for Experimental Study of the Relationship Between Hadronic and Nuclear Scaling at Very High Energies" A complete 1.5 GeV spectrometer was built and installed at Fermilab to study the reaction $p + A \rightarrow (p, d, t, \text{He}^3, \text{He}^4, \pi^+, \pi^-, K^+, K^-) + X$ using 400 GeV protons. The experiment is presently being analyzed. The aims of this experiment are to use these inclusive reactions and the known inclusive reactions on free proton targets to extract nuclear structure functions for nuclei from Li to Pb. These will be compared with the structure functions obtained at 0.8 GeV.

Experiments planned for the near future include:

LAMPF 258 This experiment will measure the invariant mass distribution of the final state produced in the reaction $p + A \rightarrow p + X$ by measuring coincidences between the "backwardly" produced protons in a low resolution spectrometer (under construction) and the forward particles in the existing High Resolution Spectrometer.

FERMILAB "Determination of the Nature of Nuclear Jets" We are proposing to study the forward nuclear jets in coincidence with the backward protons observed in FERMILAB 592. The purpose is to determine the mechanisms within the nucleus that provide the large nuclear recoil momenta demanded by our Fermilab data.

FERMILAB, SLAC, SACLAY We are now planning to start to use lepton probes for the study of nuclear structure functions.

Major collaborators:

G. Leksin: A. V. Arefiev, Y. D. Bayukov, V. I. Efremenko, N. A. Nikiforov, V. Tchistilin, and Y. M. Zajtzev, Institute of Theoretical and Experimental Physics, Moscow.

PRINCETON UNIVERSITY..... \$120,000
Department of Physics: Joseph Henry Laboratories

"Nuclear Chemistry Project"

R. A. Naumann and K. Krien

Present and planned work emphasizes experimental investigations of: the mechanisms by which negative muons are captured into and cascade through atomic orbits; spectroscopy of odd-odd nuclei in the medium mass region by use of charged particle-induced reactions; and electric field gradients in solid metallic systems by use of nuclear perturbed angular correlation techniques. Analysis of LAMPF Expt. #288 "Studies of Mu-Minus Capture Probabilities for Solid State Solutions" results on Cu-Al and Ag-Zn systems shows that the probability of muon capture per atom is independent of composition ratio but that the Z-law is not obeyed. To extend these muon capture studies, two new proposals "Muonic X-Ray Spectra of Gas, Phase I" and "Mu-Minus Capture Probabilities for Selected Solid Binary Compounds" are underway. The first proposal is specifically designed to study the role of electron refilling from neighboring atoms during atomic capture of muons. Study of collective states in ^{191}In , ^{193}In and ^{203}Pb has been completed. This work employed the (p,t) reaction and high resolution capabilities of the Princeton cyclotron and Q3D spectrometer. These nuclear structure studies at the Princeton cyclotron are being extended to in-beam gamma and in-beam electron conversion studies of radioactive targets prepared from LAMPF, BLIP, and HFBR irradiated material. Perturbed angular correlation work has recently concentrated on study of PdSb and PdPb₂ intermetallic compounds to determine relationships between crystal structure and electric field gradient.

During 1978, R. A. Naumann spent six months at the Technical University of Munich on United States Senior Scientist Award of the Alexander von Humboldt Stiftung, an award sponsored by the German Federal Republic. In collaboration with the Munich group of Professor H. Daniel, he carried out research on negative muon capture by atoms at the superconducting muon channel of the S.I.N. accelerator, Switzerland.

Major collaborators: J. Knight (LASL), G. Struble, (LLL), and R. Vianden (Bell Telephone Laboratories, Murray Hill, New Jersey).

PURDUE UNIVERSITY..... \$ 80,000
Chemistry Department

"Deexcitation Processes in Nuclear Reactions"

N. T. Porile

The objective of this research is the characterization of the mechanisms of nuclear reactions induced in complex nuclei by high-energy protons and intermediate-energy pions. These reactions are investigated by both recoil and in-beam techniques. Thick-target recoil studies of deep spallation products in the $A \sim 131$ mass region and of scandium fragments emitted in the interaction of ^{238}U with protons have shown the occurrence of a transition at 3 GeV proton energy. This transition is characterized by a peak in the forward-to-backward emission ratio as well as by a drop in range. In order to obtain more detailed information about this transition differential ranges and angular distributions of these products are being measured at this transition energy as well as at lower (0.8 GeV) and higher (11.5 GeV) energies. In an extension of this work the differential ranges and angular distributions of these products are being measured for a proton energy of 400 GeV. More detailed studies of the fragmentation mechanism at this energy are being started. These involve determination of the energy spectra of isotopically resolved fragments by means of time-of-flight and $\Delta E-E$ measurements. A new effort started last year is the study of fragmentation in pion-induced reactions. Preliminary comparisons with the proton data indicate that greater fragmentation occurs as a result of the high-energy transfer from the pion absorption.

Major collaborators:

E. Steinberg and S. Kaufman, Argonne National Laboratory
N. Sugarman, University of Chicago
B. Dropesky and R. Williams, Los Alamos Scientific Laboratory
R. Scharenberg and L. Gutay, Purdue University

PURDUE UNIVERSITY..... \$ 50,000
Physics Department

"Study of Muonic Atoms"

R. M. Steffen

We plan continuation of our systematic investigation, by precise muonic x-ray spectroscopy, of the charge radii of nuclei in the mass region from $A = 40$ to $A = 130$ and of the nuclear structure effects in the transition regions where nuclei change their shapes, i.e., the Sm-Gd and the Hf-W-Os-Pt regions. In particular, the charge radii of all stable Pd, Cd, and Te isotopes are proposed to be determined with an accuracy of $\pm 10^{-18}$ m or better. In addition, the quadrupole moments of the ground states of the odd - A isotopes of Pd and In will be accurately determined. The muonic atoms of Hf, W and Pt will be studied with high precision in order to extract the nuclear charge multipole moments of the excited states in a model-independent way. The problem of the nuclear polarization correction will be studied in great detail by experimental and theoretical means. The feasibility study of using finely dispersed target material in liquid H_2 in order to enhance the probability of producing muonic atoms in the target material will be continued. The effective charge radii of 34 stable isotopes in the mass region from $A = 40$ to $A = 70$ have been determined with accuracies of $\pm 10^{-18}$ m or better. Surprisingly interesting systematic trends of the isotope and isotone shifts have been discovered. The isomer shift of the 2.61 MeV 3^- state in ^{208}Pb has been measured. The quadrupole charge distribution moments of the excited state of $^{186}, ^{188}, ^{190}, ^{192}\text{Os}$ have been determined and found to disagree with the results predicted by the pairing - plus - quadrupole force model of Kumar and Baranger.

Currently our research emphasizes: 1) precise determination of the equivalent charge radii and of the isotope shifts in the Cd and Te isotopes; 2) measurement of the nuclear monopole and quadrupole moments in ^{150}Sm , ^{152}Sm , ^{186}Os , ^{190}Os , ^{192}Os and the Gd nuclei; 3) determination of the nuclear matter distribution in the even-A Cd nuclei by pionic X-ray measurements; and 4) study of the transfer of muons stopped in liquid hydrogen to heavy atoms.

Major collaborators: E. B. Shera and H. D. Wohlfahrt, LASL

RICE UNIVERSITY. \$303,533
Physics Department

"Intermediate Energy Nuclear Physics Studies"

G. C. Phillips and G. S. Mutchler

This program emphasizes basic studies of nuclear structure and reaction mechanisms at intermediate energies. It especially concentrates on experiments leading to an understanding of the N-N force and the roles played by inelastic channels such as $N-\Delta, \Delta-\Delta$, etc. Current work concentrates on the study of pion production amplitudes from nucleon-nucleon collisions in kinematically-complete two-arm experiments. The study of these amplitudes began with LAMPF Experiment E-81, "Study of Neutron-Proton and Proton-Proton Coincidence Spectra from pd and pp Reactions," which clearly demonstrated the dominance of the reaction $pp \rightarrow \Delta^{++}n$ in pion production at 800 MeV. These studies are continuing in LAMPF Experiment E-336, "Study of the Spin Dependence of Proton-Proton Pion Production Reactions" through the spin dependence of the reaction $pp \rightarrow \Delta^{++}n$; in LAMPF Experiment E-366, "Non-resonant Pion Production in the Reaction $np \rightarrow \pi^- pp$ "; and, in future experiments, through the reactions $np \rightarrow np\pi^0$ and $pp \rightarrow pp\pi^0$. Work on LAMPF Experiment E-80, "Forward Elastic Scattering of π^+ and π^- from $^{12}C, ^{13}C, ^{16}O, ^{40}Ca, ^{208}Pb$ " has been brought to the final stages of analysis. Small angle elastic cross-sections covering the nuclear-Coulomb interference region and total cross-sections were measured for $^{12}C, ^{40}Ca$, and ^{48}Ca at incident pion energies spanning the (3,3) resonance. These results provide fundamental information on both real and imaginary parts of pion-nucleus scattering amplitudes in the (3,3) resonance region. Data taking has been completed for LAMPF Experiment E-82, "Investigation of Pion Induced Reactions on Light Elements with Three Particles in the Final State," SREL Experiment IC-540, "An Investigation of the Total Inelastic Pion Scattering Spectrum for Energies Across the (3,3) Resonance;" and LAMPF Experiment E-341, "Study of $pd \rightarrow d\pi^+n$ Reaction Mechanisms." The SREL work resulted in pion inelastic scattering data through 80 MeV excitation energy in the ^{12}C target nuclei. Objectives included examination of the giant resonance region by means of pion scattering and extraction of total absorption cross-sections. Data analysis is now in progress. Experiments E-82 and E-341 are investigating quantitatively the dominant role of the Δ^{++} in medium energy pion production and scattering reactions, fundamental amplitudes for understanding pion-nucleus scattering, and the ability of Glauber theory to describe both elastic and inelastic data.

Major collaborator: University of Houston

UNIVERSITY OF ROCHESTER \$24,000
Department of Chemistry

"Muon-Induced Reactions on Actinide Nuclei"

J.R. Huizenga

Investigation of heavy muonic atoms is of considerable interest from several points of view: (i) Recently developed theories on muon capture predict a strong rate dependence on the neutron excess. Examination of capture rates for actinide nuclei provides a test of these theories for very neutron-rich nuclei. (ii) Since the energies of muonic transitions between the low-lying atomic states are larger than the neutron-binding energies and the fission barriers, radiationless muonic cascade transitions may result in neutron emission or fission in the presence of the bound muon. (iii) The presence of the muon itself leads to a perturbation of the double-humped fission barrier owing to the muon-nuclear Coulomb interaction. The present LAMPF study aims at understanding the several above processes occurring after a muon is stopped in the target. To date, capture rates have been reported for ^{232}Th , ^{235}U , ^{238}U and ^{239}Pu by detecting electrons from the normal leptonic decay of the bound muon and for ^{232}Th , ^{235}U , ^{238}U , ^{237}Np , ^{239}Pu and ^{242}Pu by detecting neutrons. Analysis of the capture rates for ^{232}Th , ^{235}U , ^{238}U , ^{237}Np , ^{239}Pu and ^{242}Pu by counting of fission fragments is in progress. In the future we plan to study the nuclear Auger process in heavy muonic atoms.

Major Collaborators

W. K. Hensley - Los Alamos Scientific Laboratory

D. W. Perry - Los Alamos Scientific Laboratory

J. C. Browne - Lawrence Livermore Laboratory

TEMPLE UNIVERSITY.....\$140,000
Physics Department

"Experimental Investigations in Particle Physics at Intermediate Energies"

W. K. McFarlane, V. L. Highland, and L. B. Auerbach

The objective of this program is to carry out experiments on the properties of elementary particles and their interactions, particularly those accessible at intermediate energies. We are investigating neutron-proton elastic scattering, neutron-deuteron and proton-deuteron inclusive scattering and single pion production in pp scattering at LAMPF. At the Brookhaven AGS we are studying proton-antiproton annihilation in flight to kaon-antikaon and lambda-antilambda pairs, and in a second experiment the possible formation of bound states or resonances of the proton-antiproton system. In electromagnetic interactions, we are searching at LAMPF for the three-gamma decay of the neutral pion, as a test of C-invariance. In weak interactions, we will measure the rate of pion beta decay, at LAMPF, as a test of the Conserved Vector Current hypothesis.

Recent contributions have included: an upper limit to direct positron production in p-p collisions at 256 and 800 MeV; an upper limit to the existence of stable condensed nuclear states; data on the production of protons, deuterons and tritons in the backward direction at 800 MeV; upper limits on the pi zero to three- and four-gamma decay modes; and forward angle n-p differential cross section at 800 MeV.

Current work includes:

- 1) LAMPF Expt. #124 "Measurement of the Neutron Energy Spectrum in $p+p \rightarrow n + \pi^+ + p$ " This experiment provides information on single pion production mechanisms--in particular, dominance of Δ production. Data analysis is in progress.
- 2) LAMPF Expt. #279 "Measurement of Neutron-Neutron Differential Cross-Section and a Test of Charge Independence" This experiment involves a comparison of inclusive neutron-deuteron scattering with inclusive proton-deuteron scattering at 500-800 MeV incident energy. Data has been collected at 800 MeV and is being analyzed.
- 3) AGS Expt. #644 "Proton-Antiproton Annihilations" The scientific motivation is a search for $\bar{N}N$ resonances in well-defined isospin channels. Data analysis is in progress.
- 4) AGS Expt. #701 "Search for Bound States and Resonances in Nucleon-Antinucleon Interactions" We are using the $\bar{p}+d \rightarrow (p\bar{p})+n$ and $\bar{p}+d \rightarrow (\bar{p}n)+p$ reactions and their favorable kinematics to search for bound states and/or resonances in the respective $\bar{N}N$ systems. Coincident γ data will be taken with a large (30" diameter X 20" long) NaI system.
- 5) LAMPF Expt. #144 "Search for the C-Violating Decay $\pi^0 \rightarrow 3\gamma$ " Data from a preliminary run have been published, reducing the upper limit on this decay by a factor of three, to 1.5×10^{-6} . This reduces the ratio of C-violating amplitude to less than a quarter of the C-nonviolating amplitude.

Major collaborators: D. M. Wolfe, B. Dieterle, and C. Leavitt (Univ. of New Mexico); J. C. Pratt, R. J. Macek, D. Bowman, M. Cooper, F. Cverna, and C. Hoffman (LASL); M. Mandelkern (Univ. of California at Irvine); T. Devlin (Rutgers Univ.); and P. Yamin (BNL).

TEXAS A&M UNIVERSITY..... \$ 20,000
Cyclotron Institute and Chemistry Department

"Angular Momentum Effects in Nuclear Reactions"

J. B. Natowitz

Our work on the identification of new isotopes produced in the reactions of 800 MeV protons with uranium has resulted in the positive identification of five new isotopes, ^{27}Ne , ^{31}Mg , ^{32}Mg , ^{34}Al , and ^{39}P . Additional data now in hand promises to yield a similar number of new nuclei even farther removed from β stability. Emphasis of these experiments is shifting from isotope identification to an attempt to make on-line mass measurements of these new very neutron rich nuclei. Time of flight measurements are made using channel plates to detect the electrons ejected when the ions pass through thin carbon foils. The Z identification is accomplished using a gas ionization detector of the type we presently employ for heavy ion reaction studies. To date, the mass resolution achieved in our experiment has been limited to $A/\Delta A = 140$ by the 500 psec FWHM time spread of the LAMPF beam. We expect to achieve time resolutions of at least 150 psec FWHM. By concentrating on low energy fragments, improving the energy resolution, obtaining high counting statistics and using as internal standards the isotopes of known mass which are simultaneously observed with this system, we expect to achieve mass measurements to ± 100 KeV.

Major collaborators:

G. W. Butler	Los Alamos Scientific Laboratory
D. G. Perry	Los Alamos Scientific Laboratory
A. M. Poskanzer	Lawrence Berkeley Laboratory
L. P. Remsberg	Brookhaven National Laboratory

TEXAS A&M UNIVERSITY..... \$125,000
Physics Department

"Study of the Neutron-Proton Interaction in the 300-700 MeV Energy Region"

L. C. Northcliffe, J. C. Hiebert, G. Glass, and T. S. Bhatia

The objectives of this work are: to determine the spectrum of neutrons produced in 500-800 MeV proton bombardment of deuterium and other light elements; to use the most suitable reaction for the development of monoenergetic neutron beams needed to study the neutron-proton interaction in the 500-800 MeV energy region; to measure the differential cross sections for elastic neutron-proton scattering and for pion production in neutron-proton collisions at 500-800 MeV; to measure the neutron-proton polarization and spin-correlation parameters at 500-800 MeV. These measurements will constitute a complete determination of the neutron-proton interaction in that energy region, realizing one of the fundamental goals of intermediate energy physics. The 500-800 MeV neutron beams will also be used to study the spectra of charged particles produced in neutron bombardment of various nuclei. The experiments will be carried out at the Los Alamos Meson Physics Facility using a magnetic spectrometer, multiwire proportional counters, scintillation counters, a polarized hydrogen target, and other appropriate instrumentation. Recent results include: Differential cross section for np elastic scattering and angular distribution for $np \rightarrow d\pi^0$ at 463, 647 and 800 MeV; cross sections for np charge-exchange and nD back-angle elastic scattering 200-800 MeV; cross sections for $np \pi^\pm$ production at 800 MeV; neutron spectra from 647 and 800 MeV proton bombardment of ^1H , ^2H and various solid targets; p and d spectra from 800 MeV neutron bombardment of various targets.

Major collaborators:

J. E. Simmons and B. E. Bonner, Los Alamos Scientific Laboratory
P. J. Riley and C. L. Hollas, University of Texas
M. W. McNaughton, Case Western Reserve University

UNIVERSITY OF TEXAS AT AUSTIN..... \$ 35,395
Physics Department

"Medium Energy Measurements of n-p Parameters"

P. J. Riley

Long term objective is accurate and complete measurement of neutron-proton scattering parameters in the medium energy range. Research in progress includes measurement of polarization parameters, angular differential cross-sections, inelastic (pion production) scattering, and charge exchange cross-sections. Priority is currently given to determination of neutron-proton polarization parameters using the P Division polarized proton target. Specific experiments at various stages of execution include:

LAMPF Expt. #262 "Test of Isospin Invariance in the Reaction $np \rightarrow d\pi^0$ "

LAMPF Expt. #263 "Measurement of the Energy and Angular Variation of the np Charge Exchange Cross Section"

LAMPF Expt. #264 "Measurement of the Energy Variation of the nD Elastic Differential Cross Section near 180° "

LAMPF Expt. # 65 "Neutron-Proton Polarization Measurements Using a Polarized Target: Phase I. The n-p Polarization Observable $P(\theta)$ "

LAMPF Expt. # 66 "Neutron-Proton Polarization Measurements with a Polarized Target: Phase II. The N-P Spin Correlation Observable, $C_{NN}(\theta)$ "

LAMPF Expt. #360 "The Measurement of the Polarization Transfer Coefficients D_t and A'_t at 800 MeV for the Reaction $d(\vec{p}, \vec{n})2p$, ${}^6\text{Li}(\vec{p}, \vec{n}){}^6\text{Be}$, and ${}^9\text{Be}(\vec{p}, \vec{n}){}^9\text{B}$ "

Major collaborators:

Los Alamos Scientific Laboratory (Group P-7: B. E. Bonner and J. E. Simmons)

Texas A&M University (L. C. Northcliffe)

UNIVERSITY OF TEXAS AT AUSTIN..... \$ 70,000
Physics Department

"High Resolution Pion-Nuclear Scattering Measurements and 800 MeV Proton
Induced Nuclear Reactions"

C. F. Moore, W. J. Braithwaite, and G. W. Hoffmann

Our intermediate energy experimental nuclear physics program emphasizes research with the High Resolution Spectrometer (HRS) and the Energetic Pion Channel and Spectrometer (EPICS) at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). Experiments are generally concerned with inelastic scattering of 800 MeV protons and 50-300 MeV pions from complex nuclei to examine specific final states in these nuclei. The objective of this work is to better understand nuclear structure and nuclear interactions with intermediate energy protons and pions. Recent efforts have included LAMPF (HRS) Expt. #311 "Elastic Scattering Survey Using Polarized Protons," and LAMPF (EPICS) Expt. #130 "EPICS Tuneup Proposal: Pion Carbon Scattering." Results of LAMPF (EPICS channel) Expt. #265 "Study of Prompt Nuclear Deexcitation Gamma Rays from Pion Interactions with ${}^6,{}^7\text{Li}$ and ${}^{12}\text{C}$ " have been published. Expt. #311 data (${}^{12},{}^{13}\text{C}$, ${}^{40},{}^{42},{}^{44},{}^{48}\text{Ca}$, ${}^{46},{}^{48},{}^{50}\text{Ti}$, ${}^{58},{}^{64}\text{Ni}$, ${}^{90}\text{Zr}$, ${}^{116},{}^{124}\text{Sn}$, ${}^{54}\text{Fe}$, and ${}^{208}\text{Pb}$ angular differential cross-section and analyzing power data at 800 MeV over the 3° to 23° (lab) range) are being very successfully analyzed in terms of the Kerman-McManus-Thaler formalism. From #311 data, extraction of reliable, quantitative neutron density distribution and spin-orbit potential information appears promising. As part of LAMPF (HRS) Expt. #355 "Further Elastic Scattering Cross Section and Analyzing Power Measurements on ${}^{208}\text{Pb}$ and ${}^{116},{}^{124}\text{Sn}$," these investigations are being extended to 35° . A central objective of #355 is to understand the sources of KMT shortcomings in reproducing analyzing power data at large (greater than 15° lab) angles. We also plan work on LAMPF (HRS) Expt. #347 "Search for 'Orbit Flip' States by Inelastic Proton Scattering" and LAMPF (HRS) Expt. #354 "Scattering of 800 MeV Protons From ${}^{12}\text{C}$ and ${}^{18}\text{O}$ at Momentum Transfers Greater than Four Fermis $^{-1}$." EPICS tuneup work (#130) on ${}^{12}\text{C}$ showed strong peaking at 19.2 MeV excitation for 164 MeV incident pions. This peaking is not immediately understandable in terms of known ${}^{12}\text{C}$ states. To explore this peaking in more quantitative detail, we plan data taking on LAMPF (EPICS Expt. #368 "Inelastic Pion Scattering To the 19.2 ± 0.3 MeV state In ${}^{12}\text{C}$ ". Also, the #130 results for $\pi^\pm$ inelastic scattering from ${}^{18}\text{O}$ will be pursued with LAMPF (EPICS) Expt. #229 " π^+ vs. π^- Inelastic Excitation of Low-lying Collective States in N=28 Nuclei." The central objective of #229 is to explore the selectivity of π^+ (π^-) inelastic scattering for excitation of states whose structure or deformation greatly differs from the ground state.

Major collaborators:

H. A. Thiessen, Christopher L. Morris, and James Amann - LASL
George Burleson and Gary Blanpied - New Mexico State University
Jerry Peterson and Dick Boudrie - University of Colorado
Norton Hintz - University of Minnesota
George Igo - University of California at Los Angeles

VASSAR COLLEGE\$11,238
Department of Physics and Astronomy

"Hypernuclear Spectroscopy"

R. L. Stearns

We are participating in quasifree scattering experiments at the LAMPF High Resolution Spectrometer and in hypernuclear experiments at the AGS Low Energy Separated Beam I. Data taking has been completed for LAMPF EXPT. #5, "Inelastic Scattering of 800 MeV Protons from nuclei to Study Quasi-free Modes". Quasielastic spectra have been obtained for ${}^6\text{Li}$, nat Li, ${}^{12}\text{C}$, ${}^{27}\text{Al}$, ${}^{40}\text{Ca}$, ${}^{51}\text{V}$, ${}^{90}\text{Zr}$ and Pb targets at nine angles ranging from 5° to 30° . From these data we hope to extract new nucleon pair correlation information as well as evidence for the existence of small clusters, particularly in light nuclei. Primary emphasis is now being given to execution of AGS Expts. 646 and 728, "Hypernuclear Spectroscopy of States Formed by the coherent interaction of K^- with nuclei." Kinematics of the $n(\text{K}^-, \pi^-) \Lambda$ reaction allow production of the Λ at rest in the target nucleus. Using a double achromatic energy difference spectrometer constructed from standard AGS magnets, we will measure the outgoing pion energy spectrum. From these data, information will be obtained on ground state hypernucleus binding energies and on excited states of hypernuclei. Preliminary experiments on hypernuclei formed using a liquid deuterium target are currently underway.

Major collaborators:

LAMPF

BNL
UCLA
Univ. of Texas
Univ of Minnesota

AGS

Princeton
MIT
Houston
Carnegie Mellon
BNL

UNIVERSITY OF VIRGINIA..... \$110,000
Physics Department

"Electron Interactions With Nuclei"

J. S. McCarthy

The electromagnetic interaction is characterized by the ability to measure unique information, less ambiguous than other methods and relied upon to supply essential information for more exotic experiment and theory. The freedom in choosing the momentum transfer and the ability to achieve a spatial resolution as small as necessary make the electron a unique probe. A series of experiments is in progress to utilize this aspect in a quantitative investigation of the structure and dynamics of nuclei. The following accelerator facilities are used: 1) the MIT-Bates 400 MeV electron linac; 2) the Stanford superconducting electron linac (SLAC); 3) the 20 GeV Stanford Linear Accelerator (SLAC). At SLAC and Bates emphasis is placed upon a systematic investigation of the few-body nuclear systems ^3He , ^3H and ^4He . It is expected that information, not accessible from two-nucleon experiments, will be generated that will address fundamental questions in nuclear structure; the short-range behaviour of the N-N force, the influence of meson degrees of freedom, and a possible break-down of traditional nuclear structure at very high energy. Certain aspects of microscopic many-body theories will be tested by accurate measurements of charge and magnetic distributions for the ground state and inelastic excitations for more complex nuclei. Data taking has been completed at SLAC for the current round of ^3He and ^4He experiments; data analysis is in progress. Investigations of quasielastic scattering on ^{56}Fe are in progress at Bates. Also, elastic and inelastic electron scattering experiments in the Pb region are planned at Bates to determine high magnetic multipole moments.

A series of pion interactions with the light nuclear systems D, ^3He , ^4He is planned at LAMPF. These consist of pion absorption, elastic scattering, quasi-free scattering (QFS) and double-charge exchange (DCE) reactions. An experiment was recently completed measuring the (π^-, n) reactions on ^3He and ^4He and (π^-, π^0) on ^3He for incident pions of energies 250 to 550 meV. The Elastic, QFS, and DCE measurements were recently completed on ^{40}Ca , ^{42}Ca , ^{44}Ca , and ^{48}Ca at the EPICS channel at LAMPF. The DCE reaction was measured for both (π^-, π^+) and (π^+, π^-) and the ejected pion was chosen to correspond to the QFS region. It is expected that by concentrating on well known nuclear system that intelligible information can be extracted concerning the basic reaction mechanism.

Major collaborators:

J. Heisenberg, University of New Hampshire

I. Sick, University of Basel, Switzerland

J. Kallne, TRIUMF, U.B.C. Canada

UNIVERSITY OF VIRGINIA..... \$155,000
Physics Department

"Experiments on the Nuclear Interactions of Pions"

R. C. Minehart and K. O. H. Ziock

We are studying pion interactions with nuclei primarily using the facilities of Los Alamos Meson Physics Facility. The purpose of these experiments is to elucidate the behavior of pions in nuclear matter and to obtain new information on nuclear structure. Processes studied will include elastic scattering from deuterium, helium isotopes and calcium isotopes. We shall also study pion absorption reactions and knock-out processes in light nuclei. These include $(\pi, \pi p)$, $(\pi, \pi \Delta)$, (π, Δ) , (π^+, p) reactions. We also will measure the (π^-, π^0) mass difference to new precision. Recent results have included: published πd elastic scattering at four energies; published results on $(\pi, \pi p)$ interactions in nuclei, measured $\pi d \rightarrow 2p$ at 7 energies with high precision; measured elastic and charge exchange scattering for pions in ^3He and ^3H ; published results on studies of cluster effects in nuclear pion capture, inclusive cross sections for particle production in p , d , α collisions with nuclei; measured reactions induced by energetic alpha particles; measured (π^-, N) and (π^-, π^0) in $^3\text{He}/^4\text{He}$; and measured $\pi \pm$ elastic, quasi-free and double charge exchange scattering in calcium isotopes.

Major collaborators:

LAMPF, UCLA, Univ. of Texas, New Mexico State University

UNIVERSITY OF WASHINGTON..... \$ 90,000

"Interactions of Pions with Nuclei"

I. Halpern and J. G. Cramer

Our main interests in intermediate energy physics center on the pion and the contributions it can make to our understanding of nuclear structure and reaction mechanisms by virtue of its unique properties (e.g., its low mass among the hadronic probes, its availability with both charge signs, etc...).

A run on total inelastic scattering of positive pions to continuum energies was completed in June. It confirmed the "giant resonance" structures we saw last year in nickel and it showed even stronger ones in magnesium and calcium. The spectra for heavier targets (e.g., Zr, Sn, Pb) were smoother than those for the light ones and showed no strong resonances above 10 MeV. In general, observed resonances are more conspicuous in the forward than in the backward hemisphere. The resonances in calcium were much less apparent at an incident energy of 85 MeV than at 67 MeV. We are in the process of trying to understand the nature of these resonances and of the integrated inelastic scattering cross-sections.

Older work still being pursued includes the analysis of data comparing total pion cross-sections on isotopes and the explanation of excitation curves for ^{11}C production from ^{12}C and ^{12}C by positive and negative pions.

Prof. Cramer has a continuing interest in relativistic effects of the Coulomb interaction, particularly as they apply to the scattering of pions and other spin-zero projectiles from high Z target nuclei. Theoretical investigations of such effects in the coming year may lead to experimental investigations later on.

Stimulated by interesting tandem results we have gotten on inelastic proton analyzing powers in the continuum, we have begun to explore the opportunities for similar investigations at the higher energies available at TRIUMF.

Major collaborators:

Carnegie Mellon
University of Wisconsin
LASL
University of Alberta

UNIVERSITY OF WYOMING..... \$125,000
Physics Department

"Pion-Nucleon Interactions And Mesonic Atoms"

G. A. Rebka, Jr. and R. Kunselman

A series of experiments has been initiated at LAMPF to study several charge states of the reaction $\pi N \rightarrow \pi\pi N$ near their thresholds and to compare the average moduli of the matrix elements extrapolated to threshold with the predictions of soft pion theory. These experiments will test the applicability of the theory to the reactions and will also provide more information about the processes just above threshold than has previously been available. We have measured $d^2\sigma/d\Omega dT$ for the π^+ mesons in the center of momentum for $\pi^- p \rightarrow \pi^- \pi^+ n$ at six energies between 229 and 356 MeV with a doubly focusing magnetic spectrometer, and these doubly differential cross sections have been integrated to find the reaction cross section. An additional experiment now in progress will measure the cross sections for this reaction at 200 and 229 MeV to reduce the uncertainty in the process of extrapolation. These experiments are expected to yield the most accurate measurements available for the S wave, isoscalar and isotensor $\pi\pi$ scattering lengths. In a second series of experiments with the same apparatus, the cross section for $\pi^\pm$ double charge exchange in the disintegration of ^{16}O , ^{40}Ca , ^{48}Ca and ^{208}Pb will be measured to study the double scattering term in nuclei. A third series of experiments will search for protons emitted in μ^- capture by nuclei. In experiments at the Bates Accelerator, the nuclear structure of ^{182}W and ^{184}W will be studied through inelastic electron scattering.

We are using muonic x-ray measurements to determine nuclear electric charge distribution parameters and are using hadronic (pions, kaons, and antiprotons) x-ray measurements to measure strong interaction energy shifts and widths and to determine isotopic changes in neutron radii. Current work includes: 1.) muonic x-ray experiments on deformed nuclei in the transition region; 2.) pionic x-ray experiments with the Cal Tech bent crystal spectrometer to test the pion as a Klein Gordon particle; 3.) pp x-ray experiments at the AGS to determine strong interaction shift and width parameters in the 1s state; and 4.) pionic x-ray experiments on medium-Z nuclei.

Major collaborators:

Los Alamos Scientific Laboratory
University of Virginia
Oregon State University
Massachusetts Institute of Technology

William and Mary
California Institute of Technology

YALE UNIVERSITY..... \$320,000

V. W. Hughes, D. C. Lu, and P. A. Souder

Our group is a User Group in Medium Energy Physics with a principal interest in muon physics from the viewpoint of elementary particle physics, but also from the viewpoints of nuclear physics and atomic physics. Experiments are in progress and are planned principally at LAMPF, but we may also utilize the Nevis Synchrocyclotron, the Space Radiation Effects Laboratory, the Brookhaven AGS, the MIT Bates Electron Linac, or possibly collaborate with foreign groups at SIN in Zurich. Specifically, researches have been and will be done on the following topics: 1) Muonium and the muonic helium atom, 2) Muon G-2 value, 3) Precise muonic and pionic X-rays with a crystal diffraction spectrometer, 4) Neutrinos from muon decay, 5) Muonic hydrogen-weak and electromagnetic interactions, 6) Rare decay modes of the muon ($\mu^- \rightarrow e^-$), 7) Parity nonconservation effects in simple muonic atoms, 8) Accelerator theory and design of muon beams. The low momentum (~ 28 MeV/c) surface μ^+ beam which our group developed at LAMPF using the existing channel now provides an extremely intense and high polarization μ^+ beam, which is ideal for obtaining very high μ^+ stopping rates in very thin targets. This beam was used in the LAMPF experiment searching for the $\mu^+ \rightarrow e^+ \gamma$ rare decay mode and is now being used in our precision muonium experiment. At LAMPF we have completed a search for the metastable 2S state of muonic hydrogen ($\mu^- p$). The neutrino experiment to test muon number conservation is operating successfully and is in the data-taking stage. A new high precision muonium experiment to measure Δv and μ_μ to 3 parts in 10^8 and 4 parts in 10^7 respectively, using the new surface μ^+ beam is in the checkout stage. At Nevis data are being obtained on the measurement of pionic X-rays with a crystal diffraction spectrometer in order to determine a precise value of the pion mass.

Major collaborators:

MEDIUM ENERGY NUCLEAR PHYSICS - OPERATIONS

(HK 03 01 02)

Includes all costs incurred in the light-ion operation of machines and facilities (for such items as salaries and wages of the operating staff, power; supplies and equipment not meeting capitalization criteria, maintenance and repairs, etc.) used for nuclear and subnuclear physics research with a primary beam energy (per nucleon or electron) in excess of the pion production threshold but less than 10,000 MeV.

LOS ALAMOS SCIENTIFIC LABORATORY.....\$18,760,000
MP Division

"Facility Operation, Development, Maintenance and User Support"

L. E. Agnew, J. F. Amann, J. Bergstein, J. A. Bridge, A. A. Browman, R. D. Brown, E. D. Bush, H. S. Butler, R. L. Cady, E. P. Chamberlin, D.R.F. Cochran, K. R. Crandall, R. A. DeHaven, J. E. Donahue, P. R. Franke, A. J. Gjovig, D. L. Grisham, D. C. Hagerman, R. A. Hamm, V. E. Hart, R. E. Harris, J. F. Harrison, R. E. Hill, E. W. Hoffman, G. W. Hoffmann, R. A. Jameson, J. J. Jarmer, R. Kandarian, S. P. Koczan, T. Kozlowski, J. D. Little, R. J. Macek, D. R. Machen, C. E. Manger, J. R. McConnell, C. L. Morris, R. H. Newell, J. K. Novak, M. A. Oothoudt, D. G. Perry, T. M. Putnam, S. E. Rislove, L. Rosen, O. R. Sander, G. H. Sanders, E. J. Schneider, D. D. Simmonds, R. R. Stevens, Jr., G. R. Swain, N. Tanaka, H. A. Thiessen, R. T. Tregellas, O. B. van Dyck, J. D. Wallace, R. F. Warner, R. D. Werbeck

I. INTRODUCTION

LAMPF is unique in that it combines the highest current proton accelerator in the world with a very versatile experimental facility so that many different fields of experimental research can be served simultaneously. The very high current requires great strength in applied physics, engineering and technology in order to effectively operate and further develop the facility. Similarly, the diverse nature of the experimental program requires expert support in many different technical fields.

The overall format of this report implies that the operation of this facility is distinct and apart from the research program. This impression is quite misleading since the success of the research program depends strongly on successful operation and development of the facility. Conversely, successful operation of the facility would be pointless, even a contradiction, without a successful research program.

Section II below gives an overall description of the scope and status of the LAMPF facility. Section III gives a more detailed scope-of-work statements for many of the activities that are a part of the operation of LAMPF.

II. SCOPE AND STATUS OF THE FACILITY

LAMPF is the major laboratory in the United States for experimental work in medium energy physics. The facility represents the state-of-the-art in nearly all important aspects of its performance. At the time of writing an H^+ current of 360 μA (nearly 300 kW of beam power) and a simultaneous H^- current of a few microamperes are routinely available for the experimental program. As required, the H^- beam can be polarized to provide a few nanoamperes of current. A maximum duty factor of 7½% is available. Typically, 10 to 13 separate experimental teams make use of the facility at the same time. Production beam is scheduled for these users some 4000 hours per year. Beam availability is in excess of 80% which is very good considering the complexity of the facility.

The extremely large proton currents used at LAMPF are difficult to produce and to use. Tuning of the accelerator is very demanding since, in addition to the high intensity requirement, the quality of the beam must be excellent. The amount of beam lost in the accelerator and beam switchyard must be limited to a very low level since all components in this part of the facility must be accessible for hands-on maintenance without significant radiation exposure to maintenance personnel. In the target cells the proton beam

II. SCOPE AND STATUS OF THE FACILITY (Continued)

produces large amounts of undesirable radiation and significant heat loads in addition to the desired meson beams. The resulting radioactive environment presents a difficult engineering problem in regions accessible only by remote handling techniques.

Figure 1 is a simplified plan view of the experimental area. This figure includes a tabulation of channel intensities.

The experimental program for the facility is based on the recommendations of a Program Advisory Committee (PAC) who review proposals for experiments submitted by the scientific community. After a particular experiment is recommended by the PAC and approved by the LAMPF Director, scheduling and experimental support is arranged through the LAMPF Scheduling Committee (LSC). Development of the facility is directed through an Experimental Area Development Committee (EADC) and an Accelerator Development Committee (ADC); members of these committees come from the senior LASL staff associated with LAMPF. A Technical Advisory Committee (TAP) provides a formal route for the LAMPF Users Organization to make recommendations for further development of LAMPF.

Near-term development goals for the facility include higher H^+ , H^- , and polarized beam intensities, further increases in duty factor, more time-sharing options so that use of the facility is made more flexible, and continued improvements of the permanent spectrometers and secondary beams.

III. MAJOR ACTIVITIES

1. Facility Operation

In a facility as complex as LAMPF it is essential that the operation be done by well-trained, professional operators. Their major responsibility is the safe operation of the facility combined with maximum beam availability. In order to fulfill this responsibility they tune the accelerator and primary beam lines, control access to many beam areas, act as liaison for experimental support problems, do on-line maintenance, and generally oversee the LAMPF site (particularly outside normal working hours).

In addition to actual operation and on-line maintenance of the machine, operations activities include: performance of experiments and measurements required for further development of the accelerator, development and documentation of accelerator operating and on-line repair procedures, maintenance of operating records, periodic testing of interlocks, contingency assistance to experimenters, and training of operating personnel.

An operations support program is closely allied with the actual operation of the machine and includes: maintenance and repair of local instrumentation and control computer interfacing equipment distributed throughout the facility, paging and interphone systems, closed-circuit television equipment, a distributed pulse-viewing system, and beam-intensity and loss-monitoring equipment. Interlock systems for personnel safety and machine protection are also maintained, improved, and extended to new experimental areas as needed.

During FY 1978 the H^+ beam intensity was increased to 360 μA and an average beam availability of over 80% was achieved. The H^- beam intensity

CHANNEL	ENERGY (MeV)	BEAM
LOW ENERGY PION	0-300	$3 \times 10^9 \pi^+/s$ OR $8 \times 10^8 \pi^-/s$
HIGH ENERGY PION (P^3)	100-600	$4 \times 10^9 \pi^+/s$ OR $6 \times 10^8 \pi^-/s$
EPICS PION BEAM	50-300	$2 \times 10^8 \pi^+/s$ OR $5 \times 10^7 \pi^-/s$
STOPPED MUON	0-165	$10^6 \mu^+/s$ OR $3 \times 10^7 \mu^-/s$
TEST CHANNEL	50-600	$5 \times 10^7 \pi^+/s$ OR $6 \times 10^6 \pi^-/s$

CHANNEL	ENERGY (MeV)	BEAM
NEUTRONS (AREA B)	795	$10^6 n/cm^2 \cdot s$
NEUTRONS (BEAM STOP)	1-20	$10^{13} n/cm^2 \cdot s$
NEUTRONS (BEAM PIPE)	1-300	$10^9 n/cm^2 \cdot s$
BIOMEDICAL	0-100	$10^9 \pi^-/s$
NEUTRINOS	20-50	$3 \times 10^7 \nu/cm^2 \cdot s$

CHANNEL INTENSITIES QUOTED ABOVE ARE FULL OPEN RATES AT 1 mA PROTON CURRENT AND THE FOLLOWING TARGET THICKNESSES: A-1 3cm CARBON

A-2 6cm CARBON

A-5 8cm CARBON

LOS ALAMOS SCIENTIFIC LABORATORY

Fig. 1

III. MAJOR ACTIVITIES

1. Facility Operation (continued)

remained at the few microampere level with an availability of about 80%. Intensity and availability of the new polarized source was marginal but this should be significantly improved in FY 1979.

2. Experimental Area Development

A continuing program of experimental area development is in progress to complete LAMPF's major experimental facilities at a level that meets or surpasses the original design objectives, to modify components for enhanced performance, and to construct new facilities. All development activities are reviewed at regular weekly meetings by the Experimental Area Development Committee, which consists of twelve senior members of the staff. This Committee schedules beam usage for development of primary and secondary channels - about ten percent of the total beam operation.

Perhaps the most important development activity has been to perform high-intensity trial beam runs to test targets, diagnostic apparatus, beam-line components, windows, the beam stop and shielding at successively higher power levels. Test runs in mid-FY 1978 at currents in the 400- μ A range led to reliable production beams of 360 μ A during the summer of 1978. Test runs at the end of FY 1978 at currents in the 600- μ A range will be conducted pointing the way for production beams of 500 μ A in early FY 1979. At 500 μ A, the main proton beam, which can be focussed to an area of a few square millimeters to a few square centimeters, has 400 kW of power. This beam poses extremely severe survival problems for targets, windows, and diagnostic apparatus from the standpoint of heat removal and radiation damage.

In addition to high-power target development, other recent accomplishments include the development of surface and cloud muon beams, better stopped pion beams, new tunes of the Biomed Pion Channel to accommodate a wider range of therapy requirements, improved beam tunes and detector systems at both the EPICS and HRS spectrometers, and a new experimental cave that is being used for a parity-conservation experiment with polarized proton beams. Progress has been made on spin precession equipment that will permit optimal simultaneous usage of polarized beams for two or more experiments. Plans have been started for modifications of the switchyard to accommodate dual-energy operation. Substantial improvements have been made in the remote handling equipment that is required for maintenance of target-cell and beam-stop hardware. Most of these improvements are mentioned more specifically in the appropriate sections of this report.

Major building construction is in progress at Area A East in order to accommodate remote-handling maintenance and to provide weather protection. The structural framework has been erected and a surplus crane has been installed. The roof and the wall enclosure will be added in FY 1979.

3. Accelerator Development

During FY 1978 the major goal of our accelerator development work was the production of increased-current low-loss beams.

Beam dynamics simulation studies of the LAMPF accelerator pointed the way toward better tunes. Transverse trajectories were improved in the initial tanks of the 201.25-MHz linac, aiding in the effort to achieve lower transverse emittance at the transition region. The effects of aberrations in steering and

III. MAJOR ACTIVITIES

3. Accelerator Development (continued)

quadrupole magnets were investigated. Transverse matching was studied extensively, both experimentally and with the simulation models to improve the match at various beam currents. Procedures for adjusting the bunchers and acceleration parameters for the 201.25-MHz linac were developed, resulting in considerably improved longitudinal performance. Other investigations continued on characterization of performance at higher currents. Analytic techniques were developed for using profile data to reconstruct multidimensional projections of both transverse and longitudinal emittance. Intensive investigation into the causes, importance, and correction of errors in emittance measurements was initiated.

By the end of FY 1978 these efforts along with the improvements in ion-source operation permitted routine operation at 360 μ A with a loss in the accelerator above 70 MeV of only a few tenths of a μ A. Development and testing of even higher currents was done as the schedule permitted.

4. Permanent Spectrometers

Two large spectrometer projects, the Energetic Pion Channel and Spectrometer (EPICS), and the High Resolution Proton Spectrometer (HRS) serve nuclear structure physics research at LAMPF.

Both the EPICS and the HRS spectrometer systems are designed for high-resolution performance at high counting rates. EPICS is a complete high-resolution pion beam and spectrometer system. The system includes a scattering chamber, a particle separator, detectors, and computer-based data-acquisition equipment. Pions at energies up to 300 MeV can be delivered by the beam line, while the spectrometer can analyze scattered particles up to 700 MeV/c. The complete EPICS spectrometer system has been in operation for research since mid-1977.

The HRS is also a complete system composed of a high-resolution beam (Line C) of protons up to 800 MeV, a spectrometer capable of analyzing scattered particles up to 2000 MeV/c, scattering chamber, detectors, and a computer-based data-acquisition system. The HRS has now been successfully used for elastic scattering, polarized-beam asymmetry measurements, and (p,d) reaction measurements. Although 100-keV resolution has been achieved, development work continues with the eventual goals of 50-keV resolution. Design has commenced on the HRS Faraday cup.

In addition to the spectrometer facilities, a PDP-11/60 computer with an array processor has been ordered for use at HRS and EPICS. This machine will initially provide about a factor of two increase in the data rate for off-line analysis. After a 6- to 12-month period of software development, the utilization of the array processor should result in an additional factor of two to four improvement.

5. Direct Support for Users

A broad range of facilities and services to support the experimental program is provided. The facilities provided include a computer-based data-acquisition system, a pool of cryogenic refrigeration equipment, polarized proton target equipment, a model and production shop, a metrology facility, and two staff machine shops. Support services are provided by a team of engineers and a multidisciplinary staff of technical experts.

III. MAJOR ACTIVITIES

5. Direct Support for Users (continued)

Each approved LAMPF experiment is assigned an experiment engineer, who is placed in contact with the research team well in advance of the scheduled beam run. This engineer helps coordinate the timely preparation and setup of the experiments.

The LAMPF Electronics Equipment Pool (LEEP) has an inventory of 2600 items representing an investment of \$1.83M. Experimenters withdraw equipment from the pool when they begin to mount an experiment. This equipment has been reconditioned and tested before it is issued and it is maintained during the course of the experiment after which it is returned to the pool. A committee of experimenters advises the LEEP personnel on new equipment to purchase or develop.

During FY 1978, a total of \$220K worth of new equipment was added to the LEEP pool. Most of this expenditure was for NIM and CAMAC modules, but some of it went for other equipment such as a disk pack cleaner and delay boxes. In addition, several devices recently introduced on the commercial market were ordered for evaluation.

The LAMPF Experimental Magnet Pool includes about 90 units, procured primarily from other facilities through excess property. When the magnets are removed from storage and placed in use for the first time, they are extensively refurbished and tested in preparation for installation in the experimental area. The magnets are catalogued and described in the Pool Magnet List that is updated and distributed to reflect new additions or more detailed operating parameters. A pool of magnet stands, target and detector mounts, instrument arms, and remote-control mechanisms is now well established and continues to expand. A magnet measurement service capable of precision field mapping is provided.

A model and production shop has been set up to support the LAMPF experimentalists' particle-detector requirements. Scintillation detectors, optical piping, light interfaces, and multiwire proportional counters (MWPCs) are currently being supplied to the user experimentalists. In addition, this shop supplies the harps used along the accelerator and beam lines for beam-diagnostic purposes. A metrology facility is maintained to provide an optical calibration service, to lend optical instrumentation to the experimentalists for on-line use, and to provide support for the experiment engineers in precision aligning the experimental apparatus.

Shop facilities, a hot-cell facility, a tool crib, and supplies of commonly used stock items are provided in the main experimental hall. Technical assistance in the mounting of experiments is made available, including crane and forklift service, mechanical assembly and welding, water systems, gas systems, liquid nitrogen supplies, and many other services as required.

Through the establishment of a modest drawing account for each outside experiment, a means for scheduled experiments to make direct use of LASL facilities, support organizations, and general stores for immediate and essential needs that arise during the preparation and performance of an experiment has been provided.

III. MAJOR ACTIVITIES

6. Cryogenics Support

A pool of refrigeration equipment is provided for experiments using liquid hydrogen and other cryogenic targets. The high-power liquid deuterium system used for neutron production is maintained. Cryogenics engineering and technical assistance are provided as required to design, construct, install, and operate existing or new equipment.

Twenty-two cryogenic target systems were built and operated for 14 experiments during FY-1978. Much of the hardware of the standard 10-W refrigeration systems was replumbed and improved substantially. A simulator system for a microprocessor controller was designed and is being constructed. Improved versions of other electronic control systems have been designed. Considerable effort was devoted to cryogenic engineering for future experiments. A cryogenic shop/laboratory with suitable safety equipment was constructed.

The HERA polarized proton target system, consisting of a 25-kG superconducting magnet and a polarized proton target cryostat, was received from CEN-Saclay. The magnet and polarized target cryostat were tested and integrated with the various auxiliary support systems (^3He and ^4He pumping systems, ^3He gas-handling system, microwave, and NMR systems). A system for recovery of the helium gas used in polarized target operation has been placed into service.

7. Computer Support

The computer systems group is charged with the development of a comprehensive computer-based data-acquisition and analysis system to support the program of experimental nuclear physics. The activities covered in this effort include (1) the purchase of computers and peripheral devices, (2) the development of general-purpose and specialized software, (3) the exploitation of the CAMAC standard for interfacing experimental apparatus to computers, (4) the development of a 24-h maintenance service for the equipment, (5) the management and maintenance of an electronics equipment pool for LAMPF users, and (6) the development of a state-of-the-art electronics capability to support the system.

A three-day study of the requirements for a data-analysis facility was held in FY 1977. A dozen specialists drawn from all sectors of the LAMPF user community met to review the present status of the data-analysis problem and attempted to forecast future needs. A number of recommendations were made in a report (LA-7034-MS) that was presented to the users at their annual meeting in November. Procurement actions were initiated for the acquisition of equipment to respond to the recommendations of the study. An order was placed for a PDP-11/70 to upgrade the PDP-11/45 as the Terminal computer. The present PDP-11/45 will be moved to P³-East to replace the PDP-11/34 that will be used on the control computer. An order was placed for a computer to support the development of software for the data-acquisition computers. The paperwork for the purchase of a VAX-11/780 was submitted. This is the first major step toward a facility to handle the data-analysis load at LAMPF. The general data-acquisition program Q was adopted by most of the experimental teams. This program was designed to provide users with all the software functions commonly used to acquire, preprocess, display, record, and analyze data. A large effort was concentrated on documentation of the program and the resulting manuals were

III. MAJOR ACTIVITIES

7. Computer Support (continued)

distributed to the user. A number of improvements were made in Q as the result of user feedback and several major enhancements are in progress.

8. Targets

The mesons and neutrons delivered to secondary beams in Areas A and B are produced by targets in the proton beams. Graphite targets are used at three locations in Area A for the pion and muon beams, and both liquid deuterium and beryllium targets are used to produce neutron beams in Area B.

Especially difficult requirements are placed on the pion production targets because of LAMPF's intense beams. These targets must operate at high temperatures in a vacuum, must survive intense radiation levels, and must be inserted remotely. At the first two target stations on the main beam line, rotating target wheels made of a standard type of graphite are used. Energy deposited in the target by the beam is distributed evenly around the circumference of the wheel and is radiated away at temperatures up to 1500°C. During FY 1978, these target systems were rebuilt with new drive mechanisms and special high-temperature bearings for increased reliability.

Pyrolytic graphite, which is denser and has more favorable strength and thermal conduction properties than standard graphite, is used for pion production at the third target station on the main beam line. This target serves the Biomedical Pion Channel. Extensive efforts have led to the recent development of a technologically-advanced water cooling system for the biomedical target that is based on a high-performance graphite-to-metal bonding method.

In Area B, high-quality neutron beams with a well-resolved high-energy spike in the forward direction are generated by 3- to 5-μA proton beams on a liquid deuterium target. A "white" spectrum of neutrons produced from relatively thick beryllium targets is also available.

9. Primary and Secondary Beam Lines

The primary beam lines deliver LAMPF's high-intensity beams to three pion production targets, several irradiation stations, a high-energy neutron facility, and the beam stops in a safe and reliable fashion for routine multiple-use operation. In Line A, operation at very high intensity requires extreme precision in beam tuning and the full utilization of advanced radiation-hardened diagnostic devices. Several-fold redundancy in protection against faulty beam control, magnet current faults, and vacuum and water systems failure is provided.

The secondary beam lines in Area A (low- and high-energy pion channels and a stopped muon channel) and in Area B (the external proton beam and the high-energy neutron beams) provide the intense high-quality beams of pions, muons, protons, and neutrons for medium-energy physics and nuclear chemistry research at LAMPF. A test channel in Area A provides a moderate quality beam of charged particles for development and testing of experimental apparatus. These facilities cover a very broad range of experimental requirements and simultaneously serve experiments at each channel.

A number of improvements in primary beam-line components, diagnostics, monitoring instrumentation, beam-line protection instrumentation, and optical

III. MAJOR ACTIVITIES

9. Primary and Secondary Beam Lines (continued)

tunes were needed for intensities at 300 μ A and beyond. A spare target-cell-triplet magnet was reconfigured to increase operational reliability and to simplify remote servicing and maintenance. Improvements to the beam-line protection system included implementation of secondary emission guard rings into the Fast Protect System and improved transmission monitors. Improvements were made to the Line A harps to increase the accuracy and reliability of their data. Additional tunes and procedures were developed to handle a variety of targeting requirements. Improved Line X strippers were installed. This improvement facilitates greatly the phase-space tailoring of beams for Line C, HRS, and EPB. Secondary emission monitors were installed in Line X and Line B to monitor low-beam currents. The data from the EPB polarimeter can now be read from CCR. Ionization profile monitors were developed for low-current beams in EPB. A spin precession system for EPB, composed of a superconducting solenoid, three bending magnets, and a stripper, was designed. It will allow the beam polarization in EPB to be set in any direction independent of the polarization direction being used simultaneously for HRS. Procurement of the superconducting solenoid was initiated in FY 1978. The bending magnets needed were obtained from the LAMPF magnet pool and from the surplus list. Vacuum plumbing, support structures, and additional diagnostics needed for the spin precessor were started in FY 1978.

10. Remote Handling

A system of special components, tools, and mobile manipulators is needed for remote handling of activated targets, beam-line components, and beam stops. The key elements of this system are two highly maneuverable and flexible remote-handling systems called Monitors I and II. These systems consist of sophisticated manipulators mounted on a remotely controlled hydraulic boom. Manipulators available include a rate-controlled electromechanical manipulator, a hydraulically operated servomaster/slave arm, and two advanced-design servomaster/slaves with force-feedback. The Monitor systems are supported by remote-control television viewing systems and remote crane controls.

With beam currents at the 360- μ A level in FY 1978, the target-cell and beam-stop components have reached activation levels that require all maintenance and component replacement to be done fully remotely. A number of difficult remote-handling operations were carried out successfully in FY 1978. Contributing factors toward these successes were improved manipulator systems, better television viewing systems, increased use of special tooling designed for specific jobs, and trained operating personnel.

The mobile Monitor remote-handling systems are augmented by a modern hot-cell installation where activated apparatus can be brought for more complex repairs than can be done in the field.

11. Shielding

The high intensity of the LAMPF beams requires extensive shielding at beam intercept locations. All main beams, target stations, beam stops, and secondary beams are shielded to permit personnel access to working areas and counting houses at radiation exposure levels as low as practicable, with upper limits set by DOE regulations. About 33,000 tons of steel shielding and 15,000 tons of concrete are in use in the LAMPF experimental areas.

Besides the massive shielding for direct radiation protection, beam channels and shielding holes are sealed in order to contain radioactive air

III. MAJOR ACTIVITIES

11. Shielding (continued)

generated by the beam in the target cells and beam stops. Based on continual radiation survey information and design analysis of operating experience, new or improved shielding is being installed in several areas to prepare for higher intensity beams.

12. Vacuum Systems

The vacuum systems at LAMPF consist of the approximately one-half-mile-long accelerator, the switchyard, the secondary beam lines, and the main beam transport through the experimental areas. Support of these systems includes preventive maintenance of pumps and other vacuum components, leak-checking and repairs of defective vacuum components, and leak-checking and installation of new systems on the accelerator and the experimental areas. Day-to-day support for vacuum systems is accomplished by on-call personnel, trained to provide fast isolation and repair of the problems. Adequate spare-parts inventories are also provided.

Substantial vacuum support is also required for maintenance and development of the beam diagnostic equipment at the low-energy end of the accelerator.

During FY 1978 the pumps and controls for the Beam Line A experimental area vacuum system were improved. New turbomolecular pumps of higher capacity were purchased. Automatic valves and controls that reduce the chances of damage due to sudden loss of vacuum were installed.

13. Power Supplies

The power-supply activities include support of the nearly 150-dc power systems for the bending, focusing, and steering magnets. The work can be separated into three main categories: (1) maintenance (including necessary improvements) of existing systems so as to maximize performance and reliability, (2) design, procurement, and installation of power-supply systems for new beam lines, and (3) power-supply systems for experiments.

During FY 1978, in addition to routine power-supply maintenance, modification of the power supplies and associated equipment to improve reliability was continued. These modifications were mostly control changes and improvements to the reversing switches. A by-pass shunt system for the EPICS spectrometer was installed. The power-supply section moved to a newly constructed shop area that is much closer to the switchyard, Area A, and other experimental areas where the majority of the power-supply systems are installed. This has improved response to trouble calls and overall efficiency.

14. Control Computer

The computer-based control system that is used to operate the facility requires a continuing development and maintenance effort. The activities associated with this work include: (1) the control computer with its system and application programs, (2) the operator consoles and display equipment in the Central Control Room (CCR), and (3) the timing and interface systems along the accelerator.

Our present control computer is approaching obsolescence. Spare parts and commercial maintenance are no longer available since that computer line has been discontinued. During FY 1978 significant progress was made toward

III. MAJOR ACTIVITIES

14. Control Computer (continued)

replacing the present computer with a new one having higher performance, a more modern architecture, and better maintenance facilities. The general plan is to surround the present SEL-840 with intelligent I/O processors that can communicate with both the present and future control computers and then phase out the present computer. The pace of this project is slow because the SEL-840 must be on-line to the accelerator throughout the year, and this commitment leaves only a limited amount of scheduled downtime in which to accomplish each step of the changeover. However, all main subsystems (the disk, RIU, console, and Master Timer) received attention during the past year.

Work continued on the third operator's console that will be totally interfaced through CAMAC. The development work on the CAMAC-based, general-purpose information bus (GPIB) controller and its integration with the function-button panel was completed. A keyboard interface to the GPIB was designed, built, and tested. A color character scope with a CAMAC interface was purchased, installed, and tested. When the supporting system software is completed it will be possible to do a GPIB system analysis using the CAMAC/GPIB controller, function-button panel, keyboard, and color display. The knob/readout panels and trackball are next on the list of developments.

The first generation of a new Master Timer was completed and integrated into the control system. The timer is organized around a microprocessor which, before every pulse, examines requests for timing signals from up to 23 gate generator modules and produces the appropriate signals on the next pulse. The new unit can operate in various modes, i.e., it can impose different constraining relations among the various timing signals. This feature will become increasingly important as the complexity of accelerator operations grows in response to the demands of the experimental program.

A major effort was invested in software to support all the new devices. The Master Timer, the new disk system, and the third console, including the color display, required several levels of systems programs in more than one computer. These developments were intermixed with diagnostic work to identify and correct computer faults. A rich variety of application programs was written in response to requests from the Operations staff. Displays and automated procedures dominated the list. The software maintenance activities touched almost every program in the repertoire. The spectrum of modifications resulted from the discovery of errors, new modes of operations, slow responses, revisions of procedures, and changes in accelerator hardware.

The extension of the accelerator control systems along the main beam lines, to provide for effective delivery of beam to the targets in the experimental area and the development of instrumentation and controls for the secondary beam lines, is essential to the operation of the experimental facilities. The activities associated with this work include: (1) the completion of the local computer controls for the primary and secondary beam lines, (2) the development of computer programs for operating and monitoring of the beam-line equipment, (3) the expansion of the satellite computer network for beam diagnostic instrumentation, (4) the extension of the accelerator timing system into the experimental areas, (5) the development of a computer-based beam-line protection system, and (6) the maintenance of all the instrumentation and controls in the experimental areas.

III. MAJOR ACTIVITIES

15. Beam Diagnostics Activities

Beam diagnostic equipment provides the beam information needed to tune the facility and to characterize different beams formed during development work. This equipment must be reliable, accurate, and suitable for the high-intensity beams used at LAMPF. The activities required are repair, preventive maintenance, calibration, development of special check-out equipment and procedures and upgrading various devices. Skills needed for this activity include systems engineering, circuit and instrumentation design, electronics fabrication, vacuum and alignment support, mechanical design and fabrication, and materials technology expertise.

During FY 1978 a nonintercepting Beam Position Monitor system was installed on the accelerator that permits accurate measurement of beam position at high intensity, emittance and wire scanner devices received study on lifetime and accuracy at higher currents, and an accurate method of measuring beam-phase width at 121 MeV was developed.

16. Radio Frequency Power Systems

The rf systems supply the power to accelerate the beam. These are divided into four categories: (2) 805-MHz high-power rf, (2) 201.25-MHz high-power rf, (3) low-level rf, and (4) phase and amplitude control. There are some 108 separate rf subsystems. All of these must operate simultaneously near peak performance to satisfy the requirements for acceptable beam. To achieve this level of performance with good availability requires: (1) diagnosing and correcting weak points in system design, (2) training and maintaining a highly skilled crew that can be available at any time to repair failures in a minimum amount of time, (3) developing preventive maintenance procedures and schedules to minimize machine failures during operational periods, (4) ensuring that adequate spare parts are available in the event of failures, and (5) taking advantage of any advances in the state-of-the-art that will improve performance and reliability of the systems.

Upgrading the rf systems is accomplished through modification of spare units that are then cycled into the machine during maintenance periods, thus releasing more units for modification. Work was done on recabling, marking cables and components, and documenting the rf source room and the Δt system in order to improve performance and increase maintainability. Effort was put into studies and minor changes to improve stability of the Δt system and accelerator tank resonance controllers. Problems that developed with the high-power rf transmission lines in the 201.25-MHz system and the closed-loop controllers on the buncher cavities due to the higher rf duty factors and higher peak beam intensities were resolved by design changes to the hardware. Changes to the machine fast-protect system to avoid the problems of transients on the closed-loop controllers required redesign and installation of new detection hardware on all of the rf systems. The 805-MHz solid-state IFA design was enlarged to include a strip-line fast phase shifter in the same package. Construction and installation of these new units was well under way by the end of FY 1978. Modifications to the rf system that resulted in significant energy savings were made. Capacitors were procured and installed to increase the size of the rf energy storage banks. This change increases overall system efficiency, thus generating a new energy savings and also enables the systems to better handle the higher intensity, high-duty beams being run in the machine. An effort was also made to attempt to standardize gain and set up of the rf system components in order to reduce the control margin needed for the equipment.

III. MAJOR ACTIVITIES

16. Radio Frequency Power Systems (continued)

This procedure, along with reductions in delay times used for building fields in the cavity, resulted in additional energy savings.

17. Injectors

There are three injectors in use that provide simultaneous H^+ and H^- beams with the option of either polarized or unpolarized H^- beams. These injectors require a continuing maintenance effort. A number of development programs are in progress that are aimed at improving the performance of existing systems, implementing new systems to provide greater flexibility in modulating injector beams, and in designing and testing new ion sources to meet anticipated requirements for brighter beams at higher intensities.

During FY 1978, development on the H^+ source was directed at optimizing the performance of the LAMPF duoplasmatron to produce high brightness and this has resulted in an increase of injected beam brightness by a factor of three. The operation of the H^- injectors continued with half of the H^- beam time being devoted to polarized and the other half to unpolarized beams. Polarized beam currents of a few nA on targets have been produced while unpolarized beams up to 6 μA have been supplied. Considerable effort was spent in improving the transverse emittance of the unpolarized H^- beam to permit simultaneous operation with the higher intensity H^+ beams now required. A fast-spin-flip capability has been installed on the polarized ion injector and is now being used to provide suitable polarized beams for experiments looking for parity violation. Development of higher intensity polarized beams by optimizing accel-decel geometry is continuing.

18. Klystron and Vacuum Pump Rebuilding

The life of klystrons at LAMPF has been surprisingly long; one klystron has demonstrated in excess of 40,000 hours of operation. However, in view of the large number (44) of klystrons used and the fact that these tubes are manufactured specially for LAMPF, it is an operational and economic necessity to operate an in-house klystron rebuilding facility. This facility is in routine operation rebuilding approximately one tube per month. As further experience is gained in tube rebuilding, both tube design and the repair facility will be upgraded as required. In connection with this rebuilding a modest effort is made on improved tube design.

The switchtubes used in the klystron modulators require reprocessing several times to maximize their total life. This work is done in the klystron repair shop.

Some 127,000 liters per second of pumping capacity (176 ion pumps) are operational in the facility. One hundred forty-three of these pumps are associated with the accelerator, with the remainder installed on the main and secondary beam lines. Operational experience indicates that these pumps have a normal life expectancy of three years. An ion-pump rebuild facility provides replacements for the active units. Two large brazing furnaces are used routinely in the rebuilding program, on work in support of experiments, and for general fabrication.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

"Bates Linear Accelerator Facility Operations"\$2,812,000

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During FY/77 the accelerator was operated for a total of 5189 hours and during FY/78 for 5088 hours. Compared with FY/77 when the beam was available for experimental purposes 63% of the scheduled time, in FY/78 there was a reduction in this fraction to 60%. Whereas in FY/77 about 80% of the lost time was due to modulator failures, owing to the improvements made to the modulators under the AIP, this fraction has been reduced to 5%. The decline in efficiency during FY/78 has been due mainly to a combination of vacuum and rf problems in the low-energy part of the accelerator and rf window problems. The sources of these problems have been identified, and some corrective measures have been taken, with others under study. In the last two running cycles, efficiency has been near 70%, and it is reasonable to expect further improvement.

A 180° electron-scattering system, designed and built by the UMass group, was completed during the past year for use at the Bates Accelerator Center. It consists of four dipole magnets, the first three of which have similar pole-piece profiles and serve only as beam transport elements. The fourth magnet directs the incident beam onto a target, and also receives and deflects the back-scattered electrons into the energy-loss spectrometer. The system may be used for both elastic and inelastic scattering without requiring the spectrometer to be moved. The incident electron beam and the post-target beam travel along the same line. Thus the same beam-dumping apparatus may be used as is for forward angle scattering. The fourth magnet may be removed easily and replaced with the scattering chamber which is used in forward angle studies. The system was installed in the Spectrometer Room in late September and early October, 1977. The system was first tested in the beam on October 22. Several additional performance tests requiring 108 hours of beam time were carried out until December 10. It was found that the system met design specifications with a resolution better than 3×10^{-4} and a constant solid angle. The first measurement not related to tests was performed on December 19. It is now in routine operation.

In the spring of 1977 in connection with the proposed research program to be developed in the Second Experimental Hall, a long-range plan was made for capital equipment. In this plan we proposed a first-round procurement of spectrometers, beam lines, computer and data acquisition equipment, and general laboratory equipment at a total cost of \$4 million. Our plan at present is during FY/79 and FY/80 to procure the pion spectrometer, to start development of beam line B which services the spectrometer complex, to purchase a few essential items of general lab equipment, and to augment

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the computation and data-handling capability of the laboratory by the procurement of additional computer hardware. A subcontract has been negotiated with RPI for the procurement of the pion spectrometer. It is our belief that experimental research in photopion spectroscopy can begin in FY/80. Development of the proton spectrometer, further development of line B, and the development of beam line C is planned to begin in FY/80, with checkout and the start of research extending over FY/80 and FY/81.

Work continues on the development of the high-resolution electron-scattering facility. A large-diameter dumping system has been procured, and is now in service. Included in this system is a multi-port parasitic scattering chamber which will be used to check experimental ideas for feasibility and, in some favorable cases, to take data in series with thin targets in the electron-scattering program. This system has resulted in a significant reduction in the background at the detector array. Further background analysis is required to evaluate shielding options. Work continues to develop the spectrometer system so that form factors may be measured at a fixed electron energy by changing the scattering angle. A sliding seal has been ordered for installation in the fall of 1978.

We plan to operate the accelerator and research facilities approximately 5000 hours during FY/79. Most of the accelerator facility development effort will be devoted to the installation of the Beam Transport System to the Second Experimental Hall as part of the construction line item. In addition, using AIP funds we will design, procure, and install a magnetic beam deflection system which will allow the switching of the beam, on an alternate pulse basis, between the present experimental beam lines and the new area. We will also design and start the construction of a modulator which will be completed and commissioned in FY/80.

HEAVY ION NUCLEAR PHYSICS

(HK 03 02)

Includes all costs associated with experimental Nuclear Physics activities carried out at facilities with primary beam particles more massive than helium-4.

HEAVY ION NUCLEAR PHYSICS - RESEARCH

(HK 03 02 01)

Includes all costs of heavy-ion nuclear research activities.

ARGONNE NATIONAL LABORATORY \$151,000
Chemistry Division

Heavy-Ion Physics Research

K. L. Wolf, B. B. Back, I. Ahmad, A. M. Friedman, J. P. Unik

This program is directed to obtaining a comprehensive understanding of the interactions which take place during collision between heavy nuclei ranging from intermediate to relativistic energies. A collaborative effort with the Universities of Rochester and Maryland (RAM Group) continues at the LBL Super HILAC studying deep inelastic processes with very heavy ions below 8.5 MeV/nucleon. Recent measurements have shown that the neutrons emitted from deep inelastic events are predominately due to evaporation processes from post-scission fragments. Studies of the $^{56}\text{Fe} + ^{209}\text{Bi}$ reaction have shown an apparent departure from the "universal" energy dissipation vs charge dispersion relationship. Resonances have been observed in the energy spectrum of products resulting from the $^{56}\text{Fe} + ^{56}\text{Fe}$ reaction which may be indicative of an entirely new reaction mechanism. Another multilaboratory collaboration, led by ANL and including MSU, University of Maryland and LBL is conducting experiments at the LBL 88-inch cyclotron. Complex three body correlation experiments studying the $^{16}\text{O} + ^{238}\text{U}$ reaction at 20 MeV/nucleon are used to determine the linear momentum transfer for events with projectile-like reaction products (^6Li to 160). The results, to date, show that this mechanism is neither fragmentation nor deep inelastic transfer, but a new process with an intermediate momentum transfer. Relativistic heavy-ion research, performed at the LBL Bevelac in collaboration with LBL staff, utilizes π^+ cross section measurements to provide information on collective phenomena, Fermi motion, and tests of several collision models. In the reaction $^{40}\text{Ar} + ^{40}\text{Ca} \rightarrow \pi^+ + \text{X}$ at 1.05 GeV/nucleon, there is a strong indication of the nuclear fireball mechanism being operative. Several other interesting effects have also been observed which are interpreted in terms of nuclear shadowing and π^+ absorption in nuclear matter at high density and temperature. Experiments with high-precision beams from the ANL Superconducting Linac, when available, will emphasize gamma-ray and light charged-particle multiplicity measurements to provide a detailed understanding of the excitation energy balance and angular momentum transfer in heavy-ion reactions as well as the nature of high-spin states in nuclei.

ARGONNE NATIONAL LABORATORY \$415,000
Physics Division/Chemistry Division

Superconducting Linac Development

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This program, carried out jointly by the Chemistry and Physics Divisions, is concerned with investigations of the general aspects of applications of superconducting technology to the acceleration of heavy ions. Most of the recent activities have been related to the development of an accelerating structure of the split-ring type made of niobium. Specific tasks, some of which are ongoing, include development of (1) a good rf joint, (2) a new superconducting material consisting of niobium sheet that is explosively bonded to copper, (3) resonator-diagnostic techniques, (4) a new kind of phase-control device, and (5) beam-dynamics computer programs.

Since FY 1976, there has been a companion project (see "Heavy-Ion Energy Booster") concerned with the specific task of adding a small superconducting linac as an energy booster for heavy ions from the FN tandem Van de Graaff accelerator. This booster project will be completed by the end of FY 1979,

During FY 1978, the effort in the Superconducting-Linac Development Program is focussed on the specific developmental needs of the heavy-ion energy booster. It is planned that this approach will continue during the first part of FY 1979, but then, when the booster project has been completed, the nature of the developmental program will change substantially; the level of effort will be somewhat reduced, and the function of the group will be broadened to include: (1) a less focussed program of development of superconducting-linac technology, including investigations of basic technical problems that have necessarily been bypassed during the booster-construction phase, (2) the solution of problems of specific interest for the booster, (3) the transfer of the new rf technology to other institutions, and (4) the investigation of other technologies of interest to the nuclear science community.

ARGONNE NATIONAL LABORATORY \$490,000
Physics Division/Chemistry Division

Heavy-Ion Energy Booster

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This project, started in FY 1976, is concerned with the design, construction, installation, and testing of a small superconducting linear accelerator (linac) that will serve as an energy booster for heavy-ion beams from the FN Tandem accelerator. The principal objectives of the project are to develop a new accelerator technology and to build the prototype for a heavy-ion-energy booster that can be used to upgrade the performance of any tandem accelerator. The prototype linac, now being assembled, consists of 14 superconducting resonators of the split-ring type. The overall design is highly modular in character in order to provide maximum flexibility for future modifications and/or improvements. The first section of the booster, with 6 resonators, went into operation in mid-1978, and installation and testing of the whole system will be completed by the end of FY 1979.

The minimum objectives of the project are to produce a superconducting linac that (1) provides at least 13.5 MV of acceleration and that (2) has an output beam with very good quality. In order to achieve the second objective, we are using an accelerating structure with a relatively low (about 97 MHz) rf frequency. The linac will consist of independently-phased resonators so as to make it useful for a wide range of projectiles. The system is being formed of modular components and is designed to be as simple and flexible as possible so as to be able to make use of future improvements in a rapidly developing technology.

The design and development of the booster is carried out with guidance from the results of technical investigations described under "Superconducting Linac Development."

ARGONNE NATIONAL LABORATORY \$935,000
Physics Division

Heavy-Ion Research at the Tandem and Superconducting Linac Accelerators

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The scope of the research program at the Argonne Physics Division in heavy-ion physics is a broad one. Research now is carried out with the upgraded FN Tandem Van de Graaff and in the future will also make extensive use of the new superconducting linac energy booster. Currently, a survey of fusion reactions and their connection with other reaction modes and to nuclear structure is being carried out. In direct reactions, the program has focussed on the macroscopic distribution of reaction flux, as well as on a careful study of the ramifications of strong channel couplings on other reaction modes. Substantial studies aimed toward the understanding of resonance phenomena are also in progress. Finally, the study of high-spin isomers in heavy nuclei is an important area in which our research effort has been initiated.

The Argonne tandem accelerator is the principal heavy-ion facility used by the Physics Division. During the past year this accelerator has undergone a major, and completely successful, upgrading that changed its capacity to accelerate beams of heavy ions by very substantial factors. Concurrently, the development of a superconducting linac to boost the energy of ions from the tandem progressed rapidly, and operation of a first section started in September 1978.

The study of heavy-ion fusion reactions has continued to be very fruitful. Under investigation is the probability that two nuclei, when they collide, will fuse, and stick together on a time scale long compared to the collision time. Two new effects have emerged from the work at Argonne. One is the observation of resonance-like phenomena in a few very tightly-bound symmetric systems. These provide a hint of a link between gross reaction properties and nuclear-structure effects. The second new result is an unexpected dependence of the fusion probability on the details of nuclear structure within the fusing nuclei. The ramifications of these phenomena are being explored in other processes, so far principally the elastic and quasielastic reaction modes.

The careful systematic study of other macroscopic features of heavy-ion reactions is being continued. The relation between competing direct-reaction channels is investigated both for different target nuclei and at different energies.

ARGONNE NATIONAL LABORATORY

Heavy-Ion research at the Tandem and Superconducting Linac Accelerators

The high-resolution study of inelastic scattering has produced a set of data of unique quality. It is proving to be an interesting testing ground for the indirect effects of strongly-coupled channels in direct reactions, and tends to confirm the qualitative picture that has been evolving from the study of the more macroscopic features of direct processes.

The investigation of high angular momentum states is one of the major frontiers in nuclear physics. An important advance in this field came in the discovery by a Danish-German-US(Argonne) collaboration of high-spin isomerism--a feature of nuclear structure that holds out considerable promise for the future and has great potential in connection with the pulsed beam of the superconducting linac energy booster.

An important activity during this period has been the design and partial implementation of an experimental beam line to carry out research with the heavy-ion beams from the superconducting energy booster to the tandem. The objective is to have a working experimental system when the booster becomes available for research in late 1978. The initial beam line is at 0°, requiring no bending magnet after the linac sections. It is designed to have carefully controlled beam optics in order to allow focusing of the beam at any one of four potential beam stations along it. The vacuum system is designed to be free of organic contaminants, in order to reduce problems associated with carbon contamination. The beam stations will be occupied by a 65-inch scattering chamber, a single-arm chamber suitable for simultaneous charged-particle and neutron time-of-flight measurements, a gamma-ray multiplicity counter and a He-jet system for the study of delayed radiations. This set of experimental stations will allow for a strong initial program in heavy-ion research on the superconducting linac.

In the first experimental use of the linac (September 1978), an ^{16}O beam was used to study the fragmentation of ^{40}Ca in a small temporary scattering chamber on the zero-degree beam line. The pulsed character of the beam was used to measure the velocity and hence the mass of reaction products.

BROOKHAVEN NATIONAL LABORATORY \$131,000
Chemistry Department

Nuclear Reactions Induced by Energetic Heavy Ions

J. B. Cumming, P. E. Haustein, J. Hudis, S. Katcoff

A few years ago it became apparent that the nuclear interactions of high-energy heavy ions were similar in many ways to those of protons. Although studies of emitted particles did reveal more copious emission of more energetic light fragments for incident heavy ions, evidence for predicted new processes such as shock waves or states of abnormal density has not materialized.

The BNL research seeks a comprehensive understanding of the more usual types of reactions as well as evidence for novel processes through measurements of radioisotopes produced by irradiation of targets with heavy ions and by the use of nuclear track techniques. Data from similar experiments with energetic protons and π mesons are valuable for comparison with the heavy ion results within the framework of a theory originally developed to account for elementary particle interactions. This theory predicts the onset of asymptotic behavior in which target-fragmentation cross sections become energy independent, and dependence on the bombarding particle is only via a total cross section term. Experimental cross section surveys of the interaction of various heavy ions with copper have shown broad mass regions where such predictions appear valid.

Attention is now being focused on the measurement of more detailed properties -- the mean kinetic energy of and the momentum transferred to selected products. Significant differences in the latter quantity when reactions of 25-GeV ^{12}C ions are compared with those of 28-GeV protons are interpreted as indicating deviations from limiting behavior at 2.1 GeV/nucleon. The dependence of such deviations on energy and projectile type is being further explored in experiments with lower energy ^{12}C ions and high- and low-energy ^4He ions. As techniques improve and heavy-ion beam intensities increase, direct measurements of product angular distributions and energy spectra are planned. These are of special interest in light of the novel sideward peaked angular distributions reported recently for reactions induced by very high energy protons. Cross section surveys will be extended to Kr and Xe projectiles if these become available.

BROOKHAVEN NATIONAL LABORATORY. \$1,292,000
Physics Department

Heavy-Ion Physics with the Tandem Van de Graaff Facility

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The basic questions in heavy-ion nuclear physics are concerned with (a) the way in which large pieces of nuclear matter interact with one another in regions of energy, angular momentum, and even density not present for stable nuclei near their ground states, (b) how matter, energy and angular momentum pass between such aggregates, and (c) the manner by which excess matter, energy and angular momentum is disposed of by the residues of heavy-ion induced reactions.

The Tandem Van de Graaff Facility provides unique capabilities for studying these fundamental problems of nuclear physics. Continuously adjustable high energies and a great variety of different heavy projectiles, combined with the excellent beam characteristics of Van de Graaff accelerators, offer new opportunities for probing the properties of nuclear states in a totally new region of angular momentum as well as investigating the dynamics of such new nuclear reactions.

The rich diversity of available heavy-ion beams makes it possible to carry out a multi-faceted heavy-ion experimental program at the Tandem Facility. This experimental program is carried out both by the resident staff and by an outside user community with approximately equal allocations of beam time. Crucial to the success of the entire experimental program is the availability of important analytic tools such as the QDDD spectrometer with its large solid angle, forward angle capability and superior focal-plane detector energy resolution, as well as data-collection and data-analysis capability of the on-line Tandem computer system. General areas of research which are currently being actively pursued include: studies of states of high angular momentum produced by heavy-ion compound nuclear reactions, studies of heavy-ion direct reaction mechanisms, production of "exotic" nuclei far from the line of stability and spectroscopic studies of their level structures, and examination of heavy-ion induced fission and fusion processes. In addition, heavy-ion beams are used for investigations of atomic processes such as x-ray production by heavy ions and the energy-loss mechanisms of heavy ions in matter. The range of ion species and energies as well as the variety of major pieces of experimental equipment and data accumulation systems make possible many experiments that cannot be carried out elsewhere. Heavy-ion reactions result in the excitation of a rich variety of nuclear states and afford unique methods to investigate

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Heavy-Ion Physics with the Tandem Van de Graaff Facility

many aspects of nuclear structure. Fusion reactions, followed by particle evaporation give rise to nuclei in excited states of high angular momentum. The γ -ray spectroscopy of such nuclei is actively pursued and results in significant new information about nuclear structure. The primary objective is to understand and describe how nuclear matter responds to the large stresses of centrifugal and Coriolis forces associated with large angular momentum. Discrete states with angular momentum of at least $36\hbar$ have been identified in ^{154}Er . In this and similar nuclei near major shell closures, changes in nuclear shape and in the way the nucleus accommodates large angular momentum and excitation energy may be occurring. Shell-model isomers definitely occur in this region, and searches for predicted yrast "traps" have been made. When isomerism does occur, the strong spin alignments resulting from the heavy-ion fusion which lead to highly anisotropic γ -ray angular distributions make possible magnetic g-factor measurements by methods of perturbed angular distributions. Such measurements are often of decisive importance for the correct assignment of nuclear configurations to high-spin states excited in these reactions.

In lighter nuclei at high-excitation energy, α particles can be emitted from these aligned systems. In such cases, particle correlation studies can yield important information about high-lying states in the "continuum region" of the excited nuclei.

The large charge of heavy-ion projectile-target combinations permits strong coulomb excitation. Accurate measurements of excited state quadrupole moments and electro-magnetic transition probabilities between excited states of stable nuclei become feasible to reasonably high spin. Such information is an important complement to the results derived from (heavy-ion, xn) reactions since such reactions rarely lead to stable nuclei.

Another program emphasizes the study of elastic scattering, inelastic excitation, and few-nucleon transfer reactions initiated by heavy-ion beams of varying energy, charge, and mass, generated by the Tandem Van de Graaff Facility. The magnetic QDDD spectrometer plays an important analytic role in such studies, not only for reasons of energy resolution, but also to examine reaction yields near and actually in the forward direction. Such yields play an increasingly important role with rising beam energy. In the last year there were significant, surprising results obtained at BNL and elsewhere for elastic scattering, at far back angles of systems as heavy as $^{40}\text{Ca} + ^{16}\text{O}$. Unexpectedly large cross sections, oscillatory angular behavior, and significant structure in excitation functions; all at energies well above the coulomb barrier were observed. Phenomena such as nuclear orbiting made possible by extremely weak absorption in the surface regions of heavy ions are strongly suggested by the data. Although possibly similar effects were observed for lighter systems such as $^{16}\text{O} + ^{16}\text{O}$ or $^{12}\text{C} + ^{16}\text{O}$, interpretation of these data is

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Heavy-Ion Physics with the Tandem Van de Graaff Facility

always modified by the identical nature of the projectile and target or the possibilities of elastic transfer. The recent program at BNL was particularly successful because of the availability of Si and Ca beams and the QDDD spectrometer. Due to kinematic considerations, it is almost impossible to study these back-angle reactions in the scattering of light beams on the heavier target. With the heavy beam on the light target, the "back-angle" cross section becomes a measurement at forward angle in the laboratory, and the magnetic spectrometer makes these measurements possible.

In the past a concentration on one- and two-nucleon transfer reactions revealed both strengths and weaknesses of the single-step Distorted Wave Born Approximation (DWBA) analysis of these reactions. Some multi-step analysis is probably required to produce an explanation of the difficulties encountered in some reactions studied here. There was an increased emphasis on inelastic scattering for its possible importance in multistep processes and its possible effect on elastic scattering. A beginning was made to investigate the nature of the mechanism in larger mass transfer to determine whether the process is primarily single step or multistep. In addition some rather extensive studies of the systematics of the " α transfer" reactions ($^6\text{Li}, d$), ($^{18}\text{O}, ^{12}\text{C}$) began to elucidate both the nature of the reaction and the spectroscopy of the nuclei involved.

Close cooperation between experimental and theoretical programs in the heavy-ion induced direct reactions is essential and was particularly fruitful. An earlier collaboration was extended to investigate the polarizations of reaction products in heavy-ion direct reactions. It appears that experiments involving such measurements would be useful in determining the reaction mechanism.

One of the fundamental reasons for studying heavy-ion physics is to gain an understanding of the dynamics and interaction of two massive pieces of nuclear matter. An important aspect is the study of how nuclei fuse, exchange mass and energy, and then split apart. The study of the evaporation of particles from the fused system may shed considerable light on the questions of production of super-heavy elements--since if they exist, they probably must be made by fusion-fission or fusion-evaporation reactions. If a system formed in fusion lives a long time on a nuclear scale, then the subsequent particle emission is called "evaporation" and is characteristic mainly of the excitation energy and spin of the system and not on the details of its production. Whether any "precompound" or non-evaporation light particles come from fused systems is an open question which is addressed in some of the works carried out in this program.

UNIVERSITY OF CALIFORNIA AT LOS ANGELES \$ 60,000
Department of Physics

Relativistic Heavy Ion Nuclear Reactions

G. J. Igo, J. B. Carroll

At the Bevalac, relativistic heavy ion probes, ~ 2 GeV/N ^{40}Ar and ^{12}C have been used to measure the rapidity dependence of light-ion, single-particle inclusive reactions on light nuclear targets. The associated multiplicity distribution of high-energy, singly and doubly charged particles were measured. The principal conclusions of this experiment are: 1) the shape of the rapidity distributions are insensitive to the multiplicity, 2) no enhancements in the rapidity distributions were found which could be attributed to coherent (shock waves for instance) phenomena; and 3) the single-particle inclusive spectra are in good agreement with the "firestreak" model. (The "firestreak" model has been found to be capable of explaining single-particle inclusive data taken under a broad variety of experimental conditions, i.e. various beam energies, targets, projectiles, and in a large range of the rapidity region).

CARNEGIE-MELLON UNIVERSITY \$103,500
Department of Chemistry

Nuclear Research with Heavy Ions

M. Kaplan

The research program is directed towards experimental studies of nuclear reactions induced by heavy ions in complex nuclei. It involves a collaboration between Carnegie-Mellon University and SUNY at Stony Brook and utilizes the SuperHILAC and 88" Cyclotron accelerator facilities of the Lawrence Berkeley Laboratory. Our emphasis is on the detection and measurement of light charged particles emitted in deeply inelastic collisions using counter telescopes to record both the singles events and the coincidences with heavy fragments. The identification of ^1H , ^2H , ^3H , and ^4He particles is accomplished by means of three-element Si surface barrier detector telescopes, and energy spectra and angular distributions are obtained. Heavy fragments from the reactions are measured with gas-ionization chamber telescopes which provide atomic number identification and fragment energies. Correlations between light charged particles and heavy fragments, and between two heavy-fragment partners, provide detailed insights into the dynamics of the reaction mechanism. The light particles evaporated from fully accelerated fragments yield information on the excitation energies and spins of the equilibrated reaction products, whereas those particles which are emitted prior to thermal equilibration give us a view of the early stages of the reaction. Parallel studies of charged particle emission and fission in closely related compound nucleus reactions allow us to model the de-excitation properties of heavy nuclei at high energy and spin. These models can then serve as experimental calibrations and input for theoretical calculations which are needed for interpreting the more complex deeply inelastic processes observed in nuclear reactions of very heavy ions.

GEORGIA INSTITUTE OF TECHNOLOGY \$ 72,428
Department of Chemistry

Nuclear and X-ray Spectroscopy with Radioactive Sources

R. W. Fink, J. L. Wood

This program is a systematic study of nuclei far from stability with radioactive sources produced with heavy ions from the Oak Ridge Isochronous Cyclotron and mass-separated on-line by the UNISOR facility. Such experiments complement in-beam reaction spectroscopy (which is confined to high-spin states) and are the only means of exploring the low-spin structure of nuclei far from stability. This research investigates: (1) core-particle coupling models and the role of the Fermi energy; (2) shapes of transitional nuclei; (3) pairing correlations in transitional nuclei; (4) shape and pairing isomerism; (5) shell model intruder states; and (6) proton-neutron correlations; as well as a search for new radioactive nuclides. Currently the emphasis is on transitional regions bordering $Z = 82$ (isotopes of Pt, Au, Hg, Tl, Bi, and Po).

These studies are complemented on-campus by related work on x-rays from radioactive sources (fluorescence and Coster-Kronig yields for $Z = 64-83$), lifetimes of certain nuclear excited states, computer codes for data analysis, and radioactive nuclides produced in the 5 MW Georgia Tech Research Reactor.

JOHNS HOPKINS UNIVERSITY \$136,800*
Department of Physics

Nuclear Moments and Nuclear Structure

Y. K. Lee, L. Madansky, J. C. Walker

The technical scope of the program involves the completion of an apparatus designed to study central collisions of relativistic heavy ions in order to investigate the properties of nuclear matter via the emission of gamma rays. An initial run at the Bevalac proved very successful and the group is approved for further experimental run. We found appropriate triggers for identifying central collisions and were able to determine the level of pi-zero production. We intend to use Pb-glass, wide angle counters to study more directly the measure of the emission from hot nuclear matter, and detect possible "phase transition" to new states in hadronic matter.

LAWRENCE BERKELEY LABORATORY \$175,000
Nuclear Science Division

Relativistic Heavy-Ions at the Bevatron/Bevalac

O. Chamberlain, H. Steiner, S. Nagamiya

We have continued our study of particle production and fragmentation of the projectiles p, d, α , and ^{12}C in collisions with targets of Be, C, Cu, and Pb at beam energies of 1 to 2 GeV/nucleon. These measurements bear on such questions as possible coherent production mechanisms, nuclear correlations inside nuclei, limiting fragmentation, and the connection between $B \geq 2$ interactions at Bevatron energies and other high energy phenomena.

The main objectives of another set of recent experiments are to select and study heavy-ion central collisions. A rotatable magnetic spectrometer is used to momentum analyze charged fragments over a wide range of transverse momenta. It allows us to separate π^+ , π^- , K^+ , p, d, t, ^3He and ^4He fragments and to measure their energies up to a few GeV at various laboratory angles from 10° to 160° . We have observed that energetic fragments produced at large angles have exponential-type energy distributions. The beam energy dependence of fragment emission has also been measured. From the detection of d, t, ^3He and ^4He , the mechanism of complex-nucleus production has been studied. As to meson production, we are still measuring the production rate as a function of beam energy.

In order to select head-on collisions, 20 additional tag-counter telescopes have been prepared. With these we are measuring how the energy and angular distributions change as we go to higher multiplicities. Preliminary results have shown noticeable differences between high and low multiplicity events, and we are pursuing more detailed studies of such differences. Using these tag counters we are also measuring two-particle correlations in order to study direct emission processes in heavy-ion collisions.

In forthcoming experiments we plan to measure kaon production and to extend our study of pion production. Some effort is also being devoted to work on detection systems for the HISS spectrometer.

LAWRENCE BERKELEY LABORATORY \$445,000
Nuclear Science Division

Coulomb Excitation and In-Beam Spectroscopy

R. M. Diamond, F. S. Stephens

Our aim is to study and to understand some of the important aspects of nuclear structure, and especially the changes induced by high angular momentum. We use beams of very heavy ions (^{40}Ar through ^{208}Pb) from the SuperHILAC and of smaller ions (^4He through ^{40}Ar) from the 88" cyclotron. We have exploited the especially useful properties of heavy ions, namely, their large nuclear charge, their large linear momentum leading to large recoil velocities of the struck target nuclei, and the large amounts of angular momentum they may bring to a compound system.

The high charge makes the heaviest ions those of choice for Coulomb excitation studies of the highest spin states possible, for Coulomb-induced fission studies, and for the transient production of supercritical nuclei during the collision of the projectile with a high-Z target nucleus. The large recoil velocities given to product nuclei allow for lifetime determinations of excited states in the 10^{-10} - 10^{-14} second range by recoil-distance Doppler shift and Doppler-broadened lineshape analysis. The high angular momentum imparted to a reaction product leads to the production of nuclei in spin states greater than $50\hbar$, and studies of the de-excitation of these states by continuum γ -rays gives information about the moment of inertia and the shape of these nuclei as a function of spin. This is one of the most recent and exciting fields of nuclear structure, and includes a number of evolving techniques, such as multiplicity filters, γ -ray sum spectrometers, γ -ray polarimeters, Compton-suppressed spectrometers, and the use of conversion-electron spectrometers in the continuum region.

LAWRENCE BERKELEY LABORATORY \$545,000
Nuclear Science Division

Heaviest Element Research

A. Ghiorso, J. M. Nitschke, M. Nurmia

The objective of this project is to extend our knowledge of the heaviest elements. New technologies and new capabilities of the SuperHILAC make it possible in principle to create new elements, but many barriers present themselves. The world-wide failure of recent attempts to produce superheavy elements via fusion or other types of reactions has been quite disappointing and makes it clear that a better understanding of the basic physics of heavy-ion collisions is needed. A start in this direction has been made by our recent experiments with the doubly-magic nuclei ^{40}Ca , ^{48}Ca , and ^{208}Pb .

Another approach to the hypothesized superheavy element "island" is to try and extend the "coastline" above element 106 so as to better understand the reasons for the failures to reach the island. The time-tried technique of bombarding the heaviest element available with the lightest suitable projectile suffers from the handicap of miniscule cross section but can be used for at least element 107. An alternate method is the use of heavier projectiles to bombard ^{208}Pb and ^{209}Bi and this technique will be explored soon.

A largely unexplored path to the synthesis of new isotopes and perhaps even new elements has emerged through the discovery of the deep inelastic reactions. Since many of these nuclides will be short-lived and will decay predominantly by spontaneous fission, their identification as to A and Z will present a difficult experimental problem. We are therefore preparing an instrument which will yield information about the mass of a nucleus before it decays. This device will be especially helpful for those cases where the angular distribution of the reaction products is too broad for use in conventional magnetic instruments.

LAWRENCE BERKELEY LABORATORY \$370,000 *
Nuclear Science Division

Instrumentation Service for Nuclear Science

F. S. Goulding, G. Haller, D. Landis, M. Maier, C. Maples, R. Pehl

The scope of this program is to provide general services in connection with all electronic instruments and computers used in Nuclear Science Division programs. In addition to maintenance of all community equipment (i.e., shared by groups), this includes operation of an equipment pool, maintaining files of drawings and records on instruments and providing operating manuals and a consulting service for all aspects of instruments and detectors used in research programs. The experimental programs covered include LBL and outside users at the SuperHILAC, 88" Cyclotron and the Bevalac accelerators.

A major component in this project is the provision of a software system and service for the Mod. Comp. IV data acquisition systems at the SuperHILAC (three systems) and the 88" Cyclotron. This work has recently been expanded to include the development of general-purpose data acquisition systems for use in experiments at the Bevalac.

* Additional funding provided under Nuclear Sciences: \$75,000

LAWRENCE BERKELEY LABORATORY \$165,000*
Nuclear Science Division

Instrument Development for Nuclear Science

F. S. Goulding, G. Haller, D. Landis, M. Maier, A. Thompson, J. Walton.

The scope of this program is to carry out research and development on advanced instrumentation for use in nuclear research. This includes development of new circuit techniques, instrument modules and systems, computer data acquisition systems and detectors as follows:

1. Circuit design work on a number of new modules for use in nuclear experiments has been carried out. Of particular interest is completion of work on a very fast (5 μ s for 12 bits) ADC for pulse height analysis applications.
2. A considerable amount of work has been carried out on microprocessor systems with particular reference to their use in association with general purpose data acquisition computer systems. Here the speed of the microprocessor used for special processing is of paramount importance (unlike many data logging microprocessor applications). The TI 9900, 16-bit processor is being employed in this work and the whole complex for providing convenient programming of these devices has been developed and assembled. This work also forms an important base for the proposed "data center" which is a key item in the future off-line data-sorting plans at LBL.
3. Among a number of detector developments supported by this program was the development of large area (5 cm dia), thick (0.5 cm) silicon detectors exhibiting extreme uniformity of thickness ($\pm 10 \mu$ m over the area) and with very thin dead layer associated with contacts on either side. A substantial number of these detectors have been made for use in identifying isotopes (up to Fe) in space and Bevalac experiments.

* Additional funding provided under Nuclear Sciences: \$40,000.

LAWRENCE BERKELEY LABORATORY \$470,000
Nuclear Science Division

Relativistic Heavy-Ion Physics

H. Heckman, D. Greiner, P. Lindstrom, G. D. Westfall

The Heckman/Greiner group pursues an interrelated program of experimental research and instrument development in the fields of high-energy heavy-ion physics and cosmic rays. This project involves a strong collaborative effort with the University of California Space Sciences Laboratory in both Bevatron/Bevalac and space-flight heavy-ion experiments. The group also contributes significantly to Bevatron beam development and outside-users support.

The principal program of research is a Bevatron/Bevalac study of the nucleus-nucleus reaction at relativistic energies. These studies include experiments on the fragmentation of heavy ion projectiles, systematic measurements of the total cross sections for the production of elements and isotopes in heavy ion collisions, and searches for rare isotopes (in collaboration with the Hendrie/Scott group at LBL).

Primary emphasis in coming years will be placed on multiple-particle inclusive measurements using wide-gap magnetic spectrometers. We believe the effects of kinematics which dominate the single-particle inclusive measurements of nucleus-nucleus interactions may be understood and suppressed in multiple-particle measurements which provide a more complete definition of the final state. Our measurements will be directed at the projectile-like fragments which, because they are confined to a small solid angle in the laboratory, are easier to identify in a more complete fashion. The earlier single-particle inclusive studies have shown that the projectile fragment system is independent of target, thus allowing us to isolate and more completely define a strongly-interacting subset of the nucleus-nucleus reaction.

In FY 1979 and FY 1980, our group's major effort will move to the construction and instrumentation of the HISS spectrometer with major group expenditures for HISS experiment instrumentation.

A space-flight version of the particle identifiers used in Bevalac rare isotope experiments will be used to perform isotopic-mass measurements of the heavy primary cosmic rays. This UCSSL-LBL experiment, funded by NASA, forms an integral part of the group's heavy-ion research program. It will be carried out on the ISEE-C (International Sun-Earth Explorer) satellite, to be launched and placed in a heliocentric orbit in 1978.

LAWRENCE BERKELEY LABORATORY \$735,000*
Nuclear Science Division

Nuclear Reactions

D. L. Hendrie, J. Cerny, H. Conzett, D. Scott, B. G. Harvey

The project performs basic experimental research in nuclear science, supports developments in instrumentation and experimental techniques, provides support and collaboration with visiting researchers, trains graduate students, and provides positive feedback into the operation and development of accelerators and facilities. Most of the work is performed at the 88-inch cyclotron and at the Bevalac. Close contact and cooperative efforts are maintained with theoretical groups at LBL and elsewhere.

Cyclotron beams of light ions from protons to alpha particles, with maximum energies of 55 MeV for p,d and 120 MeV for α , and intensities of up to 100 μ amps are used for about 20% of the work. Polarized beams of protons and deuterons of up to 300 na are used 10% of the time. The remaining 70% uses heavy-ion beams from ${}^6\text{Li}$ to ${}^{40}\text{Ca}$, with various available intensities up to 100 μa , and with energies from 1/3 to 35 MeV/nucleon. Bevalac beams of interest range from 80 to 2100 MeV/nucleon. Particles are detected by a variety of sophisticated solid-state counters, both Li(Si) and Ge, with scintillation counters, and with a high resolution spectrometer.

Much of the research activity goes toward investigation of heavy and light-ion reaction mechanisms. Light-ion reactions with unbound resonant final systems such as ${}^2\text{He}$ and ${}^4\text{He}$ requires a sophisticated solid-state detector system and provides a comparison with more traditional transfer reactions. Heavy-ion transfer reactions to the continuum probes the interaction in more exotic ways, and at cyclotron and Bevalac energies, provides a link between deep-inelastic studies and the fragmentation results at relativistic energies. The good duty factor of the cyclotron facilitates the extension of this work to coincidence measurements. Other types of heavy-ion reactions, such as investigation of giant resonances and perturbations of elastic scattering below the Coulomb barrier require the use of the spectrometer.

The properties of nuclei far from the valley of stability are actively explored. These investigations test the various theoretical models used to predict the ground-state masses and level schemes of exotic light nuclei and permit one to search for new radioactive decay modes, such as direct proton radioactivity or the still unobserved two-proton

* Additional funding provided under Nuclear Sciences: \$125,000

LAWRENCE BERKELEY LABORATORY

Nuclear Reactions

radioactivity. Techniques for observing the properties of very low yield nuclear reactions have been developed on the magnetic spectrometer to permit these mass measurements. Decay schemes of exotic nuclei are investigated either as retained in their target in a pulsed beam experiment or, more often, after mass analysis via an on-line magnetic spectrometer system. This Recoil Atom Mass Analysis (RAMA) system employs a helium jet to transfer rapidly the radioactive species to a universal ion source followed by a magnetic analyzer. Measurements of nuclei from mass 20 to mass 200 with half-lives down to 100 milliseconds are currently under investigation.

LAWRENCE BERKELEY LABORATORY \$110,000*
Nuclear Science Division

88-Inch Cyclotron Pool Maintenance and User Support

D. L. Hendrie, D. K. Scott, H. Wieman

The project provides assistance to experimental programs at the 88-inch Cyclotron. It maintains and oversees the use of common experimental equipment. It provides general purpose services and supplies. Especially, it provides information, assistance, and coordination of off-site experimental users of the 88-inch Cyclotron.

Specifically the project is charged with inventory, allocation, and maintenance of all electronic pool equipment, including analyzers, oscilloscopes, computers, NIM modules, etc. It also recommends acquisition of new equipment. It supervises, maintains, and prepares general purpose beam lines, scattering chambers and other ancillary equipment. It provides general services and supplies, such as liquid nitrogen, telephone service, and specialized computer and analyzer paper and tapes.

Secondly, it provides experimental assistance and coordination of off-site user groups. This often includes minor machine shop work, electronics and assistance, and some target fabrication.

* Additional funding provided under Nuclear Sciences: \$30,000.

LAWRENCE BERKELEY LABORATORY \$265,000*
Nuclear Science Division

Nuclear Fission

L. G. Moretto, G. Wozniak

The fast-paced activities of the last few years in the field of heavy ion reactions have now made quite clear that the interaction of two large ions provides the most powerful testing ground available as yet for the understanding of the large scale many body features of nuclear matter. In these collisions several collective degrees of freedom can be excited with excellent control of the initial conditions, and their relaxation towards equilibrium can be observed with dramatic clarity. As an example it will suffice to say that while the collective modes observed are the same as those involved in fission, we have learned more in four years of heavy-ion reactions studies than in almost forty years of fission research.

Our research activities, as in the past, continue to be oriented towards the experimental and theoretical characterization of the time-dependent processes associated with the collective modes excited in heavy-ion processes, where we believe we have had already a substantial impact.

The major lines of experimental work concentrate along the problems of the equilibration of rotational degrees of freedom, the characterization of fissioning nuclei at large angular momentum prepared by means of deep-inelastic collisions, the study of the damping of the E1 mode at high energies from the charge distribution of reaction products at fixed mass asymmetry and the test of the one-body dissipation mechanism. The rotational degrees of freedom are being studied by means of both γ -ray multiplicities associated with deep-inelastic collisions and by means of sequential fission. The concept of angular momentum fractionation along the mass asymmetry coordinate, predicted from our theoretical work is being verified as a dominant feature of the relaxation of rotational modes. The angular distributions of γ -rays and sequential fission fragments are being used to establish the degree of depolarization of the fragment spins as well as the source of the depolarization itself.

* Additional funding provided under Nuclear Sciences: \$45,000

LAWRENCE BERKELEY LABORATORY \$ 80,000
Nuclear Science Division

Relativistic Heavy-Ion Interactions

V. Perez-Mendez

We are continuing our experimental study of relativistic heavy-ion collisions to test various collision models and to look for possible collective effects such as the formation of shock waves or density isomers occurring in regimes of high nuclear density and/or temperature. We are presently making additional single particle inclusive measurements to find the upper limit in bombarding energy for which the projectile and target nuclear material merge.

In the near future we will be performing a series of correlation experiments to:

1. Measure the correlation between projectile and target fragments to further test whether the projectile nucleus is stopped by the target nucleus. This will establish upper limits for the densities achievable in relativistic heavy-ion collisions.
2. Measure the correlation between fragments very close in phase space. By measuring the correlation of identical particles as a function of relative momentum, we hope to learn the size, life time and possibly the density of the interaction region from which these fragments come.
3. We hope to also look for more exotic particles, such as K mesons. Since these "strange" particles do not interact enough to thermalize, they might provide an excellent probe with which to study the time evolution of the collision process.

Development of detectors and associated electronics will be undertaken in conjunction with the experimental program. This experimental program is carried out as a collaboration between our LBL group and the U.C.L.A. group of G. Igo. For some of the correlation experiments, we will also be collaborating with the BNL group of H. Palevsky.

LAWRENCE BERKELEY LABORATORY \$190,000
Nuclear Science Division

High-Energy Nuclear Reactions

A. M. Poskanzer, H. H. Gutbrod

The project is concerned with understanding the mechanisms of relativistic heavy ion reactions, particularly the effects due to high nuclear temperature and density. The experiments measure the energy spectra of light fragments (π^+ , p, d, t), heavy fragments, and fission fragments in ΔE -E telescopes of silicon and germanium detectors, or gas and silicon detectors. In addition, the multiplicity of charged particles associated with those fragments, is measured in an array of plastic scintillators surrounding the scattering chamber. This is done in order to sort out central from peripheral collisions.

Our first experiments obtained evidence for having produced high temperature nuclear matter, and we devised a "fireball model" to describe the results to first order. A completely new, more detailed set of experiments has been completed and is presently being analyzed. The following generation of experiments which are being planned, will consist of an array of ΔE -E telescopes constructed by partitioning a spherical shell of liquid argon.

LAWRENCE BERKELEY LABORATORY \$110,000
Nuclear Science Division

Nucleus-Nucleus Collisions

P. B. Price

A. Relativistic Nucleus-Nucleus Collisions: Two experiments that used Lexan plastic track detectors are being analyzed. Inclusive cross sections are being measured for production of fragments with charges from $Z = 5$ to 10 from the reaction $100 \text{ MeV/N } ^{40}\text{Ar} + \text{U}$ at lab angles 10° to 145° and fragments up to 100 MeV/N , thus providing a complete picture of the processes of projectile fragmentation and central collisions at intermediate energy. A search for new neutron-rich and proton-rich nuclei among the fragments of ^{40}Ar (and later ^{48}Ca) projectiles in conjunction with the Heckman 0° spectrometer is at the stage where the method has been demonstrated and evidence for several possible new nuclides is being assembled.

A classical many-body model of relativistic heavy-ion collisions with improvements over other models has been developed and shown to account quantitatively for inclusive proton production at all angles in numerous experiments.

B. Development and Theory of Nuclear Particle Detectors: Data is being analyzed from our recent scintillation experiment in which ~ 25 samples of liquid, plastic, and inorganic scintillators were exposed to beams of ^{20}Ne , ^{40}Ar and ^{56}Fe at energies between 0 and 600 MeV/N . The experiment promises to yield information relating to the pure molecular and solid state aspects of the scintillation process (energy migration and quenching mechanisms) in addition to that regarding the behavior of scintillators as would be of interest to experimental nuclear and astrophysicists.

C. Energy Loss by Heavily Ionizing Particles: Our recent achievements in this area include theoretical and experimental work demonstrating the existence of higher order contributions to the stopping power of relativistic heavy ions as well as the completion of a comprehensive review article to be published in Reviews of Modern Physics. We have also examined the properties of the diffraction radiation emanating from microscopic crystalline grains in response to relativistic heavy ions and have shown that it consists predominately of pure Cerenkov radiation.

D. Future Experiments: We plan a search for high-energy gamma rays from $2 \text{ GeV/N Fe} + \text{U}$ resulting from nuclear bremsstrahlung as well as from neutral pions. With $\sim 200 \text{ MeV/N}$ beams of ^{40}Ca and ^{48}Ca we will search for exotic nuclides far from stability. We plan direct measurements of multiple Coulomb scattering by relativistic heavy ions and a study of higher-order contributions to Cerenkov radiation.

LAWRENCE BERKELEY LABORATORY \$165,000
Nuclear Science Division

Heavy-Ion Collisions and Pion Studies

J. O. Rasmussen

The main experimental effort of the group involves study of low-energy pions as a probe of relativistic collisions of complex nuclei. This Bevalac study involves collaboration with scientists from Japan and from Michigan State University. We have observed interesting structure in π^+ inclusive spectra from 800 MeV/A Ne beams, structure that indicates shadowing effects and a fast time scale for pion emission. Next will be pion interferometry experiments that may be an indicator for the phase transition, pion condensation. The spectrometer will involve four wire chambers of three plans each with a large 1.8 meter pole face magnet with 20cm gap. It combines our equipment with Professor Crowe's brought back from LAMPF. The spectrometer with its large acceptance ~ 20 msr and large dynamic range in momentum should prove quite versatile. It can, for example, also be used as a high resolution pair spectrometer for gamma rays. It can also be used to view the region a short distance downstream of the target, picking up hyperfragment decay radiation. The theoretical studies of the group primarily now are on heavy ion collisions, in support of the experimental effort.

LAWRENCE BERKELEY LABORATORY \$320,000
Nuclear Science Division

Heavy-Ion Radiochemistry

G. T. Seaborg

The scope of this program is the synthesis and identification of superheavy elements using heavy-ion reactions, and the study of the mechanism of low and relativistic energy heavy-ion reactions using radiochemical techniques combined with high-resolution gamma-ray and x-ray spectrometry. The project can be summarized as having three main objectives: (1) Attempts at the synthesis and identification of superheavy transactinide elements, and new isotopes in the actinide region, with radiochemical techniques and using heavy ion reactions using the fusion and deep inelastic transfer mechanisms; (2) The study of heavy ion reactions in order to advance the understanding of mechanisms of the various types of reactions (fusion, fusion-fission, deep inelastic, quasi-elastic, etc.). Progress in the latter will also help determine reasons for success or failure in the former; (3) The study of the mechanisms involved in relativistic heavy-ion reactions involving heavy targets. Measurements of the target residue mass, charge and momentum distributions can yield information about the relative importance of various reaction mechanisms and in the case of the heavy reaction products provide unique information about processes leading to their formation.

The intent is to continue to build up a radiochemical effort at LBL, a powerful method for identifying new elements, investigating the mechanism of nuclear reactions and the nuclear properties of short-lived isotopes, and studying the chemical properties of rare, known elements. The results to date confirm that this is a powerful technique, capable of making substantial contributions to the chemistry and physics of heavy-ion reactions.

LAWRENCE BERKELEY LABORATORY \$180,000
Nuclear Science Division

Experimental Nuclear Science

L. S. Schroeder

The group is involved in high-energy heavy-ion nuclear science research using the Bevatron/Bevalac Facility. This work is often performed in collaboration with other groups at LBL as well as other institutions (U.S. and foreign). Research activities involve the use of standard electronic techniques, and electronics combined with visual techniques to study high-energy heavy-ion nuclear interactions in the LBL streamer chamber.

Since the acceleration of nuclear beams at the Bevatron in the early 1970's, we have been actively involved in nuclear science research, including some of the earliest work on single-particle inclusive spectra. Recent work has included: the production of high energy fragments (π, p, d, t) at 180° by a variety of projectiles (p, α, C, Ar); particularly at energies either forbidden or highly constrained for free nucleon-nucleon collisions, use of the LBL streamer chamber to study $\pi\pi$ correlations in central collisions of equal mass target and projectile and studies with proton beams to understand more fully the pA process, and projectile fragmentation studies between 50 and 125 MeV/nucleon to study the transition region between 88" Cyclotron and Bevalac energies. The majority of our experiments involve one or more graduate students and most experiments can form the basis for a thesis. The group is involved in both the scientific planning and technical aspects of the Heavy Ion Spectrometer System (HISS) which will be built at the Bevalac.

LOUISIANA STATE UNIVERSITY \$ 66,500
Department of Physics and Astronomy

A Study of the Two-Body Dissociation of Light Nuclei in Nuclear Fields

P. M. Kirk, R. W. Huggett

The objective of the experiment is to measure the cross sections for the dissociation of light nuclei into two-body nuclear final states during peripheral nuclear collisions at relativistic energies. The cross section for dissociation into a specific two-body nuclear final state is proportional to the square of the probability that the projectile nucleus existed as a configuration of the two final state nuclei at the time of collision. The results will be of significance to cluster models of nuclear structure.

The nuclide of principal interest is ${}^6\text{Li}$ because it has long been regarded as a test case for cluster theories. The kinetic energy of the ${}^6\text{Li}$ projectiles will be 12 GeV. Those interactions in which the projectile nucleus dissociates into two fragments within the target will be selected electronically and recorded on magnetic tape for analysis. The measured quantities will include the trajectories and charges of the incident nucleus and both final state nuclei. The momenta of both final state nuclei will be deduced from their bending angles in a magnetic field of 38 kG-m. Wire spark chambers with magnetostrictive readout will be used to encode the positions of projectile and final state nuclei. Charges will be measured in scintillation counter hodoscopes.

The first stage of data acquisition was completed in January 1978, and initial reports of results are now in preparation. Clear signals have been observed in the dominant channel, ${}^4\text{He}-{}^2\text{H}$, and also in other channels such as ${}^3\text{He}-{}^2\text{H}$ which imply the removal of a nucleon from the projectile.

LOUISIANA STATE UNIVERSITY \$ 30,000
Department of Physics

The Structure of Nuclei Far From Beta Stability

E. F. Zganjar

Studies on nuclei far from the line of beta stability is the central aspect of the research. The work is primarily involved with neutron-deficient nuclei produced at the Oak Ridge Isochronous Cyclotron (ORIC) and mass separated, prior to spectroscopic analysis, by the UNISOR isotope separator which is operated on-line to the cyclotron. The underlying objective of the experiments is to test and refine the concept of a particle or hole moving in a moderately deformed and possibly triaxial potential; and in this way to ultimately examine the spherical to deformed and prolate to oblate types of transitions of the core nucleus. The past work has centered on the neutron-deficient nuclei near $Z=82$. Similar studies are proposed for nuclei in the $Z=50$ region. A number of isotopes under investigation at UNISOR are also being studied by in-beam gamma-ray and conversion electron spectroscopy in order to determine their high-spin structure.

UNIVERSITY OF MARYLAND \$ 77,000
Department of Chemistry

Studies of Heavy-Ion Induced Nuclear Reactions

V. E. Viola, Jr.

This is a continuing program for the study of heavy-ion nuclear reaction mechanisms. The research is conducted at the Lawrence Berkeley Laboratory SuperHILAC and 88-inch cyclotron in collaboration with groups from the University of Rochester and Argonne National Laboratory. Major goals of these studies are (1) to understand the energy dissipation process in strongly-damped collisions and (2) to characterize the mechanism(s) of reactions induced by light heavy ions with energies up to 20-MeV/nucleon.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY \$526,000
Laboratory for Nuclear Science

Heavy-Ion Nuclear Physics Research

H. A. Enge, L. Grodzins, E. R. Cosman, A. Sperduto, S. G. Steadman

The objective of the research is to understand in detail the varied processes by which complex nuclei interact, and thereby, to gain new insights into nuclear structure, to create and study new nuclear species, and to develop appropriate detection techniques necessary for future investigations in this area. Processes of interest when two nuclei collide are, for instance, formation of a compound system by way of unusual short-lived states resembling a molecule, inelastic collisions leaving both members heated up as a result of surface friction, brief coalescing of the two nuclei with subsequent fission into two massive fragments or fragmentation into many pieces, or compound nucleus formation with subsequent de-excitation by few-nucleon emission. In the latter process, isotopes not accessible by other means can be synthesized and studied. The experience gained and techniques developed in the above studies will be important for the ongoing search for new transuranic elements.

The research of the Heavy Ion Group is performed principally at the Tandem Facility of the Brookhaven National Laboratory and at the Lawrence Berkeley Laboratory. There is also an ongoing collaboration with the University of Rochester, with experiments performed at both Rochester and at BNL. All of the work at Berkeley and the heavy-ion induced fusion work at Brookhaven are collaborative efforts with resident physicists. A time-of-flight spectrometer was installed by our group at the 88" cyclotron at LBL. Further extensive development of the energy-mass spectrometer is proceeding at BNL. We are presently heavily involved in the design and implementation of the Recoil Mass Spectrograph on the SuperHILAG at LBL and in the design of such a spectrometer at the Holifield Heavy-Ion Research Facility of the Oak Ridge National Laboratory.

STATE UNIVERSITY OF NEW YORK (STONY BROOK) \$106,000
Department of Chemistry

Nuclear Reaction Studies

J. M. Alexander

This proposal involves a continuation of studies of reactions between complex nuclei. The experimental attack which utilizes heavy-ion beams from the SuperHILAC and 88-inch Cyclotron at Berkeley, has recently emphasized the detection of H, He and heavier fragments such as evaporation residues or fission products. Reactions that proceed through the compound-nucleus mechanism have been used to systematize the decay of various equilibrated nuclei as a function of energy and spin. This information is then used in the study of deeply-in-elastic collisions that occur between very heavy nuclei. In parallel to the experimental work, the statistical model has been parametrized, for the nuclei studied, by fits of theoretical calculations to measured cross sections and energy spectra. Also the potential between complex nuclei has been explored by a series of calculations that address cross sections for elastic scattering, fusing collisions, and other reactive collisions.

OAK RIDGE ASSOCIATED UNIVERSITIES \$150,000

UNISOR, University Isotope Separator Oak Ridge

E. H. Spejewski, H. K. Carter, R. L. Mlekodaj

UNISOR is a cooperative effort of 14 institutions and the DOE designed to provide forefront research opportunities for a large group of scientists in a way that makes efficient and economical use of their own university resources and the resources of the federal government. This research program is based on an on-line isotope separator which is part of the ORIC accelerator facility of Oak Ridge National Laboratory. The primary purpose of the consortium is the investigation of nuclear structure in the region far from the line of beta stability by means of a unique experimental facility. At present, this facility provides research opportunities for approximately 40 scientists and students from the 14-member institutions, as well as for scientists from other laboratories and universities.

OAK RIDGE NATIONAL LABORATORY \$650,000
Chemistry Division

Nuclear Chemistry; Nuclear Reactions & Structure

R. L. Hahn, J. R. Beene, C. E. Bemis, R. L. Ferguson, N. R. Johnson,
B. H. Ketelle, G. D. O'Kelley

The heavy-ion program has focussed on areas that are among those being most intensively explored in nuclear science today:

1) Synthesis, characterization and identification, by determination of atomic and mass numbers, of isotopes of the heaviest elements. While the development of definitive identification techniques has been a major part of this effort, current interest in the spontaneous fission properties of the transactinides, elements 104 and above, has led to studies of details of the fission process such as total kinetic energy and mass distributions.

2) Studies of the mechanisms of nuclear reactions induced by heavy ions, with particular attention to reactions involving large excitation energies and high angular momenta. Measurements include such techniques as a) in-beam determinations of the charges, masses, energies and angles of reaction products, and γ -ray multiplicities, and b) out-of-beam determination of radioactive recoil nuclei. Information on complete fusion and deep-inelastic processes provides knowledge particularly of fundamental macroscopic properties of nuclei such as energy dissipation, inertial parameters, nuclear shapes at high angular momenta and transport phenomena. Study of the quasi-elastic process provides a link between these macroscopic descriptions of heavy-ion reactions and microscopic theories.

3) Investigations of the rotational and vibrational behavior of states in deformed nuclei, such as the actinides and lanthanides. Experiments involving Coulomb excitation, lifetime measurements, isotope shifts due to hyperfine interactions, and nuclear reaction γ -ray production are used to probe the static and dynamic properties of nuclear matter, and to explore, in particular, properties of high-spin nuclear states, such as "backbending".

4) A new aspect of the program involves laser-nuclear spectroscopic investigations of short-lived nuclides produced in heavy-ion reactions. The optical pumping LINUP technique (Laser-Induced Nuclear Polarization) is being applied at the one-atom level to yield fundamental information for the heaviest elements relevant to such questions as nuclear deformation and the ordering of atomic energy levels.

The expertise gained in these areas of heavy-ion nuclear science is relevant to the development of the Holifield Heavy-Ion Research Facility at Oak Ridge.

OAK RIDGE NATIONAL LABORATORY \$1,740,000
Physics Division

Heavy-Ion Nuclear Physics

P. H. Stelson, J. K. Bair, J. B. Ball, J. Beene, F. E. Bertrand,
J. A. Biggerstaff, J. L. C. Ford, Jr., C. B. Fulmer, J. Gomez del
Campo, C. D. Goodman, E. E. Gross, M. L. Halbert, D. C. Hensley,
C. M. Jones, H. J. Kim, I-Y. Lee, F. K. McGowan, W. T. Milner,
F. E. Obenshain, F. Plasil, R. L. Robinson, R. G. Stokstad, K. S.
Toth

The general aim of nuclear research with heavy-ion beams is to increase our knowledge and understanding of the behavior of nuclear matter at ever increasing conditions of excitation, angular rotation, volume distortion, nuclear density, and neutron-to-proton ratio. New knowledge is generated primarily by experiments with beams from the Oak Ridge Isochronous Cyclotron (ORIC) and occasionally by experiments at other heavy-ion facilities. Understanding comes from analyses of the data within the framework of an appropriate nuclear model--e.g., statistical model, collective model, shell model, hydrodynamical model, optical model, etc.--depending on the aspect of nuclear behavior under study. The many nuclear models testify to the richness and complexity of nuclear phenomena. This richness is reflected in a broad research program which may be categorized by the following areas:

I. Macroscopic Nuclear Physics

The scope of experimental research in macroscopic nuclear physics is to obtain information on fundamental gross properties of nuclei such as potential energies, energy dissipation, inertial parameters, nuclear shapes at high angular momenta and transport phenomena. This information is obtained by means of studies of the full range of heavy-ion reactions, from fusion and fission, to deeply-inelastic and quasi-elastic collisions. Studies of evaporation residue products resulting from fusion of complex nuclei provide information on the fission barriers of systems with very high angular momenta, as well as on the statistical characteristics of the de-excitation of compound nuclei at high excitation energies and angular momenta. From the results information is extracted on such nuclear properties as moments of inertia and level densities. Projectiles used range from C to Kr, and targets from C to rare earth region. These studies involve the use of the time-of-flight system and two scattering chambers at ORIC and similar facilities at the Lawrence Berkeley Laboratory.

In addition to heavy-ion-induced fission, heavy ion reactions are used to synthesize exotic nuclei such as $^{262}_{105}$ which undergo spontaneous fission. Studies of mass and energy distributions from the

OAK RIDGE NATIONAL LABORATORY

Heavy-Ion Nuclear Physics

fission of these transplutonium nuclei provide information on the influence of shell effects on the potential energy surface.

II. Microscopic Nuclear Physics

A complete understanding of nuclei requires information such as: the excitation, spin values, and other parameters of their energy levels; transition rates for excitation and de-excitation of these levels; the parameters specifying the shape of the nucleus; and the interactions responsible for the reactions produced by colliding nuclei. Such information can lead to the microscopic description, in terms of the wave functions involved, of nuclear structure and nuclear reactions which is the goal of all physical sciences. However, such detailed information must result from experiments in which individual reaction processes are isolated, the different reaction products identified in both atomic number and mass, and discrete energy levels populated within the nucleus. Angular distributions and excitation functions provide information on resonant structure, intermediate structure, highly excited high-spin states, as well as the responsible reaction mechanisms. A broad-range spectrograph and a 30" scattering chamber, both outfitted with advanced detector systems are employed to obtain this information. Inelastic scattering with heavy ions has proven to be a powerful tool for investigating nuclear shape parameters. In heavy ion reactions from one to many nucleons can be transferred, and can emphasize nuclear structure effects of either single-particle behavior or many nucleon correlations. Most of the above phenomena are not well understood and will need further study with higher energy and heavier projectiles than presently available. Furthermore, many of the macroscopic effects now being uncovered in heavy-ion research, such as the oscillations observed in excitation functions for fusion, will probably require more microscopic analysis for their explanation. In the future, the new tandem facility now under construction at ORNL, with its precise energy variation and well-collimated high resolution beams of heavy ions, will be admirably suited for this research.

III. Spectroscopy of Nuclei at High Spin and High Excitation

Observation of γ -rays emitted in the last stages of nuclear de-excitation has taken an important place in the last few years for investigations of reaction mechanisms. Basically two approaches have been used. In the first, specific final products are identified by their characteristic radiation. The other approach measures the number and energy of γ -rays to reveal the energy and angular-momentum distributions of the nuclei

OAK RIDGE NATIONAL LABORATORY

Heavy-Ion Nuclear Physics

following particle decay of the composite system. In many experiments both techniques are combined; in others, charged particles and/or neutrons are observed in coincidence. Such measurements give a more nearly complete picture than previously available of the disposition of the large quantities of angular momentum and energy involved in heavy-ion reactions. The same techniques are immensely valuable when applied to spectroscopy of high-spin nuclei since they decay by very long cascades of γ -ray multiplicity (involving as many as 15 γ -ray detectors) and/or high total γ -ray energy will emphasize the transitions de-exciting these interesting states.

IV. Nuclear Instrumentation

The above research programs place heavy demands on instrumentation. Heavy-ion collisions produce a multitude of reaction products with varying masses, atomic numbers, and charge states. Distinguishing these different products requires that the energy and other parameters specifying a particle be measured with good resolution. Furthermore, the small cross sections involved place a premium on apparatus having a large solid angle capable of multiparameter and coincidence measurements. These difficult, and sometimes conflicting, requirements of heavy-ion research mean that imaginative, new concepts in instrumentation are needed in order to exploit the full capabilities of the new heavy-ion accelerators. Examples under design or consideration include: very large two-dimensional x-y detectors capable of measuring parameters such as the total energy and the energy loss as well as the position of the detected particle; precise time-of-flight apparatus; very large solid angle magnetic spectrographs; velocity filters together with a sea of other particles; and apparatus for simultaneous detection of many gamma rays and neutrons or charged particles.

OREGON STATE UNIVERSITY \$ 8,147
Department of Chemistry

Radiochemical Studies of Low-Energy and Relativistic Heavy-Ion
Reactions.

W. D. Loveland

Radiochemical techniques are used to measure product mass, charge, angular and momentum distributions for the interaction of low-energy (< 10 MeV/amu) and relativistic heavy ions (RHI's) with medium and heavy nuclei (Ag-U). Amongst the problems pursued in low-energy research is the "calibration" of isomer ratios for measuring angular momentum in heavy-ion reactions, the measurement of complete fusion cross sections for magic and non-magic systems (such as $^{40}\text{Ca} + ^{208}\text{Pb}$) and in symmetric heavy-ion reactions. In the RHI studies, we seek to delineate the reaction mechanisms contributing to the heavy target residue yields from the interaction of 8-43 GeV ^{20}Ne with Ta and V and to explore the use of RHI reactions as probes of ground-state correlations in nuclear matter.

PURDUE UNIVERSITY \$ 10,000
Department of Chemistry

Deexcitation Processes in Nuclear Reactions

N. T. Porile

The objective of this project is an elucidation of the mechanisms of importance in the interaction of relativistic heavy ions with complex nuclei. Measurements of the charge dispersion and mass-yield curve for the interaction of 2.1 GeV/n ^{12}C ions with silver have been performed. The results are compared with similar data obtained for high-energy protons. The main difference between these projectiles lies in the enhanced yield of light fragments in ^{12}C reactions. The dependence of this enhancement on target Z is presently being investigated.

UNIVERSITY OF ROCHESTER \$102,264
Nuclear Structure Research Laboratory

Nuclear Reaction Mechanisms

M. Blann

This program mainly involves work on the physics of heavy-ion reactions. It emphasizes highly precise experimental measurements of heavy-ion reaction products carried out using accelerator facilities at Rochester and Brookhaven and the LBL SuperHILAC. It also includes theoretical investigations which are relevant to the understanding and interpretation of those experimental data. Additional investigations of precompound decay involving emission of clusters in the medium-energy region may also be undertaken.

Some of the topics under investigation are the following: nucleus-nucleus potentials; fission at high angular momenta; precompound decay during fusion; mass and charge yields for Ar and Kr induced fission; quasielastic and quasifission reactions; statistical analysis of HI reactions with explicit angular momentum dependence; and sub-barrier fusion excitation functions.

UNIVERSITY OF ROCHESTER \$140,167
Nuclear Structure Research Laboratory

Studies of Heavy-Ion Reactions and Transuranic Nuclei

J. R. Huizenga

Our research program in heavy-ion reactions aims to understand the nucleon exchange and energy-damping processes occurring during a heavy-ion collision. Classical and statistical concepts are applied to experimental distributions in E , θ , Z and A in order to achieve a phenomenological analysis of various heavy-ion reactions as a function of the projectile and target charges and masses, bombarding energy and impact parameter (or angular momentum). Results indicate that the kinetic-energy loss reflects the reaction stage or interaction time. Measurements of fusion cross sections for heavy-ion systems at high energies where the excitation functions are falling have been initiated in order to test a dynamical model of fusion developed during this past year. The light particles (n, p, α) emitted from the heavy residual fragments during the deexcitation process also carry important information on the heavy-ion reaction mechanism. Preliminary measurements of the energy spectra and angular correlations of these neutrons indicate that at energies a few MeV/amu above the Coulomb barrier, thermal equilibration is achieved during the reaction time.

UNIVERSITY OF TENNESSEE \$ 43,000
Department of Physics

Nuclear Spectroscopic Studies

C. R. Bingham, L. L. Riedinger, M. W. Guidry

The proposed research involves studies of nuclear structure by a variety of techniques with experimental data obtained at several heavy-ion accelerators, principally the ORIC cyclotron facility. Experimental data will be obtained from 1) on-line mass-separated radioactive sources produced at UNISOR, 2) observation of prompt γ -rays from products of (HI,xn) reactions, 3) prompt and delayed γ -rays following Coulomb and nuclear excitation of target nuclei, 4) observation of delayed α -particles from recoiling reaction products, and 5) direct measurement of energy spectra of reaction products. The decay and in-beam γ -ray studies will give information on states of nuclei far from β -stability. These level structures will be interpreted in terms of various nuclear models, incorporating the characteristics dependent on one or a few nucleons with the collective degrees of freedom of the nucleus. Excitation functions for inelastic scattering to high-spin states in very deformed nuclei will provide a sensitive technique to determine the nuclear scattering (optical) potential, as obtained from a classical-limit S-Matrix theory. The possible α -decay of yrast traps (high-spin isomers) in the $A = 150$ mass region will be investigated. The low-energy nuclear structure of the nuclei suspected to have yrast traps will be investigated through radioactive decay studies in order to better understand the underlying nuclear structure leading to the formation of yrast traps.

TEXAS A&M UNIVERSITY \$ 57,000
Cyclotron Institute

Angular Momentum Effects in Nuclear Reactions

J. B. Natowitz, M. N. Namboodiri

Heavy-ion projectiles have been used to probe the mechanism of nuclear reactions and the properties of nuclei with high angular momenta. Gamma-ray multiplicities and average gamma energies associated with the products of completely damped collisions of 237-MeV ^{40}Ar with ^{89}Y have been determined and the angular momenta of the primary heavy fragments have been extracted from the results. The multiplicities of H and He nuclei emitted during the deexcitation of the complete fusion products in the system 120-MeV $^{20}\text{Ne} + ^{27}\text{Al}$ have been measured and compared with the results of statistical model calculations. As part of a program to study the mechanism of reactions at ~ 20 MeV/amu the emission of light charged particles in the deep inelastic and fusing collisions of 310-MeV ^{160}O with Ti has been investigated in heavy fragment-light particle coincidence experiments. In a collaboration involving LASL, LBL, ORNL and TAMU, work has been continued on a study of new neutron rich nuclei produced in the reactions of 800-MeV protons on various targets.

TEXAS A&M UNIVERSITY \$ 74,000
Cyclotron Institute

Nuclear Spectroscopy with Heavy Ions

T. T. Sugihara, D. R. Zolnowski

The general motivation for this project has been to study collective excitations in nuclei. The emphasis in recent years has been (1) on nuclei soft to deformation since these nuclei are the most difficult to describe in a microscopic model and (2) on high-spin states in deformed nuclei. Very recently an interesting new way to excite high-spin states selectively has been discovered, leading us to concentrate on (3) "massive transfer" in heavy-ion reactions.

Our studies of types (1) and (2) have used all of the standard methods of in-beam and out-of-beam spectroscopy with γ -ray and conversion-electron spectrometers. In the latter case we have developed methods of obtaining conversion-electron spectra of recoil nuclei; such spectra are of much higher quality than those typically obtained by in-beam methods. Initial application has been to the study of delayed states in even-even Po nuclei. The results of many experiments of type (1) have been analyzed in context of the boson-expansion method of Kishimoto and Tamura to obtain a microscopic solution to the collective Hamiltonian. This model, although nearly parameter-free, has accounted very well for energies of states and transition rates in transitional nuclei lying between the 82-neutron shell and the onset of deformation.

It has long been known that fast α particles (well above the Coulomb energy) are produced in large yield in the forward direction when heavy ions are used as the projectile. A γ -ray spectrum taken in coincidence with these fast α particles shows that the remainder of the incident heavy ion frequently fuses with the target nucleus, forming a compound nucleus which then deexcites in the usual way. These reactions have been called massive transfer reactions because (a) they occur over a rather narrow range of impact parameters at radii corresponding to a surface reaction and (b) a massive fraction of the incident heavy ion is transferred to the target nucleus. This type of reaction is found to occur with a variety of target nuclei in the rare earth region, with incident heavy ions ranging from ^{10}B to ^{20}Ne , and over a wide range of bombarding energy. Cross sections are typically in the range of 100 mb. The mechanism of the reaction is currently under study as well as the possible use of this type of reaction to excite a relatively narrow range of spin states in a controlled way.

VANDERBILT UNIVERSITY
Department of Physics

\$100,000

Experimental Nuclear Physics Research

J. H. Hamilton, C. F. Maguire, A. V. Ramayya

This continuing research program has activities planned in the following areas: (1) In-beam gamma ray studies at the ORNL EN tandem and the ORIC cyclotron facility. There are plans to build an on-line conversion electron detector system to assist in assigning parities and spins to nuclear energy levels. (2) Nuclei far from stability. The n-deficient Hg and Tl isotopes will continue to be examined at the UNISOR facility hopefully down to ^{182}Hg . Calculations indicate that this isotope should be deformed in its ground state. Collaborative work with groups in Delft, Netherlands and Heidelberg is planned. Feasibility studies on the production of n-rich isotopes by the (HI, fission) reaction using the new HHIRF tandem are also planned. (3) Coulomb excitation studies at ORNL and SuperHILAC. (4) Heavy-ion transfer reactions. This will be a continuation of single nucleon transfer reactions. A new program will be (5) Neutron-capture γ -ray studies at ORELA.

WASHINGTON UNIVERSITY, ST. LOUIS \$ 80,000
Department of Chemistry

Investigations of Nuclear Structure and Nuclear Reactions Induced
by Complex Projectiles

D. G. Sarantites

This research is aimed at advancing our understanding of nuclear interactions among heavy-ions at energies above ~ 5 MeV/nucleon. The experimental program is carried out primarily at the ORIC cyclotron facility at Oak Ridge. There are essentially three major areas of interest: (a) Mechanism of fusion reactions. In particular, here we ask the question what is the path that leads to fusion and how is the decay of the compound nucleus so formed influenced by excitation energy and angular momentum; (b) Mechanism of strongly damped collisions between heavy ions. Here we ask the question what is the relative importance of incident energy, angular momentum and Coulomb energy in the outcome of the reaction and how do the separating fragments dissipate their energy and angular momentum; and (c) Selective investigations aimed in obtaining information on the structure and properties of nuclei at very high angular momenta. In this case we are interested in developing techniques that will permit utilizing our present knowledge of nuclear reaction mechanisms in order to prepare and investigate the decay properties of nuclei at angular momenta upward of $30\hbar$ units

UNIVERSITY OF WASHINGTON \$320,000
Nuclear Physics Laboratory

Heavy-Ion Physics Research

R. Vandenbosch, J. G. Cramer

The purpose of this program is to study the interactions of complex projectiles with a broad spectrum of target nuclei. These interactions may be either nuclear or atomic.

A major fraction of the laboratory effort goes into studies of nuclear reactions induced by relatively light heavy ions produced with our two or three stage tandem Van de Graaff. Among the questions being addressed, we here mention: How strong is the attractive potential between two nuclei? What factors control absorption in the region of the nuclear surface? What lies behind the observation of "resonances" in the elastic scattering from other light nuclei? Why does the fusion cross section exhibit gross structure resonances with twice periodicity expected from the role at which new partial waves start contributing? What wave equation is appropriate to the description of heavy ion scattering and reactions? As our understanding of reaction mechanisms becomes more firm, heavy-ion reactions can provide a tool for studying nuclear structure.

Another component of our heavy-ion program deals with the interactions of very heavy projectiles (Fe, Kr, Xe) with heavy targets. These studies are performed using the SuperHILAC at the Lawrence Berkeley Laboratory. Some of the questions we are attempting to answer in these studies are: Under what circumstances do the target and projectile fuse? In the large fraction of interactions where they do not fuse, what are the mechanisms responsible for the large energy losses (deeply-inelastic scattering)? To what extent are particles transferred in these deeply-inelastic reactions? How does this depend on the mass and charge asymmetry in the entrance channel? What is the angular momentum deposition in the reaction products? How well aligned is this angular momentum? What is the deexcitation process for the excited products? The answers to these questions will help us to understand the dynamics of the interaction between two large nuclei, the projectile and the target.

YALE UNIVERSITY \$465,000*
A. W. Wright Nuclear Structure Laboratory

Fundamental and Applied Research in Nuclear Physics

D. A. Bromley, C. K. Bockelman, J. S. Greenberg, P. D. Parker,
R. Betts, K. Erb, W. Lanford

This activity covers a very broad spectrum of activity spanning the nuclear sciences and centers on utilization of our upgraded MP tandem accelerator. Substantial activity is reported in interface fields including nuclear astrophysics, high energy atomic physics, particle surface interactions and materials science. The program ranges from basic studies on the equivalence principle in general relativity, the validity of the conserved vector current hypothesis in light nuclei and the quantum electrodynamics of high fields through more standard nuclear physics topics including the structure of both light and heavy nuclei, the mechanisms (particularly higher order) of nuclear transfer reactions and inelastic scattering, precision study of heavy ion induced reactions, nuclear molecular phenomena, deep inelastic scattering and fusion, high angular momentum effects and coupling between single particle and collective degrees of freedom, to extremely applied topics including the role of hydrogen in amorphous silicon for solar cells, the behavior of potential fusion reactor inner wall materials under ionic bombardment, the dating of both natural and manmade glasses, the controlled modification of superconductor transition temperatures and the study of the stability of potential nuclear waste solidification matrix materials. In all cases full advantage is taken of nuclear techniques, concepts, and devices.

Some 80% of the program utilizes ion beams of mass heavier than lithium and 20% lighter than lithium.

* Additional funding provided under Nuclear Sciences: \$238,000.

HEAVY ION NUCLEAR PHYSICS - OPERATIONS

(HK 03 02 02)

Includes all costs incurred in the heavy-ion operation of machines and facilities (for such items as salaries and wages of the operating staff, power, supplies and equipment not meeting capitalization criteria, maintenance and repairs, etc.) used for nuclear research.

ARGONNE NATIONAL LABORATORY \$520,000
Physics Division

Operation of the Tandem-Linac Accelerator

G. T. Garvey, P. R. Fields, L. M. Bollinger, J. L. Yntema

This activity is concerned with operating the tandem-linac accelerator system for nuclear physics research. Prior to FY 1978, the facility consisted of a 9-MV tandem Van de Graaff and its associated experimental system, which was operated continuously, seven days a week. During 1978 major changes were made to the tandem in order to adapt it for the heavy-ion beam requirements of the superconducting linac booster; as a result the tandem was used for research only ~50% of the time. The following changes were made: (1) a new NEC high-vacuum accelerator tube was installed, with magnetic electron traps and its own separate corona voltage-distribution system; (2) all vacuum components in the accelerator were replaced with organic-free materials; (3) a 150-kV injection system was constructed; (4) the optics of the low-energy beam line were redesigned and a new line with organic-free vacuum components was built incorporating the harmonic buncher required for the linac.

This system functions very satisfactorily, for both stand-alone research and the linac, and indeed accelerates heavy-ion beams with excellent transmission. The Argonne tandem is the first major electrostatic accelerator in the U.S. to operate with the NEC accelerator tubes, and a number of other new developments of NEC electrostatic accelerator technology.

Starting in mid-1978, an important function of the tandem is to serve as the injector for the superconducting-linac energy booster. In the initial operation in this new mode, the main emphasis was on study of the linac itself and the linac was operated and maintained by the development team. However, during the next year the tandem crew will gradually assume increasing responsibility for linac operation.

BROOKHAVEN NATIONAL LABORATORY \$1,415,000
Physics Department

Tandem Van de Graaff Facility Operations

N. P. Samios, M. Blume, C. Chasman, M. LeVine, P. Thieberger,
C. Thorn, H. Wegner

The BNL Tandem Facility is at present the most powerful electrostatic accelerator facility in the world. The great versatility and precision of this class of accelerator, together with BNL's uniquely high energies and large variety of light and heavy-ion beams, make this facility a very important physics research tool.

The Tandem Facility includes the two MP Tandem Van de Graaff accelerators, the additional apparatus required for their operation and maintenance, and the major pieces of auxiliary equipment that form the experimental facility. This auxiliary experimental equipment includes the Tandem Computing Facility, and large-scale experimental equipment such as magnetic spectrometers, scattering chambers, and gamma-ray goniometers. In addition to the operations staff, the research staff also contributes to the growth of the overall capability through continuing contributions to the design and development of equipment.

The two Tandem accelerators can be used either separately or in a coupled mode in which one of the MP's, MP-6, injects an accelerated beam into the other, MP-7, to obtain the highest energies. Extensive improvements of MP-7, implemented in 1977, led to beam energies which, even for this single accelerator, exceed the capabilities of any other tandem now operating, including the ones which are somewhat larger than the model MP. Several of these improvements are original BNL developments which have now been adopted by other laboratories and by the High Voltage Engineering Corporation (HVEC), the manufacturer of these accelerators.

Scientists from many universities working independently or in collaboration with Brookhaven scientists conduct their research at this Facility. During the past year, 36 physicists and 19 students from ten U.S. universities, and 18 visitors from Europe, Israel, and South America received beam time. In addition, there were 8 users from other U.S. laboratories and from industry. All users enjoy around-the-clock professional operation of the accelerators, full use of experimental equipment, and technical assistance.

Development of the machines to further improve operation and to increase the variety of heavy ions available, especially in the three-stage mode, is a necessary and continuing process. The development of the auxiliary equipment to enlarge the full capability of the facility is an important part of the effort. The nature and direction of developments are determined by the needs of the total research community.

An active planning and development program is being conducted to study the addition of a further acceleration stage to the Facility. A considerable fraction of the available R and D funds are used for this purpose. Different types of accelerators were considered and it was concluded that a cyclotron would provide the best capabilities in terms of energies, beam quality, and versatility. The final energies would be increased by as much as ten or twenty times, opening many new and important areas of research.

LAWRENCE BERKELEY LABORATORY \$9,040,000*
Accelerator and Fusion Research Division

Operation of Bevalac/SuperHILAC as a National Facility for Nuclear Physics

E. J. Lofgren, H. A. Grunder, F. B. Selph, J. Alonso, T. Criswell,
J. Howard, H. Kim, B. Leemann, C. Leemann, J. Staples

The SuperHILAC and the Bevatron/Bevalac are operated as National Research Facilities for studies in nuclear physics, biophysics, nuclear chemistry, biomedical studies and astrophysics. Ions from carbon to lead are accelerated to energies up to 8.5 MeV per nucleon at the SuperHILAC. With now standard time-share operation, beams of two different ions can be produced on alternate pulses and delivered to one or two experimenters and the Bevalac. Currently, beams as heavy as iron are accelerated for researchers at the Bevatron/Bevalac at energies up to 2.5 GeV per nucleon. Operation of the two accelerators requires continual improvement in machine and experimental facilities to remain at the cutting edge of scientific inquiry.

The Bevatron/Bevalac and SuperHILAC are relied upon as unique research tools by an international community of users. Besides opening exciting regions for nuclear physics studies, the Bevatron/Bevalac provides the only source of experimental cosmic rays for NASA's astrophysics work. The promising application of these same heavy ion beams for cancer therapy is evaluated here in programs sponsored by DBER in DOE and by the National Cancer Institute. About half the on-target beam time serves LBL users from the Nuclear Science, the Biomedical and Environmental Research, and the Physics Divisions. The remainder is devoted to work for some three dozen other institutions. Cross-fertilization of research ideas has supported such productive projects as heavy-ion induced fusion and compact dedicated-medical accelerator design.

Operating efficiency, and resulting on-target research hours, show a satisfying steady rise. We surpassed the 3600 on-target research hours scheduled for both accelerators during FY 77, and project that the FY 78 total will be between 3200 and 3600 hours each, that is, eight to nine months operation at 400 hours per month. With an eye to constantly improving efficiency, we continue our efforts to squeeze extra research hours out of operating dollars, since both machines have approximately one year backlogs of approved research time.

- * Additional funding provided by DOE's Division of Biomedical and Environmental Research: \$2,350,000

LAWRENCE BERKELEY LABORATORY \$910,000*
Nuclear Science Division

88-Inch Cyclotron Operation

D. L. Hendrie, D. J. Clark, R. A. Gough, D. K. Scott, B. G. Harvey

The 88-inch Cyclotron is a variable isochronous cyclotron with spiral ridge focussing. The maximum energies of the output particles are 60 MeV for protons, 70 MeV for deuterons, 140 MeV for α particles and 145 MeV for ^3He . The energies of heavy ions are limited by magnetic field strength to $140 Q^2/A$, where Q is the charge state of the ion, and A the mass in AMU. Intensities of the light ions are practically limited by the deflector to about 3000 watts of power output; heavy-ion and polarized beams are limited by source intensities. Ion sources for the cyclotron include filament arc sources for light ions, various PIG sources for heavy ions, and an axially injected polarized proton and deuteron source. The axial injection line has the capability of injecting other charged ions prepared in an external source, and will inject heavy ions upon completion of an FY 79 Accelerator Improvement Project.

The project operates, maintains, and improves the cyclotron and beam transport facilities up to the experimental area, maintains the buildings and shop facilities, and coordinates the use by local and external experimenters.

The Cyclotron operates 20 eight-hour shifts per week for in-beam experiments in nuclear chemistry and physics, isotope production and beam development.

* Additional funding provided under Nuclear Sciences: \$560,000

OAK RIDGE NATIONAL LABORATORY \$810,000
Physics Division

Heavy-Ion Laboratory Development

J. B. Ball, J. A. Martin, G. D. Alton, J. A. Biggerstaff, C. M. Jones,
R. S. Lord, R. L. Robinson, E. D. Hudson

This program comprises a number of continuing research and development tasks which provide support for the Holifield Heavy Ion Research Facility:

Facility Development: This task provides for the improvement of the experimental facilities of HHIRF. Criteria for new experimental apparatus and beam lines are established. Direction for design, fabrication and installation of these devices is provided. Existing beam lines and apparatus are upgraded. The selection of new apparatus is made in consultation with the Users Group of HHIRF. Those aspects of building construction that are relevant to the research program are monitored.

Electrostatic Accelerator Technology: This task is responsible for managing technical aspects of the 25 MV tandem accelerator procurement and installation. It is also responsible for the supporting development activities whose goal is to improve the performance and reliability of the new accelerator.

Computer Systems and Data Handling: The objectives of this task are to monitor the control system aspects of the 25 MV tandem accelerator and to provide future system development. This task is also responsible for procurement and development of the experimental data acquisition and processing system for the Heavy Ion Facility.

Negative Ion Source Development: This task is responsible for development and preparation of ion sources which are to be utilized on the 25 MV tandem accelerator. In a broader sense, this task has the objective of advancing the state of negative ion-source technology to provide increased performance capabilities of electrostatic accelerators.

Cyclotron Technology: This task provides for management of the technical aspects of the conversion of ORIC to serve as an energy booster for the 25 MV tandem accelerator. It also provides development support for ORIC in support of present programs of heavy-ion research utilizing the internal ion source. This task is responsible for design activities for a larger booster cyclotron to be added as the next phase in expanding the capabilities of the Heavy Ion Facility.

OAK RIDGE NATIONAL LABORATORY \$1,540,000
Physics Division

Heavy-Ion Laboratory Operations

J. B. Ball, S. W. Mosko, N. F. Ziegler

This program provides for the operation, maintenance and continued improvement of the 25 MV tandem electrostatic accelerator, the Oak Ridge Isochronous Cyclotron (ORIC), and associated beam transport and research equipment that comprise the Holifield Heavy Ion Research Facility. The Facility provides the heavy-ion beams and research equipment required to serve the needs of the national program in heavy-ion science. The program makes available to users throughout the United States and the world, represented by a formal Users Group of over 200 persons, beams with a wide variety of particles, energies and intensities. During the past year, approximately 40% of available research time was accounted for by outside users.

ORIC Accelerator

During FY 1978 the ORIC operated on a 15 shift/week schedule except during a 3-month extended shutdown period which was used primarily for installation of major equipment. About 90% of this year's experimental time was scheduled with accelerated beams of ions heavier than helium. Oxygen and neon beams in the range of 43 to 170 MeV and 70 to 213 MeV respectively accounted for more than 50% of available experiment time.

25 MV Tandem Accelerator

In this fiscal year a number of steps were taken in preparation for operation of the 25 MV accelerator:

1. Assignment of the accelerator operating staff was completed and staff training was begun in conjunction with installation and acceptance testing of the accelerator system by the manufacturer.
2. Commissioning plans and preliminary operating procedures (provided by the accelerator manufacturer) for the complete gas handling system were reviewed and approved. Inspection, testing, and commissioning of the SF₆ storage and transfer system was completed. Receipt of SF₆ was begun.

Several activities associated with development and operation of the EN tandem accelerator also served as support functions for development and operation of the 25 MV tandem accelerator.

OAK RIDGE NATIONAL LABORATORY \$100,000
Physics Division

Heavy-Ion Laboratory User Support

J. B. Ball, R. L. Robinson

This program provides liaison between members of the Users Group and the staff of HHIRF. The primary function of this program is to maintain an experimental support group which assists all users of the Holifield Heavy Ion Research Facility. Direct support is given to the users by: 1) providing information on services and resources at HHIRF, 2) providing assistance with the setup of experiment equipment and helping to deal with the variety of problems that occur during the experiment, 3) providing instruction in the use of apparatus, computers and electronics which are part of the HHIRF, and 4) providing standard tools and hardware. Indirect support is given by this group through maintenance and minor modifications of experimental apparatus, electronics and computers at HHIRF. The latter is done in collaboration with ORNL mentors who are responsible for specific apparatus and/or beam lines. This program will also assist nonresident users in the procedures required to work at ORNL.

Approximately 200 users are expected to have research programs at HHIRF. About three-quarters of these are anticipated to be from other national laboratories and universities. For the most part, these will be funded by NSF and DOE. Within ORNL, research members of the Physics Division, Chemistry Division, Solid State Division, and Metals and Ceramics Division will use the facilities at HHIRF. Assistance to these researchers and facility liaison are provided by the experimental support group.

UNIVERSITY OF WASHINGTON \$ 90,000*
Nuclear Physics Laboratory

Nuclear Physics Operations

R. Vandenbosch, W. G. Weitkamp

The operations project includes the operation, maintenance, and development of the Nuclear Physics Laboratory three-stage Van de Graaff accelerator and facilities such as computers and detection systems. It provides for technical services in mechanical, electrical and electronic construction and maintenance, and in target and detector fabrication. It provides technical and administrative support for the Heavy Ion, Charged Particle and Medium Energy projects described in this budget request, and DOE supported projects in the University of Washington Department of Nuclear Engineering, as well as outside user research. The Operations project is also responsible for developing and constructing new equipment in anticipation of future research needs. Subject to manpower and monetary constraints, the Operations project includes development of new ideas and knowledge in areas such as accelerator physics, ion source physics and particle detection techniques.

* Additional funding provided under Nuclear Sciences: \$208,000

YALE UNIVERSITY \$465,000
A. W. Wright Nuclear Structure Laboratory

Accelerator Operations

D. A. Bromley, K. Sato, P. Parker

The Yale MP accelerator currently operates more reliably and at substantially higher terminal potentials than at any time since its installation in 1965-66. A substantial fraction of the past year's operation has involved terminal potentials between 12.5 and 13.5 MV. Reduction of the ambient vacuum in the total acceleration system to $\sim 10^{-8}$ torr has yielded major benefits including improved voltage holding, essentially permanent conditioning and greatly improved heavy-ion beam transmission e.g. 60% for niobium. Differential pumping has been used to isolate the injector from the accelerator and thus permit use of corrosive gases such as ammonia in improving ion source output; studies on optimum gas mixtures in the accelerator tank and in test chambers together with examination of the pertinent atomic physics collision data have led to the surprising conclusion that all gas mixtures containing SF_6 (or pure SF_6) require very small H_2O components for optimum performance. The Yale Pelletron chains (the first installed in an MP configuration) now have been used for some 25,000 hours of operation and display no wear or deterioration; they have been vastly superior to the original fabric and rubber belts. Use of a second foil stripper in the high-energy tube is now routine and extremely important in the laboratory research program; the electrostatic triplet quadrupole lens in the accelerator terminal has been found to be extremely useful.

The ICT, insulating core transformer, providing AC power to the injector terminal has always been a weak point in the MP accelerator design; we are currently replacing it with an insulating shaft driven motor generator set in order to obtain both greater reliability and more power in the terminal for use with more exotic and more demanding ion sources.

NUCLEAR THEORY

(HK 03 03)

Includes all costs incurred in the theoretical study of nuclear phenomena.

AMES LABORATORY \$110,000
Nuclear Science Program

Nuclear Theory

J. P. Vary, S. A. Williams

The evolution of the nuclear theory program towards a major effort in relativistic heavy-ion interactions has been vigorously pursued. While the traditional emphasis on macroscopic and microscopic models of nuclear structure phenomena has been curtailed to devote efforts towards the heavy-ion program, nuclear structure studies remain a strong basic component of the program.

The initial thrust of the relativistic heavy-ion research has been to develop a simple multiple collision model in order to address the possibility of novel coherent collision phenomena as well as to obtain an understanding of the validity of the fireball model for central collisions. An exciting possibility has emerged from a comparison of the negative pion multiplicity data with our predictions. There is evidence which allows for a collective (coherent) production mechanism. This possibility of a novel collision phenomena is being studied intensively.

The interactions with the experimental nuclear science program at Ames Laboratory continue to be fruitful based on mutual interests in problems of fundamental nuclear structure - especially those related to recent experiments in Ames and planned experiments at the TRISTAN II facility at Brookhaven.

In nuclear structure the theory program devotes effort to the collective model and the microscopic shell model with realistic effective Hamiltonians. The ultimate goal is to unite these two theoretical activities to address phenomena that display both collective and shell behavior. This continues to be a basic long-term goal of fundamental nuclear many-body theory.

The program is also marked by an ongoing effort directed at low and intermediate energy heavy-ion interactions through development of a theoretical folding model. Important developments in the microscopic folding model of the nucleus-nucleus optical potential and inelastic form factors have led to breakthrough in understanding clustering phenomena in light nuclei and inelastic transition strengths.

ARGONNE NATIONAL LABORATORY \$710,000
Physics Division/Chemistry Division

Theoretical Nuclear Physics

M. H. Macfarlane, A. R. Bodmer, R. R. Chasman, F. Coester, B. Day,
D. Kurath, R. D. Lawson, T.-S. H. Lee, J. E. Monahan, M. Peshkin,
S. C. Pieper, E. P. Steinberg, B. D. Wilkins

The nuclear theory program attacks most of the central problems of theoretical nuclear physics. We emphasize (a) the systematic study of nuclear structure and the application of the best nuclear-structure information to diverse nuclear phenomena, and (b) the development of advanced computing techniques for theoretical physics and the application of those techniques to the major computational challenges that arise in nuclear theory.

Current trends and highlights include the following:

Heavy-Ion direct reaction theory - Studies of heavy-ion direct reactions over the past few years have made it clear that the single-channel distorted wave Born-approximation (DWBA) description is deficient in many important respects. The physical situation clearly involves close coupling of many reaction channels. Computational techniques are being developed to accelerate coupled-channel calculations by an order of magnitude beyond the current state of the art. The coupled partial-wave radial equations are solved by an iterative technique inside the range of nuclear interactions and matched to solutions of the coupled equations that describe Coulomb scattering and Coulomb excitation. Many of the simplifying features of HI reactions that were exploited in the DWBA calculations can be adapted to the coupled-channel problem. The resulting coupled-channel extension of Ptolemy (the ANL heavy-ion direct-reaction program) will be used to study HI direct reactions as a function of energy from the Coulomb barrier to the onset of strongly-damped processes.

Work is in progress, in collaboration with R. P. Goddard of the University of Wisconsin, to produce a version of Ptolemy appropriate for light-ion induced reactions. The light-ion version will allow for spin-dependent forces, and it will be able to compute polarizations.

Nuclear-structure research - A shell-model analysis of the non-normal parity states in the 1p shell has been completed to give a good representation of the observed non-normal parity states from $A = 7$ to $A = 13$. Also in the 1p shell, it has been shown that recent inelastic electron scattering data on ^{14}C provide the information needed to determine the odd-state part of the residual nucleon-nucleon interaction; calculations are in progress. A detailed calculation of the isobaric mass-multiplet energies in the 1p shell indicates the need for a small isotensor component in the nucleon-nucleon effective interaction. A careful analysis shows that, in contrast, it is very difficult to extract unambiguous information about the isovector part of the interaction from the data

ARGONNE NATIONAL LABORATORY

Theoretical Nuclear Physics

on ^8Be and ^{12}C .

The importance of nuclear structure for interpreting the pion double charge exchange reaction was shown for the ^{16}O and ^{18}O cases. The observed ratio of cross sections at forward angles cannot be understood with the simplest nuclear model for those nuclei, but a model which includes multiparticle-multihole excitations leads to the observed magnitude. The important ingredient is the coherence resulting from the pairing correlation. Other nuclear structure research includes an interpretation of the E2 transition rates in $N = 35$ and $N = 37$ nuclides, and a study of alpha-transfer reactions for ^{14}C and ^{14}N targets.

Intermediate-energy physics - We interpret intermediate-energy experiments by application of a relativistic particle theory with a phenomenologically-determined Hamiltonian, making use of the best available nuclear-structure information. The pion-nucleon mass operator is based on the Δ resonance model with separable potentials in other channels. The parameters in the NN and $N\Delta$ interactions are determined, by fitting the NN phase shifts and by analysis of the reaction $\pi^+ + d \rightarrow pp$. The pion-nucleus optical potential has been calculated including some effects of pion absorption. Pion inelastic scattering charge exchange and (p, π^+) reactions are being calculated with shell-model wave functions.

High-energy heavy-ion collisions - We have continued studies of high-energy heavy-ion collisions with the classical-equations-of-motion (CEOM) approach. Calculations, mostly nonrelativistic, have been made for projectile and targets with $A = 20$ (Neon) and $A = 40$ (Argon) for laboratory energies from 100-800 MeV/nucleon. Static potentials and momentum-dependent potential which give the same nucleon-nucleon scattering have been used. The results indicate that large momentum components can be obtained as a result of multiple scattering, that for collisions of Neon on Neon there are no collective effects whereas such effects (including significant equilibration) are seen for central collisions of Argon on Argon, that scattering-equivalent potentials give very similar final angular distributions although the potential energies during the collision are very different. The dependence of nucleon multiplicity on the impact parameter has been calculated. Relativistic calculations have been initiated. Improvements to the interactions and extensions to heavier nuclei as well as studies of pion production and short-range correlations are being considered.

Nuclear-matter theory - Our program focusses on the problems of finding valid approximations to the exact solutions of the nuclear-matter equations and of using the validated approximate solutions to test assumed nuclear forces. During the past two years, calculations based on the three-body correlations within the Bethe-Brueckner-Goldstone approximation, using the full Reid potential, have been brought into reasonable agreement with the data and the discrepancy between BBG results and variational calculations based on the hypernetted chain approximation

ARGONNE NATIONAL LABORATORY

Theoretical Nuclear Physics

have been greatly reduced. The program for calculating the three-body term in the BBG approximation is now being modified to include long-range correlations induced by successive three-body correlations in chains of triplets. We are also improving the three-body computer programs to facilitate their application to a variety of assumed nuclear forces.

Other theoretical physics - includes weak interactions in nuclei, quark model calculations, magnetic monopole theories, and theoretical calculations directly in support of our experimental program.

We have discontinued our development of the Speakeasy computer language. That development, which we initiated as a utility for nuclear theory, will now be carried on elsewhere as a commercial enterprise.

We normally have several post-doc appointees and thesis students as part of our program. Short term visitors also play a significant role in our research.

Nuclear structure studies and implications of fission mass distributions for the astrophysical r-process - The purpose of this research is to understand the properties of nuclear ground states and low-energy excited states using an effective interaction. This involves both the determination of the form and parameters of a residual interaction and the development of techniques for calculating the properties of a system of nucleons governed by such interactions. An extensive study of the effective single-particle potential in the actinides has been completed and the detailed structure of the pairing-force interaction has been deduced. The present emphasis is on the treatment of multi-modal residual interactions (particle-particle and particle-hole interactions together with a pairing interaction) in all regimes of the interaction strengths.

A program to investigate the implications of nuclear fission for the astrophysical r-process has been successfully completed and results have been published.

BROOKHAVEN NATIONAL LABORATORY \$460,000
Physics Department

"Nuclear Theory"

N. P. Samios, M. Blume, S. H. Kahana, E. H. Auerbach, A. J.
Baltz, C. B. Dover, R. Fuller, M. Golin, J. Weneser

The nuclear theory group participates in research in a broad range of nuclear structure and nuclear reaction subjects. Principal areas of investigation that may be identified in recent work are heavy-ion physics, intermediate-energy physics, and shell and cluster structure studies. The emphasis is determined by the interests of present members of the group, by relationships to experimental work at Brookhaven National Laboratory (BNL) and elsewhere, and also in response to ideas currently of importance in the larger nuclear community.

In the immediate past, theoretical heavy-ion physics concerned itself with setting up reaction theories which could be applied to recently obtained data, and then with interpretations of such applications. Work at this Laboratory has contributed much to the understanding of quasi-elastic reactions. Further directions have resulted from an examination of the problems arising in this early analysis. A recent focus of attention was interesting new elastic scattering data obtained at the BNL Tandem Facility, which hint at the existence of quasi-molecular behavior in some ion-ion systems. The weakly absorbing nature of the inter-ion interaction, strongly emphasized by the theory group at BNL, plays a key role in permitting such behavior.

Intermediate-energy studies continued to embrace both conventional subjects and boundary regions with particle physics. Recent and past work on the kaon-nucleus system became especially relevant in view of the experimental program on (K^-, π^-) reactions and $K^\pm$ -nucleus scattering at the BNL Alternating Gradient Synchrotron. Emphasis was placed on stimulating further experimental interest by the review of present knowledge in the subject and by the suggestion of new possibilities for experiments. Current interest in matter-anti-matter bound and resonant states was intensified by the probable observation of new, narrow levels. The investigation of such states, their relation to nucleon-nucleon forces and of analogous systems involving strangeness and charm quantum numbers, is a major activity of this group.

Structure studies concentrated on light nuclei, mainly with valence nucleons in the 1p and 2s-1d shells. Both cluster and SU(3) shell model calculations were performed and the relationship between these models explored. The SU(3) shell model provides a rich and detailed tool for comparison with observed data and was streamlined to allow for extended calculations including higher shell components. Interest continued in the weak interactions which play a role in the solar-neutrino puzzle.

BROWN UNIVERSITY. \$ 70,000
Department of Physics

Nuclear Excitations and Reaction Mechanisms

S. Fallieros, F. S. Levin.

The contract supports work in the following areas:

The interaction of photons with nuclei in the long-wavelength limit, properties of the photon-nucleus scattering amplitude above the giant-resonance region, permanent and induced electric-dipole moments, magnetic susceptibilities of nuclei.

Model nuclear reaction calculations; many-body scattering theory; time-delay in multi-channel scattering; arrangement channel quantum mechanics; bound state calculations on simple nuclei, molecules and atoms.

Model nuclear reaction calculations; unitarity and the Efimov effect; N/D four-body calculations.

CALIFORNIA INSTITUTE OF TECHNOLOGY \$ 37,000
Normal Bridge Laboratory of Physics

Research in Nuclear Physics at Low and Intermediate Energies,
Neutrinos, and X-Rays

F. Boehm, P. Vogel

Theoretical work on the formation of the muonic atom will be continued. The theory on atomic muon capture developed during the past year will be applied to specific cases, notably to different chemical systems. The "Z-law" will be derived and compared with experiment.

The structure of the negative parity states in deformed and transitional nuclei will be further investigated theoretically. An attempt at a unified description of all these low-lying states will be undertaken.

The antineutrino spectrum of a nuclear reactor will be calculated and used to predict reaction yields of various antineutrino induced reactions. We shall study the various ways to estimate the beta decay characteristics of short lived isotopes with unknown decay schemes and the uncertainties of the final antineutrino spectrum.

UNIVERSITY OF COLORADO \$ 71,000
Department of Physics

Theoretical Nuclear Physics

P. D. Kunz, E. S. Rost

The theoretical program is, to an important extent, related to the results from the pion physics experiments now underway at LAMPF. Calculations are also being carried out for high energy (up to about 1 GeV) nucleon-induced reactions such as the (p,d) reaction, where some new and interesting features of the reaction mechanism are called for. There is a strong continuing theoretical interest in two-step processes and finite-range effects in low-energy reactions.

UNIVERSITY OF CONNECTICUT \$ 20,000
Department of Physics

Deuteron-Nucleus Spin Orbit and Tensor Optical Potential as Affected
by the Process of Break Up

G. H. Rawitscher

The proposed work covers theoretical investigations of the effects
of deuteron breakup on elastic scattering and deuteron stripping
reactions.

The main results to be learned from the break up study are:

1. The type of treatment of breakup investigated here is promising
in that it is beginning to give results close to the phenomenological
elastic optical model ones.
2. The effects of breakup on the elastic deuteron nucleus inter-
action are large; spherically symmetric as well as spherically
asymmetric breakup states are strongly excited during the collision.
3. The propagation of the deuteron through the nuclear interior is
not yet well described in the present formulations, presumably be-
cause of the need to include the Pauli exclusion principle and
further nucleon-nucleon correlations.
4. The effects of breakup give rise to equivalent potentials in
the elastic channel which are strongly angular momentum (L) and
energy (E_D) dependent.

LAWRENCE BERKELEY LABORATORY

Nuclear Science Division \$590,000

"Nuclear Theory"

N. K. Glendenning, M. Gyulassy, W. D. Myers, J. Randrup, W. J. Swiatecki

Over the past years the two main themes of research in the Nuclear Theory group (consisting of the above listed staff, as well as post-doctoral researchers, and visitors) were nuclear reactions and the macroscopic-microscopic theory of nuclear structure and dynamics. The special interest in these areas is associated with several major experimental programs, the 88-inch cyclotron, and heavy nucleus fission and heavy ion reactions. In addition, more recently the study of high-energy collisions between nuclei including the relativistic regime, has been vigorously taken up. This activity has intensified concurrently with the rapid growth of experimental programs at the Bevalac. The primary incentive has been the hope that the nuclear equation of state at high density and excitation energy could eventually be studied. An added incentive is the realization that at sufficiently high energies the quark structure of hadrons should begin to manifest itself in nucleus-nucleus collisions. In this way the extension of nuclear physics to the relativistic regime should throw light on the next level of the quantum structure of matter and provide tests for the emerging theory of Quantum Chromodynamics.

The recent accomplishments in the high-energy field include the initiation and development, often in collaboration with experimental groups, of the "abrasion-ablation", "fireball", and "firestreak" models of nucleus-nucleus collisions, and the coalescence and thermodynamic models of composite particle formation. These models seem to provide a semi-quantitative understanding of the main features of a high-energy nucleus-nucleus collision. Attempts are being made to account for the finer features through non-statistical aspects of the collisions. At the same time there has been continuing progress on formulating a quantum many-body theory of scattering appropriate for a detailed description of such inclusive processes. Already the "fireball" model has been derived from such a fundamental theory in a suitable approximation. It is expected that the coalescence model can similarly be derived from that theory.

In addition to developing models of nuclear collisions based on known ingredients such as nuclear geometry and nucleon-nucleon scattering, speculative studies are also carried out in the Theory Group on possible exotic collective phenomena at high nuclear densities. These speculative studies include the role of pionic instabilities on the scattering dynamics and the experimental signatures of such phenomena. For example, while the pion multiplicity distribution was shown to be insensitive to pionic instabilities, it was found that the coherence of the pion field produced in nuclear collisions could be measured via the double ($\pi^+\pi^-$) inclusive cross sections. The interpretation of such measurements in the light of final state interactions is also under investigation.

LAWRENCE BERKELEY LABORATORY

Two theoretical studies which go beyond the presently available range of Bevalac energies are also underway. One is the discussion of the level density of hadronic states and how information on this fundamental property of matter might be obtained from ultra-relativistic collisions. A recent development in this research is the generalization of Walecka's relativistic mean field theory to an arbitrary number of baryon fields. This provides an improved equation of state for the high densities and temperatures expected in very high energy nuclear collisions. The other study investigates quantitatively the thermodynamics of quark matter as described by Quantum Chromodynamics, with a qualitative discussion of the transition to hadronic matter.

Research in low energy reactions continues, but at a reduced level, to accommodate the research at relativistic energies. For example, we are no longer pursuing the study of higher order transitions in direct reactions, which was pioneered in this Group, and has become an active topic of research in many laboratories. One recent development of the research that continues in direct reactions is the identification of the effects of wave function polarizability on certain heavy ion transfer reactions involving weakly bound nucleons and the formulation of the theory in the adiabatic limit and the molecular orbital approach. Another is the derivation, in closed form, of a long-range absorptive contribution to the optical potential in heavy ion scattering associated with a strong quadrupole inelastic channel.

The macroscopic-microscopic theory of nuclear structure and dynamics, developed in the studies of fission properties, led to the prediction of a possible island of stability beyond the end of the periodic table of known nuclei. The Theory Group played a major role in developing the theory of such "super-heavy elements" and the search for these exciting new nuclei, though so far unsuccessful, has been a major element in the growth of the field of heavy-ion reactions.

The study of nuclear statics in the two-part approach has reached a culmination with the publication of a monograph on the Droplet Model of Atomic Nuclei. This model has been applied over the years to the interpretation of nuclear masses, deformations, fission barriers, charge distributions, single-particle potential wells, the isotope and isotone shifts, the structure of the nuclear surface region and other properties of nuclei. A recent application has been to the interpretation of the nuclear Giant Dipole resonance, which has led to a major re-assessment of the physical features governing this much studied nuclear process.

The phenomenon of "deep-inelastic collisions" that prevents compound nucleus formation when very heavy targets and projectiles collide, promises to be even more useful than nuclear fission in revealing the large scale collective properties of nuclei. The outstanding recent development in this area, initiated in the Theory Group, is the one-body theory of nuclear dissipation. This theory predicts that in many situations, nuclei ought to exhibit highly damped (super-viscid) characteristics. The theory predicts a specific

LAWRENCE BERKELEY LABORATORY

"creeping" behavior of nuclei in the process of fission. It has also been applied to the interpretation of deep inelastic collisions and has been extended to the calculation of transport coefficients in the diffusion treatment of nuclear interactions. Research on deep inelastic and quasi-elastic phenomena, and the transition between low and higher Bevalac energy reactions will continue with increased intensity in the coming year.

Recently a new line of basic research has been added to our program, namely the development and application of the coupled-cluster or e^S theory. This is probably the most promising and sophisticated quantum many-body theory that presently exists, and indeed one which has already provided us with the world's best calculations on several finite nuclei. The theory is now developed to the point where it can handle both the ground-state density matrix (e.g., in order to derive expectation values of arbitrary few-body operators) and the excitation spectrum, as well as just the ground-state energy. We are presently interested in 1) investigating the fundamental structure of the theory and various approximation schemes within it, 2) extensions and applications of the theory to several model problems; 3) using the theory to bridge the existing perturbative methods (e.g. Brueckner theory) and variational methods (e.g. hypernetted chains) applied to nuclear matter and finite nuclei; and 4) extending the theory to time-dependent situations to develop a true many-body scattering formalism, in order to quantify the errors and systematically improve upon such existing methods as TDHF.

LAWRENCE LIVERMORE LABORATORY \$ 40,000
Theory Division

Thermonuclear Neutron Capture Studies

H. Meldner

We propose to continue our study of nuclear theory problems relevant to the question of producing and detecting very heavy, perhaps superheavy isotopes by multiple neutron capture in nuclear explosives involving various design types, sizes, target configurations and novel exposure schemes.

Improving the reliability of extrapolations to very heavy transactinium isotopes is the major task. Although a complete understanding would involve more nuclear theory than we can possibly address with the proposed budget, we have singled out two topics which we consider to be really crucial. First is the understanding of fission-stability and -dynamics of neutron rich nuclei which can be stabilized only by shell structure effects. And the second topic is the relation of transactinium nuclear structure, in particular fission barrier details and other energy surface effects to the various thermonuclear neutron cross sections which determine the competition of capture and fission (vs. beta decay).

We have completed a first version of a computer program, NIFPR, which combines various semi-empirical nuclear theories for the calculation of all significant cross sections for heavy elements exposed to thermonuclear neutron spectra. This code is also useful in astro-physical calculations as well as in the actinide waste problem in the nuclear power industry.

In collaboration with R. Y. Cusson, we also began to investigate the potential of various time dependent Hartree Fock approximations for the description of fission dynamics and related improvements of our long-range extrapolations. We have developed TDHFB codes with pairing which handle the fission of heavy nuclei.

LOS ALAMOS SCIENTIFIC LABORATORY \$490,000
T Division

Medium Energy Theory

P. A. Carruthers, G. J. Stephenson, Jr., J. L. Friar, W. R. Gibbs,
B. F. Gibson, J. N. Ginocchio, T. J. Goldman, L. Heller, P. Herczeg,
R. R. Silbar

The theoretical effort in T-5 is directed primarily at the understanding and analysis of medium-energy experiments with special emphasis on those performed at LAMPF. It is through the interplay of experimental observation and theoretical prediction that we hope to clarify the underlying principles of medium-energy physics and to further our understanding of the fundamental interactions of nature. A large body of fundamental research must necessarily underlie such comparison of experiment with theory, and such research is also pursued in T-5, although it is only briefly touched upon in this proposal.

Group T-5 was formed as a theoretical center for medium-energy physics in connection with the opening of LAMPF (the meson physics facility at LASL), where a very active experimental program is carried out. This experimental program is aimed largely at the study of nuclear physics. However, research in elementary particles, weak interactions, radiation studies, and biomedical applications is pursued as well. From the start, Group T-5 has been involved in collaborative efforts with LAMPF and P-Division personnel, suggesting and designing experiments, interpreting data, and extracting final results. In addition, Group T-5 is providing theoretical guidance for a large number of experimental groups outside the Los Alamos laboratory, thereby enhancing its international reputation.

It is difficult to separate the research interests of the group into categories, since one of the strengths of the group is the strong overlap and interaction among the individual members and the interplay between various specific research efforts. However, one may categorize these interests as including 1) the interactions of pions with nuclei, 2) the interactions of protons with nuclei, 3) the fundamental nucleon-nucleon interaction including pion production, 4) the study of nuclear properties with weak and electromagnetic probes, 5) few body physics, 6) classical nuclear structure studies and 7) fundamental processes involving the weak interaction. All of these programs are of a continuing nature and the emphasis given to particular problems varies largely in response to new and often puzzling experimental data, or to the availability of new experimental techniques.

UNIVERSITY OF MARYLAND \$ 345,000
Department of Physics & Astronomy

Theoretical Studies in Nuclear Reactions and Nuclear Structure

M. K. Banerjee, J. J. Griffin, W. M. MacDonald, E. F. Redish,
S. J. Wallace, M. Dworzecka

Theoretical studies are proposed in four major areas of nuclear physics: 1) reaction theory for both few-body and many-body systems, 2) intermediate energy reactions including nucleon-nucleus processes, 3) pion physics, and 4) nuclear dynamics. Special emphasis will be given to applying a new theory of many-body reactions, to extending a dynamical theory of the pion-nucleon interaction and using it to discuss the pion-nucleus interaction, to establishing the magnitude of the charge-symmetry-breaking nucleon-nucleon interaction, to confirming the effects of nucleon isobars on nucleon-nucleus processes, and to a new $\mathcal{S}$ -matrix theory of time-dependent Hartree-Fock calculations.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY \$547,000
Center for Theoretical Physics

Nuclear Theory

A. K. Kerman, M. Baranger, H. Feshbach, E. L. Lomon, E. J. Moniz,
J. Negele, F. Villars

The nuclear theory group continues to work on a very broad set of problems in nuclear structure and nuclear reactions. This includes a substantial effort in intermediate-energy nuclear physics and in heavy-ion reactions over the full range of available energies.

Formulation of the microscopic theory of nuclear collective motion is a continuing interest. Detailed comparison between Hartree-Fock predictions for the shapes of deformed nuclei and high-resolution electron scattering measurements from the Bates Linac have been made, but more sophisticated approaches are also being worked on.

The time-dependent variational approach to heavy-ion collisions is being extended and applied, and work towards a quantum mechanical understanding of nuclear "friction" is advancing.

A unified formulation of direct reactions and statistical processes in low-energy nuclear reactions has been proposed and will be tested against experiment.

The role of pion and isobar degrees of freedom in nuclei is being studied in several contexts, including modification of nuclear charge and current distributions, development of a theory of pion-nucleus reactions, and consideration of the properties of dense matter.

Various approaches to the theoretical description of relativistic heavy-ion collisions are being developed.

The nuclear and particle theory groups continue to have a broad exchange on the use of many-body techniques familiar in nuclear physics in calculations of quark dynamics and on the application of quantum chromodynamics to nuclear physics.

OAK RIDGE NATIONAL LABORATORY \$500,000
Physics Division

Theoretical Nuclear Physics

J. B. McGrory, K. T. R. Davis, E. C. Halbert, G. R. Satchler, T. A. Welton, C. Y. Wong

The nuclear theory program covers basic research on nuclear reactions and nuclear structure. The direction of the program is influenced by the type of experimental nuclear physics facilities available at ORNL since one important aim of our work is to provide theoretical help and stimulus for the experimental program. Our present work strongly emphasizes various aspects of heavy-ion physics.

Another strong component of the nuclear theory program is the extensive use of large computers, particularly for broad, long-term efforts which often cannot be made easily at universities. This has resulted in our developing almost unique capabilities for exploring the consequences of theories of nuclear behavior. At the same time, development of the underlying physical theories is pursued vigorously.

The theoretical efforts in the past year can be broken down as follows. Three programs deal with gross properties of collisions of heavy ions-- a hydrodynamic model, a classical microscopic scattering model, and the Time-Dependent Hartree-Fock (TDHF) theory. Another major program is theory of reactions for both light and heavy ions. A fifth program, nuclear spectroscopy, is being reactivated this year. Progress in these areas this year can be summarized as follows:

Time-Dependent Hartree-Fock Theory - A new 2-dimensional code has been developed which allows for mass asymmetry, finite-range components of the Skyrme force, separate neutron and proton states, and a self-consistent model of the moment of inertia. 2-D calculations have been compared with exact 3-D calculations. The results suggest 2-D calculations of low-energy collisions between heavy ions are useful where 3-D calculations are impractical. 3-D calculations of light systems, such as O on Ca and Ni have been performed. The results suggest that the calculated fusion cross sections for low-bombarding energies are in reasonable agreement with experiment, the angular distributions of direct inelastic cross sections are in quantitative disagreement with experiment. Preliminary results where some added quantal effects and evaporation corrections are included give significant theory-experiment agreement. A formalism for systematically including high-order effects of residual interactions has been developed which introduces time-dependent single-particle occupation probabilities. The formalism suggests a means of quantifying temperature and equilibrium.

OAK RIDGE NATIONAL LABORATORY

Theoretical Nuclear Physics

Hydrodynamics - Much effort in this field this year was in the area of technical development of the three-dimensional hydrodynamic codes. The effects of mesh size were studied closely, and the knowledge gained there is being used to optimize the existing codes to make such calculations economically feasible. Liquid-drop models of fission focussed on diffuse-surface corrections to sharp-surface macroscopic calculations, and the effects of non-zero fission neck radii in fission were studied.

Microscopic Classical Models - SIMON - The computer program SIMON for studies of the classical scattering of many-body systems was modified this year to allow the calculation of the particle density for off-center asymmetric scattering and to calculate energy-angle distributions during the course of the calculations, and to allow the efficient storage of calculated results on tape for later analysis. Analysis of U + Ne scattering indicates that the energy-angle distributions are relatively insensitive to "excluded-volume" effects in nucleon-nucleon scattering, but the particle densities are very sensitive to this volume.

Direct Reactions - An extended study of dynamic polarization potentials which include Coulomb excitation effects in elastic scattering was completed. Such potentials were used in folded potential studies for nucleons, α , and heavy ions. The various folding potentials are "deep" in most cases. One anomaly, the folded-potential description of ${}^6\text{Li}$ scattering gives incorrect cross section magnitudes for a number of targets, although the angular distributions are fit.

STATE UNIVERSITY OF NEW YORK/STONY BROOK \$300,000
Department of Physics

Research in Theoretical Nuclear Physics

G. E. Brown, A. D. Jackson, T. T. S. Kuo, R. A. Smith

The proposed work covers a broad range of topics in theoretical nuclear and intermediate energy physics and in nuclear astrophysics. Beginning with free nucleon-nucleon interactions, effective forces in nuclei are constructed via a chain of field theoretic, dispersion and many-body techniques. Dynamical theories of nuclear excitations are constructed. Infinite nuclear systems at a variety of densities are studied in order to determine reliable equations of state for nuclear and neutron matter. These equations of state are applied in astrophysical problems, such as the gravitational collapse of stars, as well as in standard nuclear contexts.

RICE UNIVERSITY \$ 15,000
T. W. Bonner Nuclear Laboratory

Intermediate Energy Nuclear Physics Studies

G. C. Phillips, I. M. Duck

The theoretical research program has closely paralleled the experimental program. In particular, $pd \rightarrow nd\pi^+$ data have been interpreted in terms of double-scattering diagrams; $pp \rightarrow \Delta^{++}n$ data have been analyzed in terms of π and ρ meson exchange amplitudes; and multiple-scattering theory has been applied to backward elastic pd scattering. The plans are to continue these studies and to emphasize polarization reactions.

RENSSELAER POLYTECHNIC INSTITUTE \$ 41,000
Department of Physics

Theory of Heavy Ion Collisions

D. Sperber

The purpose of the program consists of a theoretical study of heavy ion collisions for a wide range of systems and energies using dynamical and statistical methods, focusing on the investigation of: fusion excitation functions, the role of collective degrees of freedom in strongly damped collisions, and the role of compression and sound waves for reactions at higher energies. The fusion studies are directed to extract information about the ion-ion potential. The analysis of strongly damped collision is being performed so as to extract information about 1) the ion-ion potential, 2) the role of dissipative forces in heavy-ion reactions, 3) the role of collective degrees and deformations in strongly damped collisions, 4) the mechanism of nucleon transfer and its relation to energy dissipation, and 5) the time scales for the equilibration of various degrees of freedom. The above calculations are classical. Quantum models will be constructed to determine the validity of the classical model as a limiting case. For higher energies the time evolution of the colliding system is being studied using a hydrodynamical model assuming the equation of state being a field. The measured and calculated inclusive spectra for central or near central collisions are compared.

UNIVERSITY OF ROCHESTER \$135,338
Department of Physics

Nuclear Structure Theory

J. B. French, D. Koltun

Our research program is, broadly, the development and application of nuclear theory including nuclear structure and nuclear reactions. This involves the development of new general theoretical methods, as well as the detailed examination of particular nuclei or nuclear reactions. We are working in the following areas:

1. Spectral distribution methods in complex nuclei, including level densities and strength distributions, as well as general studies of nuclear symmetries by spectral methods. This work has been in progress for several years and is currently being extended considerably in its applications, to level densities at high excitation making use of new trace-reduction methods and new computer programming for them, and to studies of nuclear symmetries making use of new results for asymptotic distributions in model subspaces defined by groups.
2. Nuclear fluctuations including the general theory, and applications to energy-level and strength fluctuations and to fluctuations in reaction cross-sections. Recent work in this domain has included: new calculations of the measures used, for example, for slow-neutron resonances, by means of which the question of the independence of the measures has been cleared up and new relationships found between them: proofs of the ergodicity and quasi-stationary behavior of the standard random-matrix ensembles.

In general terms these two subjects combine to give a basis for a general statistical theory for nuclei and other systems describable via spectroscopic model spaces; we propose to continue further development along this line.

3. Statistical methods in nuclear reaction theory. Recent work on random matrix models leads to transport theory, which has been applied to "deep inelastic" collisions of heavy ions. Extensions of the method to include collective motion have been made. Further application to the theory of pion absorption by nuclei is under way.
4. Meson scattering and absorption by nuclei. Recent work has been on the inclusion of absorption channels in the theory of the optical potential, models for pion absorption, theory of the absorption vertex function.

Other topics include a dispersion approach to πN scattering off-shell, and multiple scattering theory in general. Under the last heading we have new results concerning the reactive content of optical potentials, in which the role of non-elastic channels on the elastic scattering is made explicit.

UNIVERSITY OF TEXAS \$120,594
Department of Physics

Research in Theoretical Nuclear Physics

T. Tamura, W. R. Coker, T. Udagawa

Among the topics in theoretical nuclear physics we propose to study in the coming year are sophisticated analyses of (p,t) reaction data; coupled-channel and Regge pole analysis of heavy-ion elastic scattering and possibly transfer reactions; analyses of light- and heavy-ion induced reactions populating the nuclear continuum; analyses of medium-energy elastic and inelastic scattering and reactions induced on a wide range of target nuclei by 800 MeV protons, emphasizing extraction of nuclear neutron-matter densities; analyses of pion-induced nuclear reactions; and the boson expansion method for the study of nuclear collective excitations. Our objective is to increase our understanding of various fundamental aspects of nuclear structure and nuclear reactions.

TEXAS A&M UNIVERSITY \$: 41,047
Department of Physics

Intermediate Energy Nuclear Theory

R. A. Bryan, R. B. Clark, B. J. VerWest

Our research program is primarily devoted to the nucleon-nucleon problem. We have carried out fully relativistic calculations of $NN \rightarrow NN\pi$ for N and Δ intermediate baryon states and a variety of exchanged bosons. We have also carried out phase-shift analysis of NN scattering data at intermediate energies and will analyze new data as they become available. We have also investigated the $N\bar{N} \rightarrow \pi\pi$ amplitude and the $NN\pi$ vertex as they relate to NN scattering. We are currently calculating the short-range NN force in the framework of the constituent-interchange quark model. We continue to provide theoretical expertise and data analysis for NN experimental groups at LAMPF and TRIUMF.

VIRGINIA POLYTECHNIC INSTITUTE \$ 80,000
Physics Department

Partial Wave Analyses of Scattering Reactions Below 2 GeV

R. A. Arndt, L. D. Roper

It is proposed to continue analyses of πN , NN , K^+p and $\pi\pi N$ reactions below 2 GeV into partial-wave representations. Efforts shall be undertaken to make results of these analyses available through computer programs and data bases compiled and maintained at VPI&SU and accessible through telephone linkages.

UNIVERSITY OF WASHINGTON \$200,000
Department of Physics

Theoretical Physics Concerned with Nuclear Physics, Atomic Physics
and Statistical Physics

E. M. Henley, J. S. Blair, G. A. Miller, R. D. Puff, L. Wilets

This grant will support work in a variety of fields of theoretical physics: low-energy and intermediate-energy nuclear physics, heavy-ion reactions, quantum statistical mechanics, many-body problems, and some field theory. The work on low energy and intermediate energy nuclear physics will include studies of forces which violate parity conservation and charge symmetry, spin dependence in nuclear reactions, muonic and hadronic atoms, and pion-nucleus reactions. Heavy-ion reactions to be studied range from those produced by projectiles with energies below the Coulomb barrier to those in which the projectiles are relativistic. Atomic calculations for tests of weak interaction theories will be carried out. Investigations of many-body problems will emphasize the meson-nucleus system, ^3He fluids, and low density systems.

YALE UNIVERSITY \$100,000
Department of Physics

Nuclear Theory

D. A. Bromley, R. Ascutto, P. Haff, E. Seglie

Major activity has centered on extension of our study of higher order reaction processes. We have been successful in developing detailed nuclear reaction models which reproduce our experimental data on both transfer--inelastic processes and sequential multinucleon transfers induced by both light and heavy projectiles. This group has also made a fundamental breakthrough in the basic formalism for both transfer and inelastic scattering mechanisms in which the nucleon particle-hole interaction plays a central role. In consequence, with this new formalism much of the elaborate theoretical framework developed over the years in nuclear structure calculations becomes available for nuclear reaction theory as well. The new formalism has been shown to resolve in detailed fashion, a number of long standing puzzles in the reaction literature--and of course suggests a wide range of new measurements.

A second major area of activity focusses on the development of more adequate theories for sputtering induced by particle bombardment and for the stopping of charged particles in matter. This work has already led to a model of sputtering that allows isotope fractionation on the lunar surface and in the Martian atmosphere to be understood quantitatively as a consequence of bombardment by the solar wind.

Nuclear structure calculations have been focussed on the zirconium region where new experimental data have made possible the direct testing of a variety of model suggestions where ^{88}Sr is considered the core configuration.

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