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NUCLEAR CHEMISTRY RESEARCH OF HIGH ENERGY NUCLEAR REACTIONS

AT CARNEGIE INSTITUTE OF TECHNOLOGY

AND

CARNEGIE-MELLON UNIVERSITY

1961-1977

Albert A. Caretto, Jr., Principal Investigator

SUMMARY REPORT

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TABLE OF CONTENTS

ABSTRACT.....	ii
I. INTRODUCTION.....	1
II. PERSONNEL.....	3
A. Supervision.....	3
B. Graduate Students.....	3
C. Postdoctoral Research Associates.....	4
D. Other Research Assistants and Technicians.....	4
E. Undergraduate Students.....	4
F. Supporting Personnel.....	4
III. FACILITIES.....	5
IV. PUBLICATIONS AND REPORTS.....	6
NYO-2897 Reports.....	6
COO-3239 Reports.....	9
Early Publications.....	10
Doctoral Dissertations.....	11
V. RESEARCH ACTIVITIES AND RESULTS.....	12
A. Overview.....	12
B. Specific Results.....	13
1. "Simple" Nuclear Reaction Studies.....	13
2. Spallation Reaction Studies.....	17
3. Heavy Ion Reaction Studies.....	20
C. Current Research.....	21
REFERENCES.....	22

ABSTRACT

This report summarizes the activities and the results of research in the study of high energy nuclear reactions carried out at Carnegie Institute of Technology from 1957 to 1967 and at Carnegie-Mellon University from 1967 to 1977. This work was supported by the United States Atomic Energy Commission (1957-1974) and by the Energy Research and Development Administration (1975-1977) under the supervision of Professor Albert A. Caretto, Jr. Until 1961 AEC Contract E(11-1)3236 provided support for both the research program of Professor Truman P. Kohman and Albert A. Caretto, Jr. Since 1961 Professor Caretto's research project was supported by Contract AT(11-1)3239.

A list of the students that obtained Ph.D. degrees in Chemistry with dissertations based on research supported by this Project is included, along with the names of the postdoctoral research associates, technicians, and other personnel.

A complete list of all publications, doctoral dissertations, and reports resulting from the research of this project is also included.

A major part of the report is a review of the research activities and results. The objective of the research of this project was the study of reactions initiated by projectiles of energy above about 100 MeV. The main effort was the investigation of simple nuclear reactions with the objective to deduce reaction mechanisms. These reactions were also used as probes to determine the nuclear structure of the target.

In addition, a number of studies of spallation reactions were undertaken which included the determination of excitation functions and recoil properties. Recent research activities which have involved the study of pion induced reactions as well as reactions initiated by heavy ions is also discussed.

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I. INTRODUCTION

In 1957 the writer accepted a one year appointment in the Department of Chemistry at Carnegie Institute of Technology to replace Professor Truman P. Kohman who was on sabbatical leave of absence. In 1958 Professor Caretto returned to the Lawrence Radiation Laboratory to complete some unfinished research. Since 1960 he has been on the faculty of Carnegie Institute of Technology (changed to Carnegie-Mellon University in 1967). He immediately initiated a research program in the study of high energy nuclear reactions making use of the 440-MeV proton synchrocyclotron then available at Saxonburg, Pennsylvania. Until 1961 this work was jointly supported with the research of Professor Truman P. Kohman by Contract No. E(11-1)-3236 with the Atomic Energy Commission. From 1961 to this date this research was supported by Contract No. AT(30-1)2897 of the U. S. Atomic Energy Commission and later with the U. S. Energy Research and Development Administration.

From the beginning the research undertaken was in the area of high energy proton-induced nuclear reactions. Until 1969 the vast amount of this research made use of the 440-MeV proton synchrocyclotron located at Saxonburg, Pennsylvania. On the phase-out of that accelerator, Professor Caretto initiated a number of research problems making use of other accelerators. The 600-MeV proton and 500-MeV alpha particle accelerator of the Space Radiation Effects Laboratory became the major focus for a number of studies. In addition, research was initiated at the 300-GeV accelerator of the Fermi National Accelerator Laboratory and the Zero Gradient Synchrotron of Argonne National

Laboratory. Also at this time, the Principal Investigator began to study heavy-ion induced nuclear reactions using the Yale University Heavy Ion Linear Accelerator.

Except for the periods 1964-1965 and 1974-1975 Professor Caretto has directly supervised the research efforts of this contract. Professor Caretto had sabbatical year leaves of absence in these two periods which he spent at CERN, the European Center for Nuclear Research. In 1964-1965 the contract research was supervised by Dr. John A. Panontin, who received his Ph.D. from the University of Chicago under the direction of Professor N. Sugarman. In 1974-1975 the research was supervised by Professor M. Kaplan who joined the faculty of the Department of Chemistry of Carnegie-Mellon University in 1970. Also, in 1969 Dr. Paul J. Karol joined the faculty of Carnegie-Mellon University. Thus, since 1970 a group of four faculty members having interest in the field of nuclear chemistry have been present at Carnegie-Mellon University. Since the arrival of Dr. Karol, the Principal Investigator and Karol have collaborated on a number of experiments.

During the period of AEC-ERDA support of this work the Principal Investigator has been supported by the National Science Foundation (1961-1963) for special studies of gas recoil range measurements. In addition, the National Science Foundation provided half the funds for the renovation of the nuclear chemistry laboratories at the Nuclear Research Center at Saxonburg, PA.

The most recent research efforts of this contract have involved experiments involving pion induced reactions at the Los Alamos Meson Physics Facility of the Los Alamos Scientific Laboratory and the study of heavy ion reactions using the Oak Ridge Isochronous Cyclotron. A common research objective throughout most of the studies of the past eighteen years has been the investigation of the so-called "simple" nuclear reactions at high energies. The cross sections of these reactions, such as (nucleon, 2 nucleon), (p,xn), (p,pxn), (α , α n), (α , α p), (π , π n), etc., are related to the target nuclear structure. Thus, an objective of this work has been both to understand the mechanism for such reactions and to use these reactions as probes of nuclear structure.

This report consists of sections summarizing the personnel who were associated with this project, the facilities used by it, a list of publications and reports, and a narrative summary of the research activities and results obtained by means of the AEC-ERDA support.

II. PERSONNEL

A. Supervision

Throughout the period of this project except for two sabbatical leaves, the writer has been the Principal Investigator. As explained in the Introduction, Dr. John A. Panontin and Professor Morton Kaplan assumed the duties of supervision during the 1964-1965 and 1974-1975 academic years, respectively. During the period 1970 to 1974 Professor Caretto was the Chairman of the Department of Chemistry at Carnegie-Mellon University. In view of his extensive administrative duties at that time, one graduate student supported by this contract received his day-to-day supervision from Professor Paul J. Karol.

B. Graduate Students

1. Graduate Students who Obtained the Ph.D. degree with Professor Caretto

David J. Morrison	1961
John H. Gray III	1962
Donald J. Reuland	1963
William J. Treytl	1963
Larry B. Church	1966
William J. Nieckarz, Jr.	1966
F. Michael Kiely	1967
Roy F. Schall, Jr.	1969
Allan C. Stalker	1969
Martin A. Molecke	1973
Robert A. Williams	1973
John A. Urbon	1973
Mary Anne Yates	1976

2. Graduate Student Still Working Toward Ph.D. Degree with Professor Caretto

James L. Clark

3. Graduate Student who Obtained Ph.D. Degree with other Faculty of the Department

Thomas H. Ku	1976
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4. Graduate Students Who Left the University without Obtaining Ph.D. degree

Myron Meek	1963-1965
Richard E. Fredericks	1966-1968
James R. Noyce	1967-1969
Paul G. Wassel	1968-1971
Richard Spector	1973-1977

5. Special Graduate Student

Peter Strohal received Ph.D. from Institute Rudjer Boskovic, Zagreb, Yugoslavia based on research undertaken at Carnegie Institute of Technology under the direction of Principal Investigator. He was under the auspices of U. S. International Cooperation Administration and Government of Yugoslavia, 1958-1960.

C. Postdoctoral Research Associates

Dr. N. K. Ganguly (1962-1963) is now at the Tata Institute, India.

Dr. R. G. Korteling (1962-1965) is now Professor of Chemistry, Simon Fraser University

Dr. John A. Panontin (1964-1965)

Dr. Donald J. Reuland (1966) is now at Indiana University, Terre Haute, IN.

Dr. F. Michael Kiely (1967-1968) is now at Simon Fraser University

Dr. Yu-Wen Yu (1967-1969) is now Professor of Nuclear Science, National Tsing Hua University, Taiwan, Republic of China

Dr. Daniel M. Montgomery (1970-1972) is now at the Environmental Protection Agency, Research Division, Cincinnati, OH

Dr. Michael W. Weisfield (1970-1972) is now at the Radiation Management Corporation, Philadelphia, PA

Dr. Michael V. Yester (1972-1975) is now Professor of Physics, University of Alabama in Birmingham, AL

D. Other Research Assistants and Technicians

Edward Schneider	1962-1963
Lew A. Daughette	1962-1964
Christa Hombach	1963-1965
Walter L. Smith	1/66-4/66
Waltraud Pfaffe	1966-1967
James Robeson	1966-1970
Gary Smay	Summers, 1966-1969
James Thompson	1966
Carol Kier	1967-1970
Linda Hood	Summer, 1967
Jacques Garcin	Summer, 1967
Robert Faust	Summer, 1971
Karol Williams	10/71-6/72

E. Undergraduate Students

Undergraduate students have been associated with the project in a variety of ways. Often they would use their research experience to write an undergraduate senior thesis. Sometimes they were employed as technicians during the summer or part-time. The following list is incomplete:

Michael Robison	1960
Christopher Root	1961
Dennis Cillo	1970-1971
Bonnie Whitsel	1970-1971

F. Supporting Personnel

Persons employed by the project for important services although not actually engaged in research were:

Frank Bomba	Health Physicist
Ralph Bish	Electronics
Charles M. Parks	Machine Shop
Robert Findley	Electronics

Secretarial Services have faithfully and reliably been performed by Dorothy Ponsetto - 1961-present.

III. FACILITIES

Until 1969 when the 440 MeV proton synchrocyclotron was phased out at Saxonbrug, PA, Professor Caretto spent considerable time in designing and developing new laboratories for nuclear chemistry research adjacent to the cyclotron. At the time of shutdown there existed well equipped chemistry laboratories, offices and well shielded underground counting room facilities.

In 1970 the writer moved his group and facilities to new space made available in the Mellon Science building located adjacent to the main campus. This space consists of five laboratories for radiochemistry with adjacent offices for graduate students and postdoctoral research associates. In addition there are two large rooms used for counting and instruments. Finally there is a small room used for target preparation in which is housed the vacuum evaporator, the electro-spray apparatus, electroplating assembly, and hydraulic press die.

Instrumentation for the counting room consists of six beta proportional detectors, four NaI crystal detectors for gamma counting, three Ge(Li) detectors for high resolution gamma spectroscopy, a silicon detector for α -counting, two thin NaI detectors for X-ray counting, a xenon filled proportional counter for X-ray counting, and two low level beta detectors.

All the detectors have the requisite associated electronics consisting of amplifiers, scalars, coincidence units, timers, single channel analyzers, etc. In addition there are three 100-channel analyzers, two 4096 channel analyzers, one of which is interfaced with a PDP-9 computer. Finally, there also exists a 1024 channel analyzer.

It is possible to use a number of kinds of data acquisition equipment with the various detectors. High speed paper punches, teletypes, automatic scaler serial registers, can be used. The PDP-9 can be used to store data on paper tape or magnetic tape for later analysis.

IV. PUBLICATIONS AND REPORTS

NYO Report Numbers - NYO-2897-1 - NYO-2897-43, 1961-1971

1. David Lee Morrison, "A Systematic Study of (p,xp) Reactions in the 100-400 MeV Region", Doctoral Thesis, June 1961.
2. John H. Gray, III, "Excitation Functions and Recoil Behavior of Specific Products from the Interaction of High-Energy Protons with Aluminum, Cobalt, Silver, and Gold", Doctoral Thesis, April 1962.
3. Annual Progress Report, 1961-1962 - June 1962.
4. D. L. Morrison and A. A. Caretto, Jr., "Excitation Functions of (p,xp) Reactions", September 1962. [Phys. Rev. 127, 1731-1738 (1962)].
5. Donald J. Reuland, "A 2π -Differential Recoil Study of the $\text{Cu}^{65}(\text{p,pn})\text{Cu}^{64}$ Reactions at Incident Proton Energies of 396 and 130 MeV", Doctoral Thesis, February 1963.
6. Annual Progress Report, 1962-1963 - June 1963.
7. William Joseph Treytl, "A Systematic Study of (p,n) Reactions in the 100-400 MeV Region", Doctoral Thesis, October 1963.
8. D. L. Morrison and A. A. Caretto, Jr., "Recoil Study of the $\text{Zn}^{68}(\text{p},2\text{p})\text{Cu}^{67}$ Reactions, March 1964. [Phys. Rev. 133, No. 5B, B1165-B1170 (1964)].
9. D. J. Reuland, N. K. Ganguly and A. A. Caretto, Jr., "The 2π -Differential Recoil Study of the $\text{Cu}^{65}(\text{p,pn})\text{Cu}^{64}$ Reaction", March 1964. [Phys. Rev. 133, No. 5B, B1171-B1177 (1964)].
10. Annual Progress Report, 1963-1964 - June 1964.
11. A. A. Caretto, Jr., "Literature Survey of Nucleon, 2 Nucleon Reaction Cross Sections at Energies above 100 MeV", July 1964. [NYO-10693].
12. J. R. Grover and A. A. Caretto, Jr., "Nucleon, Two-Nucleon Reactions above 100 MeV", July 1964. [Ann. Rev. Nucl. Sci. 14, 51-100 (1964)].
13. Annual Progress Report, 1964-1965 - June 1965.
14. W. J. Nieckarz, Jr. and A. A. Caretto, Jr., "Half-Lives of Neutron Deficient Yttrium Nuclides", July 1965. [J. Inorg. Nucl. Chem. 27, 919-925 (1965)].
15. W. J. Treytl and A. A. Caretto, Jr., "A Study of (p,n) Reactions between 100 and 400 MeV", June 1966. [Phys. Rev. 146, 836-840 (1966)].

16. J. A. Panontin and A. A. Caretto, Jr., "Half-Life of Ag^{101} and Formation Cross Section from Ag and In", June 1966. [J. Inorg. Nucl. Chem. 28, 1795-1801 (1966)].
17. Annual Progress Report, 1965-1966 - June 1966.
18. Larry Borden Church, "A Study of (p,xn) Reactions", Doctoral Thesis, June 1966.
19. William J. Nieckarz, Jr., "Proton Induced Reactions on the Separated Isotopes of Cadmium from 70 to 400 MeV", Doctoral Thesis, September 1966.
20. A. A. Caretto, Jr., " Sn^{118} (p,2p) In^{117} Excitation Functions and Isomeric Ratio at High Energies", 1967. [Nuclear Physics A92, 133-138 (1967)].
21. F. Michael Kiely "Detailed Study of Simple Reactions on Light-A Nuclei", Doctoral Thesis, May 1967.
22. Annual Progress Report, 1966-1967 - June 1967.
23. R. G. Korteling and A. A. Caretto, Jr., "Systematics of ^{24}Na and ^{22}Na Production with 400 MeV Protons", 1967. [J. Inorg. Nucl. Chem. 29, 2863-2878 (1967)].
24. J. A. Panontin, N. T. Porile and A. A. Caretto, Jr., "Nuclear Reactions of Silver and Indium with 200 and 400 MeV Protons", 1968. [Phys. Rev. 165, 1273-1281 (1968)].
25. J. A. Panontin, N. T. Porile and A. A. Caretto, Jr., "Recoil Properties of Products from the Spallation of Silver and Indium", 1968. [Phys. Rev. 165, 1281-1286 (1968)].
26. Annual Progress Report, 1967-1968 - June 1968.
27. L. B. Church and A. A. Caretto, Jr., "A Study of (p,xn) Reactions at 400 MeV", 1969. [Phys. Rev. 178, 1732-1742 (1969)].
28. R. F. Schall, Jr., "Simple Nuclear Reactions on the Separated Isotopes of Tellurium at 300 MeV", Doctoral Thesis, July 1968.
29. D. J. Reuland and A. A. Caretto, Jr., "The Measurement of Some (p,n) and (p,2n) Reaction Cross Sections at 400 MeV", 1969. [J. Inorg. and Nucl. Chem. 31, 1915-1921 (1969)].

30. W. J. Nieckarz, Jr. and A. A. Caretto, Jr., "The Production of In^{111} and In^{114m} from the Separated Isotopes of Cadmium Using 70 to 400 MeV protons", 1969. [Phys. Rev. 178, 1887-1893 (1969)].
31. A. A. Caretto, Jr. and T. T. Sugihara, "Nuclear Concepts as Part of the Undergraduate Chemistry Curriculum", 1970. [J. Chem. Ed. 47, 569-573 (1970)].
32. R. G. Korteling and A. A. Caretto, Jr., "Energy Dependence of Cross Sections for the Production of ^{22}Na and ^{24}Na with 100-400 MeV Protons", 1970. [Phys. Rev. C1, 1960-1971 (1970)].
33. R. G. Korteling and A. A. Caretto, Jr., "Production of ^{18}F , ^{22}Na , and ^{24}Na from Separated Isotopes of the Light Elements with 300 and 400 MeV Protons", 1970. [Phys. Rev. C1, 193-201 (1970)].
34. Allan C. Stalker, "A Recoil Study of (p,n) and (p,2n) Reactions for Proton Bombarding Energies of 100 to 400 MeV; Doctoral Thesis, March 1969.
35. Annual Progress Report, 1968-1969 - June 1969.
36. D. J. Reuland and A. A. Caretto, Jr., "A Model for the Production of (p,n) and (p,2n) Reactions at High Energy", 1970. [Nucl. Phys. A151, 449 (1970)].
37. Y-W. Yu, L. B. Church and A. A. Caretto, Jr., "The Angular Distribution of Recoil Productions from Some Simple Reactions of 400 MeV Protons with ^{58}Ni and ^{197}Au ", 1970. [Nucl. Phys. A152, 295 (1970)].
38. W. J. Nieckarz, Jr. and A. A. Caretto, Jr., "Nuclear Structure Effects in (p,2 Nucleon) Reactions on the Separated Isotopes of Cadmium at 400 MeV", 1970. [Phys. Rev. C3, 1921-1923 (1970)].
39. R. F. Schall, Jr. and A. A. Caretto, Jr., "Nuclear Structure Effects in (p,2 nucleon) Reactions on the Separated Isotopes of Tellurium at 300 MeV", 1970. [Phys. Rev. C3, 1924-1929 (1970)].
40. F. M. Kiely and A. A. Caretto, Jr., "Differential Recoil Study of the $^{25}\text{Mg}(p,2p)^{24}\text{Na}$ Reaction at 300 MeV", 1971. [Phys. Rev. C4, 137 (1971)].
41. Annual Progress Report, 1969-1970 - June 1970.
42. Y-W. Yu and A. A. Caretto, Jr., "The Half-Lives of ^{84}Zr and ^{85}Zr :", 1971. [J. Inorg. and Nucl. Chem. 33, 3223 (1971)].
43. Annual Progress Report 1970-1971 - June 1971.

C00-3239 Report Numbers - C00-3239-1 - C00-3239-17, 1971-1977

1. Annual Progress Report, 1971-1972 - June 1972.
2. Robert Allen Williams, "Transfer vs. Compound Nuclear Mechanisms in the Reaction of Heavy Ions with Medium-Mass Targets", Doctoral Thesis, June 1972.
3. Martin A. Molecke, "Differential Recoil and Angular Distribution Study of Several (p,pxn) and (p,xn) Reactions of ^{133}Cs with 550 MeV Protons", Doctoral Thesis, November 1972.
4. John A. Urbon, "A Study of the Reaction Mechanisms Involved in the Formation of ^{24}Na from ^{75}As at High Proton Bombarding Energies", Doctoral Thesis, February 1973.
5. A. A. Caretto, Jr., P. J. Karol, R. L. Klobuchar, D. M. Montgomery, R. A. Williams and M. V. Yester, "Cross Sections for (π , π n) Reactions on ^{14}N and ^{19}F at (3/2,3/2) Resonance", 1973. [Phys. Letters 44B, 459 (1973)].
6. Annual Progress Report, 1972-1973 - June 1973.
7. M. W. Weisfield, R. A. Williams and A. A. Caretto, Jr., "Mechanisms of Heavy Ion Induced (p,n)- and (n,p)-Type Reactions", 1973. [Phys. Rev. C13, 128 (1975)].
8. M. W. Weisfield, R. A. Williams and A. A. Caretto, Jr., "Evidence for Target-to-Projectile Transfer Mechanisms in Heavy Ion Reactions", 1973.
9. M. V. Yester, A. A. Caretto, Jr., M. Kaplan, P. J. Karol, and R. L. Klobuchar, "Cross Section of (π^+ , π^+ n + π^0 p) Reaction on ^{12}C at the 3/2,3/2) Resonance, 1973. [Phys. Letters 45B, 327 (1973)].
10. R. A. Williams and A. A. Caretto, Jr., "Transfer Versus Compound-Nuclear Mechanism in the Reaction of ^{12}C and ^{11}B with ^{63}Cu and ^{65}Cu ", 1974. [Phys. Rev. C10, 601 (1974)].
11. Annual Progress Report, 1973-1974 - June 1974.
12. Annual Progress Report, 1974-1975 - June 1975.
13. P. J. Karol, M. V. Yester, R. L. Klobuchar and A. A. Caretto, Jr., "Absolute Cross Sections for Pion Reactions on Light Nuclei at the (3,3) Resonance", 1975. [Phys. Letters 58B, 489 (1975)].

14. Mary Anne Yates, "A Systematic Study of Proton- and Alpha-Induced Simple Reactions", Doctoral Thesis, April 1976.
15. P. J. Hornshøj, P. Tidemand-Petersson, R. Bethoux, A. A. Caretto, Jr., J. W. Grüter, P. G. Hansen, B. Jonson, E. Hagberg and S. Mattsson, Phys. Lett. 57B, 147 (1975).
16. M. A. Molecke and A. A. Caretto, Jr., "The Study of (p,xn) and (p,pxn) Reactions and Mechanisms on ^{133}Cs at 550 MeV", Phys. Rev. C15, 719-729 (1977).
17. Summary Report, 1961-1977 - November 1977.

Early Publications on Contract AT(30-1)844

(Joint Contract with Professor T. P. Kohman)

1. J. H. Gray, H. L. Hamster and A. A. Caretto, Jr., "New Nuclide, Kr^{74} ", Phys. Rev. 120, 977-979 (1959).
2. P. Strohal and A. A. Caretto, Jr., "Excitation Functions of (p,2 nucleon) Reactions", Phys. Rev. 121, 1558-1563 (1961).
3. E. R. Merz and A. A. Caretto, Jr., "Neutron Deficient Nuclides of Hafnium and Lutetium", Phys. Rev. 122, 1558-1563 (1961).
4. E. R. Merz and A. A. Caretto, Jr., "Recoil Behavior of the $\text{Cu}^{65}(\text{p,pn})\text{Cu}^{64}$ Reactions", Phys. Rev. 126, 1173-1180 (1962).

Doctoral Dissertations

- 1961 - D. L. Morrison "A Systematic Study of (p,xp) Reactions in the 100-400 MeV Region"
- 1962 - J. G. Gray, III "Excitation Functions and Recoil Behavior of Specific Products from the Interaction of High-Energy Protons with Aluminum, Cobalt, Silver, and Gold"
- 1963 - D. J. Reuland "A 2π -Differential Recoil Study of the $\text{Cu}^{65}(\text{p,pn})\text{Cu}^{64}$ Reactions at Incident Proton Energies of 396 and 130 MeV"
- 1963 - W. J. Treytl "A Systematic Study of (p,n) Reactions in the 100-400 MeV Region"
- 1966 - L. B. Church "A Study of (p,xn) Reactions"
- 1966 - W. J. Nieckarz, Jr. "Proton Induced Reactions on the Separated Isotopes of Cadmium from 70 to 400 MeV"
- 1967 - F. M. Kiely "Detailed Study of Some Simple Reactions on Light-A Nuclei"
- 1968 - R. F. Schall, Jr. "Simple Nuclear Reactions on the Separated Isotopes of Tellurium at 300 MeV"
- 1969 - A. C. Stalker "A Recoil Study of (p,n) and (p,2n) Reactions for Proton Bombarding Energies of 100 to 400 MeV"
- 1972 - R. A. Williams "Transfer vs. Compound Nuclear Mechanisms in the Reaction of Heavy Ions with Medium-Mass Targets"
- 1972 - M. A. Molecke "Differential Recoil and Angular Distribution Study of Several (p,pxn) and (p,xn) Reactions of ^{133}Cs with 550 Protons"
- 1973 - J. A. Urbon "A Study of the Reaction Mechanisms Involved in the Formation of ^{24}Na from ^{75}As at High Proton Bombarding Energies"
- 1976 - M. A. Yates "A Systematic Study of Proton- and Alpha-Induced Simple Reactions"

V. RESEARCH ACTIVITIES AND RESULTS

A. Overview

The main thrust of the research undertaken under this contract has been in the investigation of high energy "simple" nuclear reactions at energies above 100 MeV. These are reactions of the type: (p,n) , $(p,2N)$, $(\alpha,\alpha N)$, (π^+, π^+N) , (p,xn) , etc. The objective of these studies has been to attempt to understand:

(i) The mechanism of the "simple" nuclear reactions. This has been done by measuring the product recoil angular distribution^{1,2} and the range distribution³⁻⁶ resulting from (p,pn) and $(p,2p)$ reactions. The two prime mechanisms for reactions of this type are: (A) Nucleon knockout, in which a bound nucleon is ejected by the incident particle, both collision partners promptly escaping and the residual nucleus left with excitation energy below that needed for particle evaporation. (B) Inelastic scattering followed by nucleon evaporation. In this mechanism the incident particle undergoes an inelastic scattering, a (p,p') event, which leaves the residual nucleus with sufficient excitation energy to evaporate one and only one nucleon.

(ii) The use of simple nuclear reactions as a probe of nuclear structure.

The recoil behavior of the product nucleus resulting from $(p,2 \text{ nucleon})$ reactions, if mechanism (A), above, is dominant should be dependent on the quantum state of the struck nucleon prior to collision. The experimental determination of the recoil range distribution and a comparison with nuclear structure was made in a study of the $^{25}\text{Mg}(p,2p)^{24}\text{Na}$ reaction by Kiely.⁶ In addition, a dependence of the (p,pn) and $(p,2p)$ cross sections on the nucleon density in the skin region of the nucleus was observed by Nieckarz⁷ and Schall.⁸

(iii) Determination of the relative importance of the cascade path vs. evaporation path for several classes of "simple" reactions. In the study of (p,xn) reactions, Church⁹ demonstrated that the dominant pathway involved a p-n charge exchange interaction followed by the evaporation of x-1 neutrons. Similar conclusions could be drawn from other studies, namely: the study of (p,pxn) reactions^{2,7} and the study of (p,xp) reactions. Morrison¹⁰ indicated that the pattern of yields was determined by the initial cascade step.

In addition a number of studies were undertaken in the general area of spallation reactions. The focus of most of this work was to attempt to understand the mechanism for the production of specific products from a variety of targets. For example, the work of Korteling¹¹⁻¹³ was designed to elucidate the

mechanism for ^{24}Na production from a large number of targets at proton energies above 100 MeV. The experiments of Gray,¹⁴ Yu,¹⁵ and Panontin^{16,17} examined the recoil behavior of products in or near the fission region from a series of targets. Finally, the work of Urbon¹⁸ was a detailed experiment in which the angular distribution of ^{24}Na was determined from arsenic at high energies.

Since 1970 a number of problems involving heavy ion reactions was initiated. Again the main thrust for these studies is to determine the reaction mechanism. In particular, the studies have involved the investigation of several kinds of transfer processes and recently, the production probabilities of light fragments using a particle identifier telescope.

B. In the following section a brief summary of the specific results will be presented.

(1) "Simple" Nuclear Reaction Studies

The first experiments initiated by the writer were performed by Morrison¹⁰ in which the systematics of (p,xp) reactions were determined. Before these experiments the literature was essentially devoid of (p,xp) cross sections. It was possible to infer from Morrison's data that (p,xp) reactions took place predominantly by a knock-out or cascade mechanism. Contributions from evaporation paths involving protons are of low importance.

At approximately this same time Strohal¹⁹ undertook to determine a number of (p,pn) reaction excitation functions. His data helped to confirm the observation made by Remsberg and Miller²⁰ that at 400 MeV and for targets above $A=50$, all (p,pn) cross sections are about 60 ± 5 mb.

In 1960 Merz,³ using the thick target-thick catcher recoil technique, studied the $^{65}\text{Cu}(p,pn)^{64}\text{Cu}$ reaction and at essentially the same time Morrison⁴ studied the $^{68}\text{Zn}(p,2p)^{67}\text{Cu}$ reaction. This was the first time that the product recoil behavior resulting from simple reactions had been examined. Both these experiments produced data which exhibited interesting structure but were difficult to interpret. The thick target, thick catcher experiments are not particularly suitable for (p,2 nucleon) reactions because the data interpretation involves difficult averaging problems. Furthermore, the fundamental assumption of this recoil technique, designed for high energy fission, namely of a clear two step momentum deposition process, cannot be easily employed to study the simple reactions.

In view of these difficulties the 2π differential recoil behavior of the $^{65}\text{Cu}(p,pn)^{64}\text{Cu}$ reaction was determined by Reuland and Ganguly.⁵ The technique employed was to examine the number of ^{64}Cu recoil nuclei which penetrate a successively thicker layer of aluminum deposited on an iron backing. The resulting 2π range distribution exhibited peaks, one of which could be associated with target neutrons in the $1f_{5/2}$ state.

Since much of the interpretation of $(p,2 \text{ nucleon})$ reactions involves an understanding of the initial proton-nucleon interaction in a complex nucleus, a survey of (p,n) reactions was carried out by Treytll.²¹ The excitation functions for these reactions exhibited an inverse dependence on incident energy. Furthermore, the magnitude of the (p,n) cross section at any given energy increased roughly with the mass number of the target. However, a structure in the cross section vs. A dependence was discernable and a number of attempts were made to relate this behavior to the population of particular nucleon shells.

In 1964 a survey of the cross sections of (p,xn) reactions was undertaken on a number of targets by Church.⁹ These excitation functions exhibited the same dependence on the inverse of the incident energy for all values of x as was found for the (p,n) reactions. Furthermore, it was observed that the ratio $\sigma(p,2n)/\sigma(p,n)$ correlated with the excitation energy of the isobaric analogue state of the target. If the excitation energy of the isobaric analogue state was above the neutron separation energy in the (p,n) product, then the cross section for the $(p,2n)$ reaction was enhanced. This laboratory was the first to report this important result.

In order to pursue these results, Reuland returned during the summer of 1966 as a postdoctoral research associate and measured several additional (p,n) and $(p,2n)$ pairs.²² Later, he and the writer devised a simple model which explains the observed ratio of $(p,2n)$ to (p,n) cross sections in terms of the enhancement of the population of the isobaric analogue state.²³

Finally, in 1969 Stalker measured several more (p,xn) reactions²⁴ and was able to devise a more rigorous model for predicting (p,xn) cross sections.

In 1970 Nieckarz⁷ and Schall⁸ measured a series of (p,pn) , $(p,2p)$ and (p,n) cross sections on the separated isotopes of cadmium and tellurium, respectively. Their data exhibited a clear dependence of the (p,pn) cross section on the

magnitude of the neutron skin thickness of the various target nuclides. Furthermore, in the case of cadmium, the $(p,2p)$ cross sections exhibited an inverse dependence on the size of the neutron skin thickness, as would be predicted. This discovery was first observed in this laboratory. It has since been observed in other situations including pion initiated nucleon knock-out reactions.

In a collaborative experiment with L. B. Church, who was at the University of Buffalo at the time and was making use of the Saxonburg accelerator, and Yu-Wen Yu, the angular distribution of the (p,pn) product recoils was determined for several targets.¹ The yield of recoils found at 90° is a measure of the contribution to the total reaction from mechanism (B), the (p,p') followed by evaporation mechanism. It was observed that the contribution of this ISE mechanism was sizeable and varied from target to target. This is a very important result not fully appreciated. There are numerous suggestions to use pions as probes of nuclear structure. However, unless the mechanisms for nucleon removal reactions are understood, and the contribution from the various mechanisms determined by experiment, the investigation of nuclear structure will be obscure.

The most ambitious $(p,2 \text{ nucleon})$ product recoil study attempted in this laboratory was undertaken by Kiely.⁶ This was a study of the $^{25}\text{Mg}(p,2p)^{24}\text{Na}$ reaction and involved the determination of the recoil ^{24}Na by electrolytic anodic oxidation of the aluminum catcher foil. His results were compared to a plane-wave calculation and clearly indicated that some of the protons knocked out were in the $1d_{5/2}$ state.

After the phase-out of the Saxonbrug synchrocyclotron some of this work was continued at the Space Radiation Effects Laboratory. Molecke² measured the $^{133}\text{Cs}(p,pn)^{132}\text{Cs}$ reaction at 550 MeV. He was able to measure both the ^{132}Cs angular and range distribution. Although the range distribution could only be determined at a few angles this is the first time that the product recoil double differential cross section was measured for a $(p,2 \text{ nucleon})$ reaction. Again, the results can be correlated with contributions from knock-out processes and inelastic scattering followed by evaporation. The knock-out processes indicate that the (p,pn) interaction takes place with target neutrons residing at the top of the nuclear well. However, his data indicate that the ISE mechanism, mechanism B, accounts for about 80% of the cross section of the $^{133}\text{Cs}(p,pn)$ reaction.

Since considerable evidence exists that most of these "simple" reactions take place in the peripheral region of the nucleus, it was decided that by

changing the incident projectile it would be possible to change the extent of sampling of the skin region. Therefore around 1972 it was planned to initiate experiments where the same products could be made by (p,pn) , $(\alpha,\alpha n)$, and $(\pi^+, \pi^+ n)$ reactions, for example. Thus Yates²⁵ measured $(\alpha,\alpha n)$ and $(\alpha,\alpha p)$ reactions on enriched targets of ^{90}Zr , ^{96}Zr , ^{96}Mo , ^{96}Ru , and ^{106}Pd using the 600 MeV α -beam available at the Space Radiation Effects Laboratory. In addition, approved LAMPF Experiment #123 was designed to measure most of these same cross sections initiated by π^+ and π^- mesons as well as protons. A team consisting of Dr. L. B. Church of Reed College, Dr. Paul Karol of Carnegie-Mellon, Dr. Robert Williams of Los Alamos, Mr. James Clark, a graduate student at Carnegie-Mellon, and the writer have begun these experiments. These experiments are still underway. To date there have been two pion runs at Los Alamos on Experiment #123 and the data acquired is being analyzed. The proton irradiations at LAMPF have been completed.²⁵

During the period from 1971 to 1974 a series of experiments were undertaken at the Space Radiation Effects Laboratory which were designed to compare the cross sections for neutron knock-out reactions as initiated by π^+ and π^- mesons. The motivation for these experiments was the unexplainable results obtained by Chivers et al.²⁶ in which the $\sigma(\pi^-)/\sigma(\pi^+)$ for the neutron knock-out on ^{12}C was 1.0 ± 0.1 as compared to the theoretical value of 3.0. Dr. Dan Montgomery, a postdoctoral research associate who joined the project in 1970, measured pion induced nucleon removal cross sections at the 3/2-3/2 resonance energy on the same targets that the Chivers' group used. He was joined in these experiments by Dr. Paul Karol, Robert Williams, a graduate student of Dr. Caretto, now Dr. Williams, and the writer. Dr. Kaplan and Dr. Klobuchar joined us in a number of these experiments. The results of these measurements clearly indicated that the Chivers' measurements were in error.²⁷⁻²⁹ However, the combination of our π^+ measurements with the π^- values of Reeder and Markowitz³⁰ still did not agree with the theoretical results. Our results were later confirmed by a more ambitious and sophisticated experiment performed at LAMPF by a group from the Los Alamos Scientific Laboratory, Brookhaven National Laboratory and the Argonne National Laboratory.³¹ The results of our pion experiments at the Space Radiation Effects Laboratory provided part of the motivation to initiate LAMPF Experiment #123.

In 1976 a second LAMPF experiment was proposed and approved. This is Experiment #320 by Church and Caretto and involves the study of (π^+, xn)

reactions. The object of this experiment is to determine the excitation energy spectrum following π^+ or π^- absorption. By measuring $(\pi^{\pm}, xn)$ cross sections on isobaric targets in which Z differs by two, the same products are observed for the π^+ and π^- absorption processes. Thus, by comparing the data with cascade-evaporation calculations, the excitation energy can be determined. Very little experimental data currently exist relative to pion absorption processes. The Vegas cascade pion codes assumes pions are absorbed via p-state deltas. The experiments proposed and currently underway should help to justify these fundamental assumptions.

(2) Spallation Reaction Studies

In 1961 Gray¹⁴ measured the excitation functions and thick target-thick catcher recoil behavior of ^{38}S from cobalt, silver, and gold targets. Even at 400 MeV the yields of ^{38}S from gold could only be interpreted as some type of fragmentation process. The ranges were less than that predicted on the basis of a fission mechanism and the yields were far too large if it was assumed that ^{38}S was a spallation residue.

These results were the first of several which indicated that the systematics of spallation in the 100 to 400 MeV region was not well understood. To this date this writer believes that a study of the production characteristics of a number of specific nuclides from different targets would reveal some new and unexpected trends.

Partly based on this philosophy, Korteling, in 1962-1965, initiated a series of studies of the production of ^{24}Na from about 50 different targets.^{11,13} This was a very ambitious project. The data revealed that the cross section for ^{24}Na production exhibited an exponential decrease with increasing atomic number of the target element. In addition, there appeared to be a structure in the cross section dependence superimposed on the exponential trend. The most interesting feature was that the cross section exhibited peaks whenever the difference between the target mass and that of ^{24}Na was approximately equal to particularly stable nuclides such as ^{16}O and ^{40}Ca . This work was extended to include the measurement of the production cross sections of ^{22}Na and ^{18}F . Similar trends were observed.

Finally, a very detailed series of experiments were carried out on the determination of the cross section of ^{18}F , ^{22}Na and ^{24}Na from separated

isotope targets of low mass number.¹² For example, the production cross section of ^{24}Na was determined from targets of ^{25}Mg , ^{26}Mg , ^{27}Al , ^{28}Si , ^{29}Si , ^{30}Si , ^{31}P , ^{32}S , ^{33}S , ^{34}S , ^{35}Cl , and ^{36}S . Detailed data of this type, never before obtained, enabled the prediction of the dominance of the cascade part of the interaction and the importance of the neutron to proton ratio of the target-product system in understanding the yields of the reaction products. Thus, Korteling was able to measure the quantity $d^2\sigma/dAdZ$. This differential quantity is directly related to the nature of the cascade. These data enabled one to show that products with N/Z greater than unity would have a higher cross section from targets with N/Z greater than unity than from targets with N/Z less than unity. Korteling's experiments enabled one to deduce the extent of the cascade path vs. evaporation path directly, rather than to rely on comparisons of spallation results with predictions based on intra-nuclear cascade and evaporation calculations.

The excitation function data¹³ for the production of ^{18}F , ^{22}Na , and ^{24}Na from about 50 targets with $Z > 12$ at energies from 100 to 440 MeV enabled Korteling to devise mathematical expressions to fit these data in terms of probabilities related to the cascade-evaporation model. These expressions are directly related to physically meaningful quantities and, unlike the empirical treatment of Rudstam³² can be used to make predictions related to intranuclear cascade calculations.

In 1964-1965 Panontin measured excitation functions and recoil properties for the production of a large number of products from silver and indium. He initiated this work during the author's leave of absence at CERN (1964-1965). Panontin continued these experiments for about five months after Caretto returned. He then continued his postdoctoral research with Dr. Norbert Porile of Purdue University at which time he continued some of these experiments. As a result a three-way collaboration developed resulting in several publications.^{16,17} The object of these experiments was to ascertain the mechanism for the production of a number of products from silver and indium, to deduce the excitation energies involved, and to explore the nature of the contributing mechanisms. His results were compared with intranuclear cascade and evaporation calculations. Panontin was able to demonstrate a proportional relationship between the ratio of the product recoil momentum to that of a pseudo compound nucleus, P_R/P_{CN} , with the ratio of the excitation energy of

the product recoil to that resulting from a pseudo compound nucleus, E_R^*/E_{CN}^* . He was not the first to suggest this relationship; however he provided considerable data to help substantiate it.

Dr. Yu-Wen Yu joined the research project in 1967, having undertaken postdoctoral work with Professor Blann at the University of Rochester. Dr. Yu became involved in an extensive number of experiments, some of which have already been described. He continued the measurement of the excitation functions and recoil properties of spallation products from a variety of elements, particularly uranium. Some of his data are still to be published. A recurring observation, found in Korteling's work, Panontin's work, and again in Yu's work, was that the cascade-evaporation model was inadequate to explain all the yield and recoil patterns. Furthermore, for some products, fission was definitely not responsible. Thus, some of these data could be interpreted by another process, possibly the elusive fragmentation process. Some of the phenomena observed, such as structure in the recoil fractions, excitation energy anomalies, and peaks in excitation functions are "washed out" at higher energies and thus not observed. Many of these effects should still be investigated, in the 100 to 500 MeV region. There is no doubt that more physics could be learned in a careful examination of these events of low probability.

Motivated by this series of anomalous results, particularly the structure in the ^{24}Na yield distributions as observed by Korteling, Urbon (1967-1973)¹⁸ investigated the mechanism of ^{24}Na production from arsenic. He used the 500 MeV proton accelerator of the space Radiation Effects Laboratory and the 11.7 GeV protons available at the ZGS of Argonne National Laboratory. He determined the ^{24}Na angular distribution and was able to show that his data were inconsistent with the cascade-evaporation mechanism. In fact, the only way he could explain the production of ^{24}Na from ^{75}As at 400 MeV (it is also observed at 100 MeV), which requires a loss of 50 nucleons, was to assume that the ^{75}As splits, possibly at mass 40, and the resulting fragment deexcites to ^{24}Na via a path involving many alpha evaporations.

From 1971 to 1976, Ku investigated the yields of the mass 72 isobaric chain, and nuclides close to it, from molybdenum isotopes. The experiments were undertaken with 500 MeV α -particles from the Space Radiation Effects Laboratory. Dr. Paul Karol directed this research. The object of this research was similar to that of Church and Porile³³ in which the yields of the 72 mass chain were investigated from the targets ^{96}Zr , ^{96}Mo , and ^{96}Ru .

The Gaussian distribution (or skew Gaussian) of yields are observed to peak near the same N/Z of the target. This is again an indication of the importance of the cascade step.³⁴

With the availability of 300 GeV protons at the Fermi Laboratory, in 1973 a collaborative experiment was undertaken to survey the spallation of copper. This experiment was undertaken with Dr. James B. Cumming and Dr. Jerry Hudis of Brookhaven National Laboratory, Dr. Ellis Steinberg and Dr. Sheldon Kaufman of the Argonne National Laboratory, and Dr. Michael Yester and Professor A. A. Caretto, Jr. Dr. Yester was a postdoctoral research associate on this project. The yields of the copper spallation products were measured by gamma counting using Ge(Li) detectors. The three laboratories confirmed each other's work. No appreciable changes in yields take place between 12 GeV and 300 GeV. This work will be published soon.

(3) Heavy Ion Reactions

In 1969 the writer initiated some experiments designed to study heavy ion reactions. Until 1975 these studies were carried out at the Yale University heavy ion linear accelerator.

Robert A. Williams undertook his thesis research in a study of transfer reactions resulting from the interaction of ^{12}C with ^{65}Cu .³⁵ By measuring excitation functions, recoil angular and range distributions, he was able to show that the mechanism for the production of ^{68}Ga involved an α -transfer from the projectile to target followed by neutron evaporation. Furthermore, the yields and recoil behavior of ^{72}As could be interpreted as involving ^8Be transfer mechanism followed by neutron evaporation. As was pointed out by the late J. M. Miller,³⁶ this was one of the few studies of transfer processes which was undertaken by radiochemical techniques in which the heavy fragment was measured rather than the normal technique of detection of light fragments.

During this same period of time, Michael Weisfield, a postdoctoral research associate with the project, undertook the measurement of the cross section of ^{65}Zn and ^{65}Ni from ^{65}Cu irradiated with ^{12}C and ^{11}B projectiles. He also determined the excitation function for the production of ^{65}Zn , its thick target-thick catcher range distribution, and its angular distribution. These data were inconsistent with a compound nucleus mechanism or a transfer mechanism. Furthermore, only an upper limit could be placed on the production of ^{65}Ni . Since ^{65}Zn can be made from ^{65}Cu by a $\Delta T = 0$ isospin transition,

while ^{65}Ni cannot, it was suggested that the ^{65}Zn could be made by a charge exchange process.³⁷

In order to verify this suggestion it was decided to examine the light fragments, particularly the boron fragments, which might be partners to the charge exchange resulting from the conversion of ^{65}Cu to ^{65}Zn . Richard Spector, a graduate student, Dr. Michael Yester, Professor M. Kaplan, and the writer set up a particle identifier telescope at the Yale Heavy Ion Accelerator. The help of Professor Miller is acknowledged. The yields of the boron nuclides exhibited no unusual characteristics and it was thus impossible to conclude that ^{12}B and/or ^{11}B are partners to ^{65}Zn .

The boron Angular distribution measured at Yale did not include angles less than about 16° . Thus, it was decided to remeasure the boron nuclide angular distribution, using the ORIC heavy ion accelerator at Oak Ridge National Laboratory. Special attention was paid to the measurement of the angular distribution at small angles. The data exhibit an interesting structure in the fragment distribution. For example, the distributions in the carbon nuclides exhibit peaks at different masses depending on angle. These data are still being analyzed and thus have not been completely interpreted as yet.

C. Current Research

There are still a number of research projects underway. It is the intention of the writer to continue these studies and hopefully to obtain funding support.

(i) Approved Experiment #123 at LAMPF. The object of this experiment is to measure pion induced nucleon removal reactions on a series of target nuclides chosen to exhibit nuclear structure effects, if present.

(ii) Approved LAMPF Experiment #320. The object of this experiment is to measure (π^+, xn) reactions, to deduce the mechanism of pion absorption processes, and to ascertain if any differences exist in the excitation energy spectrum resulting from π^+ or π^- absorption.

(iii) The Study of double charge exchange in the $^{209}\text{Bi}(\pi^+, \pi^-)^{209}\text{At}$. This study is being undertaken by a graduate student, James Clark, in collaboration with Dr. Jerry Hudis of Brookhaven National Laboratory. This study is part of approved LAMPF Experiment #103.

(iv) The study of light fragments produced in heavy ion reactions will be continued at Oak Ridge National Laboratory. Also, the charge exchange reaction will be investigated in other target-projectile systems.

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