NUCLEAR CHEMISTRY RESEARCH
OF HIGH ENERGY NUCLEAR REACTIONS
AT CARNEGIE-MELLON UNIVERSITY

1972-1973

ANNUAL PROGRESS REPORT

The Nuclear Chemistry Research Project
on the Study of High Energy Nuclear
Reactions at Carnegie-Mellon University
is sponsored by the United States Atomic
Energy Commission under Contract Number
AT(11-1)-3239.

Albert A. Caretto, Jr., Supervisor
Carnegie-Mellon University
Department of Chemistry

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

June 1973

Pittsburgh, Pennsylvania 15213

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
leg

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

PART I. GENERAL REPORT	Page
a. Introduction	1
b. Personnel	1
c. Facilities	2
d. Publications	3
PART II. RESEARCH PROGRESS AND PLANS	
A. High Energy Reactions	
1. Reactions of Light Nuclei with π^+ and π^- Mesons at 190 MeV. M. V. Yester	4
2. Reactions of Copper with Protons at 200 and 300 GeV. M. V. Yester	8
3. Isobaric Yield Curves in the Interaction of 720 MeV Alpha Particles with ^{92}Mo , ^{96}Mo , and ^{100}Mo . T. H. Ku	11
4. A Study of Alpha-Induced Simple Nuclear Reactions. M. A. Yates	13
5. A Differential Recoil and Angular Distribution Study of Several (p,pxn) and (p,xn) Reactions of ^{133}Cs with 550 MeV Protons. M. A. Molecke	16
6. A Study of the Reaction Mechanisms Involved in the Formation of ^{24}Na from ^{75}As at High Proton Bombarding Energies. J. A. Urbon	17
B. Heavy Ion Reactions	
1. Transfer vs Compound Nuclear Mechanisms in the Reaction of Heavy Ions with Medium-Mass Targets. R. A. Williams	19
2. Mechanisms of Heavy Ion Induced (p,n)- and (n,p)-Type Reactions. M. W. Weisfield, R. A. Williams, and A. A. Caretto, Jr.	21
3. Evidence for Target-to-Projectile Transfer Mechanisms. M. W. Weisfield, R. A. Williams, and A. A. Caretto, Jr.	21

RESEARCH PROGRESS REPORT

I. GENERAL REPORT

a. Introduction

This report summarizes progress in research supported by this contract between June 1, 1972 and May 31, 1973. This work made use of the heavy ion accelerator at Yale University, the zero gradient synchrotron at Argonne National Laboratory, the 600 MeV proton and 720 MeV alpha synchrocyclotron of the Space Radiation Effects Laboratory at Newport News, Virginia, and the 300 GeV proton synchrotron at the National Accelerator Laboratory.

It is anticipated that the future research program will continue to make use of these off-site facilities. However, prime emphasis will be centered on research involving pions available at both SREL and the Los Alamos Meson Physics Facility as well as more extensive studies using the 300 GeV protons available at NAL. The Yale University heavy ion accelerator probably will not be used due to lack of suitable manpower.

b. Personnel

This nuclear chemistry research program has continued to be under the direction of Professor Albert A. Caretto, Jr.

Currently there are two graduate students undertaking their doctoral research under this program and one postdoctoral research associate. The following persons were associated with the project during the past contract year:

Postdoctoral Research Associates

Dr. Michael V. Yester, B.S., Physics, Christian Brothers College, 1966; Ph.D., Physics, Iowa State University, 1972, joined the project in September 1972.

Dr. Michael W. Weisfield left July 31, 1972 after having been with the project since September of 1970. Currently he has a nuclear chemistry appointment at ANL on assignment to NAL.

Graduate Students

Mr. Tommy Ku	B.S., National Taiwan University, 1971 M.S., Carnegie-Mellon University, 1973 Continuing at Carnegie-Mellon University for his Ph.D.
Mr. Martin A. Molecke	B.S., Bowling Green State University, 1967 M.S., Carnegie-Mellon University, 1970 Ph.D., Carnegie-Mellon University, 1973 Accepted employment at Westinghouse-Bettis Atomic Power Laboratory
Mr. John A. Urbon	B.S., Wayne State University, 1966 M.S., Carnegie-Mellon University, 1972 Ph.D., Carnegie-Mellon University, 1973 Accepted a postdoctoral research appointment at Washington University with Professor D. G. Sarantites
Mr. Robert A. Williams	B.A., Oberlin College, 1966 M.S., Carnegie-Mellon University, 1969 Ph.D., Carnegie-Mellon University, 1973 Accepted a postdoctoral research appointment at Los Alamos Scientific Laboratory
Miss Mary Anne Yates	B.S., University of Rochester, 1971 M.S., Carnegie-Mellon University, 1973 Continuing at Carnegie-Mellon University for her Ph.D.

c. Facilities

The only major facility acquisition during the past year was a high-resolution gamma-ray spectrometry system. The detector is a Ge(Li) crystal, nominal volume 50 cc, which provides 1.90 keV resolution for the 1332 keV ⁶⁰Co peak with 9.1% efficiency relative to NaI(Tl) at 25 cm. Highest quality performance spectroscopy electronics couple the detector through a 100 MHz-8192 ADC to a 1024 channel Nuclear Data model ND2200 analyzer. This was aquired by Professor Karol by an NSF University matching grant and is available for general use in nuclear chemistry research.

d. PublicationsAccepted for Publication

Cross Sections for $(\pi, \pi n)$ Reactions on ^{14}N and ^{19}F at the $(3/2, 3/2)$ Resonance, P. J. Karol, A. A. Caretto, Jr., R. L. Klobuchar, D. M. Montgomery, R. A. Williams and M. V. Yester, Phys. Letters B (in press). *Penning*

Submitted for Publication

Mechanisms of Heavy-Ion Induced (p, n) - and (n, p) -Type Reactions, M. W. Weisfield, R. A. Williams and A. A. Caretto, Jr., Phys. Rev.

Evidence for Target-to-Projectile Transfer Mechanisms in Heavy Ion Reactions, M. W. Weisfield, R. A. Williams and A. A. Caretto, Jr., Phys. Rev.

Cross Section of $(\pi^+, \pi^+ n + \pi^0 p)$ Reaction on ^{12}C at the $(3/2, 3/2)$ Resonance, M. V. Yester, A. A. Caretto, Jr., M. Kaplan, P. J. Karol, and R. L. Klobuchar, Phys. Letters B.

In Preparation for Publication

Transfer vs. Compound Nuclear Mechanisms in the Reaction of Heavy Ions with Medium-Mass Targets, R. A. Williams and A. A. Caretto, Jr.

Differential Recoil and Angular Distribution Study of Several (p, pxn) and (p, xn) Reactions of ^{133}Cs with 550 MeV Protons, M. A. Moecke and A. A. Caretto, Jr.

A Study of the Reaction Mechanisms Involved in the Formation of ^{24}Na from ^{75}As at High Proton Bombarding Energies, J. A. Urbon and A. A. Caretto, Jr.

A Recoil Study of (p, n) and $(p, 2n)$ Reactions for Proton Bombarding Energies of 100 to 400 MeV, A. C. Stalker and A. A. Caretto, Jr.

Spallation Reactions of Nickel and Zirconium, Y-W. Yu and A. A. Caretto, Jr.

II. Research Progress and Plans

A. High Energy Reactions

1. Reactions of Light Nuclei with π^+ and π^- Mesons at 190 MeV

M. V. Yester

As discussed in previous Progress Reports,^{1,2} the purpose of this study is to investigate pion-nucleon interactions in light nuclei. In particular, the mechanisms for $(\pi^-, \pi^- n)$, $(\pi^+, \pi^+ n)$ and $(\pi^+, \pi^0 p)$ reactions are being studied. Particular attention is being given to the results of Chivers *et al.*³ for the ratio $\sigma_{\pi^+}(Z^A \rightarrow Z^{A-1})/\sigma_{\pi^-}(Z^A \rightarrow Z^{A-1})$ measured for ^{12}C , ^{14}N , and ^{16}O targets. The values obtained were unity within experimental uncertainties. It is expected that such reactions should take place by quasi-free scattering by a nucleon at the $T = 3/2$ pion-nucleon resonance energy. Thus, the expected value of the ratio is $1/3$.

Experimental

Determination of the absolute cross section for the reaction $^{12}\text{C}(\pi^+, \pi^+ n + \pi^0 p)^{11}\text{C}$ at the $(3/2, 3/2)$ pion-nucleon resonance has been the primary emphasis of this study during the year. Two runs were made at the Space Radiation Effects Laboratory (SREL) in which 16 hours and 48 hours of prime time were allocated.

In the first run, three separate determinations of the absolute cross section for the production of ^{11}C were made using our beam monitoring apparatus, consisting of a counter telescope and sampler as discussed in the 1971 Progress Report¹. The downstream member of the counter telescope consisted of a 6" x 6" x 1/4" piece of plastic scintillator (NE 102) mounted to a phototube via an appropriate light pipe. After irradiation this detector assembly was carried to the counting room and used to count the β^+ activity. The absolute disintegration rate was determined by the β - γ coincidence technique; a 5" x 4" NaI(Tl) detector was used for counting the annihilation radiation. The values of 114 ± 2 mb, 65 ± 2 mb, and 127 ± 4 mb were obtained where these results have not been corrected for the presence of muons in the beam which amount to approximately 15% of the total beam intensity.

As there were serious discrepancies between the results, the experimental procedure was examined for possible sources of error, and several observations

were made. The beam intensity was quite low, (about 2×10^4 pions per second) so that the absolute beam intensity could be obtained directly with the counter telescope alone without the aid of the sampler. The value of the absolute beam intensity obtained with the counter telescope differed from the value obtained using information derived from the sampler. The disagreement was a dramatic function of sampler location. It was believed that the discrepancy was attributable to the sensitivity of the sampler to radiation scattered from the walls of the target area. In addition questions were raised concerning the counting setup. In the β - γ coincidence technique the absolute disintegration rate can be determined from a ratio of the β -singles, γ -singles and β - γ coincidences rates solely if the response of at least one of the detectors is independent of the location of the radiation in the source. Since the β^+ detector was composed of a 6" x 6" area of scintillator, then problems could arise if the radioactivity was produced in a corner of the scintillator, as all of the scintillator was not covered by the face of the NaI(Tl) detector. Following these observations plans were made to rectify the above problems.

In addition to the above measurements some relative cross sections were obtained using the stacked foil method.¹ An oxygen target, in the form of B_2O_3 fused into a crystal, was irradiated, and the ratios of the cross sections of $^{16}O(\pi^+\pi^+n + \pi^0p)^{15}O/^{12}C(\pi^+\pi^+n + \pi^0p)^{11}C$ and $^{16}O(\pi^+,x)^{11}C/^{12}C(\pi^+\pi^+n + \pi^0p)^{11}C$ were determined from two separate irradiations. The values obtained for $\sigma_{\pi^+}(^{16}O \rightarrow ^{15}O)/\sigma_{\pi^+}(^{12}C \rightarrow ^{11}C)$ were 0.87 ± 0.09 and 0.85 ± 0.13 as compared to the value measured by Chivers *et al.* of 0.55 ± 0.06 .³ The values for the ratio of $\sigma_{\pi^+}(^{16}O \rightarrow ^{11}C)/\sigma_{\pi^+}(^{12}C \rightarrow ^{11}C)$ were found to be 0.55 ± 0.06 and 0.55 ± 0.08 . No comparison is available for this latter result.

As mentioned previously, modifications were made in the experimental apparatus in preparation for determining the absolute cross section of ^{11}C induced by pion-bombardment of ^{12}C during the 48 hours of prime time. First, 3" disks of plastic scintillator (NE 102), 1/4" thick, were used for the counter telescope, and two scintillator detectors in coincidence were used for the sampler. (Further mention of the sampler arrangement refers to the two detector setup.) Also, the targets used were disks of plastic scintillator (Pilot-B) similar in size as the scintillators used for the counter telescope. The targets were mounted onto a phototube assembly (RCA 8575) in the counting room after irradiation. No changes were made in the apparatus used for gamma

counting. The targets were placed between the two members of the counter telescope and next to the downstream detector. With these modifications, the difficulties with the original setup were overcome. Furthermore, the beam intensity for this second run was $1-2 \times 10^5$ pions per second.

As a check on the counting setup, an auxiliary target-counting system was employed. Disks of paraffin were molded to the size of the scintillator target and irradiated at the same time as the scintillator target. After irradiation the paraffin disks were rapidly melted and, after thorough mixing, approximately 25% of the material was placed in a plastic vial that fit in a well of a 3" x 3" NaI(Tl) well detector. Annihilation radiation was counted. This latter method required an accurate determination of the efficiency for detecting 511-keV gamma rays. This was accomplished with a standardized aqueous solution of ^{22}Na in a vial of equal volume to the ones used with the paraffin.

The values obtained for the ^{11}C cross section for the scintillator targets were 43.0 ± 0.6 mb, 42.1 ± 0.9 mb, and 44.8 ± 0.5 mb for a weighted average of 43.8 ± 0.1 mb. The values obtained with the paraffin target were 41.0 ± 4.0 mb and 49.4 ± 5.0 mb with a weighted average of 44.3 ± 3.1 mb. The overall weighted average is 43.8 ± 0.4 mb which does not include the muon contamination that has been measured by J. Kane of the College of William and Mary at SREL for a 190 MeV π^+ beam. Assuming that $85 \pm 10\%$ of the particles in the beam are pions, a value of 52 ± 6 mb was obtained as compared to the value of 75 ± 4 mb obtained by Chivers et al.³

An attempt was made to measure the beam contamination ourselves by a differential range experiment to separate out the contribution of pions, muons, and electrons. Lead absorbers 3" x 3" x 1/4" were fabricated and placed between the counter telescope. Data of the coincidence counting rate in the counter telescope as a function of absorber thickness were taken in 1/4" increments from 0" to 4 1/2". The data were normalized to a constant beam intensity with the sampler set up to detect scattered radiation from a plexiglass sheet placed in front of the counter telescope. The counting rate in the sampler was quite low such that upon normalization the overall quality of the data was affected to such a degree that no useful information was obtained.

A relative measurement was made with a phosphorus target in the form of red phosphorus packed in a thin aluminum cannister 3" in diameter and 1/4" thick.

A value for the ratio of $\sigma_{\pi^+}(^{31}\text{P} \rightarrow ^{30}\text{P})/\sigma_{\pi^+}(^{12}\text{C} \rightarrow ^{11}\text{C})$ of 0.089 ± 0.6 was obtained.

Conclusion

With the success obtained with the $^{12}\text{C}(\pi^+, \pi^+n + \pi^0p)^{11}\text{C}$ measurement, the same measurement will be made with a π^- beam. In addition, further measurements of the muon contamination in the π^+ beam will be made.

Concerning the discrepancy between our results and Chivers et al. for the $\sigma_{\pi^+}(^{12}\text{C} \rightarrow ^{11}\text{C})$ cross section, if we use our value for the $^{12}\text{C}(\pi^+,)^{11}\text{C}$ monitor reaction combined with our relative value for the production of ^{15}O we obtain an absolute value of 45 ± 6 mb as compared to the Chivers et al. result of 41 ± 4 mb.³ It should be noted that Chivers et al. measured the ^{15}O activity in a different manner compared to that used for determining the ^{11}C activity.

References

1. Nuclear Chemistry Research of High Energy Nuclear Reactions at Carnegie-Mellon University: Annual Progress Report, NYO-2897-43, 1970-1971, p. 5.
2. Nuclear Chemistry Research of High Energy Nuclear Reactions at Carnegie-Mellon University: Annual Progress Report, COO-3239-1, 1971-1972, p. 66.
3. D. T. Chivers, E. M. Rimmer, B. W. Allardyce, R. C. Whitcomb, J. J. Domingo, and N. W. Tanner, Nucl. Phys. A126, 129 (1969).

42420

2. Reactions of Copper with Protons at 200 and 300 GeV

M. V. Yester

The radioactive products formed in the bombardment of copper foils with 200 and 300 GeV protons at the National Accelerator Laboratory (NAL) have been studied. These experiments will provide information on the reaction mechanisms involved at the highest proton energies available, and particular attention will be given to any changes observed compared to similar studies conducted at lower energies. This present study is part of a collaboration with J. Hudis at Brookhaven National Laboratory (BNL) and M. Weisfield at Argonne National Laboratory (ANL). In two separate bombardments, a stack of copper foils, 99.98% pure and 0.0005" thick, with appropriate monitor foils were irradiated by M. W. Weisfield, and individual foils were sent to the participating laboratories for study.

Experimental

a. 200 GeV - One copper foil irradiated for seven hours with 200 GeV protons was received, and a small section of the foil containing the "hot spot" was counted with a Ge(Li) detector. Individual isotopes were identified by gamma energy and half-life. From the usual half-life analysis and correction for relative efficiency of the Ge(Li) detector, relative yields of the reaction products observed were calculated.

b. 300 GeV - A particular reaction product that is of interest is ^{64}Cu . This isotope is not suited to a study by gamma counting, as the only gamma transition is very weak (0.5%). Thus, preparations were made to study ^{64}Cu by β -counting. Two copper foils bombarded with 300 GeV protons for 16 hours were provided for study. One foil was counted in the same manner as before, and the other was used for chemical separation of copper. Since no monitor foils were made available to us, it was necessary to determine the yield of ^{64}Cu relative to the production of other products. A gamma count of the small target section used for the chemical purification of ^{64}Cu was determined prior to performing chemistry. The ratio of the yield of ^{64}Cu to other products in this foil was then available. The copper was precipitated as CuSCN and β -counting was begun.

Results

Because of delays incurred in shipping, the foil from the 200 GeV irradiation did not arrive until 42 hours after the end of bombardment. Thus, only products with half lives greater than 12 hours were studied, and the results are contained in Table I. The results, as presented, are only relative since the beam monitors were measured at BNL and the absolute cross section for the monitor reaction $^{27}\text{Al}(p,3pn)^{24}\text{Na}$ has not been determined. The results are normalized to ^{54}Mn so that a comparison of the results from the different laboratories could be readily made. The choice of normalization of the yields on the yield of ^{54}Mn was based on the consideration that only one gamma ray is emitted in its decay, thus eliminating discrepancies between the experimenters due to summing corrections. Also ^{54}Mn is produced with a high independent yield and has a relatively long half life.

The foils from the 300 GeV bombardment were received approximately 10 hours after the end of bombardment so that it was possible to observe many of the shorter lived products. Partial and preliminary results are given in Table I and are normalized to ^{54}Mn as previously stated.

Conclusions

A comparison of the present results with the 30 GeV results from Hudis et al.¹ is given in Table I. For the comparison, all results are given relative to ^{24}Na , and it is observed that no significant change occurs in the processes involved in the formation of the reaction products between 30 GeV and 200 GeV or 300 GeV.

References

1. J. Hudis, I. Dostrovsky, G. Friedlander, J. R. Grover, N. T. Porile, L. P. Remsberg, R. W. Stoener, and S. Tanaka, Phys. Rev. 129, 434 (1963).

Table I. Ratio of Formation Cross Sections of Cu Spallation Products
at 200, 300, and 30 GeV

Muclide	200 GeV	300 GeV	30 GeV [*]
⁷ Be	0.85 ± 0.09	1.1 ± 0.1	0.84
²⁴ Na	0.31 ± 0.01	0.35 ± 0.03	0.29
²⁸ Mg	-	0.07 ± 0.01	-
⁴² K	0.20 ± 0.04	0.27 ± 0.02	0.23
⁴³ K	0.094 ± 0.004	0.11 ± 0.01	0.08
^{44m} Sc	0.301 ± 0.005	0.37 ± 0.03	-
⁴⁶ Sc	0.34 ± 0.02	-	-
⁴⁷ Sc	0.151 ± 0.004	0.18 ± 0.08	-
⁴⁸ Sc	0.031 ± 0.007	-	-
⁴⁸ V	0.53 ± 0.01	-	-
⁴⁸ Cr	0.012 ± 0.001	0.017 ± 0.001	-
⁵¹ Cr	0.99 ± 0.07	-	-
⁵² Mn	0.324 ± 0.005	0.40 ± 0.03	-
⁵⁴ Mn	1.00 ± 0.07	1.00 ± 0.1	-
⁵² Fe	-	0.015 ± 0.001	0.009
⁵⁹ Fe	0.14 ± 0.03	-	0.12
⁵⁵ Co	0.05 ± 0.01	0.063 ± 0.006	0.07
⁵⁶ Co	0.30 ± 0.02	0.46 ± 0.04	0.46
⁵⁷ Co	0.81 ± 0.03	-	1.16
⁵⁸ Co	1.45 ± 0.03	1.44 ± 0.05	1.445
⁵⁷ Ni	0.030 ± 0.005	0.041 ± 0.004	-
⁶¹ Cu	-	1.04 ± 0.15	0.92

* Data is from Hudis et al.¹ For purposes of comparison, these data have been normalized such that ratio for ⁵⁸Co is 1.445.

Note: only one gamma transition is involved in the decay of ⁵⁸Co.

3. Isobaric Yield Curves in the Interaction of 720 MeV Alpha Particles with ^{92}Mo , ^{96}Mo , ^{100}Mo

T. H. Ku

In 1964 Porile and Church¹ have shown that the distribution of the isobaric chain at mass 72 is a function of the neutron-to-proton ratio of the target nucleus when ^{96}Zr , ^{96}Mo and ^{96}Ru are irradiated with 1.8 GeV protons. The charge of the most probable product with $A = 72$ increases by 0.6 units in going from ^{96}Zr to ^{96}Ru , resulting in large changes in the ratio of pairs of isobars, especially those which fall on the wings of the isobaric curves. They suggested that for medium mass target, the larger probability of producing cascade products far from stability and the higher coulomb barrier experienced by charged particles in this mass region will cause the evaporation process to retain a memory of the original target composition.

Recent work by Thibault-Philippe², looking at the sodium isotopes formed by irradiation of ^{92}Mo and ^{100}Mo with 25 GeV protons, showed that the width of the curve changed from ^{92}Mo to ^{100}Mo while the peak position did not.

The present α -particle experiment is an attempt to provide an answer to the question whether the peak position indeed shifts from one target to another or only the width of the isobaric curves changes thereby leading to large differences in isobaric yield ratios for different targets.

Experimental

Cross sections for the formation of $A = 72$ isobars together with a number of nuclides in the mass range 65-76 in the bombardment of ^{92}Mo , ^{96}Mo and ^{100}Mo with 720 MeV alpha particles have been measured.^{3,4,5}

Bombardments were done in the synchrocyclotron at the Space Radiation Effects Laboratory (SREL). The targets were prepared from enriched isotopes and pressed into 1.5 cm by 2.0 cm pellets using aluminum powder as a binder.

After irradiation, the target pellet and aluminum catcher foils were dissolved in hot H_2SO_4 and H_2O_2 containing carriers of germanium, arsenic, selenium, copper, gallium, and zinc. The solution was then made 5M in HCl and GeCl_4 distilled in a stream of Cl_2 gas which served to oxidize arsenic to its +5 state and prevent volatilization as chloride. Arsenic and selenium

were then distilled in HBr which caused their reduction to the volatile bromides. Selenium was separated from arsenic by SO_2 . The residue solution was then made 3N in HCl and CuS precipitated with H_2S . The H_2S was boiled away from the supernatant and gallium separated from zinc by ether extraction.

After further purifications, the chemical yield for each element was determined gravimetrically.

The activity of the aluminum foil monitors was measured on β proportional counters. The activity of all the other nuclides was determined by gamma counting on Ge(Li) detectors.

Results

Formation cross sections of ^{72}Ga , ^{72}Se , ^{72}As , ^{65}Zn , ^{66}Ga , ^{67}Cu , ^{67}Ga , ^{69}Ge , ^{71}As , ^{73}As , ^{73}Se , ^{74}As , ^{75}Se , ^{76}As for the different targets have been measured with 720 MeV incident alpha particles. Some of these are independent cross sections, some are cumulative. These cross sections may be plotted against the N/Z or $Z-Z_A$ of the products to construct the isobaric yield curves. The uncertainties of the preliminary data around the peak positions are not sufficiently precise at this time to give a definite answer to the question of whether the peak positions have shifted for these three targets. However, it is evident that the width of the curves broadens from ^{92}Mo to ^{100}Mo . For instance, the ratios of independent cross sections of ^{74}As and ^{76}As for ^{100}Mo , ^{96}Mo , and ^{92}Mo are 3.9, 6.3, and > 30 respectively. This effect is much greater than expected from differences in length of cascade-evaporation chains for the three target isotopes. The broadening effect is less pronounced on the neutron deficient side of the peak than the neutron excessive side.

References

1. N. T. Porile, L. B. Church, Phys. Rev. 133, B310 (1964).
2. C. Thibault-Phillipe, Doctoral Thesis, University of Paris, 1971 (unpublished).
3. S. Kaufman, Phys. Rev. 126, 1189 (1962).
4. S. Kaufman, Phys. Rev. 129, 1866 (1963).
5. Collected Radiochemical Procedures, Los Alamos Scientific Laboratory, 1967.

4. A Study of Alpha-Induced Simple Nuclear Reactions

M. A. Yates

In the past several years there has been extensive investigation of the mechanism of simple nuclear reactions induced by high energy (> 100 MeV) protons. The simplest of these, namely (p,pn) and (p,2p) may be explained by the clean knockout mechanism (CKO) of the Serber model. It has been shown^{1,2,3} that there is an apparent correlation between the cross sections for such single nuclear knockout reactions on both the thickness and composition of the nuclear skin.

In the case of alpha bombardment, there are four reasonable mechanisms which would yield a residual nucleus with A one less than the target. The alpha particle could be captured forming an excited compound nucleus which would then lose either two protons and three neutrons or three protons and two neutrons. However, at the high bombardment energy employed in this work, 720 MeV, this mechanism is unlikely.

Analogous to the Serber model, the alpha particle could interact in a rapid cascade step and leave immediately. This interaction could involve either the direct knockout of a single nucleon with no further particle ejection or an inelastic scattering in which sufficient energy is deposited for just one nucleon to evaporate in the second step. There are two important considerations to be noted relative to both of these mechanisms. First, the ejected nucleon must be near the top of the nuclear potential well so that the resulting hole energy will not cause the loss of another particle. Also, the initial interaction is assumed to take place in or near the skin region due to the greatly increased probability that the alpha particle could escape after only one interaction in this part of the nucleus.

The fourth possibility is that, during the cascade step, the alpha particle breaks apart resulting in multiple interactions with some particles leaving promptly and the rest being evaporated later.

It is noted that a fifth mechanism, that of a ${}^5\text{He}$ or ${}^5\text{Li}$ "pick-up" is deemed so unlikely as not to be considered in this case.

The purpose of the present work is to study the effect of nuclear composition on the previously described skin region reactions. A set of targets has been chosen to give maximum systematic variation of Z, A, and N

in medium weight elements. 720 MeV He-ions have been chosen to induce the single nucleon ejection in the following reactions:

where ${}^A_Z = {}^{90}_{Zr}, {}^{96}_{Zr}, {}^{96}_{Mo}, {}^{96}_{Ru},$ and ${}^{102}_{Pd}$.

Cross sections for these will be determined and studied to find any structural effects on the proposed mechanism.

Experimental

To date investigations of the following reactions have been begun:

- 1) ${}^{90}_{Zr}(\alpha, an){}^{89}_{Zr}$
- 2) ${}^{96}_{Zr}(\alpha, an){}^{95}_{Zr}$
- 3) ${}^{96}_{Zr}(\alpha, ap){}^{95}_Y$
- 4) ${}^{96}_{Mo}(\alpha, ap){}^{95m}_{Nb}, {}^{95}_{Nb}$

All irradiations have been completed at the Space Radiation Effects Laboratory at Newport News, Virginia. The targets for (1) and (4) are pressed pellets prepared from enriched isotopes mixed with aluminum powder, while those for (2) and (3) are natural zirconium foil. The products from (1), (2), and (3) are chemically separated immediately following irradiation. The product nuclides are identified by measurement of gamma energy and half-life using lithium-drifted germanium solid-state detectors. The data are analyzed using programs written and revised by Dr. Robert Williams and Dr. Michael Yester on the PDP-9 and Sigma V computers.

Results

The data are now being analyzed; however two preliminary cross sections have been computed as follows:

$${}^{96}_{Mo}(\alpha, ap){}^{95}_{Nb}, {}^{95m}_{Nb} \quad \sigma = 37.3 \pm .9 \text{ mb}$$

$${}^{90}_{Zr}(\alpha, an){}^{89}_{Zr} \quad \sigma = 3.7 \pm .3 \text{ mb}$$

The chemical yields in the latter determination are being rechecked.

References

1. W. J. Nieckarz, Jr., and A. A. Caretto, Jr., Phys. Rev. C2, 1917 (1970).
2. R. F. Schall, Jr., and A. A. Caretto, Jr., Phys. Rev. C2, 1924 (1970).
3. P. J. Karol and J. M. Miller, Phys. Rev. 166, 1089 (1968).

5. A Differential Recoil and Angular Distribution Study of Several (p,pxn) and (p,xn) Reactions of ^{133}Cs with 550 MeV protons

M. A. Molecks

(Abstract from Ph.D. Thesis submitted November 27, 1972)

Differential range and angular distributions of the recoil nuclei produced from the $^{133}\text{Cs}(p,pn)$, $(p,p4n)$, $(p,3n)$, and $(p,6n)$ reactions at 550 MeV have been measured in order to determine the reaction mechanisms occurring. These simple and near-simple reactions have been interpreted in terms of the two stage Serber model of nuclear reactions. Two-body proton-nucleon kinematic calculations simulating the initial cascade portion of the Inelastic Scattering plus Evaporation or Charge Exchange Scattering plus Evaporation mechanisms, essentially specific, simple cases of the Serber model, were performed. Product recoil angles calculated on the basis of this model were in very good agreement with the observed peaking in the experimental angular distributions, which was attributed to the stated mechanisms. The remainder of the experimental distribution, minus the observed transverse peaking, was attributed to a Clean (or possibly Unclean) Knock Out-type mechanism.

Differential ranges (thin target/thin catcher technique) of the recoil nuclei were measured at $0^\circ \pm 30^\circ$ and $90^\circ \pm 30^\circ$ relative to the incident proton beam, as well as over a 2π geometry in order to determine the relative amounts of energy or momentum transferred to the nucleus via different mechanisms for the reactions investigated. Results were compared with extensions of the two-body kinematic model calculations. The differential recoil range and angular distribution data were found to correlate well with the proposed reaction mechanisms.

Also measured radiochemically were the $^{133}\text{Cs}(p,pxn)^{133-x}\text{Cs}$ and $^{133}\text{Cs}(p,xn)^{134-x}\text{Ba}$ cross sections at the single energy of 550 MeV, with values for x extending up to ten, non-inclusively. These data, as well as angular distribution and differential recoil range results were compared with the results of Monte Carlo computations. These calculations utilized the VEGAS program (STEPNO version), which simulates the high-energy cascade phase of the Serber model, and the EVAP program, which simulates the statistical nucleon evaporation phase of the reaction model. Agreement with the experimental data ranged from good to limited in most cases.

6. A Study of the Reaction Mechanisms Involved in the Formation of ^{24}Na from ^{75}As at High Proton Bombarding Energies

J. A. Urbon

(Abstract from Ph.D. Thesis submitted February 9, 1973)

The production of highly charged fragments with $Z \geq 3$ in nuclear reactions with high energy protons and alpha particles has been investigated over a wide range of bombarding energies, and a wide region of targets, from the light mass region of magnesium, aluminum, etc. up to the heavy mass elements such as bismuth and uranium. No single reaction mechanism has been postulated to satisfactorily describe the excitation functions, recoil kinetic energies and differential cross-section angular distributions for these fragments. For the light mass targets, the recoil properties and production cross sections for fragments such as ^{18}F , ^{24}Na , and ^{28}Mg are satisfactorily explained in terms of the two-step Serber model in which a fast cascade of neutrons and protons is followed by a slower de-excitation step; for light targets, this involves the evaporation of nucleons or simple nucleon clusters to form fragments as spallation residues. For heavy mass targets, the recoil properties of these fragments seems to rule out a two-step model in which the second step retains no memory of the first. Their formation is envisioned as taking place through a fast, single step, two-body breakup process. Fragment production from intermediate masses, ranging from iron to silver, has been described by a variety of two-step mechanisms, with varying degrees of success, where the de-excitation step can proceed via a variety of fission mechanisms (emission fission; high temperature fission), spallation or direct fragment evaporation; contributions from a fast fragmentation mechanism have not been ruled out, however.

The $^{75}\text{As}(p,x)^{24}\text{Na}$ reaction yields at energies from 100 MeV to 400 MeV have been shown previously to differ from expected spallation predictions. To ascertain whether this deviation persisted at higher bombarding energies, cross section measurements were made at 550 MeV, 3, 6 and 11.5 GeV. These data, coupled with the 100 MeV to 400 MeV cross sections, were used to construct an ^{75}As - ^{24}Na excitation function. Comparisons were made with

Rudstam's empirical equation which describes the ^{24}Na excitation function behavior in terms of a spallation mechanism, and with Silberberg's and Tsao's fragmentation-spallation formula which incorporates both a spallation and a fission or fission-like contribution to the functional form of the theoretical excitation function. In addition to the integral cross sections, differential cross section angular distribution measurements on the $^{75}\text{As}-^{24}\text{Na}$ system were conducted at 550 MeV and 11.5 GeV, for varying target thicknesses, to provide further data on the ^{24}Na formation mechanism(s). The 550 MeV experimental results were then compared with a variety of theoretical calculations, based on the Serber model, in which the first step of the proton induced reaction was simulated by the VEGAS-STEPNO Monte Carlo computer code, and the de-excitation step was simulated by (1) the EVAP Monte Carlo evaporation code (spallation residue calculations), (2) a high temperature fission program followed by further de-excitation with the EVAP code, and (3) a composite calculation using the results from (1) and (2). After comparisons between the theoretical and the experimental angular distributions were made, it was concluded that none of the simple two-step mechanisms, spallation and high temperature fission, could satisfactorily reproduce the experimental results, but that the combined spallation plus high-temperature fission mechanism could adequately account for the production of ^{24}Na from ^{75}As with high energy protons. In the absence of ^{24}Na recoil kinetic energy data, no conclusion could be made on the applicability of a fast, one-step fragmentation mechanism.

B. Heavy Ion Reactions

1. Transfer vs Compound Nuclear Mechanisms in the Reaction of Heavy Ions with Medium-Mass Targets

R. A. Williams

(Abstract from Ph.D. Thesis submitted June 23, 1972)

The mechanistic processes responsible for the production of nuclides, removed from the completely fused system of target and heavy ion projectile by several mass units, was the subject of this work. Excitation functions and average ranges have been measured for the production of ^{66}Ga and ^{70}As from the reaction of ^{11}B and ^{12}C projectiles with targets composed of the separated isotopes of copper. In addition, angular and range distributions have been determined for ^{12}C reactions with ^{63}Cu and ^{65}Cu . A computer program which simulates the evaporation of particles from a highly excited nucleus, a kinematic analysis of hypothetical reaction pathways, and a quasi-elastic scattering model which includes the effects of nucleon absorption were used in conjunction with the experimental measurements to propose mechanisms by which the observed nuclei, ^{66}Ga and ^{70}As , are produced from the separated isotopes of copper.

A comparison of the experimental results with the predictions, calculated as mentioned above, based on various reaction pathways is summarized in Table I.

Table I. Reaction Mechanisms at 90 MeV Bombarding Energy

Reactants	Observed Nuclei	Methods of Production
$^{12}\text{C} + ^{63}\text{Cu}$	^{66}Ga	CFCN* + α -transfer [†]
	^{70}As	CFCN
$^{12}\text{C} + ^{65}\text{Cu}$	^{66}Ga	α -transfer + (^8Be transfer?)
	^{70}As	CFCN + (^8Be transfer?)

* CFCN denotes complete fussion compound nucleus.

† α -transfer from projectile to target includes deexcitation by nucleon evaporation as part of the reaction pathway.

These proposed mechanisms could only be deduced by combining all the different types of measurements made. No one experiment: excitation function, range distribution, or angular distribution would suffice to determine the reaction pathway.

2. Mechanisms of Heavy Ion Induced (p,n)- and (n,p)-Type Reactions

M. W. Weisfield, R. A. Williams, and A. A. Caretto, Jr.

(Abstract from a paper submitted to Physical Review)

Excitation functions and recoil ranges for the reactions $^{65}\text{Cu}(^{12}\text{C},x)^{65}\text{Zn}$ and $^{65}\text{Cu}(^{11}\text{B},x)^{65}\text{Zn}$ were measured for ^{12}C ion energies between 15 and 122 MeV and for ^{11}B ion energies between 60 and 115 MeV. The angular distribution for the production of ^{65}Zn by the $^{65}\text{Cu}(^{12}\text{C},x)^{65}\text{Zn}$ reaction was determined at 88.6 MeV. The forward projected recoil ranges are not in satisfactory agreement with ranges which would be predicted on the basis of the complete fusion compound nucleus mechanism or the quasi-elastic scattering model. The experimental results are apparently consistent with a charge-exchange mechanism, between projectile and target. The conservation of isospin supports this contention in that only an upper limit could be placed on the production of ^{65}Ni , as might be predicted.

3. Evidence for Target-to-Projectile Transfer Mechanisms

M. W. Weisfield, R. A. Williams, and A. A. Caretto, Jr.

(Abstract from a paper submitted to Physical Review)

Excitation functions up to a maximum projectile energy of about 10 MeV amu⁻¹ are presented for the following reactions: $^{63}\text{Cu}(^{11}\text{B},x)^{58}\text{Co}$, $^{63}\text{Cu}(^{12}\text{C},x)^{58}\text{Co}$, $^{51}\text{V}(^{11}\text{B},x)^{46}\text{Sc}$ and ^{48}V , $^{51}\text{V}(^{12}\text{C},x)^{46}\text{Sc}$, ^{44}Sc , and ^{48}V , and $^{51}\text{V}(^{14}\text{N},x)^{46}\text{Sc}$ and ^{48}V . Average recoil ranges for ^{46}Sc and ^{58}Co products are also included. The predictions of various mechanisms for the formation of products whose mass approximates that of the target are compared with these results; the one most consistent with the data involves the transfer of either a neutron or an alpha particle to the projectile.