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

1973-1974

ANNUAL PROGRESS REPORT

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ABSTRACT

Progress in the study of high energy nuclear reactions between June 1, 1973 and May 31, 1974 is reported. Five different major experiments were investigated:

(i) The $^{48}\text{Ti}(p,2p)^{48}\text{Sc}$ and $^{48}\text{Ti}(p,p\pi^+)^{47}\text{Sc}$ reaction cross sections were measured at 300 GeV. The production ratio of $^{48}\text{Sc}/^{47}\text{Sc}$ was about the same as for other systems at lower energies. These cross sections will be measured at lower energies and the effect of secondaries determined.

(ii) Cross sections for the production of (α,an) and (α,ap) reactions on ^{90}Zr , ^{96}Zr , ^{96}Mo , ^{96}Ru and ^{102}Pd were measured with 700 MeV alpha particles. When final values are available they will be compared with the neutron skin thickness of the target since nucleon knock-out reactions might be expected to be dependent on this quantity,

(iii) The isobaric yield distribution of $A \sim 72$ products from ^{92}Mo , ^{96}Mo , and ^{100}Mo has been determined using 700 MeV alpha particles. The peak position of the distribution seems insensitive to target composition, however the yields in the wings varies markedly with target, the neutron excess yields increasing with increasing neutron number of the target.

(iv) Pion-neutron knock-out reaction cross sections were measured at the $3/2-3/2$ pion nucleon resonance energy. The value for the $^{12}\text{C}(\pi^+, \pi^+ n + \pi^0 p)^{11}\text{C}$ reaction is 52 ± 6 mb distinctly different from a previously reported value. Cross sections for other target systems are also reported.

(v) A study of α -transfer reactions involving the interactions of heavy ions with ^{63}Cu and ^{65}Cu to produce ^{68}Ga and ^{71}As is reported. The probability of the various mechanisms is discussed.

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R E S E A R C H P R O G R E S S R E P O R T

I. GENERAL REPORT

a. Introduction

This report summarizes progress in research supported by the U. S. Atomic Energy Commission between June 1, 1973 and May 31, 1974. Investigations currently underway and reported here made use of off-site accelerator facilities at the zero gradient synchrotron at Argonne National Laboratory, the 600 MeV proton and 720 MeV alpha synchrocyclotron at the Space Radiation Effects Laboratory at Newport News, Virginia, and the 300 GeV proton synchrotron at the National Accelerator Laboratory.

A summary of the connection between research problem and off-site accelerator usage is as follows:

<u>Research Investigation</u>	<u>Researcher</u> *	<u>Off-site Facility</u>	<u>No. of hours of Irradiation</u>
Simple Nuclear Reactions at 300 GeV (Report II-A-1)	Postdoctoral Research Associate	National Accelerator Laboratory.	73 hours in three runs
Simple Proton and Alpha Induced Reactions (Report II-A-2)	Graduate Student	Space Radiation Effects Laboratory (α-studies) and Los Alamos Meson Physics Facility (proton studies)	36 hours 4 hours
Isobaric Yield Distributions (Report II-A-3)	Graduate Student	Space Radiation Effects Laboratory	36 hours
Simple Pion Induced Reactions (Report II-A-4)	Postdoctoral Research Associate Several Graduate Students Prof. P. J. Karol	Space Radiation Effects Laboratory	80 hours June 1974
Pion Induced Reactions (Report II-A-5)	Postdoctoral Research Associate Prof. P. J. Karol Several Graduate Students	Los Alamos Meson Physics Facility Approved Experiment #123	This is to be allocated in 1974

* The Principal Investigator was involved in all of these investigations.

In the future prime research emphasis will involve the study of pion induced reactions at LAMPF. Research problems involving the study of the interaction of 300 GeV protons with complex nuclei will be continued at NAL. However, these problems probably will not receive a major emphasis.

During the past year a new graduate student has expressed his desire to undertake research under the direction of the principal investigator and is expressly interested in heavy ion reaction studies. Depending on the prospects for continued support of the Heavy Ion Accelerator at Yale, a new research problem may be initiated there. Barring this the Berkeley facilities may be used.

It is anticipated that most of the research at the Space Radiation Effects Laboratory will be phased out over the next year or so.

b. Personnel

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

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

Postdoctoral Research Associate

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

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. Richard Spector	B.S., Carnegie-Mellon University, 1973.
Miss Mary Anne Yates	B.S., University of Rochester, 1971 M.S., Carnegie-Mellon University, 1973 Miss Yates is presently at the Los Alamos Scientific Laboratory continuing her Ph.D. research by carrying out proton irradiations utilizing Los Alamos Meson Physics Facility

c. Facilities

In the past year a new ADC, Northern Scientific, Model NS-623, 8192 channels, 100 MHz, and the necessary interfacing, was obtained for use with the PDP-9 Computer as a 4096 channel analyzer. This system now has the capability to function as a 1024 or 4096 channel analyzer with excellent stability. In addition, a new power supply, Power Designs, Model AEC-5000, 5000 volt DC, and amplifier, Canberra, Model 1413 spectroscopy amplifier was obtained for use with Ge(Li) detectors owned by the group.

d. Publications

Published

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 44B, 459 (1973).

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 45B, 327 (1973).

Accepted for Publication

Transfer versus Compound Nuclear Mechanism in the Reaction of ^{12}C and ^{11}B with ^{63}Cu and ^{65}Cu , R. A. Williams and A. A. Caretto, Jr., Phys. Rev. (in press).

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.

In Preparation For Publication

Differential Recoil and Angular Distribution Study of Several (p,pxn) and (p,xn) Reactions of ^{133}Cs with 550 MeV Protons, M. A. Molecke 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. $^{48}\text{Ti}(p,2p)^{47}\text{Sc}$ and $^{48}\text{Ti}(p,p\pi^+)^{48}\text{Sc}$ Cross Sections at 300 GeV

M. V. Yester

Initial studies of the yields of products formed in the bombardment of copper with 200- and 300-GeV protons have showed no noticeable major differences compared to similar studies performed at 30 GeV.¹ To further explore different mechanisms that might be occurring at the higher energies, the cross sections for the $(p,2p)$ and $(p,p\pi^+)$ reactions in ^{48}Ti have been measured at 300 GeV in three separate irradiations at the National Accelerator Laboratory (NAL).

Experimental

The separated isotope of ^{48}Ti , in the form of TiO_2 and enriched to 99.13% ^{48}Ti , with 0.46% ^{46}Ti , 0.26% ^{47}Ti , 0.19% ^{49}Ti , and 0.17% ^{50}Ti , was used as the target material. Two targets were prepared by sedimentation of the powder onto an aluminum backing (0.0005 in. thick) in an acetone and Duco cement medium. After the acetone evaporated, a thin layer of TiO_2 ($\sim 4.0 \text{ mg/cm}^2$) covered by a thin layer of Duco cement and bound to the aluminum backing remained. The third target was formed in a slightly different manner. The enriched TiO_2 powder was sedimented as before but no Duco cement was added. Instead the dried sediment was covered by a piece of aluminum foil similar to that used for the backing and this sandwich was pressed in a 1.5 cm x 2.0 cm die under a force of 20 tons. A further discussion of this type of target preparation is presented elsewhere.² Thus the problem of damage to the Duco cement due to heating by the intense proton beam as encountered in the second irradiation was alleviated. It should be noted that the proton beam at the target position was 1 cm x 1 mm and precaution was used in mounting the target in the beam to insure that the beam was near the center of the 2.0 cm x 1.5 cm target.

The irradiations were handled by Dr. M. W. Weisfield at NAL. After irradiation the targets were shipped back and the usual gamma counting was initiated. The 159-keV gamma ray in the decay of ^{47}Sc and the 1037-keV gamma ray in the decay of ^{48}Sc were counted with a Ge(Li) detector.

The $^{27}\text{Al} \rightarrow ^{24}\text{Na}$ reaction was used as the monitor reaction and the monitors were counted with β -proportional counters or were gamma counted with a Ge(Li) detector.

The amount of titanium contained in the samples counted for the first two irradiations was determined spectrophotometrically using the yellow complex formed by the reaction of titanium and hydrogen peroxide in a sulfuric acid solution. The amount of titanium in the third target was determined gravimetrically although this will be checked using the spectrophotometric method.

Results

The ratios of the formation of ^{47}Sc to ^{48}Sc obtained for the three runs are 174 ± 29 , 177 ± 10 , and 166 ± 11 , respectively. Assuming that the monitor reaction is constant above 10 GeV with a value of 8.6 mb, the value obtained for the $^{48}\text{Ti}(p,2p)^{47}\text{Sc}$ cross section is 24 ± 2 mb. As the $(p,p\pi^+)$ cross section is quite small, contributions from reactions due to secondaries produced in the target and from the $^{49}\text{Ti}(p,2p)^{48}\text{Sc}$ and $^{50}\text{Ti}(p,2pn)^{48}\text{Sc}$ reactions must be accounted for.

A study of the effect of secondaries was initiated by varying the target thickness. The thicknesses used (including aluminum monitor and guard foils) to date are 21 mg/cm^2 , 27 mg/cm^2 , and 13 mg/cm^2 , respectively, for the three ratio results listed above. The values of the ratios of formation of ^{47}Sc to ^{48}Sc do not follow the expected trend if secondaries are contributing to the ^{48}Sc yield.

Estimates of the $^{49}\text{Ti}(p,2p)$ and $^{50}\text{Ti}(p,2pn)$ contribution have been made. From these estimates the value of the $^{48}\text{Ti}(p,p\pi^+)^{48}\text{Sc}$ cross section is taken to be $75 \pm 15 \text{ } \mu\text{b}$. For comparison at lower energies, the $^{65}\text{Cu}(p,p\pi^+)^{65}\text{Ni}$ cross section is $200 \text{ } \mu\text{b}$ at 2 GeV and $93 \text{ } \mu\text{b}$ at 28 GeV³ while the cross section for the same reaction in ^{27}Al is $138 \text{ } \mu\text{b}$ at 1.7 GeV and $62 \text{ } \mu\text{b}$ at 28 GeV.⁴

Future

The contributions to the production of ^{48}Sc from the ^{49}Ti and ^{50}Ti contaminations will be determined experimentally. The ratio of ^{49}Ti to ^{50}Ti in the enriched powder is virtually the same as that found in natural

titanium. A thick target stack containing natural and enriched titanium targets will be irradiated and, from the ratio of formation of ^{48}Sc in each, the correction for the presence of ^{49}Ti and ^{50}Ti in the enriched target thickness will be of the order of 70 mg/cm^2 , with the enriched titanium target itself the same thickness as before, a better check on the contributions due to secondaries will be possible.

The same study of the $(p,2p)$ and (p,pn^+) reactions in ^{48}Ti will be performed at the Zero Gradient Synchrotron at Argonne National Laboratory to provide a direct comparison to results at lower energies.

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2. Study of (α , α nucleon) Reactions at High Energies

M. A. Yates

Introduction

In June, 1972, a study was begun to investigate the possible effect of target neutron skin thickness on the cross section of (α , α nucleon) reactions.¹ Targets in the vicinity of $A \approx 100$ were selected so that the dependence of the cross section on the variation of neutron number with constant proton number and the variation of proton number with constant neutron number could be measured. The overall scope of this study is to measure single nucleon knock-out reaction cross sections of the type $A(X,XN)B$, where X may be a pion, proton, or alpha particle, and N either a proton or neutron. These measurements will be made on a series of nuclides having a systematic change in skin thickness. Specific reactions under study to date are illustrated in Figure 1.

Experimental

Irradiation: The irradiations were performed in the internal alpha beam of the synchrocyclotron at the Space Radiation Effects Laboratory, Newport News, Virginia. Target stacks containing the targets, monitors, and catchers were inserted to a radius of 87.5 ± 1.0 inches corresponding to an alpha energy of 707 ± 7 MeV.²

For the targets of ^{90}Zr , ^{96}Mo , ^{96}Ru , and ^{102}Pd , enriched isotopes were obtained from Union Carbide Corporation's Nuclear Division at Oak Ridge. In all cases a known amount of the enriched isotope was thoroughly mixed with a known amount of aluminum powder, and portions ranging from 239 mg to 320 mg were pressed into 1.5 x 2.0 cm pellets.

Since the lighter zirconium isotopes are not likely to cause interference in the production of ^{95}Zr and ^{95}Y , natural zirconium foil was used for the ^{96}Zr targets.

Radiochemical purification of the reaction products from the ^{40}Zr and ^{96}Zr targets was performed immediately after irradiation. The analysis of product decay for these and the other targets was undertaken at Carnegie-Mellon University.

All the product activities were determined by the measurement of gamma spectra taken with lithium drifted germanium solid state detectors. The beam intensity was determined by measurement of the yield of ^{24}Na from ^{27}Al by beta detection. Decay curves of all species of interest were fit by a least squares decay curve analysis program. This served both to verify the half-life and compute the activity at end of bombardment.

Cross Section Calculations

The cross section of each product was determined by the standard relationships taking into account the growth of daughter activity prior to chemical separation.

In the case of the ^{102}Pd targets, a correction was applied for the production of ^{101}Pd and ^{101m}Rh from the heavier isotopes of palladium present in the enriched ^{102}Pd target. For example, ^{102}Pd was enriched to 75.45% and ^{104}Pd was present to 12.13%, the balance being heavier isotopes of palladium. Similar corrections were not necessary for the other targets since the target isotope was always enriched to greater than 96%.

Using the data of Nieckarz³ in which the cross section of (p,pxn) and (p,2pxn) reactions was reported, it is possible to estimate the contribution of ^{101}Pd and ^{101}Rh from the heavier palladium isotopes taking into account the differences between proton and alpha particle induced reactions.

Results

The computed cross sections are presented in Table I. At present the separate values for $^{96}\text{Zr}(\alpha, \text{ap})^{95}\text{Y}$, $^{96}\text{Zr}(\alpha, \text{an})^{95}\text{Zr}$, and $^{102}\text{Pd}(\alpha, \text{ap})^{101g}\text{Rh}$ have not been determined. Since no chemical separation was performed on ^{96}Ru or ^{102}Pd targets, the values for ^{95g}Tc and ^{101m}Rh were corrected for the decay of the parent nuclides of ^{95}Ru and ^{101}Pd respectively.

The product yield isomeric ratio will be determined wherever possible. Thus far isomeric yield ratios for the production of ^{95}Nb and ^{95}Tc have been determined and the ratio for ^{101}Rh will be obtained soon. Uncertainties quoted reflect reproducibility of multiple measurements.

Although these results are still incomplete and preliminary, the (α, an) and (α, ap) cross sections do not appear to follow the trend of

Table I. Results

Target	Neutron Skin Thickness (Fermi)	Reaction	Cross Section (mb)	Product Isomeric Ratio (m/g)
$^{90}_{40}\text{Zr}_{50}$	0.1400	(α ,an)	132.9 ± 6.8	
$^{96}_{40}\text{Zr}_{56}$	0.2238	(α ,an) + (α ,ap)	140.1 ± 9.4	
$^{96}_{42}\text{Mo}_{54}$	0.1612	(α ,ap) meta state	19.0 ± 3.8	0.77
		(α ,ap) ground state	25.5 ± 5.1	
		(α ,ap) total	44.5	
$^{96}_{44}\text{Ru}_{52}$	0.0986	(α ,an)	84.8 ± 5.8	0.61
		(α ,ap) meta state	24.5 ± 0.1	
		(α ,ap) ground state	36.7 ± 11.3	
		(α ,ap) total	61.2	
$^{102}_{46}\text{Pd}_{56}$	0.1208	(α ,an)	85.8 ± 0.3	
		(α ,ap) meta state	32.7 ± 4.9	

neutron skin thickness as has been reported for the analogous (p,pn) and (p,2p) reactions.^{4,5} A possible explanation for this observation is that perhaps most of the alpha induced nucleon knock-out reactions take place by an (α,α') scattering followed by neutron or proton evaporation. It will be necessary to determine from angular distribution experiments the extent of direct alpha-nucleon knock-out versus (α,α') followed by nucleon evaporation.

Beginning January 1, 1974 a similar study of the effect of target neutron skin thickness on the cross section of (p,2 nucleon) reactions has been initiated using the 700 MeV protons available at the Clinton P. Anderson Meson Physics Facility at Los Alamos. The same target systems will be studied and data collection will begin soon.

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

Tommy Hsiu-Heng Ku

The work described in the last progress report¹ has been continued during this report period. Through September 1973, four targets each of ^{92}Mo , ^{96}Mo , and ^{100}Mo had been irradiated and analyzed for $A=65 \rightarrow 75$ products. Results of poor reproducibility were obtained from these runs. It is believed that problems associated with dissipation of heat from the high flux beam ($\sim 10^{12}$ alphas/cm²-sec) passed through the thick pellet targets (prepared by pressing enriched target powder mixed with Al powder, ~ 60 mg/cm²) very probably might have caused loss of volatile products. In fact, irradiated target stacks sometimes showed physical evidence of evaporation or fusion even with reduced beam intensity.

To avoid the product volatilization problem, a new technique was developed to prepare thinner targets. This technique consists of a modified sedimentation of powdered target material onto thin aluminum backing followed by pressing. It provides a convenient way to prepare uniform target stacks with thickness ranging from 1 to 20 mg/cm². In this work, 5 to 8 mg/cm² target material is used.

So far four runs each of ^{92}Mo and ^{96}Mo , and three runs of ^{100}Mo have been carried out using the thin targets. The cross sections obtained from different runs are in good agreement even though the beam intensities for these runs vary by a factor of as much as three.

Chemical Procedures

Improvements have been made on the purification and precipitation steps so that accurate chemical yields could be obtained. The gravimetric yields were also confirmed by spectrophotometric methods.

Since the ^{72}Zn cross sections are very small, special runs with long bombardment times were performed to obtain the yield of ^{72}Zn relative to ^{65}Zn . After irradiation, the molybdenum target powder was dissolved and zinc extracted at pH 7.5 into dithizone phase with diethanoldithiocarbamate as masking agent.^{3,4} After back extraction into 2N HCl, the zinc solution was purified by running through a Dowex 1-8 ion exchange column. Zinc was

then precipitated as $\text{ZnHg}(\text{SCN})_4$ and counted on a NaI detector. One measurement on each of ^{96}Mo and ^{100}Mo has been completed.

Results

The cross sections are listed in Table I using the value of 24 mb for the $^{27}\text{Al}(\alpha, \alpha 2\text{pn})^{24}\text{Na}$ monitor reaction. The uncertainties have not been evaluated at this time. Germanium samples are currently being analyzed on a thin Ge X-ray detector to provide ^{68}Ge ^{71}Ge data. Note that since about 20% of $^{73\text{m}}\text{Se}$ decays directly to ^{73}As , the listed $^{73}\text{Se} + ^{73\text{m}}\text{Se}$ value should be higher while that of ^{73}As lower.

Isobaric Yield Curves

The measured cross sections are used to construct isobaric yield distribution curves. The following corrections have to be considered:

1. Nuclides with masses other than 72 have to be corrected for mass yield effect to fit the $A = 72$ curves. As a first approximation the assumption is made that the mass yield relationship between two adjacent product chains is:

$Y_A = (Y_{A+1})(X)$, where the mass yield coefficient X represents an average change in mass yield per mass number in the region of interest. It is further assumed that the form of the mass yield curve does not vary greatly from target to target over a small mass range such as between ^{92}Mo and ^{100}Mo . Then one can write, for example,

$(Y_{72})_{92\text{Mo}} = (Y_{72})_{100\text{Mo}} \cdot (X)^8$, where $(Y_{72})_{92\text{Mo}}$ and $(Y_{72})_{100\text{Mo}}$ are the chain yields at $A = 72$ from ^{92}Mo and ^{100}Mo targets respectively.

From the measured $A = 72$ chain yields (the cross sections for the stable ^{72}Ge have to be estimated first), the mass yield coefficient X is calculated to be about 1.1; or about 10% correction for the change of one mass unit. This value is comparable with the result obtained by Karol⁵ for alpha spallation of copper.

2. The independent yields of nuclides for which only cumulative yields are available must be estimated.

Cumulative cross sections are used to estimate independent yields with a successive approximation technique. The principle used in this pro-

Table 1. Spallation Cross Sections^a (mb)

		⁹² Mo (98.27%)	⁹⁶ Mo (96.80%)	¹⁰⁰ Mo (97.42%)
⁷³ Se + ^{73m} Se		18.1	*	3.91
⁷² Ga	b	0.030	0.178	0.330
⁶⁷ Cu	b	0.096	0.220	0.380
⁶⁹ Ge	b	15.9	7.47	3.22
⁶⁷ Ga	b	14.7	7.58	3.33
⁷⁶ As	c	0.133	0.511	1.95
⁷¹ As	b	21.4	11.1	4.70
⁷⁴ As	c	2.72	4.69	4.78
⁶⁵ Zn	b	13.6	6.73	2.04
⁶⁶ Ga	b	8.32	3.27	1.16
⁷² Zn	b	*	0.023	0.086
⁷⁵ Se	b	38.1	*	16.0
⁷² Se	b	10.4	*	1.37
⁷² As	c	13.1	*	5.20
⁷³ As	c	16.2	*	9.63
⁶⁸ Ge	b	*	*	*
⁷¹ Ge	c	*	*	*

^a not corrected for minor isotopic constituents of the targets

^b cumulative yield

^c independent yield

* will be available later

cedure is to require extrapolated and/or interpolated independent yields for a particular mass chain to add up to the measured cumulative yield for that chain. This correction can vary greatly in significance depending on whether the precursors lie on the peaks or wings of the curves.

After both corrections, the isobaric yield curves are plotted in Fig. 1. For easier comparison and consistent with the argument in (1), the ^{96}Mo and ^{100}Mo curves are normalized to cover the same area as the ^{92}Mo curve.

Discussion

The neutron to proton ratio of the initial system (incident particle plus target nucleus) in the present work is 1.182 for ^{92}Mo , 1.273 for ^{96}Mo and 1.364 for ^{100}Mo . The results indicate the yields of products far from maximum are strongly affected by these ratios. For example, the isobaric yield ratio of $^{72}\text{Zn}/^{72}\text{Ga}$ increases from 0.129 for ^{96}Mo to 0.261 for ^{100}Mo , and $^{72}\text{Ga}/^{72}\text{As}$ ratio increases from 2.29×10^{-3} for ^{92}Mo to 6.35×10^{-2} for ^{100}Mo , i.e., a more neutron excess target favors formation of neutron excess nuclides. This memory effect is clearly illustrated by the isobaric yield curves; the slope on the neutron excess wing decreases (in a negative sense) from ^{92}Mo to ^{100}Mo therefore broadening the curve for the neutron excess target. The slope seems to remain unchanged on the neutron deficient side. There seems to be only a slight shift in the peak positions for the three targets. However, the uncertainties around the peak positions cannot give a definite answer at this time.

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Fig.1. Isobaric Yield Curves ($A=72$) from Mo targets

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

M. V. Yester

As discussed in previous Progress Reports,^{1,2,3} 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.*⁴ for the ratio $\sigma_{\pi^+}(^A Z \rightarrow ^{A-1} Z) / \sigma_{\pi^-}(^A Z \rightarrow ^{A-1} Z)$ 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 via quasi-free scattering by a nucleon at the $T = 3/2$ pion-nucleon resonance energy, and the expected value of the ratio is $1/3$.

Results

To date the absolute cross section for the $^{12}\text{C}(\pi^+, \pi\text{N})^{11}\text{C}$ has been measured, and a value of 50 ± 4 mb was obtained.⁵ In addition, the ratio of the $(\pi^+, \pi\text{N})$ cross sections relative to that of ^{12}C have been measured for ^{14}N , ^{16}O , ^{19}F , and ^{31}P , as well as, the ratio of the $(\pi^-, \pi^- n)$ cross section for ^{19}F relative to ^{12}C .⁶ A summary of the present results is given in the following table:

(Target, $^A Z \rightarrow \text{Product}^{A-1} Z$)	$\frac{\sigma_{\pi^+}(^A Z \rightarrow ^{A-1} Z)}{\sigma_{\pi^+}(^{12}\text{C} \rightarrow ^{11}\text{C})}$	$\sigma_{\pi^+}(^A Z \rightarrow ^{A-1} Z)$	$\frac{\sigma_{\pi^-}(^A Z \rightarrow ^{A-1} Z)}{\sigma_{\pi^-}(^{12}\text{C} \rightarrow ^{11}\text{C})}$
$^{12}\text{C} \rightarrow ^{11}\text{C}$	----	50 ± 4 mb	----
$^{14}\text{N} \rightarrow ^{13}\text{N}$	0.236 ± 0.018	12 ± 1	----
$^{16}\text{O} \rightarrow ^{15}\text{O}$	0.86 ± 0.09	43 ± 6	----
$^{19}\text{F} \rightarrow ^{18}\text{F}$	0.652 ± 0.012	33 ± 3	0.614 ± 0.014
$^{31}\text{P} \rightarrow ^{30}\text{P}$	0.89 ± 0.06	44 ± 5	----
$^{14}\text{N} \rightarrow ^{11}\text{C}$	0.525 ± 0.022	26 ± 2	----
$^{16}\text{O} \rightarrow ^{11}\text{C}$	0.55 ± 0.006	28 ± 4	----
$^{19}\text{F} \rightarrow ^{13}\text{N}$	0.107 ± 0.034	5.4 ± 1.8	----
$^{19}\text{F} \rightarrow ^{11}\text{C}$	0.186 ± 0.017	9.3 ± 0.9	----

Future

Beam time of 80 hours has been granted for a run at SREL in the near future. At this time the absolute cross section for the $^{12}\text{C}(\pi^-, \pi^- n)^{11}\text{C}$ reaction will be measured. In addition the ratios of the $(\pi^-, \pi^- n)$ cross sections for ^{14}N , ^{16}O , and ^{31}P relative to ^{12}C will be obtained. Also, the beam purity (fraction of pions in the beam) will be measured by performing a range measurement with a suitable material for our particular counting geometry.

At the conclusion of these measurements, ratios for the cross sections $\sigma(\pi^+, \pi N)/\sigma(\pi^-, \pi^- n)$ will be known for several light elements at the $(3/2, 3/2)$ pion-nucleon resonance. This information will be used to clarify existing experimental data and provide new data for theoretical interpretations.

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5. Nuclear Structure Effects in Pion Induced Nuclear Reactions

Summary of Accepted Proposal #123, LAMPF

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The objective of these proposed experiments is to determine the cross sections of two classes of nuclear reactions induced with π^+ and π^- mesons, both on and off the $3/2-3/2$ resonance, on a series of targets designed to elucidate the effect of different aspects of nuclear structure on production yields. The two classes of reactions to be studied are (i) simple pion-induced reactions, and (ii) pion-induced "deep" spallation.

i) Pion-Induced Simple Nuclear Reactions

The cross sections to be measured are for reactions analogous to (p,pn), (p,2p) and (p,n) reactions, namely:

$$Z^A(\pi^\pm, \pi^\pm n)Z^{A-1} \quad (1^\pm)$$

$$Z^A(\pi^\pm, \pi^\pm p)Z^{A-1} \quad (2^\pm)$$

$$Z^A(\pi^\pm, \pi^0)Z_{\pm 1}^A \quad (3^\pm)$$

Cross section measurements for reactions $(1^\pm)$ and $(2^\pm)$ on a series of target isotopes and isotones would be expected to probe the quasi-free scattering nature of the reaction mechanism helping to clarify the apparent discrepancy between theory and existing experimental results.

Anticipating that reactions $(1^\pm)$ and $(2^\pm)$ take place in the peripheral-spatial region of the nucleus, the changing neutron to proton density ratio in this "skin" region for the various targets selected should effect the reaction probabilities in a manner analogous to what has been observed for (p,pn) and (p,2p) reactions. Because of the large pion-nucleon interaction cross section at the resonance, one anticipates that these and the $(3^\pm)$ reactions would be even more sensitive to skin structure than the equivalent proton-induced reactions thereby hopefully providing information regarding the existence and extent of the neutron halo.

Several isomer yield ratios are implicitly accessible in these investigations and would be expected to provide insight regarding population

of particular "hole" states in the residual nuclei.

ii) "Deep" Spallation Reactions

Of considerable importance to understanding the nature of complex high-energy nuclear reactions are the isobaric production cross sections of one or more mass chains. Targets chosen for these studies will be the same as in part (i). Thus the detailed effects of systematically changing Z , N , and A should become evident. In particular a given isobaric yield distribution is to be determined for each target nuclide in order to establish the effect of target structure on production probabilities. This information is of fundamental importance in constructing the yield surface from spallation reactions and must be carefully determined in order to make meaningful comparisons between proton and pion interactions with complex nuclei.

THE FOLLOWING IS A PREPRINT ACCEPTED
FOR PUBLICATION BY THE PHYSICAL REVIEW.

Transfer vs. Compound Nuclear Mechanism in the Reaction
of ^{12}C and ^{11}B with ^{63}Cu and $^{65}\text{Cu}^*$

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Abstract: Excitation functions and average projected ranges have been measured for the production of ^{66}Ga and ^{70}As from enriched ^{63}Cu and ^{65}Cu targets with ^{11}B and ^{12}C projectiles of 10.5 MeV/amu. In addition, angular and range distributions were determined for the same products from ^{63}Cu and ^{65}Cu with 90 MeV ^{12}C ions. The results are compared with predictions based on the complete fusion compound nucleus mechanism (CFCN) and a quasi-elastic scattering model designed to represent transfer mechanisms. The results indicate that a number of the reactions must take place by more than one pathway.

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INTRODUCTION

Recent studies^{1,2,3,4} of heavy ion reactions have shed new light on the role of transfer reactions. Their most significant impact has been nearly to dissolve the clear experimental distinction between transfer and complete fusion compound nucleus (CFCN) mechanisms for some reaction products. The early qualitative model of Kaufman and Wolfgang^{5,6} has been largely substantiated and extended to describe the transfer of masses comparable to that of the projectile. Thus far, most of the research reported has involved the measurement of the lighter fragments ejected from such reactions. This work investigates the use of the somewhat more restrictive radiochemical measurements of the heavy residues as a means for distinguishing between transfer and CFCN mechanisms. Product excitation functions, angular, and range distributions were determined in order to indicate the probability of the various reaction paths.

EXPERIMENTAL PROCEDURE

Self-supporting ^{63}Cu and ^{65}Cu targets of $2\text{--}3\text{mg}/\text{cm}^2$ thickness and enriched to 99.73% and 99.70% respectively, were prepared by an electrodeposition technique described in detail elsewhere.⁷ These were used in the measurement of excitation functions and average ranges. Thinner ($\sim 300\text{ }\mu\text{g}/\text{cm}^2$) targets, electrodeposited via a similar technique onto backings of thin

carbon sheet, were used in the determination of angular and range distributions. ^{12}C and ^{11}B beams, with a maximum energy of 10.5 MeV/amu, were provided by the heavy ion linear accelerator at Yale University. Average currents were approximately 80 nA for ^{11}B and 120 nA for ^{12}C (1.2 and 1.5×10^{11} heavy ions per second, respectively). Collimation reduced the beam intensities for the angular and range distributions well below these values.

Excitation functions and average (projected) ranges were ascertained simultaneously by the stacked foil method, with aluminum foils of varying thicknesses used both as recoil catchers and as beam energy degraders. No catcher was less than 2.5 mg/cm^2 thick. The beam energy at any point in the stack was determined by a two-dimensional interpolation in Northcliffe's tables.⁸ (These tables were used for all range-energy conversions throughout this work.) The range distribution measurements employed a stack of aluminum leaf foils ($\sim 160 \text{ } \mu\text{g/cm}^2$ each) mounted on 3 mil aluminum annuli. Each foil corresponded to about seven (7%) percent of the maximum range observed. The apparatus for the angular distributions utilizes a flat catcher foil mounted perpendicular to the heavy ion beam and has been described in detail elsewhere^{9,10}. For these experiments, the catcher foil was mounted close enough to the target to result in a maximum observable recoil angle of about 54° . After irradiation the catcher foil was cut into

concentric rings for product analysis. Each annulus thus obtained corresponds to an exactly known range of recoil angles.

The activity of each sample was determined, without performing chemical separation, by use of a large-volume, high resolution Ge(Li) detector at Yale. All gamma spectra were analyzed by the BRUTAL computer program¹¹ which involved a search of the entire spectrum for peaks, the identification of doublet and triplet peaks, and the integration of each peak which was significantly above background. A decay curve least squares fit of the integrated gamma activities was obtained by use of the CLSQ computer program. This yielded end-of-bombardment activities from which all cross sections were calculated.

RESULTS

Excitation functions for eight different reactions were determined; specifically, those involving the production of ^{66}Ga and ^{70}As from ^{63}Cu and ^{65}Cu separated isotope targets from the interaction with ^{11}B and ^{12}C projectiles. These excitation functions are presented in Figures 1 and 2. The open circles with arrows in these figures represent a lack of measurable activity for that energy and are plotted at a height of either 1 mb or the estimated upper limit, whichever is greater.

Fig. 3 shows the variation of average projected range in copper with energy for some of these reactions. The solid lines in this figure are the ranges that would result by assuming that

the reaction takes place via a CFCN mechanism, i.e. that the product range is primarily a result of the center of mass motion. For simplicity it is also assumed that subsequent particle evaporation has a negligible effect on the range. For alpha particle emission, however, deviations from the predicted CFCN ranges might be anticipated.

In addition to the experimental angular distributions for all four ^{12}C reactions, Fig. 4 displays the results of a Monte-Carlo computer simulation (by a program named EVAP¹²) of the evaporation of particles (n, p, d, t, ^3He , or ^4He) from a completely fused system of target and projectile at the proper excitation energy (75.3 MeV for ^{75}Br and 74.8 MeV for ^{77}Br). At each step in the evaporation the perturbation on the excited nucleus' original momentum and angle caused by the emitted particle was noted so that the final angular distribution of a given product could be determined. The ordinate of these calculated angular distributions was adjusted such that the calculated peak height was approximately the same as the experimental angular distribution peak height. The $^{12}\text{C} + ^{65}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$ system is lacking the theoretical histogram because the ^{77}Br excitation energy was insufficient to produce any ^{66}Ga residue nuclei out of 1500 nuclei "evaporated". These angular distributions and the range distributions described below were measured only at a projectile energy of approximately 90 MeV.

The range distributions in aluminum for these ^{12}C reactions are displayed in Fig. 5. These data were arbitrarily fit (by a weighted least squares procedure) with single or double gaussian forms. The result of these fits are superimposed on the experimental histograms and, for the double gaussians, the relative areas of each component are given. Asterisks appearing in the angular and range distributions indicate that that sample was not counted soon enough to ascertain the intensity of the ^{70}As component. The target thickness employed ($\sim 300 \mu\text{g}/\text{cm}^2$) causes a broadening of the distribution but does not appreciably affect the peak position.¹³

The uncertainties in these data arise entirely from the known or estimated probable errors of each parameter involved in the calculations, combined according to the appropriate relations.⁷ The major contributor to these uncertainties was the random error associated with integration of spectral peaks, but uncertainties in half-life values and branching ratios taken from the literature, beam intensity, and target density were also folded into the computations.

DISCUSSION

There is a striking difference between the excitation functions illustrated in Figs. 1 and 2. The excitation functions initiated by ^{12}C projectiles exhibit multiple peaks which are strong indications of more than one mechanistic pathway,

especially when compared to the ^{11}B induced reactions where this behavior is not exhibited. The former set was therefore chosen for primary attention in this study. In consideration of the Q-values for the four reactions in Fig. 2, the higher energy peak can most probably be assigned to a process involving fusion of most or all of the projectile with the target followed by multiple particle evaporation. For example, for the reaction $^{63}\text{Cu} + ^{12}\text{C} \rightarrow ^{66}\text{Ga} + \text{X}$, if X represents four protons and five neutrons the Q value is approximately -71 MeV, while if X represents two alpha particles and a neutron the Q value is about -15 MeV. In a similar manner for the reaction $^{63}\text{Cu} + ^{12}\text{C} \rightarrow ^{70}\text{As} + \text{X}$, the Q value is about -40 MeV when X represents individual nucleons, and -12 MeV when a alpha particle is involved. Thus, the assignment of the CFCN mechanism for the high energy peaks in the excitation functions is consistent with the reaction Q values. Depending on reaction pathway, the low energy peaks may not be consistent with this mechanism.

The average projected range measurements (Fig. 3) are useful in detecting gross changes in the amount of forward momentum given to the products in the reaction. A simple kinematic model representing quasi-elastic scattering¹⁴ clearly demonstrates the changes in forward momentum which take place as a result of the fusion of less than the full projectile mass with the target. The model first assumes that a portion of the projectile mass is

completely absorbed by the target, and this fused system is given a momentum equal to that fraction of the projectile momentum represented by the absorbed part of the projectile. The remainder of the projectile is then assumed to elastically scatter from the fused system, giving the latter an additional recoil momentum. Both steps are described by standard equations of energy and momentum conservation. An example of the results of this calculation for the $^{12}\text{C} + ^{63}\text{Cu}$ reaction is illustrated in Fig. 6. The shape of the $^{12}\text{C} + ^{65}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$ average range curve Fig. 3d matches well that for alpha-transfer as predicted by this quasi-elastic model. The deviation of the ranges illustrated in Fig. 3 from the predicted CFCN range, within the limitations of the experimental uncertainties and the neglect of the affect of particle evaporation on range, indicates a degree of admixture of non-CFCN processes which is roughly proportional to the extent of deviation. If this admixture is large enough, the trend of the data will be altered as well, as in Figs. 3d and 3e.

The energies at which the angular and range distributions were done encompasses a wide range of conditions in the four reactions as can be seen by an examination of Fig. 2. Where 90 MeV falls at a minimum in the excitation function, e.g. in the $^{12}\text{C} + ^{63}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$ reaction, two components are observed in the angular and range distributions; however, in other reactions, when it is near a maximum in the excitation function, simple angular and range distributions result. These considerations are important in assigning mechanisms to the reactions.

Of equal value are predictions calculated from treating the reaction as if it takes place by the CFCN mechanism. The evaporation calculation results included in Fig. 4 are such predictions. Within the limitation of the statistics based on 1500 evaporations from ^{77}Br at 75.3 MeV excitation energy, the failure of the calculation to predict the production of any ^{66}Ga , resulting from the interaction of ^{12}C with ^{65}Cu , implies that there is probably a negligible CFCN contribution in this case. The somewhat larger peak angle of the theoretical distribution in the $^{12}\text{C} + ^{63}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$ reaction, as compared with the $^{12}\text{C} + ^{63}\text{Cu} \rightarrow ^{70}\text{As} + \text{X}$ reaction, arises from the sole evaporation mode at this energy (as predicted by the evaporation calculations) of two alphas and a neutron, causing a less forward peaked reaction product than if there had been only single nucleon emissions. The agreement of the evaporation predictions with the low-angle part of the angular distributions, as well as the wide separation of peaks in the angular and range distributions provides support for the assignment of the reaction mechanisms.

In view of the previous discussion, the notation, "CFCN Product" in Fig. 5 for the $^{12}\text{C} + ^{65}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$ reaction may be misleading. Alternative reaction paths and or mechanisms other than CFCN may play an important role in this reaction. The lack of "peak" separation in Figs. 4 and 5 is consistent with this suggestion. One alternative might be ^8Be transfer, which is

consistent with the work of Bimbot et al.³ It requires the subsequent evaporation of one alpha and three neutrons (or the equivalent) causing a broad range distribution like the one shown in Fig. 5 for the major component of this reaction.

The experimental results for the production of ^{70}As can also be compared with the predictions based on the evaporation calculation results. The reasonable agreement in the peak angle predictions for both reactions, despite the significant difference in the angle observed for the ^{63}Cu and ^{65}Cu targets, is support of a CFCN interpretation of the reaction mechanism. Furthermore, the evaporation calculations provide an explanation for the peak angle difference in that a predominance of single nucleon emissions from the $^{12}\text{C} + ^{63}\text{Cu}$ compound nucleus was observed compared with the absence of any mode other than one alpha-three neutron evaporation observed from the ^{77}Br fused system. This implies that both reactions proceed primarily by CFCN mechanisms. The range distributions, however, are not completely consistent with this interpretation. While the peak of the ^{70}As range distribution from the $^{12}\text{C} + ^{63}\text{Cu}$ reaction falls at 1.09 mg/cm^2 (12.6 MeV), see Fig. 5, and agrees well with the predicted CFCN recoil energy (13.2 MeV), the other ^{70}As peak falls at 0.91 mg/cm^2 , a range corresponding to a recoil kinetic energy a full 2.8 MeV below the CFCN predicted range of 12.6 MeV. This discrepancy might result, at least

partly, from the assumption that alpha evaporation does not affect the CFCN ranges predicted solely on the basis of center of mass motion. However, the location of 90 MeV in the excitation function, Fig. 2, well below the higher-energy peak suggests that this product does not result exclusively by the CFCN mechanism.

Consistent but not necessarily conclusive support for the proposed reaction mechanisms can be ascertained by calculating the excitation energy available resulting from various transfers to the target. The standard conservation equations are applied:

$$E_i = E_L + E_R + E^* - Q$$

$$P_i = P_L \cos \theta + P_R \cos \varphi$$

$$P_L \sin \theta = P_R \sin \varphi$$

where the subscript i refers to the incident particle, L the light reaction product, and R the heavy recoil product. These can be easily solved for E^* , the excitation energy of the residual system, in terms of the experimentally determined parameters E_R and φ obtained from the 90 MeV incident energy experiments. The Q-value is determined by assuming a specific pathway for the reaction. If, for instance, we assume that an alpha is transferred from ^{12}C to ^{63}Cu , then the ^{67}Ga residue must have an E^* consistent with the evaporation of one and only neutron, about

8-10 MeV. If the resulting excitation energy is too low, then the reaction as depicted is disallowed; if too high the reaction as depicted may still take place since some of the excitation energy may be associated with the light product. The results of these computations for several hypothetical pathways are given in Table I. This method is particularly well suited to the study of transfer reactions in which only neutrons need to be evaporated from a direct transfer product in order to obtain the observed nuclide. All of the trial cases considered in Table I are examples of this type of mechanism. The number of neutrons which need to be evaporated determines the allowable range of excitation energies, E^* . The table shows that ^{66}Ga production via ^5He -transfer (^7Be residual light nucleus) to either ^{63}Cu or ^{65}Cu is energetically disallowed because of insufficient excitation energy. While either ^4He - or ^3He -transfer is consistent with the observed angles and energies, the former is more probable, since we are dealing with a projectile which has a definite alpha structure. Alpha-transfer therefore is expected to be the dominant transfer mode in the $^{12}\text{C} + ^{65}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$ system also, even though the present analysis shows ^3He -transfer and two-proton-transfer to be about as consistent with the observed quantities. Note that none of the trial paths for the formation of ^{70}As from $^{12}\text{C} + ^{63}\text{Cu}$ are energetically plausible. This result is in agreement with previously mentioned indications that this is a CFCN product.

^{70}As production from ^{65}Cu , however, is shown to be consistent with a ^9Be -transfer mechanism. Although the E^* resulting from the ^8Be -transfer assumption seems too high, the extra energy above that necessary for neutron evaporation may be taken up by ^4He excitation. (Note that this is the only pathway for which the Q -value is positive.)

All of the above considerations are summarized in Table II. The results presented here clearly indicate that the CFCN mechanism is not solely responsible for all the reactions studied. Various types of transfer processes are the most likely contributors.

Table II. Postulated Reaction Mechanisms at 90 MeV

Reactants	Observed Nuclide	Method(s) of Production
$^{12}\text{C} + ^{63}\text{Cu}$	^{66}Ga	CFCN + α -transfer
	^{70}As	CFCN
$^{12}\text{C} + ^{65}\text{Cu}$	^{66}Ga	^8Be -transfer + α -transfer ^a
	^{70}As	^8Be -transfer ^b

^a the α -transfer mode appears to play a minor role here.

^b CFCN may also be responsible for the production of this nuclide.

Acknowledgements

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Table I. Kinematic Plausibility of Various Reaction Pathways

Reaction		Observed Nuclide	Q ^a (MeV)	E _R (MeV)	φ (deg)	E* (MeV)
Reactants	Products					
$^{12}\text{C} + ^{63}\text{Cu}$	$^{66}\text{Ga} + ^9\text{Be}$	^{66}Ga	-13.227	1.60	25	13.4
	$^{67}\text{Ga} + ^8\text{Be}$	^{66}Ga	- 3.662	1.60	25	15.8
	$^{68}\text{Ga} + ^7\text{Be}$	^{66}Ga	-14.278	1.60	25	< 0
$^{12}\text{C} + ^{65}\text{Cu}$	$^{66}\text{Ga} + ^{11}\text{Be}$	^{66}Ga	-22.058	2.48	24	23.5
	$^{67}\text{Ga} + ^{10}\text{Be}$	^{66}Ga	-11.325	2.48	24	30.5
	$^{68}\text{Ga} + ^9\text{Be}$	^{66}Ga	- 9.859	2.48	24	27.4
	$^{69}\text{Ga} + ^8\text{Be}$	^{66}Ga	- 1.201	2.48	24	30.3
	$^{70}\text{Ga} + ^7\text{Be}$	^{66}Ga	-12.455	2.48	24	11.7
$^{12}\text{C} + ^{63}\text{Cu}$	$^{70}\text{As} + ^5\text{He}$	^{70}As	-12.715	12.36	6	59.7
	$^{71}\text{As} + ^4\text{He}$	^{70}As	- 0.114	12.36	6	71.6
	$^{72}\text{As} + ^3\text{He}$	^{70}As	-12.295	12.36	6	58.1
$^{12}\text{C} + ^{65}\text{Cu}$	$^{71}\text{As} + ^6\text{He}$	^{70}As	-15.288	9.24	12	50.4
	$^{72}\text{As} + ^5\text{He}$	^{70}As	- 8.818	9.24	12	54.6
	$^{73}\text{As} + ^4\text{He}$	^{70}As	+ 2.914	9.24	12	62.8
	$^{74}\text{As} + ^3\text{He}$	^{70}As	- 9.659	9.24	12	44.3

^aComputed from the 1964 atomic mass table of Mattauch, et al.¹⁵

Figure Captions

- Figure 1 Excitation functions for the production of ^{66}Ga and ^{70}As from the reaction of ^{11}B with the separated isotopes of Cu. The excitation energy resulting from the production of the compound nucleus is indicated by the top scale.
- Figure 2 Excitation functions for the production of ^{66}Ga and ^{70}As from the reaction of ^{12}C with the separated isotopes of Cu. The excitation energy resulting from the production of the compound nucleus is indicated by the top scale.
- Figure 3 Variation of average projected range with laboratory projectile energy for five reactions: (a) $^{11}\text{B} + ^{63}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$, (b) $^{12}\text{C} + ^{63}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$, (c) $^{12}\text{C} + ^{63}\text{Cu} \rightarrow ^{71}\text{As} + \text{X}$, (d) $^{12}\text{C} + ^{65}\text{Cu} \rightarrow ^{66}\text{Ga} + \text{X}$, (e) $^{12}\text{C} + ^{65}\text{Cu} \rightarrow ^{70}\text{As} + \text{X}$.
- Figure 4 Variation of differential production cross section with laboratory angle for the four ^{12}C reactions indicated on graphs. Dotted histograms are theoretical predictions resulting from an assumed CFCN mechanism.
- Figure 5 Variation of differential production cross section with projected recoil fragment kinetic energy for the four ^{12}C reactions indicated on the graphs. The ^{66}Ga product distributions are divided into moieties resulting from CFCN and direct reaction mechanisms.
- Figure 6 Average projected range in mg/cm^2 versus laboratory projectile energy for various mass transfers to the target based on the quasi-elastic scattering model. The $^{12}\text{C} + ^{63}\text{Cu}$ reaction is illustrated.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6