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Deexcitation Processes in Nuclear Reactions

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Progress Report for the period May 1972 to April 1973

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Department of Chemistry



Purdue University
Lafayette, Indiana

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DEEXCITATION PROCESSES IN NUCLEAR REACTIONS

Progress Report

Norbert T. Porile

**Purdue University
Lafayette, Indiana**

May 1, 1972 - April 30, 1973

**PREPARED FOR THE U. S. ATOMIC ENERGY
COMMISSION UNDER CONTRACT NO. AT(11-1)-1505**

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ABSTRACT

Preliminary results have been obtained for the spallation of silver by 300 GeV protons. The weighted average value of $\sigma_{300}/\sigma_{11.5}$ is 0.89 ± 0.08 on the basis of 19 individual cross sections; this ratio appears to be independent of product mass number. The charge distribution and recoil properties at $A=131$ from the interaction of gold with 11.5 GeV protons are being determined. It has been found that, contrary to uranium, fission does not significantly contribute to the yield of the neutron deficient products. The energy spectra of protons and α -particles emitted in the decay of ^{56}Fe , ^{60}Ni , ^{63}Cu , ^{64}Zn , and ^{66}Zn compound nuclei produced in reactions induced by protons and α -particles, have been measured. Comparison of the α and np exit channels permits a test of the independence hypothesis and the latter is confirmed in all 5 cases. Comparison of the α and p exit channels shows that isospin conservation is of importance and permits the determination of the isospin mixing fraction μ , whose value is 0.4 ± 0.2 for all 5 compound nuclei. The highly excited levels of ^{63}Cu and ^{65}Cu are being populated in 4 different compound nuclear reactions at several bombarding energies to determine if all reactions are consistent with a given set of level density parameters.

I. Research Activities

This report summarizes the research performed during the last year in the areas of high- and intermediate-energy nuclear reactions. Two main lines of research have been followed in our high-energy program: the study of the interaction of 11.5 and 300 GeV protons with silver, and the study of charge dispersion and recoil properties in reactions of heavy elements. Our intermediate-energy program concerns the study of compound nuclear reactions and during the past year has focused on tests of the independence hypothesis, pre-compound emission, and isospin effects in reactions induced by protons and α -particles.

A. High-Energy Nuclear Reactions

The most exciting development in this area has been the completion of a 300 GeV proton beam line at the National Accelerator Laboratory. We have performed some initial measurements of the spallation of silver by 300 GeV protons. In the course of the year we have also performed extensive measurements at 11.5 GeV in order to determine the energy dependence of the various cross sections.

The measurements were made by direct assay of the target foil with a calibrated Ge(Li) detector and the experimental technique is described in detail elsewhere (1,2). A typical spectrum obtained approximately one day after a 300 GeV irradiation is shown in Figure 1. The various peaks were assigned to the specific nuclides on the basis of energy and half-life measurements as described elsewhere (1,2). Table 1 summarizes our latest results for the 19 nuclides whose cross sections have to date been measured at both 300 and 11.5 GeV. The ratios of cross sections at these energies, $\sigma_{300}/\sigma_{11.5}$ are based on the assumption that the cross section of the $^{27}\text{Al}(p,3\text{pn})$ monitor reaction is the same at 300 as at 10-30 GeV.

This assumption is supported by recent measurements at 300 GeV of the spallation of cobalt and vanadium (3). Our overall impression of these results is that this order-of-magnitude change in bombarding energy has very little effect on the cross sections. The weighted mean value of $\sigma_{300}/\sigma_{11.5}$ is 0.89 ± 0.08 . This may indicate a slight reduction in the magnitude of the 300 GeV cross sections but additional data are needed before firm conclusions can be drawn.

In the course of the year our studies of the charge dispersion and recoil properties at $A=131$ as well as those of the isotopic distribution of xenon nuclides from the interaction of uranium with 11.5 GeV protons were completed. We have started to make similar measurements on a gold target. The purpose of this investigation is to perform a detailed study of the charge dispersion and recoil properties associated with the spallation-fragmentation mechanism leading to neutron deficient products in the fission region. Our studies of the interaction of uranium with high-energy protons, as well as other reported charge dispersion and recoil studies (4,5), indicate that this mechanism is not completely understood. Since the fission of uranium makes an important contribution to the yields of neutron deficient products, the properties of the spallation-fragmentation process are thereby obscured. We have, to date, established that the contribution of the fission of gold to neutron deficient products with $A \sim 131$ is negligibly small. This should allow a more unambiguous characterization of the spallation-fragmentation mechanism than is possible for uranium.

B. Intermediate-Energy Nuclear Reactions

During the past year we have concentrated on studies of the decay of several medium-A compound nuclei formed in reactions induced by

14 MeV protons and 15-19 MeV α -particles. We have measured the energy spectra and angular distributions of protons and α -particles emitted in these reactions using beams from the Purdue tandem Van der Graaff. Figure 2 shows the spectra of particles emitted at 150° to the beam in the decay of the ^{64}Zn compound nucleus. A particularly interesting feature of the proton spectra is the occurrence of a fairly well resolved low-energy peak. This peak is due to protons emitted in (p,np) or (α ,np) reactions and is clearly resolved for most of the targets that we have studied. Our experiment thus involves the determination of 3 separate exit channels: p, α , and np. The α and np exit channels are not affected by isospin conservation and the precompound process is unimportant for these reactions at the energies of interest. The comparison of the α and np exit channels thus permits a straightforward test of the independence hypothesis.

If a given compound nucleus is formed with the same excitation energy and angular momentum distribution in reactions induced by protons and α -particles the independence hypothesis demands that the quantity $\sigma(p,np)\sigma(\alpha,\alpha')/\sigma(p,\alpha)\sigma(\alpha,np)$ be equal to unity. The various cross sections are obtained by integration of the evaporation peaks over angle assuming that the angular distribution is symmetric about a plane perpendicular to the beam direction. Since the angular momentum brought in by an α -particle is larger than that brought in by a proton of comparable energy the above condition is not strictly valid. The effect of the difference in angular momentum can be evaluated by use of the spin-dependent statistical theory, and a correction factor obtained. Table 2 summarizes the experimental cross section ratios, the calculated correction factors, and their respective ratios, which should be equal to

unity if the independence hypothesis is obeyed. It is seen that, within the limits of error, this result is obtained in all cases. To our knowledge, this constitutes the first test of the independence hypothesis in reactions induced by protons and α -particles based on differential cross section measurements.

Previous comparisons of the proton and alpha exit channels (6-8) in the decay of a given compound nucleus have indicated an enhancement in the (p,p') cross section which has been attributed to the effect of isospin conservation. A recent analysis (9) suggests that the Coulomb interaction may mix a fraction of the $T_>$ states of the compound nucleus into the $T_<$ states prior to particle emission and indicates that it is possible to extract a value of the fractional mixing, μ , from the data. Before determining the magnitude of μ it is necessary to subtract the contribution of the precompound process to the (p,p') reaction, which alone among the reactions of present interest is affected by this process at low energies. This contribution was determined in the manner described in previous publications from this laboratory (10,11) and was found to amount to some 10%.

The analysis of our data for the p and α exit channels is summarized in Table II. The experimental quantity, $\sigma(p,p')\sigma(\alpha,\alpha')/\sigma(p,\alpha)\sigma(\alpha,p)$, when divided by a calculated factor which corrects for the difference in the angular momentum of the two entrance channels, should lead to unity if the independence hypothesis is obeyed. Table II shows that, contrary to the comparison of the α and np exit channels, the p and α channels lead to ratios that are uniformly larger than unity. This result can be understood in terms of the preferential proton decay of the $T_>$ states of the compound nucleus due to isospin conservation. Following

the approach by Grimes et al (9) we have extracted values of the fractional mixing, μ . The values of μ are summarized in Table II and, within the limits of error, are equal to 0.4 for all 5 compound nuclei. This is one of the few available results that any future theory of the role of isospin conservation in compound statistical processes must account for.

During the past year we have extended our previously reported (10) work on the highly excited levels of a given nucleus, ^{59}Co , populated in 4 different compound nuclear reactions to two other nuclides: ^{63}Cu and ^{65}Cu . The purpose of this study is to see if the differential cross sections of the (α, α') , (α, p) , (p, α) and (p, p') reactions obtained at several bombarding energies can be fit by the spin-dependent statistical theory using the same set of pairing energies and level density parameters for the product nucleus. Such a comparison constitutes a stringent test of the statistical model and also permits a more reliable determination of level density parameters than is obtainable from a single reaction. We are presently in the process of completing the various experimental measurements after which the calculations will be performed.

In the main, the research performed this past year followed the outline submitted in the last renewal proposal. However, there were two notable exceptions. The study of γ -rays emitted in compound nuclear reactions involving charged particle emission was not initiated because the funding level was inadequate to obtain the required equipment. Very little progress was made on the study of the energy dependence of the recoil ranges of independently formed products from the interaction of uranium with 1-29 GeV protons. This was due to a long ZGS shutdown as well as to difficulties experienced in operating this accelerator below 11.5 GeV.

Since the beginning of the present contract year the principal investigator has devoted approximately 45% of his time and effort to this project. It is expected that this figure will be maintained at about the same level for the remainder of the year.

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11. A. Sprinzak, A. J. Kennedy, J. C. Pacer, J. Wiley, and N. T. Porile, Nucl. Phys. A 203, 280 (1973).

Figure 1

γ -ray spectrum of silver foil obtained one day after irradiation by 300 GeV protons. Nuclidic assignments are made wherever possible. γ -rays useful for cross section determinations are starred.

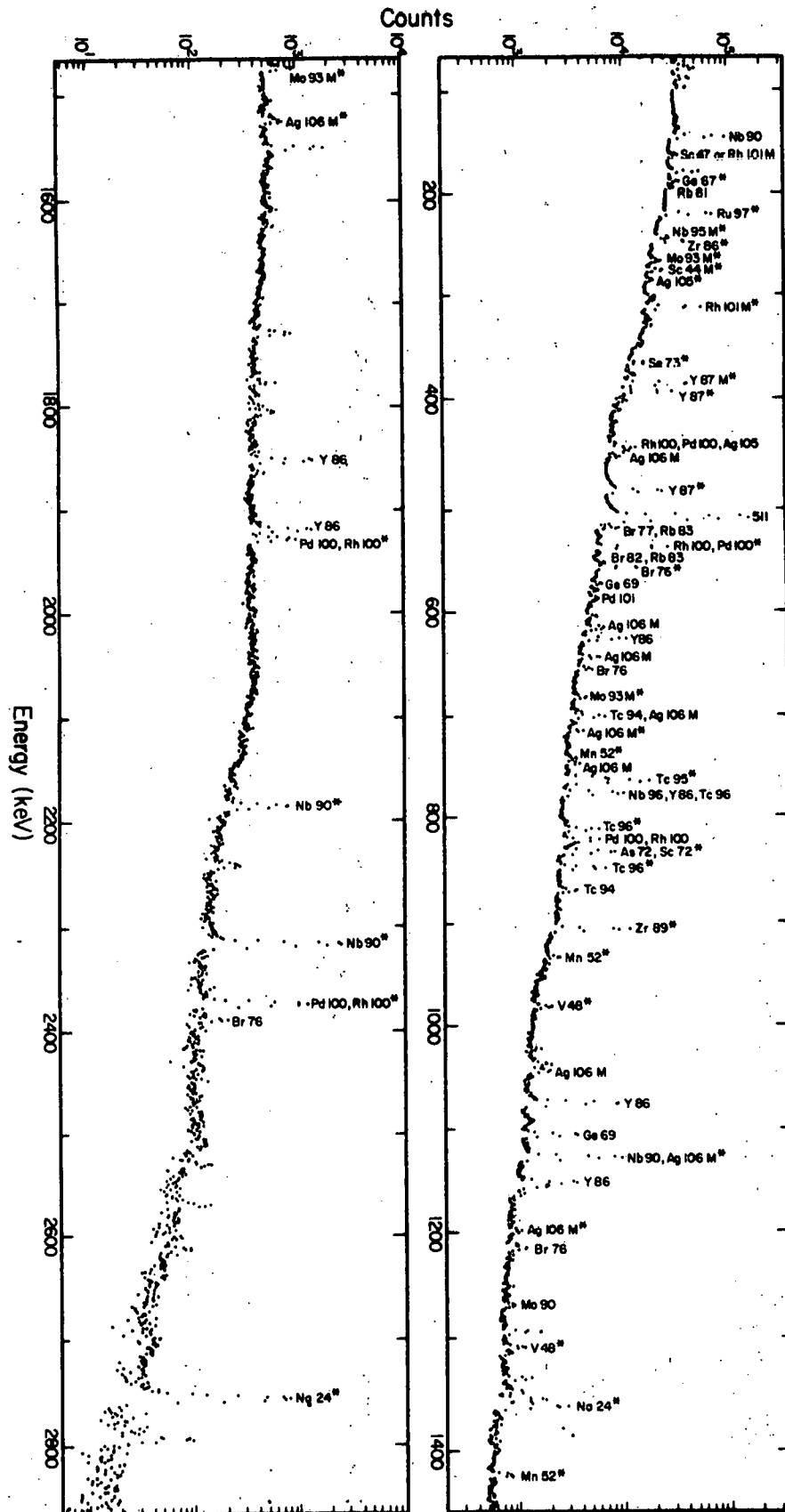


Figure 2

Energy spectra (c.m.) at 150° to the beam of protons and α -particles emitted in the decay of the ^{64}Zn compound nucleus at an excitation energy of 21.5 MeV.

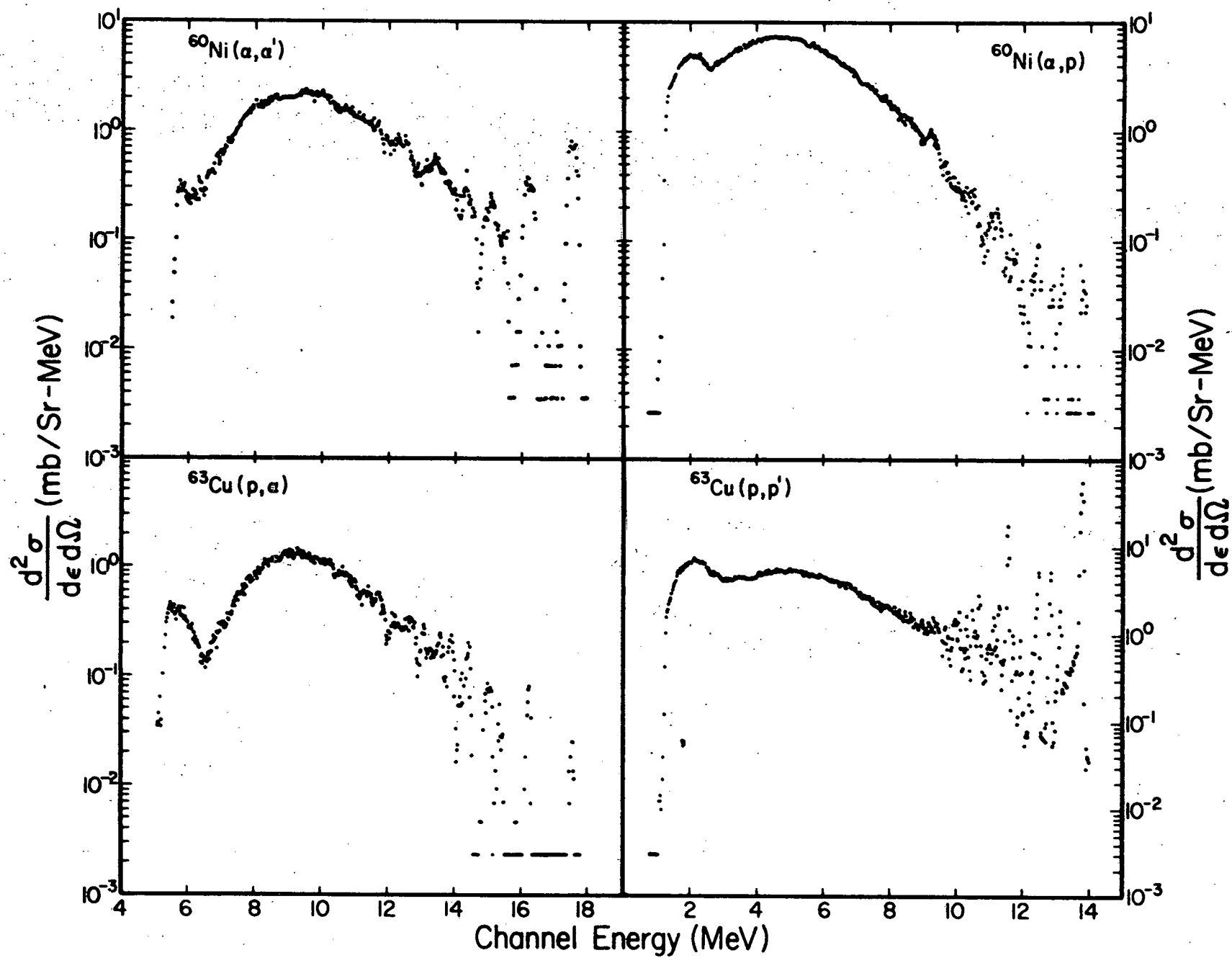


Table I

Comparison of cross sections of products from 300 GeV proton bombardment of Ag, σ_{300} , with similar results at 11.5 GeV, $\sigma_{11.5}$. The nuclides are labelled to denote independent (i) or cumulative (c) formation.

Nuclide	$\sigma_{11.5}^{(mb)}$	$\sigma_{300}/\sigma_{11.5}$
$^{106m}\text{Ag}(i)$	9.4	0.94 ± 0.06
$^{101m}\text{Rh}(c)$	21.5	1.01 ± 0.10
$^{97}\text{Ru}(c)$	14.2	0.95 ± 0.05
$^{96}\text{Tc}(i)$	7.1	0.96 ± 0.07
$^{95}\text{Tc}(c)$	15.7	0.92 ± 0.11
$^{90}\text{Nb}(c)$	16.0	0.87 ± 0.09
$^{89}\text{Zr}(c)$	15.7	0.92 ± 0.07
$^{86}\text{Zr}(c)$	5.0	0.90 ± 0.06
$^{87m}\text{Y}(c)$	15.0	0.86 ± 0.12
$^{87}\text{Y}(c)$	18.3	0.77 ± 0.04
$^{76}\text{Br}(c)$	8.1	0.75 ± 0.08
$^{73}\text{Se}(c)$	3.8	0.92 ± 0.20
$^{74}\text{As}(i)$	5.9	0.78 ± 0.10
$^{67}\text{Ga}(c)$	7.6	0.94 ± 0.06
$^{52}\text{Mn}(c)$	1.8	0.93 ± 0.10
$^{48}\text{V}(c)$	2.5	1.01 ± 0.10
$^{44m}\text{Sc}(i)$	2.0	0.92 ± 0.24
$^{24}\text{Na}(c)$	4.1	1.08 ± 0.16
$^7\text{Be}(c)$	19.1	0.90 ± 0.15

Table II

Test of the independence hypothesis by comparison of the α and np exit channels; comparison of the p and α exit channels and isospin conservation.

Compound Nucleus	Excitation Energy	$R_{\text{exp}} = \frac{\sigma(p,np)\sigma(\alpha,\alpha')}{\sigma(p,\alpha)\sigma(\alpha,np)}$	R_{calc}	$R_{\text{exp}}/R_{\text{calc}}$	$R'_{\text{exp}} = \frac{\sigma(p,p')\sigma(\alpha,\alpha')}{\sigma(p,\alpha)\sigma(\alpha,p)}$	R'_{calc}	$R'_{\text{exp}}/R'_{\text{calc}}$	μ
^{56}Fe	23.9 MeV	1.33 ± 0.18	1.64 ± 0.16	0.81 ± 0.14	1.56 ± 0.22	1.07 ± 0.05	1.46 ± 0.22	0.4 ± 0.2
^{60}Ni	23.3	1.47 ± 0.19	1.63 ± 0.16	0.90 ± 0.15	1.34 ± 0.20	0.85 ± 0.04	1.58 ± 0.25	0.3 ± 0.2
^{63}Cu	19.9	2.63 ± 0.41	2.22 ± 0.22	1.18 ± 0.22	1.34 ± 0.28	0.74 ± 0.04	1.81 ± 0.39	0.4 ± 0.2
^{64}Zn	21.5	2.50 ± 0.31	2.27 ± 0.23	1.10 ± 0.18	1.38 ± 0.18	0.94 ± 0.05	1.47 ± 0.20	0.4 ± 0.2
^{66}Zn	22.7	-	-	-	1.72 ± 0.20	1.11 ± 0.06	1.55 ± 0.20	0.6 ± 0.2

II. Publication Abstracts

Abstracts are given for articles published or submitted to journals during the period covered by this report.

Oxygen and Carbon Assay of Metal Foils by Nuclear Reactions.

A. J. Kennedy, J. C. Pacer, A. Sprinzak, J. Wiley, and N. T. Porile, Nucl. Instr. and Meth. 101, 471 (1972).

Oxygen and carbon impurities in metal foils have been assayed with a sensitivity of 2-25 ppm by measurement of proton energy spectra in reactions induced by 14 MeV protons. Energy spectra of α -particles from (p, α) reactions have been used to distinguish between surface and body impurities.

Charge Dispersion and Recoil Properties at A=131 from the Interaction of ^{238}U with 11.5 GeV Protons. Y. W. Yu and N. T. Porile, Phys. Rev. C 7, 1597 (1973).

Independent and cumulative yields have been measured for eight A=131 nuclides formed in the interaction of ^{238}U with 11.5 GeV protons. A good fit to the cross sections was obtained with a charge dispersion consisting of two overlapping gaussians peaking at Z=52.2 and 56.5. The neutron excessive curve accounts for about 40% of the total isobaric yield of 23.3 ± 0.4 mb. Thick-target recoil properties were determined for all the nuclides. The recoil ranges are characteristic of fission fragments for ^{131}Sb through ^{131}Cs but decrease by a factor-of-two between ^{131}Cs and ^{131}La . This decrease occurs some 2 Z-units beyond the minimum between the two humps in the charge dispersion. The depo-

sition energies derived from the recoil data exhibit a similar trend as the ranges, increasing in the manner expected for fission products up to barium but not beyond. The transformation of isotopic to isobaric yield distributions is considered and it is concluded that the use of N/Z as the composition variable gives the best agreement with experiment.

Systematics of (p,p') and (p,α) Spectra from 14 MeV Proton Bombardment of Medium-A Targets. A. Sprinzak, A. J. Kennedy, J. C. Pacer, J. Wiley, and N. T. Porile, Nucl. Phys. A 203, 280 (1973).

Differential cross sections have been measured between 30° and 150° for the (p,p') and (p,α) reactions induced by 14 MeV protons in the following targets: ^{55}Mn , ^{56}Fe , ^{58}Ni , ^{59}Co , ^{62}Ni , ^{63}Cu and ^{64}Zn . The results have been compared with the spin-dependent statistical theory and good agreement was obtained for the (p,α) reactions with a level density parameter $\underline{a} = (0.138 \pm .008) A \text{ MeV}^{-1}$. This value is substantially lower than that obtained in a spin-independent analysis of the same data. The agreement of the (p,p') spectra with theory is poor and it is found that a 15-40% contribution from precompound emission is required. The emission of low-energy protons from the (p,np) reaction was observed in all cases and comparison of the cross sections with those of the corresponding (p,n) reactions yields information on the competition between γ -ray and proton emission.

Cross Sections and Recoil Properties of Xenon Isotopes Formed in 11.5 GeV Proton Bombardment of ^{238}U . Y. W. Yu, N. T. Porile, R. Warasila, and O. A. Schaeffer, submitted to Physical Review C.

Partial cumulative yields and thick-target recoil properties of 14 xenon nuclides formed in the interaction of ^{238}U with 11.5 GeV protons and ranging from ^{122}Xe to ^{136}Xe have been measured. Independent yields and recoil ranges were deduced with the aid of reported data. The isotopic yield distribution consists of two peaks with a broad region of near-constant yields between them. The recoil ranges exhibit the characteristic dropoff on the near neutron deficient side of stability. Comparisons with other isotopic and isobaric yield distributions and ranges of products in the same mass region are presented.

Nuclear Reactions of Silver with 300 GeV Protons. G. English, Y. W. Yu, and N. T. Porile, submitted to Physical Review Letters.

Cross sections of 19 radionuclides formed by the interaction of 300 GeV protons with silver were determined on the assumption that the cross section of the $^{27}\text{Al}(p,3pn)$ reaction remains the same as at 10-30 GeV. The results are compared with the corresponding values obtained at 11.5 GeV. The average value of the ratio $\sigma_{300}/\sigma_{11.5}$ for all products ranging from ^7Be to ^{106m}Ag is 0.89 ± 0.08 and is independent of mass number. This result is only marginally significant but it suggests that the total reaction cross section of silver may be somewhat lower at 300 than at 11.5 GeV.

III. Personnel

Senior Staff

Dr. N. T. Porile, Professor of Chemistry, Principal Investigator

Dr. A. Sprinzak*, Visiting Assistant Professor of Chemistry

Dr. Y. W. Yu, Research Associate

Graduate Students

G. English

C. R. Lux

J. C. Pacer

J. Wiley

Service Staff

E. Grenat, part-time electronics technician

* Resigned during year

IV. Publications and Talks

Oxygen and Carbon Assay of Metal Foils by Nuclear Reactions.

A. J. Kennedy, J. C. Pacer, A. Sprinzak, J. Wiley, and N. T. Porile, Nucl. Instr. and Meth. 101, 471 (1972).

Charge Dispersion and Recoil Properties at $A=131$ from the Interaction of ^{238}U with 11.5 GeV Protons. Y. W. Yu and N. T. Porile, Phys. Rev. C 7, 1597 (1973).

Systematics of (p,p') and (p,α) Spectra from 14 MeV Proton Bombardment of Medium-A Targets. A. Sprinzak, A. J. Kennedy, J. C. Pacer, J. Wiley, and N. T. Porile, Nucl. Phys. A 203, 280 (1973).

Cross Sections and Recoil Properties of Xenon Isotopes Formed in 11.5 GeV Proton Bombardment of ^{238}U . Y. W. Yu, N. T. Porile, R. Warasila, and O. A. Schaeffer, submitted to Physical Review C.

Nuclear Reactions of Silver with 300 GeV Protons. G. English, Y. W. Yu, and N. T. Porile, submitted to Physical Review Letters.

 "Charge Dispersion and Recoil Properties at $A=131$ in the High-Energy Fission of Uranium", given by N. T. Porile at the Chemistry Division Seminar, Argonne National Laboratory, October, 1972.

"Nuclear Reactions at Medium and High Energies", given by N. T. Porile at the Physical Chemistry Seminar, Purdue University, October, 1972.

"Studies of Compound Nuclear Reactions at the Tandem", given by J. C. Pacer and J. Wiley at the Nuclear Structure Seminar, Purdue University, April, 1973.

"Nuclear Reactions Induced in Silver by 300 GeV Protons", given by
G. English at the Washington meeting of the American Physical Society,
April, 1973. Abstract published in Bull. Am. Phys. Soc., Ser. II, 18,
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