Deexcitation Processes in Nuclear Reactions

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Progress Report for the period May 1973 to April 1974

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Department of Chemistry

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Progress Report

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ABSTRACT

High- and low-energy nuclear reaction studies have been performed. The high-energy projects include a comparative study of the nuclear reactions of silver with 300- and 11.5-GeV protons; a comparative study of cross sections and recoil properties of products in the $A=120-140$ mass region from the interaction of ^{238}U with 300- and 11.5-GeV protons; measurement of the charge dispersion and recoil properties of products in the $A\sim 131$ region from the interaction of ^{197}Au with 11.5 GeV protons; study of the energy dependence of the recoil properties of neutron deficient products with $A=131$ from the interaction of ^{238}U with high-energy protons; differential range study of products with $A\sim 131$ from the interaction of ^{238}U with 11.5 GeV protons; study of a fragmentation product, ^{24}Na , in pion-induced reactions. The low-energy research includes a study of the energy dependence of isospin mixing in the ^{69}Ga compound nucleus; tests of the independence hypothesis in the decay of the ^{49}V , ^{52}Cr , ^{55}Mn , and ^{69}Ga compound nuclei formed in proton- and α -induced reactions; a test of the independence hypothesis in the decay of ^{75}Br formed in reactions induced by ^{12}C and ^{16}O ions.

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I. Research Activities

This report summarizes the research performed during the last year in the areas of high- and low- energy nuclear reactions. The high-energy program has principally been concerned with (1) a comparison between the interaction of 300- and 11.5-GeV protons with complex nuclei, and (2) studies of charge dispersion and recoil properties in the interaction of heavy elements with 11.5-GeV protons. The low-energy research has involved various studies of compound nuclear reactions with the Purdue tandem Van de Graaff.

A. High-Energy Nuclear Reactions

We have completed the measurements of formation cross sections for the interaction of silver with 11.5- and 300-GeV protons. The data were obtained by direct assay of the irradiated targets with a Ge(Li) spectrometer followed by computer analysis of the γ -ray spectra. We were able to measure 72 formation cross sections at each energy and use the data to determine charge dispersion and mass yield curves. The mass-yield curve obtained at 11.5-GeV is shown in Fig. 1. The curve is based on a combination of experimentally determined yields and values obtained from the charge dispersions. The isobaric cross sections decrease with decreasing A from ~ 30 mb near the target to a broad minimum of ~ 5 mb at $A \sim 25-45$ and increase again at lower mass numbers. The two plateaus observed at $A \sim 60-75$ and $A \sim 85-95$ appear to be real features but more careful measurements would be needed to establish their existence beyond question. The mass yield curve, as well as the individual cross sections, are in good agreement with the values reported by Katcoff et al. (1) on the basis of a conventional radiochemical study.

The comparison between the 11.5- and 300-GeV data reveals that, within the limits of error, there are no differences in the formation cross sections.

This is shown graphically in Fig. 2 which displays all the cross section ratios as a function of A. The weighted average value of $\sigma_{300}/\sigma_{11.5}$ is 1.01 ± 0.10 . The constancy of all the cross sections is somewhat surprising in view of the fact that the production of pions in p-p collisions is known (2) to increase by about a factor of 3 between 10 and 300 GeV.

We have also studied the interaction of 300 GeV protons with uranium. In this case we focused our attention on products in the $A \sim 130$ mass region for which we had previously (3,4) obtained detailed results on charge dispersion and recoil properties. While the recoil properties were found to be essentially the same at 300- as at 11.5-GeV, the cross sections showed a rather unusual energy dependence, as displayed in Fig. 3. It is seen that the cross sections of products with $A \geq 130$ are equal at both energies while those of lower A show a marked decrease at 300 GeV. The observed trend is primarily exhibited by the neutron deficient iodine nuclides, the value of $\sigma_{300}/\sigma_{11.5}$ becoming as low as 0.64 ± 0.05 for ^{123}I . This effect is not one primarily reflecting differences in the charge dispersion because it does not correlate well with the charge dispersion variable, $Z_A - Z$. The observed decrease is rather localized in mass as it doesn't appear to extend into the $A \sim 100$ region (5). We are as yet at a loss to explain this effect and are actively continuing our measurements in this mass region. This is the first indication that there are at least some significant changes in the interaction of complex nuclei with very high-energy protons and it is clear that a good deal of further investigation is needed.

Considerable progress has been made on the determination of the charge dispersion and recoil properties of products with $A \sim 131$ from the interaction of gold with 11.5 GeV protons. This study is intended to complement our similar investigation for uranium (3) by examining the interactions of a target nucleus

for which fission is unimportant. In this fashion we can focus our attention on the deep-spallation process leading to the formation of neutron deficient products in the fission region, a process whose nature is not as yet completely understood. We intend to perform a detailed comparison with the uranium data as well as with calculations based on spallation systematics (6). To this end we are in the process of examining the literature on range-energy relations in order to convert the measured recoil ranges to momenta.

Relatively minor progress has been made during the past year on the following two recoil studies of products in the $A \sim 130$ region from the interaction of ^{238}U with high-energy protons. The first study is concerned with the measurement of the energy dependence of recoil properties of independently formed ^{131}Ba and ^{131}La , as well as cumulatively formed ^{131}Ce . This study is designed to refine previous findings (7) by our group of a decrease in the ranges of neutron deficient products lying in the fission region and of a concomitant peaking of their forward-to-backward ratio occurring between ~ 1 - and 4-GeV. Our previous work involved cumulatively formed products and so the results represent the average behavior of several isobaric nuclides. In the present work we attempt to perform similar measurements on independently formed products in order to determine how this unusual, and as yet poorly understood transition depends on the composition of isobaric products. While some experiments have been performed at 3 GeV we have been unable to obtain data at lower energies due to difficulties in obtaining such bombardments at the ZGS.

The second recoil study in progress involves the measurement of the differential ranges of independently formed products with $A \sim 131$ at 11.5 GeV. We wish to probe the transition between fission and spallation and, possibly, obtain the first direct evidence for the simultaneous contribution of both mechanisms to the formation of a single product by observation of a double-

peaked differential range curve. The apparatus for differential range irradiations has been fabricated but we have been plagued with problems in inserting this assembly into the ZGS vacuum without breaking the very fragile thin targets. In collaboration with E. P. Steinberg of Argonne, we have been working on a procedure to overcome this difficulty.

Preliminary work has begun on approved LAMPF experiment #118 entitled "Fragment Emission in Pion-Induced Reactions." In this study we propose to measure the cross sections for the formation of ^{24}Na from heavy elements in reactions induced by pions and to compare them with those of the same reactions induced by protons in order to obtain information about the fragmentation mechanism. Briefly, if this process occurs because of pions absorption in a local region of the nucleus the cross sections should be higher for incident pions of a given energy. On the other hand if the process results because of the correlated motion of cascade nucleons, the cross section should be higher for protons. A relatively straightforward choice between mechanisms is thus afforded. We have, to date, worked out the necessary radiochemical procedures and counting techniques, taking into account the fact that the cross sections are likely to be in the μb range.

B. Low-Energy Nuclear Reactions

A number of experiments dealing with isospin effects and the independence hypothesis in compound statistical reactions have been performed during the past year. Our most intriguing results were obtained in a study of the energy dependence of isospin mixing in the ^{69}Ga compound nucleus. The amount of isospin mixing between the T_+ and T_- states of the compound nucleus can be determined from the enhancement in the cross section of the (p,p') reaction. This enhancement results from the fact that the only decay channels open to the T_+

states of the compound nucleus are proton emission and damping into the $T_{\leq}$ states by the Coulomb interaction (8-10). The (p,p') cross section thus is enhanced to the extent that the isospin of the compound nucleus is conserved. The degree of isospin mixing can be obtained from the experimental determination of the quantity $R_{\text{exp}} = \sigma(p,p')\sigma(\alpha;\alpha')/\sigma(p,\alpha)\sigma(\alpha,p)$. We have determined this quantity by measurement of the energy spectra of protons and α -particles emitted in the reactions $^{68}\text{Zn} + p$ and $^{65}\text{Cu} + \alpha$, followed by integration of the evaporation peaks over energy and angle. Before the extent of isospin mixing can be extracted from the data a correction has to be applied for the fact that the compound nucleus is formed with different angular momentum distributions in the case of proton- and alpha- bombardment. This correction factor, denoted by R_{calc} , can be evaluated on the basis of the spin-dependent statistical theory. The quantity of interest is the ratio $R_{\text{exp}}/R_{\text{calc}}$. If isospin is not conserved in compound nuclear reactions this ratio should, according to the independence hypothesis, be equal to unity. On the other hand, if isospin is completely conserved this quantity will be larger than unity and its value, denoted by $(R_{\text{exp}}/R_{\text{calc}})_{\text{max}}$, can be calculated (8-10). If fractional isospin mixing occurs the values of $R_{\text{exp}}/R_{\text{calc}}$ will lie between these two limits.

Table 1 summarizes the results of this experiment. The ^{69}Ga compound nucleus was formed at excitation energies ranging from 17.4 to 22.4 MeV. It is seen that the values of $R_{\text{exp}}/R_{\text{calc}}$ are larger than unity at all energies but only approach those of $(R_{\text{exp}}/R_{\text{calc}})_{\text{max}}$ at the lowest energy. Evidently isospin mixing is of some importance and the value of the mixing fraction, μ , is seen to increase with energy from essentially 0 to about 0.3. This constitutes the first determination of the energy dependence of isospin mixing in compound nuclear reactions and we find the trend of the μ values to be intri-

guing and somewhat difficult to understand. The fact that the mixing increases with energy in a region where the compound nuclear levels are completely overlapping indicates that mixing competes to an increasingly favorable degree with particle emission. This idea seems difficult to reconcile with the well known relative strength of the Coulomb and nuclear interactions that are responsible for these two processes, respectively. It is quite possible that other factors may be at play and further work is clearly required.

During the past year we have also performed a number of experiments designed to test the validity of the independence hypothesis in compound nuclear reactions. The first truly valid test of the hypothesis for reactions induced by protons and α -particles was recently reported by us (10) on the basis of measurements on the α and np exit channels. These channels are not open to the T_1 states of the compound nucleus and so the extent of isospin conservation does not affect the results. We have performed these measurements on the ^{49}V , ^{52}Cr , ^{55}Mn , and ^{69}Ga compound nuclei. A similar test was also performed on the ^{75}Br compound nucleus formed in the reactions $^{59}\text{Co} + ^{16}\text{O}$ and $^{63}\text{Cu} + ^{12}\text{C}$. The independence hypothesis has been confirmed in all the cases that have been analyzed to date.

The research performed this past year closely followed the outline submitted in the last renewal proposal and further effort will be devoted to these projects during the remainder of the present contract year. The principal investigator has devoted approximately 50% of his time and effort to this project during the present contract year. It is expected that this figure will be maintained at the same level for the remainder of the year.

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Figure 1

Mass-yield curve for the interaction of silver with 11.5 GeV protons. The various symbols refer to the fractions of the total isobaric yields that were experimentally determined: $\bullet$ (>50%), $\circ$ (30-50%), Δ (10-30%), Δ (<10%).

Figure 2

Variation of $\sigma_{300}/\sigma_{11.5}$ with product mass. The target in these experiments was silver.

Figure 3

Dependence of $\sigma_{300}/\sigma_{11.5}$ on product A for the interaction of ^{238}U with 300- and 11.5-GeV protons; o - I nuclides, Δ - Cs, ∇ - Ba, $\square$ - Ag (ref. 5), $\diamond$ - Pd (ref. 5). Open points represent neutron deficient products and closed points neutron excessive ones. The dashed line shows the trend of the data.

Table 1

Isospin mixing in the decay of the ^{69}Ga compound nucleus

U_{CN} (MeV)	R_{exp}	R_{calc}	$R_{\text{exp}}/R_{\text{calc}}$	$(R_{\text{exp}}/R_{\text{calc}})_{\text{max}}$	μ
17.4	2.63 ± 0.10	0.81 ± 0.04	3.25 ± 0.20	3.32	0.03
18.4	2.28 ± 0.11	0.82 ± 0.04	2.78 ± 0.19	3.25	0.19
20.4	2.14 ± 0.23	0.82 ± 0.04	2.61 ± 0.31	3.11	0.22
22.4	2.05 ± 0.20	0.86 ± 0.04	2.39 ± 0.23	3.01	0.29

II. Publication Abstracts

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

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, Phys. Rev. C. 8, 1091 (1973).

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, Phys. Rev. Lett. 31, 244 (1973).

Cross sections of 27 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 0.91 ± 0.07 and is independent of mass number.

Test of the Independence Hypothesis and Isospin Conservation in Compound-Statistical Reactions. J. Wiley, J. C. Pacer, C. R. Lux, and N. T. Porile, Nucl. Phys. A212, 1 (1973).

Energy spectra and angular distributions of protons and α -particles emitted in the decay of ^{56}Fe , ^{60}Ni , ^{63}Cu , ^{64}Zn , and ^{66}Zn were measured. These compound nuclei were produced with a given excitation energy by irradiation of appropriate targets with 14.0 MeV protons and 15-19 MeV α -particles. The proton spectra featured a low-energy peak ascribable to the (p,np) or (α ,np) reaction as well as a higher energy peak due to the (p,p') or (α ,p) reaction. These peaks were sufficiently well resolved that differential cross sections could be obtained for the p, np, as well as α exit channels. The α and np exit channels were found to be free of pre-compound effects and are not affected by isospin conservation. Comparison of these particular cross sections for both entrance channels permits a test of the independence hypothesis provided a correction is made for the different angular momentum distributions in the entrance channels. When this correction is applied on the basis of the spin-dependent statistical theory it is found that the independence hypothesis is confirmed in all cases. Comparison of the p and α exit channels leads to values of the isospin mixing fraction, μ , between the T_+ and T_- states of the compound nucleus. The values of μ are 0.4 ± 0.2 for all five compound nuclei and correspond to Coulomb mixing widths whose value is approximately 20 keV.

New Neutron Deficient Pb and Bi Nuclides Produced in Cross-Bombardments with Heavy Ions. Y. Le Beyec, M. Lefort, J. Livet, N. T. Porile, and A. Siivola, Phys. Rev. C 9, 1091 (1974).

New α -emitting bismuth nuclides ranging in mass number from 189 to 197 and lead nuclides ranging from 186 to 192 have been produced in the following

reactions: $^{203}\text{Tl}(^3\text{He},\text{xn})^{206-x}\text{Bi}$, $^{187}\text{Re}(^{16}\text{O},\text{xn})^{205-x}\text{Bi}$, $^{185}\text{Re}(^{16}\text{O},\text{xn})^{203-x}\text{Bi}$, $^{181}\text{Ta}(^{20}\text{Ne},\text{xn})^{201-x}\text{Bi}$, $^{159}\text{Tb}(^{40}\text{Ar},\text{xn})^{199-x}\text{Bi}$, $^{181}\text{Ta}(^{19}\text{F},\text{xn})^{200-x}\text{Pb}$, $^{182}\text{W}(^{16}\text{O},\text{xn})^{198-x}\text{Pb}$, and $^{155}\text{Gd}(^{40}\text{Ar},\text{xn})^{195-x}\text{Pb}$. Assignments were made on the basis of excitation function measurements and comparison with similar reactions leading to the formation of the analogous well-known Po nuclides. The following assignments were made, where for each nuclide the two listed numbers are the α -ray energy in MeV and half-life: $^{197\text{m}}\text{Bi}$ -5.77, 10 min; ^{195}Bi -5.43, 170 sec; $^{195\text{m}}\text{Bi}$ -6.11, 90 sec; ^{194}Bi -5.61, 105 sec; ^{193}Bi -5.90, 64 sec; $^{193\text{m}}\text{Bi}$ -6.18; ^{192}Bi -6.06, 42 sec; ^{191}Bi -6.32, 13 sec; $^{191\text{m}}\text{Bi}$ -6.63; $^{191\text{m}}\text{Bi}$ -6.86; ^{190}Bi -6.45, 5.4 sec; ^{189}Bi -6.67, <2 sec; ^{192}Pb -5.06, 2.3 min; ^{191}Pb -5.29, 1.3 min; ^{190}Pb -5.58, 1.2 min; ^{189}Pb -5.72, 51 sec; ^{188}Pb -5.98, 26 sec; ^{187}Pb -6.08, 17 sec; ^{186}Pb -6.32, 8 sec. Estimates of α branching ratios are also presented.

Nuclear Reactions of ^{118}Sn , ^{121}Sb , and ^{127}I with Argon Ions. H. Gauvin, Y. Le Beyec, and N. T. Porile, Nucl. Phys. A (in press).

Excitation functions have been measured for a number of $(^{40}\text{Ar},\text{xn})$, $(^{40}\text{Ar},\text{pxn})$, $(^{40}\text{Ar},2\text{pxn})$, and $(^{40}\text{Ar},3\text{pxn})$ reactions induced in ^{118}Sn , ^{121}Sb and ^{127}I over the laboratory energy interval 150-280 MeV. Values of the total fusion cross section are obtained and J_{crit} is deduced. J_{crit} increases with energy and becomes as large as $110-140\hbar$, in reasonable agreement with the yrast limit deduced from the ellipsoidal liquid drop model. The competition between proton and neutron emission from the compound nucleus is examined and $\frac{\Gamma_p}{\Gamma_n}$ is found to increase rapidly with the number of emitted nucleons, thereby imposing severe limits on the production of very neutron deficient nuclides via compound nuclear reactions. The effect of very high angular momentum on the excitation functions is examined.

Energy Dependence of Isospin Mixing in Compound-Statistical Reactions.

N. T. Porile, J. C. Pacer, J. Wiley, and C. R. Lux, Phys. Rev. C (in press).

The ^{69}Ga compound nucleus was formed at excitation energies ranging from 17 to 22 MeV in the reactions $^{65}\text{Cu}+\alpha$ and $^{68}\text{Zn}+p$ and energy spectra of the emitted protons and α -particles were measured between 30° and 150° . The extent of isospin mixing between the T_+ and T_- states of the compound nucleus was determined by comparison of the quantity $\sigma(p,p')\sigma(\alpha,\alpha')/\sigma(p,\alpha)\sigma(\alpha,p)$ with theory and the fractional mixing was found to increase from 0 to 0.3 over the above energy range. The mixing width shows a corresponding increase from 0.2 to 16 keV. The independence hypothesis was verified at all energies by measurements of the α and np exit channels. The various spectra were compared with the spin-dependent statistical theory. It was not possible to fit the data for various energies with energy-independent parameters in the Fermi gas model level density expression suggesting that this expression is inadequate.

Interaction of ^{238}U with 300- and 11.5-GeV Protons: Cross Sections and Recoil Properties in the $A\sim 130$ Mass Region. Y. W. Yu and N. T. Porile, Phys. Rev. C (in press).

Formation cross-sections and thick-target recoil properties of 13 products in the $A\sim 130$ mass region from the interaction of ^{238}U with 300 and 11.5 GeV protons have been determined. The values of $\sigma_{300}/\sigma_{11.5}$ are consistent with unity for $A>130$ and decrease with decreasing A below this mass number, a trend that is most notably exhibited by neutron deficient iodine nuclides. The recoil ranges and F/B values are essentially the same at both energies.

Level Densities of ^{63}Cu and ^{65}Cu from the Analysis of Evaporation Spectra.

J. C. Pacer, J. Wiley, C. R. Lux, and N. T. Porile, Nucl. Phys. A (in press).

The levels of ^{63}Cu and ^{65}Cu were populated in (p,p') , (p,α) , (α,p) and (α,α') reactions induced by 12.5-16.0 MeV protons and 16.8-21.3 MeV α -particles.

Energy spectra were measured between 30° and 150° and the evaporation spectra were compared with the spin-and isospin-dependent statistical theory. The comparison permitted the determination of the level density parameter, a , and the pairing energy parameter, δ , in the Fermi gas model level density expression.

It was found that while a given set of parameters could give a good fit to the spectra obtained at a given energy, the energy dependence of some of the differential cross sections was not very well reproduced. The implications of this disagreement for the validity of the Fermi gas model level density are discussed.

III. Personnel

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IV. Publications, Theses, and Talks

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, Phys. Rev. C 8, 1091 (1973).

Nuclear Reactions of Silver with 300 GeV Protons. G. English, Y. W. Yu, and N. T. Porile, Phys. Rev. Lett. 31, 244 (1973).

Test of the Independence Hypothesis and Isospin Conservation in Compound-Statistical Reactions. J. Wiley, J. C. Pacer, C. R. Lux, and N. T. Porile, Nucl. Phys. A212, 1 (1973).

New Neutron Deficient Pb and Bi Nuclides Produced in Cross-Bombardments with Heavy Ions. Y. LeBeyec, M. Lefort, J. Livet, N. T. Porile, and A. Siivola, Phys. Rev. C 9, 1091 (1974).

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Interaction of ^{238}U with 300- and 11.5-GeV Protons: Cross Sections and Recoil Properties in the $A \sim 130$ Mass Region. Y. W. Yu and N. T. Porile, Phys. Rev. C (in press).

Level Densities of ^{63}Cu and ^{65}Cu from the Analysis of Evaporation Spectra. J. C. Pacer, J. Wiley, C. R. Lux, and N. T. Porile, Nucl. Phys. A (in press).

Isospin Effects in Compound-Statistical Reactions. John Wiley, Ph.D. Thesis, Purdue University, May 1974.

"Test of the Independence Hypothesis and Isospin Conservation in Compound-Statistical Reactions," presented at the American Chemical Society meeting, Chicago, August, 1973.

"Isospin Effects in Compound Nuclear Reactions," given by N. T. Porile at the Radiochemistry Seminar, Los Alamos Scientific Laboratory, Los Alamos, N. M., August, 1973.

"Energy Dependence of Isospin Mixing in Compound Nuclear Reactions," presented at the American Physical Society meeting, Bloomington, November, 1973.

"Interaction of 300 GeV Protons with Heavy Elements" given by N. T. Porile at European Conference on Physics and Chemistry of Complex Nuclear Reactions, Kibbutz Ginosar, Israel, January, 1974.

"Reactions of Complex Nuclei with Energetic Particles," given by N. T. Porile at the Physical Chemistry seminar, Purdue University, February, 1974.

"Isospin Effects in Compound-Statistical Reactions," given by J. Wiley at the Nuclear seminar, Purdue University, April, 1974.