Transfer reaction cross sections from the interactions of ^{20}Ne and ^{22}Ne with ^{232}Th

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A target of ^{232}Th has been bombarded with 114 MeV ^{22}Ne and with 114 MeV and 129 MeV ^{20}Ne beams. Recoiling reaction products were chemically isolated and the cross sections for protactinium, uranium, and neptunium isotopes were determined. The width of the cross section distributions for a given Z and their neutron-richness are the same as those for similar transfers in Ne+^{248}Cm reactions. Population of low spin isomeric states is favored in these reactions over population of high spin states. As was seen in reactions with heavier targets, an increase in reaction energy does little to shift the evaporation residues toward neutron deficiency. The implications are that only primary products with little or no excitation energy and angular momentum survive the fission process to become evaporation residues in these systems, and that the production of these nuclides is more controlled by the change in the identity of the projectile than by the corresponding change in the target.

I. INTRODUCTION

There has recently been a lot of interest in the possibility of synthesizing new neutron-rich actinide and transactinide nuclides in transfer reactions of light heavy ions ($A \leq 40$) with actinide targets.[1-3] In these reactions, the complicated way in which the energy and angular momentum states in the primary products are originally populated and then deexcited by the emission of particles or photons or by fission makes the extremes of the cross section distributions of the evaporation residues hard to predict theoretically. In order to pick the optimum projectile-target-reaction energy combination, it is important to systematize the reaction product cross sections in the known regions of nuclear mass and charge.

Most of the work on these transfer reactions in the actinide region has been concentrated on bombardments of the heaviest available target materials; very little work has been done in the light actinide region except for that concentrating on reaction products in the charge and mass vicinity of the projectile.[4-6] In order to further systematize these reactions in the actinide region, we have bombarded a target of ^{232}Th with ^{20}Ne and ^{22}Ne and chemically isolated the reaction products, concentrating on those elements with one, two, and three more protons than the target, at energies not far in excess of the calculated Coulomb barrier of approximately 105 MeV.

II. EXPERIMENTAL

A uniform target of 1.0 mg/cm^2 ^{232}Th was electroplated[7] in a 7 mm diam spot on a 2.3 mg/cm^2 beryllium substrate. This target was irradiated with 0.5 to 1.0 electrical microamperes of ^{20}Ne^{5+} (two experiments) and ^{22}Ne^{5+} (one experiment) at the 88-inch Cyclotron of the Lawrence Berkeley Laboratory. The target system has been described previously.[1] The incident projectile energies of 136 MeV for ^{22}Ne and 132 and 146 MeV for ^{20}Ne were degraded[8] by an isolation foil and the target substrate to the values given in Table I, which describe the experiments performed for this work. Recoiling reaction products between 0° and roughly 50° to the beam direction were collected with a 2 mg/cm^2 nickel foil and isolated chemically.

TABLE I. Experimental systems.

Target	Thickness	Projectile	Center-of-target projectile energy (MeV,lab)	Irradiations
^{232}Th	1.0 mg/cm^2	^{22}Ne	114	Recoil catcher-chemistry
^{232}Th	1.0 mg/cm^2	^{20}Ne	114	Recoil catcher-chemistry
^{232}Th	1.0 mg/cm^2	^{20}Ne	129	Recoil catcher-chemistry, long run and fast chemistry run

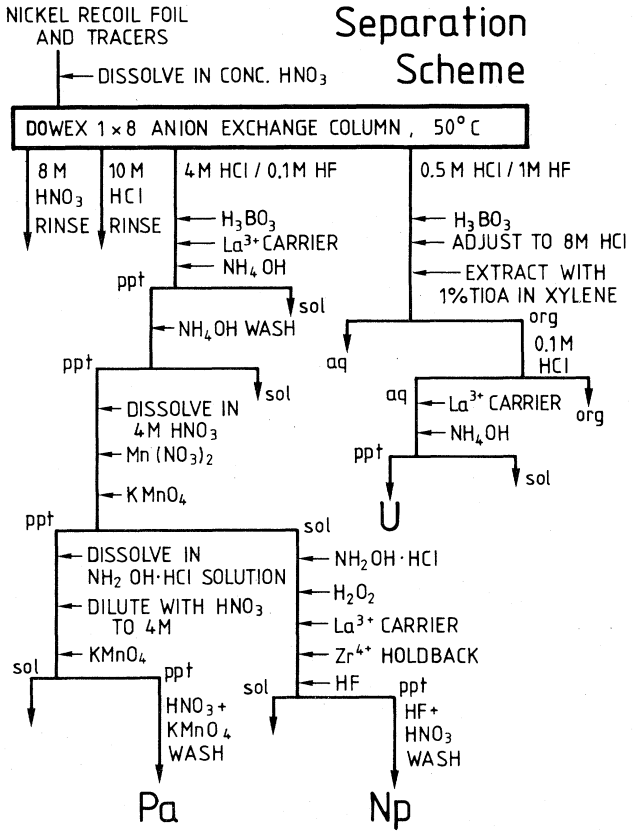

FIG. 1. The chemical separation scheme for preparing samples of protactinium, uranium, and neptunium suitable for use in cross section determinations by means of gamma-ray detection.

Figure 1 shows an outline of the chemical separation scheme. The chemical yields of protactinium and uranium isotopes were determined by the addition of standard aliquots of ^{231}Pa and ^{233}U at the beginning of the chemical procedure. Neptunium yields in the first two experiments were determined from a ^{237}Np tracer from which the ^{233}Pa daughter was removed just prior to the experiments. In the third experiment, the ^{239}Np in equilibrium with ^{243}Am was used as the tracer. In the full procedure, depicted in Fig. 1, samples were ready for counting 40 min after the end of irradiation. An abbreviated chemistry performed for the third experiment resulted in a neptunium fraction after 20 min. Typical chemical yields from the procedure are 80% for protactinium, 50% for uranium, and 70% for neptunium. The protactinium and uranium fractions were essentially free of contaminants. The neptunium fraction often contained small amounts of protactinium and thorium which did not seriously interfere with the activity measurements.

The decay of the nuclides in the chemical fractions was followed for about two weeks. Gamma-ray photons were observed with a Ge(Li) detector whose efficiency at various energies was determined with a mixed radionuclide standard source mounted with the same geometry relative to the detector as were the experimental samples. A given data acquisition interval was shorter than the half-lives of the species of interest which were still observable in the sample. Gamma-ray peaks in the pulse-height analyzer (PHA) spectra of high intensity and good statistics were integrated with the SAMPO computer code.[9] Those peaks which were too small for this procedure were integrated by hand, subtracting a background averaged over several PHA channels, both below and above the peak in energy. The areas of the gamma-ray peaks were analyzed as a function of time to give a set of initial activities which were converted to cross sections. It was assumed that the fraction of the reaction products of interest which stopped in the target or which were emitted at angles not collected by the nickel catcher foil was negligible; we consider the cross sections to be of absolute magnitude. No corrections were made for parent-daughter feeding during the irradiations or before the chemical separations; this is a negligible effect except in the case of the ^{233}Th-^{233}Pa pair, where much of the observed intensity of ^{233}Pa is due to decay from the 22-min ^{233}Th produced via simple neutron pickup or stripping reactions. Absolute gamma-ray intensities were determined using data from the Table of Isotopes.[10]

III. RESULTS AND DISCUSSION

Cross sections obtained from these bombardments are given in Table II, and are plotted in Figs. 2–4. Comparison of Figs. 2 and 3 shows the difference between ^{22}Ne- and ^{20}Ne-induced reactions at roughly the same energy relative to the Coulomb barrier. The maximum of the cross section distribution for the neptunium isotopes produced in the ^{22}Ne+^{232}Th reaction is about two mass units more neutron-rich than is the maximum for the same distribution arising from ^{20}Ne+^{232}Th. This is the same result observed when comparing above-target isotopic yields

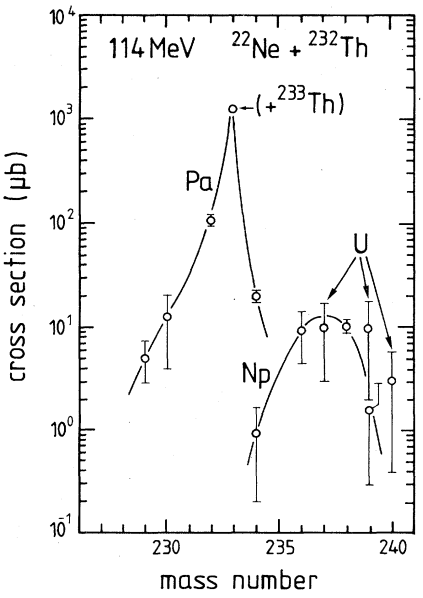

FIG. 2. Product cross sections from the reaction of 114 MeV ^{22}Ne with ^{232}Th. Cross sections for nuclides of the same element are connected only to guide the eye.

TABLE II. Ground state Q values and measured cross sections (mb).

	^{22}Ne		^{20}Ne		
	Q_{gg}	(114 MeV)	Q_{gg}	(114 MeV)	(129 MeV)
^{227}Pa			−11.3		$(6.9\pm6.6)\times10^{-3}$
^{228}Pa			−9.1	$(1.6\pm1.3)\times10^{-3}$	$(2.2\pm2.0)\times10^{-2}$
^{229}Pa	−15.3	$(5.1\ \pm2.2)\times10^{-3}$	−4.8	$(2.9\pm1.6)\times10^{-2}$	$(4.6\pm1.8)\times10^{-2}$
^{230}Pa	−13.3	$(1.2\ \pm0.8)\times10^{-2}$	−6.6	$(3.7\pm0.6)\times10^{-2}$	$(8.1\pm0.9)\times10^{-2}$
^{232}Pa	−11.3	$(1.08\pm0.12)\times10^{-1}$	−7.5	$(3.7\pm0.5)\times10^{-1}$	$(8.1\pm0.9)\times10^{-1}$
^{233}Pa	−10.0	(1.29±0.09)	−7.6	(2.8±0.1)	(2.6±0.1)
^{234}Pa^{g}	−12.9	$(1.98\pm0.22)\times10^{-2}$	−12.8	$(1.1\pm0.1)\times10^{-2}$	$(4.2\pm0.6)\times10^{-2}$
^{231}U			−13.5	$(2.2\pm1.6)\times10^{-2}$	$(3.8\pm2.0)\times10^{-2}$
^{237}U	−17.2	$(1.0\ \pm0.7)\times10^{-2}$	−19.8	$(1.7\pm1.5)\times10^{-3}$	$(7.3\pm5.8)\times10^{-4}$
^{239}U	−26.0	$(1.0\ \pm0.8)\times10^{-2}$			
^{240}U	−33.3	$(3.1\ \pm2.7)\times10^{-3}$			
^{232}Np			−31.1		$(2.7\pm2.3)\times10^{-3}$
^{233}Np			−25.2	$(5.0\pm4.6)\times10^{-3}$	$(1.1\pm0.9)\times10^{-2}$
^{234}Np	−34.7	$(9.3\ \pm7.3)\times10^{-4}$	−24.8	$(3.2\pm0.2)\times10^{-2}$	$(4.2\pm0.3)\times10^{-2}$
^{236}Np^{m}	−29.3	$(9.2\ \pm4.7)\times10^{-3}$	−20.7	$(3.7\pm2.2)\times10^{-2}$	$(3.1\pm2.0)\times10^{-2}$
^{238}Np	−25.7	$(1.04\pm0.16)\times10^{-2}$	−21.9	$(1.9\pm1.5)\times10^{-4}$	$(3.6\pm3.0)\times10^{-4}$
^{239}Np	−22.0	$(1.6\ \pm1.3)\times10^{-3}$			

from massive transfers of ^{20}Ne and ^{22}Ne to ^{248}Cm,[1] and ^{16}O and ^{18}O to ^{248}Cm.[1] It is not possible from our data to make a quantitative statement about the shift in the protactinium and uranium distributions, but they are shifted toward neutron excess in the ^{22}Ne-induced reaction relative to the ^{20}Ne-induced reaction.

The full width of half maximum of the cross section distributions for the neptunium isotopes is roughly 2.5 mass units in each experiment, the same as that for an equivalent transfer in the reactions of ^{20,22}Ne with ^{248}Cm. In the Ne + ^{248}Cm systems, it was observed that at the same energy relative to the Coulomb barrier, transfer cross sections were enhanced in ^{20}Ne reactions over those from ^{22}Ne reactions. A similar effect is observed in this work; the ^{20}Ne+^{232}Th peak cross sections are larger than those from ^{22}Ne+^{232}Th for an equivalent number of protons transferred. In the Ne + ^{248}Cm systems, products with two more protons than the target were formed with enhanced cross sections relative to those products with only one more proton than the target. Insufficient information was obtained on the cross sections of the uranium isotopes in the experiments reported here to be able to establish whether the same effect occurs in the Ne + ^{232}Th systems. However, since the ground state Q values[11] (see

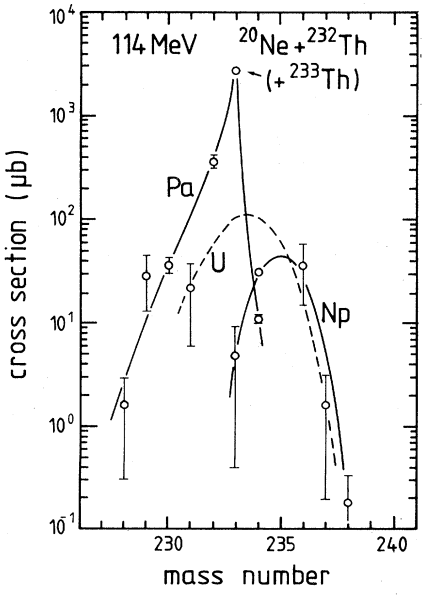

FIG. 3. Product cross sections from the reaction of 114 MeV ^{20}Ne with ^{232}Th. Cross sections for nuclides of the same element are connected only to guide the eye.

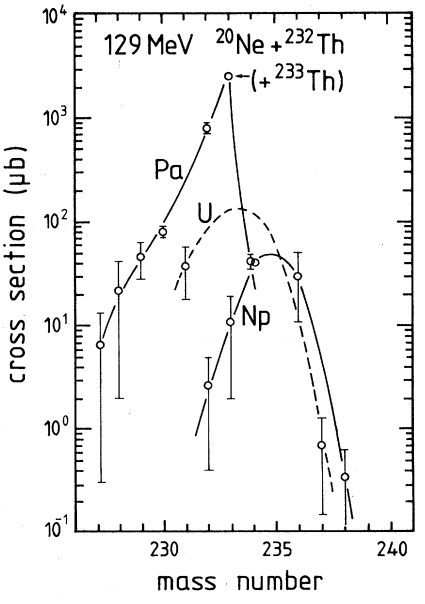

FIG. 4. Product cross sections from the reaction of 129 MeV ^{20}Ne with ^{232}Th. Cross sections for nuclides of the same element are connected only to guide the eye.

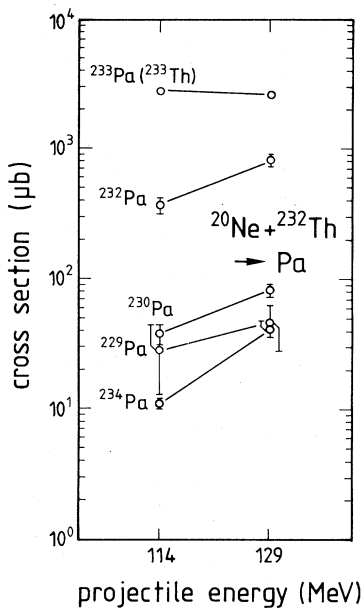

FIG. 5. Partial excitation functions for the protactinium isotopes produced in the bombardment of ^{232}Th with ^{20}Ne. Projectile energies are center of target in the laboratory frame.

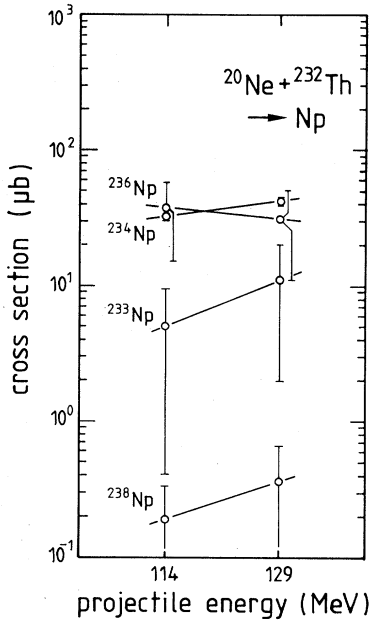

FIG. 6. Partial excitation functions for the neptunium isotopes produced in the bombardment of ^{232}Th with ^{20}Ne. Projectile energies are center of target in the laboratory frame.

Table II) and Coulomb potentials of these reactions are dominated by changes in the mass and charge of the relatively light projectile, it would not be surprising to find that the Ne+^{232}Th cross sections strongly mimic the behavior of the Ne+^{248}Cm cross sections in this regard as well as in the others.

Figures 5 and 6 show the behavior of product cross sections with projectile energy for the reaction of ^{20}Ne with ^{232}Th. The increase in reaction energy causes an increase in the product cross sections for all the observed products; this increase is roughly the same for all the observed products, with few exceptions. The ^{233}Pa (^{233}Th) cross section is roughly constant, implying that the neutron pickup cross section to make the ^{233}Th parent activity is not as energy dependent as those processes involving the transfer of charge. The expected depletion of neutron-rich products relative to neutron-deficient products with an increase in projectile energy is not seen in these data, implying that most of the transfer products which survive deexcitation by fission arise from primary products with excitation energies on the order of, or less than, the neutron binding energy. In fact, the steepest increase in product cross section with reaction energy is for ^{234}Pa^{g} ($J^{\pi}=4^{+}$), the most neutron-rich protactinium nuclide observed in these experiments. We propose that this is due to an increase in that fraction of the reaction cross section going to form ^{234}Pa which results in the high spin (4^{+}) ground state, and a corresponding decrease in the fraction which forms the unobserved $J^{\pi}=0^{-}$ metastable state. For ^{236}Np, where only the low spin isomer (^{236}Np^{m}) was observed, we would expect a decrease of the fraction of the total ^{236}Np cross section going to form ^{236}Np^{m} with an increase in projectile energy. Our data for this nuclide are not of a quality which lets us state this unequivocally.

In previous work,[2] where the excitation functions of actinide products were determined in the reaction of ^{18}O with ^{248}Cm and ^{249}Cf, only the low spin isomeric species ^{248}Bk^{m} and ^{254}Es^{m} were reported because the high spin species could not be observed. There was little discrepancy observed between the behavior of the excitation functions for these nuclides and those of neighboring nuclides. There was also no difference observed between the magnitude of these cross sections and what one would expect from extrapolation if all of the product cross section were in the low spin state. The magnitude of the cross sections for ^{236}Np^{m} in our own work is also consistent with representing most of the (^{236}Np^{g} + ^{236}Np^{m}) cross section. We use this evidence, and the evidence of the ^{234}Pa cross sections, to state that the primary reaction products formed in these reactions which deexcite to form actinide products are all of very low intrinsic angular momentum, on the order of the spins of the isomers themselves.[12,13] The bulk of the reaction cross section resulting in a particular isomer pair will end up in the low spin state at these reaction energies. An increase in projectile energy, resulting in an increase in the average angular momentum of the composite system, will remove some of the cross section to the high spin state; this has a smaller relative effect on the large cross section of the low spin isomer than on the smaller cross section of the high spin isomer.

IV. CONCLUSIONS

In reactions of light heavy ions with actinide targets, actinide transfer products arise from those processes which result in primary fragments of very low intrinsic excitation energy and angular momentum. Across a broad selection of possible actinide targets, the cross section of a given transfer is more a function of the change in the identity of the projectile than of that of the target.

In these reactions, cross sections from ^{20}Ne bombardments are enhanced over those from ^{22}Ne bombardments.

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