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Transfer cross sections from reactions with ^{254}Es as a target

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We report radiochemically determined cross sections for the heaviest known actinides produced in transfer reactions of ^{16,18}O and ^{22}Ne with ^{254}Es as a target. A comparison with data for similar transfers from ^{248}Cm targets is made. Transfer cross sections are extrapolated for the production of unknown, neutron-rich isotopes of elements 101–105, and the unique potential of ^{254}Es as a target to make these exotic nuclei accessible is demonstrated.

We report for the first time the yields of neutron-rich actinide nuclides from transfer reactions of light projectiles with ^{254}Es as a target. This target isotope, a 270-day α emitter with $Z=99$, is the heaviest nuclide that can be produced in the multimicrogram quantities necessary for heavy-ion bombardments. The aim of our experiment was to measure production cross sections for the known most neutron-rich isotopes of trans-Es elements with radiochemical techniques and from that construct isotope distributions that allow not only comparison with data from other experiments but also extrapolations into the region of yet unknown isotopes. These more neutron-rich isotopes are expected to have increasingly longer α-decay half-lives and may thus allow the study of the influence of increasing relativistic effects on valence-electron ground-state configurations in chemical experiments. Also spontaneous fission (sf) decay properties in this region are of considerable interest in view of the remarkable results obtained in sf studies of, e.g., ^{259}Md,[1] ^{260}104,[2] and ^{262}105.[3] Even though we have not observed new isotopes in the present work, our cross-section systematics give a basis for the assignment of individual isotopes and will help in the design of future experiments with more specific detection techniques. Our results demonstrate that cold, multinucleon transfer reactions with ^{254}Es as a target offer a unique possibility to access and investigate new neutron-rich actinide nuclides.

Compound nucleus reactions between actinide targets such as ^{248}Cm, ^{249}Cf, or ^{249}Bk and light ions were previously used to establish the present limits of known neutron-rich actinide and transactinide isotopes.[4–7] Production of still heavier nuclides is prohibited due to losses from the relatively high excitation energy of the compound nucleus and the severe fission competition in the deexcitation process. An alternative approach, using "cold" fusion reactions of medium-heavy projectiles (e.g., ^{58}Fe) with ^{208}Pb or ^{209}Bi targets, provided a successful path to synthesize new elements up to $Z=109$.[8] Nevertheless, relatively neutron-poor nuclides are produced in these reactions because of the limited number of available target and projectile combinations. Short sf half-lives for the most neutron-rich nuclei make it impossible to produce nuclides heavier than ^{257}Fm in multiple neutron capture reactions.[9]

However, systematic studies of transfer reactions with ^{248}Cm targets and light projectiles like ^{16,18}O and ^{20,22}Ne have demonstrated that the problem of high excitation energies and subsequent losses due to fission competition can be partially avoided in transfer reactions.[10]

Our experiments were performed with 101 MeV ^{16}O, 98 MeV ^{18}O, and 127 MeV ^{22}Ne ions at Lawrence Berkeley Laboratory's 88-inch cyclotron and the UNILAC accelerator at Gesellschaft für Schwerionenforschung. The particle flux was typically kept between 1×10^{12} s^{-1} and 2×10^{12} s^{-1}. Es-oxide targets which contained 24.2 and 27.5 μg/cm^2 ^{254}Es (96.5% and 92% isotopic purity) were produced by electrodeposition on 2.4 mg/cm^2 Be foils. These were mounted in target chambers designed either to catch products with a recoil angle of $\leq 45°$ in Au catcher foils, or to transport the activity by means of a He jet containing KCl clusters to an automated rapid chemistry apparatus (ARCA) or a rotating wheel multidetector apparatus (ROMA).[11] Chemical fractions of ^{100}Fm through ^{103}Lr were separated with classical radiochemical procedures from Au catcher foils within 1–2 h and with ARCA within 5–15 min after irradiation. These fractions were assayed for α-particle and sf activities. Reaction products were continuously transported into ROMA within one second of production and were deposited there on 70 μg/cm^2 polypropylene foils which were stepwise rotated between 15 pairs of surface barrier detectors to measure α and sf decays. Total transport and deposition efficiencies for the jet system were determined to be 13% for the experiments with ^{22}Ne and 50% with ^{18}O as a projectile. The efficiencies were obtained by normalizing cross sections for longer-lived species like ^{255}Fm to results from catcher foil experiments, where chemical yields (typically 80%) were known. For ^{16}O a 50% efficiency was assumed.

Formation cross sections for the transeinsteinium isotopes are shown in Fig. 1 for 101 MeV ^{16}O, 98 MeV ^{18}O (left side) and 127 MeV ^{22}Ne (right side) as projectiles. The data points for the new isotope ^{260}Md are from a recent experiment.[12,13] All curves are Gaussian with a variance of $\sigma^2=0.914$ u^2 [full width at half maximum (FWHM) $=2.25$ u]. Of most interest are the high cross sections in comparison with other possible reactions forming the same product. Peak cross sections of about 1 mb for Md compare with

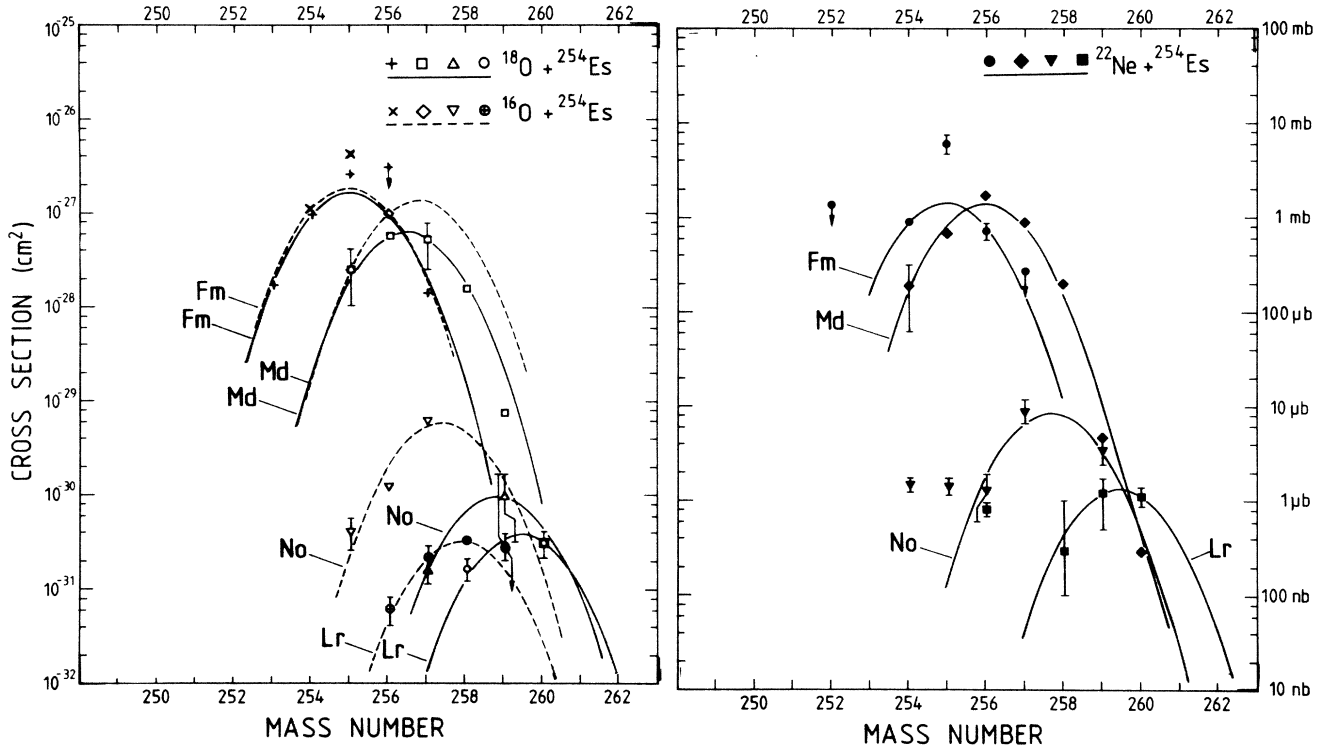

FIG. 1. Isotopic distributions measured for 101 MeV ^{16}O and 98 MeV ^{18}O (left) and for 127 MeV ^{22}Ne (right) on ^{254}Es. The data points for ^{260}Md are from Ref. 12.

only about 1 μb in $^{18}O+^{249}Cf$,[14] 100 nb in $^{238}U+^{248}Cm$,[15] and 10 nb in $^{18}O,^{22}Ne+^{248}Cm$ (Ref. 10) reactions. The neutron-rich isotopes ^{259}No and ^{260}Lr are produced with 3.5 and 1.1 μb, respectively, in the $^{22}Ne+^{254}Es$ transfer reactions, while fusion reactions like $^{248}Cm(^{18}O,\alpha 3n)^{259}No$ and $^{248}Cm(^{15}N,3n)^{260}Lr$ give cross sections of about 27 nb (Ref. 7) and 2 nb (Ref. 4), respectively. These larger cross sections with ^{254}Es as a target can easily be understood when one keeps in mind that for systems with light projectiles and heavy targets at barrier energies (i) about 50% of the total reaction cross section appears in transfer channels,[16] (ii) transfer products heavier than the target are formed predominantly, and, most importantly, (iii) because of the differences in ground-state Q values, Q_{gg}, these primary fragments are formed with very low excitation energies ($\leqslant 10$ MeV), so that in most cases the observed products are directly formed or they arise from the one-neutron evaporation channel.[14,15] This results in a much higher survival probability against fission in the deexcitation process, compared with the three or four neutrons evaporated after compound nucleus formation or from fragments formed in transfer reactions between two very heavy partners like $^{238}U+^{238}U$ (Ref. 17) or $^{238}U+^{248}Cm$.[15]

A systematic feature, which is most pronounced with ^{18}O as a projectile (see Fig. 1), is equally high cross sections for the 1p (Fm) and the 2p (Md) transfer followed by a large gap of two to three orders of magnitude and then again only slightly higher cross sections for the 3p (No) over the 4p (Lr) transfer. Such a relative enhancement of products formed in transfers of even numbers of protons can also be seen in product yields from $^{18}O+^{248}Cm$ (Ref. 10) and from lighter targets like ^{181}Ta and ^{208}Pb,[16] clearly indicating a structural effect in the light projectile which is possibly due to differences in the Q_{gg} values. As one may also speculate about a diproton transfer, it is somewhat surprising that the data do not show any evidence for an intense α-transfer channel. No such strong "odd-even effect" is observable in reactions between two heavy nuclei like $^{238}U+^{238}U$ (Ref. 17) or $^{238}U+^{248}Cm$.[15]

It is surprising to see in our experiments that the difference in neutron number for ^{16}O and ^{18}O projectiles is not fully reflected in the peak position of the isotope distributions for 1p (Fm)- and 2p (Md)-transferproducts as was observed earlier with ^{248}Cm targets[10] while for heavier products it is again. Because of the similarity of Q_{gg} values for similar transfers from ^{248}Cm and ^{254}Es targets one would not expect such a pronounced difference. In order to gain additional insights into the reaction mechanism and to base extrapolations of cross sections on firmer grounds, comparison with yield data from other reactions can be made by correlating cross sections for isotopes which are formed in equal transfer channels, (xp,yn).[15] This is shown in Fig. 2, where cross sections are plotted for two-, three-, and four-proton and y-neutron (ΔN) transfer products from the reactions of the two projectiles ^{18}O (left side) and ^{22}Ne (right side) with ^{248}Cm (Ref. 10) and ^{254}Es as targets. Positive ΔN values characterize neutron transfer from the projectile to the target. The heights and positions of the isotope distributions for elements near the target Z match very well for similar transfers from the different targets. However, for 3p (Es, No) and 4p (Fm,Lr) transfers, the situation is not so simple. The ^{22}Ne systems match fairly well, but the ^{18}O yields are different by an order of magnitude. This cannot be explained by small differences in the incident pro-

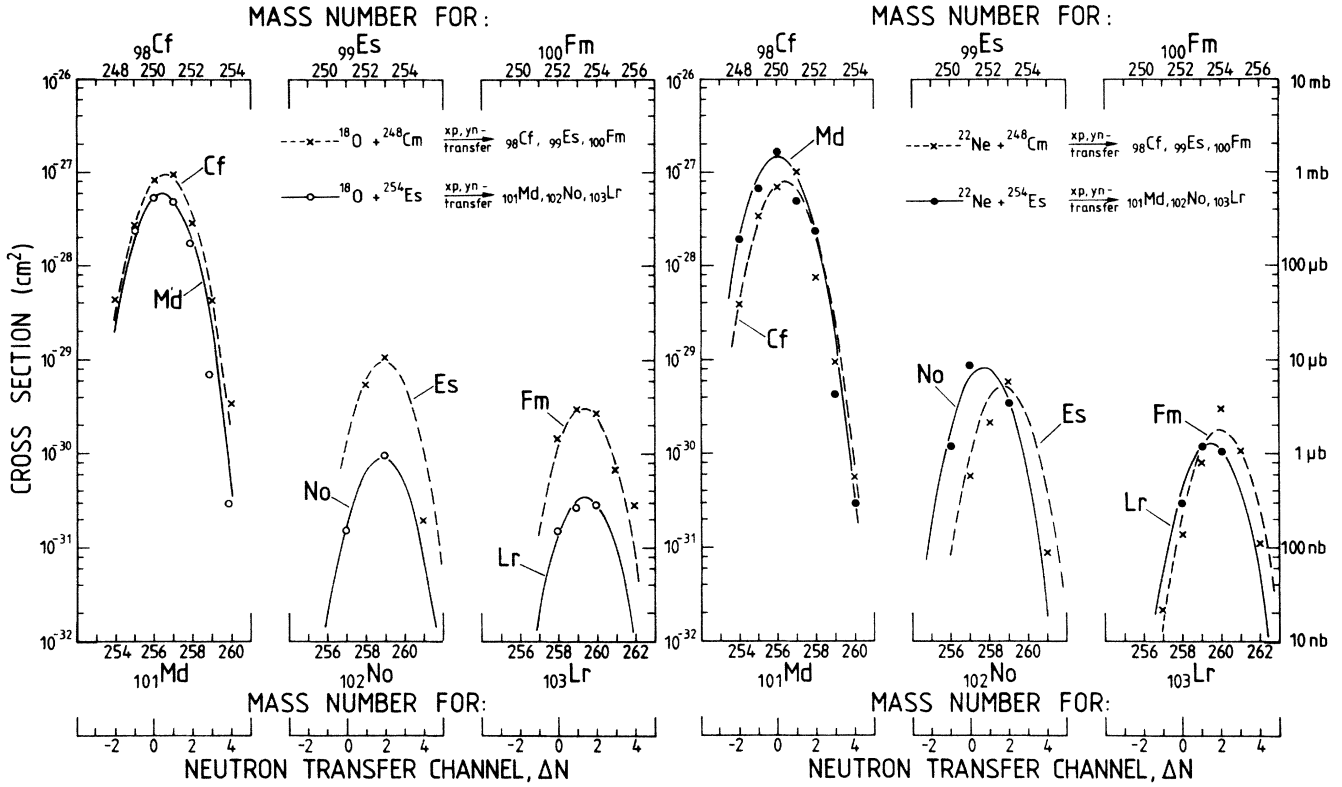

FIG. 2. Comparison of measured isotopic cross sections for two-, three-, and four-proton and y-neutron (ΔN) transfer products from ^{248}Cm and ^{254}Es as targets and ^{18}O (left) and ^{22}Ne (right) as projectiles. Data for ^{248}Cm targets are from Ref. 10.

jectile energy, because in all reactions the energy was chosen high enough above the barrier to be in a region where cross sections do not change drastically with small changes in energy.[14] A calculation of the maximum excitation energy, $E^*_{max} = Q_{gg} + (E_i - E_f)$, with E_i being the incident energy and E_f being the Coulomb energy in the two fragment exit channel, does not show any significant differences in energies to account for the observed effect. An explanation has to await further studies. As a result, we find that simple extrapolations from one reaction system to another, which in some cases lead to surprisingly good predictions, may not always do so.

We base our predictions for cross sections of yet unknown, heavy actinide nuclides on the isotope distributions fitted to the measured data. The results are given in Table I. These predictions can be uncertain by about one order of magnitude. A comparison between the predicted cross section for ^{260}Md based on data from our first experiments and the measured cross sections (the numbers given in parentheses in Table I) from a very recent bombardment of ^{254}Es with 108 MeV ^{18}O and 126 MeV ^{22}Ne followed by off-line mass separation[12,13] may indicate the accuracy of these predictions. These cross sections should be high enough to permit not only the identification of these isotopes but also the investigation of their decay properties. First measurements of the new isotope Md-260 (Ref. 13) and more precise data for other sf isotopes produced in ^{18}O, ^{22}Ne + ^{254}Es reactions already have revealed an unexpected bimodal way of spontaneous fission.[12] Especially if the proposed large 40-μg Es target[18] should become available more data also for yet unknown nuclei will be accessible. For isotopes of elements 104 and 105, at the maxima of the isotope distributions around mass numbers 262 and 264, respectively, cross sections between 1 and 10 nb can be expected. The predicted increase of α-decay half-lives for these more neutron-rich isotopes (see column 2 of Table I) may provide the chemist with sufficiently long-lived isotopes to study the onset of relativistic effects in the electron configurations which may cause deviations of chemical properties in these high-Z elements.[19] The adsorption behavior of these elements on different surfaces in a gas-phase chemistry experiment will, for example, answer the question

TABLE I. Extrapolated cross sections for heavy, neutron-rich actinides in ^{18}O and ^{22}Ne on ^{254}Es reactions. Measured data for ^{260}Md are given in parentheses.

Isotope	Predicted half-life	Cross section (nb) ^{18}O + ^{254}Es	Cross section (nb) ^{22}Ne + ^{254}Es
Md-260	99y[a]	740 (320)	240 (298)
261	1440y[a]	9	2
No-260	100 ms[b]	490	470
261	. . .	85	22
262	15 ms[b]	5	0.3
Lr-261	6h[a]	100	380
262	18d[a]	12	43
263	164d[a]	0.5	2

[a]α-decay half-life.
[b]sf-decay half-life from G. A. Leander (private communication).

whether the ground state of Lr is $7s^27p$ rather than $7s^26d$ as expected from simple extrapolations.[20]

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