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Publication Date
1974-06-01

Submitted to Physical Review Letters

LBL-2947 c.2
Preprint

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June 1974

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

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MASS YIELD DISTRIBUTIONS IN THE REACTION OF ^{84}Kr IONS WITH ^{238}U*

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June 1974

Abstract:

Yields of 156 nuclides were measured radiochemically to delineate the mass distribution in the reaction of 605 MeV ^{84}Kr with thick ^{238}U targets. The yields are consistent with decomposition of the mass distribution into five components: transfer products (700 ± 120 mb), "quasi-Kr" products centered at A ≈ 85 (470 ± 70 mb) and the products from symmetric fission of their complements (420 ± 60 mb), products from low energy fission of Z ≈ 92 nuclides (200 ± 40 mb), products from complete fusion-fission (55 ± 15 mb), and unexplained neutron-deficient yields at A ≈ 195 (∿ 40 mb).

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A new phenomenon has been observed in heavy ion reactions and has been termed "multinucleon transfer",[1] "quasifission",[2] "relaxation phenomena",[3] and "deep inelastic scattering".[4] These reactions are characterized by energy equilibration without mass equilibration, resulting in (i) two fragments with masses close to the target and projectile masses, (ii) fragment kinetic

*Work supported by the U. S. Atomic Energy Commission.
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energies close to the calculated Coulombic repulsion of two normal fission fragments, and (iii) angular distributions distinct from those for complete fusion-fission. For ions with $Z \lesssim 18$, these new reactions were observed to have modest cross sections[1-3] in contrast to the complete fusion process that accounts for an important part of the reaction cross section.[5] For reactions of ^{84}Kr ions with ^{209}Bi, much of the total interaction cross section goes into the new reaction channel,[2,4] contrary to expectations, whereas the complete fusion-fission cross sections were found to be low.[4,5] The ^{84}Kr results were obtained by measuring fragment-fragment coincidences at correlated angles.

The work reported here is a radiochemical measurement of the mass yield distribution for the reaction of ^{84}Kr with thick targets of ^{238}U. This technique provides yields of radioactive products uniquely characterized with respect to Z and A. The integral nature of these cross sections supplies information that is independent of any assumptions about the reaction mechanism. These data are used below to complement the information about mass distributions obtained in kinematic coincidence measurements, in which masses are deduced indirectly from the laboratory energies of the two fragments by assuming full momentum transfer from the projectile to the combined system. Also, kinematic coincidence measurements lack strict differentiation between inelastically scattered projectiles and nucleon transfer products--a limitation not inherent in radiochemical measurements. However, the advantages of the technique used in this work are obtained at the expense of a loss of information on energy dependence and angular distribution of reaction products.

Thick uranium targets were bombarded at the SuperHILAC with 605 MeV ^{84}Kr ions, dissolved shortly after the end of bombardment, and separated chemically into 7 fractions[6] that were assayed for α-particle and γ-ray activities. We have measured cross sections for 129 isotopes. Through an interlaboratory collaboration a lanthanide-actinide fraction from an intense 24 hour bombardment was radiochemically analyzed by the Los Alamos Scientific Laboratory Nuclear Chemistry Group, which resulted in yield information on 27 additional nuclides.[7] The independent and cumulative yields are plotted vs. mass number in Fig. 1(a). A detailed listing of the data and a description of their analysis will be given elsewhere.[9] The apparent scatter in the data in Fig. 1(a) occurs because independent yields, and even many of the cumulative yields, represent only a fraction of the total mass yields. Figure 1(b) is a contour map of the independent yields in a Z-A plane, indicating yield locations relative to the stability line. The pronounced structure revealed by the isopleths in the figure indicate that several yield distributions with different charge and mass dispersions, hence different origins, are superimposed on each other. These results differ from those obtained in a parallel study of the yield distributions in ^{40}Ar on ^{238}U,[10] where the overall distribution was dominated by the high yields of transfer products centered on the target and projectile masses ("rabbit ears") and by one broad, continuous distribution of products from complete fusion-fission. To calculate the final mass yields, we integrated at each mass number the Gaussian charge dispersion curves that were fitted to the data.[9] The final results are shown in Fig. 1(c).

Component A is determined by the yields of heavy rare earth nuclides and by the yields of very neutron-deficient Mo, Tc, Ag, In, Sn, Sb, I, and

Cs isotopes. This component shows the expected characteristics of the binary fission product distribution originating from the fission of a composite nucleus. For component B, the heavy mass branch is defined by the cumulative yields of neutron-rich nuclides peaking at $A \approx 140$. Figure 1(b) shows how distinctly the neutron-excess yields are separated from those of component A in this mass region. Guided by our results from the reaction ^{40}Ar on ^{238}U, where a low energy fission of transfer products near ^{238}U was observed,[10] we assign this component to a double-humped low energy fission product distribution. The light branch of this distribution was obtained by reflecting the well defined shape of the heavy one, and its mass location was deduced from the cumulative yield balances for the isotopes ^{112}Pd, ^{111}Ag and ^{107}Rh. From the observed charge distribution and the peak-to-valley ratio, we estimate an excitation energy of the fissioning nuclei of $\sim$ 15 MeV. In agreement with the assignment of component B (200 mb) to transfer-induced fission, the heavy rabbit ear (component F) cross section is $\sim$ 280 mb lower than that of the light rabbit ear (component E).

After subtraction of contribution B from the yield data in the mass range $67 \leqslant A \leqslant 140$, we are left with yields that can be resolved into two Gaussian distributions (components C and D in Fig. 1(c)), peaking around $A = 85$ and $A = 112$. Distribution C (FWHM $\approx$ 20 mass units) is probably identical with the "quasi-Kr" events observed in Refs. 2 and 4, representing the new phenomenon referred to above. Apparently, the complementary "quasi-U" distribution is missing. Because much kinetic energy in the deep inelastic interaction of ^{84}Kr with the target nucleus goes into excitation, one would expect a high energy cascade fission of the "quasi-U" nuclei leading to a symmetric fission product distribution centered slightly below A = 119. Actually, we do observe such a distribution (component D). From a mass and charge balance for the complete process--"quasifission" followed by cascade fission of the "quasi-U", (which process might be termed "quasi-ternaryfission")--one can conclude that in the most probable interactions 13 neutrons and no protons are evaporated. The yield of component D is 840 ± 120 mb (200%), indicating that 67-100% of the "quasi-U" nuclei undergo fission. The shape and width of the distribution suggest that the average excitation energy of the "quasi-U" must have been $\geqslant$ 45 MeV.

The excess yields around A = 195 (component G) are unexplained. Suggested explanations such as target contamination and feeding of these mass chains by α-decay from higher masses can be excluded. The interpretation of these yields as the surviving tail of the "quasi-U" distribution due to high fission barriers seems inadequate too. The primary "quasi-U" distribution (FWHM ≈ 20 mass units) could hardly extend into a mass region ∿ 40 mass units below the target mass while still yielding cross sections of a few mb. Attempts to force a considerably broader complementary distribution through the mass yields around A = 85 resulted in an unreasonable imbalance in cross section for the quasi-ternaryfission process. We conclude, then, that the excess yield around A = 195 more likely originates from a hitherto unobserved reaction channel.

As a consequence of the interpretation presented here, the total reaction cross section is the sum of the production cross sections for components A/2, C, E, and G: 1265 ± 205 mb. The mean geometrical cross section in the energy interval 450 to 605 MeV (lab.) can be estimated as

$$\bar{\sigma}_R = \pi R^2 \frac{\int_B^E (1 - \frac{B}{E})\, dE}{E-B} = 1130 \text{ mb} \quad ,$$

where B = 450 MeV,[8] E = 605 MeV, and R = 16.0 Fermi.

To conclude, we wish to point out that our analysis of the total mass yield distribution, and its decomposition into the components indicated in Fig. 1, is consistent with the results obtained for ^{84}Kr on ^{209}Bi in the kinematic coincidence experiments.[2,4] Our data confirm the assumption[2,4] that the quasi-Kr distribution is centered close to the projectile mass. It appears that > 92% of the Kr interactions with U in the investigated energy interval feed inelastic and deep inelastic reaction channels where only little mass transfer occurs. It is only in very few collisions (∿ 4%) that a composite nucleus is formed.

We want to thank Dr. A. Ghiorso for his active interest in the progress of this work and Dr. J. O. Liljenzin, Mr. I. Binder, Mr. R. Otto and Mrs. D. Lee for helpful assistance.

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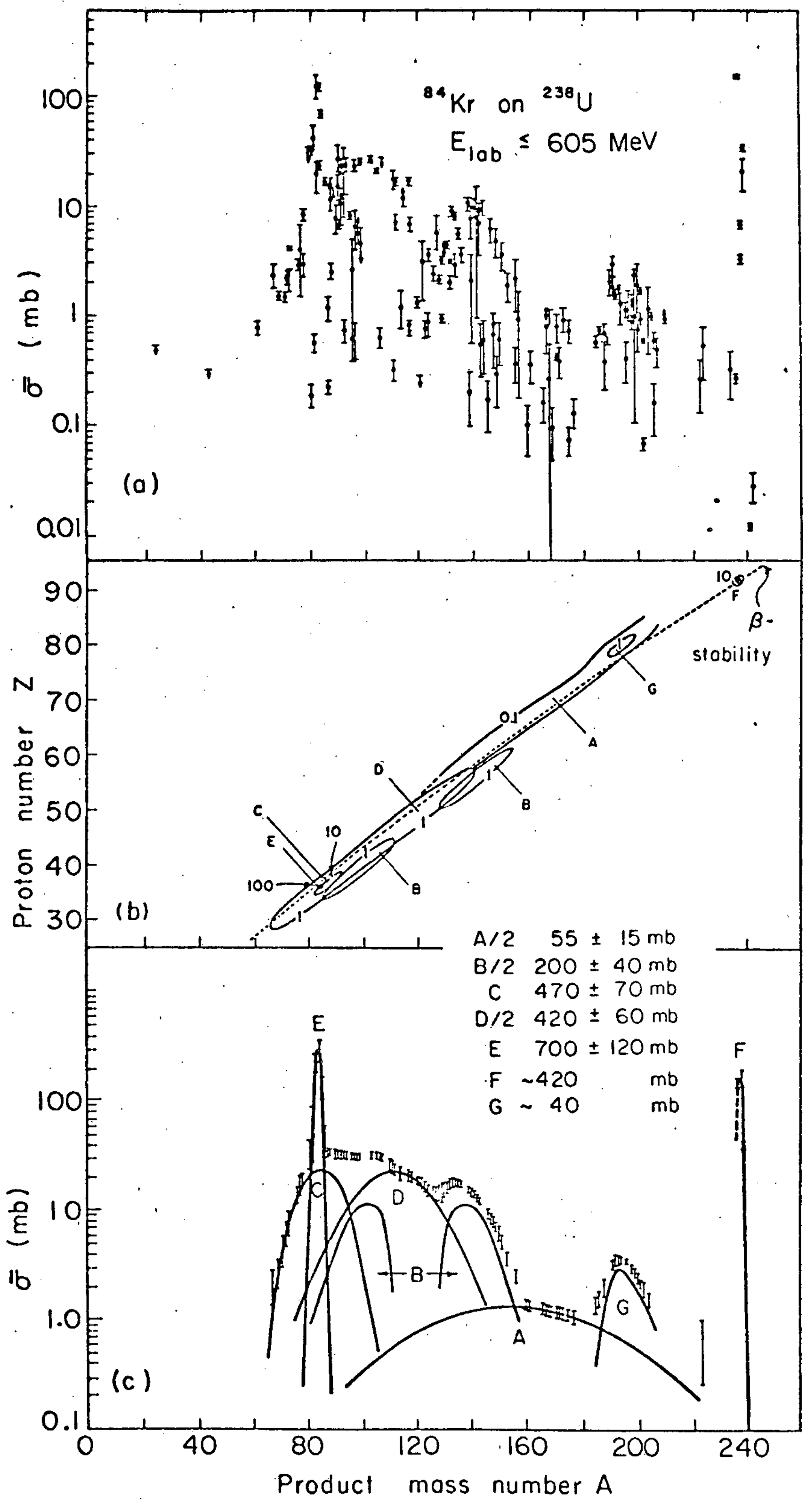
Figure Caption

Fig. 1. (a) Independent and cumulative yields of individual isotopes, calculated with the assumption of a general interaction barrier of 450 MeV (see Ref. 8), corresponding to an effective target thickness of 11.6 mg U/cm^2. (b) Contour lines for equal independent yields in mb. (c) Total integrated mass yields (upper and lower limits are indicated at those mass numbers for which experimental data were obtained) and their decomposition into individual components: (A) complete fusion-fission, (B) transfer-induced fission, (C) quasi-Kr, (D) cascade fission of the quasi-U, (E) and (F) transfer reactions ("rabbit ears"), (G) yields of unknown origin.



^{84}Kr on ^{238}U
E_{lab} ≤ 605 MeV
(a)
$\bar{\sigma}$ (mb)
100
10
1
0.1
0.01
90
80
70
60
50
40
30
Proton number Z
(b)
β-stability
A/2 55 ± 15 mb
B/2 200 ± 40 mb
C 470 ± 70 mb
D/2 420 ± 60 mb
E 700 ± 120 mb
F ~420 mb
G ~ 40 mb
(c)
1.0
0 40 80 120 160 200 240
Product mass number A
XBL746-3449

Fig. 1

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