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Mass-Yield Distributions in the Reaction of ^{56}Fe Ions with ^{238}U

U. Reus, A. M. Habbestad Wätzig, R. A. Esterlund, and P. Patzelt
Institute for Nuclear Chemistry, University of Marburg, D-3550 Marburg, West Germany

and

I. S. Grant
Physics Department, University of Manchester, Manchester, England
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Radiochemical measurements of cross sections for 173 nuclides produced in the reaction of 538-MeV ^{56}Fe ions with thick ^{238}U targets were performed and the mass-yield curve determined. Seven components were resolved, corresponding to three reaction mechanisms: (1) quasielastic transfer (810 ± 160 mb); (2) quasifission (350 ± 55 mb); (3) fusion-fission (190 ± 30 mb). Comparison with data from other systems indicates that the fusion-fission cross section for heavy targets depends strongly on projectile mass and target- to projectile-mass ratio.

It is by now a well-known[1] fact that in heavy-ion reactions where very heavy targets such as U or Bi are involved, the fusion process becomes increasingly less probable as the projectile Z and A get very large, and that a new process often called quasifission overshadows or even replaces it. This is clearly seen when one compares the radiochemical studies of the systems ^{40}Ar + ^{238}U [2] and ^{84}Kr + ^{238}U.[3] In terms of percentage of total-reaction cross section, 9% quasifission and 55% fusion-fission are observed in the former system, while 38% quasifission and only 4% fusion-fission are seen in the latter.

We report here the first measurements on a thick uranium target irradiated with a projectile with Z and A values intermediate between those of ^{40}Ar and ^{84}Kr, with the objective of obtaining information regarding the rate at which quasifission begins to dominate over fusion-fission as the projectile Z and A increase. In addition, the system studied here leads to a fusion nucleus which is essentially the same as that expected for the system $^{84}Kr + ^{209}Bi$,[4,5] and thus also yields information with regard to the effect of target- to projectile-mass ratio on the relative probabilities of fusion-fission and quasifission. The answers to these questions are of interest not only to workers involved in heavy-ion reactions *per se*, but also to those attempting to produce superheavy elements via heavy-ion fusion reactions.[6]

We have measured cross sections for production of 173 nuclides in the reaction of ^{56}Fe ions with thick uranium targets, using radiochemical techniques. Such cross sections differ from those obtained by on-line counter experiments in that these cross sections are integrated over product kinetic energies and all angles, and also from full projectile energy to reaction barrier. However, this technique allows the exact determination of product Z and A, thus yielding accurate charge-dispersion information, and its integral nature makes it equally sensitive to all reaction channels, without the necessity of any assumptions about the reaction mechanisms.

Two bombardments were performed, each one involving a thick (47.6 mg/cm^2) depleted uranium metal target bombarded with 538-MeV ^{56}Fe ions from the University of Manchester linac. The first experiment was designed primarily to look for products with relatively long half-lives (>few hours), and was $6\frac{1}{2}$ h in duration with a total integrated flux of 5.9×10^{12} particles. This target was subjected to a chemical separation procedure essentially that of Kratz, Liljenzin, and Seaborg[7] but with minor changes. The resulting chemical samples were each assayed for γ activities using Ge(Li) detectors and multichannel analyzers for a 3-month period starting 12 h after bombardment. Spectra were computer analyzed via the program CAOS[8] and decay curves via the program CLSQ.[9] Identification of each nuclide was based on its chemistry, γ-ray energies, and half-life. Cross sections were calculated, taking into account chemical yields previously determined from tracer experiments, detector efficiencies, and γ-ray abundances.[10] The effective target thickness, corresponding to the energy range from full projectile energy to measured[11] reaction barrier, was taken[12] to be 27.66 mg/cm^2. The second experiment was similar to the first and was designed to look for short-lived activities. The bombardment lasted 3 h with a total integrated flux of 3.4×10^{12} particles, and the target was counted intact, for 15 h starting 10 min after bombardment. Data processing was as described above, except that the contributions of long-lived

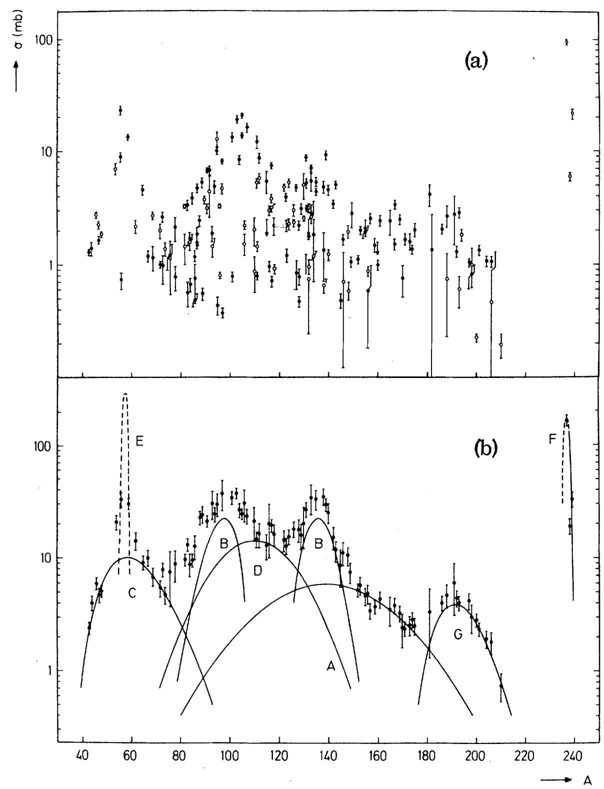

FIG. 1. (a) Independent and cumulative cross sections for products from the reaction of 538-MeV ^{56}Fe ions with a thick ^{238}U target. (b) Mass-yield curve for the same system. For explanation of labeled areas, see text and Table I.

components to the γ lines assayed were corrected for using data from the first run.

The resulting cross sections, both cumulative and independent, are shown as a function of mass number in Fig. 1(a). Gaussian charge-dispersion curves for various mass regions in the range $43 \leq A \leq 239$ were fitted to the above-mentioned data via an iterative procedure. Most mass regions were resolved into two Gaussian curves with differing Z_p values. Chain yields were then calculated, and the resulting mass-yield curve is shown in Fig. 1(b). Using the information gained from resolution of Gaussian components corresponding to different reaction mechanisms in the charge-dispersion curves, and also inferring which mechanisms might be present in a particular mass region using Ref. 2 and 3 as a guide, we resolved the mass-yield curve into seven components corresponding to three different reaction mechanisms. Component A is determined by mass yields in the range $151 \leq A \leq 165$, and is assigned to fusion-fission since this mass range is expected to include fission products from fusion nuclei, and the form of the mass-yield curve in this region is consistent with that of a broad Gaussian distribution peaking at a mass value ($A = 137 \pm 2$) which is the estimated most probable mass for fusion-fission products in this system. Component B is unfolded from the composite mass mass-yield curve with help from the charge-dispersion curves in this region which indicate a component peaking at neutron-rich nuclei, and its shape and location indicate its origin to be low-energy asymmetric fission following quasielastic transfer of a few nucleons to or from the target. Component D is obtained by subtraction of A and B from the composite mass-yield curve, and its maximum corresponds to a mass number consistent with symmetric fission of nuclei formed by deep-inelastic transfer of up to several tens of nucleons between target and projectile, and thus we assign it to fission following quasifission ("sequential fission"). Component G is also obtained by difference, and corresponds to those nuclei formed by deep-inelastic transfer from target to projectile which survive sequential fission. Component C by deduction is the light quasifission partner. Components E and F are the "rabbit ears" characteristic of quasielastic transfer. The lack of data points and resulting uncertainty in mass yields for these components result from the large number of nuclides in these regions which have half-lives unsuitable for radiochemical assay. Cross-section values for the above components are listed in Table I with the $^{40}Ar + ^{238}U$ [2] and $^{84}Kr + ^{238}U$ [3] data for comparison. Yields of components A, B, and D are possibly low because of losses of fission fragments recoiling out of the front of the target. However, we estimate these losses to be lower than those estimated for the system $^{40}Ar + ^{238}U$,[2] since the average momentum transfer from projectile to target, the average product mass in question, and the total target thickness in the present system are all larger than in the case of $^{40}Ar + ^{238}U$,[2] and we consider it unlikely that these recoil losses are larger than our experimental errors. Possible losses to component E due to transmission through the target of high-energy "Fe-like" quasielastic transfer products are not relevant, since we can determine only a lower limit for component E. The total geometric thick-target reaction cross section, calculated[3] with an interaction radius of 13.6 fm [11] and a reaction barrier in the center-of-mass system of 254 MeV,[11] is 1425 mb, which agrees with our experimental total reaction cross section of 1350 ± 230 mb.

When one examines (see Table I) the percentage contribution of each reaction mechanism with respect to the total reaction cross section for all three systems, it becomes obvious that for a very heavy target such as ^{238}U, the fusion-fission process declines quickly in importance as a major reaction mechanism when projectile Z and A increase above that of ^{40}Ar, and that quasifission (and quasielastic transfer) quickly start to dominate. This would imply that heavy-ion fusion experiments designed to produce superheavy elements are considerably less feasible then previously conjectured.[6] Moreover, only upper limits[4] or no cross sections at all[5] are reported for fusion-fission in the system $^{84}Kr + ^{209}Bi$ (leading to

TABLE I. Comparison of mass yields.

Mechanism	Label, Fig. 1(b)	σ Ar + U (mb)[a]	σ Fe + U (mb)[a]	σ Kr + U (mb)[a]
Fusion-fission	A/2	620 ± 150	190 ± 30	55 ± 15
Quasi-elastic transfer-induced fission	B/2	150 ± 30	330 ± 60	200 ± 40
Quasifission (low mass)	C	100 ± 50	280 ± 60	470 ± 70
Sequential fission	D/2	(not reported)	270 ± 50	420 ± 60
Quasi-elastic transfer (projectile)	E	400 ± 120	> 500	700 ± 120
Quasi-elastic transfer (target)	F	220 ± 65	480 ± 150	ca. 420
Quasifission (high mass)	G	(not reported)	80 ± 25	ca. 40
Quasifission	D/2 + G	100 ± 50 (9%)	350 ± 55 (26%)	470 ± 70 (38%)
Fusion-fission	A/2	620 ± 150 (55%)	190 ± 30 (14%)	55 ± 15 (4%)
Quasi-elastic transfer	B/2 + F	400 ± 120 (36%)	810 ± 160 (60%)	700 ± 120 (57%)
Reaction cross section	A/2+D/2+G+B/2+F	1120 ± 200	1350 ± 230	1225 ± 205

[a]Percentages are with respect to total cross section.

essentially the same hypothetical fusion nucleus as the system $^{56}Fe + ^{238}U$), implying that quasifission and quasielastic transfer might constitute almost all of the reaction cross section. This indicates that for any very massive heavy-ion system to exhibit a reasonable fusion cross section, a large degree of asymmetry between target and projectile masses is required.

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"Correlated Clusters" and Inclusive Spectra of Energetic Protons at 180° in Proton-Nucleus Collisions

T. Fujita
Max-Planck-Institut für Kernphysik, Heidelberg, West Germany
(Received 31 May 1977)

This paper presents a model based on the assumption of the existence of "correlated clusters" which stay as they are during a fast collision. The model can explain remarkably well the inclusive spectra of energetic protons at 180° in the proton-nucleus experiments by Frankel *et al.*

Recently, Frankel *et al.*[1] have measured the inclusive cross section for 180° production of high-energy protons ($E_p = 150-450$ MeV) in proton-nucleus collisions with an incident proton energy E_i of 600 and 800 MeV. To understand the data, Amado and Woloshyn[2] proposed a model based on a single-scattering mechanism and showed that the model gives results which are a few orders of magnitude smaller than the experiment if one uses for the Fermi-momentum distribution in the nucleus that corresponding to a zero-temperature, noninteracting Fermi-gas model. To explain the data, they employed a phenomenological Fermi-momentum distribution which is quite different in the higher-momentum region from the one usually adopted in low-energy nuclear physics,[3] even though the Fermi-momentum distribution in nuclei is not well investigated in such a high-momentum region ($k \gtrsim 700$ MeV/c).

In this Letter, I consider the backward-scattering problem as being caused by the reaction between the incident proton and a group of nucleons. I assume the existence of a group of nucleons which stay as they are during the fast collision. I call these nucleons "correlated clusters." The number of the correlated clusters (hereafter referred to as CC) to be found in the nucleus may be expressed by

$$G_N = \binom{A}{N} \frac{1}{A^{N-1}} P_N \quad (A \gg N), \tag{1}$$

where A is the mass number of the target nucleus, and P_N denotes the probability of finding N nucleons in the CC state. P_N consists of two parts: One is the probability of finding N nucleons in a small volume V_c, whose radius is an