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Isotopic distributions and elemental yields for the photofission of ^{235,238}U with 12–30-MeV bremsstrahlung

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Combining independent yields directly measured or calculated from the charge distribution, the Kr, Rb, Sr, Sn, Sb, Te, Xe, Cs, and Ba isotopic distributions were investigated for the 12–30-MeV bremsstrahlung-induced photofission of ^{235}U. At the same bremsstrahlung end point energies the Rb, Sn, Sb, Te, I, and Xe isotopic distributions were studied for the photofission of ^{238}U. For both fissioning systems the tin distributions were significantly broader than all other distributions. From the elemental yields the proton odd-even effects were calculated as a function of Z. They turned out to be almost zero.

Recently we obtained for the photofission of ^{235}U and ^{238}U with 12-, 15-, 20-, and 30-MeV bremsstrahlung fractional independent and cumulative chain yields using the catcher foil technique, direct gamma spectrometry of irradiated uranium samples, and chemical separation methods. Based on these chain yields an experimental study of the charge distribution for the photofission of ^{235}U and ^{238}U was performed.[1] In the present report we will discuss the results for the isotopic and elemental yield distributions from the photofission of ^{235}U and ^{238}U with 12–30-MeV bremsstrahlung, deduced from those chain yields. For all details concerning the measurements and analysis of the data, we refer to Ref. 1. Up to now, no analogous photofission results are reported in the literature.

In a former study[1] we could deduce for a number of mass chains the width parameter c and the most probable charge Z_p of the charge distribution simultaneously. By averaging the experimentally obtained c values, Z_p values for another 20 mass chains were calculated at each bremsstrahlung end point energy. In the present study the fractional independent chain yields of the different members of the mass chains which could not be obtained experimentally are calculated using the c and Z_p values from our previous work.[1] They are converted into indepenent chain yields by means of the corresponding post neutron mass yield distribution obtained in former experiments.[2]

Combining the directly measured independent yields and those calculated from the charge distribution the isotopic distributions of the krypton, rubidium, strontium, tin, antimony, tellurium, iodine, xenon, cesium, and barium isotopes were studied for the photofission of ^{235}U with 12–30-MeV bremsstrahlung. For the photofission of ^{238}U at the same bremsstrahlung end point energies the rubidium, tin, antimony, tellurium, iodine, and xenon isotopic distributions were investigated. Due to the influence of the mass distribution on the isotopic distributions built up with independent chain yields, those distributions are in general not Gaussian. The average value, $\langle A\rangle$ and the variance of

TABLE I. Average value $\langle A\rangle$ of the isotopic distributions for the photofission of ^{235}U with 12–30-MeV bremsstrahlung.

Element \ E_e (MeV)	12	15	20	30
Krypton	89.5 ± 0.3	89.5 ± 0.4	89.4 ± 0.3	89.4 ± 0.5
Rubidium	91.8 ± 0.5	91.8 ± 0.5	91.7 ± 0.5	· · ·
Strontium	94.2 ± 0.3	94.2 ± 0.4	94.1 ± 0.4	· · ·
Tin	· · ·	128.4 ± 0.2	128.4 ± 0.1	128.4 ± 0.1
Antimony	131.0 ± 0.3	130.7 ± 0.2	130.8 ± 0.2	130.7 ± 0.2
Tellurium	133.1 ± 0.3	132.8 ± 0.2	132.7 ± 0.2	132.8 ± 0.3
Iodine	135.5 ± 0.4	135.2 ± 0.3	135.0 ± 0.4	135.0 ± 0.4
Xenon	137.7 ± 0.3	137.6 ± 0.3	137.4 ± 0.4	137.4 ± 0.4
Cesium	140.1 ± 0.5	140.0 ± 0.6	139.8 ± 0.4	139.7 ± 0.5
Barium	· · ·	142.5 ± 0.4	142.4 ± 0.6	142.2 ± 0.5

TABLE II. Average value $\langle A \rangle$ of the isotopic distributions for the photofission of ^{238}U with 12–30-MeV bremsstrahlung.

Element \ E_e (MeV)	12	15	20	30
Rubidium	93.0 ± 0.8	93.0 ± 0.6	93.1 ± 0.6	$\cdots$
Tin	130.7 ± 0.2	130.9 ± 0.2	130.4 ± 0.3	130.5 ± 0.3
Antimony	132.1 ± 0.3	131.8 ± 0.3	131.9 ± 0.3	131.8 ± 0.3
Tellurium	134.2 ± 0.5	134.1 ± 0.4	134.0 ± 0.3	133.9 ± 0.4
Iodine	136.7 ± 1.0	136.3 ± 0.5	136.4 ± 0.5	136.2 ± 0.4
Xenon	139.0 ± 0.4	138.8 ± 0.3	138.9 ± 0.3	138.7 ± 0.2

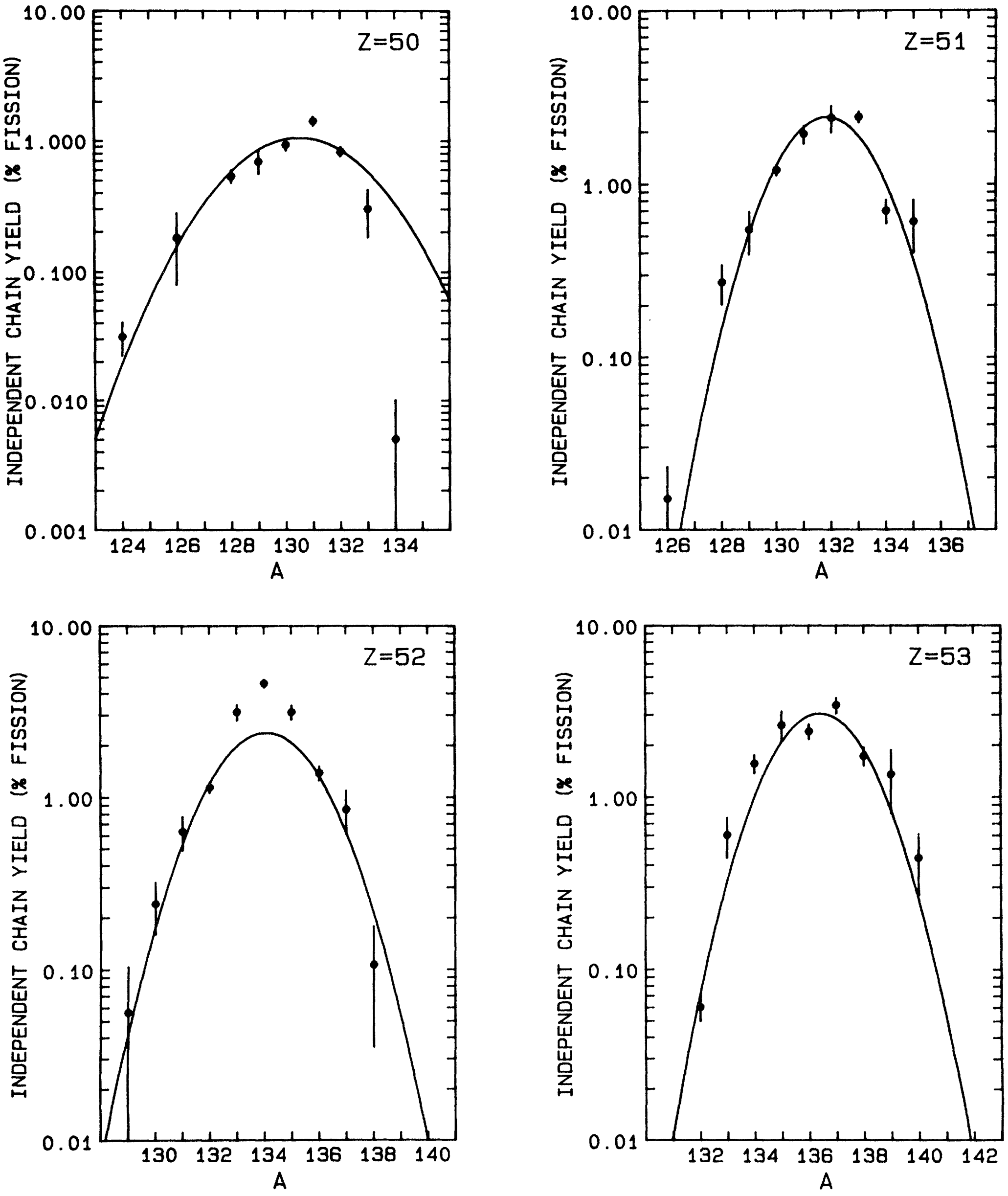

FIG. 1. Distributions for the tin, antimony, tellurium, and iodine isotopes for the photofission of ^{238}U with 20-MeV bremsstrahlung. The full lines represent the Gaussian fit through all experimental data except for the tellurium distribution where the independent chain yields of ^{133,134,135}Te are excluded in the fit and for the tin distribution where the independent chain yield of ^{134}Sn was not taken into account.

TABLE III. Elemental yields (% fission), for the photofission of ^{235}U with 12–30-MeV bremsstrahlung. Bracketed values represent the percentage of the elemental yields which could neither be measured nor calculated.

E_e (MeV) Element	12	15	20	30
Kr	$11.9\pm0.7(17)$	$12.3\pm0.8(17)$	$11.2\pm0.7(17)$	$10.9\pm0.6(23)$
Rb	$13.8\pm0.9(26)$	$14.6\pm1.0(27)$	$13.1\pm0.8(25)$	$\cdots$
Sr	$15.9\pm0.8(28)$	$15.3\pm0.8(28)$	$15.0\pm0.9(28)$	$\cdots$
Sn	$\cdots$	$4.0\pm0.4(22)$	$3.7\pm0.2(17)$	$4.2\pm0.1(15)$
Sb	$8.5\pm0.6(4)$	$8.1\pm0.3(2)$	$8.0\pm0.4(4)$	$7.8\pm0.3(2)$
Te	13.5 ± 0.8	13.4 ± 0.6	13.2 ± 0.7	13.7 ± 0.9
I	12.4 ± 0.8	11.9 ± 0.7	11.7 ± 0.7	11.7 ± 0.7
Xe	16.4 ± 0.6	15.7 ± 0.7	14.7 ± 1.0	14.4 ± 0.9
Cs	$14.4\pm1.0(15)$	14.4 ± 1.2	14.4 ± 1.0	14.5 ± 1.1
Ba	$\cdots$	$12.5\pm0.9(27)$	$12.5\pm0.9(26)$	$11.6\pm0.8(23)$

the distributions σ_A^2 are given by the following expressions:

$$\langle A\rangle=\frac{\sum_{i=1}^{n} A_i Y_i}{\sum_{i=1}^{n} Y_i}\,,\quad \sigma_A^2=\frac{\sum_{i=1}^{n}(A_i-\langle A\rangle)^2 Y_i}{\sum_{i=1}^{n} Y_i}\,,$$

with A_i and Y_i being, respectively, the mass and the independent yield of the ith fission product with the considered Z value. In Tables I and II the parameters $\langle A\rangle$ of the studied isotopic distributions are given. As an example the tin, antimony, iodine, and tellurium distributions for the photofission of ^{238}U with 20-MeV bremsstrahlung are shown in Fig. 1.

As can be seen from Fig. 1, the tin distributions are significantly broader than the other distributions. From the same figure it is clear that the independent chain yield of ^{134}Sn is more than one order of magnitude lower than the yield expected by fitting a Gaussian through the other data. Simultaneously, as will be discussed later on, an enhanced independent chain yield for ^{134}Te is observed. Moreover, it is also clear that the independent yield of ^{131}Sn is significantly higher than the one expected from a Gaussian fit through the other data. As mentioned earlier[1] this very high chain yield was also the reason for the abnormally broad charge distribution for the mass chain $A=131$ for the photofission of ^{235}U as well as ^{238}U.

From Fig. 1 it also follows that the independent yields of the odd-Z, $N=83$ nuclei, ^{134}Sb and ^{136}I, are much lower than the expected values while this effect seems to be absent for the even-Z, $N=83$ nuclei. This different behavior for the odd and even-Z, $N=83$ nuclei cannot be explained by a difference in the low neutron separation energy of those nuclei because this separation energy is very similar for all $N=83$ nulcei.[3] A possible explanation of the low independent chain yields of ^{134}Sb and ^{136}I could be wrong or

TABLE IV. Elemental yields (% fission), for the photofission of ^{238}U with 12–30-MeV bremsstrahlung. Bracketed values represent the percentage of the elemental yields which could neither be measured nor calculated.

E_e (MeV) Element	12	15	20	30
Rb	$10.6\pm1.5(21)$	$11.2\pm1.2(22)$	$11.3\pm1.2(18)$	$\cdots$
Sn	$4.9\pm0.3(2)$	$5.3\pm0.2(5)$	$5.0\pm0.8(7)$	$5.6\pm0.3(8)$
Sb	10.1 ± 0.5	10.6 ± 0.5	10.3 ± 0.4	9.7 ± 0.5
Te	15.3 ± 0.9	14.6 ± 0.9	15.2 ± 0.6	13.4 ± 0.6
I	13.6 ± 1.1	14.3 ± 1.3	14.3 ± 1.0	12.5 ± 0.6
Xe	$14.9\pm1.5(25)$	$14.8\pm0.8(13)$	14.5 ± 0.7	$14.4\pm0.6(9)$

incomplete spectroscopic data for the β^- decay of both isotopes. As can be seen from Fig. 1 the independent chain yields of ^{133,134,135}Te are significantly higher than the ones expected by fitting a Gaussian through the other data points. Those high yields reflect the fine structure observed in this mass region for the post neutron mass distribution in the photofission of ^{238}U with different bremsstrahlung end point enrgies.[4] As expected from the absence of this fine structure in the mass distribution for the photofission of ^{235}U (Ref. 2) these higher yields are not observed for the photofission of ^{235}U.

Except for the tin distributions the value of the dispersion σ_A of the isotopic distributons lies between 1.4 and 1.8 for all our photofission experiments on ^{235}U as well as ^{238}U. For the tin distributions $1.7 < \sigma_A < 2.1$ for the photofission of ^{235}U and $1.4 < \sigma_A < 2.4$ for the photofission of ^{238}U. The obtained σ_A values are, except for the cesium distributions, in good agreement with comparable data for other low energy fissioning systems.[5-7] Mobed *et al.*[7] have studied the distribution of the indium, rubidium, and cesium isotopes in the $^{233}\mathrm{U}(d,f)$ reaction with $E_d = 18$, 31, and 44 MeV. They found for the cesium isotopes very broad distributions compared to our photofission results, with $2.25 < \sigma_A < 2.38$. This abnormal behavior was explained by a possbile double shell effect: the yield of the light cesium isotopes should be enhanced by the influence of the spherical $N = 82$ shell while the higher yields of the heavy cesium isotopes could be due to the deformed $N = 88$ shell. If this explanation is correct, it is not clear why, neither in the 3-MeV neutron induced fission of ^{235}U (Ref. 8) nor in our photofission experiments such broad cesium distributions are observed, although the excitation energy of the compound nuclei in both cases is much lower than in the experiments of Mobed *et al.*[7]

The element yields were obtained by adding up the individual independent chain yields of the different members of the corresponding isotopic distribution. They are given in Tables III and IV. The bracketed values in these tables represent the percentages of the element yields which could not be measured directly or calculated indirectly using the charge distribution curves. They are given only for the cases where they exceed 1% of the total element yield. The missing yields are obtained by interpolation or extrapolation, fitting a Gaussian distribution through all experimental data.

The proton odd-even effect as a function of the charge of the elements was calculated explicitly from the yields of the different elements using the third difference method proposed by Mariolopoulos *et al.*[8]

$$\delta(Z+3/2) = \exp\{(-1)^{Z+1}[L_3 - L_0 - 3(L_2 - L_1)]/8\} - 1 \ .$$

Here $L_n = \log Y(Z+n)$ with $(n = 0,1,2,3)$ and $Y(Z+n)$ the yield of the element $Z+n$. These calculations show that the proton odd-even effect in the photofission of ^{235}U and ^{238}U is negligible, about 2 ± 3%. Such small values for the proton odd-even effect for low energy even-even fissioning systems can be expected in the framework of the Nörenberg model[9] if one assumes that the ratio of broken-to-unbroken proton pairs is conserved during the descent from saddle to scission point and is the same for photofission of ^{238}U as for thermal neutron induced fission of ^{235}U. A similar assumption was used by Nifenecker *et al.*[10] for the explanation of the small proton odd-even effect observed in the 3-MeV neutron induced fission of ^{235}U. Using the same reasoning we expect for the proton odd-even effect in the photofission of ^{238}U with 12-, and 15-MeV bremsstrahlung values of ≅5% and ≅3%, respectively. Estimates for the proton odd-even effect for the odd ^{235}U fissioning nucleus cannot be made in the framework of this model.

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