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Products from Thermal-neutron Induced Fission of ^{235}U — A Correlation of Radiochemical Charge and Mass Distribution Data*

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Abstract

Mass and charge distribution data for fission products after prompt neutron emission have been compiled and used to determine ν_t , the average number of prompt neutrons emitted in forming products with complementary mass numbers ($A_L + A_H = 236 - \nu_t$), and also Z_p and σ , parameters in a new charge-distribution formulation. The compilation includes both new data and older data, some of it re-evaluated using current values for fission-product half-lives and delayed-neutron yields.

The values of ν_t determined using Terrell's method with normalized chain yields are generally consistent with results derived from direct physical measurements.

The Z_p values, the most probable (or average) charge for isobars, derived from radiochemical data are also consistent with those determined by physical methods involving measurement of x-rays or beta-decay chain lengths. The new Gaussian width parameter σ has a value of 0.56 ± 0.06 , which corresponds to a full-width at half-maximum of 1.50 ± 0.12 charge units.

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The new charge-distribution formulation has been used with the normalized chain yields to estimate "normal" independent yields for all fission products, for elements, and for isotones. The estimated "normal" yields for complementary elements ($Z_l + Z_h = 92$) are essentially equal, as they should be.

Comparison of estimated "normal" yields for elements with sums of experimental independent yields for the isotopes, shows, where sufficient data exist, that even-Z elements have higher yields than odd-Z elements. The maximum in the "normal" isotone-yield curve occurs at $N = 82$, and the sum of the measured independent yields for the $N = 82$ isotones is ~30% higher. It is shown that the probable modes of fission (those giving asymmetric mass and charge division) occur only when the heavy fragment has 50 or more protons.

INTRODUCTION

A number of new yields for products of thermal-neutron induced fission of ^{235}U have been reported recently; in addition, new accurately determined half-life values for many short-lived fission products have made possible the re-evaluation of some older yield data. It seemed desirable, therefore, to summarize the yield data now available and to examine it for evidence of possible effects of nuclear structure on yields, i.e., enhanced probability for mass and charge divisions giving nuclei with even, odd, and/or magic numbers of protons or neutrons.

Although more yield data are available for thermal-neutron induced fission of ^{235}U than for other fission processes, the data are far from complete, and it is usually not possible to compare many measured yields in a region of interest. It is useful, therefore, to have estimated yields for reference, derived either theoretically or empirically. We have estimated yields empirically using measured chain yields and estimated fractional independent yields derived from empirically determined Z_p and charge-dispersion curves.

In deriving the empirical curves and in discussing the results it is convenient to identify atomic and mass numbers of complementary products. Since light charged particles, e.g., alpha particles, are emitted only rarely in fission, the sum of the atomic numbers of essentially all complementary products is 92, $Z_l + Z_h = 92$. The relationship between complementary mass numbers is less exact since varying numbers of neutrons are emitted; we adopt the approximate relationship, $A_l + A_h = 236 - \nu_t$, where ν_t is the average number of prompt neutrons emitted in forming products with mass numbers A_l and A_h .

NEUTRON EMISSION

The variation of v_t with A was derived from the chain yields listed in Table II in the Appendix using Terrell's summation method [1].¹ Most of the chain yields listed were derived from measured yields by normalizing them so that the sum of yields in each mass-yield peak was 100.00% and by correcting for delayed-neutron emission (see Table III in the Appendix). Some chain yields were estimated from a smooth mass-yield curve and are so designated in Table II. Normalization decreased measured yield values in the light-mass peak ($A \leq 116$) by 0.98%; those in the heavy-mass peak were increased by 1.22%, changes that are within the uncertainties of the experimental measurements.

The derived v_t values are shown in Fig. 1, where they are compared with values derived from data from physical measurements [2, 3, 4]. Terrell's method gives no information about v_t for symmetric fission since the value is affected directly by the arbitrary but necessary selection of the point of division between light and heavy mass-yield peaks. Three curves are shown which are in the range of the v_t values derived from physical measurements; the curves converge rapidly near $A_h = 125$, where yields increase rapidly, so for $A_h \geq 127$ ($A_l \leq 107$) the selection of the point of division between peaks has no appreciable effect on the results.

Correction of the yields for delayed-neutron emission decreases v_t values only slightly (≤ 0.05) in the range $A_h = 136 - 150$ ($A_l = 83 - 98$) so the considerable uncertainty in the correction affects the results very little. Also, use of another compilation of chain yields [5] gave similar results, except the dip at $A_h = 130$ was not as deep.

The deep dip at $A_h = 130$ is due to the relatively small yields for $A = 127$ and $A = 129$ recently measured [6] and the 1.5% yield estimated for $A = 130$. (Assumption of a 2.0% yield for $A = 130$ increases v_t at $A_h = 130$ by 0.15.) The difference in the results derived from physical and radiochemical measurements near $A = 130$ may be due in part to uncertainties in the chain yields and in the use of Terrell's method in regions of rapidly changing yields [7] and in part to the limited mass resolution inherent in the physical measurements.

There is no support for the large increase in v_t for large mass numbers derived from one set of data [3] either from the results of other physical measurements or from the radiochemical data.

¹The computation was programmed for the IBM 7072 and 360 computers, and the results were checked graphically for a typical set of data.

Fig. 1 Variation of ν_t , the number of neutrons emitted in forming products of complementary mass numbers, with A_h , the mass number of the heavy product.

Since $v_t = 4$ gives a satisfactory energy balance² for symmetric mass division, the central curve has been used in the treatment that follows; values of v_t are listed in Table II in the Appendix. The average number of prompt neutrons calculated from the curve and chain-yield values is 2.48, in agreement with the experimental value of 2.43 ± 0.03 [11].

The average number of neutrons v_p emitted in forming products of a given mass number was derived by multiplying v_t by the fraction of neutrons (v_h/v_t) or $(1 - v_h/v_t)$ emitted in forming the products of interest. The fraction was derived from a smooth curve drawn through points calculated from the data obtained from the physical measurements [2, 3, 4]. (Above $A = 140$ the data from [3] were not used.) The curve drops from 0.50 at $A = 116$ to 0.17 at $A = 128$ and rises irregularly to 0.70 at $A \geq 155$. The v_p values are listed in Table II in the Appendix; a plot (not shown) of v_p vs. $A' = A + v_p$ shows an irregular saw-tooth curve with a maximum value of $v_p = 2.7$ at $A' = 112$ and a minimum value of $v_p = 0.3$ at $A' = 129$.

The uncertainties in the v_t and v_p values listed are estimated to be 0.2 to 0.3 mass units for $A_h > 130$ and $A_l < 104$. The uncertainty is due in part to inherent uncertainties in the method (± 0.1 to 0.2 mass units in v_t [7]) and in part to uncertainties in the yield values. For intermediate mass numbers the uncertainties may be considerably larger because of uncertainties in estimated yield values and because of the uncertainty in the point of division of the light and heavy mass-yield peaks.

CHARGE DISTRIBUTION

The fractional independent and cumulative yields presently known from radiochemical and mass-spectrometric measurements are summarized in the last column of Table II in the Appendix. The values were derived from data given in the listed reference using new half-life and yield values for re-evaluation of some of the data and taking averages where appropriate. All known data have been considered, but a few have been omitted because they were in disagreement with other data and were judged to be in error.

Fractional cumulative yields that are significantly less than unity are now known for two or more products for 19 mass numbers; these yields (except for $A = 84$) are plotted in Fig. 2 on a probability scale against atomic number. The straight lines fitted visually to the points show that the charge distributions are represented reasonably well for most mass numbers

²The method of calculation of Schmitt, Neiler, and Walter [8] was used with data from Myers and Swiatecki's mass tables [9] and Signarbieux, Ribrag, and Nifenecker's [10] kinetic-energy measurements.

Fig. 2 Probability-scale plots of measured fractional cumulative yield against atomic number. Mass numbers are given near the lines fitted visually to the data.

by Gaussian distributions [12], although the representation is certainly not exact. For some mass numbers the odd Z isobars have lower yields than the even Z isobars, an effect reported previously by Runnalls, Troutner, and Ferguson [13] and which will be discussed in more detail later. This effect may cause "abnormal" Z_p and σ values for mass numbers with yields for only two adjacent isobars [13].³ In addition, the enhancement or depletion of yields by shell closures, an effect to be discussed later, can lead to "abnormal" Z_p and σ values or non-Gaussian charge dispersion.

Figs. 3 and 4 show, respectively, the plots of σ and a function of Z_p , both determined from the lines in Fig. 2, against $A' = A + \nu_p$. Although there is considerable scatter when all values are considered, the grouping is reasonably close when only data are considered for mass numbers with yields for three or more isobars not having 50 ± 1 or 82 ± 1 neutrons or protons or being complementary to such nuclides (filled circles and squares in Figs. 3 and 4).

The average of the selected σ values (for $A = 92 - 95$ and $141 - 144$) is 0.56, the same as the average derived from the yields of only the even Z nuclides with these mass numbers [13]. (The average of all 19 σ values is 0.55.) It can be seen from Fig. 3 that all of the selected values and a number of the others fall within the range $\sigma = 0.50$ to 0.62. The average σ value with its estimated uncertainty, 0.56 ± 0.06 , corresponds to a value of $c \approx 2 (\sigma^2 + 1/12) = 0.80 \pm 0.14$ and to a full-width at half-maximum (f.w.h.m.) value of 1.50 ± 0.12 ; the width is somewhat smaller than those previously derived from less complete data [12, 17], but it is within the uncertainties that were estimated.

The charge dispersion width for products after prompt-neutron emission is appreciably greater than the width for primary fragments before neutron emission (f.w.h.m. = 1.04 ± 0.12) recently determined by Glendenin, Unik, Griffin, and Reisdorf [14]. The difference is most probably due to the increase in charge dispersion from dispersion in the number of prompt neutrons emitted.

Fig. 4 shows the difference between experimental Z_p values and those for unchanged charge distribution, $Z_p(\text{UCD}) = 92 \times (A'/236)$. The figure shows that there is agreement between most radiochemical values and the results of various physical measurements. The average value of $Z_p(h) - Z_p(\text{UCD})$ is -0.44 for mass numbers $92 - 95$ and $141 - 144$ and is -0.45 for all 19 mass numbers for which Z_p was determined radiochemically.

³ Z_p is the atomic number, not necessarily integral, for which the fractional independent yield for isobars is a maximum; σ is the width parameter for Gaussian charge dispersion in cumulative form [12].

Fig. 3 Plot of the Gaussian charge-dispersion width-parameter σ against average mass number A' of primary fragment precursors. O, heavy A ; $\square$, light A ; $\bullet$, $\blacksquare$, A 's with yields for 3 or more isobars not having 50 ± 1 or 82 ± 1 neutrons or protons or being complementary to such nuclides. Dashed line, with shaded area indicating estimated uncertainty, was used for estimating "normal" independent yields.

Fig. 4 Plot of the difference between Z_p and $Z_p(UCD) = 92(A'/236)$ against A' . Results of radiochemical measurements: symbols have same meaning as those in Fig. 3. Results of physical measurements: A [14], B [15], C [16]; cross hatching indicates the reported uncertainty in the Z_p function and the range of mass numbers investigated. Dashed line, with shaded area indicating estimated uncertainty, was used for estimating "normal" independent yields.

For reasons already discussed, we believe it is more informative to discuss yields of individual fission products than the obvious "abnormal" σ and Z_p values plotted in Figs. 3 and 4. It is useful for this discussion to estimate "normal" independent yields by multiplying fractional independent yields, derived from average or assumed "normal" σ and Z_p values, by the experimental chain yields (listed in Table II in the Appendix).⁴ The value of $\sigma = 0.56 \pm 0.06$ was used and was assumed to be independent of A . Values of Z_p were derived from $Z_p(h) - Z_p(UCD) = -0.45 \pm 0.1$ for $A'_h > 134$ ($A'_h < 102$), and since it is reasonable that for symmetric mass division there is also symmetric charge division, and the large fractional cumulative yields of ^{115}Pd [18] and ^{117}Pd [19] show that this assumption is at least approximately correct, the $Z_p(h) - Z_p(UCD)$ function was extrapolated to zero at $A'=118$ as shown by the dashed line in Fig. 4. The values of Z_p used are listed in column 5 of Table II in the Appendix.

Calculations were made to determine the "best" estimate of a "normal" independent yield using $\sigma = 0.56$ and the listed Z_p value and also, since these values are not known precisely, a range of reasonable estimated values was determined by taking the highest and lowest value calculated from the four combinations of $\sigma = 0.50$ or 0.62 with $Z_p - 0.1$ or $Z_p + 0.1$. Both the "best" estimated values and the ranges of estimated values are plotted as open areas in Figs. 5 and 6, which show estimated and measured independent yields for isotopes of the complementary elements $_{37}\text{Rb} - _{55}\text{Cs}$, and $_{38}\text{Sr} - _{54}\text{Xe}$, respectively. It is clear that with realistic uncertainties in σ and Z_p , independent yields which are a small fraction of a chain yield can be estimated only approximately.

Also given in Figs. 5 and 6 are the sums of the "best" estimated independent yield values, and it can be seen that the sums for complementary elements are the same within 1%, as they should be. This is true for all complementary elements from $_{30}\text{Zn}$ through $_{82}\text{Sm}$, except the estimated yields for $_{43}\text{Tc}$, $_{44}\text{Ru}$, and $_{45}\text{Rh}$ are 1 to 4% higher than those of their complements. The condition of nearly equal yields for complementary elements is a necessary one for any satisfactory charge-distribution formulation, but the fulfillment of this condition does not prove that the formulation is correct.

Examination of Figs. 5 and 6 shows that most measured independent yields fall in or near the ranges of estimated yields, indicating that the charge-distribution formulation used is a reasonably good one for isotopes of Rb, Sr, Xe, and Cs. Comparison of estimated and measured independent yields for all of the 88 fission products for which data exist indicates that the formulation is reasonably good in general. The 16 fission products for which the discrepancies between measured and estimated fractional yields are greatest are listed in Table I with yields and with brief comments concerning possible

⁴The computation was programmed for the IBM 7072 and 360 computers.

Fig. 5 Independent yields of Rb and Cs isotopes. Elongated areas indicate range of estimated values.

Fig. 6 Independent yields of Sr and Xe isotopes. Elongated areas indicate range of estimated values. The estimated cumulative yield of the I isobar has been subtracted from the measured cumulative yield of a Xe isotope; the estimation of the uncertainty in the resulting Xe independent yield is discussed in the text.

TABLE I. MAJOR DISCREPANCIES BETWEEN
MEASURED AND ESTIMATED FRACTIONAL YIELDS

Fission product	Fractional independent {cumulative} yield		Comments
	Measured	Estimated (range)	
^{84}As	$\{0.17 \pm 0.02\}$	$\{0.45(0.36-0.52)\}$	Z odd, N = 51
^{105}Tc	<0.05	$0.13(0.08-0.19)$	Z odd, $_{48}\text{In}$ complement
^{106}Tc	<0.11	$0.34(0.26-0.39)$	Z odd, $_{49}\text{In}$ complement
^{123}Sn	$\sim 0.13 \pm 0.06$	$0.01(<0.04)$	Z = 50
^{125}Sn	$\sim 0.35 \pm 0.15$	$0.08(0.04-0.13)$	Z = 50
^{128}I	$(4 \pm 1)10^{-5}$	$0.02(<0.5)10^{-5}$	
^{132}Sn	$\{0.33 \pm 0.05\}^a$	$\{0.10(0.05-0.16)\}$	Z = 50, N = 82
^{133}Sn	$\{<0.002\}$	$\{0.020(0.006-0.045)\}$	N = 83
^{134}Sb	$\{0.03 \pm 0.01\}$	$\{0.13(0.08-0.19)\}$	Z = 51, N = 83^b
^{134}Te	0.86 ± 0.08	$0.62(0.55-0.71)$	Z even, N = 82^b
^{134}I	0.11 ± 0.01	$0.24(0.17-0.31)$	Z odd, N = 81
^{136}Xe	$\sim 0.35 \pm 0.15$	$0.19(0.11-0.24)$	Z even, N = 82^b
^{140}Xe	$\{0.60 \pm 0.01\}$	$\{0.44(0.36-0.51)\}$	Z even
^{140}Cs	0.34 ± 0.03	$0.51(0.44-0.60)$	Z odd
^{146}Pm	$(4.2 \pm 1.2)10^{-7}$	$0.002(<0.2)10^{-7}$	
^{148}Pm	$(7 \pm 2)10^{-5}$	$0.14(<2.4)10^{-5}$	

^aBoth a lower value of 0.14 ± 0.04 [20] and a higher value of ~ 0.85 [21] have been reported; these are discussed later.

^bShort-lived beta-decaying isomers of ^{134}Sb and ^{136}I that were not detected in the yield measurement but have been proposed [22, 23] could also cause the large discrepancies.

causes for the differences, most of which are probably associated with nuclear-structure effects discussed in a later section.

The discrepancies between the measured and estimated yields for ^{128}I , ^{146}Pm , and ^{148}Pm could be due to errors, such as contamination, in the measurement of very small yields. They could also reflect our uncertainty about the Z_p and σ functions for near symmetric and for very asymmetric mass division. The values used for estimation are extrapolated, since there has been no direct determination of either Z_p or σ for fission products in these mass regions. A value of σ could be assumed and Z_p calculated from a single fractional yield, as was done previously [12], or Z_p could be assumed and σ calculated from a single yield as Crouch has done [24], but it is not clear that either procedure is superior to extrapolation.

The estimation of Z_p values from single yields of odd-Z nuclides (^{134}I , ^{136}Cs , and ^{138}Cs , in particular), yields that are now believed to be low because of their nuclear structures, as will be discussed later, contributed to the dip to -0.7 at $A_h \approx 135$ in the $Z_p(h) - Z_p(\text{UCD})$ function proposed previously [12]. Also contributing to the dip were the "abnormal" Z_p values determined for $A = 139$ and $A = 140$ from yields of adjacent isobars and/or yields of nuclides with 83 neutrons.

The value of σ might be expected to vary with A since a portion of the charge dispersion for products is due to dispersion in the number of neutrons emitted and since the average number of neutrons emitted varies with A . A difficulty that we found in investigating this effect is that varying σ (and using the same Z_p function) results in unequal yields of complementary elements. Another potential difficulty with deriving σ from a single fractional yield is that an incorrect or correct but "abnormal" yield results in poor estimates of the yields for all other products with the same mass number.

DELAYED NEUTRON PRECURSORS

Table III in the Appendix is a summary of the delayed-neutron yields presently known or estimated. The table was compiled primarily to allow correction of measured chain-yields, but comparison of measured and estimated delayed-neutron emission probabilities, P_n , gives additional information about how well the proposed charge-distribution formulation correlates fission-product yield data. The agreement is satisfactory except for ^{134}Sb , ^{137}I , and ^{138}I , and the discrepancy between the estimated and measured yields of ^{134}Sb has already been noted in Table I and will be discussed in the next section.

Division of the ^{137}I and ^{138}I delayed-neutron yields by the measured P_n values gives $7.3 \pm 1.8\%$ and $5.0 \pm 1.8\%$, respectively, for the ^{137}I and ^{138}I cumulative yields. These values

are large fractions of the total chain yield and would require much lower independent yields for ^{137}Xe and ^{138}Xe than those shown in Fig. 6. We consider this unlikely and suggest that uncertainties in the P_n values and/or delayed-neutron yields are probably larger than indicated.

NUCLEAR STRUCTURE EFFECTS ON YIELDS

Careful examination of Figs. 5 and 6 reveals that there is a general tendency for measured yields for the odd-Z elements, Rb and Cs, to fall below and for the measured yields for the even-Z elements, Sr and Xe, to fall above the "best" estimated yields. This tendency is substantiated by comparing the sums of the "experimental" and estimated yields given in the figures. These values, along with those for Kr, Sb, Te, I, and Ba, are plotted in Fig. 7, which also shows ranges of estimated yields for other elements. It is clear that yields for even-Z elements are higher than those of odd-Z elements.

Included in the "experimental"-yield sums are some estimated yield values for nuclides for which measurements have not been made. Also, estimated cumulative yields of Br and I iso-bars have been subtracted from measured cumulative yields of Kr and Xe isotopes to give independent yields. The estimated yield contribution and/or correction expressed as percentage of the total yield of each element is: Kr (32%), Rb (0.5%), Sr (30%), Sb (13%), Te (10%), I (48%), Xe (34%), Cs (1.5%), Ba (16%). The uncertainty in the sums of "experimental" yields shown has been estimated by adding to the lower (upper) "limit" of a measured sum (value - (+) uncertainty) the low (high) end of the range of sums of estimated yields used. Since the estimated yield contribution is quite large for some elements, agreement between sums of "experimental" and estimated yields for these could not be considered significant; however, the differences observed are probably significant since inclusion of estimated yields only reduces the differences (to zero if the estimated yield contribution were 100%), provided the odd-even Z effect is real as is so strongly indicated.

The odd-even Z effect on yield reflects a preference for scission into even-Z fragments; thus proton pairing does enhance the probability of certain fission modes. A similar effect would be expected from neutron pairing, but as shown in Fig. 8 there is little evidence for it, except near the 82-neutron shell, probably because neutron emission disperses the effect so that it is not observed.

The yields for 82-neutron species are shown in Fig. 9, where the oscillation in yield for even- and odd-Z nuclides is seen again. The yields of even-Z nuclides are considerably larger than estimated, and the yields of odd-Z nuclides are about equal to the estimated values, rather than being lower as are those for most other odd-Z nuclides. The sum of yields for 82-neutron species is ~30% larger than the estimated sum, which, as seen in Fig. 8, is the highest of the estimated isotonic yields.

Fig. 7 Isotopic yield plot. ●, "experimental" value; ○, range of estimated values (a circle indicates range $\leq$ the diameter).

Fig. 8 Isotonic yield plot. ●, "experimental" value; ○, range of estimated values (a circle indicates range $\leq$ the diameter).

Fig. 9 Independent yields for 82-neutron species. Symbols have the same meaning as those used in Figs. 5 and 6.

The low cumulative yield of ^{84}As (Table I) indicates that the 50-neutron species ^{84}Se has a high independent yield [25]. There is also evidence that 50-proton species have high independent yields (see Table I). The low yields of ^{133}Sn and ^{134}Sb , both 83-neutron species, may result from the ease of neutron loss due to low neutron binding energies. Conversely, the low yield of ^{134}I , an 81-neutron species, may result from high neutron binding energy of the 82-neutron precursor, ^{135}I .

It is interesting to note that the principal cause of "fine structure" in the mass-yield curve at $A = 134$ (yield = 8.1%) is the large independent yield of $^{134}\text{Te}_{82}$ (6.9%). Since $^{135}\text{Te}_{83}$ has a "normal" yield of 3.1%, compared to the estimated value of 2.8(2.4 - 3.3)%, it seems unlikely that the large ^{134}Te yield can be due mainly to neutron evaporation. Structural effects at scission probably contribute.

The yield of the doubly magic nuclide $^{132}\text{Sn}_{82}$ is of considerable interest. A large fractional cumulative yield of ~ 0.85 has been determined [21] by counting beta tracks in photographic emulsions exposed to one of the charge peaks for $A = 132$ separated with an Ewald-type mass spectrometer. This large yield has been used to support several theoretical models of nuclear-charge distribution [26, 27]. Two lower values of 0.14 ± 0.03 [20] and 0.33 ± 0.05 [28] have been determined by radiochemical methods. Possible causes of the discrepancies are complex and probably not well understood at present. The central and most recently determined value has been selected for discussion in this paper, and it may be noted that this value, corrected for a small estimated ^{132}In cumulative yield, fits in well with the odd-even Z effect for 82-neutron species shown in Fig. 9.

The causes of the high probability of fission modes giving asymmetric mass and charge divisions is, of course, of greatest interest. It will be noted in Fig. 7 that asymmetric charge division becomes probable only when the heavy fragment has 50 or more protons. The same conclusion can be drawn for many other fission processes, almost regardless of the charge-distribution formulation assumed, since the light sides of the heavy mass-yield peaks fall in the same narrow mass-number region (e.g., see Fig. 4 in [29]). The objection may be raised that the yields being compared — those of elements ^{43}Tc through ^{49}In with those of ^{42}Mo and ^{50}Sn — are only estimated. However, the estimates are much more dependent on the known chain yields than on the charge-distribution formulation assumed, at least for the reasonable ones that have been investigated, and in addition the data available indicate that the estimated yields used in this paper for ^{50}Sn isotopes are low (see Table I) and those for the elements between ^{42}Mo and ^{50}Sn are high (see Fig. 10). It may be that the mass-yield curve for near symmetric charge division ($Z = 43 - 49$) is essentially flat topped as illustrated by the dashed line in Fig. 10.

Fig. 10 Mass-yield curves for the mass-number regions in which chain yields increase rapidly from the small yields for symmetric mass division. Dashed line illustrates possible mass-yield curves for near symmetric charge division ($Z = 43 - 49$).

Although the probability for fission increases sharply at $Z = 50$ for the heavy fragment, the maximum is reached only when $N = 82$, as shown in Fig. 8. Thus both shell-closure and pairing effects, as shown in Fig. 7, enhance the probability of some modes of fission.

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APPENDIX
TABLE II. SUMMARY OF FISSION YIELD DATA^a

A	Chain yield, %	v_t	v_p	Z_p	Element, fractional independent (cumulative) yield
72	$(2.0 \pm 0.3) 10^{-5}$ [30]	2.00	0.60	28.75	
73	$(1.0 \pm 0.2) 10^{-4}$ [30]	2.00	0.60	29.14	
74	$(3.4 \pm 0.5) 10^{-4}$ [30]	2.00	0.60	29.53	
75	$\sim 1 \times 10^{-3b}$	2.00	0.60	29.92	
76	$\sim 3 \times 10^{-3b}$	2.00	0.60	30.31	
77	$(7 \pm 1) 10^{-3}$ [30]	2.06	0.62	30.71	Ga, (0.573 ± 0.014) [31]
78	$(2.1 \pm 0.3) 10^{-2}$ [30]	2.25	0.68	31.12	As, $(8.5 \pm 2.5) 10^{-3}$ [32]
79	$(5.3 \pm 0.8) 10^{-2}$ [30]	2.50	0.78	31.55	
80	$\sim 0.11^b$	2.54	0.79	31.94	Br, $\sim (6 \pm 1) 10^{-6}$ [33]
81	0.22 ± 0.02 [34]	2.57	0.82	32.35	
82	$\sim 0.35^b$	2.60	0.86	32.75	Br, $\sim (1.3 \pm 0.2) 10^{-4}$ [30, 33]
83	0.543 ± 0.011 [35]	2.64	0.90	33.16	As, (0.80 ± 0.08) [25]
84	0.96 ± 0.02 [35]	2.67	0.96	33.57	As, (0.17 ± 0.02) [25] Rb, $(2.4 \pm 0.02) 10^{-9}$ [36] ^c
85	1.30 ± 0.03 [35]	2.67	1.01	33.98	
86	2.00 ± 0.04 [35]	2.64	1.08	34.40	Rb, $(1.4 \pm 0.2) 10^{-5}$ [30, 37]
87	2.37 ± 0.05 [35]	2.61	1.17	34.82	Se, (0.48 ± 0.10) [38]
88	3.56 ± 0.07 [35]	2.60	1.27	35.25	
89	4.71 ± 0.09 [35]	2.59	1.32	35.66	Kr, (0.960 ± 0.004) [39] Rb, 0.047 ± 0.016 [40] ^d
90	5.84 ± 0.12 [35]	2.59	1.35	36.06	Kr, (0.86 ± 0.02) [39] Rb, 0.13 ± 0.02 [40] ^d Y, $< 8 \times 10^{-5}$ [41, 42]

TABLE II. SUMMARY OF FISSION YIELD DATA^a

A	Chain yield, %	ν_t	ν_p	Z_p	Element, fractional independent [cumulative] yield
91	5.91±0.12[35]	2.60	1.38	36.46	Kr, {0.59±0.01}[39] Rb, 0.40±0.02[40] Sr, 0.03±0.03[12] ^e Y, <0.01[41,42]
92	5.91±0.12[35]	2.62	1.41	36.86	Kr, {0.31±0.01}[39] Rb, 0.55±0.03[40,55] ^{d,e} Y, (1.3±0.2)10 ⁻³ [17] ^d
93	6.35±0.13[35]	2.65	1.46	37.27	Kr, {(7.8 ^{+1.2} _{-0.2})10 ⁻² }[12] ^e Rb, 0.48±0.03[40,55] ^{d,e} Y, (1.6±0.2)10 ⁻² [17] ^d
94	6.60±0.13[35]	2.66	1.49	37.67	Kr, {(1.5 ^{+0.9} _{-0.2})10 ⁻² }[12] ^e Rb, 0.23±0.01[40] ^d Y, (6±2)10 ⁻² [17] ^e
95	6.52±0.13[35]	2.66	1.52	38.08	Kr, {(1.1 ^{+5.0} _{-0.1})10 ⁻³ }[12] ^e Rb, (9.8±0.5)10 ⁻² [40] ^d Y, 0.13±0.06[17] ^e Zr, (4.0±0.6)10 ⁻³ [56]
96	6.36±0.13[35]	2.65	1.54	38.47	Rb, (2.06±0.12)10 ⁻² [40] ^d Nb, (1.0±0.2)10 ⁻⁴ [12,57]
97	6.26±0.13[35]	2.62	1.55	38.87	Kr, {<10 ⁻⁵ }[12] Rb, (5.6±0.7)10 ⁻³ [40] Nb, (1.7±0.8)10 ⁻³ [12]
98	5.79±0.12[35]	2.58	1.55	39.26	Tc, (1.5±0.2)10 ⁻⁷ [58]
99	6.20±0.12[35]	2.48	1.54	39.65	Nb, {>0.83}[59]
100	6.52±0.13[35]	2.27	1.48	40.01	
101	5.1±0.3[30]	2.07	1.43	40.38	
102	4.1±0.2[30]	1.92	1.40	40.75	Rh, <2x10 ⁻⁷ [60]

TABLE II. SUMMARY OF FISSION YIELD DATA^a

A	Chain yield, %	ν_t	ν_p	Zp	Element, fractional independent [cumulative] yield
103	$2.8 \pm 0.2 [30]$	1.76	1.36	41.11	Mo, (>0.98) [61]
104	$1.8 \pm 0.1 [30]$	1.65	1.32	41.47	
105	$1.0 \pm 0.1 [30]$	1.69	1.42	41.88	Mo, (>0.95) [61]
106	$0.38 \pm 0.02 [30]$	1.82	1.55	42.29	Mo, (>0.89) [61]
107	$0.19 \pm 0.02 [30]$	2.10	1.67	42.72	
108	$\sim 0.05^b$	3.10	2.45	43.32	
109	$0.024 \pm 0.003 [62]^c$	3.71	2.67	43.75	
110	$\sim 0.017^b$	3.94	2.60	44.08	
111	$0.014 \pm 0.002 [62]^c$	4.00	2.48	44.40	
112	$0.012 \pm 0.001 [62]^c$	4.00	2.32	44.70	Ag, $(6 \pm 3) 10^{-5} [18]$
113	$\sim 0.011^b$	4.00	2.20	45.01	
114	$\sim 0.011^b$	4.00	2.08	45.31	
115	$0.011 \pm 0.001 [30]$	4.00	2.04	45.66	Pd, $(0.89 \pm 0.01) [18]$
116	$\sim 0.011^b$	4.00	2.00	46.00	
117	$\sim 0.011^b$	4.00	1.96	46.34	Pd, $(0.68 \pm 0.07) [19]^c$
118	$\sim 0.011^b$	4.00	1.92	46.69	
119	$\sim 0.011^b$	4.00	1.80	46.99	
120	$\sim 0.012^b$	4.00	1.68	47.30	
121	$0.014 \pm 0.001 [6]$	4.00	1.52	47.60	Cd, $(\geq 0.53 \pm 0.06) [63]^f$ Sn, $< 0.23 [64]^e$
122	$\sim 0.015^b$	3.95	1.34	47.90	
123	$0.016 \pm 0.001 [6]$	3.80	1.10	48.27	Sn, $\sim 0.13 \pm 0.06 [65]$
124	$\sim 0.019^b$	3.48	0.84	48.43	Sb, $\sim (6 \pm 2) 10^{-4} [66, 67]$
125	$0.027 \pm 0.003 [6]$	3.06	0.61	48.71	Sn, $\sim 0.35 \pm 0.15 [65]$

TABLE II. SUMMARY OF FISSION YIELD DATA^a

A	Chain yield, %	ν_t	ν_p	Zp	Element, fractional independent [cumulative] yield
126	$\sim 0.05^b$	2.55	0.46	49.01	Sb, $\geq (1.7 \pm 0.5) 10^{-2}$ [66,67,68] ^f I, $< \sim 2 \times 10^{-4}$ [33]
127	0.104 ± 0.004 [6]	2.10	0.34	49.32	Sb, 0.057 ± 0.010 [69]
128	0.36 ± 0.06 [6]	1.84	0.28	49.66	I, $(4 \pm 1) 10^{-5}$ [33]
129	0.64 ± 0.04 [6]	1.72	0.28	50.02	Sb, $\sim 0.12 \pm 0.07$ [70]
130	$\sim 1.5^b$	1.64	0.30	50.39	I, $\sim (1.6 \pm 0.2) 10^{-4}$ [33, 71]
131	2.97 ± 0.06 [72]	1.73	0.38	50.80	Sn, $\geq 0.39 \pm 0.08$ [20] ^f Te, 0.124 ± 0.014 [73] I, $(1.4 \pm 0.2) 10^{-3}$ [74]
132	4.43 ± 0.09 [72]	1.90	0.49	51.21	Sn, $\{0.33 \pm 0.05\}$ [28] Te, 0.20 ± 0.03 [20] I, $(3.9 \pm 0.3) 10^{-3}$ [74] Cs, $< 4 \times 10^{-8}$ [37]
133	6.70 ± 0.13 [72]	2.10	0.65	51.65	Sn, < 0.002 [20] Sb, 0.33 ± 0.10 [20,75] I, 0.025 ± 0.003 [20,74] Xe, $< 10^{-3}$ [76]
134	8.13 ± 0.16 [72]	2.35	0.85	52.12	Sb, $\{0.03 \pm 0.01\}$ [22,75] I, 0.11 ± 0.01 [74,77] Cs, $(1.1 \pm 0.1) 10^{-6}$ [37] ^c
135	6.56 ± 0.13 [72]	2.55	0.99	52.56	I, 0.46 ± 0.03 [74,78] Xe, 0.04 ± 0.01 [76,79, 80,81]
136	6.33 ± 0.13 [72]	2.61	1.07	52.98	I, $\{0.65 \pm 0.15\}$ [82,83] Cs, $(9.3 \pm 0.5) 10^{-4}$ [30,37,84]

TABLE II. SUMMARY OF FISSION YIELD DATA^a

A	Chain yield, %	ν_t	ν_p	Z _p	Element, fractional independent [cumulative] yield
137	6.37±0.13[72]	2.64	1.11	53.39	Xe, {0.978±0.003}[12]
138	6.75±0.14[72]	2.66	1.14	53.79	Cs, 0.047±0.002[12] ^e
139	6.51±0.13[72]	2.66	1.17	54.19	Xe, {0.82±0.02}[39] Cs, 0.24±0.04[40] ^d Ba, (1.1 ^{+0.5} _{-0.3})10 ⁻² [12] ^e
140	6.43±0.13[72]	2.65	1.19	54.59	Xe, {0.596±0.010}[39] Cs, 0.31±0.04[40] ^d Ba, (4.6±3.0)10 ⁻² [12] ^e La, (7±1)10 ⁻⁴ [41]
141	5.79±0.12[72]	2.63	1.21	54.99	Xe, {0.205 ^{+0.019} _{-0.004} }[85] Cs, 0.55±0.07[40] ^d Ba, 0.26±0.05[12] ^e La, (3.7±1.3)10 ⁻³ [12] ^e
142	5.86±0.12[72]	2.61	1.23	55.39	Xe, (5.9 ^{+0.8} _{-0.3})10 ⁻² [85] ^e Cs, 0.41±0.05[40] ^d La, (1.7±0.4)10 ⁻² [12] ^e
143	5.80±0.12[72]	2.60	1.25	55.78	Xe, ((8.5 ^{+0.7} _{-0.5})10 ⁻³)[39] ^e Cs, 0.25±0.03[40] ^d Ba, {0.88±0.06}[13] Ce, (5.3±2.6)10 ⁻³ [12] ^e
144	5.37±0.11[72]	2.59	1.27	56.18	Xe, ((1.1 ^{+0.5} _{-0.1})10 ⁻³)[39] ^e Cs, (5.2±1.6)10 ⁻² [40] ^d Ba, {0.78±0.04}[13]
145	3.85±0.08[72]	2.59	1.30	56.58	
146	2.93±0.06[72]	2.60	1.38	57.00	Pm, (4.2±1.2)10 ⁻⁷ [86]
147	2.19±0.04[72]	2.63	1.55	57.46	Ce, {0.963 ^{+0.037} _{-0.063} }[87]

TABLE II. SUMMARY OF FISSION YIELD DATA^a

A	Chain yield, %	ν_t	ν_p	Z_p	Element, fractional independent {cumulative} yield
148	1.63 ± 0.03 [72]	2.66	1.62	57.88	Pm, $(7 \pm 2)10^{-5}$ [88]
149	1.03 ± 0.02 [72]	2.67	1.68	58.29	
150	0.636 ± 0.013 [72]	2.65	1.72	58.70	Pm, $(2.1 \pm 0.1)10^{-3}$ [89]
151	0.404 ± 0.008 [72]	2.62	1.73	59.09	
152	0.263 ± 0.005 [72]	2.58	1.75	59.49	
153	0.150 ± 0.003 [72]	2.55	1.76	59.88	
154	0.073 ± 0.002 [72]	2.53	1.75	60.27	
155	$(2.95 \pm 0.06)10^{-2}$ [72]	2.45	1.69	60.63	
156	$(1.3 \pm 0.1)10^{-2}$ [90, 91]	2.18	1.53	60.96	
157	$(6.1 \pm 0.5)10^{-3}$ [90, 91]	2.06	1.44	61.31	
158	$(3.1 \pm 0.6)10^{-3}$ [90]	2.01	1.41	61.69	
159	$(1.05 \pm 0.09)10^{-3}$ [90, 91]	2.00	1.40	62.08	
160	$\sim 4 \times 10^{-4b}$	2.00	1.40	62.47	Tb, $< 1.3 \times 10^{-3}$ [67]
161	$(9 \pm 1)10^{-5}$ [91]	2.00	1.40	62.86	

^aYield values are corrected for delayed neutron emission (see Table III) and are normalized so the sum of yields for each peak ($A \leq 116$ or ≥ 117) is 100.00%. References are to sources of yield data from which listed values were derived. Uncertainties are for the yield measurements; some small additional, but generally unknown, uncertainty is introduced by the correction for delayed-neutron emission.

^bEstimated from smooth mass-yield curve.

^cUncertainty of $\sim 10\%$ of value assumed.

^dRelative independent cross sections for ^{89}Rb , ^{90}Rb , ^{91}Rb , ^{92}Rb , and ^{93}Rb and for ^{139}Cs , ^{140}Cs , and ^{141}Cs measured with a mass-spectrometer [40] were normalized to the independent yields determined radiochemically; the normalization factors were used to calculate independent yields for these and the other Rb and Cs fission products measured. The radiochemical yields were measured or determined from differences between measured Kr or Xe cumulative yields and the Sr or Ba independent yields.

^eFractional yield data were re-evaluated using the following new half-life values ^{91}Kr (8.4 ± 0.2 s), ^{91}Rb (58 ± 2 s), ^{92}Kr (1.88 ± 0.04 s), ^{92}Rb (4.5 ± 0.1 s), ^{93}Kr (1.24 ± 0.06 s), ^{93}Rb (5.9 ± 0.3 s), ^{94}Kr (0.4 ± 0.1 s), ^{94}Rb (2.7 ± 0.2 s), ^{94}Sr (78 ± 2 s), ^{95}Rb (0.4 ± 0.1 s), ^{95}Sr (26 ± 1 s), ^{138}I (6.3 ± 0.7 s), ^{138}Xe (14.0 ± 0.2 m), ^{139}Xe (40 ± 1 s), ^{139}Cs (9.2 ± 0.2 m), ^{140}Xe (13.5 ± 0.2 s), ^{140}Cs (64 ± 1 s), ^{141}Xe (1.72 ± 0.02 s), ^{141}Cs (25 ± 1 s), ^{142}Xe (1.25 ± 0.15 s), ^{142}Cs (2.0 ± 0.1 s), and ^{143}Xe (0.96 ± 0.02 s) [43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54]. The fractional cumulative yield of ^{143}Ba [13] and the yields of the ^{121}Sn isomers [6] were also used.

^fMeasured yield was taken as a lower limit because isomerism is known or appears probable from analogy with neighboring nuclides with similar structures and from consideration of simple shell-model states.

TABLE III. DELAYED-NEUTRON YIELDS

Delayed-neutron precursor	Delayed-neutron yield, % ^a	P _n , %	
		Measured	Estimated ^b
55-s ⁸⁷ Br	0.055±0.005[67]	3.1±0.6[93]	2.6(2.2-3.1)
Sum	0.055±0.005		
55-s period yield	0.052±0.005[92]		
16-s ⁸⁸ Br	0.12±0.03[67]	6.0±1.6[93]	5.1(3.4-7.3)
24-s ¹³⁷ I	0.22±0.04[67]	3.0±0.5[93]	6.0(4.3-8.1)
25-s ¹⁴¹ Cs	0.0032±0.0006 ^c	0.073±0.011[46]	0.07(0.05-0.09)
Sum	0.343±0.050		
22.7-s period yield	0.346±0.018[92]		
5.9-s ⁸⁷ Se	0.005±0.002[67]	0.44±0.20 ^d	0.7(0.3-1.5)
4.4-s ⁸⁸ Br	0.16±0.06[67]	7±2[93]	9(4-15)
4.5-s ⁹² Rb	(6±2)10 ^{-4c}	0.012±0.004[46]	0.012(0.007-0.017)
5.9-s ⁹³ Rb	0.05±0.01 ^c	1.5±0.2[46,51]	1.2(0.8-1.6)
11-s ¹³⁴ Sb	(2.8±0.4)10 ⁻⁴ [94]	0.11±0.02 ^d	0.03(0.01-0.05)
6.5-s ¹³⁸ I	0.10±0.02[67]	2.0±0.6[93]	5(3-8)
Sum	0.316±0.064		
6.2-s period yield	0.310±0.036[92]		
2.0-s $\left\{ \begin{array}{l} {}^{85}\text{As}^e \\ {}^{86}\text{As}^e \end{array} \right.$	$\left\{ \begin{array}{l} 0.04\pm0.04 \\ 0.04\pm0.04 \end{array} \right\} \begin{array}{l} 0.08 \\ \pm0.02 \\ [94,95] \end{array}$		1.3(<5.0) 4(<18)

TABLE III. DELAYED-NEUTRON YIELDS

Delayed-neutron precursor	Delayed-neutron yield, % ^a	P _n , %	
		Measured	Estimated ^b
2.2-s ⁸⁸ Se	0.05±0.02[67]		1.6(0.6-4.4)
1.6-s ⁹⁰ Br	0.13±0.05[67]		14(6-33)
1.9-s ⁹² Kr	(7.4±1.3)10 ^{-4c}	0.040±0.007[46]	0.05(0.03-0.08)
1.3-s ⁹³ Kr	0.013±0.003 ^c	2.6±0.5[46]	2.5(1.1-6.2)
2.7-s ⁹⁴ Rb	0.16±0.04 ^c	11.0±1.5 ⁵¹ [46]	6.4(4.0-10)
~2-s ⁹⁸ Y ^e	0.02±0.01[67]		0.5(0.2-0.9)
1.7-s ¹³⁵ Sb	0.035±0.003[94]		18(8-95)
2.0-s ¹³⁸ I	0.11±0.04[67]		16(6-40)
1.7-s ¹⁴¹ Xe	(6.4±1.2)10 ^{-4c}	0.054±0.009[46]	0.06(0.03-0.11)
1.3-s ¹⁴² Xe	(1.6±0.4)10 ^{-3c}	0.45±0.08[46]	0.5(0.2-1.5)
2.0-s ¹⁴² Cs	(7.4±2.1)10 ^{-3c}	0.27±0.07[46]	0.22(0.14-0.32)
1.6-s ¹⁴³ Cs	0.017±0.004 ^c	1.13±0.25[51]	0.9(0.6-1.6)
1.1-s ¹⁴⁴ Cs	(3.1±1.1)10 ^{-3c}	1.10±0.25[51]	0.5(0.2-1.3)
Sum	0.628±0.081		
2.3-s period yield	0.624±0.026[92]		
~0.8-s ⁹⁹ Y ^e	0.10±0.10[96]		4(<11)
~0.8-s ¹⁴⁰ I ^e	0.10±0.06[67]		60(>10) ^f
Sum	0.20±0.12		
0.61-s period yield	0.182±0.015[92]		

TABLE III. DELAYED-NEUTRON YIELDS

Delayed-neutron precursor	Delayed-neutron yield, % ^a	P _n , %	
		Measured	Estimated ^b
0.36-s ⁸⁵ Rb	0.046±0.007 ^c	7.1±0.9[51]	5(3-9)
0.23-s ⁸⁶ Rb	0.017±0.003 ^c	12.7±1.5[51]	6(3-19)
0.14-s ⁸⁷ Rb	~0.010±0.005 ^c	>20[51]	~22(>4) ^f
Sum	0.073±0.009		
0.23-s period yield	0.066±0.008[92]		
Total	1.62±0.18 1.58±0.05[92]		

^aSome values have been adjusted within the experimental uncertainty to bring the sum of yields from precursors with similar half-lives into agreement with period yields measured by Keepin [92].

^bEstimated P_n values were calculated by dividing a delayed-neutron yield by the "best" estimate of the precursor cumulative yield. Ranges of P_n values, in (), were calculated by dividing the lower or upper "limits" of delayed-neutron yields, respectively, by upper or lower ends of the ranges of estimated cumulative yields.

^cProduct of P_n value and measured cumulative yield obtained from data in Table II.

^dRatio of measured delayed-neutron yield listed and measured cumulative yield obtained from data in Table II.

^eAssignment uncertain.

^fThe upper end of the estimated range was >100%.