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SPONTANEOUS FISSION

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I. INTRODUCTION

Since the last reviews[1,2] of experimentally determined spontaneous fission properties, more information has been obtained concerning half-life systematics, the kinetic energies and mass distributions of the fission fragments, and neutron and photon emission at scission or from the excited fragments. From the latter data, information about the excitation energies of the fragments has also been inferred. A review of light particle emission accompanying spontaneous and induced fission is given by Wagemans elsewhere in this volume; recent theoretical developments are reviewed in Volume I.

Theoretical treatments[3-15] have been formulated to try to explain the sudden changes in half-lives, fragment total kinetic-energies and mass distributions observed for the fermium (Z=100) isotopes as the mass is increased by only a few neutrons. Recently, cold fission has also been treated as a limiting case of the analytical superasymmetric fission model which is described in this volume by Poenaru, Ivascu, and Greiner. The abrupt change at ^{258}Fm to very symmetric mass division with an unexpectedly high total kinetic energy has been explained qualitatively[2,16] on the basis of symmetric division into two fragments, each of which is close to the doubly magic, spherical ^{132}Sn configuration. The total kinetic energy for these touching spheres approaches the Q-value for the reaction, the fragments can have little excitation energy, and consequently neutron or photon emission is necessarily small. Studies[17] of neutron emission as a function of fragment kinetic energy for the spontaneous fission (SF) of ^{257}Fm show that neutron emission from the highest total kinetic energy events is only 1.1 which tends to confirm these ideas. The two-center shell model[13-15] and scission-point theoretical models[12] reproduced these experimental mass and kinetic-energy data fairly well, but the models based on earlier calculations[8] of the potential energy surfaces of the fissioning nucleus did not show the observed

sudden changes. Although calculations of spontaneous fission half-lives[3-9] reproduced the general trends rather well, they can show deviations from measured values of several orders of magnitude. The "catastrophe" in SF half-life at ^{258}Fm was attributed to the disappearance of the second barrier to fission in the potential energy surface of the fissioning nucleus. However, recent calculations[10] of the potential energy surfaces, which permit the generation of nuclear shapes leading to and including touching spheres, show a new valley for fission for which the inertia is much smaller. This fission path is associated with higher total kinetic energy and a reduction in the calculated half-lives relative to those calculated using the old valley for heavy fermium, nobelium, and element-104 isotopes. Recent surprising experimental results[18,19] showed that the SF half-lives of ^{260}106 and ^{264}108 are longer than would be expected based on the experimentally observed trend of rapidly decreasing SF half-life with atomic number. This was explained on the basis of mass measurements[20] and measurements[21] of alpha-decay energies which indicated that the ground-state shell corrections were increasing with atomic number. In our article, these and other new experimental results on SF phenomena are reviewed. (Relevant published literature through mid-1986 is given in the references.)

II. HALF-LIVES

A. Introduction

Table 1 lists the 118 spontaneous fission (SF) activities, which have been assigned to specific nuclides as of mid 1986. Experimental lower limits are also indicated for some partial half-lives for SF decay. When no other decay mode except SF is known, the partial SF half-life and its uncertainty are assumed equal to the half-life and its uncertainty, except for some fission isomers (f_2) where it is assumed that a gamma-decay branch exists. There may be other cases in which undiscovered decay modes besides SF would require a longer partial SF half-life than the value in Table 1, given the measured half-life for SF decay. References are indicated only for measurements of the half-life, partial SF half-life, and SF branch since the 1978 Table of Isotopes.[22] A single question mark after the half-life, partial SF half-life, or SF branch indicates that the assignment is probable, but not proven; a double question mark denotes an uncertain assignment due to insufficient evidence. Five types of SF are distinguished in the table: 1) SF from the ground state with no designation letter after the isotope; 2) fission isomers with fission occurring from the minimum of the second well (f or f_1) or from an excited state of the second well (f_2); 3) SF from an ordinary electromagnetic isomer, denoted by the letter m; 4) electron-capture or β^+-delayed fission which is electron capture or β^+ decay to excited states above or near the top of the daughter's fission barrier, denoted by EC-SF; and 5) β^--delayed fission or β^- decay to states above or near the top of the daughter's fission barrier.

We will discuss the developments in ground state fission in a few sentences. Fission isomers will be discussed in detail by Poenaru and Ivascu in a later chapter of this Volume. With the very recent lower limit established by

Zelenkov et al.[23a] for the SF half-life of ^{242m}Am(152 yr) there are now no known examples of ordinary electromagnetic isomers with measurable fission branches. For other isomers with half-lives in parentheses, such as ^{254m}Es(39.3 hr), ^{250m}Fm (1.8 s), and ^{254m}No(0.28 s), lower limits for the partial SF half-lives have also been established. Ten examples of electron-capture-delayed fission are included in Table 1. All of them involve electron capture (EC) to states above or near the top of the fission barrier, an explanation first proposed by Kuznetsov and Skobelev.[23b] Cases such as ^{258m}Md(60 min) (Ref. 24), the possible assignments ^{258}Lr(4.35±0.59 s, ~1% EC??) (Ref. 25), and ^{256}Ha($2.6^{+1.4}_{-0.8}$ s, 10% EC??) (Ref. 26), along with ^{258}Ha($4.4^{+0.9}_{-0.6}$ s, 33^{+9}_{-5}% EC) (Ref. 27), which decay by EC to ground states decaying by SF have not been included in Table 1. These fission activities are already included under the respective EC daughters ^{258}Fm(370 μs), ^{258}No(1.2 ms), ^{256}Rf(7.4 ms), and ^{258}Rf(13 ms). Of the two reported cases of β^--delayed fission--^{236}Pa(9.1 min) and ^{238}Pa(2.3 min) (Refs. 28,29), one of them could not be found in a recent chemical separation of the protactinium products of the reaction ^{238}U(n,p)^{238}Pa by Baas-May et al.[30] Since in the original experiments[29] on ^{236,238}Pa the SF's were recorded directly from the ^{238}U target using the same reaction, Baas-May et al. suggested that the fissions attributed to ^{238}Pa could have been caused by delayed-neutron- or gamma-ray-induced fission of the ^{238}U target. Thus, in Table 1 an upper limit for β^--delayed SF of ^{238}Pa from Baas-May et al. is recorded and the assignment ^{236}Pa is uncertain, leaving no proven assignments for β^--delayed fission from excited states near the top of the fission barrier.

B. Spontaneous Fission of Even-Even Nuclei From Their Ground States

For the partial SF half-lives of even-even nuclei in their ground states, the regular systematics shown in Fig. 1 exists. In general, the half-lives decrease with atomic number. Beginning with curium (Z=96) and for increasing Z the half-lives for the isotopes of a given element show extra stability against SF decay with 152 neutrons due to a subshell closure. The SF half-life of a key isotope ^{254}No with 152 neutrons is being restudied by groups at Dubna,[31] GSI,[32] and Berkeley[33,34] since it can now be produced with a large cross section of 0.4 to 4 μb (Refs. 32,34-37) in the reaction ^{208}Pb(^{48}Ca,2n)^{254}No. Previously only a lower limit of 25 hours was set on the partial SF half-life of ^{254}No (Ref. 38). Now higher SF branches and partial SF half-lives ranging from 0.2% (8 hr) (Ref. 31), to 0.25±0.07% (6±2 hr) (Refs. 33,34) to 1.6% (1 hr) (Ref. 32) are being reported. Reinterpreting the 47±13-s SF activity produced by Somerville et al.[25] in the reaction 75-MeV ^{12}C+^{249}Cf as a possible SF branch in ^{254}No results in 0.4±0.3% (4±3 hr). A precise measurement of the SF half-life of this important isotope is needed. The half-life of this isotope has also been particularly difficult to calculate.[3,7,10]

At element 104, though, the stabilizing effect of the 152-neutron subshell on the SF half-lives seems to have disappeared. There is a drastic shift in the half-life systematics in Fig. 1 between elements 102 and 104. This shift, first proposed by Flerov et al.[39] and Oganessian et al.[40], is supported by the recent half-life measurements for the even-even isotopes of element 104: ^{256}Rf($7.4^{+0.9}_{-0.7}$ ms) (Ref. 41), ^{260}Rf(21±1 ms) (Ref. 25), and ^{262}Rf(47±5 ms) (Ref. 25).

There has been one change in half-lives from the 1975 experimental systematics of Oganessian et al.[40] Neither the 100-ms (Refs. 42,43) nor the later

80-ms (Refs. 44-48) components, attributed by the Dubna group to $^{260}104$ have been observed in the reaction $^{15}N+^{249}Bk$ in more recent experiments at Berkeley[25,49-52] or at Dubna.[53] But since the ~20-ms component, first observed by Ghiorso et al.[54] in 1969, was produced in the same reaction by groups at Berkeley, Livermore,[55] and Dubna with the approximate cross sections calculated for $^{260}104$, we have instead associated the 21-ms half-life with ^{260}Rf in Table 1.

The shift in half-life systematics has been predicted theoretically as well by Randrup et al.,[3] who extrapolated their calculations to element 104 after adjusting one parameter in their inertial-mass function to fit the half-lives for $Z \leq 102$. They attributed the shift not only to the decreasing stabilization of the 152-neutron subshell at element 104, but also to the lowering of the second barrier of the double-humped fission barrier below the ground state energy. Baran et al.[5,6] came to similar conclusions without any adjustable parameters, although the fit to the half-lives for Z=104 was not as good as by Randrup et al. Hessberger,[36,56] Armbruster,[57-59] and Hessberger et al.[60] have discussed correlations between changes in the fission barrier curvature and the lowering of the second barrier below the ground state for some isotopes with $Z \geq 100$.

However, Möller et al. very recently arrived at a different explanation.[10] These authors say that the second barrier has not disappeared below the ground state at ^{258}Fm or ^{260}Fm or for most of the isotopes of element 104, as earlier calculations by Randrup et al. had shown, but instead that a new valley for fission has appeared which gives a lower inertia. This lower inertia, rather than the decrease of the second barrier, would explain the precipitous drop in SF half-lives by ~10^7 between ^{256}Fm and ^{258}Fm, shown in Fig. 1.

The new valley in the space of fragment elongation versus distance between fragment mass centers r is represented for ^{258}Fm in Fig. 2 by a horizontal line of spherical-like fragment shapes from $r = 1.25\ R_o$ to $r = 1.75\ R_o$. Travel along this new valley leads to shorter half-lives than along the old valley. The old valley, usually leading to asymmetric fission, follows the diagonal line of sausage shapes across the figure. An alternate "switchback" path starting at $r = 1.45\ R_o$ in the lower new valley and ending at $r = 1.65\ R_o$ in the diagonal old valley is also available for ^{258}Fm.

The earlier agreement between calculations by Randrup et al.[3] and measurements for the even-even fermium half-lives was called "somewhat fortuitous" in Ref. 10, since these early calculations did not take into account the new valley. But the average discrepancies of factors of 50 to 73 (Refs. 61a,b) between the calculated and experimental SF half-lives were similar in the two calculations.[10,61b] Böning et al.[62a] have also performed calculations of the half-lives and SF half-lives for even-even isotopes of elements 104 to 110. The agreement with the calculations by Möller et al.[10] is quite good for nuclei which fission asymmetrically along the old valley. But for the neutron-rich nuclei, which would include ^{258}Fm if Böning et al. had calculated its SF half-life, the SF half-lives calculated by Böning et al. are orders of magnitude longer than calculated by Möller et al. This is because Böning et al. did not include the fission path along the new valley.

While experimentalists desire more accurate half-life calculations in the search for new isotopes, only a 300-keV change in a ground state mass is enough to alter the calculated SF half-life by a factor of 70, the average discrepancy between the calculated SF half-lives by Möller et al.[10] and the experimental values over the actinide region. Other complications in the calculations are two or more possible fission paths, each with its own inertia.

But to further test the predictions of fission along two valleys it would be useful to measure the SF half-lives and SF mass and kinetic-energy distributions for nuclei in the transition region between nuclei which fission along the old and new valleys. Two such transition nuclei are ^{258}Cf and ^{260}No, for which Möller et al.[10] have already calculated the SF half-lives along the two paths. If the possible assignment of a 106-ms SF activity[25,62b] to ^{260}No is correct,[24,25] Möller et al.[10] would predict symmetric fission along the new valley with a calculated SF half-life of 540 ms.

For element 106 Münzenberg et al.[18] found a major departure from the trend of rapidly decreasing experimental SF half-lives. The isotope ^{260}106 was found to decay primarily by α decay and had a partial SF half-life of 7 ms. This half-life for ^{260}106(7 ms) was only slightly shorter than for ^{258}Rf (13-15 ms) compared to a ~10^5 decrease in SF half-life between ^{256}No (18 min) and ^{258}Rf (13-15 ms), all isotopes with 154 neutrons.

The trend of slowly changing SF half-lives has continued to the recently discovered even-even isotope ^{264}108 (Ref. 19), which has a partial SF half-life of at least 5 ms, according to Armbruster's[58] interpretation of the data of Oganessian et al.,[63] or at least 1 ms, the shortest half-life which could be detected in Ref. 63. In this case the discrepancy with predictions[3,7] is at least $10^{2.5}$, and greater than the average discrepancy between theory and experiment. Clearly a new set of calculations or a semiempirical description is needed that not only reproduces the half-lives at element 104, but also accurately predicts the SF half-lives for isotopes of elements 106, 108, and beyond.

The reason for the slow decrease in SF half-lives with Z for Z≥104 along the line N-Z=48 is because the ground-state shell corrections determined from experimental masses[20] and α-decay energies[21] increase with Z, even though the

liquid drop barriers decrease with Z, in such a way as to keep the fission barrier almost constant at near 5 MeV (Ref. 64). Since α-decay energies are in general increasing with Z, the α decay rate catches up with and overtakes the fission rate between elements 104 and 108, making the even-even nucleus $^{264}108$ primarily an alpha emitter.

The astonishing results that $^{260}106$ and $^{264}108$ have substantial α-decay branches make the work of identifying new isotopes easier for an experimentalist. This is because observation of an α-decay sequence with a known daughter and granddaughter having precise alpha energies and half-lives is far more specific to a given nuclide than the decay properties of SF. (See the chapter by Roeckl and Schardt in Volume II.) It also gives renewed hope that superheavy elements with neutron numbers N=178-184 and Z=114 might have measurable half-lives,[9] since the shell corrections are predicted to be even larger on this island of stability[7,61a,65a] than previously anticipated.

In addition to the predicted island of stability the calculations of several authors[7,9,65a-d,66a] have shown that a "rock" of stability due to a deformed subshell should exist between neutron numbers 162 and 164, resulting in a partial half-life for alpha decay of 40 ms for $^{272}110$, according to Möller et al.[9] However, in the most recent calculations by Möller et al.[10] the stabilizing effect of N=162 is counteracted by the presence of a new valley for fission, which may mean that SF could still be an important decay mode among the heaviest elements with N=162. Böning et al.[62a] have also predicted a stabilizing effect at N=162-164. In this connection we should mention that the isotope $^{272}110$ with 162 neutrons is reachable in the reactions $^{44}Ca + ^{232}Th$ and $^{40}Ar + ^{236}U$. Oganessian et al.[66b] recently reported production of an 8.5-ms SF activity in these reactions with a possible assignment to an

unspecified isotope of element 110. At GSI, however, no such activity was observed in a similar reaction $^{40}Ar + ^{235}U$ using the recoil separator SHIP.[67]

C. Spontaneous Fission of Nuclei With Odd-Proton and/or Odd-Neutron Numbers

Many new odd-even, even-odd, and odd-odd isotopes have been discovered in the last few years. The new isotopes ^{259}Md(~100 min) (Refs. 68,69) and ^{260}Md(31.8 d) (Ref. 24), identified by the Livermore group are the only known isotopes of mendelevium which primarily decay directly by SF. For other possible decay modes of ^{260}Md Lougheed et al.[69,70] established the following upper limits for their branches, the ranges depending upon the assumed values for the α-decay energy and for the half-lives of ^{260}No and ^{260}Fm: 5-28% for EC, 3-11% for β^-, and 10-23% for α decay. In contrast, the Livermore group[71] determined that for the even-odd isotope ^{259}No(1.0 hr) (Ref. 72) less than 10% of its decay is by SF. The new isotopes ^{256}Cf(12.3 min) (Ref. 16), ^{258}Fm(370 μs) (Refs. 73a,b), ^{259}Md(100 min) (Refs. 68,69,74), the possible assignment of ^{260}No(106 ms) (Refs. 24,25,62b), and ^{262}Rf(47 ms) (Ref. 25) all have 158 neutrons and all decay predominantly by SF. Spontaneous fission has not been observed in any of the known isotopes of lawrencium (element 103) with masses 252-260, indicating both a hindrance for the odd proton and that the partial half-lives for α and/or EC decay are shorter than for SF.

For the odd isotopes of rutherfordium (Rf, Z=104) and most of the hahnium (Ha, Z=105) isotopes the assignments of the fission activities are mainly based on the agreement, within experimental errors, between the half-lives measured for SF and α decay. The velocity filter SHIP[75] (Separator for Heavy Ion Products) at GSI gives an additional position correlation between the recoil and the SF emitter. SHIP discriminates heavily against transfer products and by a factor of 10 against α-particle evaporation residues,[76] so that a recoil which has passed through SHIP is likely to be a neutron-evaporation residue.

Other separators allow a similar separation of evaporation residues from transfer products. Among those listed in Table 2 are the gas-filled separators SASSY[77,78] at Berkeley and the DQQ-spectrometer,[79] recently installed behind SHIP at GSI, along with the electrostatic separator VASILISA,[80] under construction at Dubna. The special case of the long-lived ^{258m}Md(60 min) permitted off-line chemical and mass separations before EC decaying to the short-lived ^{258}Fm(370 μs) (Refs. 24,73b). But except for some discrimination against transfer products by collimation and range sampling of the recoils, the rest of the techniques in Table 2 did not allow strong correlations to be made between SF decays and evaporation residues or products with specific Z or A. For this reason the assignments of SF activities made at GSI using SHIP and the special cases $^{258m}\mathrm{Md} \xrightarrow{EC} {}^{258}\mathrm{Fm}$ and ^{260}Md, assigned with the aid of mass separation at Livermore,[24,73b] are in general stronger than assignments made using other techniques.

The 50-percent SF branch of ^{255}Rf, first quoted by Flerov,[81] was confirmed by Münzenberg et al.[82,83] at GSI using the velocity filter SHIP. Münzenberg et al.[84] have also reported an upper limit of 3% for SF of ^{257}Rf. Somerville et al.[25] produced a 3.8±0.8-s SF activity with a cross section of 2.0±0.4 nb in the reaction 75-MeV ^{12}C + ^{249}Cf using a tape transport system with mica track detectors. If this activity is due to ^{257}Rf, the fission branch would be between 5^{+6}_{-3}% and 17^{+18}_{-11}%, depending upon the measured cross sections[85a,85b,86] assumed for production of the ^{257}Rf α activity. A SF branch of 2.4±0.3% in ^{257}Rf is suggested by Bemis,[87] based on a reanalysis of the data in Refs. 85b and 88. The situation is complicated by the fact that other 5-s SF activities which could not be due to ^{257}Rf have also been produced.[25] Thus the fission branch of ^{257}Rf is uncertain, but less than 3%. In Table 1 the value 2.4±0.3% suggested by Bemis and in Fig. 3a a lower limit on

the SF hindrance factor have been used. Bemis et al.[89] have confirmed the small fission branch of ^{259}Rf (Ref. 22) using a helium-jet transport. They obtained a value of 6.3±3.7%, but with only 9±5 SF events, uncorrelated to recoils or other assigned isotopes in a decay chain.

Direct SF has been observed in at least four isotopes of hahnium (Ha), element 105. A $1.6^{+0.6}_{-0.4}$-s SF activity produced in the reaction 270-MeV ^{48}Ti +^{209}Bi was detected by Oganessian et al.[26] using track detectors to record the SF's from a rotating wheel of bismuth target material. It was assigned to ^{255}Ha. For ^{257}Ha Oganessian[26] at Dubna established an upper limit 1.5% on the SF branch, or equivalently a lower limit of 93 s on the SF half-life, consistent with the upper limit of 17±11% established by Hessberger.[56,90a] Electron-capture branches to fissioning isotopes of rutherfordium have been reported for two hahnium isotopes--^{256}Ha($2.6^{+1.4}_{-0.8}$ s, 10% EC??), by Oganessian et al.[26] using the rotating-wheel technique, and ^{258}Ha($4.4^{+0.9}_{-0.6}$ s, 33^{+9}_{-5}% EC), by Hessberger et al.[27] using SHIP at GSI. By observing element-104 K x rays in coincidence with the fissions of ^{258}Rf, Hessberger[56] actually proved that the 4.4-s fissions were due to an EC branch of ^{258}Ha. In addition, in the one α decay chain of ^{266}109 (Refs. 58,90b) observed, one fission event was correlated in position to the α decays of ^{266}109 and the established isotope ^{262}107 and occurred 12.9 s after the α decay of ^{262}107, a time consistent with the 4.4-s half life of ^{258}Ha. These data proved both the mass and atomic number of ^{258}Ha, which EC decays to ^{258}Rf. The 4-s SF activity from EC of ^{258}Ha had previously been incorrectly assigned by the Dubna group[91] to ^{257}Ha. In contrast to ^{258}Ha, Bemis et al.[87,92] determined an upper limit of 1% for the EC branch of ^{260}Ha(1.52 s), the next odd-odd isotope, and that it instead has a direct SF branch of 9.6±0.6%. For ^{262}Ha(34.1 s) Bemis et al.[93] found a direct SF branch of 78±6% with an upper limit of about 10% for EC (Ref. 87),

assuming a 47-ms half-life for ^{262}Rf. There has been no recent work on the SF of ^{261}Ha, which Flerov et al.[94a,b] reported as a 1.8±0.6-s SF activity produced in the reaction ^{22}Ne + ^{243}Am.

A 4- to 10-ms SF activity produced in the reactions ^{54}Cr + ^{207,208}Pb was assigned by the Dubna group[95] to ^{259}106 and claimed as the discovery of element 106. But recently Münzenberg et al.[18] determined that ^{259}106(0.48 s) and ^{261}106(0.26 s) were predominantly α emitters with much longer half-lives, making the Dubna assignment incorrect. For the odd isotope ^{263}106, Druin et al.[96] reported a SF branch of 70% from the production of a $0.64^{+0.32}_{-0.18}$-s SF activity in the reaction ^{18}O + ^{249}Cf with a cross section of 0.6 nb, compared to 0.3 nb obtained by Ghiorso et al.[97] for production of a 0.9±0.2-s α emitter assigned to ^{263}106.

Oganessian et al. found a 1- to 2-ms SF activity in the reaction ^{209}Bi(^{54}Cr,2n)^{261}107 (Refs. 91,98) which they assigned to ^{261}107. Recently the Dubna group[31] repeated the reaction ^{54}Cr + ^{209}Bi and revised the half-life to 3 ms and the production cross section to 20 picobarns. The GSI group,[99,100] however, did not observe SF of ^{261}107 in the same reaction but established an upper limit of 40 picobarns for production of the SF activity, which is equivalent to a lower limit of 20^{+14}_{-6} ms for the SF half-life of ^{261}107.

Spontaneous fission has not been observed among any other isotopes of elements 107-109, including ^{262}107 (Refs. 99,101), ^{263}108 (Ref. 63), ^{264}108 (Refs. 19,63), ^{265}108 (Refs. 63,102), and ^{266}109 (Refs. 90b,103). Again this indicates that α decay rates have overtaken the SF decay rates due to the increasing α decay energies with Z, but fission-barrier heights that are roughly constant with Z (Ref. 58).

In Figs. 3(a) and 3(b) the logarithms of the hindrance factors, log HF, for SF decay with an odd number of protons (a) or an odd number of neutrons (b) are plotted. These hindrances were computed relative to their even-even neighbors according to the following formulas for an odd-even isotope, ${}^{A}_{Z}N$ with Z and A odd and N even:

$$\log HF = \log [T^{SF}_{\frac{1}{2}}({}^{A}Z)] - \tfrac{1}{2}\{\log[T^{SF}_{\frac{1}{2}}({}^{A-1}Z-1)] + \log [T^{SF}_{\frac{1}{2}}({}^{A+1}Z+1)]\}, \qquad (1)$$

and for Z even, N and A odd:

$$\log HF = \log [T^{SF}_{\frac{1}{2}}({}^{A}Z)] - \tfrac{1}{2}\{\log[T^{SF}_{\frac{1}{2}}({}^{A-1}Z)] + \log [T^{SF}_{\frac{1}{2}}({}^{A+1}Z)]\}. \qquad (2)$$

Measured values derived from the SF half-lives of the even-even neighboring isotopes using formulas 1 and 2 are indicated as solid circles. When the SF half-life of only one even-even neighbor has been measured the hindrance factor (denoted by an open circle) was computed simply as the logarithm of the ratio of the SF half-life of the odd-A isotope to the SF half-life of the known even-even neighbor isotope. For example, for the odd-neutron hindrance factor for ^{259}No and the odd-proton hindrance factor for ^{259}Md we have denoted them by open circles because we used only the even-even neighbor ^{258}No in computing them, since the 106-ms ^{260}No is an uncertain assignment.

Because so few SF half-lives for odd or odd-odd nuclei have been measured, few hindrance factors can be determined. This has been complicated recently by the suggestion by Barwick et al.[104] that several old SF half-life measurements could be incorrect, because previous authors actually detected Ne, Mg, or Si heavy cluster emission rather than SF. (See the chapter by Price and Barwick in Volume II.) We have corrected such SF half-life measurements in Table 1 by either considering the older measurements to be lower limits for SF for the case ^{232}U (Ref. 105) and ^{234}U, or by obtaining new lower limits or values for SF half-lives from recent investigations sensitive to both heavy

cluster emission and fission for the cases of ^{230}Th (Ref. 106) and ^{231}Pa (Ref. 107). (See the chapter by Haşegan and Tretyakova in Volume II concerning heavy-ion radioactivity studies in ^{231}Pa, ^{233}U, and ^{230}Th.) Measurements by Paul et al.,[108] which could distinguish between ^{34}Si emission and fission fragments, confirmed the accuracy of the previous SF half-life measurement for ^{241}Am (Ref. 109).

From the limited number of odd-proton hindrance factors plotted in Fig. 3(a) values are 10^4 to 10^7 for proton numbers 93 to 101. For the odd-neutron hindrance factors in Fig. 3(b) the strong hindrance for 157 neutrons has been attributed by Randrup et al.[61b] to the $9/2^+$ [615] neutron orbital, consistent with the hindrances of ^{257}Fm, ^{259}No, and ^{261}Rf. This hindrance is at least $10^{7.5}$ for ^{259}No, 10^9 for ^{257}Fm, and at least 10^4 for ^{261}Rf. Note that the measured odd-neutron hindrance factors for rutherfordium, excepting cases where only lower limits have been established, are in general lower than for lighter elements. The odd-neutron hindrance factors in cases of actual measurement, not lower limits, range from 10^5 to $10^{6.5}$ up to N=155, except for uranium and rutherfordium, which is similar to the odd-proton range of 10^4 to 10^7 up to and including Z=101.

Measurements of ground-state hindrance factors compared to neighboring even-even nuclei exist for only three odd-odd nuclei, namely ^{260}Ha to ^{258}Rf (1×10^3), to ^{260}106 (2×10^3), or to ^{260}Rf (750); ^{262}Ha to ^{260}Rf (2×10^3), or to ^{262}Rf (900); and the recently discovered ^{260}Md (Ref. 24) to ^{258}Fm (7×10^9) or to the possible 106-ms ^{260}No (Refs. 24,25,62b) (3×10^7). Of these three cases only ^{260}Md lends support to the idea (for example, Ref. 58) that the SF hindrance factors for odd-odd nuclei are given by the product of the odd-proton and odd-neutron hindrance factors. The other two cases ^{260}Ha and ^{262}Ha violate this rule by factors of 40,000 and 20,000 respectively.

But this apparent violation of the product rule for odd-odd nuclei may disappear if appropriate account is taken of fission along two valleys.[61a,110] For example, the odd-proton hindrance factor derived from a nucleus which fissions along the old valley cannot be applied to an odd-odd nucleus which fissions along the new valley.

Łojewski and Baran[111] reproduced the ground state spins and parities of odd-A, odd-Z nuclei rather well and reproduced the hindrance factors for SF of odd-A and odd-odd nuclei within about two orders of magnitude. Their results for odd-A nuclei were similar to the previous calculations of Pomorski,[112] except that Łojewski and Baran used an improved single particle spectrum in their calculations.

The domination of α, EC, or β^- decay over SF means that for most odd-odd or odd-A nuclei the partial SF half-lives are difficult to measure. They are also difficult to calculate. If the domination of α decay over SF observed for odd-A and odd-odd isotopes of elements 107-109 continues as predicted among the heaviest elements,[58] identification will be easier and the half-lives may remain in the millisecond to second range.

C. Future Identification Methods for SF Activities

For nuclei decaying by SF new methods need to be developed to positively identify the Z and A of unknown SF activities. If the LEAP project (Large Einsteinium Accelerator Program)[113] is approved in the U.S., probably many new SF activities will be abundantly produced from the ^{254}Es targets. As an example, a 106-ms SF activity[25,62b] has already been produced with the very large cross section of 1 μb in the reaction 99-MeV ^{18}O + ^{254}Es. This activity has not been identified, but ^{260}No is a possible assignment.[24,25] To identify this and many other SF activities[25] a high-efficiency, high-resolution mass

spectrometer could be developed to determine the masses of the SF emitters. Another alternative is the Heavy Element Fission Tracker (HEFT) system.[114] With an array of modules like the one in Fig. 4 masses of the fragments could be determined by measuring their positions, velocities, energy losses, and kinetic energies.

III. FRAGMENT MASS AND KINETIC-ENERGY DISTRIBUTIONS

A. Introduction

In the last few years much additional information concerning fragment mass, charge, and kinetic-energy distributions for SF of ^{252}Cf and a few lighter nuclides has been obtained from time-of-flight, kinetic-energy, and radiochemical measurements. New information about the mass and kinetic-energy distributions for still heavier nuclides has been derived primarily from the measurement of the kinetic energies of coincident fission fragments, usually with solid-state detectors. Although the mass resolution does not approach that obtained from the other types of measurements and also requires that one assume a value for the mass of the fissioning nucleus, it does allow determination of the most probable mode of mass division and the total fragment kinetic-energy distribution. Furthermore, such techniques are applicable to measurements of nuclides with short half-lives and low production rates, either with or without chemical separation. Both the kinetic-energy measurements and the radiochemical techniques measure the fission fragments after they have deexcited by prompt neutron emission. One of the problems in data analysis involves trying to determine the mass of the original fission fragments which requires a knowledge of prompt neutron emission as a function of fragment mass. The kinetic-energy measurements can be performed "on-line" as the nuclides are produced, but among the disadvantages of the on-line technique are contamination from other fissioning species and the inability to positively identify the fissioning nucleus except via half-life, fission properties, and production systematics. The use of newly developed, large gas-ionization detectors in combination with time-of-flight techniques may make it possible[114] to measure the kinetic energy, velocity, energy loss, and other

properties of the fission fragments. From such information, the Z and A of the fission products can be determined and thus the Z and A of the fissioning nucleus can be obtained to within a few units of Z and A. (See Fig. 4.) Nevertheless, until these more definitive techniques can be perfected, solid-state detector measurements of the kinetic energies of coincident fission fragments continue to furnish most of the information about the SF properties of the very heaviest nuclides.

B. Lighter Actinides

Some very careful studies of the mass and kinetic-energy distributions from SF of ^{240}Pu, ^{242}Pu, and ^{244}Pu have been made recently[115-119] by measurement of the kinetic energies of coincident fission fragments. These results show that much narrower mass distributions, higher peak yields, higher peak-to-valley ratios, and more pronounced fine structure are observed for SF than for fission of the same nucleus with more excitation energy such as in thermal-neutron or photon-induced fission. A diminuition in shell effects with increasing average excitation energy was observed which decreases the fine structure observed in spontaneous fission around masses 135 and 143. The average total kinetic energy was also higher for spontaneous fission than for induced fission in all these cases. The total kinetic-energy distributions for the SF cases were asymmetric and shifted towards higher kinetic energies and could not be well represented by a Gaussian fit. This asymmetry was attributed to the spherical N=82 shell which has its maximum influence for heavy fragments in the mass region 132-134 where the effect is enhanced by the Z=50 shell. (This effect of the doubly magic configuration is, of course, most obvious in the SF of the heavy Fm (Z=100) isotopes[1,2,120] and will be discussed in more detail later.) These data have been interpreted in the frame of the static scission-point model of Wilkins[12] in which there is preferential formation of

a nearly spherical, shell-stabilized configuration for mass splits for which the heavy mass is in the region of the N=82 closed shell. The observed asymmetry in the kinetic-energy distribution disappears for photon or thermal neutron-induced fission because of the additional excitation energy which decreases the importance of these shell effect. The N=82 shell is also responsible for the observed enhancement of yields around masses 132-134 while the enhanced yield around masses 142-144 is explained by the combined effects of a deformed N=88 shell in the heavy fragment and a deformed N=58 shell in the light fragment. With increased excitation energy these shell effects are washed out.

Recent studies[121] of the SF of ^{244}Cm also show enhanced yields around masses 134, 143, and 144. Masses 139 and 144 predominate when high kinetic-energy events are selected. Again, these results are attributed to the effects of shell structure in the nascent fragments. Fission yields have been measured[122] by radiochemical techniques for SF of ^{246}Cm and compared with those from SF of ^{244}Cm and ^{248}Cm. The results are consistent with the earlier observation that the average mass of the heavy mass group is nearly constant for low energy and spontaneous fission of U through Cm isotopes while that of the light group increases with the mass of the fissioning nucleus.

C. Trans-Bk Actinides

Since the last review of spontaneous fission properties of the very heavy actinides[2], mass and total kinetic-energy (TKE) distributions have been obtained for the SF of a number of additional very heavy element isotopes. These include ^{244}Fm (Ref. 123), ^{246}Fm (Ref. 123,124), ^{248}Fm (Ref. 124), ^{259}Md (Ref. 71,125), ^{260}Md (Ref. 125), ^{258}No (Ref. 125), ^{256}Rf (Ref. 41), ^{258}Rf (Ref. 27), and ^{260}Rf (Ref. 125). The results of these measurements are summarized in Table 3 together with properties reported

earlier for SF of trans-Bk isotopes. Fragment mass distributions can be obtained directly from radiochemical separation and measurement of the products, and such measurements have "perfect" Z and A resolution because each individual isotope is identified and measured. However, the information applies to the fragments after prompt neutron and photon emission, and often, after beta decay and delayed neutron emission as well, depending on the speed of the radiochemical determination. Most of the data for the very short-lived heavy isotopes are derived from solid-state detector measurements of the kinetic energies of the coincident fission fragments, again after prompt neutron emission. Fission-fragment yield distributions (normalized as customary to total fission-fragment yield = 200%) as a function of fragment mass are shown schematically in Fig. 5 for the trans-Bk isotopes for which this information is available. As mentioned earlier, the resolution for the solid-state detector measurements will not be as good as from radiochemical or time-of-flight measurements, and the resolution can vary considerably from one measurement to the next, depending on experimental parameters. Furthermore, because both the radiochemical and solid-state data are for the fragments after neutron emission, and neutron emission as a function of fragment mass is usually not known, "provisional" masses are often calculated by assuming the sum of the fragment masses is that of the fissioning nucleus. Such assumptions can change the calculated mass-yield distributions.[71,126] Therefore, caution in making detailed comparisons between results from different experiments and techniques should be exercised. Nevertheless, it seems clear from the results shown in Fig. 5 that a dramatic change in the most probable mass division occurs in the region of 158 neutrons for proton numbers of 100 (Fm) and 101 (Md). This change from fission into two unequal mass fragments (asymmetric fission) to two

nearly equal mass fragments (symmetric fission) was quite unexpected although there had been speculation[126] that symmetric fission might occur for Fm because it could split symmetrically into two Sn (Z=50) fragments, each having a magic number of protons. The increase in the yield of symmetric mass splits was first reported[126] in 1971 for ^{257}Fm and later data[16,127] for ^{258}Fm and ^{259}Fm showed an abrupt change to narrow, predominantly symmetric mass distributions and most probable kinetic-energies close to the total Q value for fission. It was postulated[1] that the observed increase in symmetric mass division with increasing mass of the fermium isotopes was because the heavier Fm isotopes could fission symmetrically into two fragments, each with nearly the doubly magic ^{132}Sn (Z=50, N=82) configuration, which would be expected to be spherical. The kinetic energy of the fragments is primarily the result of the Coulomb repulsion between them. Touching spherical fragments would give the maximum Coulomb repulsion and, therefore, the maximum TKE. If the effect of the proximity of the fragments to ^{132}Sn is the major influence, then spontaneously fissioning nuclides whose symmetric mass division gives fragments outside this region should again return to asymmetric fission with "normal" TKE's, or possibly liquid-drop dominated fission.

Total kinetic-energy distributions for some heavy Fm, Md, No, and Rf isotopes are shown in Fig. 6. Most of these show skewed distributions and are not well represented by simple Gaussian fits. This asymmetry was first observed for ^{257}Fm which has a most probable TKE around 200 MeV, but is skewed to the high energy side. Recent remeasurements of TKE for ^{258}Md, ^{259}Md, and new measurements for ^{260}Md, ^{258}No, and ^{260}Rf indicate[125] that this phenomenon is not unique and that many of the kinetic-energy distributions of these heavy isotopes show a "bimodal" distribution. The distributions can be fit[125] by varying the amounts of two Gaussian

distributions centered around 200 and 235 MeV (see Table 3). In the case of ^{257}Fm a fit can be obtained[128] with about 4 times as much of the 200-MeV Gaussian as of the 230-MeV Gaussian, while for ^{260}Md the higher energy group is the major component. The distributions for ^{259}Fm and ^{260}Rf do not appear to be skewed, but ^{259}Fm peaks at about 240 MeV while ^{260}Rf is centered around 200 MeV. Again, this might be because symmetric fission of ^{259}Fm results in fragments which are closer to the spherical ^{132}Sn configuration than does SF of ^{260}Rf and would, therefore, result in a higher TKE for ^{259}Fm. The other distributions represent varying amounts of the high and low energy components. This has been attributed[125] to the possibility for two different paths, or potential-energy valleys, one influenced by the presence of strong spherical shells in the fragments and the other corresponding to a more liquid-drop type fission.

D. Comparison with Theory

It is of interest to recall that triple-peaked mass distributions have been observed for particle-induced fission of nuclei in the region between Z=84 and 90. These nuclei do not spontaneously fission nor can their fission be induced by thermal-neutron capture because their fission barriers are too high. However, as early as 1958 Jensen and Fairhall[129] attributed this triple-peaked mass distribution to two different fission components, a symmetric one associated with higher excitation energies and an asymmetric one associated with the low excitation energies of fissioning nuclei formed after neutron evaporation from the original compound nucleus. In this case, the symmetric mode would be of the "liquid-drop" type because shell effects would be washed out at the higher excitation energies and the asymmetric mode would correspond to a fragment-shell stabilized fission path. The mass distribution for ^{259}Md shown schematically in Fig. 5 appears to show some evidence for

"wings", suggestive of a triple-humped mass distribution. The distribution for ^{257}Fm can also be represented as a combination of both symmetric and asymmetric mass distributions, but in this case with a larger asymmetric component. The TKE distributions of the heaviest nuclides shown in Fig. 6 show asymmetries either to the high-or low-energy side of the most probable energy. Such asymmetries have also been observed for the SF of ^{240}Pu, ^{242}Pu, and ^{244}Pu (discussed earlier in this section) where the TKE distributions cannot be represented by a Gaussian distribution because they are skewed toward the high energy side. Wagemans et al.[119] interpreted this in terms of the model of Wilkins et al.[12] in which the high-energy component is due to preferential formation of nearly spherical fragments in the region of Z=50 and N=82. The low-energy component arises from a more deformed configuration favored by a liquid-drop type fission. The disappearance of this high-energy asymmetry in excited fission of ^{240}Pu from thermal neutron-induced fission of ^{239}Pu gives credence to the hypothesis that the high TKE events are due to shell effects which are washed out by the additional 6.5 MeV of excitation energy. It now appears that an appropriate combination of liquid-drop and shell-stabilized fission (either deformed or spherical), due to competition between the two modes, can explain a wide range of observed SF and low-energy fission properties throughout the region. However, this will not necessarily result in only two distinct components because the shell effects could result in stabilization of either deformed or spherical configurations which might, in some cases, have comparable probabilities. Thus, asymmetric and symmetric shell-stabilized properties and symmetric, liquid-drop type properties might all be observed in SF of the same nucleus.

Brosa et al.[11] have calculated fission channels for ^{258}Fm as functions of a surface parameterization involving half the length of the nucleus, neck

radius, and distance of the neck from the shape's geometric center. The existence of several different channels explains various components of fission while the end of a channel, corresponding to a scissioning nucleus, determines the kinetic energy. The heights of the barriers within these channels give an estimate of the relative abundances of various fission components. For ^{258}Fm, they find just two paths through three channels and obtain 199 MeV and 236 MeV for the TKE's of the fragments resulting from these paths.

As was discussed in Section II, Möller et al.[10] have recently performed quantitative calculations of the fission half-lives and potential-energy surfaces for mass-symmetric shapes for heavy even-even nuclei from Cm through element 108. Their goal was to search for two fission valleys for symmetric fission, one leading to elongated shapes with resultant "normal" TKE's, and the other leading to compact or spherical shapes with very high TKE's. Consequently, they limited this study to symmetric shapes. However, in calculations of the fission half-lives for the old path, the effect of mass asymmetry on the barrier heights was taken into account. They also noted that for ^{264}Fm the full effect of the magic ^{132}Sn fragments is only manifested if the ends of the nuclear shapes are kept spherical. In their parameterization it is possible to generate the very important configuration of two touching spheres. Their calculated potential-energy surfaces for nuclides close to ^{264}Fm show a deep valley which can lead to compact scission shapes. They propose that fission may initially proceed along the new valley and later switch back to the old valley (see Fig. 2), thus giving rise to symmetric mass division with both spherical and elongated shapes. This path could account for the narrow, symmetric mass division with both high and low TKE's observed for both ^{258}Fm and ^{259}Fm. Similar comparisons can be made for other heavy nuclides.

IV. NEUTRON EMISSION

A. Introduction

As was discussed in Section III, a knowledge of the prompt neutron emission as a function of fragment mass $\bar{\nu}(M)$, for each fissioning system is required in order to obtain primary fragment (pre-neutron emission) mass-yield distributions from radiochemical or kinetic-energy measurements of the fission fragments. Most of the prompt neutrons are emitted[1] in less than 4×10^{-14} s after scission. Studies of prompt neutron emission furnish insights into the deformation or excitation energy of the fragments at scission since the fragment excitation energy is dissipated by neutron and gamma-ray emission. Unfortunately, there is very little information for neutron emission in SF as a function of the fragment masses and kinetic energies except for the SF of ^{252}Cf which has been studied [1,130-132] extensively by a variety of techniques.

B. Neutron Emission as a Function of Fragment Mass

Neutron emission has been found to vary significantly with fragment mass, which indicates a large variation in the distribution of excitation energy between the fragments in binary fission. A "sawtooth" curve with a minimum in the $\bar{\nu}(M)$ function of $\simeq 0.5$ in the region around mass 130 has been measured for SF of ^{252}Cf. Fine structure in the $\bar{\nu}(M)$ function has also been observed[132] in positions corresponding to those found in mass-yield curves.[133] The behavior of $\bar{\nu}(M)$ has been explained by the influence of shell effects in the fragments.

Information about $\bar{\nu}(M)$ has also been deduced for the SF of ^{254}Fm and ^{256}Fm by an interative method[133,134] in which kinetic-energy and radiochemical measurements are compared. Again, minimum neutron emission was found around fragment mass 130. Recently, a direct measurement of $\bar{\nu}(M)$ was

made[135] for the SF of ^{244}Cm for the first time. The observed "sawtooth" function for $\bar{\nu}(M)$ was compared with that for ^{252}Cf and found to be quite similar, although the maximum number of neutrons emitted per fragment was lower, consistent with the lower value for the average number of neutrons emitted per fission of ^{244}Cm. The minimum in $\bar{\nu}(M)$ appears to be around mass 128. This minimum in $\bar{\nu}(M)$ around fragment masses of 130 has been attributed to the near-spherical, closed-shell structure of these fragments which have lower excitation energies, higher neutron-binding energies and consequently lower neutron-emission than more deformed fragments. However, recently Basova et al.[131] have also seen evidence for increased neutron emission from mass 132 fragments from very low TKE events (<170 MeV) in ^{252}Cf, indicating the possibility that fragments with a magic number of nucleons can still be formed in a highly deformed configuration.

C. Neutron-Energy Spectrum

Numerous recent measurements[136-139] of the energy spectrum of prompt neutrons from the SF of ^{252}Cf have also been made and the shape of the spectrum, except at the extremes, can be well described[1,138a,138b,139] by a Maxwellian distribution. The Maxwellian temperature which determines the neutron-energy spectrum is an average over a wide range of fragment masses and excitation energies. The high-energy portion of the spectrum has been measured[140] up to 30 MeV and shows a nearly constant number of high-energy neutrons between 20 and 30 MeV. The cause of this high-energy component is unknown. Märten and Seeliger[141] have used a cascade evaporation model and realistic excitation energy distributions to obtain good agreement with the experimental data for the ^{252}Cf neutron spectrum, except for the region above 20 MeV and for fragment masses around 132. Emission mechanisms other than neutron evaporation from fully excited fragments apparently need to be considered.

Seregina and D'yachenko[138c] have examined the angular distributions as well as the energy distributions of the prompt neutrons emitted in SF of ^{252}Cf and conclude that these can be fit with a model of isotropic evaporation of neutrons to an accuracy of about 10%. This fit can be improved by assuming the existence of anisotropy in the angular distribution in the c.m.s. of the form $1 + 0.1\cos^2\theta_{cms}$, and a small dependence of the spectrum shape on the neutron emission angle in the coordinate system of a completely accelerated fragment.

Seregina et al.[138b] have performed a multiparameter experiment to investigate the shape of the energy distributions of neutrons from the SF of ^{252}Cf. They find that the shape of the distributions is not universal, but depends on the mass and TKE of the fragments. They have calculated the excitation energies of the fragments and find that the neutron energy spectra for fragments with the same mass but different excitation energy differ in shape. They also found that the neutron energy spectra for the complementary fragments, mass 120 and 132, differ in shape. They calculated an excitation energy of 28 MeV for the highly excited, deformed mass 120 fragments which emit a maximum number of neutrons, and an excitation energy of <10 MeV for the near-doubly magic 132 fragments which emit a minimum number of neutrons. From analysis of the neutron spectra, they also obtained level-density parameters for the fragments.

D. Average Neutron Emission and Neutron Multiplicity Distributions

For most spontaneously fissioning nuclides, only the average number of neutrons emitted per fission, $\bar{\nu}_T$, is known rather than the number of neutrons emitted as a function of fragment mass. Since the last review[2] of SF, more accurate numbers of $\bar{\nu}_T$ for ^{240}Pu, ^{242}Pu, ^{242}Cm, and ^{244}Cm

have been obtained.[142a,142b] Recently, very accurate values of 3.7509 ± 0.0107 and 3.773 ± 0.0007 have been reported[143,144] for ^{252}Cf. However, most of the values given in Table 3 were based on a value of 3.735 for ^{252}Cf. As shown in Fig. 7, $\bar{\nu}_T$ for SF and low-energy fission generally increases with the Z of the fissioning nuclide, and for trans-Pu nuclides it also increases with mass for a given Z. However, at Fm this trend is reversed and the average neutron emission is actually lower for ^{256}Fm and ^{257}Fm than for ^{254}Fm. (See Table 3.).

The measured average values of $\bar{\nu}_T$ are, of course, not integers, and the probability for emitting a given number of neutrons has been measured for the low-energy fission of a large number of nuclides. It was early shown that these "multiplicity" distributions could be fit by a Gaussian distribution with $\sigma_\nu = 1.08$ (variance = $\sigma_\nu^2 = 1.17$). However, as measurements were made for ^{252}Cf and other heavy actinide isotopes, it was found that larger values of the variance were required, and variances of 1.82, 2.51, and 4.0 have been measured[17,145] for ^{256}Fm, ^{257}Fm, and ^{252}No, respectively. In 1977, Lazarev[146] reviewed the data for the variances of neutron-multiplicity and TKE distributions for low-energy fission and found that the ratios of these variances were nearly constant for the nuclides studied which included ^{256}Fm and ^{252}No. If this trend were to continue for ^{259}Fm and ^{259}Md, whose TKE's have very high variances (see Table 3), then the neutron multiplicity distributions should also have large variances since the energy for binary fission appears primarily in either fragment kinetic energy or excitation energy, which is then dissipated by neutron and gamma emission. However, as the masses of the Fm isotopes approach ^{264}Fm, both variances should become very small as the fragments become nearly spherical. Touching spheres will have the maximum total kinetic energy due to Coulomb repulsion and the TKE can approach the Q-value, leaving little energy for excitation of

the fragments and little room for large variations in neutron and gamma emission. It might be expected that nuclides such as ^{259}Md with Z >100 would again be in a transition region (as were ^{256}Fm and ^{257}Fm) and that the variances would again increase because of the wide range of shapes and excitation energies available as the fragments evolve away from the ^{132}Sn configuration toward nonspherical shapes. This is consistent with the large FWHM's of the TKE distributions given in Table 3.

Neutron multiplicities as a function of mass and TKE have been measured[17] for SF of ^{250,252,254}Cf and ^{256,257}Fm. The $\bar{\nu}$ values for all of these isotopes decrease monotonically with increasing TKE for a given mass split. This might be expected since the total energy is approximately constant for a given mass split and is manifested primarily either in the kinetic or excitation energy of the fragments. As the TKE increases, the excitation energy of the fragments, and therefore the energy available for emission of neutrons and gamma rays must necessarily decrease. In the case of ^{257}Fm, $\bar{\nu}$ drops to 1.1 with a variance of only 0.7 for symmetric mass splits for the highest TKE events (240-260 MeV). For ^{256}Fm, it drops to only 2.0 with a variance of 1.2 for the highest TKE events, and for ^{252}Cf, $\bar{\nu}$ for the highest TKE events is 2.1 with a variance of 0.4. These differences may be a reflection of the fact that the TKE for symmetric and mass-weighted, near-symmetric mass splits for ^{257}Fm reaches values some 30 to 50 MeV higher than for the SF of the other nuclides studied, even though the estimated Q value is nearly the same as for ^{256}Fm and only about 15 MeV higher than for the Cf isotopes.

The contour plots of TKE as a function of mass fraction for ^{254}Cf, ^{256}Fm, ^{257}Fm, and ^{259}Fm shown in Fig. 8 illustrate the differences in the TKE and its variance for different mass fractions for these nuclides. ^{257}Fm and ^{259}Fm show much larger spreads in TKE for symmetric mass division than do the other nuclides shown. The mass-yield distribution for

^{257}Fm SF events with TKE greater than 235 MeV, where ν is only about 1, is narrowly symmetric and resembles those measured for ^{258,259} Fm (see Fig. 5), where the most probable TKE's are about 238 MeV. This suggests that the average overall neutron emission per fission may be as low as 1 for these nuclides, consistent with their high measured TKE's which are approaching the Q values of around 250 MeV estimated for their symmetric fission.

The TKE measurements[125] (Fig. 6) for ^{260}Md show a "bimodal" distribution with the maximum of the more abundant mode at about the same energy as for ^{258,259}Fm. The low-energy mode is more abundant in ^{260}Md than in ^{259}Fm and should then result in a higher $\bar{\nu}_T$ for ^{260}Md. However, $\bar{\nu}_T$ for ^{260}Md should be lower than for ^{257}Fm ($\bar{\nu}_T$ = 3.77), where the high TKE events are much less abundant. ^{259}Md, which shows many more low TKE events than ^{260}Md but many more high TKE events than ^{257}Fm, might be predicted to have a $\bar{\nu}_T$ intermediate between those for ^{260}Md and ^{257}Fm.

The large variances observed for neutron emission from ^{256,257}Fm suggest a broad distribution in fragment excitation energies, consistent with the observed large variations in TKE and suggesting that they are in a "transition" region. Although symmetric mass division gives fragments with the magic proton number of 50, they are still 3 to 4 neutrons from the 82-neutron closed shell configuration, and may be "soft" toward deformation. The observation of symmetric fragments with both very high and very low TKE (see Fig. 8) indicates a rather large difference in their shapes, ranging from elongated to nearly spherical. As discussed earlier, the number of neutrons emitted per fission should decrease very sharply for ^{258,259}Fm and heavier Fm isotopes as the fragments from symmetric mass division more closely approach the magic ^{132}Sn configuration. For Z>100, neutron emission and the

variances of the neutron multiplicity and TKE distributions should again increase. This seems to be substantiated by the measurement of $\bar{\nu}_T = 2.6$ for ^{260}Md and the observation[144] of a significant number of fission events in which as many as 11 neutrons were emitted, indicating a very large variance. A large variance would be consistent with a transition nucleus in which both deformed and spherical fragments with both low and high TKE's can be formed as has already been observed in the TKE distribution for ^{260}Md.

In summary, although information on neutron emission from the SF of nuclides other than ^{252}Cf is rather limited, a picture consistent with the more detailed studies of ^{252}Cf can probably be developed for SF of other nuclides based on the existing information about fragment mass and kinetic-energy distributions and average neutron emission per fission event. The detailed properties of neutron emission appear to be determined by the specific properties of the individual fragments at scission, i.e., their deformation (excitation) energies and kinetic energies. If these are known, for example, for specific masses and TKE's for ^{252}Cf, ^{256}Fm, or ^{257}Fm, the information may also apply to SF of other nuclides, but will have to be scaled according to the yields of these fragments as a function of TKE for the SF of the specific nuclide in question. This should allow estimation of such properties as the average values for neutron emission and the overall shape of the neutron multiplicity and energy distributions.

V. GAMMA-RAY EMISSION

A. Introduction

In the process of spontaneous fission both neutrons and gamma rays (γ) may carry away excitation energy from the fragments. While fission fragments and fission neutrons have been extensively studied, the gamma rays emitted in fission have been less investigated. Because of the high specific activity of ^{252}Cf and its availability, most studies of SF γ rays have been done with ^{252}Cf. ^{238}U, ^{240}Pu and ^{244}Cm have also been investigated.[147-149] However, neutron-induced fission γ's have been studied more extensively, as discussed by Hoffman and Hoffman[1]. The γ rays emitted in neutron-induced fission have properties similar to those emitted in SF, but there is a slight increase in the number of softer γ's below 0.7 MeV from SF of ^{252}Cf, and a slight reduction of the number of harder γ's above 7 MeV compared to neutron-induced fission of lighter targets such as ^{235}U and ^{239}Pu.

Since the Hoffman and Hoffman review article of 1974 there have been a number of interesting studies of SF γ rays. About 80% of the γ's are known to be emitted within 10^{-10} s after fission.[1] Skarsvåg[150] determined that 11% of the γ's from the SF of ^{252}Cf are emitted within 10^{-13} s after fission. He also found[151] that a sizeable fraction of neutrons could be emitted with a mean lifetime of 10^{-14} s. These two time measurements suggest that a competition between neutron and γ emission may exist in the range 10^{-14} to 10^{-13} s. Previously it had been assumed that most of the neutrons were emitted before the γ rays.

B. Gamma-Ray Multiplicity

Several groups [152-156] have measured 8-10 γ rays per SF of ^{252}Cf. Brunson[157] has shown that the measured multiplicity is a sensitive function of the detection thresholds used in these measurements. For the lowest

detection thresholds, near 40 keV, the γ-ray multiplicity is 10 for ^{252}Cf. Weber[148] measured a γ-ray multiplicity of 7 for SF of ^{240}Pu, but the detection threshold was not given.

The γ-ray multiplicity distribution for SF of ^{252}Cf has been studied by Ramamurthy et al.[155] and by Brunson.[157] Ramamurthy et al. found a Gaussian multiplicity distribution with a mean and standard deviation of 10.3±4.1 γ's per SF. However, only three γ detectors were used and the calculated detection efficiencies did not include the compound probabilities for γ rays to be missed by the detectors.[157] Brunson used eight scintillation detectors and found that the measured multiplicity distribution for a detection threshold of 140 KeV was slightly skewed toward high multiplicities. It could not be fit by a Gaussian. It could be fit by a double-Poisson probability distribution $\pi(n)$ for emitting n γ's per SF:

$$\pi(n) = 0.675 \frac{(6.78)^n}{n!} e^{-6.78} + 0.325 \frac{(9.93)^n}{n!} e^{-9.92} . \qquad (3)$$

Only minor differences exist between the γ rays accompanying ternary SF, usually with an α particle as the third fragment, compared to binary SF. First of all, the ternary-fission γ-ray multiplicity is slightly lower than the γ-ray multiplicity in binary SF — 14% lower for ^{252}Cf (Ref. 158) and 12±9% lower for ^{244}Cm (Ref. 149). The ratio between ternary and binary γ-ray multiplicities is independent of the α-particle energy between 15 and 25 MeV for SF of both ^{252}Cf and ^{244}Cm. The width of the prompt γ-ray multiplicity distribution was found by Ramamurthy et al.[159] to be 20% larger for ternary SF of ^{252}Cf compared to binary SF.

In summary, the distribution for the number of γ-rays emitted during the SF of ^{252}Cf follows the double-Poisson distribution given by equation 3 with a mean of about 10 γ's per SF. About 12 to 14% fewer γ's are emitted in ternary compared to binary SF of ^{252}Cf and ^{244}Cm. The dispersion in the γ-ray multiplicity is 20 larger in ternary compared to binary SF of ^{252}Cf.

C. Gamma-Ray Energy Measurements

The total energy per fission for all of the prompt γ's, $E_{\gamma T}$, and the average γ-ray energy, E_{γ}, have also been measured. For ^{252}Cf, the measured values[153,157,160] range from 6.7 to 9 MeV for $E_{\gamma T}$ and 0.7 to 0.9 MeV for E_{γ}. At least two different methods have reproduced the measured values of total γ-ray energy per fission. For example, Kildir and Aras[161] have used a statistical model for neutron and γ-ray emission, and Mukherji et al.,[162a] have used a liquid-drop type model.

Concerning γ spectra Sobel et al.[147] found in the SF of ^{238}U that the γ intensity between 8 and 20 MeV decreases more slowly than at lower energies where the statistical model including angular momentum fits well. Brooks and Reines[162b] have also observed high energy γ's between 10 and 16 MeV emitted in the SF of ^{252}Cf. For very high energy γ's from the SF of ^{252}Cf Aleshin et al.[163] established an upper limit of 7×10^{-6} for the γ-emission probability per fission for γ energies between 50 and 170 MeV; Zhang et al.[164] established a limit of 1.4×10^{-6} for the interval 50 to 240 MeV. The statistical model for competition between neutrons and γ's emitted from highly excited states with high angular momentum fits the γ spectra[1,162b] for ^{252}Cf quite well between 1 and 4 MeV, as well as the relative absence of γ's above 50 MeV. But it underestimates the intensity of γ's in the region 8 to 20 MeV for SF of ^{238}U. A statistical cascade of low energy γ's also cannot explain the γ's between 10 and 16 MeV for SF of ^{252}Cf. Brooks and Reines have proposed a giant dipole mechanism for emission of these γ's. A theoretical treatment is needed to fit the γ spectra in the region 4 to 16 MeV.

Adamov et al.[149] found identical γ spectra for binary and ternary SF of ^{244}Cm and that the ternary-fission γ spectra were independent of the

α-particle energy. In the SF of ^{252}Cf, Ajitanand et al.[165] found some differences in the intensities for specific γ rays assigned to definite fragments in the SF of ^{252}Cf. These differences can be understood in terms of shifts of the peaks in the mass and charge distributions for ternary SF, usually toward light fragments two charge units lighter and one mass unit heavier than for binary SF, and heavy fragments with the same charge and mass, or up to two mass units heavier.

Summarizing the γ-ray energy measurements and calculations, the total γ-ray energy per SF of ^{252}Cf is 6.7 to 9 MeV, in agreement with calculations using both the statistical model for γ-rays in competition with neutrons and with a liquid-drop type model. While this model is consistent with absence of very high energy γ's with $50 \leq E_\gamma \leq 240$ MeV in ^{252}Cf SF, it fails to reproduce the γ spectra for SF of ^{238}U and ^{252}Cf between 4 and 16 MeV. Still no satisfactory model exists to actually fit this region of the γ spectra.[1] Binary and ternary fission of ^{244}Cm produce identical γ spectra. For ^{252}Cf differences between binary and ternary fission spectra are explained by differing mass and charge distributions.

D. Gamma-Ray Anisotropy

The prompt fission γ rays are not emitted isotropically from the fission fragments. Slightly more γ's are emitted along the fission axis than perpendicular to it. This anisotropy A is defined as:

$$A = \frac{W(0^\circ)}{W(90^\circ)} - 1, \tag{4}$$

where $\theta=0^\circ$ corresponds to the fission axis. The anisotropy is similar for spontaneous and neutron-induced fission. Earlier work[166] on SF of ^{252}Cf showed that the anisotropy increased with γ-ray energy between 0 and 0.6 MeV. This could be explained both by a relatively lower anisotropy of soft γ rays[166] and a hardening of the γ-ray spectrum from more rigid fragments with increasing fragment kinetic energies.[152] The larger anisotropy for harder γ rays of 0.6 to 0.97 MeV could be due to larger fragment spins perpendicular to the fission axis, causing preferential emission of γ rays along the fission axis. Wilhelmy et al.[167] and Skarsvåg[153] have indeed measured large root-mean-square fragment spins of ~7$\hbar$. Furthermore, Wilhelmy et al.[167] and Wolf and Cheifetz[168] found direct experimental evidence in the SF of ^{252}Cf that the primary fragment angular momenta are completely aligned perpendicular to the fission axis. Wilhelmy et al. came to this conclusion from the large anisotropies they measured for $2^+ \rightarrow 0^+$ transitions in the fission fragments. Wolf and Cheifetz found that the anisotropies for $4^+ \rightarrow 2^+$ transitions in the fission fragments ^{138,140}Xe and ^{142}Ba were consistent with the anisotropies expected for nearly

complete alignment. From fits to γ-ray angular distributions for specific transitions these authors also found that the statistical model for the deexcitation of the primary fragments worked well in most cases.

Figure 9 shows the anisotropy measured by Skarsvåg[153] for ^{252}Cf SF γ rays. The anisotropy increases to a peak of ~25% at about 0.6 MeV, then decreases and flattens out in the region E_γ>2 MeV. Contrary to previous measurements,[166] Skarsvåg found essentially no difference in the anisotropies between magnetic nickel and non magnetic platinum backings for the ^{252}Cf sources used in the γ-ray measurements.

Skarsvåg also measured the angular distributions for the γ's in particular energy bins in the SF of ^{252}Cf. These angular distributions were then fitted with several adjustable parameters, assuming initially complete fragment spin alignment perpendicular to the fission axis and a statistical emission of neutrons first and then γ rays with a given angular momentum projection along the nuclear spin direction. Time-of-flight and energy measurements on one of the two fission fragments together with the direction of γ-ray emission enabled Skarsvåg to associate the γ's with heavy or light fragments. Skarsvåg's results showed that the γ rays in the region 0.57 to 0.96 MeV, where the largest anisotropies were measured, could be associated with vibrational transitions in even-even fragments, while the region of 0.0 to 0.6 MeV was due to rotational transitions in the ground-state bands of even-even fragments.

There is some information concerning the multipolarities of the prompt γ rays in the SF of ^{252}Cf. Skarsvåg found that E1 and E2 transitions were about equally strong at the highest γ-ray energies, 1.2 to 2.2 MeV, that E2 transitions dominated the intermediate-energy region, 0.3 to 1.2 MeV, and

that M1 transitions were important at the lowest energies, 0 to 0.3 MeV. All of these measurements are consistent with the statistical model for deexcitation of the fragments. Nonstatistical, stretched E2 cascades were also found below 1 MeV.

From the γ-ray anisotropy measurements, it appears that the excess γ-ray emission along the fission axis is caused by large fragment spins of ~$7\hbar$ with nearly complete alignment of the fragment spins perpendicular to the fission axis. The largest anisotropies of ~25% for γ-ray energies of ~0.6 MeV and somewhat higher could be due to vibrational E2 transitions in even-even fragments, while the lower-energy region of 0 to 0.6 MeV may be due to rotational E2 transitions in the ground-state bands of even-even fragments. The statistical model for evaporation of neutrons competing with the emission of γ rays agrees with nearly all observations except the high-energy neutrons observed by Märten and Seeliger[140] in the SF of ^{252}Cf and the γ spectrum between 4 and 16 MeV for SF of ^{238}U and ^{252}Cf (Refs. 1, 147, 162b).

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Table 1: Assigned spontaneous fission activities including their half-lives and partial SF half-lives or SF branches

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{8}Be	$(6.7^{+2.2}_{-1.3})\times10^{-17}$s	$(6.7^{+2.2}_{-1.3})10^{-17}$s	
^{230}Th	$(8.0\pm0.3)\times10^{4}$yr	$\geq2\times10^{18}$yr	SF:106
^{232}Th	$(1.41\pm0.01)\times10^{10}$yr	$>1\times10^{21}$yr	
^{231}Pa	$(3.276\pm0.011)\times10^{4}$yr	$>2\times10^{17}$yr	SF:107
^{234}Pa, g	6.75±0.03 hr	$\leq3\times10^{-10}$% SF	SF:29
m	1.175±0.003 min	$\leq10^{-10}$% SF	SF:29
^{236}Pa, β^{-}-SF	9.1±0.3 min	10^{-7}% SF??	SF:29
^{238}Pa	2.3±0.1 min	$<2.6\times10^{-6}$% SF	SF:30
^{232}U	71.7±0.9 yr	$\geq8\times10^{13}$yr[a]	SF:104,105
^{233}U	$(1.5911\pm0.0015)\times10^{5}$yr	$>2.7\times10^{17}$yr	SF:169a
^{234}U	$(2.454\pm0.006)\times10^{5}$yr	$\geq(1.42\pm0.08)\times10^{16}$yr[a]	$T_{1/2}$:169b;$T^{SF}_{1/2}$:169a
^{235}U	$(7.038\pm0.005)\times10^{8}$yr	$(9.8\pm2.8)\times10^{18}$yr	SF:169a
^{236}U, g	$(2.3415\pm0.0014)\times10^{7}$yr	$(2.43\pm0.13)\times10^{16}$yr	SF:169a
f	116±7 ns	900±200 ns, estim.	SF branch:169c
^{238}U, g	$(4.4683\pm0.0024)\times10^{9}$yr	$(8.19\pm0.06)\times10^{15}$yr	
f_1	155±33	3.4-8.3 μs	$T_{1/2}$:169d; $T^{SF}_{1/2}$:170,171a
f_2	≥1 ns	≥1 ns	SF: 171b
^{227}Np or ^{228}Np, EC-SF	60±5 s?	10^{-4}% SF?	% SF:176
^{237}Np, g	$(2.14\pm0.01)\times10^{6}$yr	$>1\times10^{18}$yr	
f	45±5 ns	24 μs, estimated	22
^{228}Pu	If $T_{1/2}\approx2$ min, then	$T^{SF}_{1/2}>22$ min.	172

[a]These SF half-lives have been taken as lower limits from the references due to a question of whether heavy-ion emission could be distinguished from SF in the experimental measurements.

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{235}Pu, f	30±5 ns	30±5 ns	
^{236}Pu, g	2.851±0.008 yr	(3.5±0.1)x10^{9}yr	
f_1	30±12 ps	30±12 ps	
f_2	34±8 ns	≥34±8 ns	
^{237}Pu, f_1	110±9 ns	110±9 ns	
f_2	1.12±0.08 μs	≥1.12±0.08 μs	
^{238}Pu, g	87.71±0.03 yr	(4.77±0.14)x10^{10}yr	
f_1	0.5±0.2 ns	0.5±0.2 ns	
f_2	6.5±1.5 ns	≥6.5±1.5 ns	
^{239}Pu, g	(2.4131±0.0016)x10^{4}yr	(7.8±1.6)x10^{15}yr	SF:173a
f_1	8.1±0.8 μs	8 μs≤ $T^{SF}_{1/2}$≤11 μs	
f_2	$2.6^{+4.0}_{-1.2}$ ns	≥$2.6^{+4.0}_{-1.2}$ ns	SF:173b
^{240}Pu, g	6570±6 yr	(1.340±0.015)x10^{11}yr	
f	3.8±0.3 ns	3.8±0.3 ns	
^{241}Pu, g	14.355±0.007 yr	~6x10^{16}yr	$T^{SF}_{1/2}$:173a
f_1	23±1 μs	23 μs≤ $T^{SF}_{1/2}$≤46 μs	
f_2	30±5 ns	≥30±5 ns	
^{242}Pu, g	(3.763±0.009)x10^{5}yr	(6.79±0.04)x10^{10}yr	SF:174a
f_1	3.5±0.6 ns	3.5±0.6 ns	
f_2	54±19 ns	≥54±19 ns	
^{243}Pu, f	58±11 ns	58±11 ns	
^{244}Pu, g	(8.05±0.10)x10^{7}yr	(6.55±0.32)x10^{10}yr	
f	0.4±0.1 ns	0.4±0.1 ns	
^{245}Pu, f	90±30 ns	90±30 ns	SF:174b
^{230}Am, EC-SF	1 min??	% SF??	175
^{232}Am, EC-SF	55±7s?	$1.3^{+4.0}_{-0.8}$% SF?	$T_{1/2}$, $T^{SF}_{1/2}$:176
^{234}Am, EC-SF	2.6±0.2 min?	8^{+24}_{-5}x10^{-4}% SF?	$T_{1/2}$:177,178; %SF:176

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{235}Am, f	fission isomer??[b]		179,180
^{236}Am, f	fission isomer??[b]		179,180
^{237}Am, f	5±2 ns	5±2 ns	
^{238}Am, f	35±4 μs	35±4 μs	
^{239}Am, f	163±12 ns	163±12 ns	
^{240}Am, f	0.942±0.038 ms	0.9 ms≤ $T^{SF}_{1/2}$≤1.8 ms	181
^{241}Am, g	432.0±0.2 yr	(1.147±0.024)x10^{14}yr	
f	1.5±0.6 μ	1.5±0.6 μs≤ $T^{SF}_{1/2}$≤ 2 μs	
^{242}Am, m	152±7 yr	>3x10^{12} yr	SF:23a
f	14.0±0.2 ms	14.0≤$T^{SF}_{1/2}$≤17.0 ms	
^{243}Am, g	7370±40 yr	(2.0±0.5)x10^{14}yr	
f	5.2±0.5 μs	5.2±0.5 μs≤ $T^{SF}_{1/2}$≤ 5.7 μs	
^{244}Am, f	1.10±0.15 ms	1.10±0.15 ms	
^{245}Am, f	640±60 ns	640±60 ns	
^{246}Am, f	73±10 μs	73±10 μs	
^{232}Cm	If $T_{1/2}$≅1 min, then	$T^{SF}_{1/2}$>3.3 min.	172
^{240}Cm, g	26.8 d	(1.9±0.4)x10^{6}yr	
f_1	10±3 ps	10±3 ps	
f_2	55±12 ns	≥55±12 ns	182
^{241}Cm, f	15.3±1.0 ns	15.3±1.0 ns	
^{242}Cm, g	162.76±0.04 d	(7.46±0.06)x10^{6}yr	SF:183
f_1	40±15 ps	40±15 ps	
f_2	180±70 ns	≥180±70 ns	
^{243}Cm, f	42±6 ns	42±6 ns	
^{244}Cm, g	18.099±0.015 yr	(1.345±0.006)x 10^{7}yr	
f_1	<5 ps	<5 ps	
f_2	>100 ns	>100 ns	

[b]Activities not observed.[180]

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{245}Cm, g	8537±53 yr	(1.4±0.2)x10^{12}yr	SF:184
f	13±2 ns	13±2 ns	
^{246}Cm	4822±22 yr	(1.80±0.01)x10^{7}yr	
^{248}Cm	(3.397±0.032)x10^{5}yr	(4.11±0.05)x10^{6}yr	
^{250}Cm	(1.13±0.05)x10^{4}yr	(1.13±0.05)x10^{4}yr	
^{240}Bk, EC-SF	5±2 min??	0.001% SF??	SF:185
^{242}Bk, EC-SF	7.0±1.3 min	≤3x10^{-5}% SF	SF:185
f_1	600±100 ns	600±100 ns	
f_2	9.5±2.0 ns	≥9.5±2.0 ns	
^{243}Bk, f	5 ns??[c]	5 ns??[c]	
^{244}Bk, f	820±60 ns	820±60 ns	
^{245}Bk, f	2±1 ns	2±1 ns	
^{249}Bk	325±7 d	(1.87±0.09)x10^{9}yr	
^{238}Cf	If $T_{1/2}$≅1 s, then	$T^{SF}_{1/2}$>4 s.	172
^{246}Cf	35.7±0.5 hr	(2.0±0.2)x10^{3}yr	
^{248}Cf	333.5±2.8 d	(3.2±0.3)x10^{4}yr	
^{249}Cf	350.6±2.1 yr	(6.87±0.33)x10^{10}yr	
^{250}Cf	13.08±0.09 yr	(1.66±0.08)x10^{4}yr	
^{252}Cf	2.650±0.002 yr	85.7±0.3 yr	$T_{1/2}$:186;$T^{SF}_{1/2}$:22,186
^{254}Cf	60.5±0.2 d	60.7±0.3 d	
^{256}Cf	12.3±1.2 min	12.3±1.2 min	
^{242}Es, EC-SF	5-25s	(1.4±0.8)% SF?	$T_{1/2}$, %SF:187
^{244}Es, EC-SF	37±4s	0.01% SF??	SF:185
^{246}Es, EC-SF	7.7±0.5 min	0.003% SF??	SF:185
^{248}Es, EC-SF	28±5 min??	3x10^{-5}% SF??	SF:185
^{253}Es	20.47±0.02 d	(6.3±0.2)x10^{5}yr	

[c]Possibly the same as ^{242f_2}Bk. See Ref 22.

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{254}Es, g	275.7±0.5 d	>2.5x10^{7}yr	
m	39.3±0.2 hr	>1x10^{5}yr	
^{255}Es	38.3±0.3 d	2600 yr	
^{257}Es	1-3s??	1-3s??	188
^{242}Fm	0.8±0.2 ms	0.8±0.2 ms	
^{243}Fm	$0.18^{+0.08}_{-0.04}$ s	≥50s	$T_{1/2}$:189;$T^{SF}_{1/2}$:190
^{244}Fm	3.3±0.5 ms	3.3±0.5 ms	
^{245}Fm	4.2±1.3 s	>4000 s	SF:190
^{246}Fm	1.2±0.2 s	15±6 s	
^{248}Fm	38±4 s	11±5 hr	
^{250}Fm, g	30±3 min	~10 yr	
m	1.8±0.1 s	>9 s	
^{252}Fm	25.39±0.04 hr	125±8 yr	$T_{1/2}$, $T^{SF}_{1/2}$:191
^{254}Fm	3.240±0.002 hr	229±1 d	
^{255}Fm	20.07±0.07 hr	$(1.0^{+0.6}_{-0.3})$x10^{4}yr	
^{256}Fm	2.627±0.021 hr	2.86±0.02 hr	
^{257}Fm	100.5±0.2 d	131±3 yr	
^{258}Fm	370±43 μs	370±43 μs	73a,b
^{259}Fm	1.6±0.1 s	1.6±0.1 s	25,192
^{248}Md	7±3s	≤0.05% SF	185
^{250}Md, EC-SF	52±6 s	0.02% SF??	185
^{255}Md	27±2 min	≥12.5 d	
^{256}Md	75±4 min	≥42 hr	
^{257}Md	5.0±0.3 hr	≥140 hr	
^{258}Md	55±4 d	≥1.5x10^{5}yr	$T_{1/2}$:193;$T^{SF}_{1/2}$:24
^{259}Md	103±12 min	103±12≤$T^{SF}_{1/2}$≤108±12 min	$T_{1/2}$:71;$T^{SF}_{1/2}$:68
^{260}Md	31.8±0.5 d	31.8≤$T^{SF}_{1/2}$≤35.3 d	24,70

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{250}No	0.25±0.05 ms??	0.25±0.05 ms??	
^{251}No	0.8±0.3 s	>10 s	SF:190
^{252}No	2.30±0.22 s	8.6±1.0 s	
^{254}No, g	55±5 s	~6 hr (1 hr≤$T^{SF}_{1/2}$≤∞)	$T^{SF}_{1/2}$:25,31-38. See section II
i	0.28±0.04 s	≥1.40±0.20 s	
^{256}No	3.2±0.2 s	18 min	
^{258}No	1.2±0.2 ms	1.2±0.2 ms	128
^{259}No	58±5 min	>9.7 hr	$T^{SF}_{1/2}$:71,128
^{260}No	106±8 ms??	106±8 ms??	24,25,74
^{252}Lr	If $T_{1/2}$>1 s, then	$T^{SF}_{1/2}$≥100 s	98,193-195
^{253}Lr	$1.3^{+0.6}_{-0.3}$ s	≥2.2 min	$T_{1/2}$:27;$T^{SF}_{1/2}$:98,194,195
^{254}Lr	$13\pm^{3}_{2}$ s	≥10^4s	$T_{1/2}$:27;$T^{SF}_{1/2}$:98,193-195
^{255}Lr	22±5 s	≥6 hr	SF:98,194,195
^{256}Lr	25.9±1.7 s	≥10^5s	SF:94a,b
^{257}Lr	0.646±0.025 s	≥10^5s	SF:94a,b
^{258}Lr	4.35±0.59 s	≥20s	SF:196
^{253}Rf	1.8 s??	3.6 s??	
^{254}Rf	0.5±0.2 ms?	0.5±0.2 ms?	
^{255}Rf	1.4±0.2 s	2.7±0.5 s	$T_{1/2}$, $T^{SF}_{1/2}$:41
^{256}Rf	6.7±0.2 ms[d]	$6.9^{+0.6}_{-0.2}$ ms	$T_{1/2}$:63; SF branch:41
^{257}Rf	4.76±0.53 s	200±25 s??	$T_{1/2}$, $T^{SF}_{1/2}$:85b,87,88
^{258}Rf	13±2 ms	13±2 ms≤$T^{SF}_{1/2}$≤15±2 ms	$T_{1/2}$:197,198;$T^{SF}_{1/2}$:101,19
^{259}Rf	3.0±1.3 s	48±35s??	89
^{260}Rf	21±1 ms??	21±1 ms??	25,49
^{261}Rf	65±10 s	≥650 s	
^{262}Rf	47±5 ms	47±5 ms	25

[d]7,440 SF events observed by Ogannessian et al.[63]

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{255}Ha	$1.6^{+0.6}_{-0.4}$ s??	>3 s	26,58
^{257}Ha	$1.4^{+0.6}_{-0.3}$ s	≥93 s	$T_{1/2}$:27;SF branch:26
^{258}Ha	$4.4^{+0.9}_{-0.6}$ s	$\geq 13^{+4}_{-3}$ s	$T_{1/2}$, $T^{SF}_{1/2}$:27,90a
^{260}Ha	1.52±0.13 s	15.8±1.7 s?	
^{261}Ha	1.8±0.6 s	"several times" 2 s[e] ≥3.6 s (Ref. 200)	
^{262}Ha	34.1±4.6 s	44±7 s≤$T^{SF}_{1/2}$≤49±8 s	$T_{1/2}$:93; $T^{SF}_{1/2}$:87,93
^{259}106	$0.48^{+0.28}_{-0.13}$ s	>2.4 s	$T_{1/2}$, $T^{SF}_{1/2}$:18
^{260}106	$3.6^{+0.9}_{-0.6}$ ms	$7.2^{+4.8}_{-2.7}$ ms	$T_{1/2}$, $T^{SF}_{1/2}$:18
^{261}106	$0.26^{+0.11}_{-0.06}$ s	>2.6 s	$T_{1/2}$, $T^{SF}_{1/2}$:18
^{263}106	0.9±0.2 s	1.3 s??	$T_{1/2}$:97;$T^{SF}_{1/2}$:96
^{261}107	$6.1^{+4.3}_{-1.8}$ ms[f]	$>20^{+14}_{-6}$ ms[f]	99

[e]Estimated from the ratio of the measured SF to calculated production cross sections quoted in Refs. 94a,b.

[f]Oganessian[31] at Dubna has reported production of a SF activity assigned to ^{261}107 (Refs. 91,98) with a half-life of 3 ms and a cross section of 20 picobarns in the reaction ^{208}Pb(^{55}Mn,2n)^{261}107. Comparing production cross section measurements for the same reaction of 20 picobarns by Oganessian et al. for SF and 100 picobarns by Münzenberg et al.[99] for α decay, and using the 6-ms half-life that Münzenberg et al. measured by α decay, the partial SF half-life would be 36^{+84}_{-11} ms, which is indeed larger than the lower limit of 20 ms derived above from Ref. 99.

Nuclide	$T_{1/2}$	$T^{SF}_{1/2}$ or % SF	References
^{262}107, g??	56^{+53}_{-18} ms	$>560^{+530}_{-180}$ ms	99
m??	$4.7^{+2.3}_{-1.6}$ ms	$>47^{+23}_{-16}$ ms	99
^{263}108	<1 s	"mainly α decay"	26,63
^{264}108	76^{+364}_{-36} μs	>5 ms[g] ≥1 ms[g]	$T_{1/2}$:19;$T^{SF}_{1/2}$:58,63
^{265}108	$1.8^{+2.2}_{-0.7}$ ms	≥20 ms	$T_{1/2}$:102;$T^{SF}_{1/2}$:199a
^{266}109	$3.5^{+16.6}_{-1.6}$ ms	≥62 ms[h]	$T_{1/2}$:58,103;$T^{SF}_{1/2}$:101,199b
$^{?}$110	$8.6^{+4.0}_{-2.4}$ ms??	$8.6^{+4.0}_{-2.4}$ ms??	37

[g]Armbruster[58] arrived at $T^{SF}_{1/2}$≥5 ms by examining Ref. 63 of Oganessian et al. The detection limit in Ref. 63 was for half-lives greater than 1 ms.

[h]Derived from the data in Refs. 101 and 199b.

Table 2: Techniques used to measure properties of short-lived SF emitters.

Techniques	Laboratories, properties measured (sample references)				
	Berkeley	Dubna	GSI	Livermore	Oak Ridge
Rotating wheel or drum	σ, $T_{1/2}$ (49,54)	σ, $T_{1/2}$ (40) collimation	--	σ, $T_{1/2}$ (49)	--
Rotating disc	--	σ, $T_{1/2}$ (190)	--	--	--
Rotating catcher foils	--	σ, $T_{1/2}$, TKE*, Mass dist., range discrim., collimation (53)	σ, $T_{1/2}$, range and ang. dist. (199c)	σ, $T_{1/2}$, TKE, Mass dist., range discrim., collimation (125)	--
Recoil tape transport	σ, $T_{1/2}$ (25)	σ, $T_{1/2}$, collimation (45,48)	--	σ, $T_{1/2}$ (25)	
Helium-jet transport, with or without aerosols	σ, $T_{1/2}$ (124,200)	--	σ, $T_{1/2}$ (201)	σ, $T_{1/2}$ (201)	σ, $T_{1/2}$ (89)
Thermochromatography or chromathermography	--	σ, $T_{1/2}$, Z (43,202,203)	--	--	
Recoil separator [name]	σ, $T_{1/2}$, evap. residue [SASSY] (77,78)	σ, $T_{1/2}$, evap. residue [VASILISA]**(80)	σ, $T_{1/2}$, evap. residue, K and L x rays, if EC → SF. [SHIP] (27,75,) [DQQ-spectrometer] (79)	--	--
Mass separation chemistry, SF + K x rays				Long $T^{SF}_{1/2}$ parent Short $T^{SF}_{1/2}$ daughter Z, A, σ, $T_{1/2}$ (24,73b)	--

* TKE=Total Kinetic Energy
** Under Construction

Table 3. Spontaneous Fission Properties of Some Trans-Bk Isotopes[a]

Nuclide	Peak-to-Valley Ratio[b]	$\overline{TKE}$[c] (MeV)	FWHM of TKE (MeV)	$\bar{\nu}_T$
^{250}Cf	⩾300 (RC)	187.0	27	3.49
^{252}Cf	⩾750 (RC)	186.5 (183.9)[d]	27	3.74
^{254}Cf	⩾265 (RC)	186.9	28	3.89
^{256}Cf	asym (SS)	189.8	34	-
^{253}Es	326 (RC)	191	31	-
^{244}Fm	asym (IC)	196	-	-
^{246}Fm	asym (SS)	199	35	-
^{248}Fm	asym (SS)	198	34	-
^{254}Fm	60 (RC)	195.1	27	3.96
^{256}Fm	12 (SS)	197.9	34	3.73
^{257}Fm	≈1.5 (SS)	197.6 {194[f], 227}	36	3.77
^{258}Fm	symm (SS),8	238*	≈ 35	-
		230.6[e] {204[f], 231}		
^{259}Fm	symm (SS),12	238*	≈ 37	-
^{259}Md	symm (SS),28	200.6[e] {201[f], 233}	≈ 60	2.6
^{260}Md	symm (SS),7.5	232.5[e] {195[f], 233}	≈ 35	-
^{252}No	asym (SS)	202.4	36	4.15
^{258}No	symm (SS)	203.2[e] {203[f], 233}	≈ 50	-
^{256}Rf	-	207±13	-	-
^{258}Rf	-	220±15	-	-
^{260}Rf	symm (SS),36	200.4[e]	44	-
^{262}Ha	asym(SS) or (if symm, 47)	-	-	-

[a]Data from refs. 24,27,41,71,123,125,128,144,146 and from compilations given in Refs. 120,124.

[b]Ratios derived from radiochemical (RC) data, or from ionization chamber (IC) or solid-state (SS) detector measurements of the kinetic energies of the fission fragments. For symmetric fission, values of the full-width-at-half maximum (FWHM) are given after the method.

[c]These are average values of the pre-neutron emission TKE's except for those designated by an asterisk(*), which are most probable pre-neutron emission values from a provisional mass analysis without corrections for neutron emission as a function of fragment mass.

[d]Solid-state measurements of TKE prior to about 1982 were usually normalized to a post-neutron emission average TKE ($\overline{TKE}$) value of 183.1 MeV (corresponding to a pre-neutron emission value of 186.5±1.2 MeV) for ^{252}Cf according to the method of Schmitt et al.[204,205] Measurements of TKE denoted by (e) have been normalized to the post-neutron value for ^{252}Cf of 181.0 MeV (corresponding to a pre-neutron value of about 183.9 MeV), recently redetermined by Weissenberger et al.[206] and are derived from a provisional mass analysis without corrections for neutron emission as a function of fragment mass. Henschel et al.[207] have also redetermined the TKE of a ^{252}Cf as 181.25±1.3 MeV and 184.07±1.3 MeV for the post- and pre-neutron emission values, respectively.

[f]Values in brackets are those of the two Guassian functions by which the TKE distributions could be represented as described earlier[125] and as determined[128] recently.

VIII. FIGURES

Figure 1. Comparison between the experimental half-lives and the partial half-lives calculated or estimated by Randrup et al.[3] for SF of even-even nuclei. A square for the possible assignment [24,25,62b] of 106-ms ^{260}No is connected to the square for 258No(1.2 ms) by a dot-dashed line. The squares for ^{260}106 ($T^{SF}_{1/2}$ = 7 ms, Ref. 18) and ^{264}108 ($T^{SF}_{1/2} \gtrsim 5$ ms, Refs. 58,63) are shown connected by a vertical dashed line and dashed curve, respectively, to the filled circles for the half-lives estimated by Randrup et al. In the case of ^{264}108 the lower limit of 5 ms on its partial SF half-life is shown as a diagonal-pointing arrow. The inset at the lower left shows a comparison between the calculated and experimental half-lives for fission isomers.

2. Shapes corresponding to various fission paths calculated by Möller et al.[10] for ^{258}Fm. Their results indicate that shapes along the upper path are not involved in the fission of ^{258}Fm. The lower path leads to compact scission shapes and high total kinetic energy fission. The shapes that break off from this path at about $r = 1.5R_0$ represent shapes along the "switchback" path, which leads back into the old valley, joining it at $r = 1.65\ R_0$. It is evolution along this switchback path that is supposed to lead to the low kinetic-energy symmetric fission component that is observed experimentally.

3. Odd nucleon SF hindrance factors for (a) odd-proton, even-neutron nuclei and (b) even-proton, odd-neutron nuclei. A filled circle indicates that the hindrance factors was calculated using the measured SF half-lives of a pair of neighboring even-even nuclei using either formula 1 or 2 in Section II. Open circles indicate that the hindrance factors were determined from a single neighboring even-even isotope.

4. Detector module for proposed Heavy Element Fission Tracker (HEFT) system. The four active regions are used to determine the position, velocity, rate of energy loss, and total kinetic energy for fission fragments.[114]

5. Schematic representation of mass-yield distributions (normalized to 200% fission fragment yield) for SF of trans-Bk isotopes. Data from refs. 24, 71, 124, 125, 128 and compilations in refs. 1 and 2.

6. TKE distributions for SF of trans-Es isotopes. Data from refs. 68, 124-126, and 128.

7. Experimental values of $\bar{\nu}_T$ as a function of A of the compound nucleus. Measurements for $\bar{\nu}_T$ for thermal neutron-induced fission have been corrected to zero excitation energy using $d\bar{\nu}_T/dE_x = 0.11$ MeV^{-1}. (Figure from ref. 124.)

8. Contour plots of TKE vs. mass fraction for ^{254}Cf, ^{256}Fm, ^{257}Fm are lines of equal numbers of events based on groupings 5 MeV x 0.01 units of mass fraction. The relative intensities range from 1 to 9. The contours for ^{259}Fm are based on groupings of 10 MeV x 0.02 units of mass fraction. The relative intensities range from 1 to 6. Data are from refs. 2 and 192.

9. The anisotropy versus gamma-ray energy for gamma-rays emitted in the SF of ^{252}Cf. In these measurements[153] by Skarsvåg both a Pt backing foil (open circles) and a Ni backing foil (filled circles) for ^{252}Cf sources have been used.

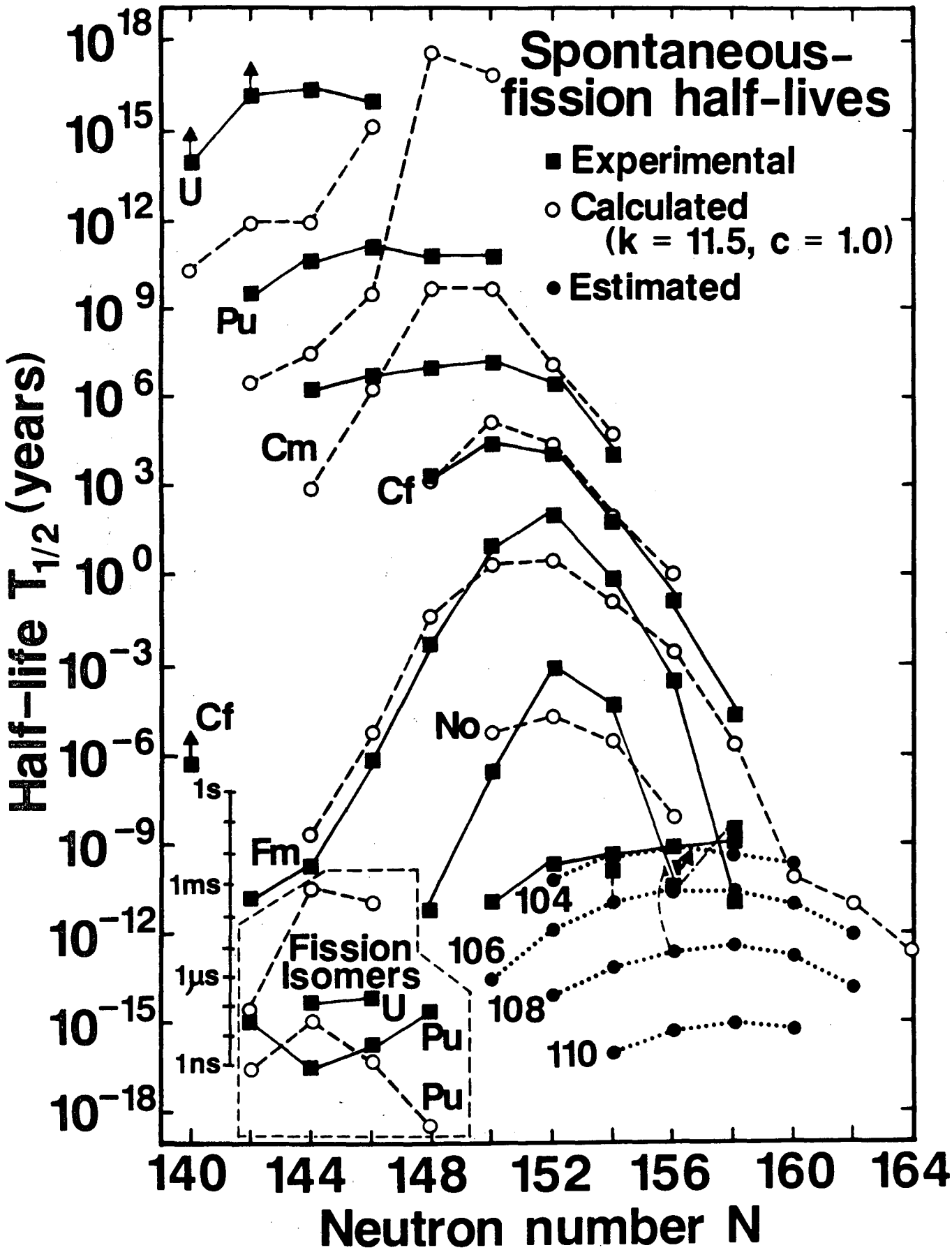

Spontaneous-fission half-lives
Experimental
Calculated (k = 11.5, c = 1.0)
Estimated
Half-life $T_{1/2}$ (years)
Neutron number N
U
Pu
Cm
Cf
No
Fm
104
106
108
110
Fission Isomers
1s
1ms
1μs
1ns

Fig. 1

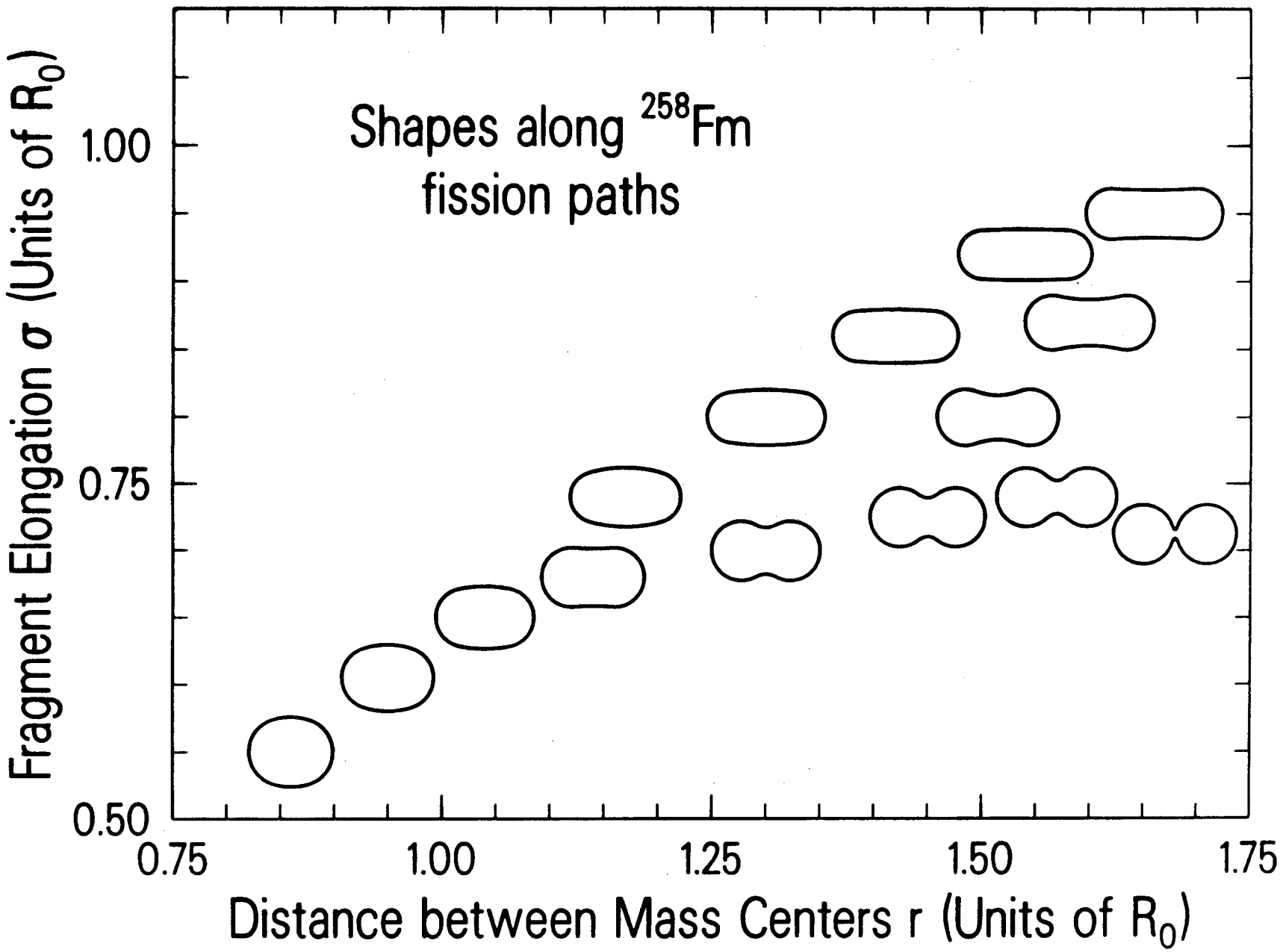

Shapes along ^{258}Fm
fission paths
Fragment Elongation σ (Units of R_0)
1.00
0.75
0.50
0.75
1.00
1.25
1.50
1.75
Distance between Mass Centers r (Units of R_0)

Fig. 2

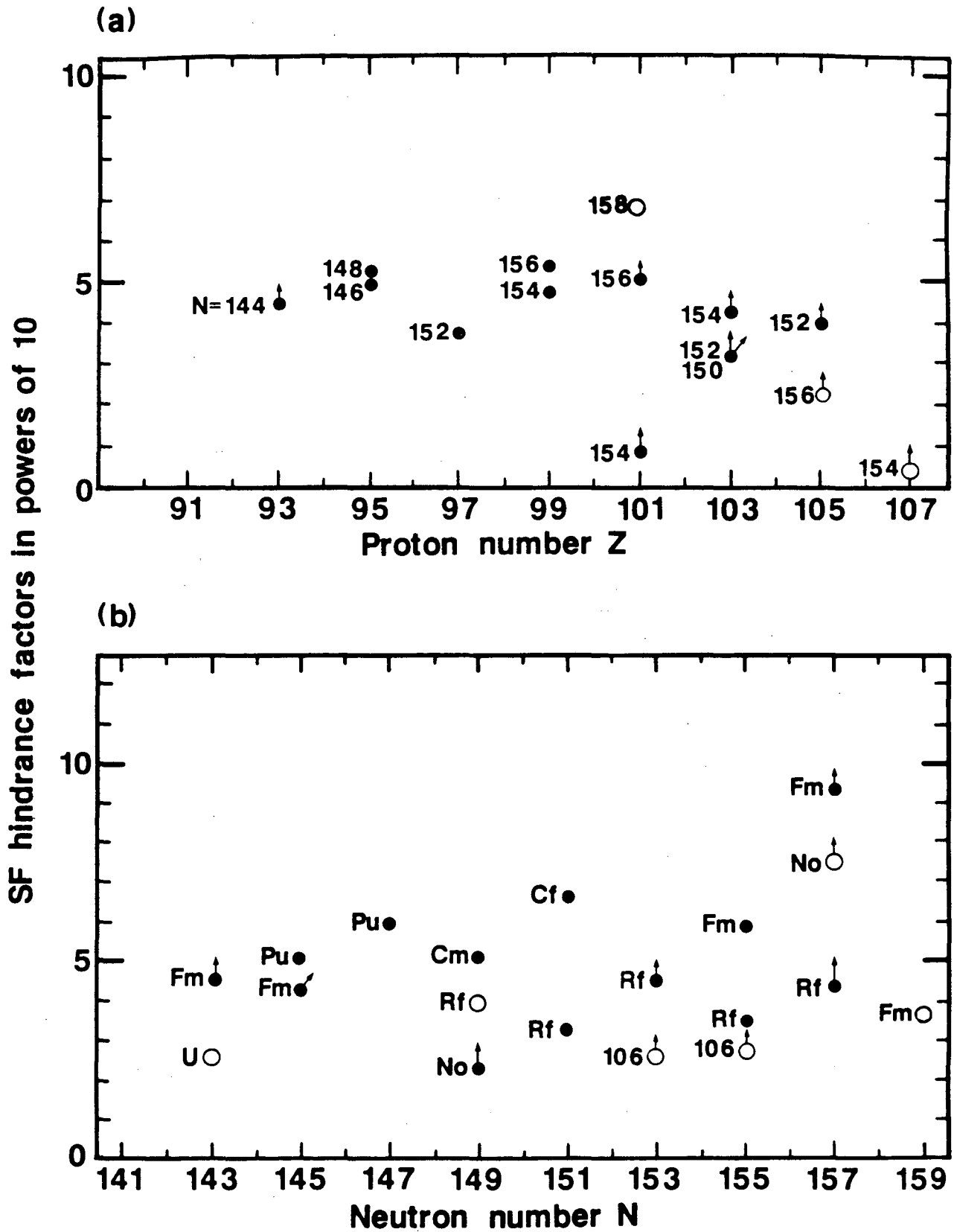

(a)
SF hindrance factors in powers of 10
Proton number Z
N=144
148
146
152
156
154
158
156
154
154
152
152
150
156
154
(b)
Neutron number N
Fm
U
Pu
Fm
Pu
Cm
Rf
No
Cf
Rf
106
Fm
Rf
106
Fm
No
Rf
Fm

Fig. 3

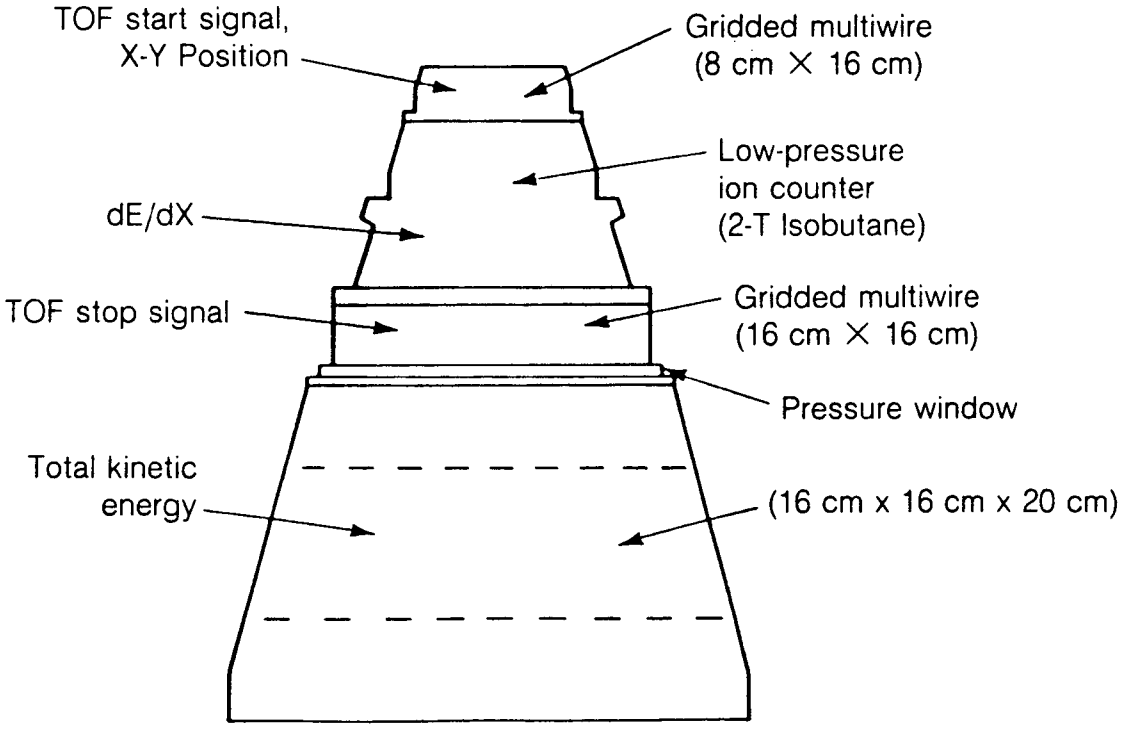


Fig. 4

XBL 8512-5152A

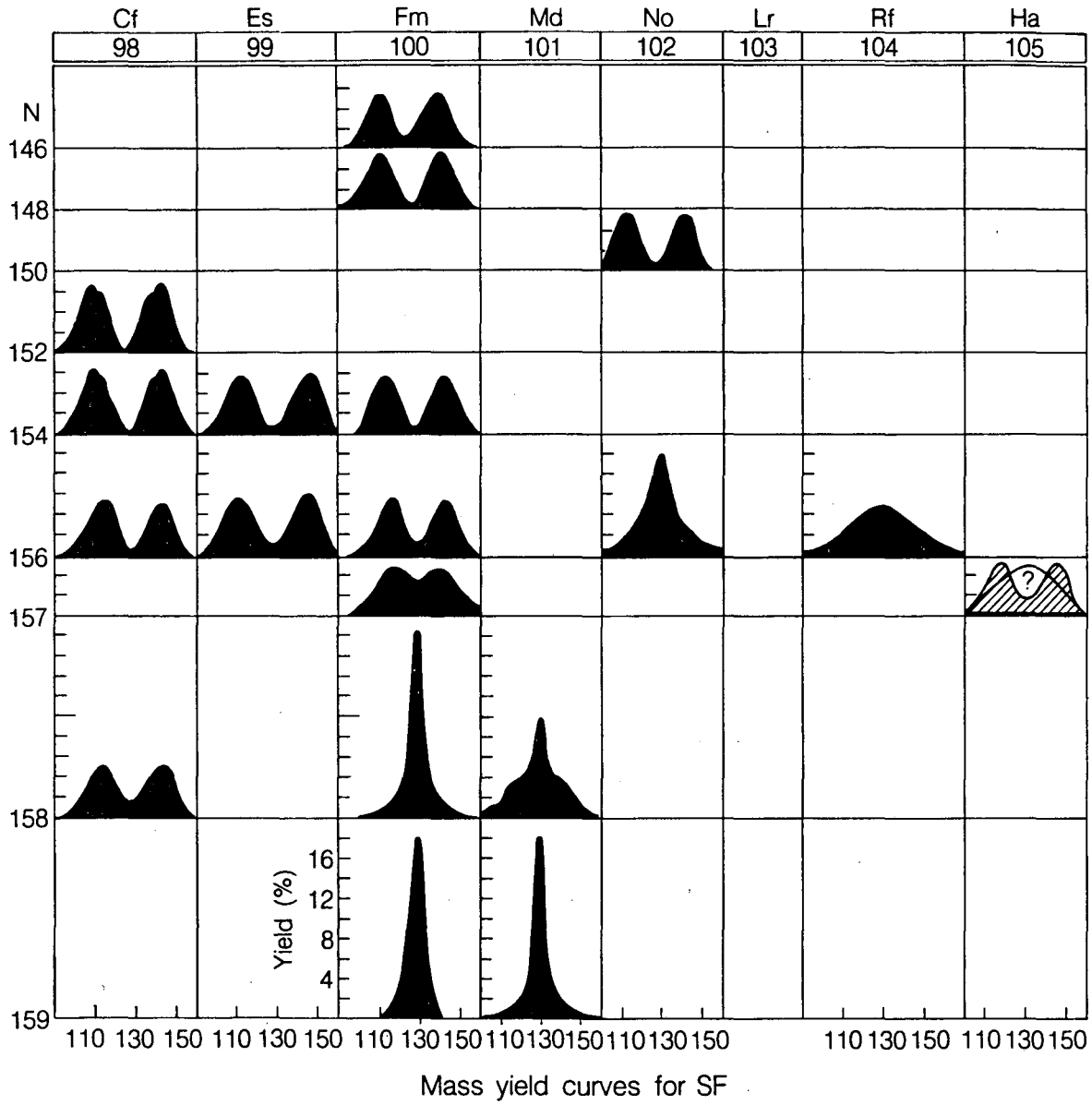
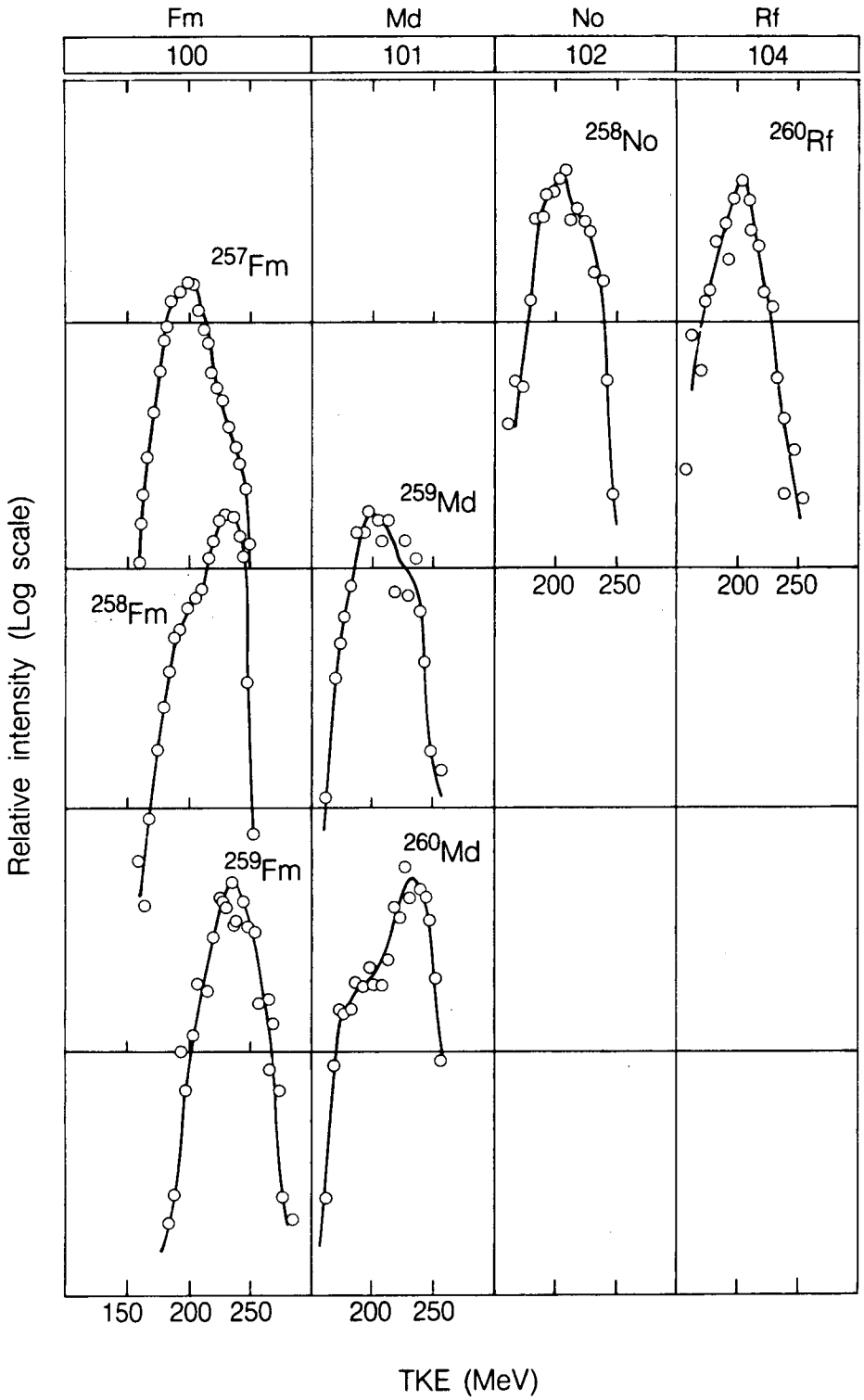


Fig. 5

XBL 871-9531



XBL 871-9532

Fig. 6

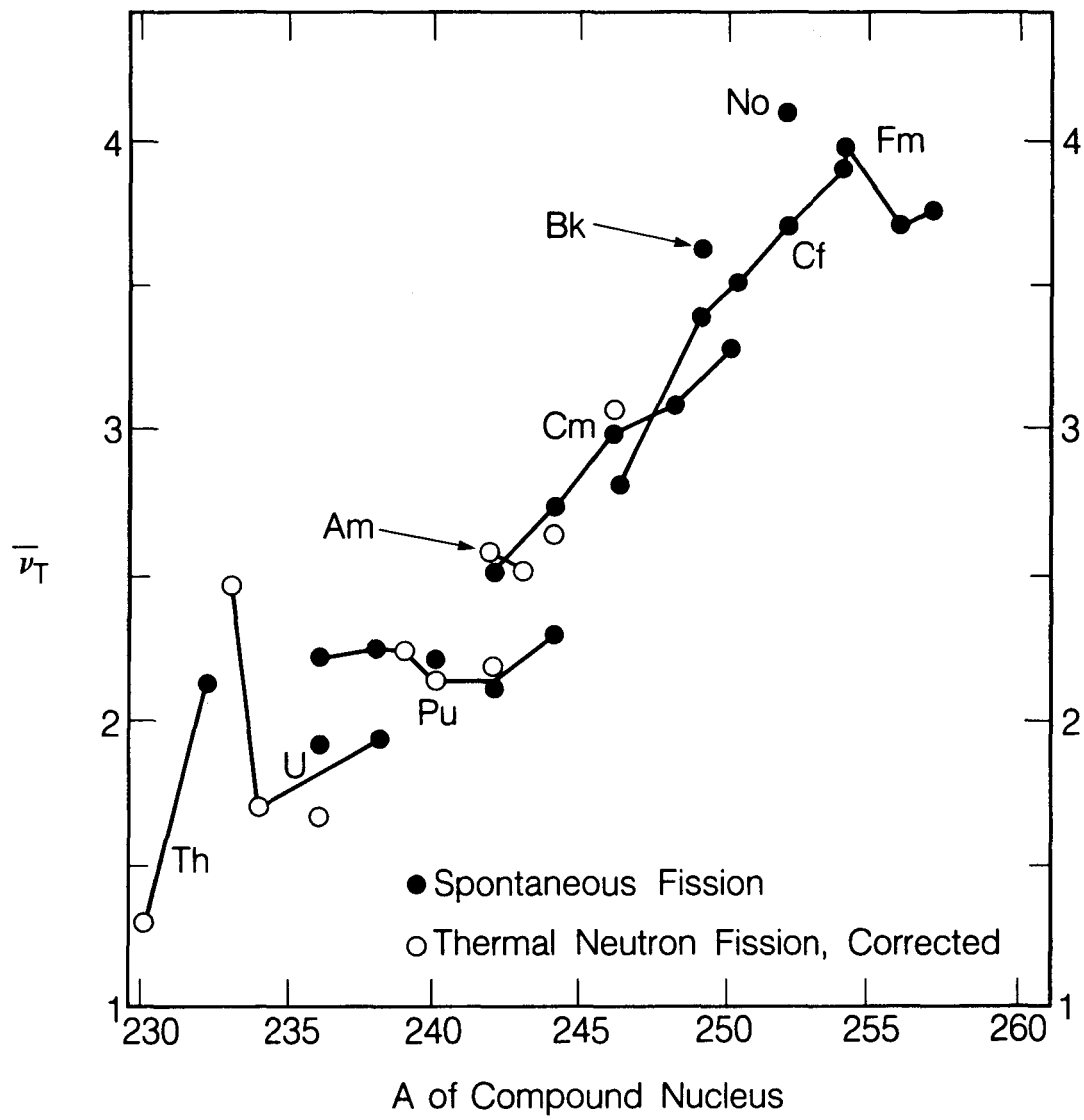

No
Fm
Bk
Cf
Cm
Am
Pu
U
Th
● Spontaneous Fission
○ Thermal Neutron Fission, Corrected
$\overline{\nu}_T$
1
2
3
4
230
235
240
245
250
255
260
A of Compound Nucleus

Fig. 7

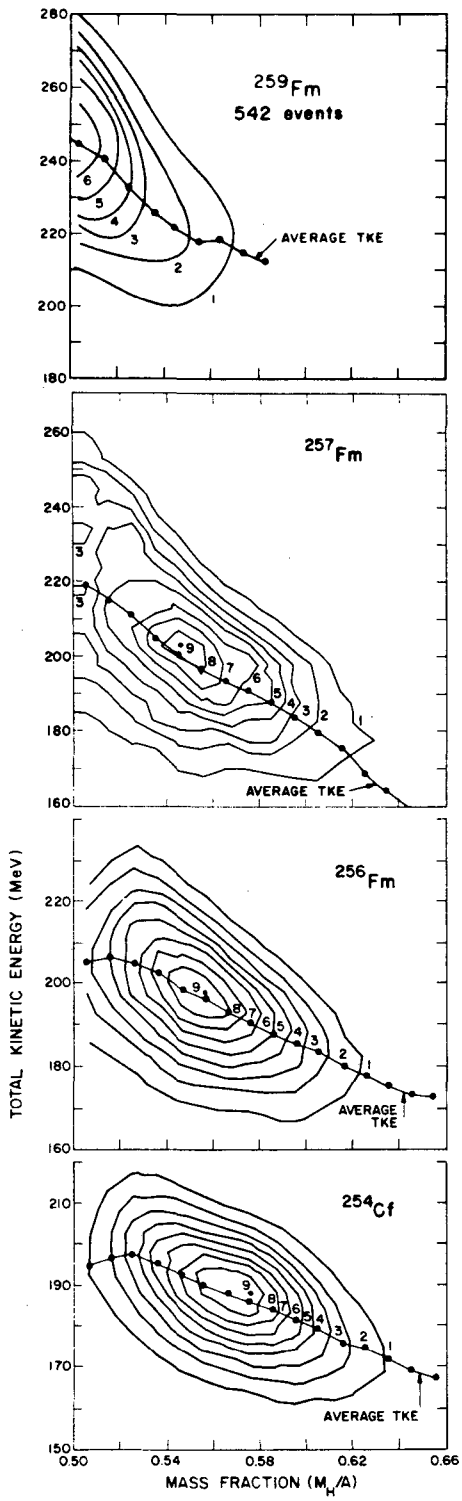

259Fm
542 events
AVERAGE TKE
257Fm
AVERAGE TKE
256Fm
AVERAGE TKE
254Cf
AVERAGE TKE
TOTAL KINETIC ENERGY (MeV)
MASS FRACTION (M_H/A)
XBL 871-303

Fig. 8

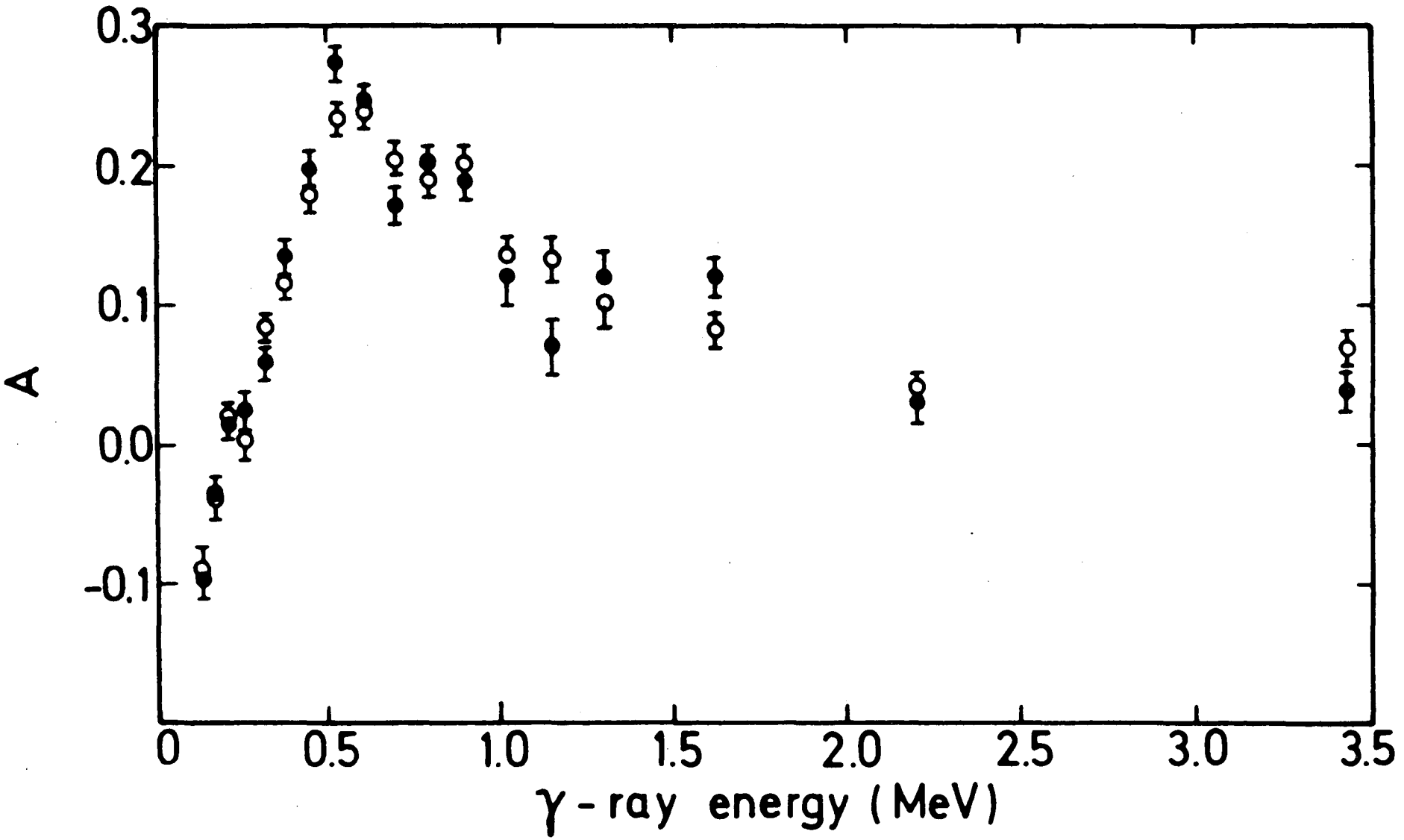


Fig. 9

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