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I. INTRODUCTION

Spontaneous fission (SF) has been found only in elements with Z≥90 where Coulomb forces make the nucleus unstable toward this mode of decay. Although SF was discovered in 1940 as a natural mode of decay ^{238}U with a partial SF half-life of nearly 10^{16} years, detailed studies of SF properties were not conducted until higher Z elements with shorter SF half-lives were synthesized. The availability of ^{252}Cf, which has a high specific activity and became available in milligram quantitites during the 1960's, stimulated numerous detailed measurements of the mass, charge, and kinetic energies of the fission fragments, and of prompt neutron and photon emission from the excited fragments. Such studies have been extended to numerous isotopes of still heavier elements as they have been synthesized at accelerators and techniques have been developed for measuring ever shorter half-lives.

Since the comprehensive Hoffman and Somerville review[1] of experimentally determined spontaneous fission properties published in 1989 (literature through mid-1986 considered), major conferences have been held at Berlin and Washington, D. C. in 1989 to commemorate the 50th anniversary of the discovery of nuclear fission. Many review papers and much new information concerning spontaneous fission were presented and are given in the proceedings of those conferences[2,3]. The intent of the present review is to update the information of Hoffman and Somerville[1] (H&S) on spontaneous fission (SF) half-lives, fission fragment kinetic-energy, mass and charge distributions, neutron and photon emission at scission or from the excited fragments, and new theoretical developments. Discussions of fission isomers by D. N. Poenaru[4], particle-accompanied fission by J. P. Theobald, N. Carjan, and M. Mutterer[5], and beta-delayed emissions by B. Jonson and G. Nyman[6], are given elsewhere in this Handbook, and will not be covered in this chapter.

In the current article new experimental results on SF phenomena are reviewed. The relevant published literature through mid-1992 has been considered.

II. HALF-LIVES

A. Introduction

Table 1A is a revised and updated version of Table 1 from H&S[1]. More recent reviews[30-32] of SF partial half-lives have also been published, but no complete tabulation of new or revised SF half- lives or branching ratios together with the overall half-lives has been published since the H&S review. Table 1A lists values for *all* of the half-lives and partial SF half-lives and/or SF branches which have been assigned to specific nuclides as of mid-1992. References are given only for those entries which are new or revised since the H&S review. In contrast to that review, the half-lives of fission isomers are not included because they are given by D. N. Poenaru[4] in this Handbook; SF decay from ordinary electromagnetic isomers, designated by (m) is still included. Half-lives or limits for electron-capture and beta$^{\pm}$-delayed fission have been removed and collected separately in Table 1B. (For additional information on delayed fission, see the review of delayed fission recently completed by Hall and Hoffman.[46]) If no other decay mode except SF is known, the partial SF half-life and its uncertainty are assumed to be the same as the half-life and its uncertainty. Unless another reference is indicated, the overall half-lives for decay of these nuclides are taken from J. K. Tuli,[7] *Table of Nuclides*, given in this Handbook. The total number of SF activities reported in Table 1A is still about 120; 70 of these are revised or new values.

B. Nuclides with Even Proton and Even Neutron Numbers

The partial SF half-lives of even-even (e-e) nuclei in their ground states are plotted vs. neutron number in Fig. 1A and a comparison with theory is shown in Fig. 1B. Although the half-lives generally decrease with increasing atomic number, Z, there is an overlapping of half-life values so that it is very difficult to identify a new SF activity based on half-life alone. The extra stability observed for N=152 beginning around curium (96) extends through nobelium (102), but seems to have been "washed out" for elements heavier than rutherfordium (104). This change has been discussed in detail in Refs. 1, 30-32 and has been attributed not only to destabilization of the N=152 subshell, but to the lowering of the energy of the second barrier to fission (see Poenaru[4]) below the ground-state energy. Because of the extreme sensitivity to details of the height and shape of the fission barrier (barriers), calculation of SF half-lives is extremely difficult. Furthermore, the barriers may be dependent on the exact route in the potential energy surface which the nucleus follows en route to fission. Shell effects are of prime importance in stabilization of the heavy element isotopes toward decay by SF and must be included in any realistic calculation of half-lives.

C. Nuclides with Odd-Proton and/or Odd-Neutron Numbers

In recent reviews[30,31] of SF half-life data and systematics, it was pointed out that hindrance factors have long been known to be associated with the SF decay of nuclides having an odd number of protons or neutrons compared to those of their e-e neighbors. This makes the theoretical calculations of these half-lives even more difficult than for the e-e nuclei and requires calculation of the hindrance due to the specialization energy arising from the conservation of spin and parity of the odd particles during fission. The experimentally observed hindrance factors (HF) for the SF decay of odd proton or neutron nuclides are calculated relative to the SF half-lives of their adjacent even-even (e-e) neighbors as follows:

For odd Z and even N, o-e, (odd A):

$$HF = T_{1/2}(^{A}Z)/[T_{1/2}(^{A-1}Z\text{-}1) x T_{1/2}(^{A+1}Z\text{+}1)]^{1/2}.$$

Similarly, for even Z and odd N, e-o, (odd A):

$$HF = T_{1/2}(^{A}Z)/[T_{1/2}(^{A-1}Z) x T_{1/2}(^{A+1}Z)]^{1/2}.$$

The logarithms of the hindrance factors calculated for the known SF partial half-lives of o-e and e-o isotopes are plotted in Fig. 2 as a function of odd Z and odd N. New values (not just lower limits) for proton hindrance factors for ^{259}Lr, ^{261}Lr, and ^{263}Ha (N=156 and 158) have been obtained since the 1989 reviews and seem to be consistent with the previously measured values for Z=103 and 105. They actually seem to show that the HF's are larger than the earlier limit values. In general, the logs of the HF's for actual measurements (not just limit values) are about 5 for both odd protons and neutrons, but for some of the high spin states such as N=157 [9/2+(615)] and Z=101 [7/2- (514)], the HF's are much larger.

It has been postulated that the HF's for o-o nuclei are the product of the odd proton and odd neutron HF's which would result in log HF's of the order of 10, if the log HF's average about 5. Now that a revised lower limit for the partial SF half-life for the o-o nuclide ^{258}Md and new values for ^{258}Lr, ^{262}Lr, ^{262}Ha, ^{262}107, and ^{266}109 have been obtained, they can be compared with this estimate. The ^{258}Md shows hindrances of $\geq 1.5 \times 10^7$ relative to its e-e neighbors ^{256}Fm and ^{258}No. ^{258}Lr (>78 sec) shows HF's of $>8 \times 10^4$ and $>5 \times 10^3$ relative to its e-e neighbors ^{256}No and ^{258}Rf. No hindrance can be calculated relative to its e-e neighbor ^{256}No whose SF partial half-life of 550 sec is actually longer than the lower limit value of >78 sec for ^{258}Lr. The unusual stability of the e-e isotope ^{256}No can be attributed to the stabilizing influence of the N=152 subshell which has disappeared by Z=104 (see Fig. 1) and may actually no longer be a stabilizing influence in Lr (Z=103) either.

Lougheed et al.[17] have calculated the HF for the o-o nuclides ^{260}Md as 9×10^9 (log HF=10) from their estimates of a hindrance of 3.6×10^6 (log HF=6.6) for the odd proton (101) in ^{259}Md and 2.4×10^3 (log HF=3.4) for the odd neutron (159) based on the hindrance from ^{259}Fm. They propose assignments of $7/2^-$ [514] for the 101st proton in ^{260}Md and ^{259} and $3/2^+$[622] for the 159th neutron in both ^{259}Fm and ^{260}Md. These are very close to the values given by Hoffman[30] and in Fig. 2 for Z=101 and N=159, respectively. The lower log HF of 3.4 for the 159th neutron, $3/2^+$[622], is consistent with the hypothesis that there is less hindrance associated with the lower spin states. However, ^{262}Ha (102 sec) exhibits HF's of only (2-5) X 10^3 relative to ^{260}104 and ^{262}104, whereas based on a log HF of about 3 for the 105th proton (see Fig. 2) and >4 to 7.4 for the 157th neutron in Rf, No, and Fm, a log HF of 7 or more might have been expected.

III. PROPERTIES OF THE FISSION FRAGMENTS

A. Introduction

A knowledge of the masses, atomic numbers, kinetic energies, and deformation energies of the individual fragments at scission, as well as their deexcitation modes, is necessary for understanding the SF process itself. An early comprehensive review of these properties for SF and low-energy fission was made in 1974 by Hoffman and Hoffman.[48] The book on nuclear fission by Vandenbosch and Huizenga[49] and a recent review of the nuclear fission process[31] contain more detailed information on the nuclear fission process in general. Recent reviews of SF[30,32,50] have tended to concentrate on the SF properties of the heavier isotopes because of the interest in the dramatic change in properties which occurs in the region of the heavy Fm isotopes. There are other reviews of specific properties such as neutron emission or kinetic-energy distributions, but they usually include other types of fission as well. The SF process is unique in that no energy is put into the nucleus before fission occurs which makes it much more sensitive than induced fission to the effects of relatively small changes in the nuclear structure and shell effects in both the fissioning nucleus and the resulting fragments. The total energy released in binary fission, E_f, is simply the energy equivalent (or Q-value) of the difference in mass of the fissioning nucleus and the masses of the two resulting fission fragments. There is, of course, a wide distribution of Q-values for SF of a given nuclide because of the multitude of different mass and charge divisions which are possible. The energy of fission is divided between the kinetic energy, E_k, and the excitation or deformation energy, E_x, of the two resulting fission fragments. This fragment excitation energy can be subsequently dissipated by prompt neutron or photon emission. From measurements of the kinetic energies, masses, and atomic numbers of the primary fragments, the excitation energy of the fragments can be deduced. E_x can also be inferred from measurements of the total numbers and energy distributions of both the prompt neutrons and gamma-rays emitted from the fragments, but these are generally not available for the heaviest isotopes which have small production cross sections and short half-lives. Average or most probable values derived from the distributions for all of these quantities are usually tabulated. As the total kinetic energy (TKE) of the primary fragments approaches the Q-value for the reaction, there can be very little excitation (or deformation) energy in the fragments and consequently fewer neutrons or photons can be emitted.

B. Fragment Mass, Atomic Number, and Kinetic-Energy Distributions

Information concerning fragment mass, atomic number or "charge" and kinetic-energy distributions can be obtained from time-of-flight, kinetic-energy, and radiochemical measurements. Much detailed information for the lighter nuclides and ^{252}Cf has been obtained via all of these methods. However, for the trans-Cf isotopes, most of the information about mass and kinetic-energy distributions has been derived from measurements of the kinetic energies of coincident fission fragments, usually with solid-state (SS) detectors, although a few radiochemical measurements of mass distributions after neutron emission have been made. Although the mass resolution for SS detectors does not approach that obtained from the other types of measurements and requires that the mass of the fissioning nucleus be known or assumed, it does allow determination of the most probable values of the mass and total fragment kinetic-energy distributions.

Fission is often characterized according to the fission fragment mass yield plotted as a function of fragment mass as being "symmetric" or "asymmetric". Fission into two nearly equal-mass fragments is called symmetric while fission into two unequal mass fragments giving a bimodal distribution is called asymmetric. A distribution of different mass splits around the most probable one has been found for all cases studied so far, but the widths of the mass peaks can vary widely. A schematic representation of mass-yield distributions (all normalized to fragment yield of 200%) for the SF of some heavy trans-Bk isotopes is given in Fig. 3. Distributions for ^{256}No, ^{262}No, ^{260}Rf, and the odd-Z isotope, ^{259}Lr have been added since the H&S review. The distribution for ^{262}Ha has not been included since it is still not certain whether its mass division is asymmetric or broadly symmetric. Most of these distributions have been derived from SS measurements of the kinetic-energies of coincident fragments. From such data, the masses are obtained via the conservation of momentum relationship, $M_1V_1 = M_2V_2$, by assuming the mass of the fissioning nucleus and a prompt neutron emission distribution for the fragments. Caution should be excercised in comparing these with radiochemical measurements because of the difference in mass resolution. Although the radiochemical measurements have "perfect" A and Z resolution because specific isotopes are identified, the information is for the fragments after prompt neutron and gamma-ray emission and often after beta decay and delayed neutron emission as well, depending on the time of the radiochemical separation.

The peak-to-valley ratios for the mass distributions, the average or most probable TKE's for the TKE distributions and their full-widths at half maximum (FWHM) which are known for the spontaneously fissioning isotopes are given in Table 2. FWHM's for symmetric mass division and the method used for determining the mass distributions are indicated. There are entries from ^{238}U through Ha (element 105) although for many SF isotopes the information is incomplete and for many others only the half-lives are known.

Prior to 1971 it was commonly believed that all SF resulted in asymmetric division, but with the discovery[69] of enhanced yields for symmetric mass division of ^{257}Fm, there was a renaissance of interest in SF of the heaviest isotopes and the unexpected and abrupt change in properties shown in Fig. 3 for the Fm isotopes with increasing mass was found. Measurements for still higher Z isotopes also showed symmetric mass division, but some had rather large FWHM's. Measurements for four No isotopes have now been made and they exhibit a similar trend toward symmetry with increasing mass although ^{262}No does not appear to have quite as narrow a distribution as ^{258,259}Fm.

The TKE distributions also showed unexpected changes and Fig. 4 shows a plot of the average or most probable TKE's for SF as a function of $Z^2/A^{1/3}$. Anomalously high values which approach the fission Q-values are observed for ^{258}Fm, ^{259}Fm, and ^{259}Md. The very high TKE's and the narrowly symmetric mass distributions observed for these isotopes have been explained on the basis of symmetric division into two fragments with configurations close to doubly magic, spherical ^{132}Sn. Coulomb repulsion would be near maximum for touching spheres, leading to much higher TKE's than "normal".

Schematic TKE distributions for some trans-Es isotopes are given in Fig. 5 taken from H&S. Careful measurements by Hulet et al.[21] of the TKE distributions for ^{258}Fm, ^{259}Md, ^{260}Md, ^{258}No, and ^{260}104 show evidence for "skewed" distributions which can be decomposed into two Gaussian distributions of varying intensities centered near 200 and 235 MeV. (See Table 2.) They called this "bimodal" symmetric fission, postulating that one symmetric mode leads to nearly spherical fragments with anomalously high TKE due to the higher Coulomb repulsion and the other to elongated fragments with lower TKE. The recently measured TKE distribution for ^{262}No has been similarly resolved[22,23] into two Gaussians. The early data for the "transition" nucleus ^{257}Fm which give a most probable TKE of about 200 MeV also show a bump on the high-energy side. The range of TKE's for symmetric mass division of ^{257}Fm is extremely large, and may indicate shapes ranging from nearly spherical with TKE's approaching the Q value to deformed shapes with low TKE, and perhaps combinations of spherical and elongated shapes, which might be dubbed multi-modal. However, the TKE distributions for ^{259}Fm (240 MeV), ^{260}104 (200 MeV), and recent measurements[20,25] for ^{256}No and ^{259}Lr (214 MeV) do not appear to show more than one component.

Essentially no information on atomic number (nuclear charge) division exists for SF except for ^{252}Cf. A recent comprehensive review by A. C. Wahl[77] gives an evaluation of data concerning nuclear-charge distribution for SF of ^{252}Cf and thermal neutron-induced fission of ^{235}U, ^{233}U, and ^{239}Pu. He derives parameters for empirical models which describe charge dispersion for constant mass number and mass number dispersion for constant atomic number. Evaluated experimental independent yields supplemented by values from the models are used to obtain recommended independent yields. The element yields as a function of atomic number which he has obtained for ^{252}Cf (SF) are given in Fig. 6. He notes that the large increase in yield between Z=49 and Z=50 indicates that there is a preference for formation of nuclides with Z=50 due to the stability of the 50-proton shell, although the maximum yields occur at higher Z values of 52, 54, 56 and at the 82 neutron shell and above.

C. Prompt Neutron Emission

1. Average neutron emission and neutron multiplicity distributions.

For most spontaneously fissioning nuclei, only the average number of prompt neutrons emitted per fission, $\bar{\nu}_T$, is known, rather than the average number of neutrons emitted as a function of fragment mass. In some cases, the neutron multiplicity distributions are also known and it was early shown that these "multiplicity" distributions could be fit by a Gaussian distribution[55] with a variance, σ_ν^2, = 1.17 for the thermal neutron-induced fission[50] of ^{235}U. As measurements were made for SF of ^{252}Cf and other heavy actinide isotopes, larger values of the variance were measured, reaching a value of about 4 for ^{252}No. Table 3 lists the $\bar{\nu}_T$'s for SF, together with the variances for their neutron distributions, if known. These values of $\bar{\nu}_T$ are also plotted in Fig. 7 as a function of the A of the fissioning nucleus. In general, they increase with the Z of the fissioning nuclide, and for trans-Pu nuclides, they increase with mass for a given Z. At Fm this trend is reversed and the average neutron emission is actually lower for ^{256}Fm and ^{257}Fm than for ^{254}Fm. For ^{260}Md, the value is only 2.57 compared to about 3.8 for ^{257}Fm, as might be expected because of its bimodal TKE distribution which has a much more abundant high energy mode than does ^{257}Fm (see Table 2). Thus, there is less excitation energy available in the fragments for neutron emission. Similar arguments can be made that other nuclides which show large variances in the neutron multiplicity distributions should also show large FWHM's (or variances) in the TKE distributions. However, caution must be excercised in comparing the TKE distributions because of the potential differences in the energy resolution of different systems and the observation that many of these cannot be fit by a single Gaussian component.

For a more detailed discussion of neutron multiplicities measured as a function of mass and TKE for SF of some Cf and Fm isotopes, contour plots of TKE as a function of mass fraction and the implications for neutron emission, see H&S, pp. 22-27. No additional new data have been reported except for ^{252}Cf.

2. Neutron emission as a function of fragment mass.

As discussed earlier, a knowledge of prompt neutron emission as a function of fragment mass 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. However, very little information of this type exists except for SF of ^{252}Cf. From an evaluation of the experimental data obtained from a variety of methods for the average number of neutrons emitted by the fragments from ^{252}Cf and thermal neutron-induced fission of ^{233}U, ^{235}U, and ^{239}Pu, Wahl[77] has derived a $\bar{\nu}_A$ function which gives reasonable agreement with the experimental values. He plots the average number of prompt neutrons ($\bar{\nu}_f$) emitted by fission fragments with mass number A_f before prompt-neutron emission vs. $A=A_f-\nu_f$, the average fragment mass number after prompt-neutron emission. (See Fig. 8.) These typical "saw-tooth" functions can be related to variation with mass number of the the fission-fragment excitation energy which is related to fragment deformation at scission.

The existence of even-odd proton effects on the ν(A) distribution for ^{252}Cf with excitation energy has been reinvestigated[92] and observed to increase as fragment excitation energy decreases. Recent measurements for ^{252}Cf of neutron multiplicity distributions from the individual fission fragments[93], and of the numbers of neutrons[94] emitted as a function of the mass and TKE of the fragments, have provided information on properties of the fragments immediately after separation and on the process of deexcitation of the excited fragments, and the distribution of excitation energy between the fragments. Measurements[95] of the correlations between neutron emission, and fragment angle, mass, and kinetic energy have shown isotropic neutron emission in the c.m. system over the whole fission neutron energy range, permitting the conclusion that fission neutron are emitted from the fully accelerated fragments and that the scission neutron component is much smaller than the previously assumed 15-20%. (Other studies[96,97] of the anisotropy of prompt neutron emission put limits of only 3 to 5% for the contributions of scission neutrons.) The mass range for ν(A) was extended beyond previous measurements and revealed two new "sawteeth" near masses 80 and 176. The measured fission neutron spectra allowed evaluation of the average neutron energy and the nuclear temperature.

3. Neutron-energy spectrum

Numerous additional measurements[98-101] of the neutron-energy spectrum for ^{252}Cf have been reported recently. Although the spectrum is reasonably well represented[98] over a wide energy range (0.124 to 15.0 MeV) by a Maxwellian distribution with T=1.42 MeV, some deviations have been observed. The negative deviation observed above 5 MeV has been described by a complex statistical model approach[99]. A comparison in Ref. 100 of all measured neutron energy distributions showed deviations of up to 15% from the Maxwellian distribution while a cascade evaporation model calculation gave reasonable agreement. Recent calculations[102,103] of the prompt fission neutron spectrum have been presented, and Madland[104] has given a review of the theory of neutron emission in fission.

D. Prompt Gamma-Ray Emission

As discussed earlier, the excitation energy of the fission fragments can be dissipated by emission of gamma-rays as well as neutrons. However, the gamma rays emitted in fission have been less well investigated; most studies have been of ^{252}Cf but the SF of ^{238}U, ^{240}Pu, and ^{244}Cm have also been investigated. Gamma-ray multiplicity, energy, and anisotropy were discussed rather thoroughly in H&S. Measurements up to then showed that about 80% of the gamma rays are emitted within 10^{-10} sec after fission and 11% of those from ^{252}Cf are emitted within 10^{-13} sec after fission. A significant fraction are emitted with a mean lifetime of 10^{-14} sec which suggests that a competition between neutron and gamma emission may exist. Gamma-ray multiplicity measurements for ^{252}Cf were found to follow a double-Poisson dstribution with a mean of about 10 gamma rays per SF. The total gamma-ray energy per SF of ^{252}Cf was found to be 6.7 to 9 MeV, in agreement with calculations from both the statistical model for gamma rays in competition with neutrons and with a liquid-drop model. No satisfactory model had been found to fit the higher energy region (4 to 16 MeV) of the gamma-energy spectrum. Investigations of the anisotropy of gamma emission indicated that the excess emission along the fission axis is caused by large fragment spins aligned perpendicular to the fission axis. The statistical model for evaporation of neutrons in competition with emission of gamma rays was found to agree with most experimental results except for the observation of high-energy neutrons and the gamma spectrum between 4 and 16 MeV for SF of ^{238}U and ^{252}Cf.

New information[105-110] reported since mid-1986 deals entirely with ^{252}Cf. Glässel et al.[105] measured gamma-ray energies and multiplicities and neutron multiplicities together with the mass and kinetic energy of the fission fragments at the Heidelberg-Darmstadt Crystal Ball with high efficiency. The neutron multiplicity for selected mass bins as a function of TKE is quite linear, but the slopes show a definite mass dependence. They found the total gamma-multiplicity for both fragments to vary by only about 10%, with lower multiplicity for symmetric and very asymmetric mass splits. Most of this variation was due to energies below 0.8 MeV. Their unfolded data for the gamma yield of individual fragments exhibited a rather flat behavior, unlike earlier measurements which resemble the neutron "sawtooth" function. They believe the earlier data were incorrect because the accuracy of the absolute mass scale was inadequate. They also found a high-energy component in the gamma spectra in the vicinity of symmetric fission. They investigated the competition of neutron and gamma emission in the life-time ranges of 10^{-13} to 10^{-14} sec and a rather linear, negative correlation with a decrease of 0.02 emitted neutrons per total gamma multiplicity for both fragments, independent of the excitation energy range. This gives the first evidence of neutron-gamma competition in the last steps of deexcitation. Varma et al.[106] measured the mean and standard deviation of the prompt gamma-ray multiplicity distribution as a function of the charge ratio of the fission fragment pairs. Their results show a small odd-even effect (larger values for even Z) as a function of the fragment charge ratio while the results of Glässel et al.[105] for the mean multiplicity as a function of the mass of the emitting fragments is nearly structureless. Varma et al. [106] determined an average spin per fragment of 6.5 to 9 h and a standard deviation of the spin distribution of each fragment in the range of 4 to 7 h from an analysis of their data using a statistical model of fragment deexcitation. Odd-even difference in the deduced values of the spin distribution widths could not be explained.

Although Kasagi et al.[107], from measurements of gamma rays with energies up to 160 MeV, reported evidence for very high energy gamma rays from the SF of ^{252}Cf, other investigators[108,109] found no evidence for this. Pokotilovskii[108] examined gamma emission in the 20 to 160 MeV range and set upper limits of about 10^{-8} to about 10^{-10} photons/MeV over the energy range from 20 to 120 MeV, more than an order of magnitude lower than reported. Luke et al.[109] also set upper limits at the level of 10^{-9} to 10^{-8} photon/MeV for the emission of gamma rays with energies above 30 MeV.

A comparison of the angular distributions of prompt gamma-rays from binary and light-charged particle (LCP) accompanied fission in ^{252}Cf has been reported by Pilz and Neubert[110]. Double- differential emission probabilities as a function of angle and gamma-energy were measured. Previous results for the anisotropy of gamma emission in binary fission were confirmed and similar anisotropic gamma emission was observed for LCP fission, but the shapes of the angular distributions differed considerably. They attributed this to the influence of the equatorial alpha particles on the alignment of angular momentum produced in bending modes. They also examined the gamma-emission probabilities as a function of complementary fragment masses and found less structure in the LCP fission, which may be due to the larger variances of the kinetic energies compared to those for binary fragments. Model calculations predicting a lower number of emitted gamma-rays for pseudospherical fragments characterized by lower moments of inertia than for deformed fragments are in rather good agreement with the data.

IV. COMPARISON WITH THEORY

As shown in Fig. 1, the known half-lives for SF of e-e isotopes are still reasonably well fit by the early calculations of Randrup et al.[47] who predicted that the extra stability observed for N=152 nuclei would no longer be present for Z=104 and higher. Based on the current data shown in Fig. 1

this appears to be the case. Comparison of the experimental partial half-lives for SF with various predictions, the disappearance of the N=152 shell for elements with Z≥104, and the effect of odd particles in lengthening SF half-lives (Section IIB) has been discussed previously in H&S and more recent reviews.[30-32]

Some recent theoretical investigations will be discussed here. Lojewski and Baran[111] used a realistic single-particle Woods-Saxon potential to estimate the half-lives for elements with Z=104 to 111. (They used k=14.1 rather than 11.5 which was used by Randrup et al.[47]; see Fig. 1.) This is one of the very few studies in which o-e and o-o as well as e-e nuclei were considered and hindrance factors for odd systems were estimated. For Z=104, 105, 106, the difference between the calculated half-lives and the experimental values was less than an order of magnitude. They calculate comparable half-lives for alpha and SF decay for the light isotopes of these elements, consistent with the recently measured (see Table IA) alpha to SF ratios for ^{262}105 and ^{263}105 of 33% and 57%, respectively, and the resultant SF half-lives of 102 and 47 seconds. However, they predict SF half-lives for Z=107 to 109 which are 3 to 5 orders of magnitude larger than calculations using the Nilsson model and microscopic mass parameters, and 4 orders of magnitude larger than the existing experimental data. Their calculations indicate a maximum in the SF half-lives at N=162. For Z≥ 107, they found that the alpha half-lives were shorter than the fission half-lives up to N=166 where the SF half-lives are predicted to be shorter and of the order of 10^{-3} to 10 seconds.

In 1989, Möller, Nix, and Swiatecki[112] reviewed the development of theoretical models for the calculation of fission barriers and half-lives, giving examples relevant to the rapidly varying fission properties of elements at the end of the periodic system. They note the large discrepancies between calculated and experimental half-lives, especially in the region of N=158 and heavier. They point out that although two different general classes of models can be used to calculate the nuclear potential energy of deformation, the more fundamental models, such as the Hartree-Fock approximation with an effective two-body interaction, have not yet been applied to these very heavy systems because of the complexity of the computations required. Most results have been obtained using the macroscopic-microscopic model which in general gives the total binding energy of a nucleus to about 10 MeV, compared to the total binding energy for a heavy nucleus of about 2000 MeV, a difference of only 0.5%. However, since a change in the calculated ground-state energy of 1 MeV changes the calculated half-life by six orders of magnitude, even this degree of precision is totally inadequate for predicting actual half-lives with the degree of accuracy required for comparison with experimental results, or for designing experiments for detecting new SF activities. Möller et al.[112] discuss the evolution since the discovery of nuclear fission of models for the fission barrier from the simple liquid-drop model to the more complex picture in which the calculation of shell effects leads to a multidimensional potential-energy surface with much structure. Both their results, which use a Yukawa plus exponential model and a folded Yukawa single-particle potential, and those of Cwiok et al.[113], which use different calculational methods, show the appearance of a new, second valley to fission in the potential energy surfaces calculated as a function of deformation energy via the macroscopic-microscopic model using the Strutinsky shell correction method.[114] The new valley is associated with lower inertia and leads to compact (near-spherical) shapes and shorter half-lives, in better agreement with the half-lives of the heavier Fm isotopes and consistent with measured[30] fragment mass and kinetic-energy distributions which show narrowly symmetric mass distributions and unusually high total kinetic energies.

Patyk et al.[115] used both static and dynamic methods to calculate SF half-lives for a wide region of e-e nuclides with Z=100 to 130. They also obtain two distinct valleys to fission, one leading to elongated and the other to compact (spherical) shapes. Furthermore, their calculations show that half-lives for Fm and No isotopes should increase for neutron numbers larger than 158 to 160 due to the influence of deformed parent shells in the region of N=162 to 164. They predict that the SF half-lives will continuously increase with increasing neutron number for element 104 and beyond, and that well-deformed superheavy element (SHE) nuclei with 164 to 168 neutrons exist for proton numbers near 112 to 114, in addition to those near the spherical N=184 shell. This would result in a peninsula of a relatively stable deformed nuclei extending from the presently known heavy nuclei to the spherical SHE's, rather than just an isolated island of stability.

The role of shell effects on the properties of the e-e nuclides with Z=92 through 108 was also investigated by Patyk et al.[116]. They find that shell effects decrease the mass of the heaviest nuclei by up to 5 MeV and increase the fission barriers by about 3.5 MeV. They calculate that the effect on the half-lives increases with increasing Z and that the SF half-lives are delayed by a few orders of magnitude for Pu isotopes and the effect increases to a hindrance of some 15 orders of magnitude for ^{252}Fm and ^{260}106. In the case of ^{260}106 this hindrance constitutes its "entire" lifetime of 7 ms; without shell effects it would have a lifetime approaching that of the compound nucleus. Such large effects for deformed nuclei were not expected. They find that there is almost no contribution to the SF half-lives of the heaviest nuclides which changes smoothly with Z and N. Thus, there should be less regularity in their systematics than for the lighter isotopes. Because of this, they caution that theoretical descriptions should incorporate as little averaging as possible over Z, N, and deformation, the parameters upon which the shell effects so strongly depend.

Patyk and Sobiczewski[117,118] have studied properties of the heaviest nuclei in multidimensional deformation space and find that the use of more dimensions in this deformation space improves the description of the experimental results and significantly changes predictions for as yet undiscovered nuclides. They find the nuclei in the region of Z=90 to 114 and N=136-148 to be well deformed with deformation energies ranging from 2 MeV at the boundaries up to 11 MeV at the center of this region. Quadrupole deformation is calculated to be the most important component although the hexadecapole deformation is significant in some regions. They emphasize the importance of the role of the deformation of multipolarity six and that it must not be disregarded in the consideration of the properties of nuclei in this region. It increases the binding energy of some nuclei by more than 1 MeV which results in an increase in the calculated SF half-lives of a few orders of magnitude and is important for formation of some of the main deformed shells in heavy nuclei. Their calculations reproduce the experimentally observed shell at N=152 which is mainly due to the quadrupole deformation. A smaller but significant proton shell is found at Z=100 which they propose as a proton partner for the N=152 shell. They confirm the previously predicted strong neutron shell at N=162 and attribute it mainly to the hexadecapole deformation in addition to quadrupole deformation. A strong, deformed shell is found at Z=108; thus, $^{270}108$ is predicted to be a strongly bound "doubly-magic" deformed nucleus with a half-life of about 0.1 second.

Cwiok and Sobiczewski[119] have calculated the potential energy and fission barriers of superheavy nuclei with Z=112 to 130 and N=152 to 210 in multidimensional deformation space. Three axially symmetric deformations and quadrupole and hexadecapole non-axial deformations were included. They calculated SF and alpha-decay half-lives. Fission barriers were 3 to 7 MeV lower than obtained previously, but the SF half-lives were still found to be longer than the alpha-decay half-lives for most of the nuclides studied and alpha decay is predicted to be the main decay mode. The longest half-lives of around 12 days are found near $^{294}112$. The nuclei with N≥176 are expected to be spherical, almost spherical transition nuclei are between N=166 and 176, and well-deformed nuclei occur below N≤166. Significant energy gaps were obtained for Z=114 and N=184, thus making $^{298}114$ a doubly magic spherical nucleus, in agreement with most previous calculations. However, the shell corrections for the well-deformed nuclei around $^{276}112$ are not much smaller and the barrier heights, and presumably the half-lives, are similar to those in the region of $^{298}114$. Again, it appears that there is not an isolated "island of stability" but a peninsula extending from the known, relatively long-lived nuclides.

Möller and Nix[120] have recently reported results obtained by use of a new mass model that includes Coulomb redistribution effects and β_3 and β_6 shape degrees of freedom. They now predict a superheavy island centered around $^{288,\,290}110$ for which they calculate alpha-decay half-lives of 161 and 438 years, respectively. They obtain shorter SF half-lives in the SHE region than before and give a "ballpark" estimate of 1 ms for nuclides in the vicinity of $^{272}110$. However, they point out that the specialization energy in odd-nucleon systems could lead to large increases in SF half-lives as has already been measured. (See Fig. 2.)

The calculations showing the two valleys to fission, one leading to elongated and the other to compact fragment shapes, can explain the symmetric mass distributions and high TKE's observed for $^{258,259}Fm$ and ^{260}Md. They are also consistent with the observation of "skewed" TKE distributions and with the proposal[21] of two "modes" of fission, one with near-spherical fragments resulting in high TKE, and the other with elongated or deformed fragments and lower TKE. However, to date only a qualitative prediction of the fraction of SF proceeding via these modes has been made and no detailed mass and kinetic-energy distributions have been calculated. Furthermore, contour plots of the experimental data for such transition nuclides as ^{257}Fm, ^{256}No, and ^{259}Lr shown in Figs. 9 and 10 indicate a wide distribution of shapes, not just two modes of fission. Calculations of Paskevich[121] for ^{264}Fm have shown three valleys on the potential-energy surface for symmetric fission in the region of the scission point. One corresponds to a compact configuration of two nearly spherical fragments, another to more separated highly elongated fragments, and a third corresponds to a combination of spherical and elongated fragments. Cwiok et al.[113] have also shown that the addition of reflection asymmetric deformations to their calculations for ^{258}Fm have dramatically changed the potential energy surface between the second saddle and the scission point. It appears that at least three modes exist in the experimental data for ^{257}Fm, judging from the wide range of TKE's found for symmetric mass division.

In 1976, Wilkins, Steinberg, and Chasman[122] used their static scission-point model of nuclear fission to calculate mass, nuclear charge, and kinetic-energy distributions. They were quite successful in reproducing the experimentally observed trends for a wide range of nuclides from Po to Fm. The model is based on the assumption of statistical equilibrium among collective degrees of freedom at the scission point; the relative probabilities (yields) of formation of complementary fragment pairs are determined from the relative potential energies of two nearly touching, coaxial spheroids with quadrupole deformations. The fissioning system at the scission point is characterized by the distance between the tips of the spheroids, the intrinsic excitation energy of the framents, and the collective temperature. They did not adjust these parameters to give the best fits to the experimental data, but used the same values for all the systems they calculated. They showed detailed mass-yield distributions for a number of spontaneously fissioning nuclides. Their scission-point configurations also provided a framework for the interpretation of a variety of other SF properties including the "saw-tooth" neutron emission function, the change in average TKE vs. Z and A, the changes in the variance of TKE distributions as a function of fragment mass ratio, and the difference in threshold energies for symmetric and asymmetric mass splits in the fission of Ra and Ac isotopes. They presented contour plots for the neutron- and proton-shell corrections as a function of deformation (β) and number of neutrons or protons. Wagemans, Schillebeeckx, and Deruytter[56] have investigated neutron shell effects and fission channels in the SF of the even-even Pu isotopes 236, 238, 240, 242, and 244 which show rapidly varying fission fragment mass and kinetic-energy distributions with a charge of only a few neutrons. They identify two fission modes, the first centered around a heavy fragment with A=135 and TKE≈190 MeV and the second around A=142 with TKE≈175 MeV. In going from ^{236}Pu to ^{242}Pu the yield around mass 142 decreases more than a factor of two while that around 135 shows a similar increase and the average TKE increases from 176.3 MeV for ^{236}Pu to 180.7 MeV for ^{242}Pu. These fission modes can be interpreted in the frame of the static scission-point model[122] as due to the changing relative importance of the N=82 spherical fragment and the N=87 deformed fragment neutron shells shown in those calculations and their interplay with the Z=50 spherical shell. The Pu results were also explained in terms of the fission channel model of Brosa and Grossmann.[123] The agreement between the calculated and experimental data for ^{240}Pu lends support to their idea of random neck rupture and the explanation of the relative peak mass yields on the basis of the relative barrier heights for their standard I and II fission channels.

The recent data for the "transition" nuclei ^{256}No and ^{259}Lr and earlier data available for $^{256, 257, 259}$Fm and ^{254}Cf can also be interpreted[124] in terms of the scission-point model of Wilkins et al. Three general configurations corresponding to the deformed and/or spherical shells generated by that model (see Figs. 1 and 2 in Ref. 122) can be identified: two deformed (elongated) fragments (d-d); two compact (spherical) fragments (c-c); one compact fragment and one deformed fragment (c-d). The fraction of each of these configurations can be estimated from the contour plots of the experimental data shown in Figs. 9 and 10 and can be roughly associated with the configurations representing the deformed and spherical shells shown in the scission-point model. For example, for the "transition" nucleus ^{257}Fm these are: d-d, 70% with TKE≈200 MeV with the following two fission fragments: β_d=0.75, Z=45, N=70, and β_d=0.65, Z=55, N=87; c-d, 20% with TKE

≈215 MeV (β_c=0.1, Z=52, N=82, and β_d=0.75, Z=48, N=75); c-c, 10% with TKE≈235 MeV (both fragments are β_c=0.1, Z=50, N=78.5). For ^{256}No, they are: d-d, 95% with TKE≈198 MeV (β_d=0.60, Z=44, N=66 and β_d=0.65, Z=58, N=88); c-d, 5% with TKE≈215 MeV (β_c=0.1, Z=55, N=82 and β_d=0.75, Z=47, N=72); c-c, <1%. For ^{259}Lr: d-d, 20% with TKE≈200 MeV (β_d=0.75, Z=47, N=70 and β_d=0.65, Z=56, N=86); c-d, 79% with TKE≈215-220 MeV (β_c=0.1, Z=54, N=82 and β_d=0.75, Z=49, N=74); c-c, ≈1% with TKE≈240 MeV (both fragments with β_c=0.1, Z=51.5, N=78). For ^{259}Fm, which shows a narrowly symmetric mass-yield distribution with very high TKE, the configurations are estimated to be: d-d, 0%; c-d, 20% with TKE≈220 MeV (β_c=0.1, Z=52, N=82 and β_d=0.8, Z=48, N=77); c-c, 80% with TKE≈245 MeV (both fragments β_c=0.05, Z=50, N=79.5). It should be possible to generate detailed calculations of mass-yield and kinetic-energy distributions for all of these nuclides from the scission-point model based on the potential energies of the complementary nascent fragment pairs, their respective neutron and proton numbers, and their deformations at or near the scission point.

The relative success of this static model implies that there is a state of quasi-equilibrium near the scission point. However, the fundamental problem of the importance of the dynamical aspects of the fission process on the various measurable distributions is still not well understood. Although much progress has been made in understanding general trends in half-lives and fragment properties, their extreme sensitivity to the nuclear structure in both the fissioning nucleus and the fragments, and to details of the fission barriers and fission paths, make the development of predictive models especially difficult. Much more theoretical investigation will be required to develop a comprehensive, dynamic model of nuclear fission which can predict not only the lifetimes of as yet undiscovered spontaneously fissioning nuclides, including hindrances due to odd particles, but which can also predict the complex and often rapidly changing properties of the fragments. A fundamental understanding of spontaneous fission, the process which will ultimately limit the number of elements which can exist, presents a formidable, but fascinating, challenge to experimentalists and theorists alike.

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Table 1A
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
^{8}Be	$(6.7^{+2.2}_{-1.3})\times10^{-17}$sec	$(6.7^{+2.2}_{-1.3})10^{-17}$sec	
^{230}Th	(7.54±0.03)x10^{4} years	>2x10^{18} years	8; SF:9
^{232}Th	(1.40±0.01)x10^{10} years	>(1.0±0.3)x10^{21} years	8; SF:9
^{231}Pa	(3.25±0.01)x10^{4} years	>2x10^{17} years	8; SF:9
^{234}Pa, g	6.75±0.03 hr	≤3x10^{-10}% SF	
m	1.175±0.003 min	≤10^{-10}% SF	
^{238}Pa	2.3±0.1 min	<2.6x10^{-6}% SF	
^{230}U	20.8 days	>4. x 10^{10} years	7; SF:9
^{232}U	70±1 years	(8±6)x10^{13} years[b]	10
^{233}U	(1.5911±0.0015)x10^{5} years	>2.7x10^{17} years	
^{234}U	(2.455±0.006)x10^{5} years	(1.5±0.2)x10^{16} years	10
^{235}U	(7.04±0.01)x10^{8} years	(1.0±0.3)x10^{19} years	10
^{236}U	(2.342±0.004)x10^{7} years	(2.5±0.1)x10^{16} years	10
^{238}U	(4.47±0.02)x10^{9} years	(8.2±0.1)x10^{15} years	10
		(9.86±0.29)x10^{15} years[c]	13
^{237}Np, g	(2.14±0.01)x10^{6} years	>1x10^{18} years	

Table 1A (continued)
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
^{228}Pu	If $T_{1/2} \cong 2$ min, then	$T_{1/2}^{SF} > 22$ min	
^{236}Pu	2.87±0.01 years	(2.1±0.1)x10^{9} years	10
^{238}Pu	87.7±0.01 years	(4.75±0.09)x10^{10} years	10
^{239}Pu	(2.410±0.003)x10^{4} years	(8±2)x10^{15} years	10
^{240}Pu	(6.56±0.01)x10^{3} years	(1.14±0.01)x10^{11} years	10; SF:14
^{241}Pu	14.4±0.1 years	< 6x10^{16} years	10
^{242}Pu	(3.75±0.02)x10^{5} years	(6.77±0.07)x10^{10} years	10
^{244}Pu	(8.00±0.09)x10^{7} years	(6.6±0.02)x10^{10} years	10
^{241}Am	432.7±0.6 years	(1.0±0.4)x10^{14} years	10
^{242}Am, m	141±2 years	>3x10^{12} years	10
^{243}Am	(7.37±0.02)x10^{3} years	(2.0±0.5)x10^{14} years	10
^{232}Cm	If $T_{1/2} \cong 1$ min, then	$T_{1/2}^{SF} > 3.3$ min	
^{240}Cm	26.8 days	(1.9±0.4)x10^{6} years	
^{242}Cm	162.8±0.2 days	(7.0±0.2)x10^{6} years	10
^{243}Cm	29.1±0.1 years	(5.5±0.9)x10^{11} years	10
^{244}Cm, g	18.1±0.1 years	(1.32±0.02)x10^{7} years	10
m	34±2 msec	≥1.4x10^{2} years	15
^{245}Cm	(8.48±0.06)x10^{3} years	(1.4±0.2)x10^{12} years	10
^{246}Cm	(4.76±0.04)x10^{3} years	(1.81±0.02)x10^{7} years	10
^{248}Cm	(3.48±0.06)x10^{5} years	(4.15±0.03)x10^{6} years	10

Table 1A (continued)
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
^{250}Cm	~9.7x10^3 years	(1.13±0.05)x10^4 years	10
^{249}Bk	325±7 days	(1.87±0.09)x10^9 years	
^{238}Cf	If $T_{1/2}$ ≅1 sec, then	$T_{1/2}^{SF}$>4 sec	
^{246}Cf	35.7±0.5 hr	(1.8±0.6)x10^3 years	7; SF:9
^{248}Cf	333.5±2.8 days	(3.2±0.3)x10^4 years	
^{249}Cf	351±2 years	(8±1)x10^{10} years	7; SF:9
^{250}Cf	13.08±0.09 years	(1.7±0.1)x10^4 years	7; SF:9
^{252}Cf	2.645±0.008 years	85±1 years	7; SF:9
^{254}Cf	60.5±2 days	60.9±0.9 days	7; SF:9
^{256}Cf	12.3±1.2 min	12±1 min	7; SF:9
^{253}Es	20.47±0.03 days	(6.3±0.2)x10^5 years	7; SF:9
^{254}Es, g	275.7±0.5 days	>2.5x10^7 years	
m	39.3±0.2 hr	>1x10^5 years	
^{255}Es	39.8±1.2 days	(2.44±0.14)x10^3 years	7; SF:9
^{257}Es	1-3 sec ??	1.3 sec ??	
^{242}Fm	0.8±0.2 msec	0.8±0.2 msec	
^{243}Fm	$0.18^{+0.08}_{-0.04}$ sec	≥50 sec	
^{244}Fm	3.3±0.5 msec	3.3±0.5 msec	

Table 1A (continued)
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
^{245}Fm	4.2±1.3 sec	>4000 sec	
^{246}Fm	1.1±0.2 sec	15±5 sec	7; SF:9
^{248}Fm	36±3 sec	10±5 hr	7; SF:9
^{250}Fm, g	30±3 min	0.83±0.15 years	15
m	1.8±0.1 sec	≥0.07 years	15
^{252}Fm	25.39±0.05 hr	125±8 years	7; SF:9
^{254}Fm	3.240±0.002 hr	228±1 days	7; SF:9
^{255}Fm	20.07±0.07 hr	$(1.0\pm0.6)x10^4$ years	7; SF:9
^{256}Fm	157.6±1.3 min	2.9±0.1 hr	7; SF:9
^{257}Fm	100.5±0.2 days	131±3 years	
^{258}Fm	0.37±0.04 msec	0.37±0.04 msec	1; SF:9
^{259}Fm	1.5±0.2 sec	1.5±0.2 sec	9; SF:9
^{260}Fm	~4 msec	~4 msec	16
^{248}Md	7±3 sec	≤0.05% SF	
^{255}Md	27±2 min	≥12.5 days	
^{256}Md	78.1±1.8 min	<2.8% (>1.9 days)	17; SF:9
^{257}Md	5.52±0.05 hr	≤1% (≥23 days)	17
^{258}Md, g	51.5±0.3 days	$\leq3x10^{-3}\%$ ($\geq5x10^3$ years)	17
^{259}Md	1.60±0.06 hr	≈100%	17
^{260}Md	27.8±0.8 days	>73% (27.8 days$<T_{1/2}^{SF}<$38.1 days)	16

Table 1A (continued)
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
^{250}No	0.25±0.05 msec ??	0.25±0.05 msec ??	
^{251}No	$0.60+^{+0.25}_{-0.15}$ sec	>7.5 sec	18
^{252}No	$2.25^{+0.18}_{-0.16}$ sec	26.9% (8.36 sec)	15; SF:7
^{254}No, g	55±5 sec	$(3.2\pm0.9)\times10^4$ sec	7; SF:15
		$(2.2^{+2.0}_{-1.0})\times10^4$ sec	19
^{256}No	2.91±0.05 sec	550^{+40}_{-70} sec	20
^{258}No	1.2±0.2 msec	1.2±0.2 msec	21
^{259}No	58±5 min	>9.7 hr	
^{260}No	106±8 msec ??	106±8 msec ??	
^{262}No	~5 msec	~5 msec	22, 23
^{252}Lr	If $T_{1/2}$ >1 sec, then	$T_{1/2}^{SF}\geq100$ sec	
^{253}Lr	$1.3^{+0.6}_{-0.3}$ sec	≥2.2 min	
^{254}Lr	$13\pm^{3}_{2}$ sec	$\geq10^4$ sec	
^{255}Lr	22±5 sec	≥6 hr	
^{256}Lr	25.9±1.7 sec	$\geq10^5$ sec	
^{257}Lr	0.646±0.025 sec	$\geq10^5$ sec	
^{258}Lr	$3.92^{+0.35}_{-0.31}$ sec	<5.0% (>78 sec)	24
^{259}Lr	6.14 ±0.36 sec	(20±2%)[d] 31±4 sec	25
^{261}Lr	39±12 min	100%?	22
^{262}Lr	216±15 min	<10.0% (>2160 min)	22

Table 1A (continued)
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
^{253}Rf	1.8 sec ??	3.6 sec ??	
^{254}Rf	0.5±0.2 msec?	0.5±0.2 msec?	
^{255}Rf	1.4±0.2 sec	2.7±0.5 sec	
^{256}Rf	6.7±0.2 msec[d]	$6.9^{+0.6}_{-0.2}$ msec	
^{257}Rf	4.76±0.53 sec	200±25 sec ??	
^{258}Rf	13±2 msec	13±2 msec $\leq T_{1/2}^{SF} \leq$ 15±2 msec	
^{259}Rf	3.1±0.7 sec	0.7±0.4 min	7; SF:9
^{260}Rf	20.1±0.7 msec	20±1 msec	7; SF:9
^{261}Rf	65±10 sec	≥650 sec	
^{262}Rf	47±5 msec	47±5 msec	
^{255}Ha	$1.6^{+0.6}_{-0.4}$ sec	> 3 sec	
^{256}Ha	2.6 sec??	≤40%??	26
^{257}Ha	$1.3^{+0.5}_{-0.3}$ sec	(17±11%)[d] 8±6 sec	7; SF:9
^{258}Ha	$4.4^{+0.9}_{-0.6}$ sec	$\geq 13^{+4}_{-3}$ sec	
^{260}Ha	1.52±0.13 sec	15.8±1.7 sec ?	
^{261}Ha	1.8±0.6 sec	"several times" 2 sec	
		≥3.6 sec	
^{262}Ha	34±4 sec	≈33%[d] (≈102 sec)	7; SF:27
^{263}Ha	27^{+10}_{-7} sec	57^{+13}_{-15}%[d] (47 sec)	27
^{259}106	$0.48^{+0.28}_{-0.13}$ sec	>2.4 sec	

Table 1A (continued)
RECOMMENDED VALUES OF HALF-LIVES AND PARTIAL SF HALF-LIVES OR BRANCHES FOR SF ACTIVITIES[a]

Nuclide	$T_{1/2}$	$T_{1/2}^{SF}$ or % SF	Ref.
$^{260}106$	$3.6^{+0.9}_{-0.6}$ msec	$7.2^{+4.8}_{-2.7}$ msec	
$^{261}106$	$0.26^{+0.11}_{-0.06}$ sec	>2.6 sec	
$^{263}106$	0.9±0.2 sec	1.3 sec ??	
$^{261}107$	$11.8^{+5.3}_{-2.8}$ msec	<10% (>0.12 sec)	28; SF:7
$^{262}107$, g	102±26 msec	≤20% (≥510 msec)	28; SF:7
m	8.0±2.1 msec	<30% (>27 msec)	28; SF:7
$^{263}108$	<1 sec	"mainly α decay"	
$^{264}108$	76^{+364}_{-36} μsec	>5 msec	
$^{265}108$	$1.8^{+2.2}_{-0.7}$ msec	≥20 msec	
$^{266}109$	$3.4^{+6.1}_{-1.3}$ msec	≥62 msec	29; SF:1
$^{272}110$	$8.6^{+4.0}_{-2.4}$ msec ??	$8.6^{+4.0}_{-2.4}$ msec ??	

a This table is a revised and updated version of Table 1 from Ref. 1. References are given here for all new or revised values. Half-lives of fission isomers are given by D.N. Poenaru, Strutinsky Method and Fission Isomers, in this Handbook.

b This activity, originally attributed to spontaneous fission, is now believed to be due to ^{24}Ne emission (Refs. 11 and 12).

c This value has been recommended for use in fission track age calculations.

d These fission branches assume the primary modes of decay are SF and alpha decay.

Table 1B
DELAYED FISSION

Nuclide[a]	$T_{1/2}$	P_{df}[b]	Measurement[c]	Ref.
^{180}Tl	$0.70^{+0.12}_{-0.09}$ sec	$\approx 10^{-6}$	$T_{1/2}$	33
^{228}Fr	39 sec	$<2x10^{-7}$	$T_{1/2}$	34
^{230}Fr	19 sec	$<3x10^{-6}$	$T_{1/2}$	34
^{232}Fr	5 sec	$<2x10^{-6}$	$T_{1/2}$	34
^{232}Ac	35 sec	$<10^{-6}$	$T_{1/2}$	34
^{228}Np	60±5 sec	nr	$T_{1/2}$	35
	61.4±1.4 sec	$2.0\pm0.9x10^{-4}$	$T_{1/2}$,P_{df},KE, MY,TKE,RC,XF	36
^{232}Am	1.4±0.25 min	nr	$T_{1/2}$	35,37
	0.92±0.12 min	$1.3^{+4}_{-0.8}x10^{-2}$	$T_{1/2}$	38
	1.31±0.04 min	$(6.9\pm1.0)x10^{-4}$	$T_{1/2}$,P_{df},KE, MY,TKE,XF,RC	39
^{234}Am	2.6±0.2 min	nr	$T_{1/2}$	35, 37
	2.6±0.2 min	nr	$T_{1/2}$	40
	2.32±0.08 min	$(6.6\pm1.8)x10^{-5}$	$T_{1/2}$,P_{df},KE, MY,TKE,XF,RC	41

Table 1B (continued)
DELAYED FISSION

Nuclide[a]	$T_{1/2}$	P_{df}[b]	Measurement[c]	Ref.
^{238}Bk	144±5.8 sec		$T_{1/2}$,XF,TKE, MY,KE	42
^{240}Bk	4 min	10^{-5}	$T_{1/2}$	43
^{242}Es?	5 - 25 sec	$(1.4\pm0.8)\times10^{-2}$	$T_{1/2}$, P_{df}	44
^{244}Es	37 sec	10^{-4}	$T_{1/2}$	43
^{246}Es	8 min	3×10^{-5}	$T_{1/2}$	43
^{248}Es	28 min	3×10^{-7}	$T_{1/2}$	43
$^{256}Es^m$	7.6 hr	2×10^{-5}	$T_{1/2}$, P_{df}, level structure	45
^{250}Md	52 sec	2×10^{-4}	$T_{1/2}$[b]	43

a The nuclide undergoing β or EC decay is given.

b Probability for delayed fission (P_{df}) for nuclei not marked with "P_{df}" in the measurements column was obtained from systematics or evaporation codes; nr = not reported.

c KE = kinetic energy of fission fragment; MY = mass-yield distribution; TKE = total kinetic energy distribution; XF = x-ray-fission coincidence measurements; RC = radiochemical confirmation of Z.

Table 2
PROPERTIES OF MASS AND TKE DISTRIBUTIONS FOR SF

Nuclide	Peak-to-Valley Ratio[a]	$\overline{TKE}$[b,c] (MeV)	FWHM of TKE[d] (MeV)	Ref.
^{238}U	>500 (RC)	163±3		48,55
^{236}Pu	≥700 (SS)[e]	176.3±0.5	24	56
^{238}Pu	≥700 (SS)[e]	177.0±0.5	25	56
^{240}Pu	>270 (RC), ≥4000 (SS)[e]	179.4±0.5	28	56
^{242}Pu	≈500 (SS)[e]	180.7±0.5	27	56
^{244}Pu		184±1	28	57
	≥2000 (SS)[f]	181±2	27	f
^{242}Cm	>700 (RC)	180±10		48,55
^{244}Cm	>5700 (RC)	183.7[g]		48
	86 (SS)	183.6±1		58
		188.6		48
^{246}Cm	142 (SS)	184.2±0.3	27	59
		183.9±0.5	25	60
^{248}Cm	asym (SS)	182.2±0.9	25	60
^{250}Cm	>10 (SS)	179.8±2.7	29	61
^{248}Cf		189.9±1.3[h]		62
^{250}Cf	≥300 (RC)	187.0±0.5	27	1,60
		184.3±2.8	30	61
^{252}Cf	≥750 (RC)	186.5 (183.9)	27	51,52,53
^{254}Cf	≥145 (RC)	186.9±0.5	28	60

Table 2 (continued)
PROPERTIES OF MASS AND TKE DISTRIBUTIONS FOR SF

Nuclide	Peak-to-Valley Ratio[a]	$\overline{TKE}$[b,c] (MeV)	FWHM of TKE[d] (MeV)	Ref.
^{256}Cf	asym (SS)	189.8±0.9	34	63
^{253}Es	326 (RC)	188±3[i]	31	64,65
^{244}Fm	asym (IC)	196±4	--	66
^{246}Fm	asym (SS)	199±4	35	67
^{248}Fm	asym (SS)	198±4	34	67
^{254}Fm	60 (RC)	195.1±1	27	68
^{256}Fm	12 (SS)	197.9±0.5	34	60
^{257}Fm	≈1.5 (SS)	197.6±3 (194, 227)	36	69
^{258}Fm	sym (SS), 8	238±3*	34	63
		230.6# (205, 50%; 230, 50%)[j]		21
^{259}Fm	sym (SS), 11	242±6#	49	70
	sym (SS), 12	234±2*	48	71
^{259}Md	sym (SS), 27	200.6# (202, 88%; 234, 12%)[j]	≈60	21
^{260}Md	sym (SS), 7.9	232.5# (200, 42%; 234, 58%)[j]	≈35	21
^{252}No	asym (SS)	202.4	36	72
	~1.6 (SS)	194.3#	--	73
^{256}No	1-1.5 (SS), ~50	196±3#	42	20
^{258}No	sym (SS)	203.2# (204, 95%; 232, 5%)[j]	≈50	21

Table 2 (continued)
PROPERTIES OF MASS AND TKE DISTRIBUTIONS FOR SF

Nuclide	Peak-to-Valley Ratio[a]	$\overline{TKE}$[b,c] (MeV)	FWHM of TKE[d] (MeV)	Ref.
^{262}No	sym (SS), 12	(237, 65%; 200, 35%)[j]		22,23
^{259}Lr	≈sym (SS), 20	214±3	40	25
^{256}Rf		207±13		74
^{258}Rf		220±15		74,75
^{260}Rf	sym (SS), 36	200	44	21
^{262}Ha	asym (SS) or if sym, >47			76
^{263}Ha	sym (SS)	≈210[k]		27

a 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.

b These are average values of the pre-neutron emission TKE's except for those denoted by (#) which are most probable values of the pre-neutron emission TKE's or by (*) which are most probable TKE's from a provisional mass analysis without corrections for neutron emission as a function of fragment mass.

Table 2 (continued)
PROPERTIES OF MASS AND TKE DISTRIBUTIONS FOR SF

c 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.*[51,52] Measurements of TKE denoted by (#) have been normalized to a post-neutron emission 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.*[53] and are derived from a provisional mass analysis without corrections for neutron emission. Henschel *et al.*[54] have also redetermined the TKE of ^{252}Cf as 181.25±1.3 MeV and 184.07±1.3 MeV for the post- and pre-neutron emission values, respectively.

d Full width at half maximum of TKE distribution as measured, or calculated from 2.35 times σ for the TKE distribution.

e Value derived from data in Ref. 56 based on the absence of events in a valley region of 5 mass units (C. Wagemans, private communication, 1992).

f Values based on measurements in progress; peak-to-valley ratio based on a valley width of 5 mass units (C. Wagemans, private communication, 1992).

g Time-of-flight measurement.

h Corrected to pre-neutron emission TKE for ^{252}Cf = 185.7 MeV, in Ref. 62.

i Relative to pre-neutron emission $\overline{TKE}$ for ^{252}Cf = 183.0 MeV.

j Values in parentheses are those of the two Gaussian functions by which the TKE distributions could be represented (Ref. 21-23).

k A pre-neutron emission value was estimated from the post-neutron emission value of 207±7 MeV given in Ref. 27.

Table 3

EXPERIMENTAL VALUES OF $\bar{\nu}_T$ AND σ_ν^2 FOR SPONTANEOUS FISSION

Nuclide	$\bar{\nu}_T$ [a]	σ_ν^2 [b]	Standard [c]	Ref.
^{238}U	1.98±0.03	0.80±0.15	^{252}Cf = 3.735	78
	1.99±0.03[d]		^{252}Cf = 3.757	79
^{236}Pu	2.23±0.19		^{240}Pu = 2.19	80
	2.12±0.13	1.26±0.20	^{252}Cf = 3.735	78
^{238}Pu	2.26±0.08		^{240}Pu = 2.19	80
	2.21±0.07	1.29±0.05	^{252}Cf = 3.735	78
^{240}Pu	2.19±0.03		^{252}Cf = 3.77	80
	2.14±0.01	1.32±0.01	^{252}Cf = 3.735	78
	2.141±0.016	1.3099	^{252}Cf = 3.743	81
^{242}Pu	2.15±0.05		^{244}Cm = 2.73	80
	2.12±0.01	1.31±0.01	^{252}Cf = 3.735	78
^{244}Pu	2.30±0.19		^{252}Cf = 3.77	80
^{242}Cm	2.57±0.09		^{240}Pu = 2.19	80
	2.51±0.06	1.21±0.03	^{252}Cf = 3.735	78
	2.562±0.020	1.3312	^{252}Cf = 3.743	81
	2.54±0.020[d]	1.22	^{252}Cf = 3.757	82
^{244}Cm	2.73±0.04		^{240}Pu = 2.19	80
	2.76±0.09		^{240}Pu = 2.19	80
	2.69±0.01	1.23±0.05	^{252}Cf = 3.735	78
	2.721±0.021	1.3246	^{252}Cf = 3.743	81

Table 3 (continued)
EXPERIMENTAL VALUES OF $\bar{\nu}_T$ AND σ_ν^2 FOR SPONTANEOUS FISSION

Nuclide	$\bar{\nu}_T$ [a]	σ_ν^2 [b]	Standard [c]	Ref.
	2.72±0.02[d]	1.26	^{252}Cf = 3.757	82
^{246}Cm	3.19±0.22		^{252}Cf = 3.77	80
	2.94±0.03	1.31±0.02	^{252}Cf = 3.735	78
	2.93±0.03[d]	1.28	^{252}Cf = 3.757	82
^{248}Cm	3.11±0.09		^{252}Cf = 3.77	80
	3.10±0.01	1.37±0.01	^{252}Cf = 3.735	78
	3.13±0.03[d]	1.29	^{252}Cf = 3.757	82
^{250}Cm	3.31±0.08		^{252}Cf = 3.77	80
	3.30±0.08[d]		^{252}Cf = 3.757	82
^{249}Bk	3.40±0.05[d]		^{252}Cf = 3.757	82
^{246}Cf	2.83±0.19		^{240}Pu = 2.19	80
	3.14±0.09	1.66±0.31	^{252}Cf = 3.735	78
	3.1±0.1[d]	1.68	^{252}Cf = 3.757	82
^{250}Cf	3.53±0.09		^{252}Cf = 3.77	80
	3.49±0.04	1.49±0.03	^{252}Cf = 3.735	83
	3.53±0.02	1.52±0.02	^{252}Cf = 3.735	78
	3.51±0.04[d]	1.53	^{252}Cf = 3.757	82
^{252}Cf	3.771±0.031		Abs. m., 1963	84
	3.738±0.015	1.566±0.003	Abs. m., 1974	85

Table 3 (continued)
EXPERIMENTAL VALUES OF $\bar{\nu}_T$ AND σ_ν^2 FOR SPONTANEOUS FISSION

Nuclide	$\bar{\nu}_T$ [a]	σ_ν^2 [b]	Standard [c]	Ref.
	3.7509±0.0107		Abs. m., 1985	86
	3.773±0.007	1.5824	Abs. m., 1981	87
	3.757±0.010[d]	1.59	^{252}Cf = 3.757	82
^{254}Cf	3.93±0.05		^{252}Cf = 3.77	80
	3.77±0.05	1.56±0.01	^{252}Cf = 3.735	83
	3.85±0.06[d]	1.53	^{252}Cf = 3.757	82
^{253}Es	4.7[e]			60
^{254}Fm	3.96±0.14	1.50±0.20	^{252}Cf = 3.735	78
	4.00±0.19		^{252}Cf = 3.77	80
	4.0±0.3[d]		^{252}Cf = 3.757	82
^{256}Fm	3.91±0.03	2.02±0.13	^{252}Cf = 3.755	88
	3.73±0.18	2.30±0.65	^{252}Cf = 3.735	78
		1.82±0.08	^{252}Cf = 3.735	83
	3.59±0.06	2.16±0.05	^{252}Cf = 3.735	89
	3.63±0.06[d]		^{252}Cf = 3.757	82
^{257}Fm	3.77±0.02	2.49±0.06	^{252}Cf = 3.735	90
	3.85±0.05	2.51±0.02	^{252}Cf = 3.735	83
	3.77±0.02	2.49±0.06	^{252}Cf = 3.735	78
	3.87±0.05[d]		^{252}Cf = 3.757	82

Table 3 (continued)
EXPERIMENTAL VALUES OF $\bar{\nu}_T$ AND σ_ν^2 FOR SPONTANEOUS FISSION

Nuclide	$\bar{\nu}_T$ [a]	σ_ν^2 [b]	Standard [c]	Ref.
^{260}Md	2.58±0.11	2.57±0.13	^{252}Cf = 3.773	91
^{252}No	4.15±0.30	4.0±1.3	^{252}Cf = 3.735	78
	4.20±0.30	4.2	^{252}Cf = 3.757	82

a $\bar{\nu}_T$ is the average number of neutrons emitted per fission event.

b σ_ν^2 is the variance for the neutron multiplicity distribution.

c Abs. m. means "Absolute measurement".

d Evaluated value from Holden and Zucker, Ref. 79 (1983) and Ref. 82 (1986).

e Estimated by comparison of pre- and post-neutron-emission mass-yield curves from SS and RC measurements.

FIGURE CAPTIONS

Figure 1a. Comparison between the experimental half-lives and the partial half-lives calculated or estimated by Randrup et al.[47] for SF of even-even nuclei. A square for the possible assignment of 106-msec ^{260}No is connected to the square for ^{258}No$^{111\text{-}113}$ by a dot-dashed line. The squares for ^{260}106 ($T^{SF}_{1/2}$ = 7.2 msec, Ref. 114) and ^{264}108 ($T^{SF}_{1/2}$ >5 msec, Ref. 115,116) are shown connected by a vertical dashed line and a 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 msec on its partial SF half-life is shown as a diagonal-pointing arrow. Taken from Ref. 1 except for the following changes: ^{232}U ($T^{SF}_{1/2}$ = 8x10^{13} years, Ref. 10), ^{234}U ($T^{SF}_{1/2}$ =1.5x10^{16} years, Ref. 10), ^{262}No ($T^{SF}_{1/2}$ ~5 msec, Ref. 23).

Figure 1b. The logarithm of the spontaneous fission half-lives of even-even nuclei plotted against the neutron number, N. Arrows are used for ^{238}Cf and ^{264}108 to indicate lower limits. All data are from Table 1A.

Figure 2. Logarithms of SF hindrance factors (HF) for odd-neutron and odd-proton nuclides (from Ref. 30). Lower limit values are indicated by arrows. An open bar indicates that the HF was calculated relative to only one even-even neighbor. A filled or hacked bar indicates that the HF was calculated relative to two even-even neighbors.

Figure 3. Schematic representation of mass-yield distributions (normalized to 200% fission fragment yield) for SF of trans-Bk isotopes (from Ref. 1). Distributions for ^{256}No, ^{262}No, and ^{259}Lr have been added. Data for these distributions are from Refs. 20, 23, and 25, respectively.

Figure 4. $\overline{TKE}$ vs. $Z^2/A^{1/3}$. The dashed line is the linear fit of Unik et al.[60]; the solid line is the linear fit of Viola[62]. All data are taken from Table 2.

Figure 5. TKE distributions for SF of trans-Es isotopes (from Ref. 1).

Figure 6. Element yield, Y(Z), vs. atomic number for the spontaneous fission of ^{252}Cf. (From Ref. 77.)

Figure 7. Experimental values of $\bar{\nu}_T$ for SF plotted as a function of A of the compound nucleus. All data are taken from Table 3.

Figure 8. Average number of prompt neutrons emitted, $\bar{\nu}_A$, to form fission products with mass number A for the spontaneous fission of ^{252}Cf. The derived function used is shown by the solid line. Symbols represent experimental values of the average number of neutrons emitted by fragments, $\bar{\nu}_f$, plotted against $A_f - \bar{\nu}_f = A$, A_f being the average fragment mass number before prompt-neutron emission. (From Ref. 77.)

Figure 9. Contour plots of pre-neutron-emission TKE vs. mass fraction for ^{254}Cf, ^{256}Fm, ^{257}Fm, and ^{259}Fm. For ^{254}Cf (104,937 events), ^{256}Fm (47,366 events), and ^{257}Fm (17,951 events), the contours represent lines of equal numbers of events based on groupings 5 MeV x 0.01 units of mass fraction (from Ref. 1). 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. 50 and 71.

Figure 10. Contour plots of pre-neutron-emission TKE vs. mass fraction.

a) ^{259}Lr. The contours indicate equal numbers of events based on data groupings of 10 MeV x 0.02 units of mass fraction. Contours labeled 1 through 5 represent 10 through 50 events, respectively.[25]

b) ^{256}No. The contours indicate equal numbers of events based on data groupings 20 MeV x 0.04 units of mass fraction. Contours labeled 1 through 6 represent 10 through 60 events, respectively.[20]

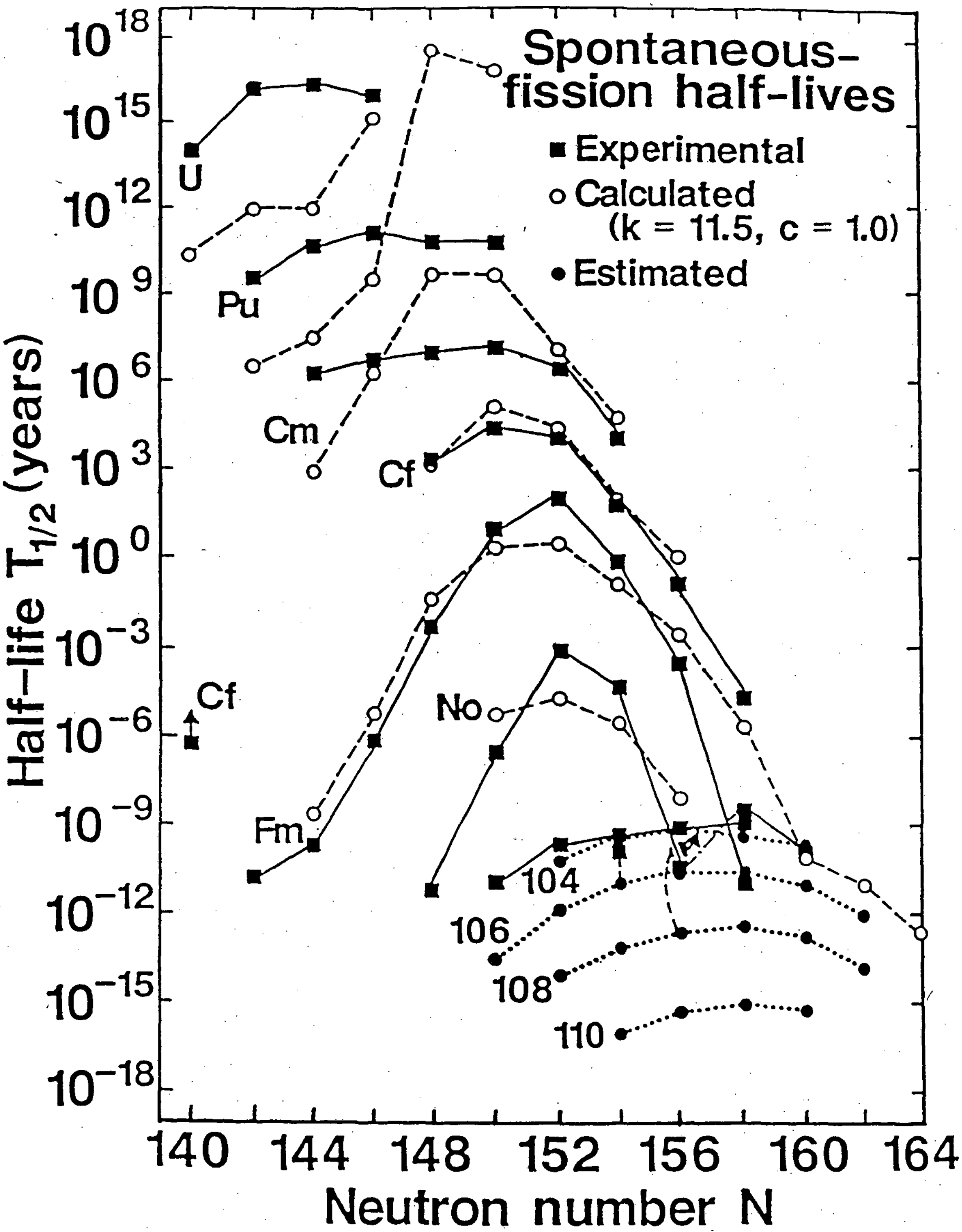


Figure 1A

XBL 873-811B

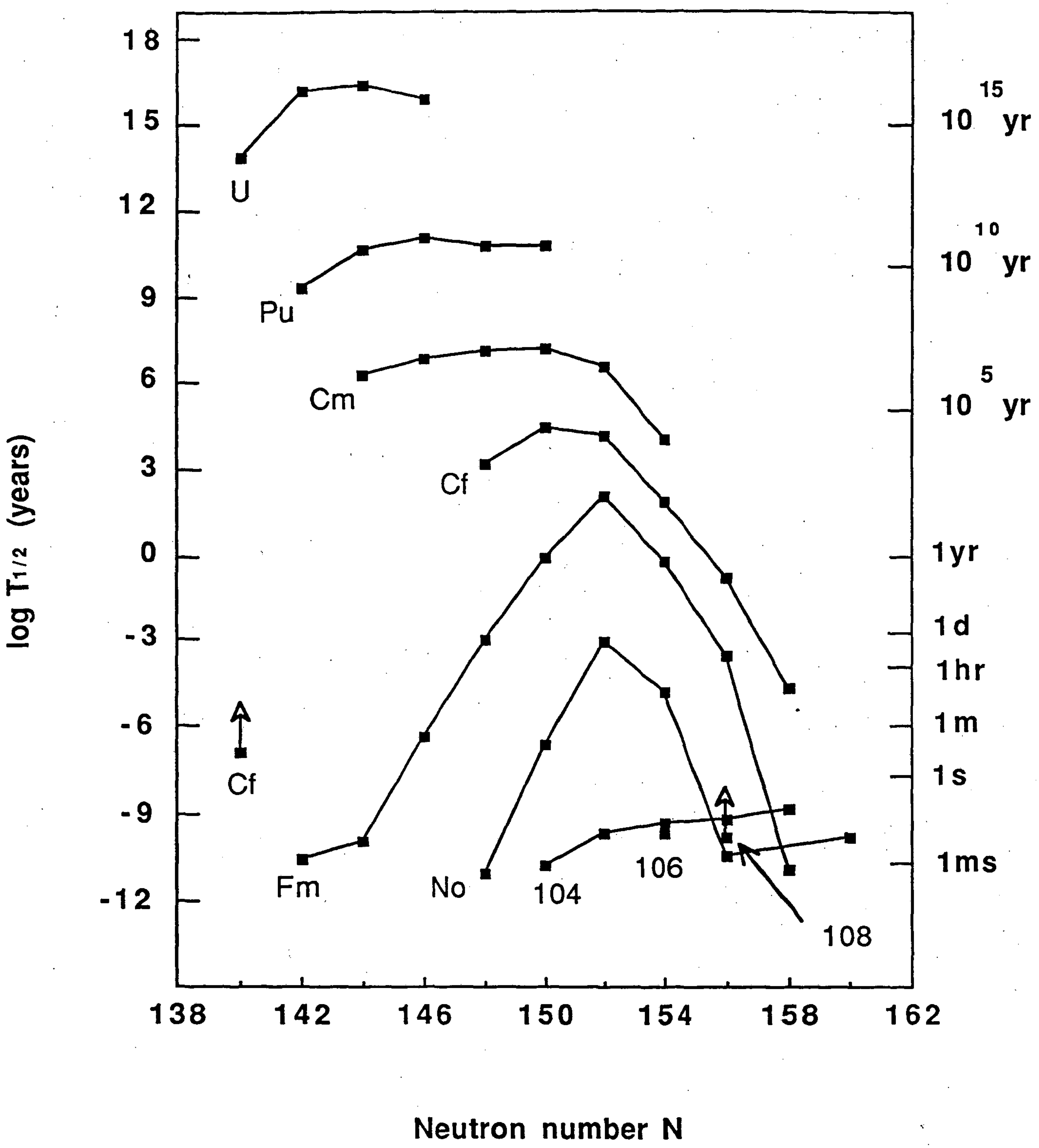

18
15
12
9
6
3
0
-3
-6
-9
-12
log T1/2 (years)
U
Pu
Cm
Cf
Cf
Fm
No
104
106
108
10^15 yr
10^10 yr
10^5 yr
1yr
1d
1hr
1m
1s
1ms
138
142
146
150
154
158
162
Neutron number N

Figure 1B

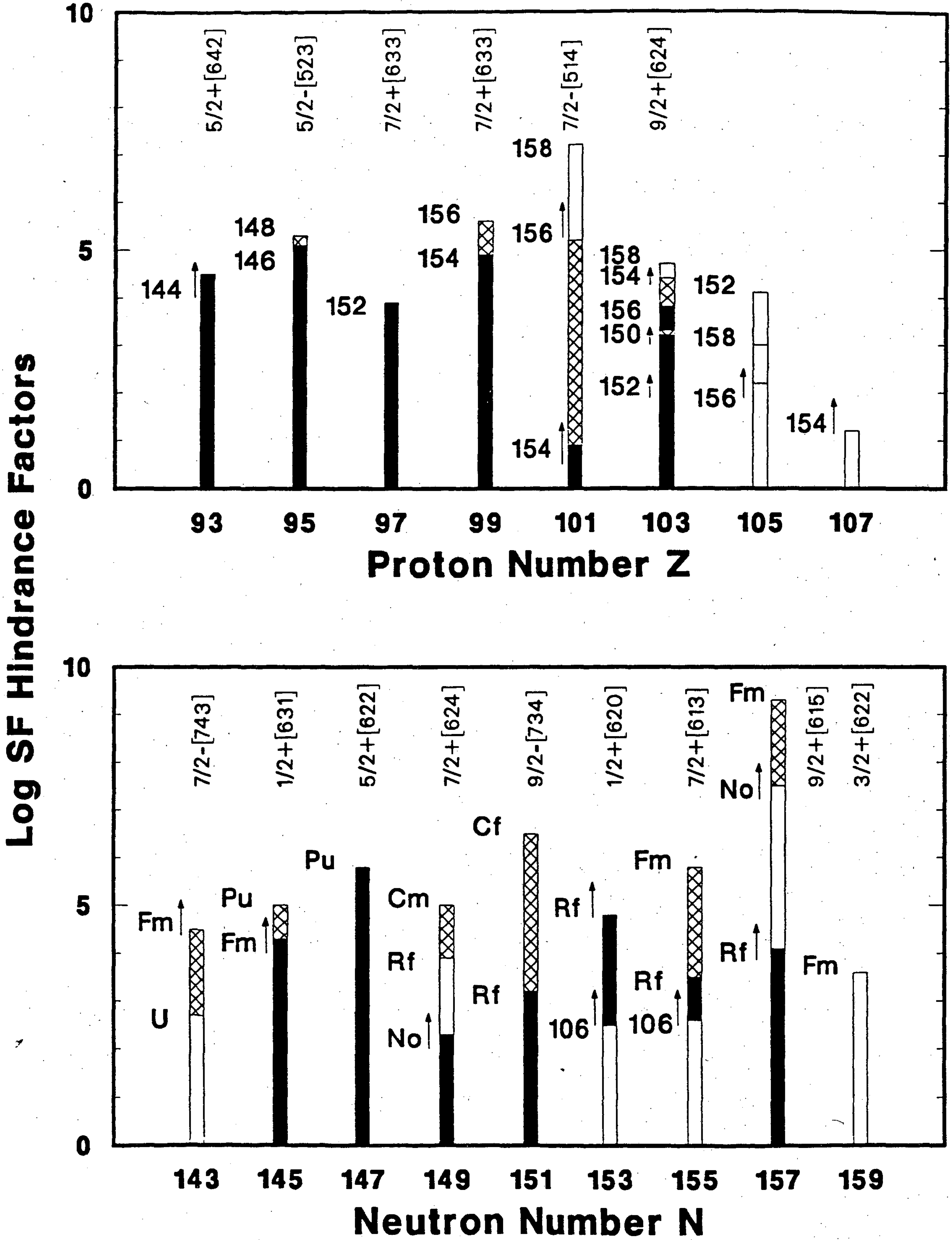

Log SF Hindrance Factors
Proton Number Z
Neutron Number N
5/2+[642]
5/2-[523]
7/2+[633]
7/2+[633]
7/2-[514]
9/2+[624]
7/2-[743]
1/2+[631]
5/2+[622]
7/2+[624]
9/2-[734]
1/2+[620]
7/2+[613]
9/2+[615]
3/2+[622]
XBL 927-1549

Figure 2

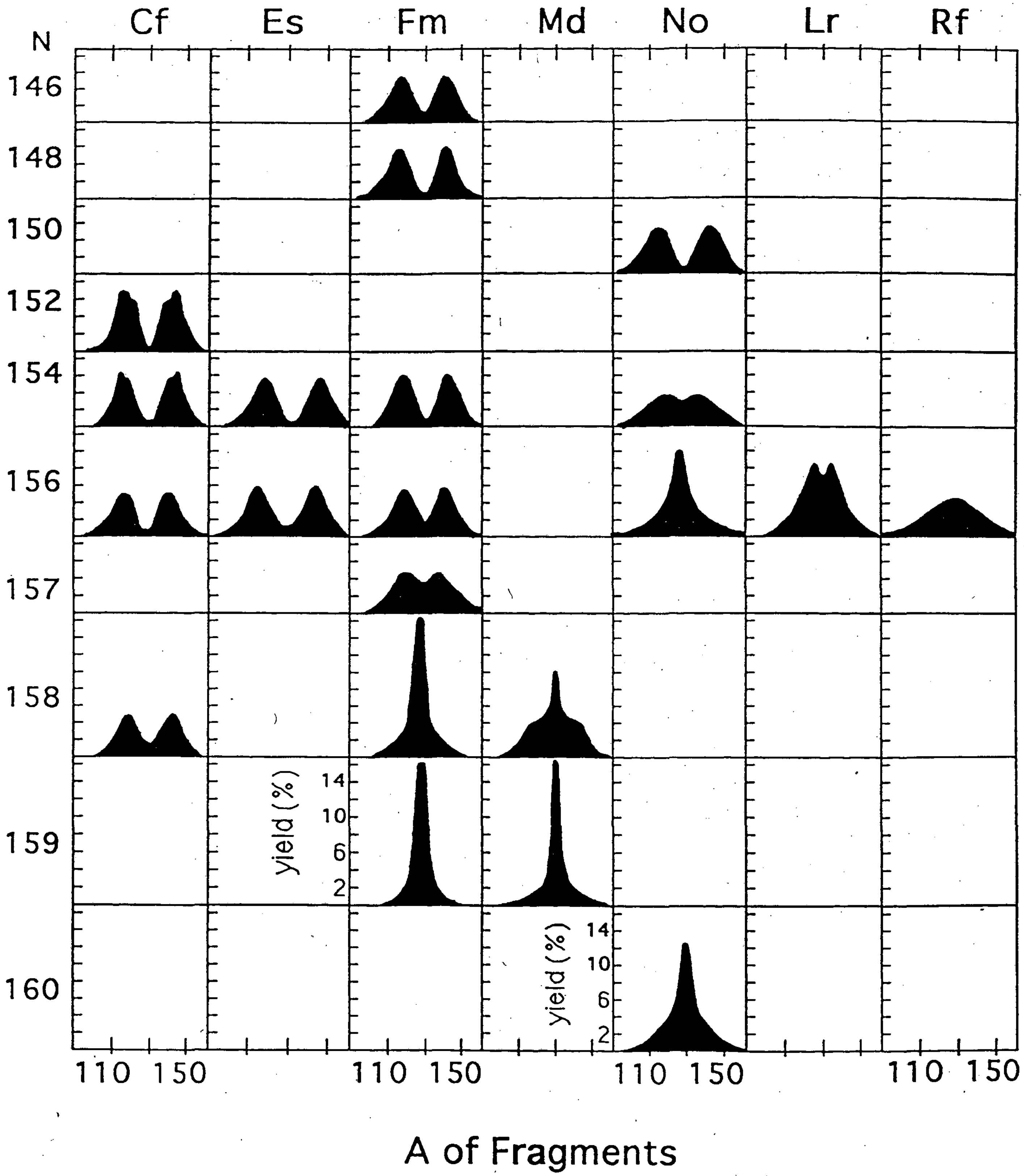

Cf
Es
Fm
Md
No
Lr
Rf
N
146
148
150
152
154
156
157
158
159
160
yield (%)
14
10
6
2
110 150
A of Fragments

Figure 3

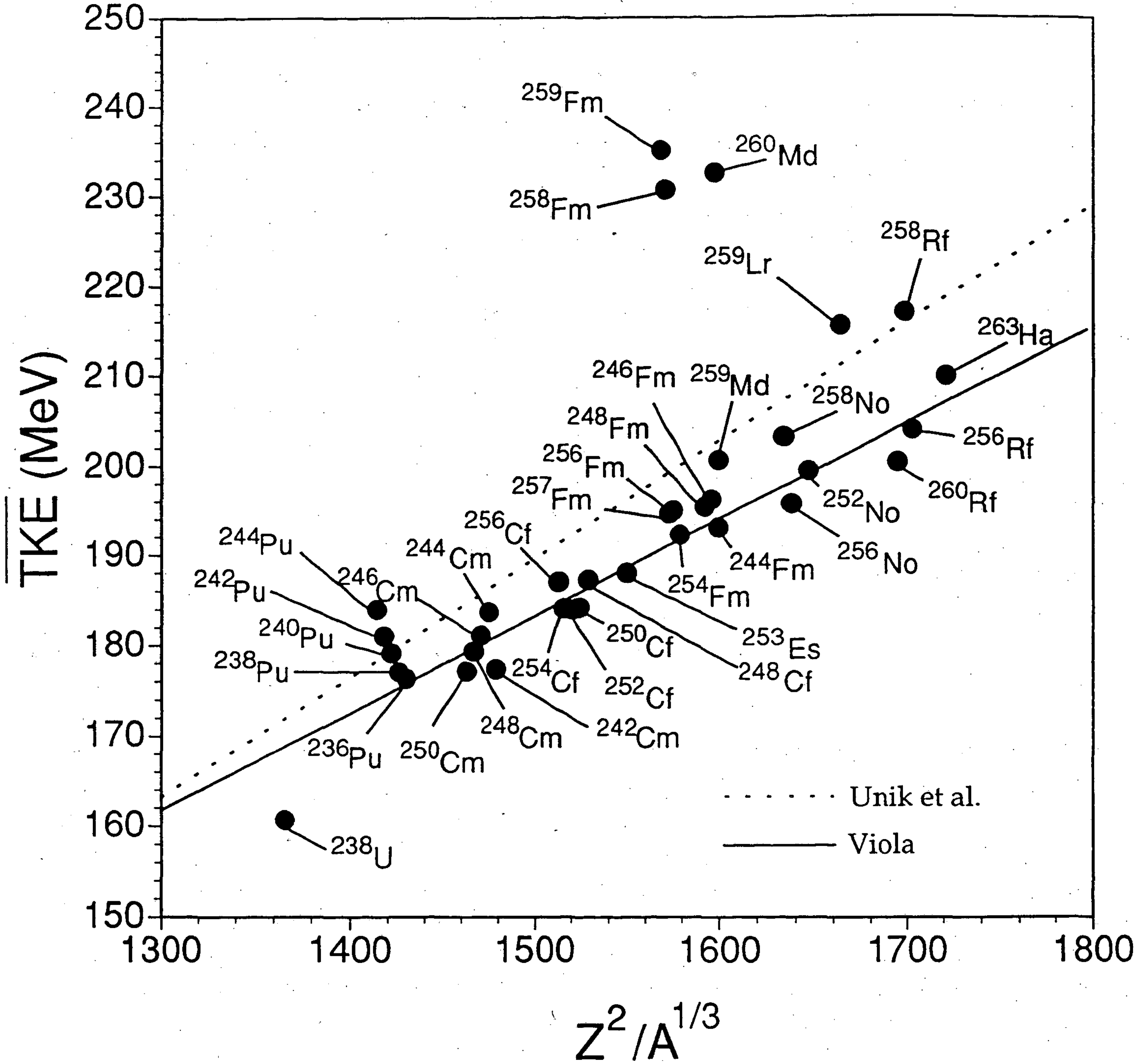


Figure 4

XBL 927-1625

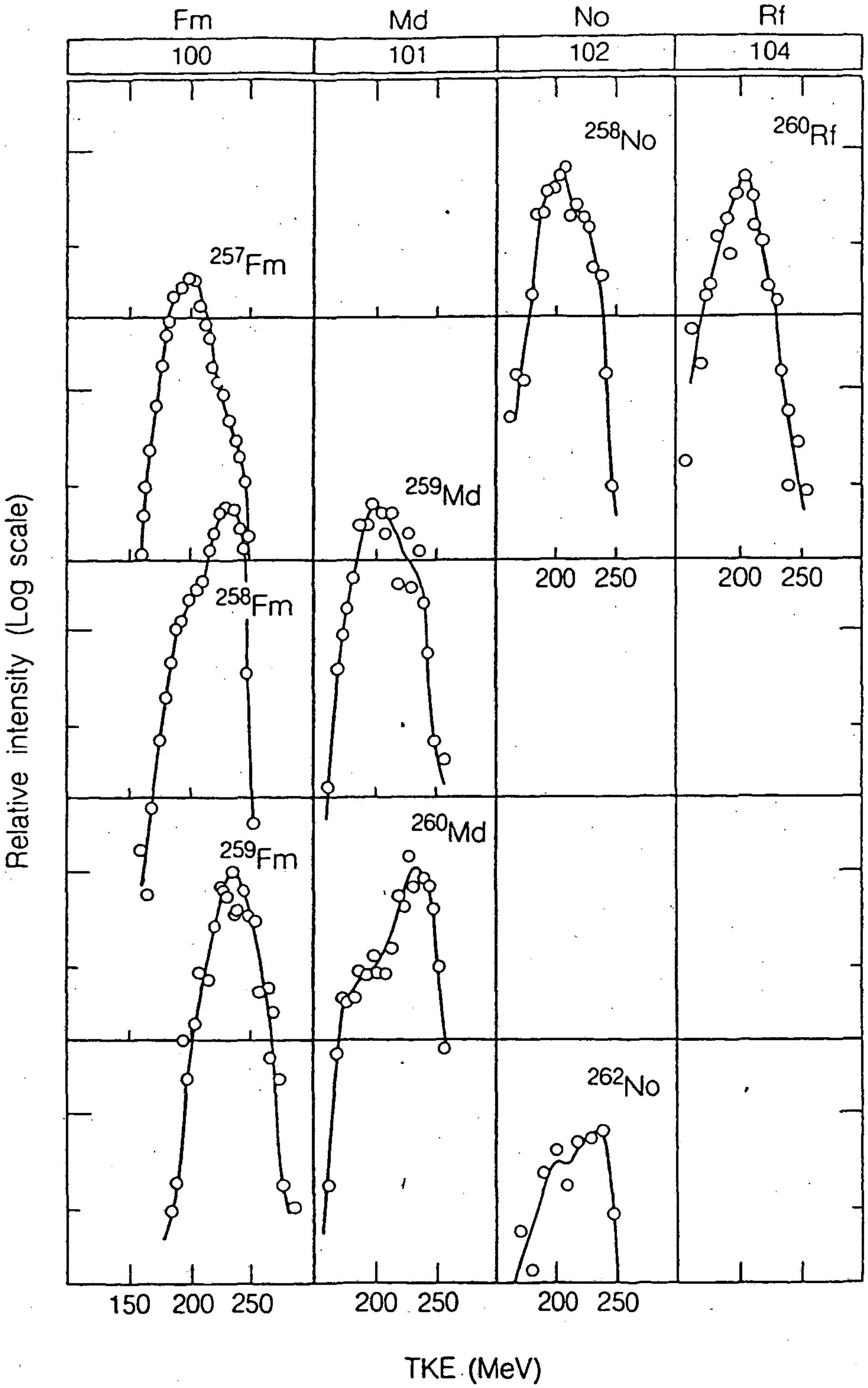


Figure 5

XBL 885-8873

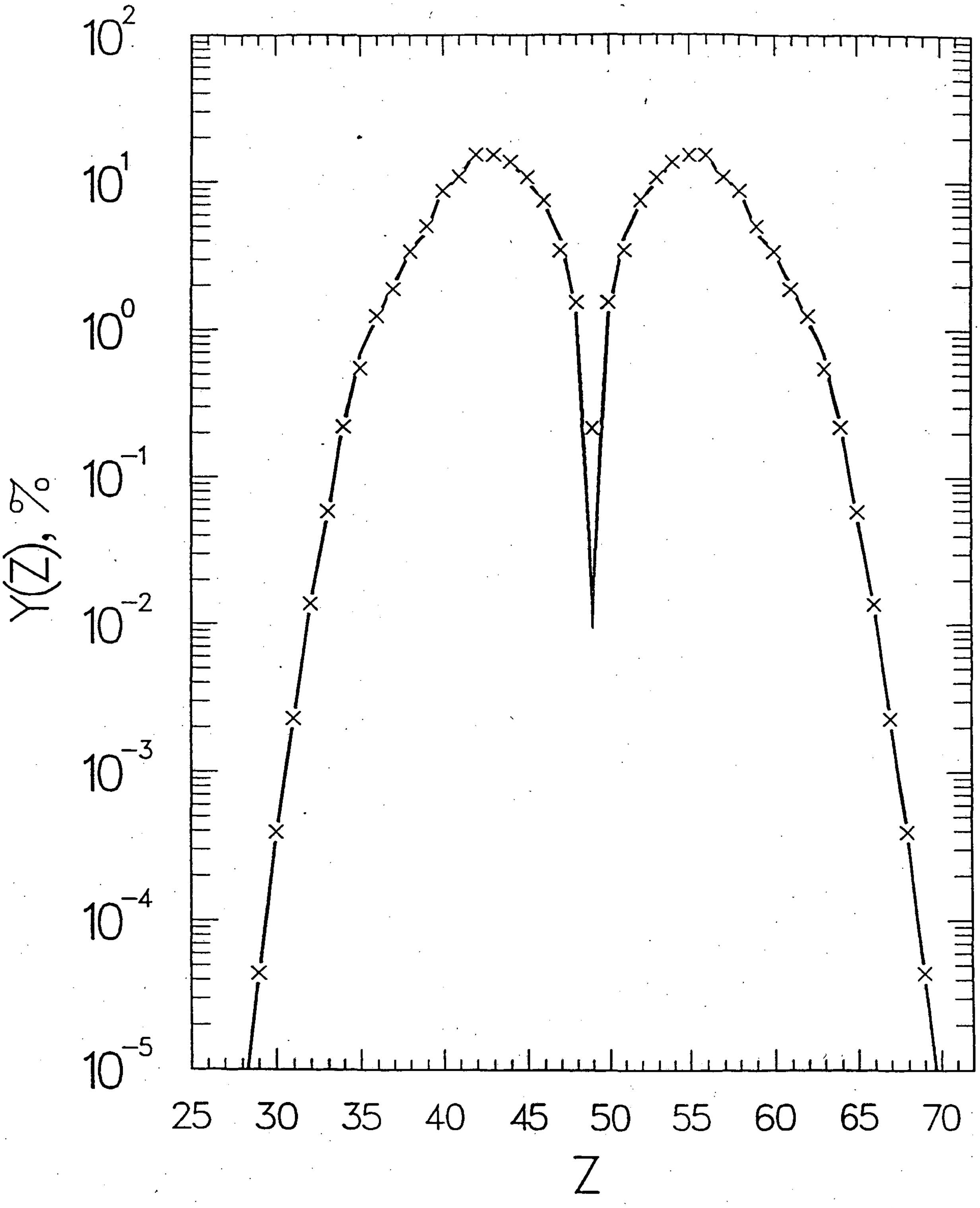


Figure 6

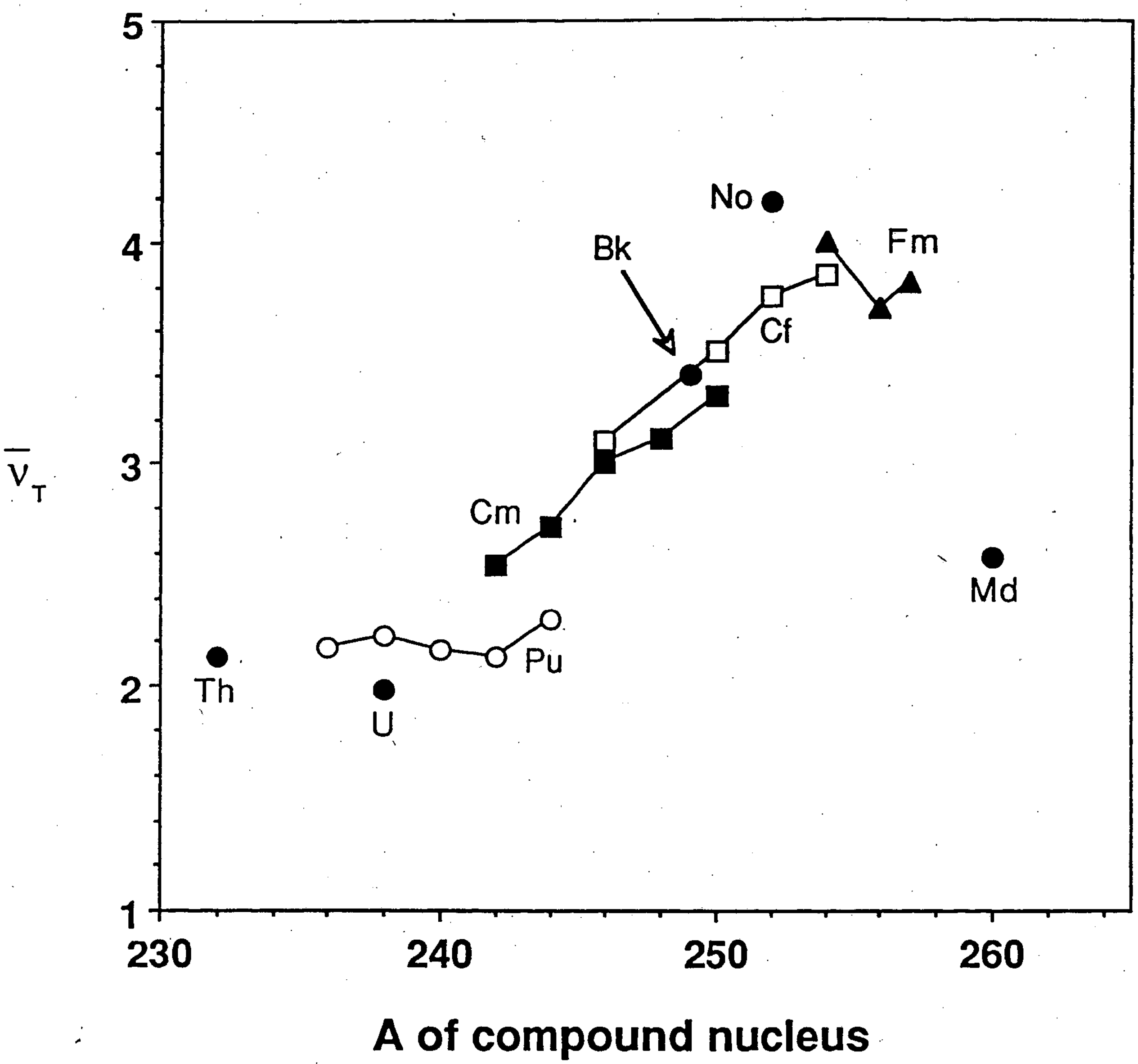
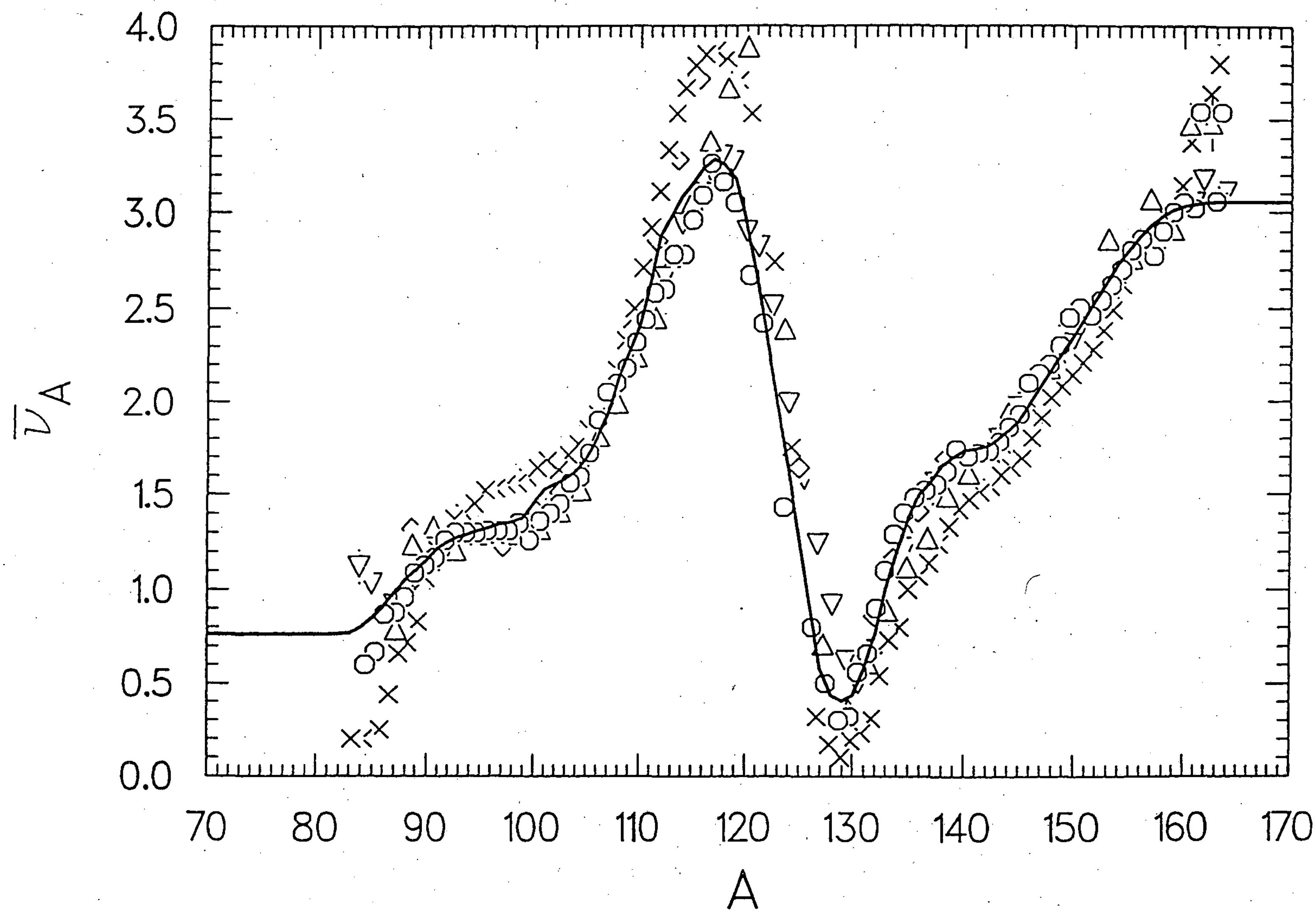

5
4
3
2
1
$\overline{\nu}_T$
230
240
250
260
A of compound nucleus
No
Bk
Fm
Cf
Cm
Md
Pu
Th
U

Figure 7



4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\bar{\nu}_A$
70
80
90
100
110
120
130
140
150
160
170
A

Figure 8

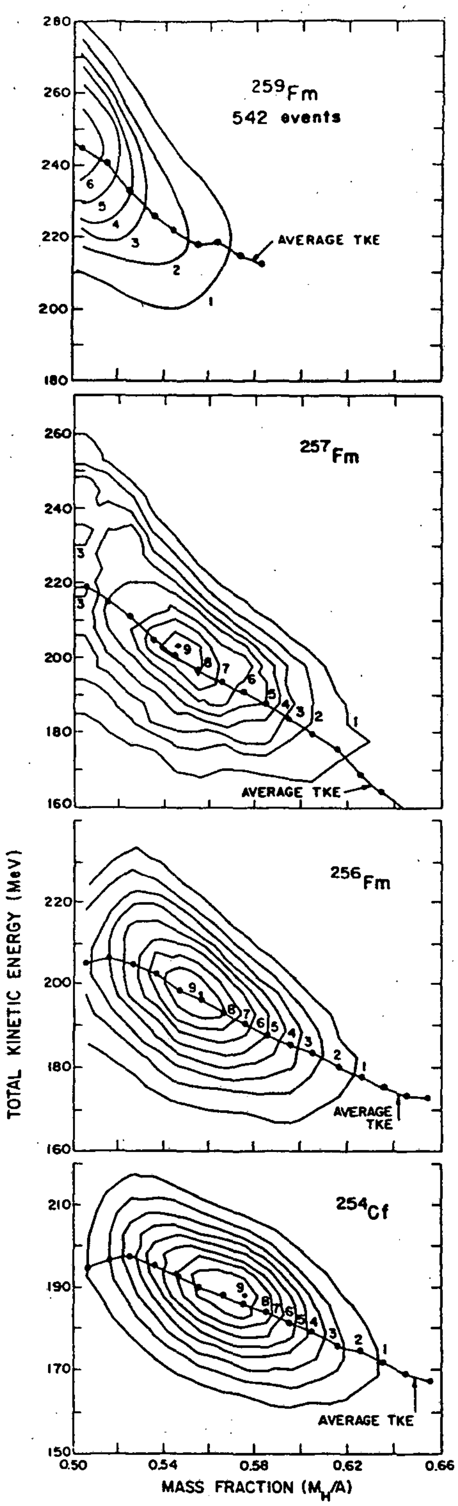


Figure 9

XBL 871-303

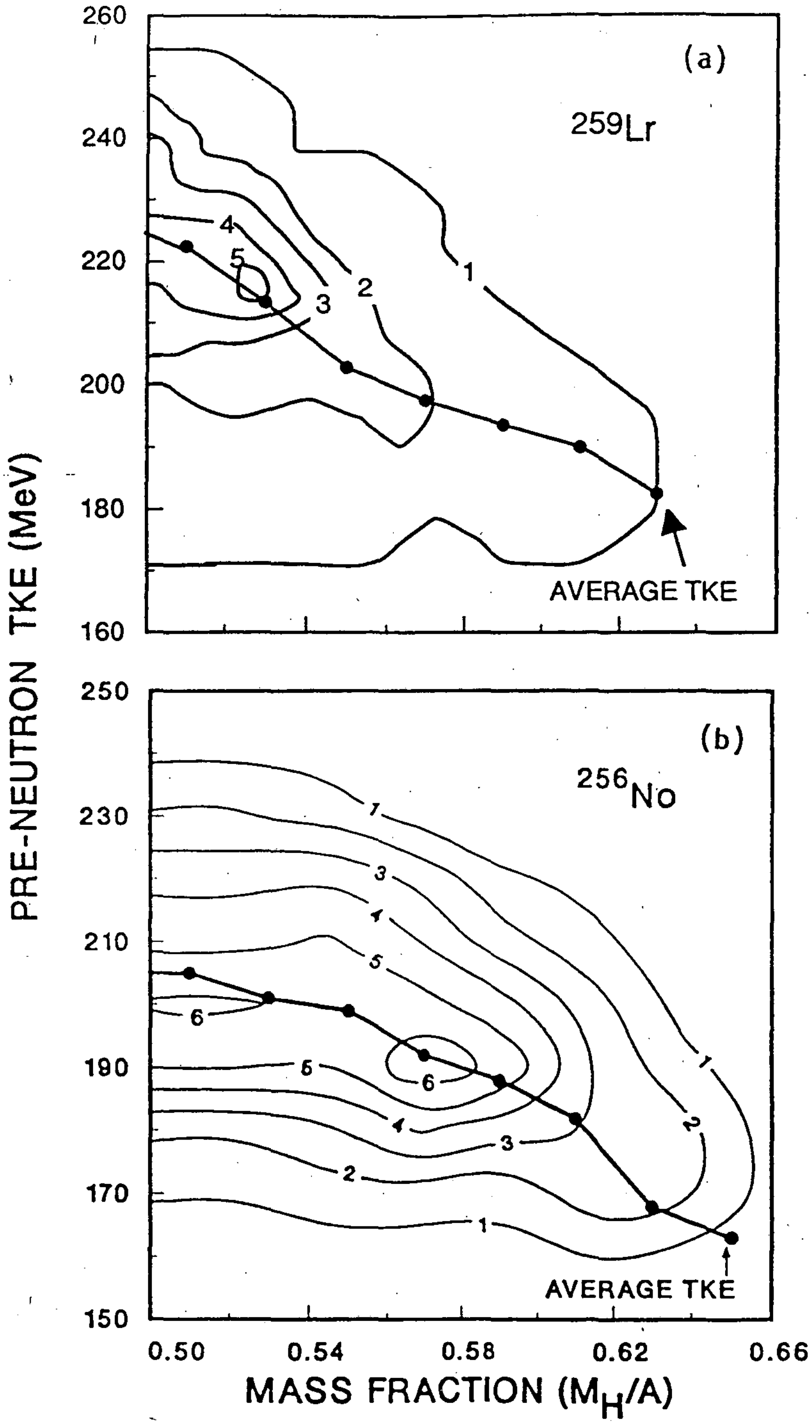

(a)
259Lr
1
2
3
4
5
AVERAGE TKE
(b)
256No
1
2
3
4
5
6
AVERAGE TKE
PRE-NEUTRON TKE (MeV)
MASS FRACTION (MH/A)
260
240
220
200
180
160
250
230
210
190
170
150
0.50
0.54
0.58
0.62
0.66

Figure 10

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