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Abstract

Recent experimental results for spontaneous fission half-lives and fission fragment mass and kinetic-energy distributions and other properties of the fragments are reviewed and compared with recent theoretical models. The experimental data lend support to the existence of the predicted deformed shells near Z=108 and N=162. Prospects for extending detailed studies of spontaneous fission properties to elements beyond hahnium (element 105) are considered.

Key words
Spontaneous fission (SF), SF properties: half-life systematics, mass division, kinetic energies, total kinetic energy, neutron and photon emission.

Spontaneous Fission

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I. Introduction

It has been 100 years since Henri Becquerel [1] found evidence for the natural decay chains in uranium by showing that uranium and its salts emitted radiation which blackened photographic plates even in complete darkness. This discovery led to extensive studies by Marie and Pierre Curie [2] who in 1898 proposed the name "radioactivity" for this new phenomenon and reported separation and discovery of the first radioactive elements radium and polonium from pitchblende, a very rich uranium ore. In addition to the alpha and beta decay exhibited by the ^{235}U and ^{238}U natural decay chains, it is interesting to note that spontaneous fission (SF), a much less common mode of natural radioactive decay, is also present. However, because of its small probability, SF was not discovered until 1940 when Petrzhak and Flerov [3] detected SF in ^{238}U with a partial half-life of some 10^{16} years, or only about one SF in 2×10^6 alpha decays. So far, SF has not been detected in any elements lighter than uranium (except for ^8Be which decays into two alpha particles), and upper limits for the probability of SF of 3.8×10^{-14} for ^{230}Th (Z=90) and 1.6×10^{-13} for ^{231}Pa (Z=91) have been set. Detailed studies of SF properties were not performed until much later when isotopes of higher Z elements with much shorter half-lives were synthesized. In the 1960's, sources of ^{252}Cf became available and measurements of the mass, charge, kinetic energies, neutron and photon emission of its fragments contributed much to our understanding of SF. Numerous reviews [4-11] of SF and low energy fission have been published and should be consulted for more detailed information.

II. Half-lives

In a recent review [11], we tabulated all of the SF half-lives reported as of mid-1992. The additional SF half-lives reported since then up until mid-1995 are given in Table I [Refs. 12-23]. The half-lives for e-e (even Z-even N) nuclides are plotted in Fig. 1, and those for e-o (even Z-odd N), o-e (odd Z-even N) and o-o (odd Z-odd N) nuclides are plotted in Fig. 2. In the case of the o-o nuclides, essentially no data except lower limits for SF half-lives have been reported and these lower limits are not included in the plot. It is extremely difficult to obtain measurements for the o-o isotopes because often they decay by electron-capture to e-e nuclides which decay via SF with very short half-lives; unless SFs in coincidence with the characteristic X-rays of the parent are measured it is nearly impossible to tell which isotope is spontaneously fissioning. In order to assess the hindrances associated with the odd nucleons, the logarithm of the experimentally determined SF hindrance factor (HF) is often plotted as a function of the odd-neutron and odd-proton numbers as shown in Fig. 3. The HF is calculated relative to the geometric mean of the SF half-lives of the two adjacent e-e neighbors [11]; if the half-life of only one e-e neighbor is known, it is used in the calculation. It can be seen that the HFs are about 10^5 for either an odd proton or an odd neutron where actual measurements and not just limits are known. The high-spin, 9/2+[615], 157th neutron seems to be especially effective in lending extra stability to elements 100, 102, and 104.

As can be seen in Fig. 1, it appears that the strong effect of the deformed N=152 neutron subshell on SF half-lives has disappeared by Z=104. However, recent reports [21,24] of longer than expected alpha and SF half-lives in the region of elements greater than or equal to 104 and near N=162 have been interpreted as a result of the predicted deformed shells [25-31] in the region of N=162 and Z=108. For example, the e-e isotope,

^{266}Sg (Z=106), was reported [21,24] to decay primarily by alpha emission with an estimated half-life of 10-30 s, rather than by SF with a few millisecond half-life as might otherwise have been expected. The known SF half-lives for elements 104 and higher are plotted in Fig. 4 together with the recent predictions [25,26] for these isotopes. As seen in Fig. 5, the predicted SF half-lives increase as a function of neutron number up to the deformed subshell at N=162 followed by a decrease to about N=170 and then another increase in half-life. Fig. 6 shows the log of the SF half-lives together with the alpha half-lives for the e-e isotopes of elements 104 through 114. For element 104 the longest predicted SF half-life of a few seconds occurs at N=162 which is still several orders of magnitude shorter than the predicted alpha half-life. At heavier neutron numbers, the SF half-life becomes still smaller, and thus SF will dominate and determine the half-lives of these nuclides. At element 106, SF will not dominate until N>164, and at element 108, SF will not dominate until N>166. For Z=110, 112, and 114, the alpha half-lives are microseconds to milliseconds until about N=172 when they reach about a second and are increasing. Since the SF and alpha half-lives are comparable it seems likely that these isotopes will have appreciable SF branches and half-lives long enough to permit study if they can be produced in reasonable yields. However, SF half-lives of seconds or more may be expected for many odd isotopes of these elements due to HF's of 10^3 to 10^5 (Fig. 3) and should allow study of still heavier isotopes.

The possibility of SF in isomeric states of actinide nuclei has been discussed by Baran and Lojewski [32]. They calculated SF half-lives of K-isomeric states on the basis of the microscopic-macroscopic method for an isomeric state assumed to be a 2-quasiparticle excited state with high angular momentum. They performed calculations for e-e nuclei with 96<Z<110 and 144<N<158 and found that the SF half-life may be comparable to that of the SF half-life of the ground state. They found for Z≥104 that the SF half-lives of the isomers and ground states may be comparable, provided the spin of the K-isomer is sufficient to prevent it from decaying by other processes. The recent assignment [33,34] of a 2.1-s SF activity to ^{262}Rf which already has a ≈50 ms SF activity assigned to it [6] could be a case in point. Reasonable neutron and proton single-particle assignments for this nuclide could give a two-quasiparticle K-isomeric state with 9+ or 10-. It is important to investigate whether or not this phenomenon can occur as there is the possibility that measured ground-state half-lives could actually be mixtures of the two states and could affect the interpretation of shell effects in these heavy nuclides [34].

III. Properties of the fission fragments

Spontaneous fission is especially sensitive to shell effects in both the fissioning system and the fragments because no additional energy is put into the nucleus before it fissions as is the case even for thermal neutron-induced fission where the excitation energy due to the neutron capture is typically 5 or 6 MeV. This is particularly noteworthy in the SF of the heavy fermium isotopes where a change of only one or two neutrons results in a dramatic change from asymmetric mass division with "normal" total kinetic energy (TKE) to narrowly symmetric mass division with very high TKE approaching the Q-value for fission. Detailed studies of the mass, charge, and kinetic-energy distributions of the fragments at scission, as well as prompt neutron and photon emission from the excited fragments, have been performed in order to help understand the SF process and aid in developing and testing predictive theoretical models.

Fragment mass, kinetic-energy, and charge distributions

Early measurements of fragment mass-yield distributions from both SF and neutron-induced fission were obtained by radiochemical and mass spectrometric methods were summarized by von Gunten [4] in 1969. Although such measurements have perfect Z and A resolution they suffer from the fact that the distributions of the fragments after neutron emission and interesting to compare the progression from asymmetric to symmetric mass distribution with increasing neutron number for Fm (Z=100), No (Z=102) and Rf (Z=104) isotopes. The change from asymmetric to symmetric in No between N=154 and 156 is not as abrupt as for Fm between N=157 and 158, nor does the mass distribution become as narrowly symmetric even at N=160 as it is for Fm at N=159. Perhaps this is because the symmetric fragments for No cannot both have the Z=50 closed shell configuration. It would be extremely interesting to measure the distributions for ^{260}No and ^{261}No, the N=158 and 159 isotopes. The data for Rf are not as complete, but Hulet [42] postulated on the basis of the data for the N=152, 154, and 156 isotopes of Rf that due to disappearance of the second barrier to fission these isotopes exhibit "liquid-drop model" (LDM) type fission with broadly symmetric mass distributions and TKE distributions with only one component, close to empirical TKE fits based on this model. (An updated plot of the most probable or average TKEs for SF is shown in Fig. 8 together with the empirical linear fits of Viola et al. [44] and Unik et al. [45].) However, the recent measurements of ^{262}Rf (N=158) show a rather narrow, symmetric mass peak with "wings", not unlike the mass distribution observed for the transition nucleus ^{259}Md which also has 158 neutrons. Both of these nuclides have most probable TKEs which are rather high compared to the fit of Viola et al. shown in Fig. 8. In order to ascertain whether or not the properties of the Rf isotopes are being determined by disappearance of the second fission barrier, it is especially important to make measurements for ^{263}Rf to see if its mass distribution becomes still more narrowly symmetric or exhibits the broad distribution characteristic of LDM type fission and whether its TKE becomes still higher or is consistent with LDM fission.

Very little information is available for the odd-proton nuclides and additional measurements for Lr (Z=103) would be most helpful. Although ^{261}Lr (39 m) and ^{262}Lr (216 m) are known [47,48] and can be produced by transfer reactions between ^{254}Es and heavy ions such as ^{18}O and ^{22}Ne, their fission properties have not been measured because

^{262}Lr decays primarily via electron-capture (EC) to 5-ms ^{262}No which spontaneously fissions and masks the SF properties of both ^{261}Lr and ^{262}Lr. An upper limit of 10% was estimated [47] for the SF branch of ^{262}Lr.

The measured TKE distributions for some trans-Es isotopes are shown schematically on a semilog plot in Fig. 9 so their shapes can be compared directly. It shows that many of the distributions, e.g., those for ^{257,258}Fm, ^{259,260}Md, and ^{258,262}No cannot be easily fit with a single Gaussian. Hulet and others [49,50] have fit the distributions for ^{258}Fm, ^{259,260}Md, and ^{258,262}No with two Gaussians, centered around 235 MeV and the other around 200 MeV. They have called this "bimodal symmetric" fission, the higher TKE symmetric mode being associated with near spherical, symmetric fragments and the lower TKE mode with LDM type fission in which the second fission barrier has disappeared, resulting in broadly symmetric mass distributions and lower TKEs. However, several "transition" nuclei such as ^{256}No, ^{259}Lr, as well as ^{262}Rf show more or less symmetric TKE distributions with no evidence for more than one component and their mass distributions range from symmetric and asymmetric in ^{256}No to broadly symmetric in ^{259}Lr to narrowly symmetric with asymmetric "wings" in ^{262}Rf. The most probable TKEs and FWHMs are 196 MeV and 42 MeV, 215 MeV and 40 MeV, and 215 MeV and 43 MeV, respectively for ^{256}No, ^{259}Lr, and ^{262}Rf, respectively. These features can be seen more clearly in the contour plots shown in Fig. 10. The fragments from these transition nuclides may show not just "bimodal" fission consisting of two compact (spherical) or two deformed fragments, but combinations [10] consisting not only of two compact or two deformed fragments, but combinations including one compact fragment and one deformed fragment (with different deformations) as discussed in the scission-point model of Wilkins et al. [51] and Lee et al. [52]. Thus, because of the extremely large variances of the TKE values for symmetric mass division, we should perhaps speak of "multimodal" [7], rather than bimodal fission and a variety of combinations of different shapes, depending on the shell structure in the fissioning systems, could be involved.

In his recent review [25] of theoretical studies of ground-state properties of the heaviest nuclei, Sobiczewski has shown contour plots of the potential energy of ^{258}Fm as a function of β_2 and β_4 deformations. In the case where the energy is minimized in β_3, β_5, and β_6 degrees of freedom and the fission trajectory is calculated statically, two paths of the same half-life result, one giving rise to compact, reflection symmetric shapes while the other leads to much more elongated shapes which are not necessarily reflection symmetric. This is consistent with the observation [49] of both high and low TKE fission in ^{258}Fm with nearly equal intensities. If only reflection symmetric shapes are included in the calculation, then the fission proceeds only to the compact shape valley. It would appear that a similar calculation, which takes into account reflection asymmetric shapes and also includes dynamical effects in the fission process following the barrier, might give paths resulting in the variety of asymmetric and symmetric fragments with different deformations as indicated by the experimental results for the transition nuclei ^{256}No, ^{259}Lr, and ^{262}Rf.

The effects of neutron shells and fission channels in the SF of the even-even Pu isotopes 236, 238, 240, 242, and 244 have been carefully investigated by Wagemans et al. [53,54]. They have found rapidly varying fission fragment mass and kinetic-energy distributions with the change of only a few neutrons. These were initially interpreted in the frame of the static scission-point model [51] as due to the changing relative importance of the N=82 spherical fragment and the N=87 deformed fragment shells and their combination with the Z=50 spherical shell. More recently, these results have been interpreted in terms of the fission channel model of Brosa and coworkers [55,56] and the relative fragment yields have been correlated in detail with this multimodal, random neck rupture model. In this model the potential-energy surface as a function of the deformation is calculated for the fissioning nucleus from ground state to scission. The pre-scission configuration is allowed to rupture in a random manner according to Rayleigh instabilities. The potential energy of the nucleus is calculated as a function of its nuclear deformation which is parameterized in terms of the half-length of the pre-scission shape, its neck radius and the position at which the neck ruptures. This gives rise to a number of different fission barriers which correspond to certain pathways within the calculated potential energy surface. These different pathways or channels give rise to different fragment mass and energy distributions, etc., and six different fission channels (three asymmetric channels called Standard I, II, and III, superasymmetric, superlong, and supershort) have been predicted for ^{252}Cf.

Essentially all of the information concerning charge division in SF is based on measurements of ^{252}Cf. Wahl [57] has comprehensively evaluated the data for SF of ^{252}Cf and thermal neutron-induced fission of ^{233}U, ^{235}U, and ^{239}Pu, and derived parameters for empirical models which describe charge dispersion for constant mass number and mass number dispersion for constant atomic number. Although he notes the preference for formation of fragments with Z=50 due to the effect of the 50-proton shell in the fragments, he also points out that the maximum fragment yields occur at higher Z values of 52, 54, 56, and at the 82-neutron shell and above.

Prompt neutron and gamma-ray emission.

In order to determine the pre-neutron emission fragment yields and kinetic energies, information concerning prompt neutron emission as a function of fragment mass is required. Unfortunately, for most spontaneously fissioning nuclides only the average number of prompt neutrons per fission, $\overline{\nu_T}$,and in many cases, not even that has been measured. The values measured for $\overline{\nu_T}$ for SF are plotted in Fig. 11 as a function of the mass number of the fissioning nuclide. It can be seen that, in general, the number of neutrons emitted increases with Z and A, and for trans-Pu nuclides, it increases with mass for a given Z. This trend is reversed in the Fm isotopes where the average neutron emission is actually lower for ^{256}Fm and ^{257}Fm than for ^{254}Fm. This is due to the increased yield of symmetric mass division with high TKE which means there is less energy left for prompt neutron and photon emission from the fragments. Early measurements [59] of prompt neutrons in coincidence with fission fragments were performed using a large Gd-loaded liquid scintillation detector and solid-state detectors to study neutron emission, multiplicities, and variances as a function of fragment mass ratio and TKE for several Cf and Fm isotopes. These studies showed that the neutron multiplicities vary greatly for these isotopes as a function of mass split and TKE. For example, for ^{252}Cf the average neutron emission for the most symmetric mass splits was found to range from 2.1 for the highest TKE (210-220 MeV) events to 5.9 for the lowest TKE (150-170) events; for the most asymmetric events, the range was from 1.7 for TKE from 190 to 210 MeV to 4.8 for TKE from 150 to 170 MeV, although the overall $\overline{\nu_T}$ was measured to be 3.735 with a variance of 1.55. For the most symmetric events from ^{257}Fm, $\overline{\nu_T}$ ranged from only 1.1 for TKE>240 MeV (close to the Q-value for fission) to 4.9 for TKE from 160 to 180 while the average neutron emission over all mass splits and TKEs was 3.8 with a variance of 2.5. These data could probably now be interpreted on the basis of Brosa's multimodal model.

In the case of ^{259}Fm and ^{260}Md, whose most probable TKEs approach the Q-values for fission, it would be expected that prompt neutron emission from the symmetric, near-spherical fragments must also be very low. This was experimentally verified for ^{260}Md, which has a much more abundant high energy component than does ^{257}Fm, by Wild et al. [60] who measured a value of 2.58 for the average neutron emission from the fragments.

Recently, Van Aarle et al. [61] performed similar measurements for ^{252}Cf of the neutrons emitted from the fragments as a function of fragment mass and kinetic energy. From an investigation of the correlations between the neutron multiplicity and the TKE of the fission event, they derived SF parameters in order to search for the six different fission channels predicted by Brosa et al. [56] and found evidence for all channels, although the intensity of the superasymmetric mode was only 0.3%. They also derived schematic pre-scission configurations for these various modes, including the number of neutrons emitted from the light and heavy fragments.

Because information about neutron emission as a function of fragment mass is not generally available for SF, various methods for use in correcting radiochemical data and SS measurements to pre-neutron emission values have been devised and fuller discussions of neutron emission and energy spectra are given in Refs. 6 and 10.

The excitation energy of the fragments can also be dissipated by gamma-ray emission. This phenomenon has been even less well investigated than neutron emission although it can give information concerning the deformation of the fragments and the configuration at scission. Most of the studies have been of ^{252}Cf, but there have been some studies of ^{238}U, ^{240}Pu, and ^{244}Cm; these are discussed in recent reviews. Sokol et al. [62] have reported one of the few studies of the trans-Cf isotopes and measured energies, intensities, total gamma-ray energy and average number of gamma-rays per fission. They found the number of photons per fission for ^{254}Cf and ^{259}Md to be about 5.3, somewhat smaller than the 6.5 to 7 measured for ^{248}Cm and ^{252,254}Cf. These data are exceedingly difficult to obtain but the information helps in inferring details about the shape of the system at scission and in deducing the deformation and excitation of the fragments and subsequent neutron emission.

IV. Future

Due to the stabilizing effect of the Z=108 and N=162 deformed shells, the SF and α half-lives of the e-e isotopes with $Z \geq 104$ are not decreasing as rapidly as previously anticipated (see Figs. 4-6). The recent discoveries of longer than expected half-lives for the e-e isotopes ^{262}Rf (2.1 s SF) and ^{266}Sg (20-110 s α) and isotopes of elements 107 through 111 [63] (see Fig. 12) which decay predominantly by alpha-emission support the results of these calculations [26]. It appears that SF should compete with alpha-decay in the e-e isotopes of Z=108 with N around 166 to 168, of Z=110 and 112 with N≥170 with half-lives in the range of tenths of seconds to tens of seconds. For Z=114, alpha decay appears to dominate for isotopes in this half-life range. The o-o isotopes would be expected to have still longer SF half-lives because of the odd particle hindrances (Fig. 3) discussed earlier; therefore, alpha-decay should predominate in these isotopes as well so the SF branches may be too small for study. One question to be answered will obviously be whether these odd-particle hindrances will be as large as previously observed for the lighter isotopes. Another question to be investigated is the possible existence of SF isomers and how to verify this experimentally.

Much progress has now been made in developing theoretical models with capabilities for predicting half-lives and scission configurations as well as properties of the fission fragments. Now, many challenges remain for the experimentalists seeking to obtain more information about SF in these new, still higher Z isotopes. The first will be to produce a sufficient number of atoms for study. Multiple-target systems utilizing the most neutron-rich actinides which can be made available, such as ^{244}Pu, ^{250}Cm, ^{249}Bk and ^{254}Es, together with appropriate high-intensity, neutron-rich heavy ion beams should greatly help in gaining access to isotopes with half-lives of seconds or longer. Another challenge will be to devise efficient, high-resolution techniques for positively assigning the atomic number and mass of nuclides which cannot be linked by alpha decay genetics to known daughter or even granddaughter isotopes. In some cases, such as for Sg (106), Ns (107), and Mt (109), chemical separations may be feasible [64] and experiments to perform chemical separations of Sg are being conducted by an international collaboration. For isotopes with half-lives much less than a second and production cross sections of picobarns or less, on-line or near on-line instrumentation techniques which can provide Z and A resolution sufficient for positive identification, as well as information about mass division, kinetic-energy distributions and neutron and photon emission from the fragments need to be developed. Furthermore, these techniques need to be efficient enough to obtain statistically significant results in a finite length of time. However, the exciting possibility of extending our knowledge of the fission process, the influence of nuclear shells, and the limits to nuclear stability at the heaviest end of the chart of the nuclides appears especially promising.

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TABLE I. Recent measurements of half-lives, SF partial half-lives, and total kinetic energies.

Nuclide[a]	Half-life	$T_{1/2}^{SF}$ or %SF	TKE (MeV)[b]	Reference
^{238}Pu	87.7±0.01 yrs	$(4.75\pm0.09)\times10^{9}$ yrs	177.0±0.5	11
			177.0±0.3	12
^{240}Pu	$(6.56\pm0.01)\times10^{3}$ yrs	$(1.14\pm0.01)\times10^{11}$ yrs	179.4±0.5	11
			179.4±0.1	12
^{242}Pu	$(3.75\pm0.02)\times10^{5}$ yrs	$(6.77\pm0.07)\times10^{10}$ yrs	180.7±0.5	11
			180.7±0.1	12
^{248}Cm	$(3.48\pm0.06)\times10^{5}$ yrs	$(4.15\pm0.03)\times10^{6}$ yrs	182.2±0.9	11
			182.0	13
^{237}Cf	2.1±0.3 sec	~10%		14
^{238}Cf	If $T_{1/2}$≈1 sec, then	>4 sec		11
	21 msec	~100%		14
^{240}Cf	0.9±0.2 min	~2%		14
^{242}Cf	3.4±0.2 min	≤0.014%		14
$^{258}Md^{m}$	57.0±0.9 min	≤30%		15
^{252}No	$2.25^{+0.18}_{-0.16}$ sec	26.9%	202.4, 194.3*	11
	2.44±0.12 sec		194.3*	16
		(21.6±4.2)%		17
^{254}No	55±5 sec	0.17%, 0.25%		11
	53±20 sec	(0.17±0.02)%	189.2*	16
^{256}Rf	6.7±0.2 msec	$6.9^{+0.6}_{-0.2}$ msec	207±13	11
	6.6±1.1 msec		197.6±1.1*	16
^{258}Rf	13±2 msec	13±2 msec≤$T_{1/2}^{SF}$≤15±2 msec	220±15	11
	14±2 msec		198.9±4.4*	16
^{262}Rf	47±5 msec	47±5 msec		11
	2.1±0.2 sec	2.1±0.2 sec	215±2#	18
^{263}Sg	0.9±0.2 sec	1.3 sec ??		11
	$1.1^{+2.8}_{-0.6}$ sec			19
		<30%		20
^{265}Sg	2-30 sec[c]	≤50%		21
^{266}Sg	10-30 sec[c]	≤50%		21
^{264}Ns	440^{+600}_{-160} msec	ND[d]		22

^{267}Hs	19^{+29}_{-10} msec	≤20%	20
^{268}Mt	70^{+100}_{-30} msec	ND[d]	22
^{269}110	270^{+1300}_{-120} μsec	ND[d]	23
^{272}111	$1.5^{+2.0}_{-0.5}$ msec	ND[d]	22

[a] This table lists half-lives, spontaneous fission branches, and TKE's measured since the review by Hoffman, Hamilton, and Lane [11]. For comparison, previous values (if available) from that review are listed along with the newly determined values.
[b] Average values of the pre-neutron emission TKE's except for those denoted by (*), which are average values of the TKE's based on a provisional mass analysis, and by (#), which is the most probable pre-neutron emission TKE.
[c] Calculated half-life based on observed alpha-decay energy and systematics.
[d] No spontaneous fission events were observed.

Figure Captions

1. Logarithms of SF half-lives of e-e nuclei plotted *vs.* neutron number. Arrows are used to indicate lower limits. [Data from Ref. 11 and Table I]

2. Logarithms of SF half-lives of e-o, o-e, and o-o nuclei plotted *vs.* neutron number. (Lower limit values are not included.) [Data from Ref. 11]

3. Logarithms of SF hindrance factors (HF) for odd-neutron and odd-proton nuclides. Lower limit values are indicated by arrows. An open bar indicates that the HF was calculated relative to only one e-e neighbor. A filled or hacked bar indicates that the HF was calculated relative to two e-e neighbors. [From Ref. 11]

4. Logarithms of experimental and theoretical SF half-lives for even-Z elements 104 through 114 as a function of even neutron number 150 through 162. [Data from Refs. 11 and 26 and Table I]

5. Logarithms of the theoretical SF half-lives for even-Z elements 104 through 114 as a function of even neutron number 142 through 174. [Data from Ref. 26]

6. Dependence of logarithm of the calculated SF half-lives, given in seconds, on the neutron number N, for elements 104-114. The α-decay half-lives are also shown, for comparison. Experimental values are given by full points. The horizontal dashed line indicates about the lowest half-life (1μs) of a nucleus, which can be detected in a present-day set-up, after its synthesis. [From Ref. 26]

7. Schematic representation of all known mass-yield distributions (normalized to 200% fission fragment yield) for SF of trans-Bk isotopes. [Data from Ref. 11 and Table I]

8. Average or most probable TKE *vs.* $Z^2/A^{1/3}$. The solid line is the linear fit of Viola et al. [44] and the dashed line is the linear fit of Unik *et al.* [45]. Data are from Ref. 11 and Table I and have been corrected to the new Weissenberger parameters [46] as discussed in Ref. 11.

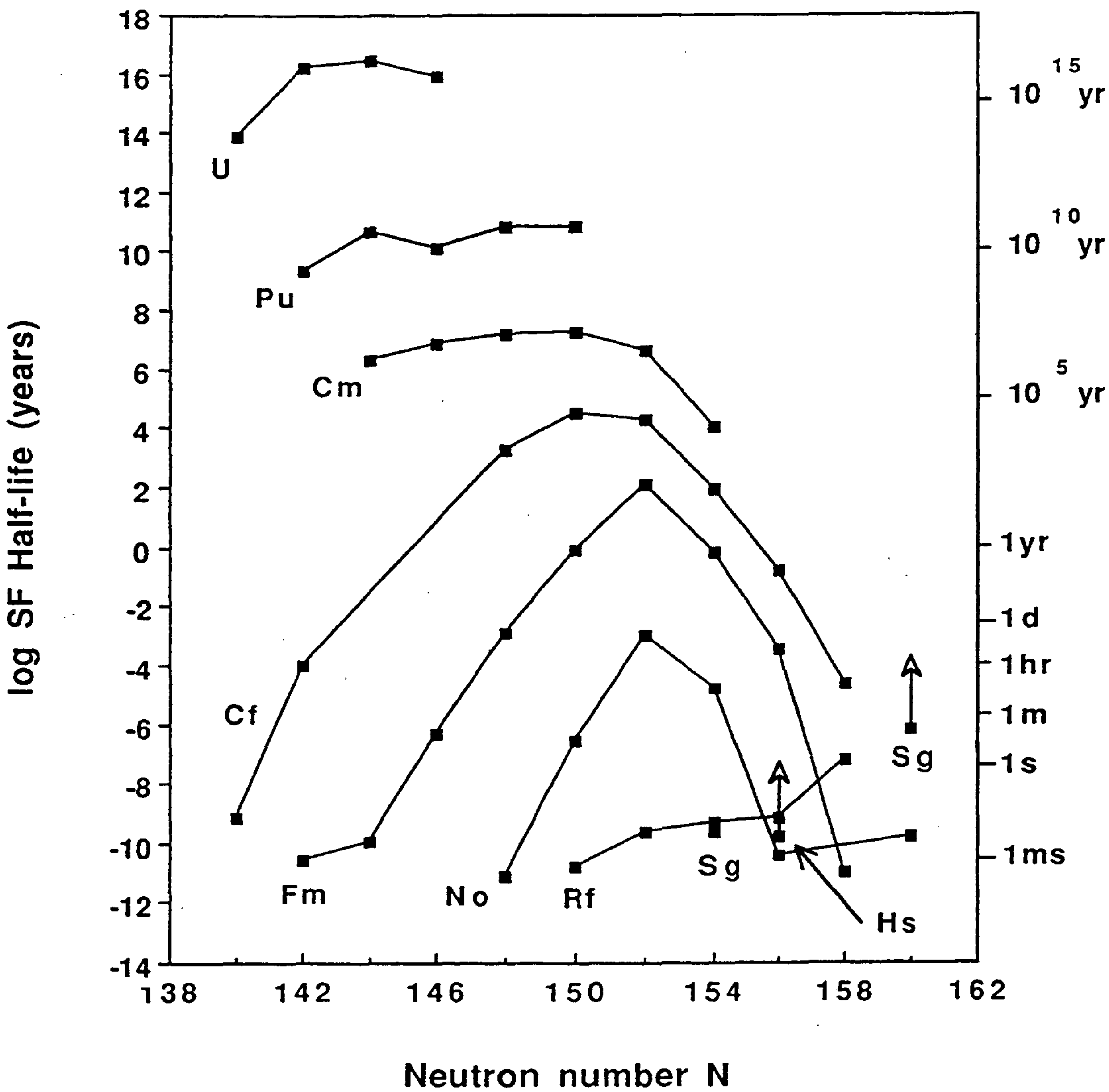
9. TKE distributions for SF of some trans-Es isotopes. [Data from Ref. 11 and Table I]

10. Contour plots of pre-neutron-emission TKE *vs.* mass fraction. The connected points represent average TKE as a function of mass fraction. a)^{256}No (346 SFs). 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. b) ^{259}Lr (442 SFs). 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. c) ^{262}Rf (200 SFs). The contours indicate equal numbers

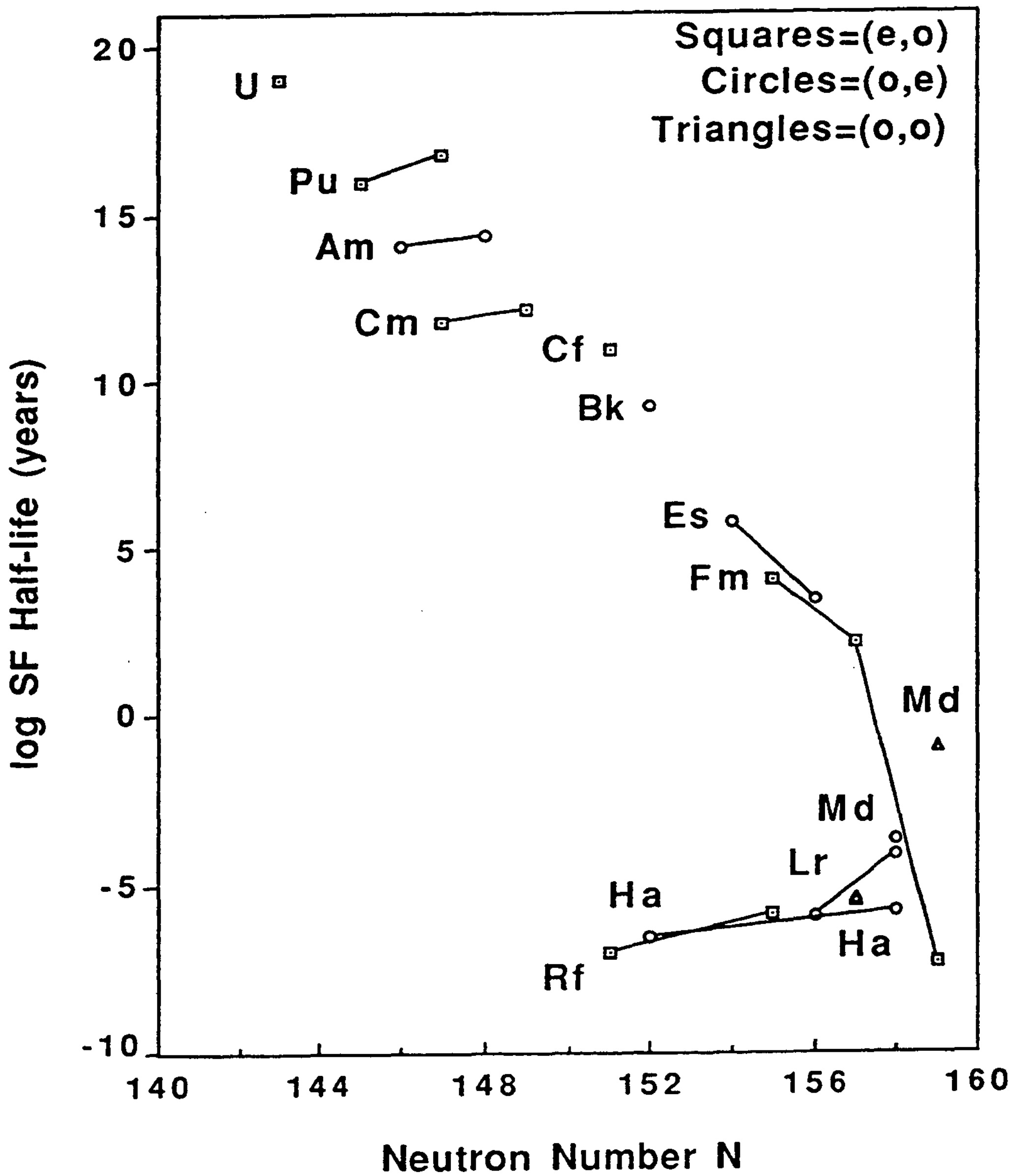
of events based on data groupings of 10 MeV x 0.02 units of mass fraction. Contours labeled 1 through 6 represent 4 through 24 events, respectively. [From Refs. 11 and 18]

11. Average total neutron emission per fission, $\overline{\nu_T}$, as a function of A of the spontaneously fissioning nucleus. [From Ref. 11, except for the addition of the value for ^{259}Md [58]]

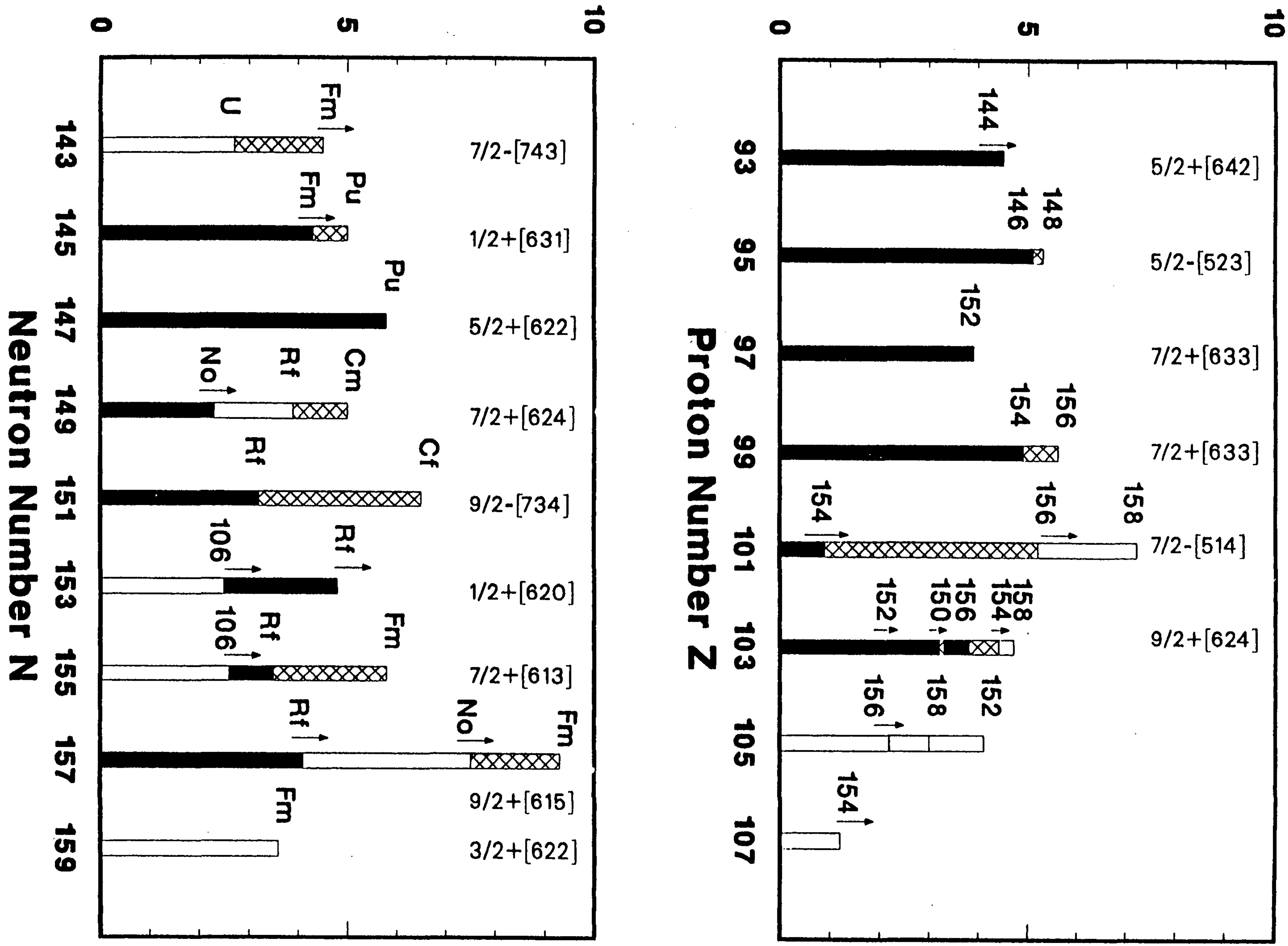
12. Chart of the trans-nobelium isotopes.

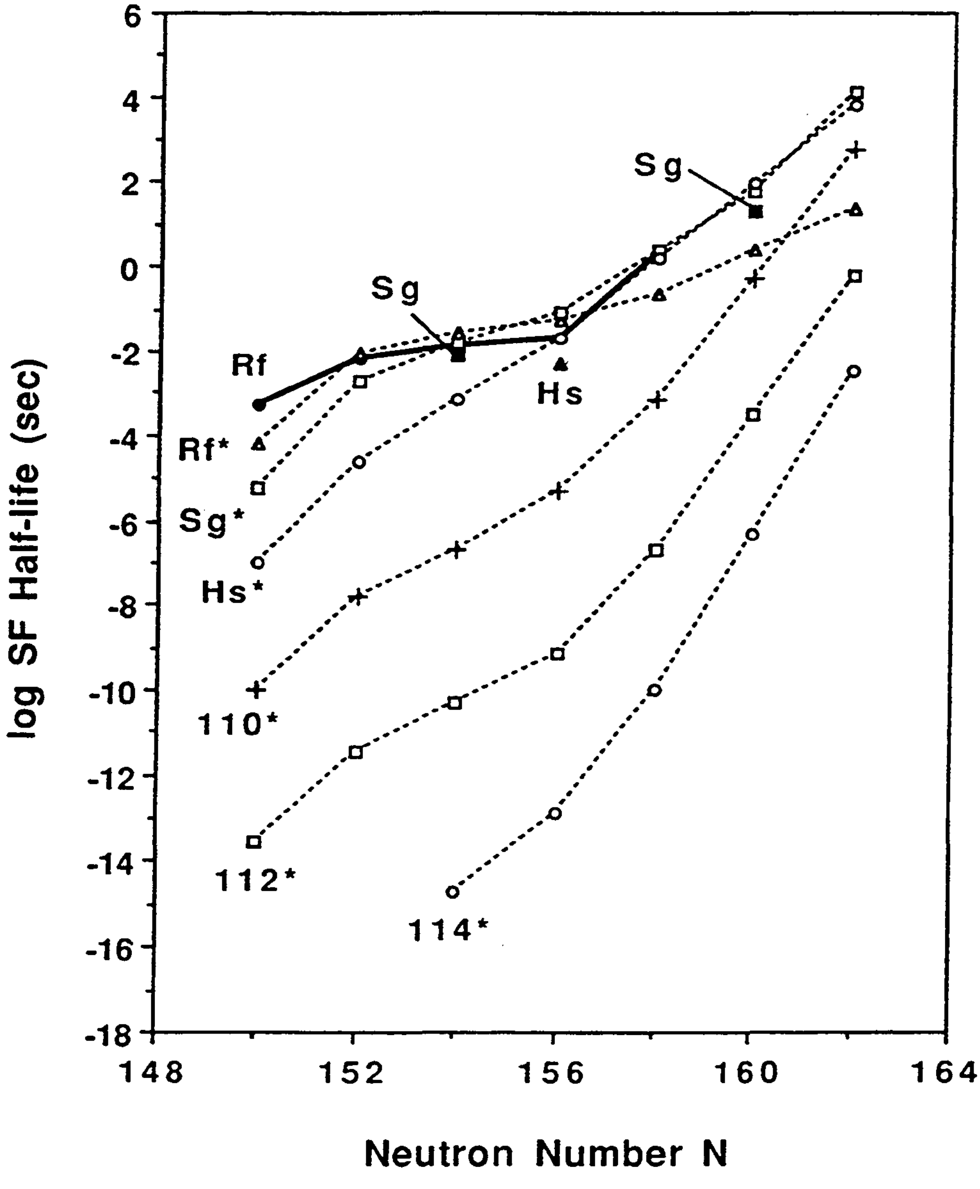


log SF Half-life (years)
Neutron number N
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
138
142
146
150
154
158
162
U
Pu
Cm
Cf
Fm
No
Rf
Sg
Sg
Hs
10 15 yr
10 10 yr
10 5 yr
1yr
1d
1hr
1m
1s
1ms

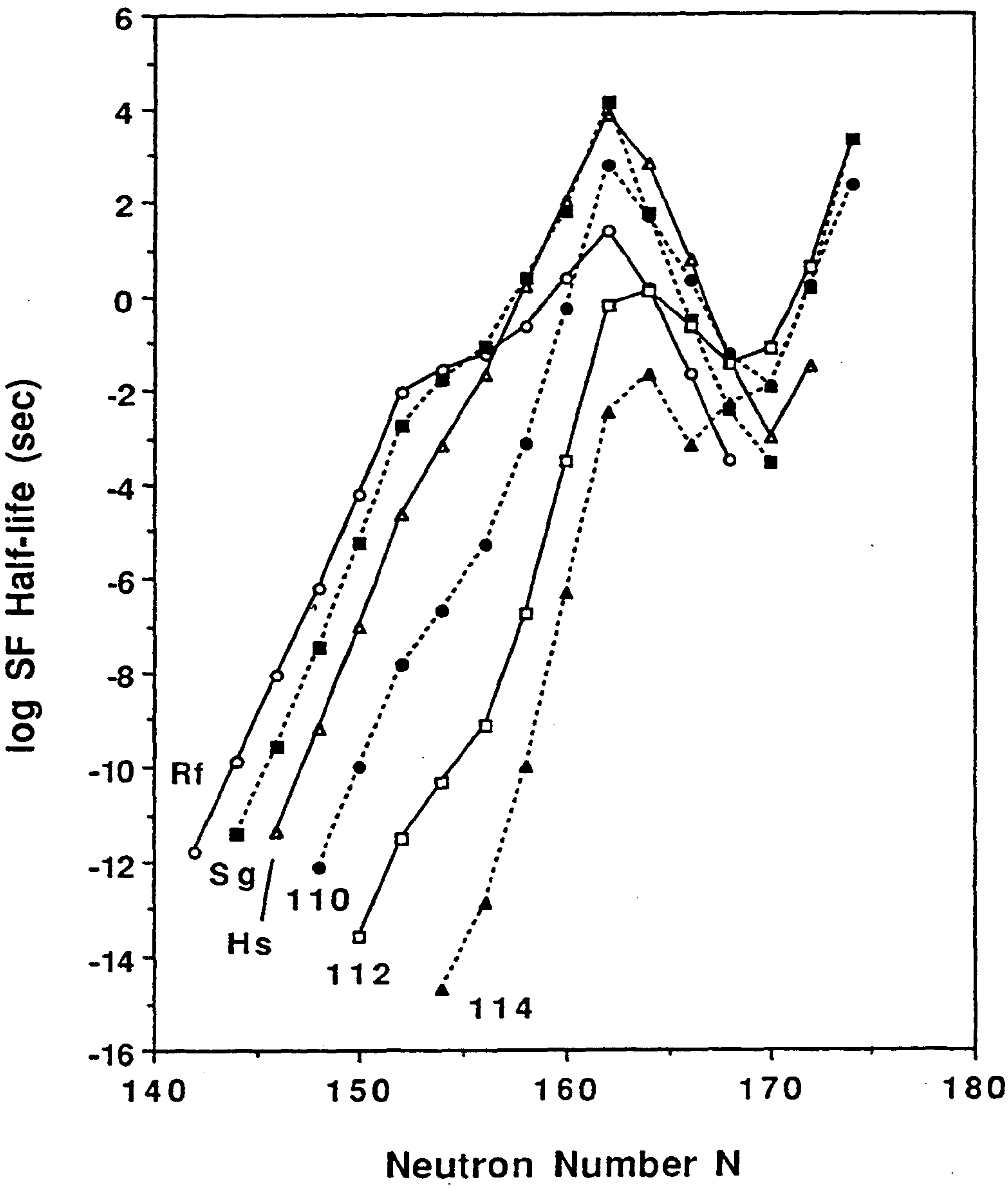

Squares=(e,o)
Circles=(o,e)
Triangles=(o,o)
U
Pu
Am
Cm
Cf
Bk
Es
Fm
Md
Md
Lr
Ha
Ha
Rf
20
15
10
5
0
-5
-10
140
144
148
152
156
160
log SF Half-life (years)
Neutron Number N

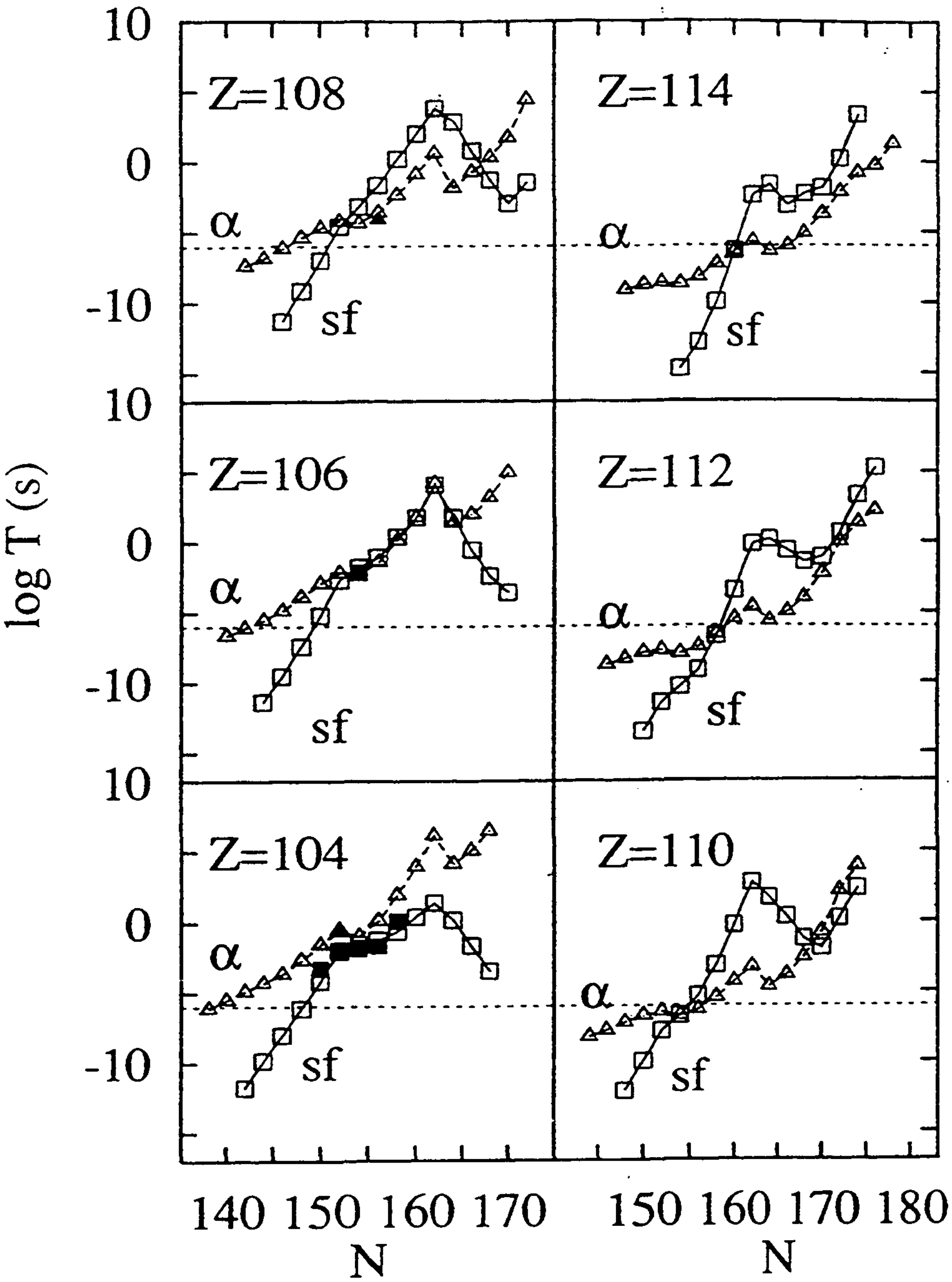
Log SF Hindrance Factors



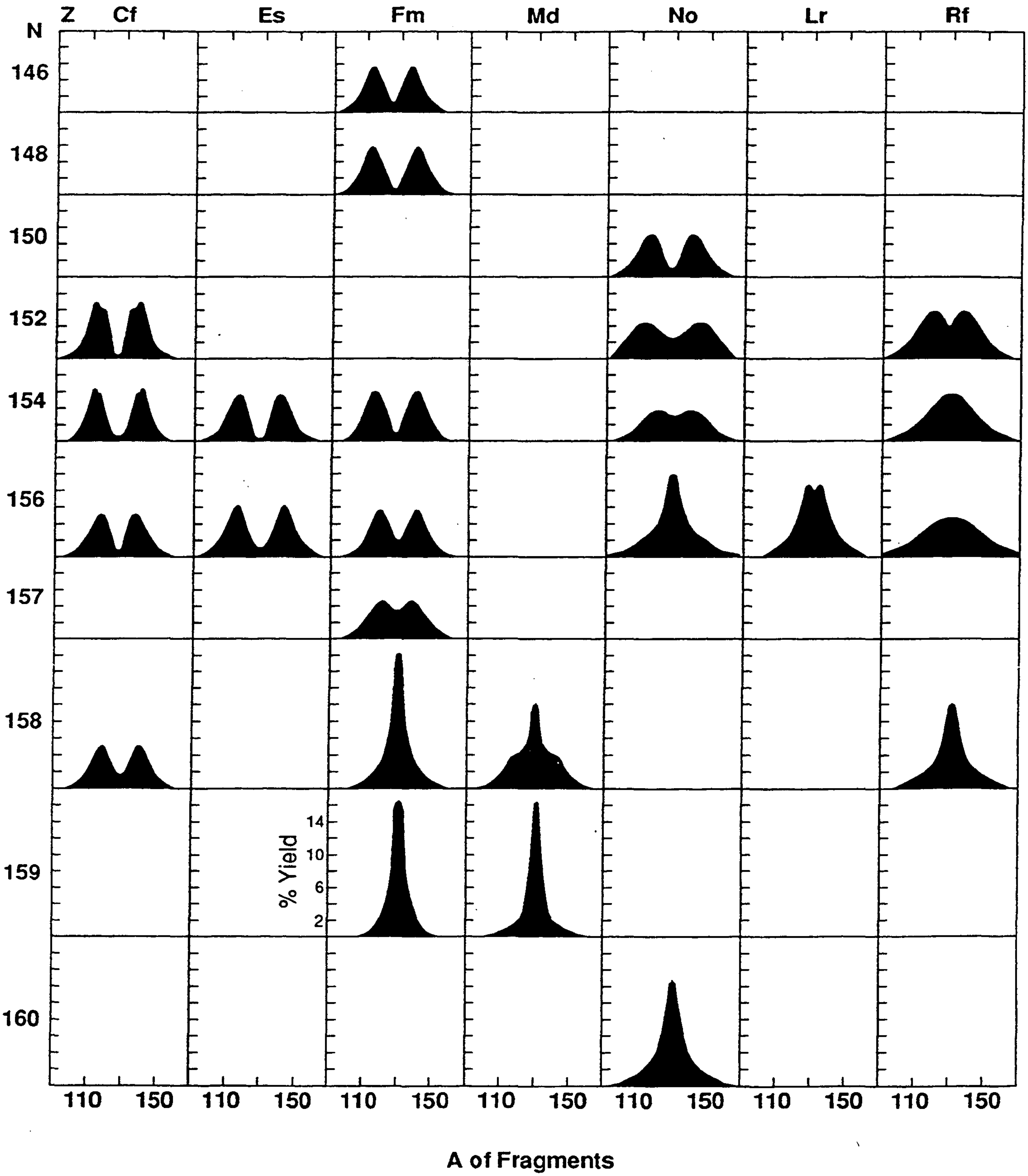


log SF Half-life (sec)
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
148
152
156
160
164
Neutron Number N
Rf
Rf*
Sg*
Hs*
110*
112*
114*
Sg
Sg
Hs

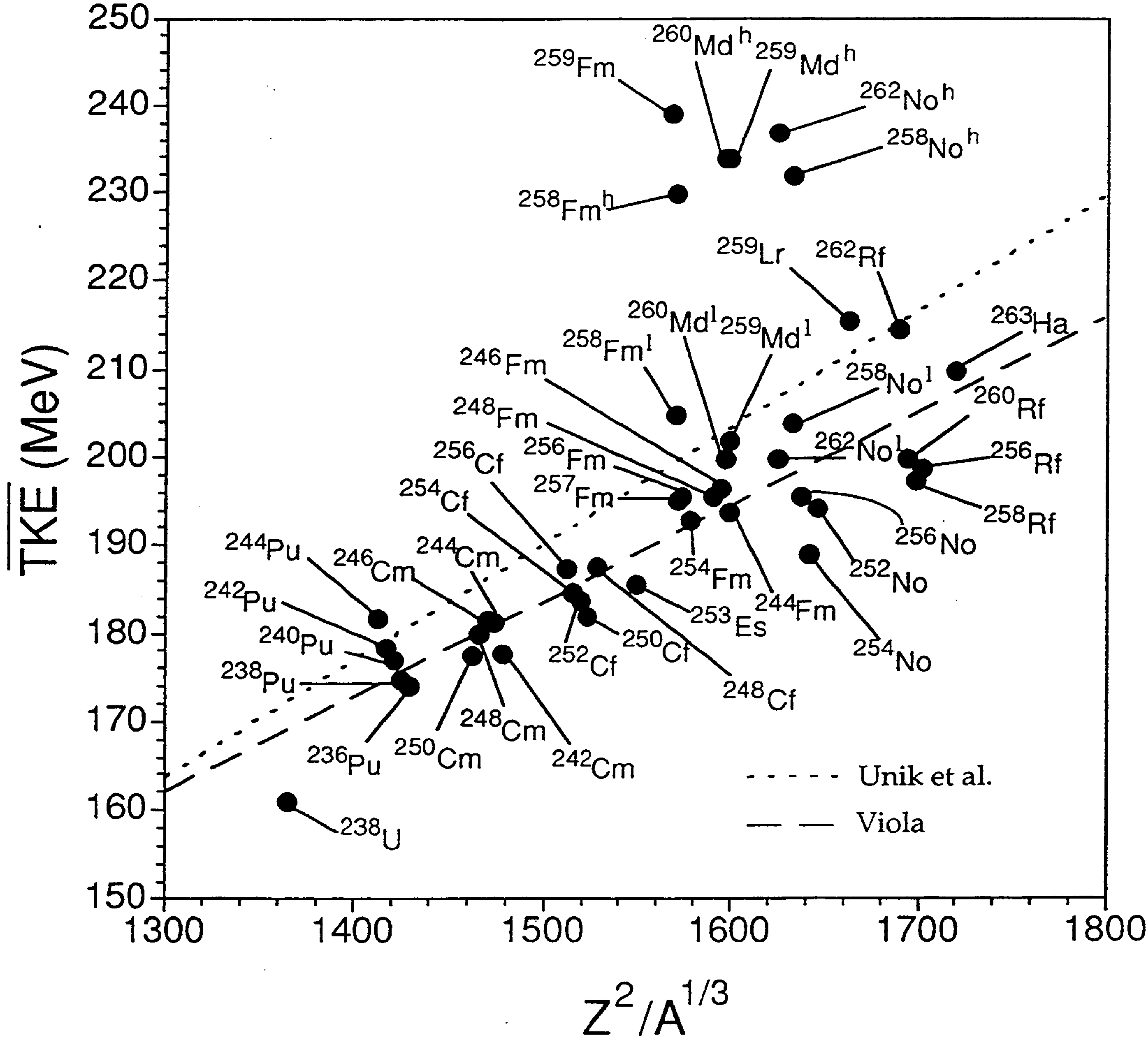

log SF Half-life (sec)
Neutron Number N
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
140
150
160
170
180
Rf
Sg
Hs
110
112
114



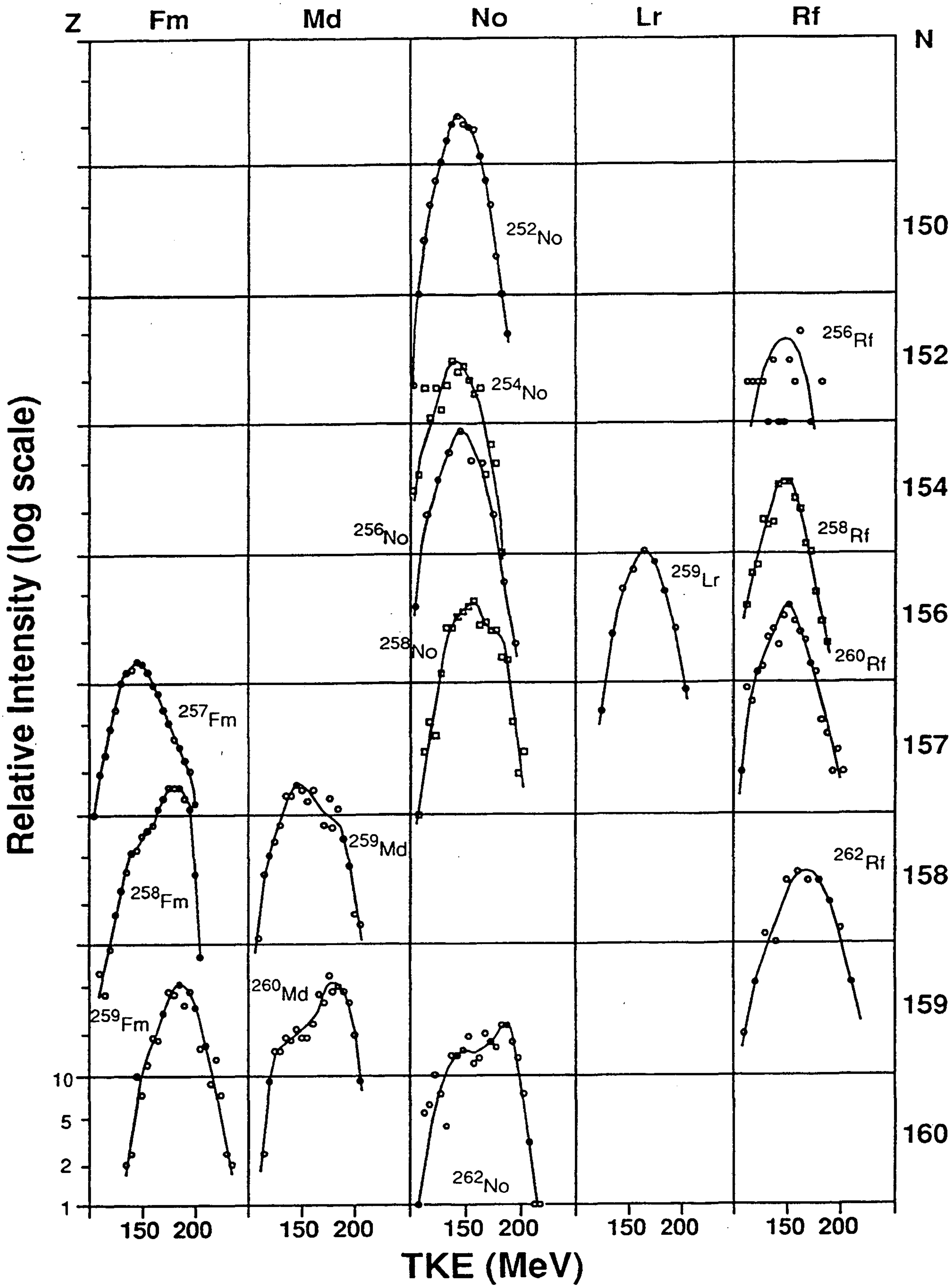
Z=108
Z=114
Z=106
Z=112
Z=104
Z=110
α
sf
log T (s)
N
10
0
-10
140
150
160
170
180



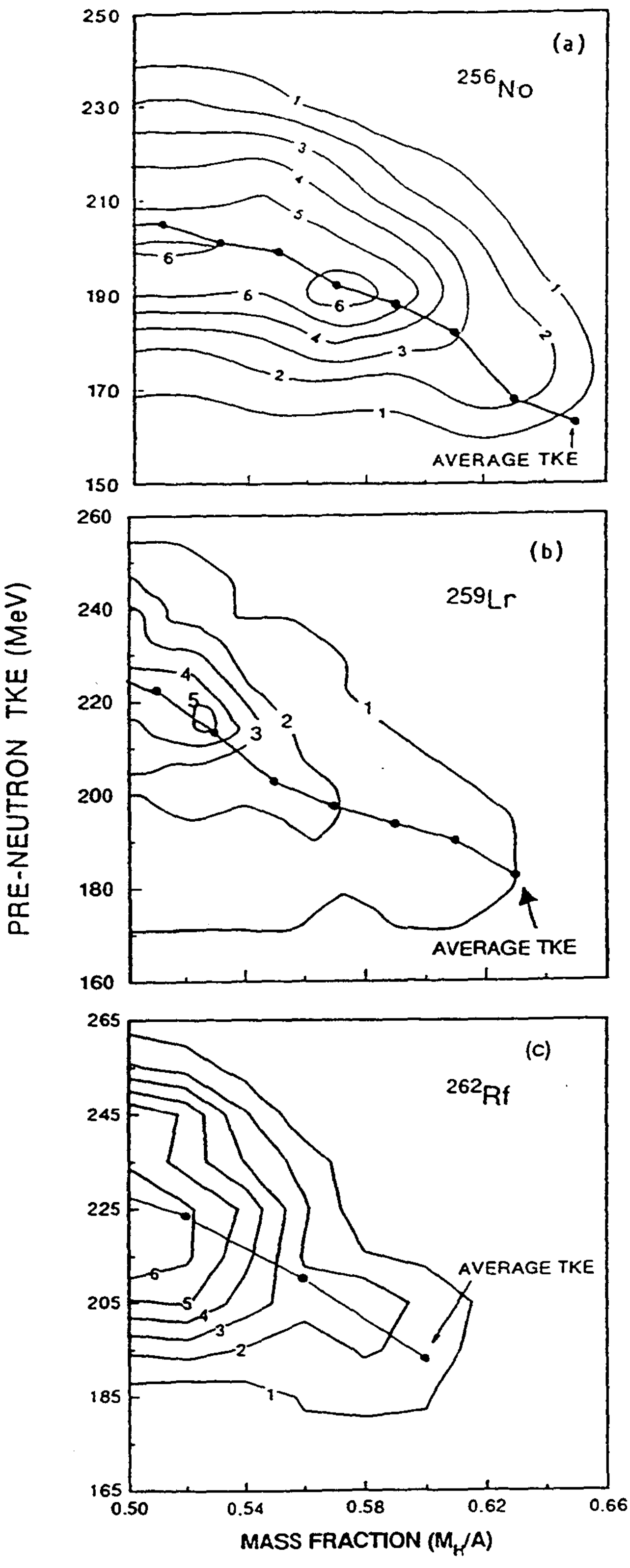
Z
N
Cf
Es
Fm
Md
No
Lr
Rf
146
148
150
152
154
156
157
158
159
160
% Yield
14
10
6
2
110
150
A of Fragments



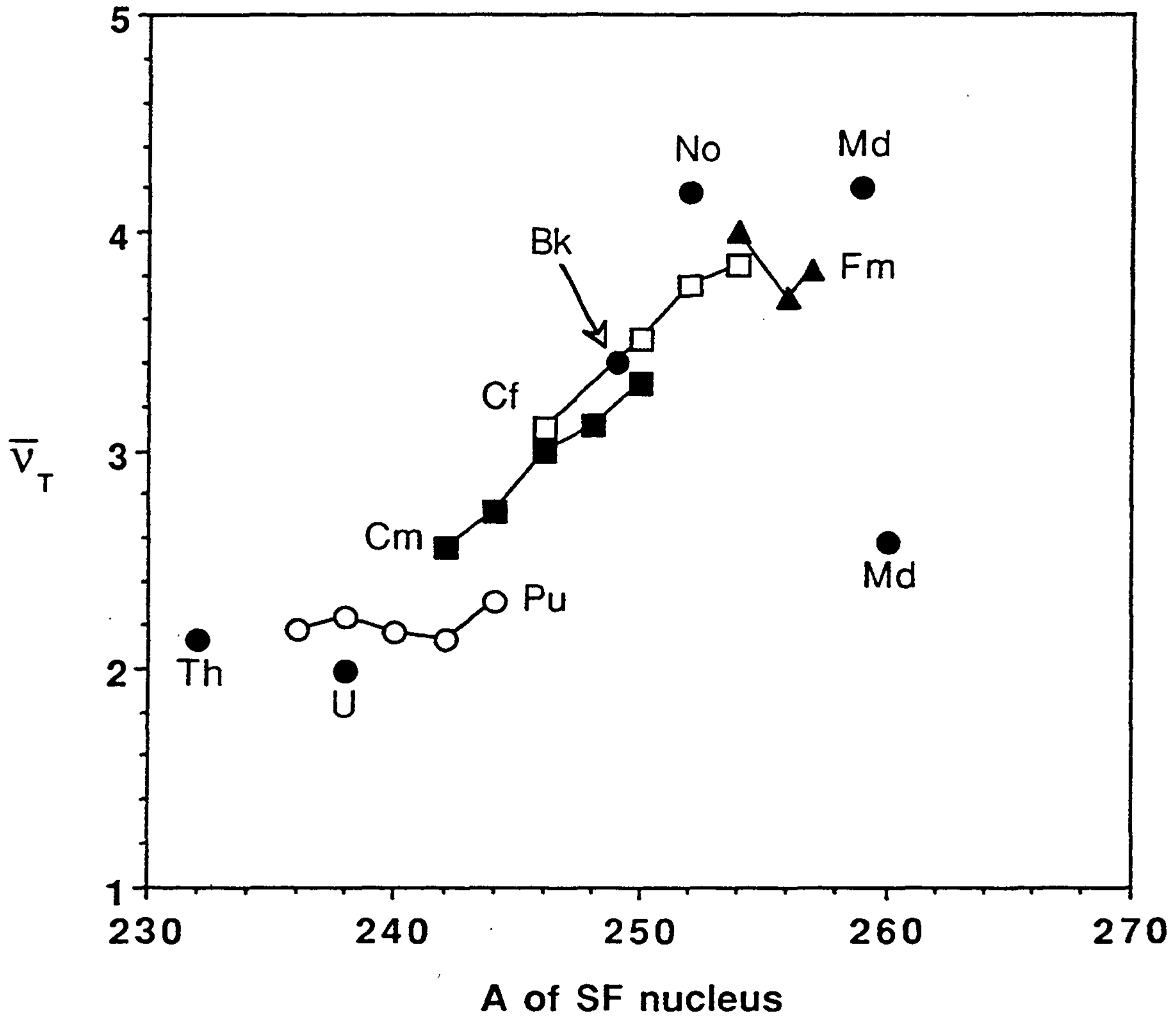
250
240
230
220
210
200
190
180
170
160
150
1300
1400
1500
1600
1700
1800
TKE (MeV)
Z2/A1/3
259Fm
260Md h
259Md h
262No h
258No h
258Fm h
259Lr
262Rf
263Ha
260Md l
259Md l
258Fm l
246Fm
258No l
248Fm
260Rf
256Cf
256Fm
262No l
256Rf
254Cf
257Fm
258Rf
256No
244Pu
246Cm
244Cm
254Fm
252No
242Pu
253Es
244Fm
240Pu
252Cf
250Cf
254No
238Pu
248Cf
248Cm
236Pu
250Cm
242Cm
238U
Unik et al.
Viola



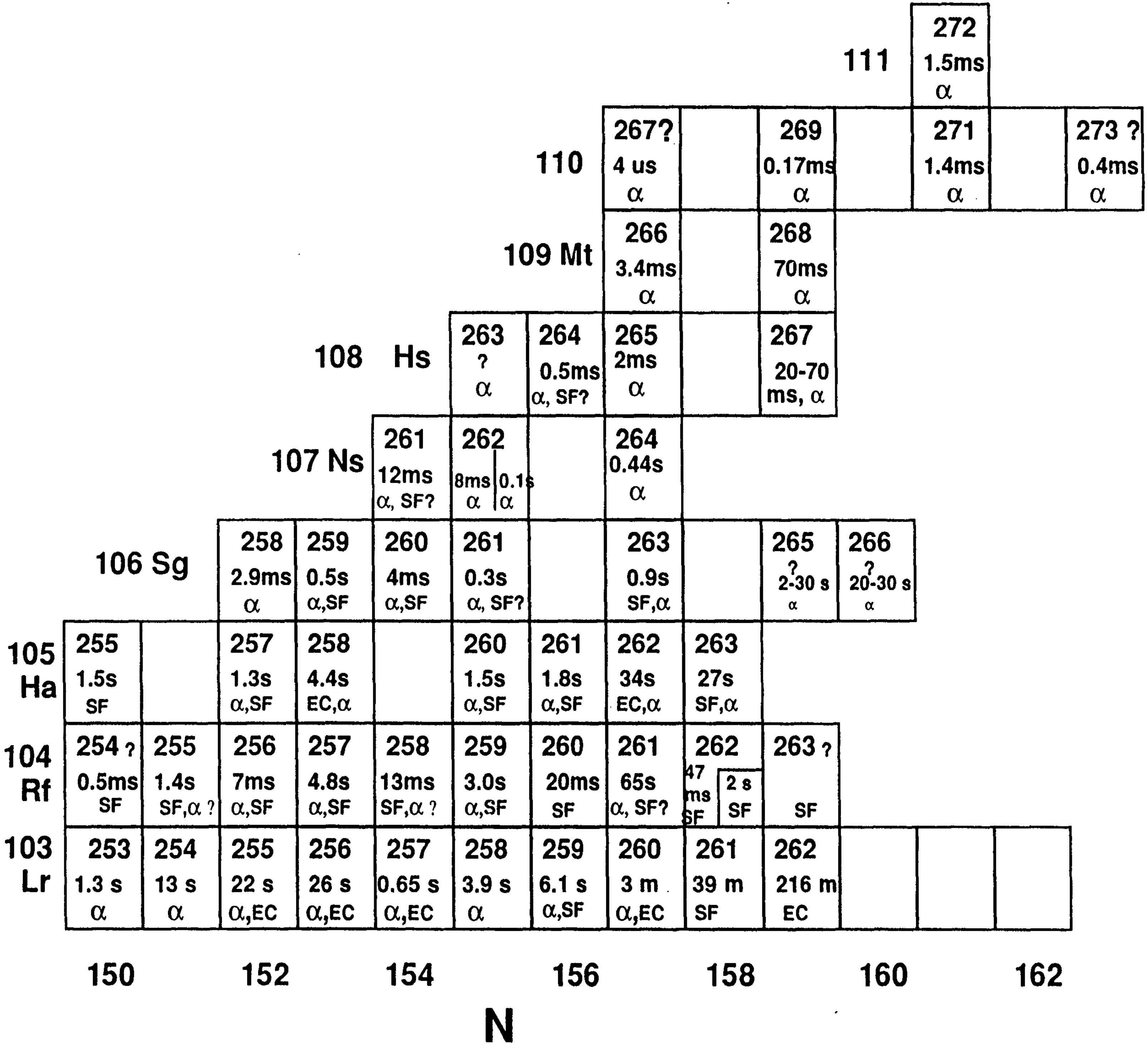
Z
Fm
Md
No
Lr
Rf
N
150
152
154
156
157
158
159
160
252No
254No
256No
258No
262No
256Rf
258Rf
260Rf
262Rf
259Lr
257Fm
258Fm
259Fm
259Md
260Md
Relative Intensity (log scale)
10
5
2
1
150
200
TKE (MeV)



(a)
256No
AVERAGE TKE
(b)
259Lr
AVERAGE TKE
(c)
262Rf
AVERAGE TKE
PRE-NEUTRON TKE (MeV)
MASS FRACTION (MH/A)



5
4
3
2
1
$\overline{\nu}_T$
230
240
250
260
270
A of SF nucleus
No
Md
Bk
Fm
Cf
Cm
Pu
Md
Th
U


111
272 1.5ms α
110
267? 4 us α
269 0.17ms α
271 1.4ms α
273 ? 0.4ms α
109 Mt
266 3.4ms α
268 70ms α
108 Hs
263 ? α
264 0.5ms α, SF?
265 2ms α
267 20-70 ms, α
107 Ns
261 12ms α, SF?
262 8ms α | 0.1s α
264 0.44s α
106 Sg
258 2.9ms α
259 0.5s α,SF
260 4ms α,SF
261 0.3s α, SF?
263 0.9s SF,α
265 ? 2-30 s α
266 ? 20-30 s α
105 Ha
255 1.5s SF
257 1.3s α,SF
258 4.4s EC,α
260 1.5s α,SF
261 1.8s α,SF
262 34s EC,α
263 27s SF,α
104 Rf
254 ? 0.5ms SF
255 1.4s SF,α ?
256 7ms α,SF
257 4.8s α,SF
258 13ms SF,α ?
259 3.0s α,SF
260 20ms SF
261 65s α, SF?
262 47 ms SF | 2 s SF
263 ? SF
103 Lr
253 1.3 s α
254 13 s α
255 22 s α,EC
256 26 s α,EC
257 0.65 s α,EC
258 3.9 s α
259 6.1 s α,SF
260 3 m α,EC
261 39 m SF
262 216 m EC
150
152
154
156
158
160
162
N

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