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Author
Hoffman, B.C.

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D.C. Hoffman

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SPONTANEOUS FISSION PROPERTIES AND LIFETIME SYSTEMATICS

Darleane C. Hoffman

Department of Chemistry
University of California and
Nuclear Science Division
Lawrence Berkeley Laboratory
7 Cyclotron Road
Berkeley, California 94720

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SPONTANEOUS FISSION PROPERTIES AND LIFETIME SYSTEMATICS

Darleane C. HOFFMAN

Department of Chemistry, University of California and Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.*

Half-lives for spontaneous fission of nuclides with even and odd numbers of particles are compared with recent theoretical calculations. A summary of odd particle hindrance factors is given. The most recent measurements of kinetic-energy and mass distributions and neutron emission for spontaneous fission of the heaviest nuclides are summarized and discussed.

1. INTRODUCTION

It is indeed an honor to participate in this Conference commemorating the 50th anniversary of the discovery of nuclear fission. It is also the 30th anniversary of the founding in March, 1959 of the Hahn-Meitner Institute which is named after the two renowned scientists, Lise Meitner (1878-1968), a physicist, and Otto Hahn (1879-1968), a chemist. They worked together over a period of some 30 years, a particularly successful collaboration incorporating both chemistry and physics in the investigation of radioactive substances and the discovery of the element protactinium. They both played important roles in the discovery and elucidation of the fission process, Hahn, together with Fritz Strassmann, proving by careful chemical separation techniques that lighter elements such as barium were produced from irradiation of uranium with neutrons, and Meitner, together with Otto Frisch, elucidating the physical characteristics and proposing the name "fission" for the process early in 1939. Hahn received the Nobel prize in 1944 for the discovery of fission and in 1966 Meitner, Hahn, and Strassmann received the Enrico Fermi Award of the United States Atomic Energy Commission, the first foreigners to be so honored. This early collaboration between chemists and physicists appears to have provided the model for subsequent fruitful studies of the fission process although Hahn later said "...Strassmann and myself, we always tried in these months ... say between October and December (1938) ... we always tried to explain what is wrong in our experiments, not to say we don't have barium, but we always thought it can't be there, and therefore, we have to say, 'What is the nonsense we are doing?' So really, it is so, that we poor

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chemists, isn't it the same with you? We are so afraid of these physics people." But he nevertheless communicated these results to Meitner in Sweden who together with Frisch (Christmas, 1938) came up with the idea of "fission".

Shortly after the discovery of neutron-induced fission, the discovery of the spontaneous fission (SF) of $^{238}$U was reported in 1940 by the Soviet scientists G. N. Flerov and K. A. Petrzhak. However, the decay of $^{238}$U by spontaneous fission occurs only about once for every $10^6$ alpha decays so detailed studies of its spontaneous fission properties are very difficult although radiochemical studies of the fragment mass distributions were carried out later. These showed that the most probable mass division was highly asymmetric, similar to that for thermal neutron-induced fission. This was difficult to explain on the basis of the liquid-drop model and explanations based on shell structure in the nascent fragments were proposed. With the availability in the 1960's of rather large sources of $^{252}$Cf, more detailed studies of fragment kinetic-energy and mass distributions, and neutron and photon emission from the fragments were performed. All of the mass distributions for spontaneous and low-energy fission were found to be highly asymmetric until 1970 when a greatly enhanced yield of symmetric mass division with anomalously high total kinetic energy (TKE) was reported in the SF of $^{257}$Fm.

This discovery initiated a renaissance of interest in the study of spontaneous fission. It provided a way of studying truly "cold" fission—that is, fission in which no external energy is brought into the system and in which, therefore, even rather weak shell effects can presumably be important. In addition, the fragments from the events with TKE's approaching the Q-value for fission can have little excitation energy. The systematics of the lifetimes for SF also abruptly changed for the heaviest fermium (Z=100) isotopes; the subshell at N=152 which seemed to lengthen the half-lives of lighter elements was less important and appeared to "wash out" for elements above nobelium (Z=102). Large hindrances to SF have been observed for both odd Z and odd N nuclei and the origin of these hindrances is not well understood nor can it be accurately predicted.

Theoretical approaches based on the Strutinsky method of shell corrections to the liquid drop model for calculating the potential energy of the fissioning nuclide were successful in explaining many fission phenomena such as the existence of fission isomers. However, in the region of the heavy fermium isotopes, the influence of shells in the fission fragments themselves seemed to be of major importance and the change to highly symmetric mass division with very high TKE was qualitatively explained on the basis of division into nearly spherical fragments which were stabilized by their
proximity to the doubly magic Z=50, N=82 (132Sn) configuration.

The SF process continues to present a challenge to both experimentalists and theoreticians alike. Spontaneous fission will ultimately limit the number of chemical elements that can exist. By the same token, a complete dynamic understanding of the process and how the stability of nuclides toward SF varies as a function of Z and N may provide insights into the reactions by which new species may best be produced. Such heavy ion fusion or synthesis reactions 6 may even be thought of as the "inverse" of spontaneous fission if they can be carried out so as to give a "cold" heavy product.

Both beta- and electron-capture delayed fission have been reported. It has been postulated 7-9 that beta-delayed fission may be important in explaining the yields of heavy elements in astrophysical models of the r-process and in the production 10 of neutron-rich heavy element isotopes in the intense neutron fluxes from thermonuclear explosions. Studies of electron-capture and beta-delayed fission can also provide 11,12 a means of probing the shapes and relative heights of the inner and outer fission barriers.

2. SPONTANEOUS FISSION HALF-LIVES AND SYSTEMATICS

2.1 Even-Even Nuclides

Our review 13 of spontaneous fission as of mid-1986 listed the partial fission half-lives for some 118 activities and several more have been reported since that time. A plot of the SF half-lives measured for the even-even (e-e) nuclei is shown in Fig. 1. Beginning with Cm (Z=96) and extending through No (Z=102), the effect of a subshell at N=152 can be readily seen. However, for heavier elements this effect seems to have disappeared.

Calculation of SF half-lives has proved to be especially difficult because of the extreme sensitivity to details of the height and shape of the fission barrier (or barriers). The barriers, in turn, may be dependent on the exact "path" in the potential energy surface which is followed en route to fission. Recently, Möller et al. 15,16 have calculated potential-energy surfaces in the macroscopic-microscopic model using a Yukawa-plus-exponential model and a folded Yukawa single-particle potential. A parameterization which permits the study of two touching spheres and similar shapes and a semi-empirical model for the nuclear inertia were used. The calculations clearly show the appearance of a new, second valley to fission which leads to configurations close to two touching spheres and is associated with much lower inertia. Fission through this new valley results in much shorter half-lives for SF in the region of the heavy Fm isotopes. They postulate that this, rather than the disappearance of the second barrier to fission in the potential energy
Comparison between experimental half-lives and the partial half-lives calculated or estimated by Randrup et al. for SF of even-even nuclides. The inset at the lower left shows the comparison for fission isomers (from Ref. 13).

The surface of the fissioning nucleus is the reason for the unexpectedly short half-life of only 0.38 ms observed for 258Fm. The half-lives for the Fm isotopes obtained by Möller et al. by considering symmetric fission via two distinct fission valleys, one leading to compact (near spherical) shapes, and the other leading to more elongated shapes are shown in Fig. 2. The half-lives for the heavy Fm isotopes calculated for the new path are in much better agreement with the experimental data than those from the old path. They actually find three paths, the old path, the new path to compact scission shapes, and a switchback path from the new to the old path. However, some remaining discrepancies suggest that fission along this switchback path and changes in inertia as the fragments depart from the magic neutron and proton configurations need to be investigated further. Cwiok et al. have calculated the collective potential energy of e-e heavy fermium isotopes using the Yukawa-plus-exponential model but they used the Woods-Saxon single-particle potential and a five-dimensional space which included reflection asymmetric
Experimental SF half-lives for Fm isotopes compared to calculated half-lives for fission along the old and new valleys. The new valley is present in the calculated potential-energy surface only for $N \geq 158$. The shorter (dominating) calculated half-lives should be compared with experimental values. The discrepancy around $N = 152$ may be partially removed through the calculation of fission half-lives along the switchback path (from Ref. 16).

The experimental data show a dramatic change in SF half-life systematics between elements 102 and 104. This change was first proposed by Flerov et al. in 1971. Calculations by Randrup et al. in 1976 reproduced this change after they adjusted one parameter in their inertial-mass function to fit the half-lives for elements with $Z \leq 102$. They attributed the change to the weakening of the 152-neutron subshell and to the lowering of the second barrier to fission below the ground-state energy. Baran et al. reached similar conclusions. However, the recent calculations of Möller et al. still show a considerable shell effect at 152 neutrons for elements 104 and 106.

The experimental results of Münzenberg et al. show that $^{260}106$ decays primarily by alpha emission and that it has a partial SF half-life of 7 ms, only a factor of two shorter than for $^{258}Rf$ which has the same number of neutrons and 2 more protons. There is an approximately $10^5$ decrease in SF.
half-life between $^{256}_{\text{No}}$ (18 min) and $^{258}_{\text{Rf}}$. Similarly, $^{264}_{\text{Rf}}$ decays primarily by alpha emission and has a partial SF half-life of at least 5 ms. This slowing of the decrease in SF half-lives for the e-e isotopes of elements with $Z \geq 104$ means that the alpha decay half-lives become shorter than the SF half-lives and alpha decay eventually predominates. This is particularly helpful in making positive identification of new isotopes (and elements) via observation of known alpha-daughter decay sequences. It also indicates that the shell effects are large enough to overcome the decreases in the liquid-drop fission barriers and lends support to the predictions that doubly magic superheavy elements will have measurably long half-lives.

Numerous calculations have indicated a deformed, subshell around 162 to 164 neutrons which gives rise to what has been called a "rock" of stability in this region. However, recent calculations indicate that the new valley is present up to at least $Z = 110$ and that compared to earlier predictions it lowers the calculated fission half-lives in the region of the "rock" around $^{272}_{\text{Rf}}$.

2.2. Nuclides with Odd-proton and/or Odd-neutron Numbers.

The calculation of half-lives for nuclides with an odd number of protons and/or an odd number of neutrons, is still more formidable 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 lengthening of the SF half-lives for such nuclides has been known for some time. Möller et al. calculated the specialization energies associated with the odd particles and the potential energy surfaces for odd systems for symmetric shapes only. They find that these specialization effects will substantially increase the calculated fission half-lives, even in the new valley.

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 $Z$ odd and $N$ even ($A$ odd):

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

Similarly for $Z$ even and $N$ odd ($A$ odd):

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

The logarithms of the hindrance factors calculated for the known SF half-lives of odd-proton, even-neutron, and even-proton, odd-neutron nuclei are plotted in Fig. 3 as a function of odd proton or odd neutron number. In general, the log HF's for actual measurements (not just limit values) are
Logarithms of SF Hindrance factors 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.

about 5 for both odd protons and neutrons, although for some Fm isotopes, the neutron HF is greater than this by 2 to 3 orders of magnitude. For N=157, the log HF for Fm is greater than 9. This was attributed by Randrup et al.\textsuperscript{28} to the high spin of the 9/2+ [615] neutron orbital although the 103rd proton which may be 9/2+[624] does not seem to show such a large effect. Perhaps the large effect seen for \textsuperscript{257}Fm is because the half-life of \textsuperscript{258}Fm is unusually short due to disappearance of the second barrier to fission or due to fission along the "new" 15•16 valley.

It has been suggested that the HF's for odd-odd (o-o) nuclei are the product of the odd-proton and odd-neutron HF's, but for \textsuperscript{260}Ha and \textsuperscript{262}Ha, the HF's relative to the neighboring e-e nuclei are only of the order of (1-3) x 10\textsuperscript{3}. However, the HF's for the o-o isotope \textsuperscript{32-d} relative to \textsuperscript{258}Fm and 106-ms \textsuperscript{260}No are 8x10\textsuperscript{9} and 3x10\textsuperscript{7},
respectively. For the recently discovered\textsuperscript{29} \(218\text{-m}\) \(262\text{Lr}\) (believed to decay \(<10\%\) by SF), the HF's are \(>10^6\) and \(>10^7\) relative to \(260\text{No}\) and \(262\text{No}\). So it is not clear whether or not these hindrances are multiplicative. In any case, the observed rather large HF's make the prospects for finding longer-lived 0-0 isotopes of the heaviest elements appear quite optimistic if methods for producing the more neutron-rich isotopes near beta stability can be devised.

3. FRAGMENT MASS AND KINETIC-ENERGY DISTRIBUTIONS

Prior to 1970, all of the experimental data for SF and thermal neutron-induced fission showed asymmetric mass division. The first observation of greatly enhanced yields for symmetric mass division was reported\textsuperscript{5} for the SF of \(257\text{Fm}\) in 1970 and confirmed\textsuperscript{30} in 1971. Shortly after, it was also found\textsuperscript{31} that the most probable mass split for the thermal neutron-induced fission of \(257\text{Fm}\) was broadly symmetric. These results brought about a resurgence of interest in spontaneous fission properties. By the time of our 1974 review\textsuperscript{32} of post-fission phenomena for SF and low-energy fission, the mass-yields for SF of \(254\text{Fm}\), \(256\text{Fm}\), and \(257\text{Fm}\), and for thermal-neutron induced fission of \(255\text{Fm}\) and \(257\text{Fm}\), i.e., \(256\text{Fm}^*\) and \(258\text{Fm}^*\), had been measured. The enhanced yield of symmetric mass division for \(257\text{Fm}\) was postulated to be due to the influence of shell structure in the fragments, i.e., the approach of the symmetric fission fragments to the doubly magic, spherical \(132\text{Sn}\) configuration (\(Z=50\), \(N=82\)). It appeared that the additional neutron and excitation energy of about 6 MeV in \(258\text{Fm}^*\) increased the yields of symmetric mass division and broadened the distribution relative to SF of \(257\text{Fm}\), in agreement with the conventional wisdom which said that with increasing excitation energy the yield of symmetric mass division should increase and the mass distribution should broaden to more "liquid-drop" type fission as the shell effects, which caused the asymmetric fission, were "washed out". A comparison of the properties\textsuperscript{33,34} of \(256\text{Fm}^*\) with those for the SF of \(256\text{Fm}\) showed that the increased excitation energy of about 6 MeV in \(256\text{Fm}^*\) again resulted in increased yields for mass-symmetric division relative to those observed for SF of \(256\text{Fm}\).

By the time of my 1979 review\textsuperscript{35}, mass-yield and kinetic-energy distributions had been measured for the SF of \(258\text{Fm}\) and \(259\text{Fm}\) and could be compared with those for \(258\text{Fm}^*\). These surprising results showed narrowly symmetric mass distributions for \(258\text{Fm}\) and \(259\text{Fm}\) with anomalously high TKE's which approached the Q values for fission and did not
TKE vs. $Z^2/A^{1/3}$. Dashed line is linear fit of Unik et al.\textsuperscript{37}; solid line is from Viola\textsuperscript{38}.

fit on the linear functions\textsuperscript{37,38} of TKE vs $Z^2/A^{1/3}$ devised for the lighter actinides. (See Fig. 4.) Similarly high TKE's had first been reported\textsuperscript{5,30} for the symmetric mass division of $^{257}$Fm where enhanced yields for symmetric mass splits were first observed. However, the variance of the TKE is extremely large, as shown in Fig. 5, indicating that in some of the symmetric mass splits the fragments may have elongated shapes with normal or even low TKE while in other symmetric splits the configuration must approach touching spheres as the TKE approaches the $Q$ value. It was postulated\textsuperscript{39} that these nearly spherical shapes are stabilized by the approach of the fragments to the doubly magic $^{132}$Sn configuration.

Another surprise was that the increased excitation energy in $^{258}$Fm* led to a large decrease in the yield of symmetric mass division. Again, this could be explained if the fragment shell effects for SF of $^{258}$Fm stabilized symmetric mass division while those in $^{256}$Fm and lighter nuclides
Contour plots of TKE vs. mass fraction for $^{254}$Cf, $^{256}$Fm, $^{257}$Fm, and $^{259}$Fm. For $^{254}$Cf, $^{256}$Fm, and $^{257}$Fm, the contours are lines of equal numbers of events based on groupings 5 MeV x 0.01 units of mass fraction. The relative intensities range from 1 to 9. The contours for $^{259}$Fm are based on groupings of 10 MeV x 0.02 units of mass fraction. The relative intensities range from 1 to 6 (from Ref. 13).
stabilized asymmetric mass division, with $^{257}\text{Fm}$ being a "transition" nucleus which showed both asymmetric and symmetric mass division. Initial measurements of the SF of $^{259}\text{Md}$ made by Wild et al. also showed a narrowly symmetric mass distribution, but in contrast to $^{258}\text{Fm}$ and $^{259}\text{Fm}$, the TKE distribution was very broad and, like $^{257}\text{Fm}$, showed a range of TKE's for symmetric mass division and a TKE which fit relatively well on the TKE vs. $Z^2/A^{1/3}$ plot. (See Fig. 4.) Hulet et al. postulated that this kinetic-energy "deficit" relative to $^{258}\text{Fm}$ and $^{259}\text{Fm}$ might be due to the emission at scission of an undetected third particle, e.g., of $Z=1$. (Md has 101 protons, one beyond where the fission fragments can both have the magic proton number of 50 protons.) However, later measurements by that group showed that this was not the case.

By 1984, mass and kinetic-energy distributions for the light Fm isotopes, 246 and 248, had been measured and data were now available for Fm

![FIGURE 6](image_url)

Schematic of mass-yield distributions (normalized to 200% fission fragment yield) for SF of trans-Bk isotopes, 1989.
isotopes spanning some 13 mass numbers. A schematic representation of the mass-yield distributions (all normalized to 200% fragment yield) comparing the mass distributions for SF of the trans-Bk isotopes was prepared.\textsuperscript{44} A plot of TKE vs. $Z^2/A^{1/3}$ still showed only $^{258}$Fm and $^{259}$Fm with "anomalously" high TKE's. The most recent data for the mass-yield and TKE distributions of some of the heaviest elements are shown schematically in Figs. 6 and 7. Hulet et al.\textsuperscript{45} decomposed the TKE distributions for $^{258}$Fm, $^{258}$No, $^{259}$Md, $^{260}$Md, and the newly discovered $^{262}$No into two Gaussian distributions, one centered around 200 MeV and the other around 235 MeV. They have called this "bimodal" symmetric fission—one symmetric mode leads to nearly spherical fragments with high TKE and the other leads to elongated fragments with much lower TKE. Other heavy nuclides appear to show similar features (See Fig. 7.) These two modes may be represented by the two paths to symmetric fission calculated recently. Because of the higher Coulomb repulsion, the path leading to compact shapes gives rise to unusually high TKE compared to that leading to more elongated shapes which will have lower or so-called "normal" TKE.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Schematic of TKE distributions of trans-Es isotopes, 1989}
\end{figure}
FIGURE 8

$\bar{\nu}_t$ vs. A of the compound nucleus. Measurements for thermal neutron-induced fission have been corrected to zero excitation energy using $d\bar{\nu}_t/dE_x = 0.11$ MeV$^{-1}$.

4. NEUTRON EMISSION

Early studies of neutron emission in the SF of $^{252}$Cf established the now well-known saw-toothed function for the average number of neutrons emitted as a function of fragment mass. Detailed studies of neutron emission in SF of $^{252}$Cf as a function of the fragment masses and kinetic energies have been performed utilizing a variety of techniques. However, studies of neutron emission for the SF of heavier actinides are limited primarily to measurements of the average neutron emission per fission, $\bar{\nu}_t$. In general, as shown in Fig. 8, neutron emission increases with the Z of the fissioning nucleus. For the trans-Pu elements, it increases with mass for a given Z. This trend is reversed for the heavy Fm isotopes, and $\bar{\nu}_t$ is lower for $^{256}$Fm and $^{257}$Fm than for $^{254}$Fm. Measurements of neutron emission for SF of $^{258}$Fm and $^{259}$Fm, both nuclides which show anomalously high TKE's, have not yet been made. However, Hoffman et al. measured neutron emission and multiplicities for SF of some Cf and Fm isotopes, including $^{257}$Fm, as a function of fragment mass and TKE. They found that
for $^{257}$Fm the average neutron emission drops to only 1 for events with TKE >240 MeV and that the mass-yield distribution is narrowly symmetric for these events. (This TKE is about the same as that of 238 MeV measured for $^{258}$Fm and $^{259}$Fm which show narrowly symmetric mass distributions.) The neutron multiplicities observed for $^{257}$Fm are shown in Fig. 9. The variance for the distributions with TKE >240 MeV is very small, suggesting a rather narrow distribution of fragment excitation energies. On the basis of these results, it was predicted that the average neutron emission for $^{258}$Fm and $^{259}$Fm should be only about 1. Recently, Dougan et al.\(^{47}\) have reported measurement of an average value of only 2.58 for $^{260}$Md, but with a large variance. In fact, Wild et al.\(^{48}\) have decomposed the neutron multiplicity curve into two Gaussian components with average values of 1.80 and 3.9. They associate these with the two components of 235 and 195 MeV, respectively, into which they have resolved the TKE distribution. (See Fig. 7.) These observations are qualitatively consistent with the picture that for symmetric mass division there can be a distribution of fission fragment shapes ranging from near spherical to rather deformed. The near-spherical fragments will have very high TKE due to Coulomb repulsion, with relatively small excitation energy and consequently little energy for emission of neutrons. The neutrons will also be more tightly bound in these near closed-shell configurations. The more deformed fragments will have lower TKE's due to Coulomb repulsion, higher excitation energy, and consequently higher neutron and gamma emission. Hulet et al.\(^{45}\) have called this "bimodal" symmetric fission, but
it may well be that in many cases it is "multimodal" rather than simply "bimodal". Brosa has derived average neutron multiplicities on the basis of multimodal fission and scission at random positions on the neck and predicts triple and simple sawtooth curves, respectively, for the SF of 252 Cf and 258 Fm. Measurement of these neutron emission functions for the heaviest, short-lived spontaneously fissioning nuclides presents a real challenge for the experimentalist!

The contour plots shown in Fig. 5 summarize the known information on the mass division and TKE release for SF of several Fm isotopes and for 254 Cf, "typical" of the SF of lighter actinides. From these and a knowledge of the Q-value for fission, which is about 255 MeV for the Fm isotopes, and about 236 MeV for 254 Cf for symmetric mass (and charge) division, and about 218 MeV for asymmetric division, the remaining energy available for neutron and gamma emission can be inferred. The transition from predominantly asymmetric mass division in 254 Cf to predominantly symmetric mass division in 259 Fm with an accompanying increase in TKE can be clearly seen. The decrease in neutron emission for symmetric mass division of the heavy Fm isotopes is consistent with the smaller excitation energy remaining because of the high TKE of these symmetric fragments. The observed decrease in average TKE at symmetry compared to that for SF of lighter isotopes such as 254 Cf can also be readily explained. So far, little information about gamma emission or direct information about charge division in SF is available except for 252 Cf. Although we assume that this information would be consistent with our current knowledge about kinetic energy and mass division, the availability of actual experimental data would give valuable information about the properties of the fragments at scission, such as their shapes and deformation energies, separation distances, etc. It has been proposed that the atomic numbers (as well as the kinetic energies and masses) of coincident fragments from SF of some of the short-lived heaviest isotopes could be made via dE/dX measurements, at the same time performing total kinetic energy and time-of-flight measurements, with the use of pairs of segmented gas ionization counters. Hopefully, by the time of the next review of SF properties such information will be available.

5. SUMMARY

An impressive body of experimental information on SF half-lives has been obtained. Equally impressive are the new measurements of mass and kinetic-energy distributions for isotopes as heavy as 262 No and atomic number as high as 104 (260 Rf). These new experiments have probed the extent of the rapid changes in half-lives and SF properties which were first
observed in the region of the heavy Fm isotopes. Some information on neutron emission in SF has been obtained for a few isotopes heavier than $^{252}$Cf, but very little information on charge division or gamma emission exists for heavier isotopes. Obtaining such information for these short-lived isotopes presents a real challenge to experimentalists! Another challenge to experimentalists is the development of instrumentation for measuring both the mass and atomic number of short-lived fissioning species so they can be positively identified even when alpha decay is not observed. The observation of large hindrance factors for odd-Z, odd-N heavy isotopes indicates that many relatively long-lived heavy isotopes can be studied if methods for the production of more neutron-rich species can be devised. One promising approach$^{50,51}$ is the use of a large $^{254}$Es target with light heavy ion projectiles.

Many challenges to the theorists remain also. Calculation of SF half-lives is so exquisitely sensitive to details of the path to fission and the details of the fission barriers that prediction of half-lives, particularly for o-o isotopes, is still not possible with the degree of precision which experimentalists need. Although general features of mass, charge, and kinetic-energy release can be understood, there is still no comprehensive, dynamic theoretical model which can predict the course of SF, taking account of the structure of the fissioning nucleus and of the fission fragments, and which can correctly predict the complex properties of the fragments, including details of the mass-yield and kinetic-energy distributions and the excitation energies.

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