ter all, the great success of the Talmi[6] approach shows the insensitivity of such transformations to configuration mixing.

(3) Finally, the great sensitivity of the $M1$ rates to the small $l \pm \frac{1}{2}$ admixtures should remind us, once again, to exercise caution in the use of wave functions generated in a truncated space and serves to illustrate again that the important terms in the wave function are not always the largest but rather need to be determined anew for each specific operator.

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Mass Symmetry in the Spontaneous Fission of ^{257}Fm†

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The kinetic energy distribution of coincident fragments from spontaneous fission of ^{257}Fm has been measured with silicon detectors. The data reveal two significant features: (1) The mass-yield distribution is markedly more symmetric than for slightly lighter nuclei (e.g., ^{252}Cf, ^{254}Cf); (2) the average total kinetic energy increases monotonically with the approach to symmetric fission.

One of the significant aspects of spontaneous fission (SF) of the heavy nuclei is that the fragment mass distribution is strongly asymmetric for $A \leq 254$. From measurements of fragment kinetic energies for a series of nuclides ranging from ^{248}Cm up to ^{254}Cf and ^{254}Fm, Brandt et al.[1] note that the average mass of the heavy fragment remains relatively constant at $A = 142 \pm 1$, while that of the light fragment increases. If this feature were to continue, a true symmetric distribution would not be reached until A approached 284. On the other hand, there has been some speculation that fission-fragment shell effects should accelerate the trend toward symmetry with the approach toward ^{264}Fm ($=2\times {}^{132}_{50}\mathrm{Sn}_{82}$). Our measurement of the fragment kinetic energies from spontaneous fission of ^{257}Fm shows definite indications of the latter trend.

The energy measurements were made with a pair of silicon surface-barrier detectors placed on opposite sides of a thin film on which the source was deposited. The amplified pulses were fed to a 512×512-channel two-parameter pulse-height analyzer; pulse heights of coincident events were stored on magnetic tape for subsequent computer processing.

Two different sources of ^{257}Fm were employed. The first was isolated from debris from the "Hutch" nuclear explosion,[2] in which the mass-257 chain was produced by rapid multiple neutron capture in a uranium-thorium target. The second was produced by neutron capture in curium targets in the high-flux isotope reactor (HFIR) at Oak Ridge. Final purification of both preparations was accomplished by the standard ethanol-HCl cation column elution for actinide-lanthanide separation, and by a hot alpha-hydroxyisobutyrate cation column elution for final isolation of fermium from other actinides. Purity of the sample was confirmed by alpha-pulse analysis. Solutions of the fermium were transferred to 35- to 40-μg/cm^2 Zapon films and "freeze-dried" under vacuum to uniform spots 4 to 6 mm in diameter. Identical procedures were used to prepare ^{254}Cf sources (also from Hutch debris) and the ^{252}Cf standard sources used for energy calibration.

The first (Hutch) source contained initially 0.8 SF/min and was measured over 32 weeks. A number of detectors and source distances were tried, and a total of 15 710 events were recorded. The second (HFIR) source started with 2.7 SF/min and was measured over 75 days (17 951 events) in a constant source-detector geometry.

Both sets of data showed substantially identical spectra; only results for the second source are presented. In order to provide comparisons with previously measured distributions, the observations on ^{257}Fm were interspersed with other's on ^{254}Cf and ^{252}Cf sources, all with the same system and source geometry. The ^{254}Cf measurements were corrected for events due to ^{252}Cf, which amounted to 12.5% of the total events recorded.

Kinetic energies of the high- and low-energy fragments from spontaneous fission of the three nuclides were calculated as follows. Initial values for preneutron masses, M, of coincident pairs were calculated from a preliminary energy calibration (i.e., uncorrected for ionization defect) derived from the ^{252}Cf standard. Approximate post-neutron-emission masses were then obtained by subtracting from each fragment mass a mass-dependent number of neutrons $\bar{\nu}(M)$ and these masses were used to obtain better values of post-neutron-emission kinetic energies by the method of Schmitt, Kiker, and Williams.[3] These energies were converted to pre-neutron-emission kinetic energies by multiplying by $1+\bar{\nu}(M)/[M-\bar{\nu}(M)]$, i.e., fragment velocities were assumed to be unchanged by neutron emission, and the preneutron energies were used, in turn, to calculate better masses. Iteration of this procedure gave the final pre-neutron-emission kinetic energy and mass spectra. The $\bar{\nu}(M)$ functions were constructed as follows: for ^{252}Cf, a smooth curve approximating the data of Bowman et al.[4]; for ^{254}Cf and for ^{257}Fm, similar curves with $\bar{\nu}(M)$ varying from $\bar{\nu}=1$ to $\bar{\nu}\approx 3$ (see Fig. 1). No corrections were made for instrumental resolution.

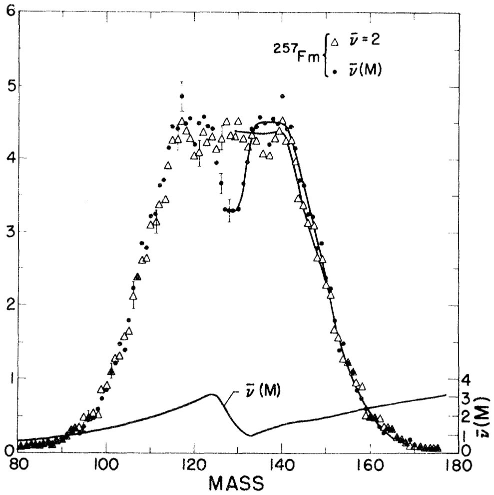

FIG. 1. Pre-neutron-emission mass-yield curve for ^{257}Fm.

Pre-neutron-emission kinetic energy distributions are shown in Fig. 2, and the corresponding masses are shown in Figs. 1 and 3. Energy distribution parameters are summarized in Table I.

Table I. Properties of the measured (post-neutron-emission) and calculated initial (pre-neutron-emission) fragment kinetic-energy distributions. Energies are given in MeV.

	^{257}Fm		^{254}Cf		^{252}Cf	
	Pre-n	Post-n	Pre-n	Post-n	Pre-n	Post-n
Total kinetic energy						
Most probable[a]	198.0	195.1	184.9	181.8	187.0	184.1
Average	197.6	194.6	177.4	174.1	183.5	180.4
FWHM[b]	36.0	36.4	33.8	31.3	30.8	29.6
Heavy fragment energy						
Most probable[a]	88.0	87.0	79.6	78.6	80.8	79.8
Average	88.5	87.6	76.2	75.2	78.9	77.9
Light fragment energy						
Most probable[a]	110.6	108.6	104.6	102.5	106.1	104.1
Average	109.0	106.8	101.1	98.8	104.4	102.3

[a] Overall error is estimated to be ≈1.5%.

[b] Full width at half-maximum, calculated from 2.35σ for Gaussian fit to the top half of the peak.

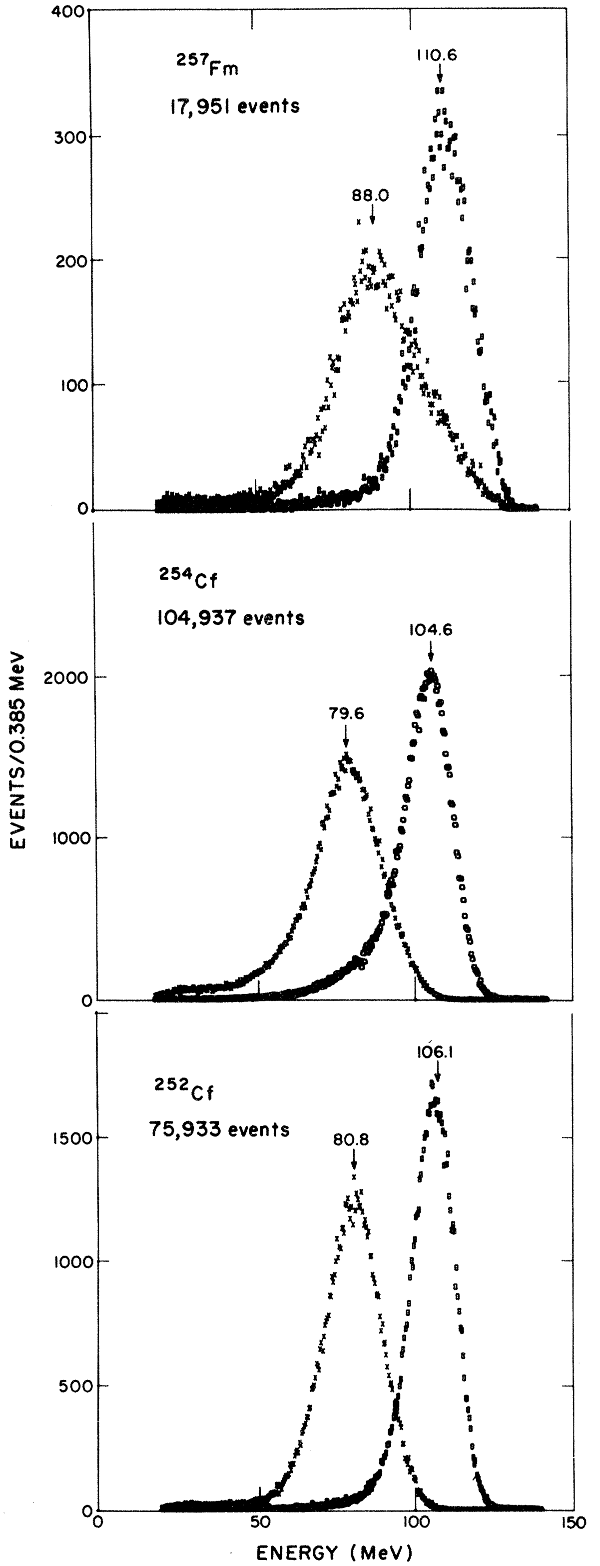

FIG. 2. Pre-neutron-emission kinetic energy distributions of high- and low-energy fragments from spontaneous fission. Detectors: Si surface-barrier, 80-μm depth × 1-cm diam. Source-detector distances, 1.3 cm.

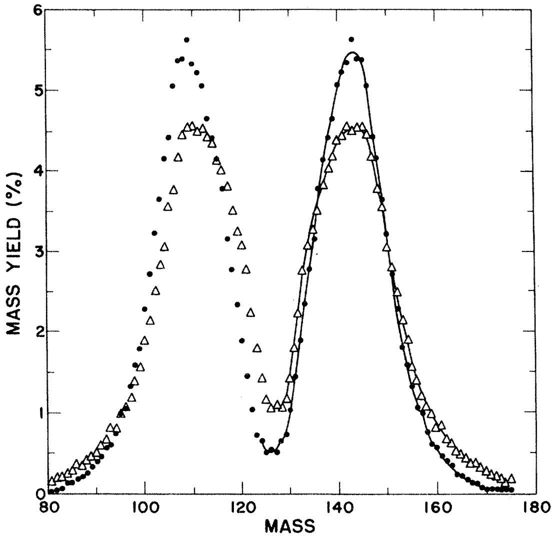

FIG. 3. Pre-neutron-emission mass-yield curve for ^{254}Cf (open triangles) and for the ^{252}Cf standard (closed circles).

The distributions in prompt kinetic energy and mass are influenced noticably by the shape of the $\bar{\nu}(M)$ function used in the calculations; a sharp drop in $\bar{\nu}$ with increasing mass introduces a notch in the calculated pre-neutron-emission mass yields. This effect is particularly noticeable in the case of ^{257}Fm, where the region of expected rapid change in $\bar{\nu}(M)$, near symmetry, is also a region of high mass yield. As shown in Fig. 1, the simple assumption of a mass-independent $\bar{\nu}=2$ produces a conspicuous increase in apparent mass yields near symmetry. Thus, an accurate deduction of the mass and energy distributions from fragment-energy measurements requires a knowledge of $\bar{\nu}(M)$ and its variation with total kinetic energy. Even with allowance for the uncertainty in $\bar{\nu}(M)$, however, it is evident that the ^{257}Fm fragment mass and energy distributions differ significantly from those for lighter fissioning nuclei. The yield at symmetry is greatly enhanced, and the "heavy peak" has moved in (i.e., toward symmetry). Another feature, illustrated in Fig. 4, is the monotonic increase in average kinetic energy with approach to symmetry, in contrast to the case for both ^{252}Cf and ^{254}Cf. The highest total kinetic energy shown for fragments form ^{257}Fm (Fig. 4) is nearly 260 MeV, which exceeds by about 8 MeV the energy available as derived from current mass formulas.[5] However, if we set $\nu=0$ for these events and take into account the possible 1.5% error in our absolute energy calibration (Table I), the experimental kinetic energy could be lowered by ~8 MeV. The

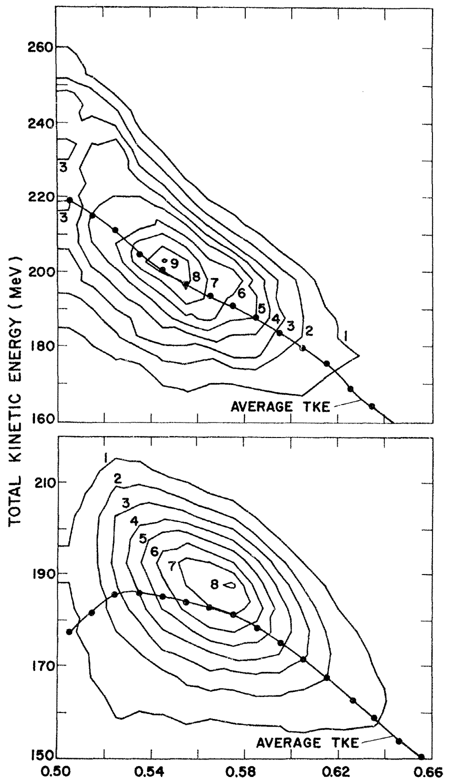

FIG. 4. Contour diagrams showing pre-neutron-emission total kinetic energy distributions for ^{257}Fm (upper diagram) and ^{254}Cf (lower diagram) as a function of mass fraction. The contours are lines of relative numbers of events, based on data groupings 5 MeV × 0.01 units of mass fraction.

contribution of instrumental resolution at the high-energy edge of the kinetic energy distribution is more difficult to estimate, but could amount to a few MeV more.

The trends in mass distribution and in total kinetic energy do not suggest the appearance of a second symmetric mode of fission, such as that associated with higher excitation energy at lower A and Z.[6] They suggest instead the continuation of a single (low-energy) mode in which the probability of symmetric fission increases as the fissioning nucleus approaches a mass and charge such that both fragments can be doubly closed-shell nuclei. Closed-shell effects become prominint only within a few nucleons of shell closure and ^{257}Fm is the first measured case in which this condition is satisfied. Current opinion, however, is that shell effects in the fissioning nucleus still dominate. Recent calculations of the nuclear potential energy of deformation have indicated that at the second saddle point, the lighter actinide nuclei are asymmetric in shape[7] as a result of single-particle effects, and the amount of asymmetry decreases with increasing mass. Unfortunately, the examples shown do not cover the region from ^{252}Cf to ^{257}Fm and so do not permit comparisons with the observed change in trend. Considerations of this kind are complicated by the fact that ^{257}Fm is an odd nucleus, and that its fission may be influenced by spin-parity constraints whose effect is different for even-even nuclei. Although the mass distribution for ^{253}Es, the only other odd nucleus for which spontaneous fission data are available,[1] appears to be consistent with those of its neighbors, the effect of the odd nucleon is still not clear. It would be of considerable interest to obtain mass and energy data on spontaneous fission of other heavy nuclei such as ^{256}Fm, ^{258}Md, and if possible, even heavier species.

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