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AUTHOR(S): DARLEANE C. HOFFMAN

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NUCLEAR PROPERTIES OF MENDELEVIUM

Darleane C. Hoffman
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

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Mendelevium is a particularly interesting element from the standpoint of its nuclear and fission properties. Isotopes from mass 248 to 259 are known--most of these are neutron deficient and decay by alpha emission or electron capture. The heaviest known isotope of mendelevium, ^{259}Md, is nearly on the line of beta stability and decays[1] predominantly via spontaneous fission (SF) with a half life of 95 minutes. So far, no heavier isotopes of mendelevium have been detected. Viola et al.[2] estimate a beta-decay energy of about 0.7 MeV and an electron-capture decay energy of about 0.5 MeV for ^{260}Md. A beta-decay energy of about 0.15 MeV is estimated for ^{261}Md, which will probably be stable toward e.c. decay. Assuming first-forbidden beta decay with a log _ft_ of 6, the half life for beta decay would be around 2 hours for ^{260}Md and 50 days for ^{261}Md, respectively. The electron-capture half life for ^{260}Md would be around 10 hours.

The even-mass isotopes of mendelevium, like those of einsteinium, are expected to exhibit isomerism due to combination of the 101st proton which has been assigned as the 7/2-(514) proton state with low-lying, high-spin neutron states such as 7/2+(613) and 9/2+(615). Isomers are currently known for ^{254}Md and ^{258}Md. The 55-d alpha-emitting isomer of ^{258}Md is believed to be the ground state and has been given an 8^- assignment because no e.c. decay[3] was observed. It is most likely composed of the low-lying 7/2-(514) proton and the 9/2+(615) neutron states. A 43-m isomer of ^{258}Md has been produced[4] by the (α,n) reaction on ^{255}Es and is believed to decay by e.c. capture. It is probably the 1^- level formed by the combination of the same two single particle states and should be excited by perhaps 100 keV over the ground state.

A high-spin (7^-,8^-) isomer of ^{256}Md, resulting from the coupling of the 7/2-(514) proton with the 7/2+(613) or 9/2+(615) neutron states should also be expected. Its decay energy can be estimated to be ≈100 keV more than for the known 76-m ^{256}Md ground state (0^-) which decays primarily by e.c. capture, but probably has a considerably longer e.c. half life due to the necessity for decay to a high-spin state in the ^{256}Fm daughter, such as the 6+ level at 332 keV or the 8+ level at 563 keV which are populated[5] by the decay of the 7.6-h high-spin isomer of ^{256}Es. It might also decay by alpha emission to ^{252}Es. A concerted search for this and other isomers of the even-mass Md isotopes should be rewarding.

The production of 43-m ^{258}Md allowed studies[4] of the SF properties of its 0.380 ms ^{258}Fm daughter to be performed which showed that its SF resulted in a highly symmetric fragment mass distribution with unusually high total kinetic energy. (See Figs. 1 and 2.) The only other spontaneously fissioning isotope known to exhibit similar properties is 1.5-s ^{259}Fm. (See Figs. 3 and 4.) So far, SF decay of mendelevium has only been observed[5] for 95-m ^{259}Md and its SF properties have turned out to be quite unusual in that although its fragment mass distribution is highly symmetric, its total kinetic energy of 189 MeV is not anomolously high (see Fig. 4) as is the case for ^{258}Fm and ^{259}Fm. The full width at half maximum of the total kinetic energy distribution of 104 MeV is unusually large compared to those for other spontaneously fissioning nuclides as shown in the summary given in Table I. Hulet et al.[6] have suggested that this relatively low total kinetic energy may be due to the emission of a Z = 1 particle which then allows the remaining mass to divide into two Z = 50, closed-proton shell fragments. If confirmed, this would be another dramatic demonstration of the strong effect exerted on low-energy fission by the fragment shells. Further examination of the fission properties of still heavier Md isotopes would be of particular interest.

The SF half life of 95-m for ^{259}Md is unusually long compared to those for the even-even isotopes. For example, ^{258}Fm which has the same number of neutrons has a half life of only 0.380 ms. The hindrance due to the odd proton, 9/2+(624), in Md is apparently sufficient to lengthen the half life for ^{259}Md by more than 10^7 relative to ^{258}Fm. Such hindrances due to specific odd proton or odd neutron single particle states have been known for some time and have been discussed in detail by Randrup et al.[7] The hindrance is typically of the order of 10^5, but can be as small as 10 and as large as 10^{10}. If the 101st proton provides ^{260}Md with the same hindrance relative to ^{259}Fm (1.5 s) as for ^{259}Md relative to ^{258}Fm, then its SF half life would be of the order of 200 d. It would then be expected to decay predominantly by beta emission with a half life of 1 to 2 hours depending on the beta-decay energy, as discussed earlier. This would provide a means for studying the SF decay of the very short-lived ^{260}No daughter which has the same number of neutrons as ^{258}Fm and afford another assessment of the effect on the fission process of protons beyond Z = 100. ^{256}Cf, also having 158 neutrons but only 98 protons, shows an asymmetric mass distribution and "normal" total kinetic energy in contrast to the SF of ^{258}Fm. (See Figs. 5 and 6.)

There is no neutron analogue for ^{261}Md in the Fm isotopes from which to scale its possible fission half life, but if we use the reduction in half life of ^{258}Fm relative to ^{256}Fm of 4×10^{-8} for the addition of two neutrons, to scale the 95-m half life of ^{259}Md, then a half life of 0.2 ms might be expected for ^{261}Md. Using the reduction in half life between ^{257}Fm and ^{259}Fm would give a still shorter estimate of only 2 μs for ^{261}Md so studying its SF properties will be extremely difficult. However, ^{262}Md which might be as long as a few-tenths of a second might furnish a still more neutron-rich (N = 161) nuclide for study. This nuclide would be of particular interest since it could fission symmetrically into nuclei with more nearly the N = 82 closed-neutron shell configuration, but which would have an extra proton over two Z = 50 closed-shell fragments. Although studies of the SF properties of the heaviest Md isotopes will obviously be most difficult and challenging they are of utmost importance in assessing the relative importance of the proton and neutron shell structure of the fragments on the fission process.

In summary, the heavy Fm isotopes (^{258}Fm and ^{259}Fm) so far appear to be unique in exhibiting very symmetric mass distributions and anomolously high fragment total kinetic energies. This effect appears to be associated with the Z = 100 proton configuration of the fissioning nuclide which can fission symmetrically into two fragments having the Z = 50 closed-proton shell configuration; ^{256}Cf which has the same number of neutrons but only 98 protons does not exhibit these fission properties. Furthermore, ^{259}Md, also having 158 neutrons but with 101 protons, fissions symmetrically but with a "normal" total kinetic energy. However, the total kinetic-energy distribution is extremely broad, indicating a range of fragment shapes at scission from spherical to highly distorted. It is extremely important to check more nuclides with Z greater than 100 and N $\gtrsim$ 158 to check the relative importance of the fragment proton and neutron shells. New methods are needed for measurements of half lives of ms or less and for providing positive identification of the Z and A of the fissioning species. Recent experiments[8] indicate that ^{259}Fm is produced with a 10 to 15 nb cross section in bombardments of ^{248}Cm with ^{18}O and that therefore extreme caution must be exercised in making assignments. However, transfer or deep inelastic reactions of this kind would appear to offer a good possibility for making the heavier isotopes of Md or Lr for study by bombarding Bk or Es targets with ^{18}O.

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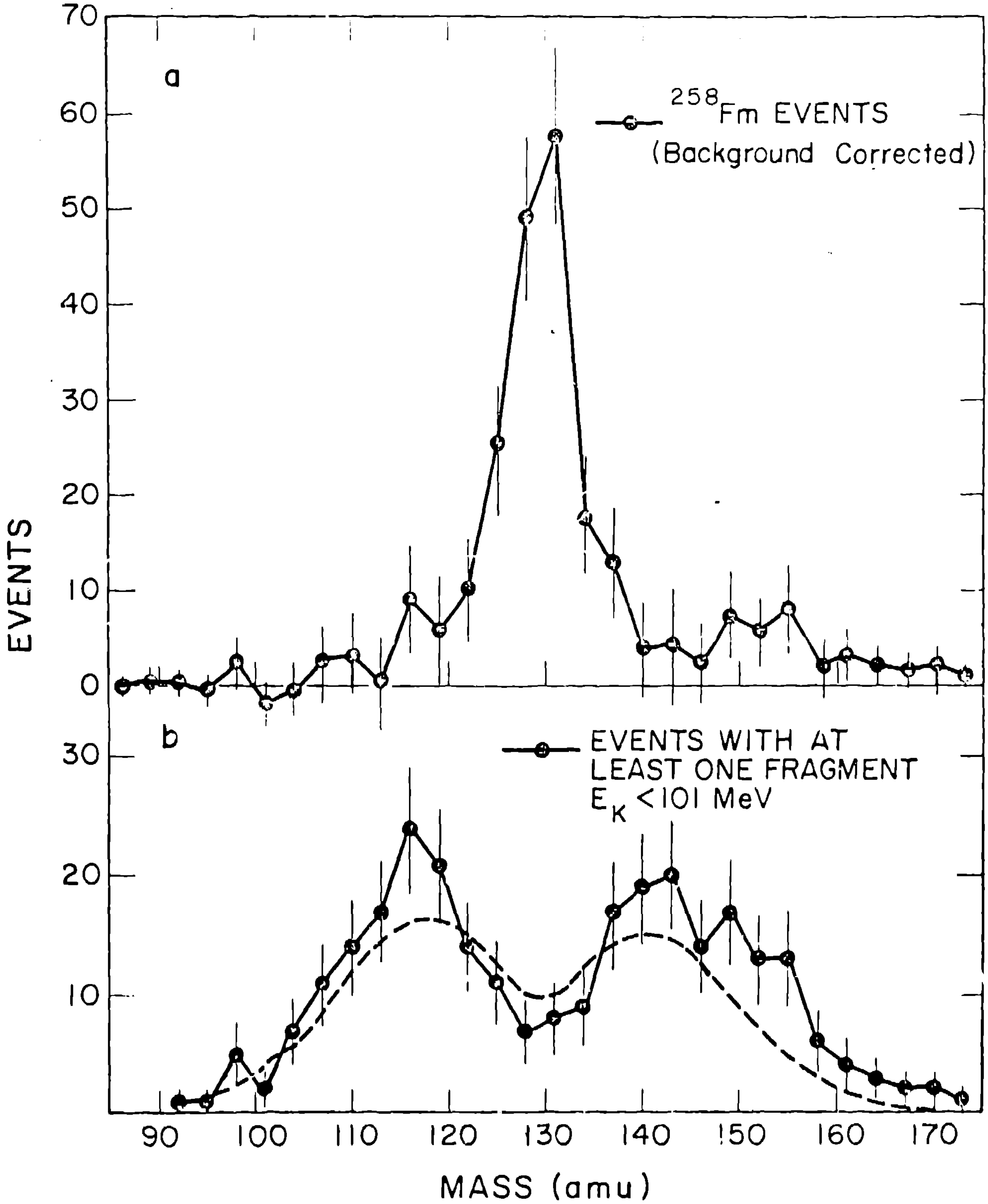
TABLE I

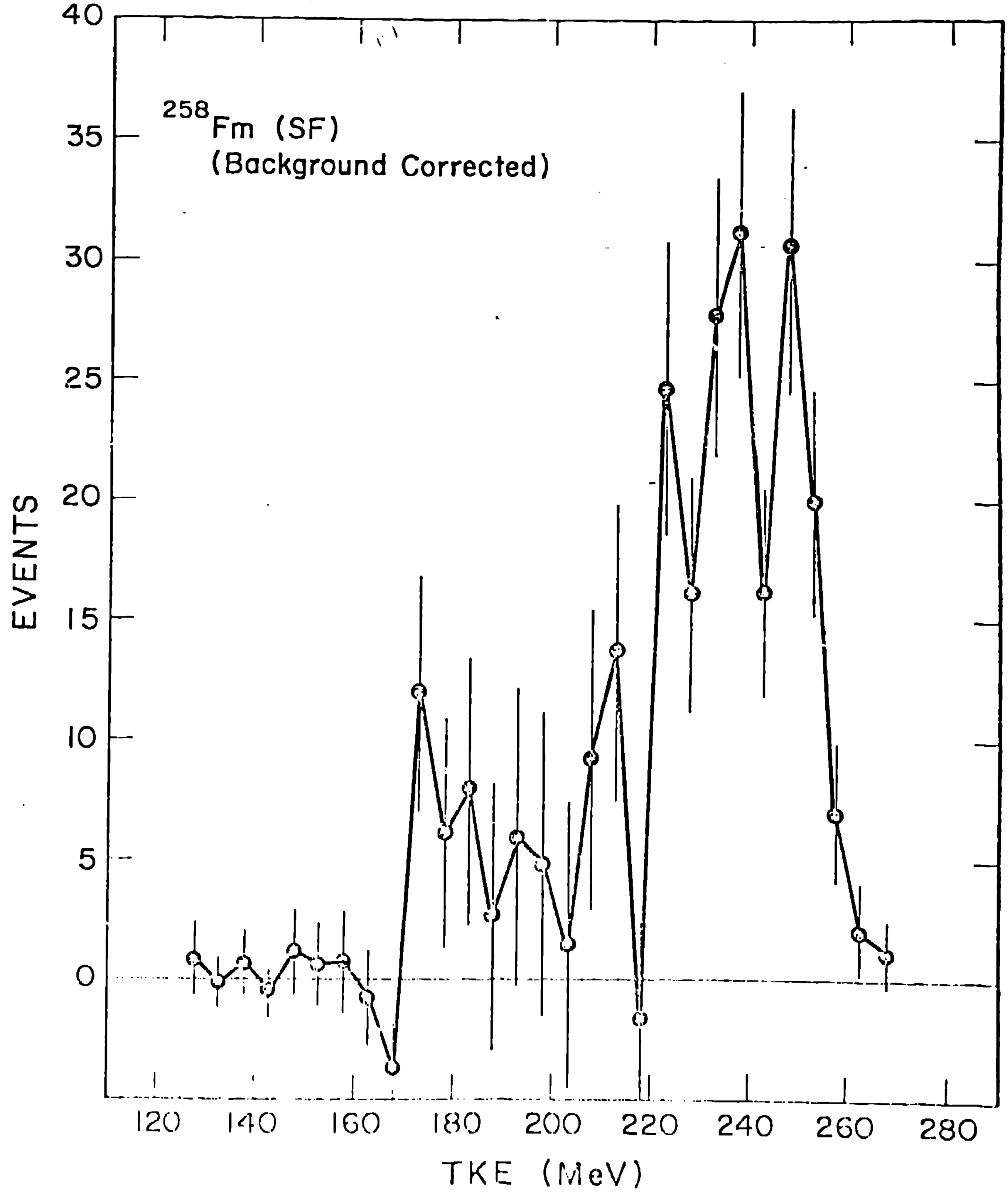
LOW ENERGY FISSION PROPERTIES OF SOME HEAVY ELEMENT ISOTOPES

FISSIONING NUCLIDE	SF $T_{1/2}$ (SECONDS)	PEAK-TO-VALLEY RATIO	$\overline{TKE}$ (MeV)	$\sigma_{\overline{TKE}}$	$\bar{\nu}_T$
^{250}Cf	5.4×10^{11}	>300(RC)	187.0	11.3	3.49
^{250}Cf*	-	≥50(RC)	189.1	13.0	-
^{252}Cf	2.7×10^{9}	≥750(RC)	185.7	11.6	3.735
^{252}Cf*	-	≈20(RC)	185	15.5	-
^{254}Cf	5.2×10^{6}	≥145(RC)	186.9	11.8	3.89
^{256}Cf	7.4×10^{2}	Asymm.(SS)	189.8	14.6	-
^{253}Es	2.0×10^{13}	326(RC)	191	13.4	-
^{255}Es*	-	≈8(SS)	194.3	15.9	-
^{254}Fm	2.0×10^{7}	≈42(RC)	195.1	11.7	3.96
^{256}Fm	1.0×10^{4}	12(SS)	197.9	14.4	3.70
^{256}Fm*	-	2.5(RC)	195.5	18	-
^{257}Fm	4.1×10^{9}	≈1.5(SS)	197.6	15.3	3.77
^{258}Fm	3.8×10^{-4}	Symm., σ = 8(SS)	238	14	-
^{258}Fm*	-	Symm., broad(SS)	197	-	-
^{259}Fm	1.5×10^{0}	Symm., σ = 11(SS)	242	21	-
^{259}Md	5.7×10^{3}	Symm., σ = 13(SS)	189	44	-
^{252}No	8.6×10^{0}	Asymm.(SS)	202.4	15.4	4.15



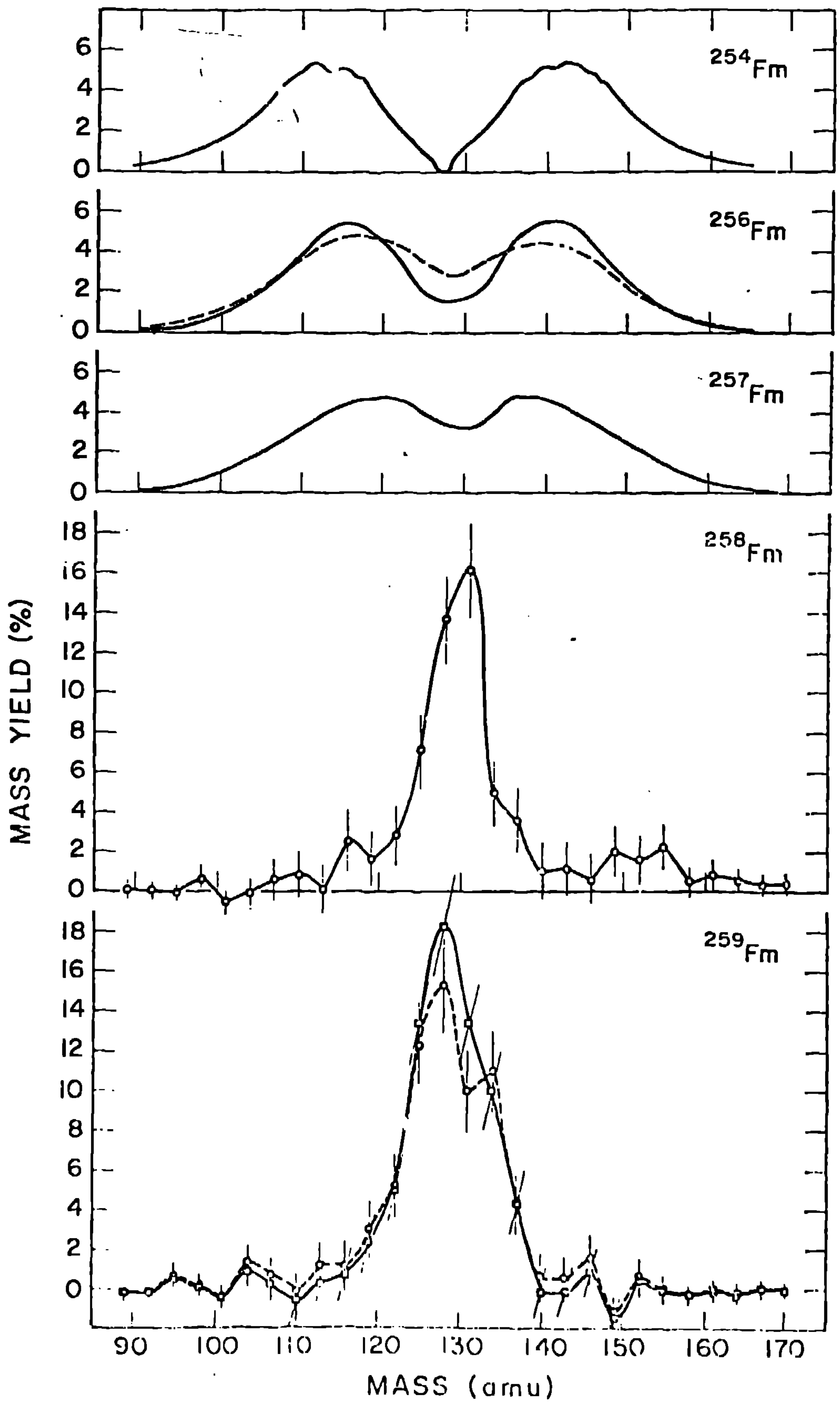
EVENTS
a
^{258}Fm EVENTS
(Background Corrected)
b
EVENTS WITH AT LEAST ONE FRAGMENT E_K <101 MeV
70
60
50
40
30
20
10
0
30
20
10
90
100
110
120
130
140
150
160
170
MASS (amu)

Figure 1



^{258}Fm (SF)
(Background Corrected)
EVENTS
TKE (MeV)
40
35
30
25
20
15
10
5
0
120
140
160
180
200
220
240
260
280

Figure 2



254Fm
256Fm
257Fm
258Fm
259Fm
MASS YIELD (%)
MASS (amu)
0
2
4
6
8
10
12
14
16
18
90
100
110
120
130
140
150
160
170

Figure 3

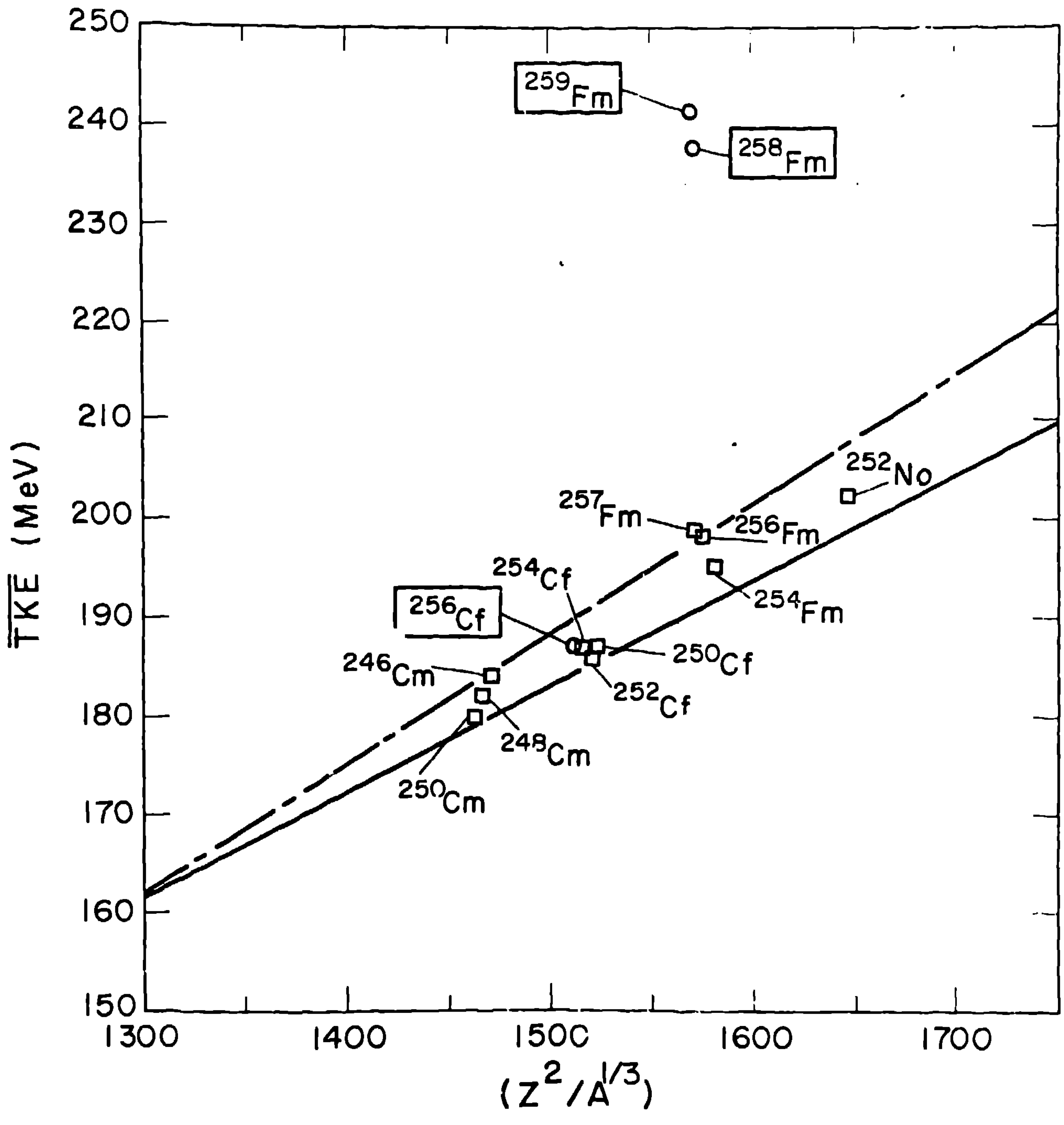

250
240
230
220
210
200
190
180
170
160
150
1300
1400
1500
1600
1700
TKE (MeV)
(Z2/A1/3)
259Fm
258Fm
252No
257Fm
256Fm
254Cf
254Fm
256Cf
250Cf
246Cm
252Cf
248Cm
250Cm

Figure 4

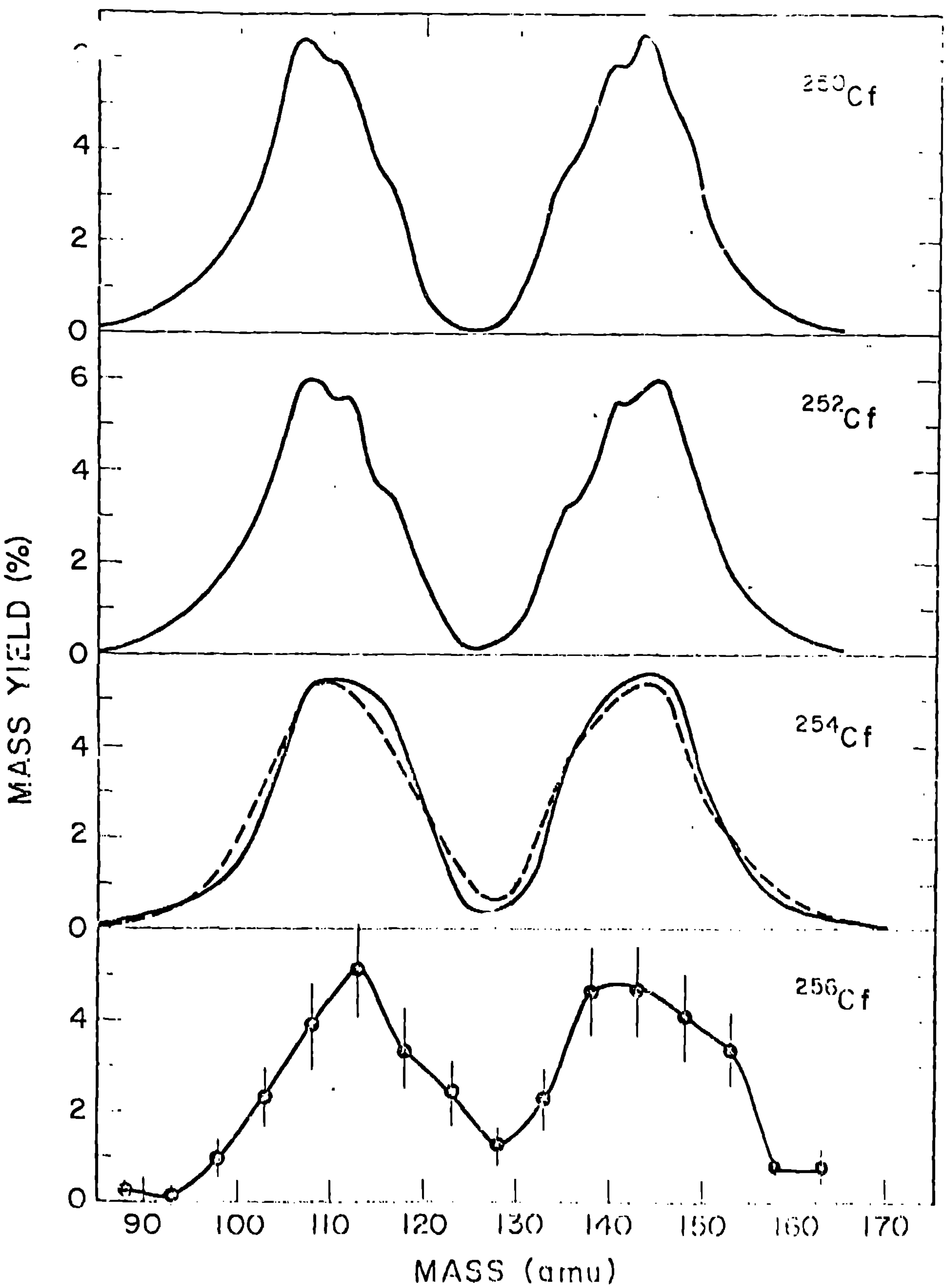
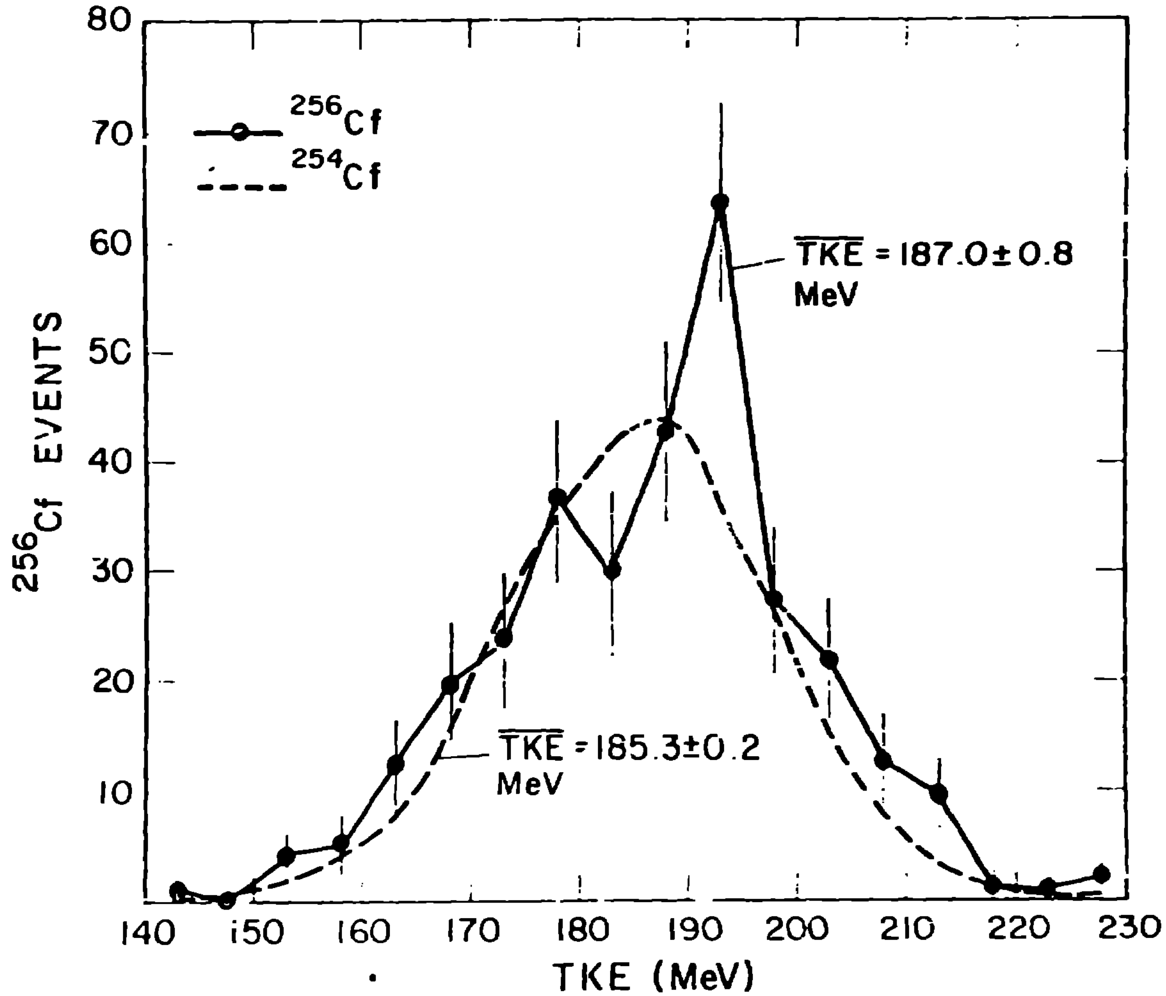


Figure 5



80
70
60
50
40
30
20
10
256Cf
254Cf
TKE = 187.0±0.8 MeV
TKE = 185.3±0.2 MeV
256Cf EVENTS
140
150
160
170
180
190
200
210
220
230
TKE (MeV)

Figure 6