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PROMPT NEUTRONS FROM SPONTANEOUS FISSION OF ^{257}Fm*

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ABSTRACT

The average number of prompt neutrons ($\bar{\nu}$) emitted in the spontaneous fission of ^{257}Fm has been measured to be 3.97 ± 0.13 (based on $\bar{\nu}$ = 3.72 for ^{252}Cf). This result and the known values of $\bar{\nu}$ for other nuclei that undergo spontaneous fission are transformed into excitation energy values and compared with the liquid-drop predictions regarding the excitation energy dependence on the fissionability parameter.

I. INTRODUCTION

The average prompt neutron yield ($\bar{\nu}$) from spontaneous fission is directly related to the excitation energy of the fragments. The value of $\bar{\nu}$ has been measured for several nuclei and exhibits a general increase with the fissionability parameter[1] x. Theoretical calculations which involve liquid-drop dynamics agree with the experimental trend. An important consequence of the calculations[2] is that $\bar{\nu}$ for isotopes of element 114 should be about 10.

The number of nuclei for which $\bar{\nu}$ of spontaneous fission can be measured is rather limited. For x values below that of ^{238}U the long spontaneous fission life times make the experiments impractical. For x values larger than those of fermium isotopes the short fission life times make the experiments difficult. In the experiment described here we measured the value of $\bar{\nu}$ for the spontaneous fission of ^{257}Fm. This is the heaviest nucleus for which such a measurement has been carried out to date. The result is discussed in terms of the theoretical predictions and the uncertainties involved in extracting a reliable value of excitation energy from a measurement of $\bar{\nu}$.

II. EXPERIMENTAL SYSTEM

The measurement of the number of neutrons was performed using a large gadolinium-loaded liquid scintillator. The fission sources and fragment detectors were placed at the center of the tank. The neutrons from the fission events underwent thermalization in the organic solvent in the tank and subsequently induced a cascade of gamma rays from thermal neutron capture in the gadolinium. The cascade of gamma rays produced signals in the photomultipliers that surrounded the tank. The system and its properties have been described in greater detail in an earlier report.[3]

In this experiment $\bar{\nu}$ for ^{257}Fm was measured relative to the value of $\bar{\nu}$ for ^{252}Cf. These two fission sources were measured simultaneously. The ^{257}Fm sample was placed 3 mm from a 3 cm^2 solid-state detector. The ^{252}Cf source self-transferred onto another solid-state detector was used for calibration purposes. The two detectors and fissioning sources were adequately sealed from each other and were both placed in close proximity at the center of the tank.

The pulses from the solid-state detectors were passed through discriminators set to avoid alphas and alpha pile-ups. The fission events triggered a 36 μsec gate with a 0.5 μsec delay after fission. During this gate all the pulses above a certain level arriving from the liquid scintillator were counted (with better than 0.3 μsec pulse-pair resolution) in a fast scaler with analog output. Detection of the prompt gamma rays from fission was eliminated by the 0.5 μsec delay. The analog output from the scaler was sent to a multichannel analyzer at the end of the 36 μsec gate and a multiplicity histogram was thus obtained. The 36 μsec gate was also triggered during the experiment by a slow rate pulser to obtain the background multiplicity distribution. The three multiplicity distributions, i.e., those triggered by ^{257}Fm, ^{252}Cf, and the pulser were recorded simultaneously on different regions of the multichannel analyzer. The spontaneous fission disintegration rate of each of the sources was sufficiently slow that any interference between the sources was negligible.

III. ^{257}Fm SAMPLE

The ^{257}Fm sample was produced in an intense explosion of the thermonuclear device "Hutch".[4] We received from E. K. Hulet a ^{257}Fm source with an intensity of 170 α/min (3×10^7 atoms, ~ 0.5 fission/min) electroplated on platinum backing. The active area had a diameter of ~ 6 mm.

IV. RESULTS

The observed multiplicity distributions are given in Table 1. The weak tail at high multiplicities in the ^{252}Cf and pulser cases are probably due to cosmic-ray-induced neutrons. From these results we obtain the efficiency, ϵ, of the detection system to be $\epsilon = (\bar{n}_{Cf} - \bar{n}_{pulser})/\bar{\nu}_{Cf} = 0.515$, where $\bar{n}$ is the average value of the recorded multiplicity distribution. The average number of neutrons emitted in the spontaneous fission of ^{252}Cf was taken to be $\bar{\nu}_{Cf} = 3.72$.[5]

The number of neutrons emitted from ^{257}Fm over the number emitted from ^{252}Cf was thus

$$\frac{\bar{n}_{Fm} - \bar{n}_{pulser}}{\bar{n}_{Cf} - \bar{n}_{pulser}} = 1.067 \pm 0.036 \quad ,$$

and therefore for ^{257}Fm $\bar{\nu} = 3.97 \pm 0.13$. The width of the neutron multiplicity distribution was derived from the equation

$$\sigma_\nu^2 = [\sigma_n^2 - \bar{n}(1 - \epsilon)]/\epsilon^2 \quad ,$$

which relates the variance σ_n^2 and mean $\bar{n}$ of the observed distribution to the variance of the real neutron distribution σ_ν^2. For ^{257}Fm $\sigma_\nu = 1.71 {+0.37 \atop -0.49}$, whereas for ^{252}Cf $\sigma_\nu = 1.37 \pm 0.03$.

V. DISCUSSION

The excitation energy of the fragments in spontaneous fission arises from the deformation of the fragments at the scission point. The excitation energy is directly related to the number of emitted neutrons and therefore by studying $\bar{\nu}$ of various spontaneously fissioning isotopes, a comparison can be made with the results of dynamical liquid-drop calculations of the deformation at the scission point as a function of the fissionability parameter. Such a comparison is of interest because of its bearing on estimates of the number of neutrons that might be expected to accompany the spontaneous fission decay of superheavy nuclei.

The total energy released in spontaneous fission, defined as ΔM, arises from the differences between the mass of the fissioning nucleus and the masses of the fragments. Most of the energy release appears as kinetic energy of the fragments E_K and a smaller part appears as excitation energy of the fragments E_x. The excitation energy is released by emission of neutrons and gamma rays and its average can be written as

$$E_x = \bar{\nu}(\bar{B}_n + \bar{E}_n) + \bar{E}_\gamma \quad . \qquad (1)$$

$\bar{B}_n$ and $\bar{E}_n$ are the average neutron binding energy of the fragments and the average neutron kinetic energies in the center of mass of the fragments respectively. (The kinetic energy of the fragments $\bar{E}_k$ is defined as pre-neutron emission kinetic energy.) The average laboratory system kinetic energy of the neutrons $\bar{E}_n^L$ is related to $\bar{E}_n$ by the relation $\bar{E}_n^L = \bar{E}_n + \bar{E}_K/A$ where A is the mass of the fissioning nucleus. $\bar{E}_\gamma$ is the average total gamma-ray energy which amounts on the average to $\bar{B}_n/2$ per fragment plus some energy (~ 1.5 MeV) that is due to angular momentum effects in the de-excitation of the fragments. The energy $\bar{E}_\gamma$ can thus be roughly estimated as $\bar{B}_n + \bar{E}_n$ and therefore Eq. (1) can be replaced by

$$\bar{E}_x = (\bar{\nu} + 1)(\bar{B}_n + \bar{E}_n) \quad . \tag{2}$$

In Table 2 we present a summary of the average excitation energies in nuclei that undergo spontaneous fission. The values of $\bar{\nu}$ for the various nuclei include the results of this experiment and results of other experiments which are referred to in the table. $\bar{B}_n$ was determined in the following manner: The most probable heavy fragment mass was assumed to be 140 in all the cases of the table because the nature of asymmetric low energy or spontaneous fission is such that the heavy mass peak remains roughly unchanged in all the known cases. The charges of the fragments were obtained from a constant Z/A ratio. The neutron binding energies of the fragments were taken from the mass tables of Garvey et al.[17] and averaged over even-odd effects in both protons and neutrons. In lieu of experimental values for the average neutron kinetic energies we used interpolated values based on the relationship $\bar{E}_n = a + b\bar{\nu}^{\frac{1}{2}}$. The constants a and b were obtained from the known experimental values $\bar{E}_n = 1.40$ MeV for $\bar{\nu} = 3.72$ in ^{252}Cf and $\bar{E}_n = 1.26$ MeV and $\bar{\nu} = 2.47$ in thermal neutron fission of ^{235}U.

In Table 2 we also present the experimental kinetic energy and the total energy release ΔM. ΔM was inferred from the Garvey mass tables[17] (when experimental masses were unavailable). Again the heavy fragment mass was taken to be 140 in all cases.

The equation $\bar{E}_x = \Delta\bar{M} - \bar{E}_K$ represents the balance of energy in spontaneous fission. The source of the difference between the values of $\bar{E}_x$ and $\Delta\bar{M} - \bar{E}_K$ in Table 2 is due mostly to the nature of the approximations that were used to obtain these quantities and which affected the accuracy of $\bar{E}_x$ as well as $\Delta\bar{M} - \bar{E}_K$. In calculation $\bar{E}_x$ the main source of error is due to replacement of a properly weighted average over all the relevant neutron binding energies by the neutron binding energies of isotopes which are near the most probable fission species. Smaller errors are perhaps due to the assumption that the number of neutrons emitted by both fragments is the same and also to the fact that the neutron binding energies in the mass tables are subject to errors; however, all of these errors are probably less than 1 MeV per emitted neutron.

The value of $\Delta\bar{M} - \bar{E}_K$ is also subject to error because we calculated the energy release corresponding to the most probable mass splits rather than taking an average over the whole mass and charge distribution. Furthermore the average kinetic energy values are probably uncertain by about 2-4 MeV. Altogether the difference between $\bar{E}_x$ and $\Delta\bar{M} - \bar{E}_K$ can amount to 4-8 MeV as is indeed seen in the table.

The excitation energies $\bar{E}_x$ and $\Delta\bar{M} - \bar{E}_K$ are plotted as a function of the fissionability parameter x for various nuclei in Fig. 1. For comparison with the experimental results we also show in Fig. 1 the excitation energies of the fragments calculated by Nix using the liquid-drop model.[18] The calculations were carried out for symmetric mass divisions and were based on liquid-drop masses. Although there is a 15-20 MeV discrepancy between the calculations, which include no adjustable parameters, and the experimental results, the trend for higher excitation energy with higher fissionability parameter is however similar in both cases. Better agreement is obtained between the calculations and experimental values of the kinetic energies of fragments from induced fission of compound nuclei have fissionability parameters in the range $0.6 < x < 0.9$ where the fission is induced by high energy projectiles. In such cases the excitation energy that is associated with the deformation is obtained from $\Delta\bar{M} - \bar{E}_K$ and these values are generally only 5-10 MeV lower than the calculated liquid-drop deformation energies.

The systematic deviation between experimental values of deformation energy in spontaneous fission and the results of the liquid-drop calculations can be attributed to single particle effects that exert an important influence on the shape of the nucleus at the saddle point or during descent to the scission point. At present no reliable estimate can be made of the average number of neutrons emitted in spontaneous fission of superheavy nuclei ($x = 0.93$) from liquid-drop dynamical calculations since the dynamical consequences resulting from the single particle effects in both the inertial parameters and the potential energy surfaces seem far from quantitative evaluation. If, however, the systematic difference of ~ 18 MeV between the experimental results and liquid-drop values persists at higher x values, then for superheavy elements with $Z \cong 114$, $A \cong 298$, the excitation energy should be about 65 MeV and $\bar{\nu} \cong 7.8$ neutrons.

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FOOTNOTES AND REFERENCES

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† On leave of absence from the Weizmann Institute of Science, Rehovot, Israel.

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Table 1. Experimental results.

Multiplicity	Observed events ^{252}Cf	^{257}Fm	Pulser
0	493,685	187	18,645
1	1,141,342	316	1,940
2	1,386,855	406	178
3	973,073	338	29
4	424,856	175	23
5	121,806	56	2
6	24,516	19	6
7	3,794	2	3
8	624		0
9	202		1
10	96		2
11	54		1
12	91		0
Total fissions	4,570,949	1,499	20,830
$\bar{n}$	2.040	2.168	0.124
σ_n^2	1.623	1.946	0.181

Table 2. Components of the energy balance in spontaneous fission. x - fissionability parameter; $\bar{\nu}$ - average number of emitted neutrons; $\Delta\bar{\nu}$ - experimental uncertainty in $\bar{\nu}$; $\bar{B}_n$ - average neutron binding energies; $\bar{E}_n$ - average neutron kinetic energy; $\bar{E}_x$ - average excitation energy; ΔM - mass difference between the fissioning nucleus and the fragments; $\bar{E}_K$ - experimental average kinetic energy of the fragments.

Isotope	x[a]	$\bar{\nu}$	$\Delta\bar{\nu}$	Ref.[b]	$\bar{B}_n$	$\bar{E}_n$	$\bar{E}_x$	ΔM	$\bar{E}_K$	Ref.[c]	$\Delta M-\bar{E}_K$
^{238}U	0.7566	2.10	0.08	6	4.90	1.21	18.9	189.4	171.9	11[d]	17.5
^{242}Pu	0.7743	2.18	0.09	7	5.06	1.23	20.0	201.0	177.6	12[e]	23.4
^{240}Pu	0.7764	2.26	0.05	7	5.06	1.24	20.5	195.3	174.4	12[e]	20.9
^{238}Pu	0.7786	2.33	0.08	7	5.32	1.24	21.8				
^{236}Pu	0.7810	2.30	0.19	7	5.67	1.24	22.8				
^{244}Cm	0.7941	2.69	0.02	8	5.35	1.29	24.5	207.6	188.6	13	19.6
^{242}Cm	0.7965	2.65	0.09	7	5.48	1.28	24.7				
^{254}Cf	0.8055	3.90	0.14	9	5.05	1.42	31.7	224.8	187.5	14[f]	37.3
^{252}Cf	0.8075	3.72	0.02	5	5.23	1.40	31.3	225.1	186.5	11	38.6
^{257}Fm	0.8242	3.97	0.13		5.23	1.44	33.1	234.5	198	16	36.5
^{254}Fm	0.8274	3.94	0.19	10	5.45	1.44	34.0	233.4	191	14[f]	42.4

Table 2. (Continued)

[a] x values taken from the table of Myers and Swiatecki.[15]

[b] References for experimental values of $\bar{\nu}$ and $\Delta\bar{\nu}$.

[c] References for experimental values of $\bar{E}_K$.

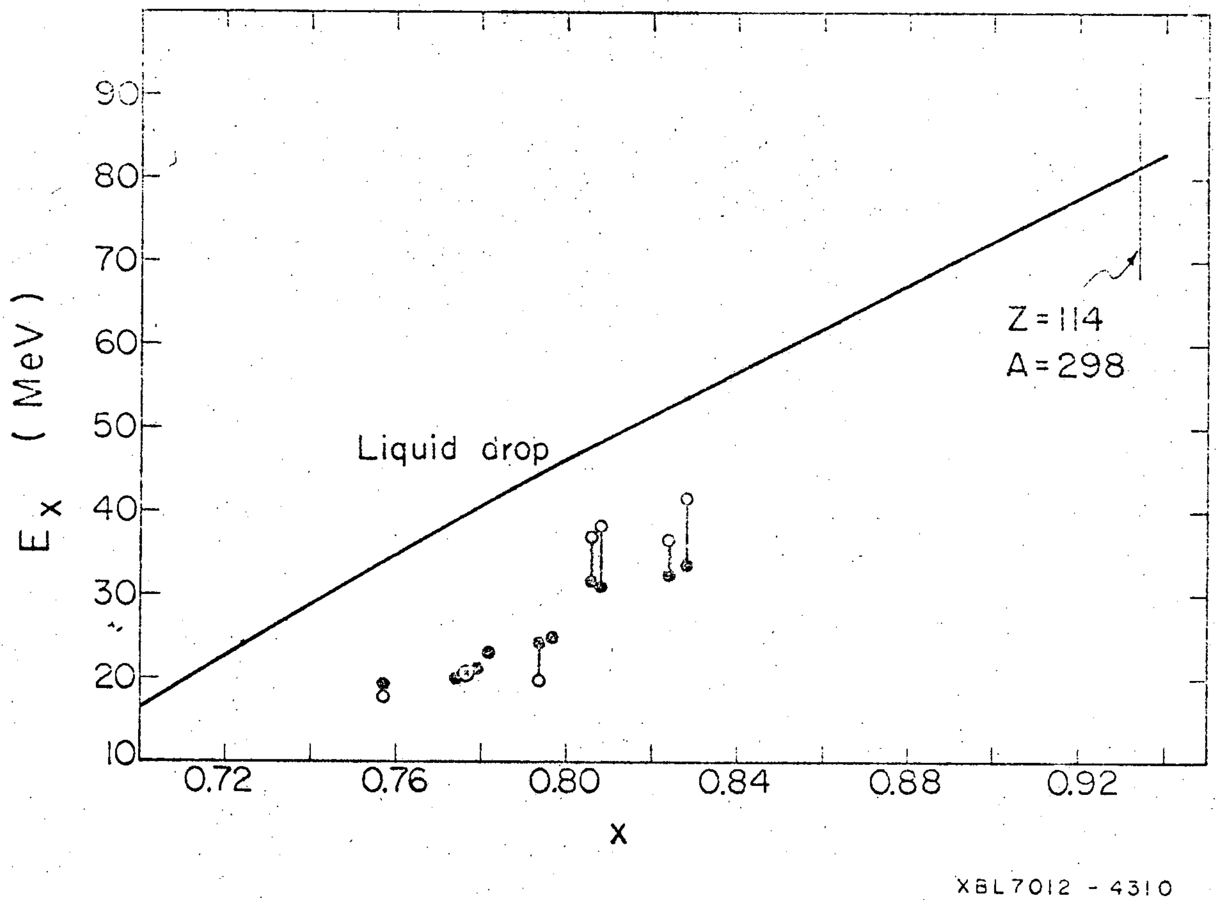
[d] The kinetic energy of fragments in thermal neutron fission of ^{235}U is cited.

[e] The kinetic energy of fragments in thermal neutron fission of ^{239}Pu and ^{241}Pu was used here.

[f] The kinetic energies of the fragments in the work of Brandt *et al.*[14] were adjusted to be consistent with the calibration of Schmitt *et al.*[11]

FIGURE CAPTION

Fig. 1. The average excitation energy in spontaneous fission as a function of the fissionability parameter. Dots—values derived from experimental results of $\bar{\nu}$. Open circles—values derived from $\Delta\bar{M} - \bar{E}_K$. Values of $\bar{E}_x$ for the same isotope are connected by a line. The continuous line represents the liquid-drop estimate taken from Nix.[18]



90
80
70
60
50
40
30
20
10
E x (MeV)
Liquid drop
Z=114
A=298
0.72
0.76
0.80
0.84
0.88
0.92
X
XBL7012 - 4310

Fig. 1

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