Romanian Reports in Physics, Volume 55, Number 4, P. 360-365, 2003

IS BIMODAL FISSION AN INDIRECT EXPERIMENTAL EVIDENCE FOR PIONIC RADIOACTIVITY?

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(Received July 28, 2003)

Abstract: In this paper new predictions for the spontaneous pion emission accompanied by fission are presented for all nuclei with $100 \leq Z \leq 108$. The bimodal fission as an indirect experimental evidence for the pionic radioactivity is demonstrated. The experimental tests of this important connection are suggested.

Key words: fission, pion emission, heavy nuclei.

INTRODUCTION

The nuclear pionic radioactivity of a parent nucleus (A,Z), introduced in 1985 by Ion, Ivascu and R. Ion-Mihai [1-4], can be considered as an inclusive reaction of form:

$$(A,Z) \rightarrow \pi + X \qquad (1)$$

where X denotes any configuration of final particles (fragments, light neutral and charged particles, etc.) which accompany emission process. The inclusive NPIR is in fact a sum of all exclusive nuclear reactions allowed by the conservation laws in which a pion can be emitted by a nucleus from its ground state. The most important exclusive reactions which give the essential contribution to the inclusive NPIR (1) are the spontaneous pion emission accompanied by two body fission::

$$^{A}_{Z}X \rightarrow \pi + {}^{A_1}_{Z_1}X + {}^{A_2}_{Z_2}X \qquad (2)$$

where $A=A_1+A_2$ and $Z=Z_1+Z_2+Z_\pi$.

contribution to the inclusive NPIR (1) are the spontaneous pion emission accompanied by two body fission::

$$^{A}_{Z}X \rightarrow \pi + {}^{A_1}_{Z_1}X + {}^{A_2}_{Z_2}X \qquad (3)$$

where $A=A_1+A_2$ and $Z=Z_1+Z_2+Z_\pi$.

Hence, the NPIR is an extremely complex coherent reaction in which we are dealing with a spontaneous pion emission accompanied by a rearrangement of the parent nucleus in two or many final nuclei. Charged pions as well as neutral pions can be emitted during two body or many body fission of parent nucleus.

The energy liberated in an exclusive nuclear reaction (1) is given by

$$Q_{\pi F} = Q_n - m_\pi \qquad (4)$$

where Q_n is the energy liberated in n-body spontaneous fission

$$Q_n = m(Z,A) - m(Z_1,A_1) - m(Z_2,A_2) - ... - m(Z_n,A_n) \qquad (5)$$

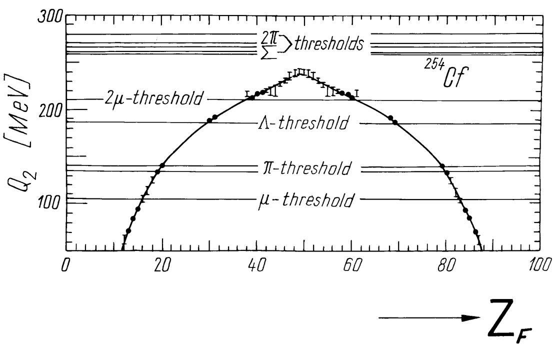


Fig. 1

Fig. 1: - Q_2-energy liberated in n-body spontaneous fission of some heavy nuclei.

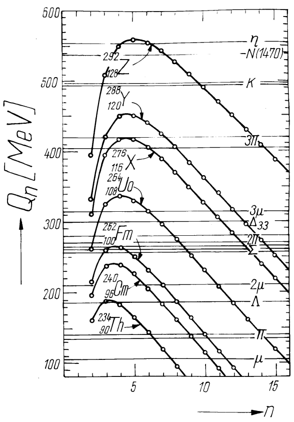
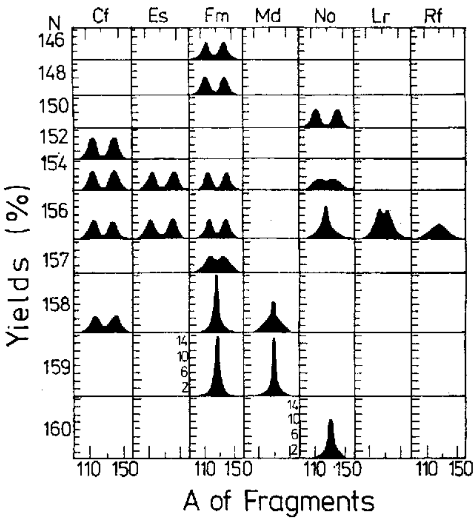


Fig. 2

Fig. 2:- Q_n -energy liberated in n-body spontaneous fission of some heavy nuclei.

In the last decades the studies of the spontaneous fission (SF) properties of heavy nuclides in the region of Fermium contributed essentially to a real progress in the understanding [5-9] of the sudden transition from the asymmetric mass division observed in the SF of all the lighter actinides to the very symmetric mass division accompanied by anomalous high total kinetic energy (TKE) found in SF of heavier Fm isotopes. This transition was first found [9] to occur in Fm between ^{256}Fm and ^{258}Fm, ^{257}Fm being a transition nucleus with much enhanced yields and high TKE`s for the symmetric mass division.

Therefore, the investigations (see quotations and the results in refs.[5-9]) of the spontaneous fission (SF) properties of heavy nuclides: ^{258}Fm, ^{259}Md, ^{260}Md, ^{258}No, and ^{260}Ha etc., shown that all these nuclides are fissioning with a symmetrical division of mass. The transitions from asymmetric to symmetric mass division for the Fm isotopes as well as for No nuclides are shown schematically in Fig. 3. The most striking feature is narrowness of the full width at half maximum ΔM of these mass distributions. Moreover, the total kinetic energy (TKE) distributions strongly deviates from the Gaussian shape characteristically found in the fission of other actinides. When the TKE-distributions are resolved in two Gaussians, one of the constituent peaks lie in the low-energy region near 200 MeV while the second peak lie at the high-energy near 233 MeV. This property of the SF TKE-distributions is called *bimodal fission*. Hence, the low-energy-SF-mode is characterized by broad symmetrical mass distribution and fragment energy in accord with liquid-drop systematics, whereas the high-energy-SF-mode produces sharply symmetrical mass distributions with the TKE of fragments approaching the Q_{SF} values for the fission reaction. Even though both SF modes are possible in the same parent nuclei, but one generally predominates. The theoretical explanation offered by Hulet et al. (see ref. [7]) for the bimodal fission is based on the calculations of static deformations. Each mode is derived from the shell structure effects; one in the parent fissioning nucleus and the other from single-particle couplings in the fragments. Theorists have found (see Refs.[11]) new appropriate valleys which can explain the bimodal fission. However, how each mode can coexist and occur with near equal probability present a challenging problem. In the the authors of the paper [12] staring the observation that this kind of symmetric fission occur for nuclei in which the initial formation of a cluster within the valence shells of the fissioning nucleus yields an energy Q_2 higher than the threshold for the creation of a pion on mass shell, sugested that this mode of fission could be related to a *new phase of nuclear matter*. So, these remarks suggest that something new happens in the symmetric spontaneous fission of the heavy actinides. But this something new happens only for *those parent nuclei which are spontaneously fissioning in two steps and for which a NPIR reaction (1) with a pion on mass shell is energetically possible even in the first intermediate step*, e.g. (see the first diagram in the right hand of Fig. 4a.): $^{258}Fm \to ^{50}Ar + ^{208}Pb,\ Q_2 \geq m_\pi$, followed by the second step: $^{50}Ar + ^{208}Pb \to ^{132}Sn + ^{126}Sn + Q$ leading to the symmetric final state. Hence, this something new could be the appearance of the pion on mass shell as a third constituent of the nucleus in which the distinction between proton and neutron disappear- due the transition $p \Leftrightarrow n$ (at equilibrium)- and for which the magic numbers remain the same as for the usual constituents n or p. These two steps can be represented as in the first (right hand) unitarity diagram in Fig.4a.



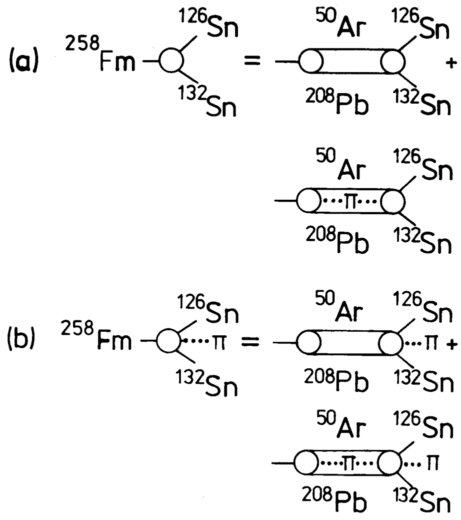


Fig. 3 Fig. 4

Fig. 3: *Mass distributions of nuclear fragments for superheavy (see Ref.* [5] *).*

Fig. 4: *Description of* <u>*spontaneous fission (SF)*</u> *of* ^{258}*Fm as well as of* <u>*spontaneous pionic fission*</u> *(* πF *) of* ^{258}*Fm in terms of two types of unitarity diagrams (see the text).*

So, according to the unitarity diagram from Fig. 4a, *the spontaneous fission (SF)* can be described as a bimodal two step process as follows

<u>*Asymmetric fission mode*</u> (A)

$$\underline{\text{first step}}:\ {}^{258}Fm \rightarrow {}^{50}Ar + {}^{208}Pb, \tag{3}$$

$$\underline{\text{second step}}:\ {}^{50}Ar + {}^{208}Pb \rightarrow {}^{126}Sn + {}^{132}Sn \tag{4}$$

<u>*Symmetric fission mode (S):*</u>

$$\underline{\text{first step}}:\ {}^{258}Fm \rightarrow \pi + {}^{50}Ar + {}^{208}Pb \tag{5}$$

$$\underline{\text{second step}}:\ \pi + {}^{50}Ar + {}^{208}Pb \rightarrow {}^{126}Sn + {}^{132}Sn \tag{6}$$

In similar way, for the *pionic radioactivity* (Fig. 1b) we have

<u>*NPIR-Asymetric mode*</u>

$$\underline{\text{first step}}:\ {}^{258}Fm \rightarrow {}^{50}Ar + {}^{208}Pb \tag{7}$$

$$\underline{\text{second step}}:\ {}^{50}Ar + {}^{208}Pb \rightarrow \pi + {}^{126}Sn + {}^{132}Sn \tag{8}$$

<u>*NPIR-Symmetric mode*</u>

$$\underline{\text{first step}}:\ {}^{258}Fm \rightarrow \pi + {}^{50}Ar + {}^{208}Pb \tag{9}$$

$$\underline{\text{second step}}:\ \pi + {}^{50}Ar + {}^{208}Pb \rightarrow \pi + {}^{126}Sn + {}^{132}Sn \tag{10}$$

Then, the scenario described in Figs. 4, which include in a more general and exact form the idea of transition to a new phase of nuclear matter, is leading us to point out a possible connection between the observed bimodal symmetric SF at the nuclides ^{258}Fm, ^{259}Fm, ^{259}Md, ^{260}Md, ^{258}No, with a significant high NPIR-yields for these nuclei. In order to illustrate this idea we give in Table 1 the π-NPIR yields, predicted by by the fission-like model [see Ref. [13]]:

$$\frac{\Gamma_{\pi}}{\Gamma_{SF}} = \left[\frac{T_{SF}}{T_{SF}^{C}}\right]^{D_{\pi}(A,Z)} \tag{11}$$

where

$$D_{\pi}(A,Z) = \frac{\Delta_{\pi}}{\pi - 5}, \tag{12}$$

and

- $\Delta\theta_\alpha = \frac{m_\pi}{\gamma A^{2/3}} \frac{\alpha - (1-\alpha)E_C{}^0 / E_S{}^0}{1-(1-\alpha)m_\pi / E_S{}^0}$,
- $E_C^0 = 0.7053 Z^2 A^{-1/3}$ (MeV) and $E_S^0 = 17.80 A^{2/3}$ (MeV)
- $T_{SF}^C = 10^{-10.95}$ (yr) for even-even parent nuclei, and

$T_{SF}^C = 10^{-8.39}$ (yr) for A-odd parent nuclei.

Table 1: Theoretical predictions of the $\Gamma_{\pi^{0,\pm}} / \Gamma_{SF}$ yields for heavy parent nuclei with Z between Z=100 and Z=108, obtained by using Eqs. (11)-(12).

	Z	A	T_{SF} (yr)	T_{SF} / T_{SF}^C	$\Gamma_{\pi^-} / \Gamma_{SF}$	$\Gamma_{\pi^0} / \Gamma_{SF}$	$\Gamma_{\pi^+} / \Gamma_{SF}$
Fm	100	242	2,535E-11	2,259E+00	3,55E-02	3,30E-02	2,43E-02
	100	244	1,046E-10	9,320E+00	8,59E-04	7,35E-04	3,85E-04
	100	245	1,255E-04	3,080E+04	1,77E-13	9,32E-14	6,33E-15
	100	246	4,753E-07	4,236E+04	1,17E-12	6,39E-13	5,16E-14
	100	248	1,141E-03	1,017E+08	3,59E-18	1,48E-18	3,74E-20
	100	250	8,000E-01	7,130E+10	3,28E-21	1,16E-21	1,54E-23
	100	252	1,250E+02	1,114E+13	1,84E-22	6,12E-23	6,26E-25
	100	254	6,242E-01	5,563E+10	9,36E-17	4,15E-17	1,41E-18
	100	256	3,308E-04	2,948E+07	8,08E-11	4,84E-11	5,77E-12
	100	257	1,310E+02	3,216E+10	2,75E-14	1,38E-14	7,93E-16
	100	258	1,172E-11	1,045E+00	9,47E-01	9,46E-01	9,41E-01
	100	259	4,753E-08	1,167E+01	5,44E-02	5,10E-02	3,91E-02
	100	260	1,268E-10	1,130E+01	6,33E-02	5,95E-02	4,62E-02
Md	101	245	2,852E-11	7,001E-03	8,66E+11	1,58E+12	1,96E+13
	101	247	6,338E-09	1,556E+00	1,73E-01	1,67E-01	1,42E-01
	101	255	3,422E-02	8,401E+06	1,20E-13	6,27E-14	4,12E-15
	101	257	6,297E-02	1,546E+07	1,37E-12	7,52E-13	6,16E-14
	101	259	1,848E-04	4,536E+04	1,28E-07	9,04E-08	2,11E-08
No	102	250	7,922E-12	7,061E-01	6,41E+00	6,67E+00	7,91E+00
	102	251	3,169E-07	7,779E+01	3,33E-09	2,17E-09	3,63E-10
	102	252	2,852E-07	2,542E+04	9,39E-18	3,96E-18	1,09E-19
	102	254	9,126E-04	8,134E+07	1,02E-24	3,02E-25	1,92E-27
	102	256	1,711E-05	1,525E+06	3,58E-16	1,64E-16	6,32E-18
	102	257	5,324E-05	1,307E+04	3,53E-10	2,19E-10	2,98E-11
	102	258	3,803E-11	3,389E+00	7,47E-02	7,06E-02	5,56E-02
	102	259	1,141E-03	2,800E+05	1,68E-11	9,75E-12	1,00E-12
	102	260	3,359E-09	2,994E+02	2,62E-05	2,08E-05	7,91E-06
	102	262	1,584E-10	1,412E+01	1,30E-02	1,18E-02	7,96E-03
Lr	103	253	4,183E-06	1,027E+03	1,39E-25	3,97E-26	2,10E-28
	103	255	6,845E-04	1,680E+05	7,00E-28	1,77E-28	5,77E-31
	103	257	6,274E-05	1,540E+04	1,25E-16	5,59E-17	1,95E-18
	103	259	9,823E-07	2,411E+02	7,32E-08	5,09E-08	1,13E-08
	103	261	7,415E-05	1,820E+04	2,85E-11	1,67E-11	1,81E-12
Rf	104	258	4,436E-10	3,954E+01	1,67E-13	8,74E-14	5,91E-15
	104	259	1,331E-06	3,267E+02	2,13E-16	9,65E-17	3,54E-18
	104	260	6,338E-10	5,648E+01	1,12E-09	7,16E-10	1,08E-10
	104	261	2,091E-05	5,134E+03	8,73E-17	3,87E-17	1,31E-18
	104	262	6,654E-08	5,931E+03	6,72E-15	3,27E-15	1,65E-16

Db	105	255	2,535E-07	6,223E+01	2,29E+11	4,08E+11	4,48E+12
	105	257	2,535E-07	6,223E+01	6,87E+20	1,97E+21	1,59E+23
	105	261	3,169E-07	7,779E+01	3,00E-34	5,48E-35	4,67E-38
	105	263	1,521E-06	3,734E+02	5,81E-21	2,08E-21	2,92E-23
Sg	106	258	9,190E-11	8,190E+00	1,04E+04	1,27E+04	2,97E+04
	106	259	7,605E-08	1,867E+01	4,36E+06	6,10E+06	2,47E+07
	106	260	2,218E-10	1,977E+01	2,12E+08	3,24E+08	1,87E+09
	106	261	8,239E-08	2,022E+01	7,76E+10	1,34E+11	1,33E+12
	106	263	8,556E-08	2,100E+01	1,31E+27	5,17E+27	1,57E+30
Bh	107	261	3,803E-09	9,334E-01	7,93E-01	7,89E-01	7,72E-01
Hs	108	264	6,338E-11	5,648E+00	1,08E+02	1,20E+02	1,84E+02

Here, as in Ref. [13] we also adopt the notions of *SF-nuclide*, *πF-nuclide*, and *T-transition nuclide,* as being those parent nuclei characterized by : $\frac{\Gamma_{\pi}^{0,\pm}}{\Gamma_{SF}} < 1$, $\frac{\Gamma_{\pi}^{0,\pm}}{\Gamma_{SF}} > 1$ and yield $\Gamma_{\pi}^{0,\pm} = \Gamma_{SF}$, respectively, with their characteristic features presented in Table 2.

Table 2 : Definitions and characheristic features of (SF, πF , T)-nuclides.

Type of nuclide	Pionic Yield	Mass Distribution (MD)	Half Lives $Z^2/A \leq 42.5$	Half Lives $Z^2/A \leq 42.5$	Dominant Unitarity Diagram
SF-nuclide	$\frac{\Gamma_{\pi}^{0,\pm}}{\Gamma_{SF}} < 1$	*Asymmetric MD*	$T_{SF} > T_{SF}^{C}$	$T_{SF} < T_{SF}^{C}$	D_{SF}
T-nuclide	$\frac{\Gamma_{\pi}^{0,\pm}}{\Gamma_{SF}} = 1$	*Bimodal MD*	$T_{SF} = T_{SF}^{C}$	$T_{SF} = T_{SF}^{C}$	$D_{\pi F} + D_{SF}$
$\pi F - nuclide$	$\frac{\Gamma_{\pi}^{0,\pm}}{\Gamma_{SF}} > 1$	*Symmetric MD*	$T_{SF} < T_{SF}^{C}$	$T_{SF} > T_{SF}^{C}$	a new phase $D_{\pi F}$ n ⇔ p

Therefore, the results presented in Table 1 can now be summarized as follows [in paranthesis we give the predicted pionic yield for π^0] :

- The nuclides ^{242}Fm (3.3 10^{-2}) are expected to be πF-nuclides, if our predictions with [illegible] $= 1$ subestimated the pionic yield determined with Eqs. (11)-(12). Then, a new transition nucleus can be predicted to be in the region of Fm with A=240-242. The experiments with parent nuclei in this Fm region are nedeed in order to clarify these predictions.
- The nuclides ^{A}Fm with $244 \leq A \leq 256$ are all "SF" nuclides since all are have asymmetric mass distribution of fission fragments (see Fig. 3).
- The problem of the nucleus ^{257}Fm (1.4 10^{-14}) as transition nuclide can also be supported not only by "bimodal" experimental observation but also by some experimental high pionic yields infered in Refs.[15,16] from the experimental data of Wild et al.,[17].
- The best π-emitter with symmetric mode of fission in this region is expected to be ^{258}Fm (0.95). If our interpretation of the bimodal fission via the saturation of the unitarity limits shown in Fig. 4a,b is correct we expect that pionic yield of ^{258}Fm to be higher than 1. The nuclei ^{259}Fm (5.1 10^{-2}) and ^{260}Fm (5.6 10^{-2}) are also interesting from experimental point of view since both can be "πF"-nuclides
- The nuclides No with A=242-250 are expected to be all πF-nuclides (infered from Fig. 4 in Ref. [3]), while the No-isotopes with $A \geq 252$ are all SF-nuclides (see Table 1). High pionic yields are obtained for ^{250}No (6.67) as well as for ^{258}No (7.1 10^{-2}) and ^{262}No (1.2 10^{-2}).
- The nuclides Lr and Rf are all predicted to be SF-nuclides (see Table 1).
- The nuclides ^{258}Sg (1.3 10^{7}), ^{259}Sg (6.1 10^{6}), ^{260}Sg (1.2 10^{8}), ^{261}Sg (1.3 10^{11}), ^{263}Sg (5.2 10^{27}) as well as ^{264}Hs (1.2 10^{2}) all are predicted to be πF-nuclides.

We note of course that all these estimations must be taken as orientating for the future experimental investigations where the πF-methods are expected to play an important role. Therefore, dedicated πF-experiments using nuclei with theoretically predicted (see Table 1) high pionic yields are desired.

For sake of completeness we recall here the results [3,14] regarding the competition between the pionic radioactivity and the spontaneous fission of the SHE-nuclides. Indeed, using the same fission-like model, it was shown that most of the SHE-nuclei lie in the region where the pionic fissility parameters attain their limiting values $X_{\pi F} = 1$. Hence, the SHE-region is characterized by the absence of a classical barrier toward spontaneous pion emission. Consequently, both decay modes π-fission and the spontaneous fission of SHE nuclides essentially will be determined only by shell effects. Then, it was seen that the usual SHE-island of stability around the double magic nucleus $^{298}[114]$ can be destroyed due to the dominant pionic radioactivity of the SHE-nuclei from this region. Therefore, we believe that in future searches for transfermium as well as for SHE-nuclei, the *π-fission* as detection method [18] can play an essential role in the discovery of this new phase of nuclear matter produced by the presence of pions on mass shell in the nuclear medium.

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