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SPONTANEOUS PION EMISSION DURING FISSION A NEW NUCLEAR RADIOACTIVITY

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Abstract: In this a short review of the theoretical problems of the pionic radioactivity is presented. The essential experimental results obtained in the 18 years of existence of the nuclear pionic radioactivity are reviewed. Moreover, using the recent results on the spontaneous fission half lives T_{SF} of the heavy nuclei with $Z \geq 100$ new predictions on the pionic yields in the region of superheavy elements are established.

Key words: spontaneous pion emission, fission halflives, heavy nuclei

1. INTRODUCTION

In 1935 Japanese physicist Hideki Yukawa predicted [1] the existence of a particle—a meson—with a mass about 200 times that of the electron, which mediated the nuclear forces. At first, the muon, discovered in 1937, looked like a good candidate for the meson, but soon it became clear that the muon's properties did not match those predicted by Yukawa. Then, in 1947, Lates, Occhialini and Powell discovered [2] the π-meson, or pion, which did have the predicted meson properties. Today, we know that the muon is an elementary particle [3], cousin to the electron, τ-leptons and neutrinos, and that mesons (π, K, η, etc.), including the pion, are combinations of quark and an antiquark. Everybody know that the discovery of π-meson was an very important finding since this was in fact a fundamental step in the understanding the subatomic world. It heralded the beginning of a deep revision of the physical concepts on the structure of matter. However, who can tell us what exactly are those π-mesons? Also, it is well known that the pion as lightest of mesons has a finite size, with a mean charge radius of 0.66 fm, and that the long range part of the nucleon-nucleon forces necessarily arises from one-pion-exchange.

The traditional picture of the nucleus as a collection of neutrons and protons bound together via the strong force has proven remarkable successful in understanding a rich variety of nuclear properties. However, it is a well grounded achievement of modern nuclear physics that not only nucleons are relevant in the study of nuclear dynamics but that pions and the baryonic resonnances like Δ's and N* play an important role too [4]. So, when the nucleus is explored at short distance scales the presence of short lived subatomic particles, such as the pion and delta, are revealed as nuclear constituents. At even shorter distance scales the basic building blocks of matter, the quarks and gluons, are also revealed as nuclear constituents. The role of pions, deltas, quarks and gluons in the structure of nuclei is one frontier of modern nuclear physics. This modern picture of the nucleus bring us to the idea to search for new kind of natural radioactivities such as: (π, μ, Δ, N^*, etc.)-emission during the nuclear fission in the region of heavy and superheavy nuclei. Moreover, new mode of nuclear fission such as: *deltonic fission* an *hyperfision,* was also suggested and investigated. So, in 1985, D. B. Ion, M. Ivascu and R. Ion-Mihai initiated [5] the investigation of the nuclear spontaneous pion emission as a new possible nuclear radioactivity called *nuclear pionic radioactivity* (NPIR) with possible essential contributions to the instability of heavy and superheavy nuclei.

In this paper we present a short review not only of the main theoretical problems of the NPIR but also of the essential experimental results obtained in these 18 years of existence of the nuclear pionic radioactivity. Moreover, in this paper by using the recent results on the spontaneous fission half lives T_{SF} of the heavy nuclei with $Z \geq 100$ we present new prediction on the pionic yields in the region of superheavy elements.

2. FISSION-LIKE MODEL FOR PIONIC RADIOACTIVITY

The nuclear pionic radioactivity of a parent nucleus (A,Z) 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

$$A=A_1+A_2 \quad \text{and} \quad Z=Z_1+Z_2+Z_\pi$$

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

$$Q_{\pi F} = Q_{SF} - m_\pi \qquad (3)$$

where Q_{SF} is the energy liberated during spontaneous fission

$$Q_{SF} = m(Z,A) - m(Z_1,A_1) - m(Z_2,A_2) \qquad (4)$$

Then the energy condition for the pionic radioactivity channel is

$$Q_{\pi F} > 0 \quad \text{or} \quad Q_{SF} > m_\pi \qquad (5)$$

In Fig. 1 we present the values of $Q_\pi = Q_{\pi F}$ calculated by using the nuclear masses of Wapstra and Audi.

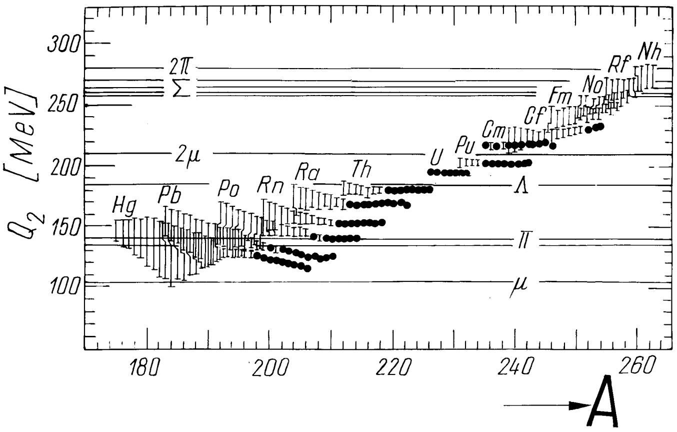

Fig. 1:- *The energies* $Q_\pi = Q_{\pi F}$ *calculated by using Eq. (3) and Tables of Wapstra and Audi.*

Other interesting new natural radioactivities predicted at IFIN-Bucharest are as follows

- *Muonic radioactivity* [25] is a nuclear process in which the lepton pair $(\mu^\pm, \nu_\mu)$ is emitted during two or many body fission of the parent nucleus. For the nuclear spontaneous emission of $(\mu^\pm, \nu_\mu)$ in binary fission we can write

$$^{A}_{Z}\mathbf{X} \rightarrow \mu^\pm + \nu_\mu + {}^{A_1}_{Z_1}\mathbf{X} + {}^{A_2}_{Z_2}\mathbf{X} \qquad (6)$$

$$\mathbf{A=A_1+A_2 \ and \ Z=Z_1+Z_2+Z_\mu} \qquad (7)$$

- *Lambdonic radioactivity* [26] is just a nuclear reaction of form

$$ {}_{Z}^{A}\mathbf{X} \rightarrow \Lambda^0 + {}_{Z_1}^{A_1}\mathbf{X} + {}_{Z_2}^{A_2}\mathbf{X} \tag{8}$$

$A = A_1 + A_2$ and $Z = Z_1 + Z_2$ (9)

- *Hyperonic radioactivities* $(\Sigma^-, \Sigma^0, \Sigma^+)$ are also the possible nuclear decays of form

$$ {}_{Z}^{A}\mathbf{X} \rightarrow \Sigma^{\pm,0} + {}_{Z_1}^{A_1}\mathbf{X} + {}_{Z_2}^{A_2}\mathbf{X} \tag{10}$$

$A = A_1 + A_2$ and $Z = Z_1 + Z_2 + Z_\Sigma$ (11)

- *Hyperfission or weak fission* [27] is a fission process in which in one of fragment is hypernucleus:

$$ {}_{Z}^{A}X \rightarrow {}_{Z_1}^{A_1}X + {}_{Z_2}^{A_2}X_Y \tag{12}$$

$A = A_1 + A_2$ and $Z = Z_1 + Z_2$ (13)

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- *Deltonic fission* [28] is also a fission process in which in one of fragment contain a delta resonance:

$$ {}_{Z}^{A}\mathbf{X} \rightarrow {}_{Z_1}^{A_1}\mathbf{X} + {}_{Z_2}^{A_2}\mathbf{X}_\Delta \tag{14}$$

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

A fission-like model (see Ref.[5]) for the pionic radioactivity was regarded as a first stage in the development of an approximate theory of this new phenomenon that takes into account the essential degree of freedom of the system: pi -fissility , pi-fission barrier height, etc.

Therefore, let us consider

$$E_C^{\pi F}(0) = E_C^{\,0} - \alpha m_\pi \tag{15}$$

$$E_S^{\pi F}(0) = E_S^{\,0} - (1-\alpha) m_\pi \tag{16}$$

where $E_C^{\,0}$ and $E_S^{\,0}$ are the usual Coulomb energy and surface energy of the parent nucleus given by

$$E_C^{\,0} = \gamma Z^2 / A^{1/3} \quad \text{and} \quad E_S^{\,0} = \beta A^{2/3} \tag{17}$$

with $\beta = 17.80$ MeV and $\gamma = 0.71$ MeV. α is a parameter defined so that αm_π and $(1\text{-}\alpha)m_\pi$ are the Coulombian and nuclear contributions to the pion mass. For $\alpha = 1$, the entire pion mass is obtained only from Coulomb energy of the parent nucleus. So, by analogy with binary fission was introduced the pionic fissility $\mathrm{X}_{\pi F}$ which is given by

$$\mathrm{X}^{(\alpha)}{}_{\pi F} = \frac{E_C^{\pi F}(0)}{2E_S^{\pi F}(0)} = \frac{E_C^{\,0} - \alpha m_\pi}{E_S^{\,0} - (1-\alpha)m_\pi},\ 0 \le \alpha \le 1 \tag{18}$$

or

$$\left(\frac{Z^2}{A}\right)_{\pi F} = \frac{Z^2}{A} - \frac{m_\pi}{\gamma A^{2/3}} \frac{\alpha - (1-\alpha)E_C^{\,0} / E_S^{\,0}}{1 - (1-\alpha)m_\pi / E_S^{\,0}} \tag{19}$$

In the particular case $\alpha = 1$ we have

$$\mathrm{X}_{\pi F} = \mathrm{X}_{SF} - \frac{m_\pi}{2E_S^{\,0}} \tag{20}$$

$$\left(\frac{Z^2}{A}\right)_{\pi F} = \frac{Z^2}{A} - \frac{m_\pi}{\gamma A^{2/3}} \tag{21}$$

We note that the definitions (18)-(20) are valid only with the constraints

$$E_C^{\pi F}(0) + E_S^{\pi F}(0) + m_\pi = E_C^{\,0} + E_S^{\,0} \tag{22}$$

while the total variation $\Delta E^{\pi F}$ of parent nucleus at small deformation of type $\varepsilon P_2(\cos\theta)$ is given by

$$\Delta E^{\pi F} = \Delta E_C^{\pi F} + \Delta E_S^{\pi F} = \frac{\varepsilon^2}{5}[2E_S^{\pi F}(0) - E_C^{\pi F}(0)] = \frac{2\varepsilon^2 E_S^{\pi F}(0)}{5}[1 - X^{(\alpha)}{}_{\pi F}] \tag{23}$$

In Fig. 2 we presented the regions from the plane (A,Z) in which some parent nuclei are able to emit spontaneously pions during the nuclear fission

Therefore, according to Fig. 2, we have the following important regions:

- SHE (super heavy elements)-region, indicated by white circles, where $X_{\pi F}>1$ and $Q_{\pi}>0$, all the nuclei are able to emit spontaneously pions during the SF since no pion fission barrier exists.
- HE (heavy elements)-zone marked by signs plus (+++), corresponding to $X_{\pi F}<1$ and $Q_{\pi}>0$, where all the nuclei can emit spontaneously pion only by quantum tunneling of the pionic fission barrier.
- E-region, indicated by signs minus (----) where the spontaneous pion emission is energetically interdicted since $Q_{\pi}<0$.

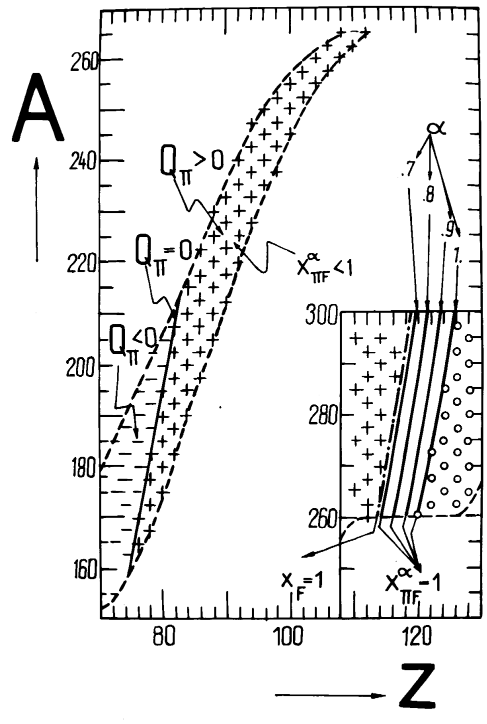

Fig. 2

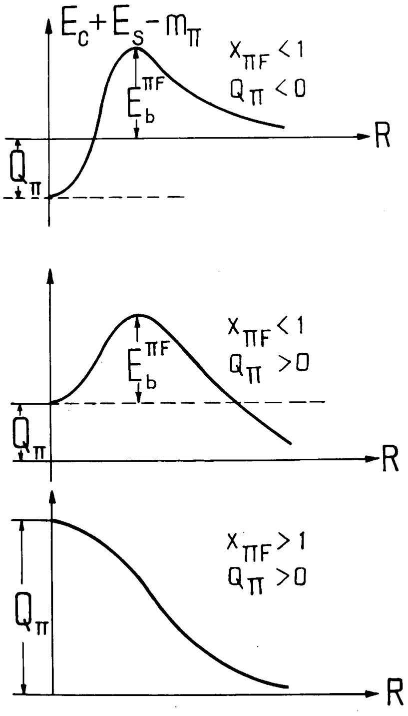

Fig. 3

Fig. 2:- *The physical regions from the plane (A,Z) in which the parent nuclei are able to emit pions by tunneling pi-fission barrier (++++) and without tunneling $\pi F-$barrier (oooo) (see the text).*

Fig. 3:- *Definition of $\pi F-$barrier as a function of distance between the fragments during the pionic fission.*

The *dynamical thresholds* for the pionic fission are obtained just as in fission case by using the substitution:

$$X_{SF}\to X_{\pi F},\quad E_C^{\;0}\to E_C^{\;\pi F}(0), E_S^{\;0}\to E_S^{\;\pi F}(0) \qquad (24)$$

So, by analogy with binary fission the *barrier height* for the pionic fission in a liquid drop model can be written as:

$$E^{\pi F}(LD)=E_S(0)\,[0.73(1-X_{\pi F})^3-0.33(1-X_{\pi F})^4+1.92(1-X_{\pi F})^5-0.21(1-X_{\pi F})^6] \qquad (25)$$

while the nuclear configuration at the saddle point is given by

$$R(\theta)=\frac{R_0}{\lambda}[1+\varepsilon_2\,P_2(\cos\theta)+\varepsilon_4\,P_4\,(\cos\theta)+\varepsilon_6\,P_6\,(\cos\theta)+...] \qquad (26)$$

where

$$\varepsilon_2=2.33(1-X_{\pi F})-1.23(1-X_{\pi F})^2+9.50(1-X_{\pi F})^3-8.05(1-X_{\pi F})^4+... \qquad (27)$$

$$\varepsilon_4 = 1.98(1-X_{\pi F})^2 - 1.70(1-X_{\pi F})^3 + 17.74(1-X_{\pi F})^4 + ...$$

$$\varepsilon_6 = -0.95(1-X_{\pi F}) + ... \qquad (28)$$

R_0 is the spherical radius and λ is a scale factor just as in binary spontaneous fission

In Fig. 4 and 5 we present the values of $E^{\pi F}(LD)$ as well as the nuclear configuration *at the saddle point compared with those from fission (F) or hypefission (HF).*

True barrier height for the pionic fission

$$E^{\pi F} = E^{\pi F}(LD) - \Delta E_{shell}{}^{\pi F}(s.p.) - \Delta E_{shell}\ (g.s.) \qquad (29)$$

where $\Delta E_{shell}{}^{\pi F}(s.p.)$ and $\Delta E_{shell}\ (g.s.)$ are correction due to shell effect at saddle point and ground state, respectively.

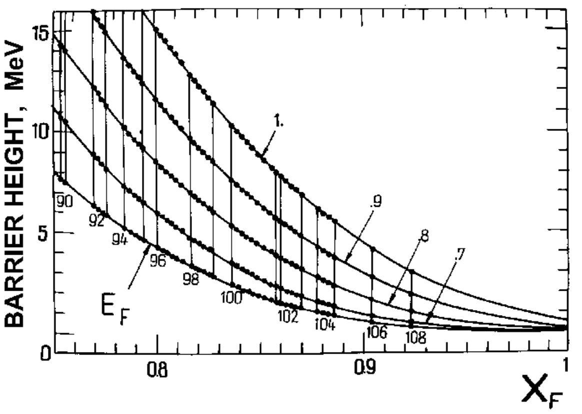

Fig. 4

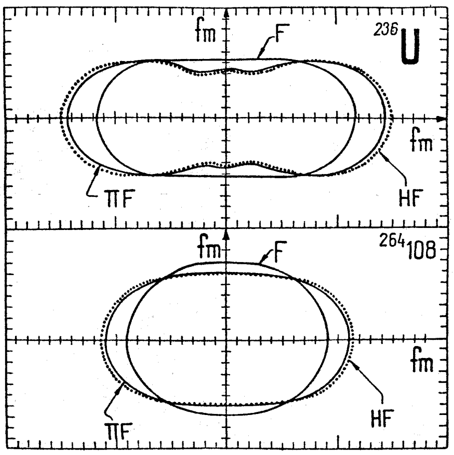

Fig. 5

Fig. 4:- *Th values of the barrier height* $E^{\pi F}(LD)$ *for the neutral pion emission during spontaneous fission.*

Fig. 5:- *The nuclear configuration at the saddle point for spontaneous fission (F), spontaneous hyperfission (HF) and spontaneous pionic fission (*πF*).*

Next, the essential ingredients used for the estimation of the relative pionic yields $\frac{\Gamma_{\pi F}}{\Gamma_{Sf}}$ are as follows:

- the variables θ and $\theta_{\pi F}$ defined by

$$\theta = \frac{Z^2}{A} - 37.5 \qquad (30)$$

$$\theta_{\pi F} = \left(\frac{Z^2}{A}\right)_{\pi F} - 37.5 = \theta - \frac{m_\pi}{\gamma A^{2/3}} \frac{\alpha - (1-\alpha)E_C{}^0 / E_S{}^0}{1-(1-\alpha)m_\pi / E_S{}^0} \qquad (31)$$

- the real function $\tau(\theta)$, defined for spontaneous fission (SF) by

$$\tau(\theta) = \log_{10} T_{SF}(\theta) + (5-\theta)\delta M = a_0 + a_1\theta + a_2\theta^2 + ... \qquad (32)$$

- the scaling property: $\tau(\theta) = \tau(\theta_{\pi F})$

$$\tau(\theta_{\pi F}) = \log_{10} T_{\pi F}(\theta_{\pi F}) + (5-\theta_{\pi F})\delta M = a_0 + a_1\theta_{\pi F} + a_2\theta_{\pi F}{}^2 + ... \qquad (33)$$

where δM is defined in Ref. [5].

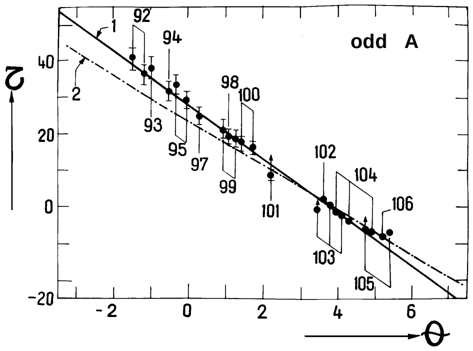

Fig. 6

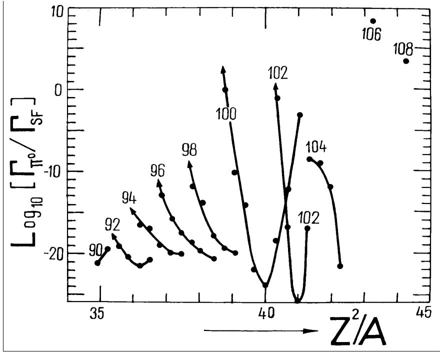

Fig. 7

Fig. 6:- *The experimental values of* $\tau(\theta)$ *are compared wit the linear fit (35).*

Fig. 7: *The predicted values of* $\frac{\Gamma_{\pi^0}}{\Gamma_{SF}}$ *calculated with (36) for* $\alpha=1$*, for eve-even parent nuclei.*

By fit was obtained the following important results.

- $\tau(\theta)=19.70\text{-}6.13\theta$ for even-even parent nuclei (34)

and

- $\tau(\theta)=28.21\text{-}7.32\theta$ for parent nuclei with A-odd (35)

For example in Fig. 6 we presented the experimental values of the $\tau(\theta)$ compared with the fitted curve (35).

Finally, by using (34)-(35) we obtain the following important prediction

$$\frac{\Gamma_\pi}{\Gamma_{SF}}=\left[\frac{T_{SF}}{T_{SF}^C}\right]^{\delta_\alpha(A,Z)} \tag{36}$$

where

$$\delta_\alpha(A,Z)=\frac{\Delta\theta_\alpha}{\theta-5}\ , \tag{37}$$

and

- $\Delta\theta_\alpha=\dfrac{m_\pi}{\gamma A^{2/3}}\dfrac{\alpha-(1-\alpha)E_C{}^0/E_S{}^0}{1-(1-\alpha)m_\pi/E_S{}^0}\ ,$ (38)
- $E_C^0=0.7053Z^2A^{-1/3}$ (MeV) and $E_S^0=17.80A^{2/3}$ (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.

Here, as in Ref. [31] we also adopt the notions of <u>*SF-nuclide*</u>, <u>*πF -nuclide*</u>, and <u>*T-transition nuclide*</u>, 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 1.

Table 1 : Definitions and characteristic features of (SF, *πF* , T)-nuclides.

Type of nuclide	Pionic Yield	Mass Distribution (MD)	Half Lives $Z^2/A\leq 42.5$	Half Lives $Z^2/A>42.5$	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*	$T_{SF}=T_{SF}^C$	$T_{SF}=T_{SF}^C$	$D_{\pi F}+D_{SF}$

		MD			
$\pi F - nuclide$	$\frac{\Gamma_{\pi^{0,\pm}}}{\Gamma_{SF}} > 1$	*Symmetric MD*	$T_{SF} < T^{C}_{SF}$	$T_{SF} > T^{C}_{SF}$	a new phase $D\pi F$ $n \Leftrightarrow p$

The predicted values of $\frac{\Gamma_{\pi^{0,\pm}}}{\Gamma_{SF}}$ calculated with (36)-(38) for $\alpha = 1$ and $\alpha = 0.75$, for eve-even and A-odd parent nuclei, are presented in Table 2a,b.

Table 2a : Theoretical predictions of the $\Gamma_{\pi^{0,\pm}} / \Gamma_{SF}$ yields for heavy parent nuclei with Z between Z=100 and Z=108, obtained for $\alpha = 1$ by using Eqs. (36)-(38) and T $_{SF}$ from Ref. [32].

	Z	A	T_{SF} (yr)	$\frac{T_{SF}}{T^{C}_{SF}}$	$\frac{\Gamma_{\pi^-}}{\Gamma_{SF}}$	$\frac{\Gamma_{\pi^0}}{\Gamma_{SF}}$	$\frac{\Gamma_{\pi^+}}{\Gamma_{SF}}$
Cf	98	238	6,654E-10	5,931E+01	9,40E-05	7,67E-05	3,21E-05
	98	240	1,008E-04	8,981E+06	2,65E-14	1,33E-14	7,67E-16
	98	242	4,654E-02	4,148E+09	3,30E-17	1,43E-17	4,45E-19
	98	246	1,800E+03	1,604E+14	2,59E-20	9,63E-21	1,50E-22
	98	248	3,200E+04	2,852E+15	3,75E-20	1,40E-20	2,33E-22
	98	249	8,000E+10	1,964E+19	5,92E-24	1,82E-24	1,32E-26
	98	250	1,700E+04	1,515E+15	2,89E-18	1,18E-18	2,95E-20
	98	252	8,600E+01	7,665E+12	1,66E-14	8,28E-15	4,52E-16
	98	254	1,667E-01	1,486E+10	7,44E-11	4,45E-11	5,24E-12
	98	256	2,282E-05	2,033E+06	1,32E-06	9,83E-07	2,87E-07
Es	99	253	6,300E+05	1,546E+14	2,18E-18	8,91E-19	2,11E-20
	99	255	2,600E+03	6,382E+11	2,99E-14	1,50E-14	8,79E-16
Fm πF	100	242	2,535E-11	2,259E+00	3,55E-02	3,30E-02	2,42E-02
	100	244	1,046E-10	9,320E+00	8,59E-04	7,35E-04	3,86E-04
	100	245	1,255E-04	3,080E+04	1,77E-13	9,32E-14	6,39E-15
	100	246	4,753E-07	4,236E+04	1,17E-12	6,39E-13	5,18E-14
	100	248	1,141E-03	1,017E+08	3,59E-18	1,48E-18	3,78E-20
	100	250	8,000E-01	7,130E+10	3,28E-21	1,16E-21	1,57E-23
	100	252	1,250E+02	1,114E+13	1,84E-22	6,12E-23	6,28E-25
	100	254	6,242E-01	5,563E+10	9,36E-17	4,15E-17	1,46E-18
	100	256	3,308E-04	2,948E+07	8,08E-11	4,84E-11	5,73E-12
T	100	257	1,310E+02	3,216E+10	2,75E-14	1,38E-14	7,98E-16
πF	100	258	1,172E-11	1,045E+00	9,47E-01	9,46E-01	9,43E-01
πF	100	259	4,753E-08	1,167E+01	5,44E-02	5,10E-02	3,91E-02
πF	100	260	1,268E-10	1,130E+01	6,33E-02	5,95E-02	4,68E-02
Md πF	101	245	2,852E-11	7,001E-03	8,66E+11	1,58E+12	1,97E+13
	101	247	6,338E-09	1,556E+00	1,73E-01	1,67E-01	1,43E-01
	101	255	3,422E-02	8,401E+06	1,20E-13	6,27E-14	4,11E-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	2,15E-08
No πF	102	250	7,922E-12	7,061E-01	6,41E+00	6,67E+00	7,96E+00
	102	251	3,169E-07	7,779E+01	3,33E-09	2,17E-09	3,69E-10
	102	252	2,852E-07	2,542E+04	9,39E-18	3,96E-18	1,05E-19
	102	254	9,126E-04	8,134E+07	1,02E-24	3,02E-25	1,91E-27
	102	256	1,711E-05	1,525E+06	3,58E-16	1,64E-16	6,30E-18
	102	257	5,324E-05	1,307E+04	3,53E-10	2,19E-10	2,97E-11
	102	258	3,803E-11	3,389E+00	7,47E-02	7,06E-02	5,58E-02
	102	259	1,141E-03	2,800E+05	1,68E-11	9,75E-12	1,06E-12
	102	260	3,359E-09	2,994E+02	2,62E-05	2,08E-05	7,96E-06

	102	262	1,584E-10	1,412E+01	1,30E-02	1,18E-02	7,94E-03
Lr	103	253	4,183E-06	1,027E+03	1,39E-25	3,97E-26	2,14E-28
	103	255	6,845E-04	1,680E+05	7,00E-28	1,77E-28	5,75E-31
	103	257	6,274E-05	1,540E+04	1,25E-16	5,59E-17	1,96E-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	1,84E-12
Rf	104	253	1,521E-12	3,734E-04	1,16E-64	4,57E-66	6,44E-72
	104	254	7,288E-13	6,496E-02	8,87E-68	2,96E-69	2,11E-75
	104	255	9,190E-08	2,256E+01	1,81E-75	4,10E-77	5,87E-84
	104	256	1,965E-10	1,751E+01	7,98E-24	2,47E-24	1,91E-26
	104	257	1,065E-05	2,614E+03	6,30E-39	9,09E-40	2,81E-43
	104	258	4,436E-10	3,954E+01	1,67E-13	8,74E-14	5,93E-15
	104	259	1,331E-06	3,267E+02	2,13E-16	9,65E-17	3,55E-18
	104	260	6,338E-10	5,648E+01	1,12E-09	7,16E-10	1,06E-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	1,62E-16
πF	105	255	2,535E-07	6,223E+01	2,29E+11	4,08E+11	4,44E+12
Db πF	105	257	2,535E-07	6,223E+01	6,87E+20	1,97E+21	1,58E+23
	105	261	3,169E-07	7,779E+01	3,00E-34	5,48E-35	4,64E-38
	105	263	1,521E-06	3,734E+02	5,81E-21	2,08E-21	2,98E-23
Sg πF	106	258	9,190E-11	8,190E+00	1,04E+04	1,27E+04	2,96E+04
πF	106	259	7,605E-08	1,867E+01	4,36E+06	6,10E+06	2,47E+07
πF	106	260	2,218E-10	1,977E+01	2,12E+08	3,24E+08	1,86E+09
πF	106	261	8,239E-08	2,022E+01	7,76E+10	1,34E+11	1,39E+12
πF	106	263	8,556E-08	2,100E+01	1,31E+27	5,17E+27	1,54E+30
	106	265	4,119E-07	1,011E+02	1,01E-91	1,00E-93	4,69E-102
Bh	107	261	3,803E-09	9,334E-01	7,93E-01	7,89E-01	7,72E-01
Hs πF	108	264	6,338E-11	5,648E+00	1,08E+02	1,20E+02	1,84E+02
	108	265	1,521E-10	3,734E-02	5,28E-05	4,25E-05	1,72E-05
	108	267	3,169E-09	7,779E-01	3,84E-01	3,76E-01	3,44E-01

Table 2b: Theoretical predictions of the $\Gamma_{\pi^{0,\pm}} / \Gamma_{SF}$ yields for heavy parent nuclei with Z between Z=100 and Z=108, obtained for 0.75 by using Eqs. (36)-(38) and T $_{SF}$ from Ref. [32].

	Z	A	T_{SF} (yr)	$\frac{T_{SF}}{T_{SF}^C}$	$\frac{\Gamma_{\pi^-}}{\Gamma_{SF}}$	$\frac{\Gamma_{\pi^0}}{\Gamma_{SF}}$	$\frac{\Gamma_{\pi^+}}{\Gamma_{SF}}$
Cf	98	238	6,654E-10	5,931E+01	3,96E-03	4,47E-03	2,41E-03
	98	240	1,008E-04	8,981E+06	7,44E-09	1,11E-08	1,39E-09
	98	242	4,654E-02	4,148E+09	1,24E-10	2,03E-10	1,61E-11
	98	246	1,800E+03	1,604E+14	1,39E-12	2,50E-12	1,20E-13
	98	248	3,200E+04	2,852E+15	1,58E-12	2,83E-12	1,38E-13
	98	249	8,000E+10	1,964E+19	7,33E-15	1,47E-14	3,97E-16
	98	250	1,700E+04	1,515E+15	2,03E-11	3,46E-11	2,24E-12
	98	252	8,600E+01	7,665E+12	3,74E-09	5,69E-09	6,58E-10
	98	254	1,667E-01	1,486E+10	6,11E-07	8,32E-07	1,69E-07
	98	256	2,282E-05	2,033E+06	2,41E-04	2,88E-04	1,14E-04
	99	253	6,300E+05	1,546E+14	1,87E-11	3,18E-11	2,04E-12
	99	255	2,600E+03	6,382E+11	5,73E-09	8,62E-09	1,04E-09
Fm	100	242	2,535E-11	2,259E+00	1,39E-01	1,45E-01	1,17E-01
	100	244	1,046E-10	9,320E+00	1,53E-02	1,67E-02	1,05E-02
	100	245	1,255E-04	3,080E+04	2,74E-08	3,99E-08	5,76E-09
	100	246	4,753E-07	4,236E+04	8,12E-08	1,15E-07	1,88E-08
	100	248	1,141E-03	1,017E+08	3,91E-11	6,56E-11	4,57E-12

	100	250	8,000E-01	7,130E+10	5,41E-13	9,94E-13	4,31E-14
	100	252	1,250E+02	1,114E+13	8,65E-14	1,65E-13	5,84E-15
	100	254	6,242E-01	5,563E+10	2,14E-10	3,47E-10	2,92E-11
	100	256	3,308E-04	2,948E+07	7,79E-07	1,05E-06	2,21E-07
	100	257	1,310E+02	3,216E+10	6,01E-09	9,03E-09	1,10E-09
	100	258	1,172E-11	1,045E+00	9,67E-01	9,68E-01	9,64E-01
	100	259	4,753E-08	1,167E+01	1,70E-01	1,76E-01	1,45E-01
	100	260	1,268E-10	1,130E+01	1,86E-01	1,93E-01	1,60E-01
Md	101	245	2,852E-11	7,001E-03	1,02E+07	7,21E+06	4,33E+07
	101	247	6,338E-09	1,556E+00	3,56E-01	3,64E-01	3,24E-01
	101	255	3,422E-02	8,401E+06	1,84E-08	2,70E-08	3,73E-09
	101	257	6,297E-02	1,546E+07	7,43E-08	1,05E-07	1,70E-08
	101	259	1,848E-04	4,536E+04	6,98E-05	8,57E-05	2,96E-05
No	102	250	7,922E-12	7,061E-01	2,97E+00	2,90E+00	3,28E+00
	102	251	3,169E-07	7,779E+01	1,02E-05	1,31E-05	3,67E-06
	102	252	2,852E-07	2,542E+04	9,10E-11	1,49E-10	1,14E-11
	102	254	9,126E-04	8,134E+07	6,25E-15	1,26E-14	3,33E-16
	102	256	1,711E-05	1,525E+06	6,61E-10	1,04E-09	9,95E-11
	102	257	5,324E-05	1,307E+04	2,35E-06	3,11E-06	7,37E-07
	102	258	3,803E-11	3,389E+00	2,12E-01	2,20E-01	1,85E-01
	102	259	1,141E-03	2,800E+05	3,64E-07	5,01E-07	9,64E-08
	102	260	3,359E-09	2,994E+02	1,80E-03	2,07E-03	1,02E-03
	102	262	1,584E-10	1,412E+01	7,37E-02	7,79E-02	5,83E-02
Lr	103	253	4,183E-06	1,027E+03	2,89E-15	5,94E-15	1,44E-16
	103	255	6,845E-04	1,680E+05	1,12E-16	2,47E-16	4,17E-18
	103	257	6,274E-05	1,540E+04	4,18E-10	6,66E-10	6,04E-11
	103	259	9,823E-07	2,411E+02	5,96E-05	7,35E-05	2,49E-05
	103	261	7,415E-05	1,820E+04	5,41E-07	7,39E-07	1,48E-07
Rf	104	253	1,521E-12	3,734E-04	9,87E-38	6,18E-37	4,77E-41
	104	254	7,288E-13	6,496E-02	1,26E-39	8,72E-39	4,15E-43
	104	255	9,190E-08	2,256E+01	3,53E-44	3,04E-43	4,51E-48
	104	256	1,965E-10	1,751E+01	3,49E-14	6,80E-14	2,17E-15
	104	257	1,065E-05	2,614E+03	4,98E-23	1,50E-22	5,00E-25
	104	258	4,436E-10	3,954E+01	3,34E-08	4,85E-08	7,16E-09
	104	259	1,331E-06	3,267E+02	6,50E-10	1,02E-09	9,77E-11
	104	260	6,338E-10	5,648E+01	5,54E-06	7,19E-06	1,87E-06
	104	261	2,091E-05	5,134E+03	3,53E-10	5,64E-10	5,02E-11
	104	262	6,654E-08	5,931E+03	4,38E-09	6,63E-09	7,82E-10
Db	105	255	2,535E-07	6,223E+01	3,41E+06	2,47E+06	1,31E+07
	105	257	2,535E-07	6,223E+01	1,09E+12	6,00E+11	1,30E+13
	105	261	3,169E-07	7,779E+01	2,93E-20	7,72E-20	5,21E-22
	105	263	1,521E-06	3,734E+02	1,44E-12	2,60E-12	1,26E-13
Sg	106	258	9,190E-11	8,190E+00	1,99E+02	1,78E+02	3,21E+02
	106	259	7,605E-08	1,867E+01	6,47E+03	5,35E+03	1,42E+04
	106	260	2,218E-10	1,977E+01	6,17E+04	4,86E+04	1,65E+05
	106	261	8,239E-08	2,022E+01	1,89E+06	1,39E+06	6,93E+06
	106	263	8,556E-08	2,100E+01	5,03E+15	2,31E+15	1,28E+17
	106	265	4,119E-07	1,011E+02	1,22E-53	1,69E-52	2,22E-58
Bh	107	261	3,803E-09	9,334E-01	8,76E-01	8,78E-01	8,66E-01
Hs	108	264	6,338E-11	5,648E+00	1,42E+01	1,34E+01	1,81E+01
	108	265	1,521E-10	3,734E-02	3,68E-03	4,15E-03	2,22E-03
	108	267	3,169E-09	7,779E-01	5,78E-01	5,85E-01	5,51E-01

3. EXPERIMENTAL SEARCH FOR NUCLEAR PIONIC RADIOACTIVITY

3.1 Experimental limits on NPIR-yield

The pionic radioactivity was experimentally investigated by many authors [13]-[24]. A short review of the results obtained on the spontaneous NPIR yields is presented in Table 3.

Table 3 Experimental results on spontaneous NPIR-yields

Year	Authors	Laboratory	Parent Nuclei	$\Gamma_{\pi^0}/\Gamma_{SF}$	$\Gamma_{\pi^\pm}/\Gamma_{SF}$
1986	D. B. Ion et al. Rev. Roum. Phys. **31,** 551	IFIN-Bucharest Romania	^{259}Md		$<10^{-5}$
1987	D. Bucurescu et al. Rev. Roum. Phys. **32,** 849	IFIN-Bucharest Romania	^{252}Cf		$<10^{-8}$
1988	M. Ivascu et al. Rev. Roum. Phys.**32,** 937	IFIN-Bucharest Romania	^{252}Cf		$<10^{-8}$
1988	C. Cerruti et al. Z. Phys. **A329**, 383	CEN-Saclay France	^{252}Cf	$< 10^{-8}$	
1988	J. R. Beene et al. Phys.Rev. **C38**, 569	O R N L USA	^{252}Cf	$<1.510^{-9}$	
1989	J. Julien et al. Z. Phys. **A332,** 473	CEN- Saclay France	^{252}Cf	$< 10^{-12}$	
1989	Yu. Adamchuk et al. Sov. J. Nucl. Phys. **49,** 932	I.V.Kurchatov Russia	^{252}Cf		$<5\ 10^{-8}$
1989	D. B. Ion et al. Rev. Roum. Phys.**34,** 261	IFIN-Bucharest Romania	^{257}Fm		(1.2 ± 0.2) $10^{-3}\,(\pi^-)$
1989	S. Stanislaus et al. Phys.Rev. **C39,** 295	University British Columbia Canada	^{252}Cf	$<3.3\ 10^{-10}$	
1989	S. Stanislaus et al. Phys.Rev. **C39,** 295	University British Columbia Canada	^{238}U	$<3.110^{-4}$	
1991	J. N. Knudson et al. Phys.Rev. **C44,** 2869	L A N L USA	^{252}Cf	$<1.3710^{-11}$	
1991	V. Bellini et al.[19] Proc. Bratislava Conference	CEN Saclay France	^{252}Cf	$<3\ 10^{-13}$	
1991	K. Janko et al. [22] Proc. Bratislava Conference	Comenius University Czechoslovakia	^{257}Fm		$< 7\ 10^{-5}$ (π^+)
1992	H. Otsu et al. Z. Phys. **A342,** 483	Tokyo University Japan	^{252}Cf		$<1.3\ 10^{-8}$ (π^-)
2002	Khryachkov et al. Instr. Exp. Tech. **45,** 615	LIPPE Obninsk Russia	^{252}Cf		Not estimated

3.2. Recent results from LIPPE-Obninsk (Russia)

Recently Khryachkov et al. [24] presented a new spectrometer for investigation of ternary nuclear fission. The measured characteristics of this spectrometer allow for its successful use in studies of ternary fission with the emission of α-particles, tritons, and protons as well as in the search for exotic nuclear fission accompanied by the emission of charged mesons $(\pi^\pm, \mu^\pm)$. This new spectrometer was tested with a reaction of spontaneous ^{252}Cf ternary fission. This choice was determined by the fact that this reaction is well studied and the available data can be employed for the performance check of this facility. So, a ^{252}Cf layer 5mm in diameter with an activity of 15 fissions/s was placed inside the spectrometer. The measurements were carried out continuously 1.5 months. A 2D spectrum of the scintilator signals obtained in coincidence with fragments is shown here in Fig.8 (see Fig. 9 in Ref. [24]).

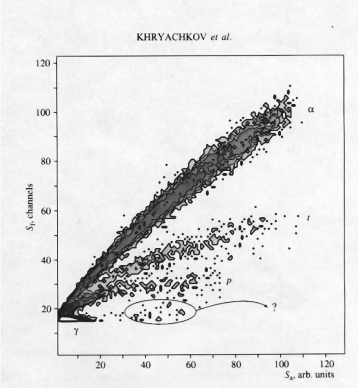

Fig. 8

Fig. 8**:-** *The experimental results* (see Fig. 9 in Ref. [27]) *on the light charged particle emission during the spontaneous fission of* ^{252}Cf **.**

Analyzing spectrum in Fig. 8 has shown that, *in the space between the electron and proton regions there are events that cannot be explained by an external background or effect of neutrons. A detailed analysis of the parameter Sf does not allow us to assign these events to protons or electrons*. We estimate these events as an indication of the possibility of existence of a ternary nuclear decay with the participation of charged mesons. Subsequently, it is suggested to *study the meson emission during the spontaneous fission* on this new facility which has a number of substantial advantages.

4. SUMMARY AND CONCLUSIONS

The experimental and theoretical results obtained on the NPIR can be summarized as follows:

1. The best experimental limit for π^0-yields has been reported for ^{252}Cf by Bellini et al. [19]. They reached an upper limit of 3.10^{-13}, a value close to the theoretical prediction [8].
2. The unusual background, observed by Wild et al.[33] in (ΔE-E)-energy region below that characteristic for long range alpha emission from ^{257}Fm was interpreted by Ion, Bucurescu and Ion-Mihai [9] as being produced by negative pions emitted spontaneously by ^{257}Fm. Then, they inferred value of the pionic yield is: Γ_π / Γ_{SF} =(1.2 ± 0.2).10^{-3} π^-/fission. In a similar way, Janko and Povinec [22], obtained the yield : Γ_π / Γ_{SF} =(7 ± 6).10^{-5} π^+/fission.
3. The supergiant radiohalos (SGH), discovered by Grady and Walker [34] and Laemmlein [35] are interpreted [12] as being the $\pi^- - radihalos$ and $\pi^+ - radiohalos$, respectively. Hence these radiohalos are experimental signatures of the integral record in time of the natural pionic radioactivity from radioactive inclusions in ancient minerals.
4. A new interpretation of the experimental bimodal fission is obtained in terms of the unitarity diagrams. is obtained in Ref. [29] So, the presence of the symmetric mode in the fragment mass-distribution at transfermium nuclei can be interpreted as experimental signature of the pionic radioactivity. Hence, it is expected that this new degree of nuclear instability can becomes dominant at SHE-nuclides. This idea is illustrated not only by the symmetrisation of

fragment mass-yields from SF of the heavy nuclei with $98 \le Z \le 104$ experimentally observed in Fig. 7 but also by high values of Γ_π / Γ_{SF}-yields obtained by using the theoretical prediction (36)-(37).

5. The nuclides No with A=242-250 are expected to be all πF-nuclides while the No-isotopes with $A \ge 252$ are all SF-nuclides (see Table 2a). 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}).
6. The nuclides Lr and Rf are all predicted to be SF-nuclides (see Table 2a).
7. 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.

Finally, we note that dedicated experiments, using nuclei with theoretically predicted high pionic yields (e.g. ^{258}Fm, ^{259}Fm, ^{258}No, ^{260}No, ^{254}Rf, Sg and ^{264}Hs (1.2 10^{2})), are desired, since the discovery of the nuclear pionic radioactivity is of fundamental importance not only in nuclear science (e. g., for clarification of high instability of SHE- nuclei) but also for geochemistry and cosmology.

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