Classification

Physics Abstracts

23.20C — 23.90 — 27.90

Two alpha, three alpha and multiple heavy-ion radioactivities

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(Reçu le 25 mars 1985, accepté sous forme définitive le 30 avril 1985)

Résumé. — La possibilité de nouveaux modes de radioactivité par émission spontanée de deux ou trois particules α ou de deux ions lourds identiques ou différents est envisagée. La variante analytique du modèle de la fission super-asymétrique est utilisée pour estimer les durées de vie.

Abstract. — New decay modes by spontaneous emission of two and three α particles and two identical or different heavy ions, are predicted. The analytical variant of the superasymmetric fission model is used to estimate the half lives.

The analytical variant of the superasymmetric fission model (ASAFM) was derived [1] in order to make a systematic search of new decay modes by spontaneous emission of heavy ions (HI) from all nuclides with known masses [2, 3]. It is an efficient alternative of the other three calculation methods used for this purpose [4] and allows to calculate half lives and branching ratios relative to α decay, which are the quantities experimentally determined. ASAFM was extended [5] to account for the angular momentum and small excitation energy effects. Stability relative to the emission of ^2H , ^3He , ^4Li , ^7B , ^9C [1] and ^{6-10}He [5] have been found. Then it was used, step by step to predict [5-9] new decay modes (see also [10-14] and the review paper [15]). From 8 modes in 1980 we arrived with more than 150 in 1984 [8, 9].

An important conclusion obtained very clearly for ^5He [5] and which is confirmed for the other modes is : the maximum emission rate is obtained for the double magic-daughter ^{208}Pb or not too far from it.

Two of these modes are already experimentally confirmed : ^{14}C radioactivity of ^{223}Ra [17-21] and of $^{222,224}\text{Ra}$ [20] ; ^{24}Ne radioactivity of ^{232}U [21] and of ^{231}Pa [23]. A superasymmetric fission model based on the proximity + Coulomb potential was derived by Shi and Swiatecki [24].

The shortcomings of penetrability calculations are analysed in reference [10] in comparison with lifetimes.

Better agreement with α -decay half lives of 380 emitters and the reproduction of ^{14}C radioactivity of ^{223}Ra and of the U isotopes spontaneous fission, has been obtained [8, 9] by introducing shell effects in the zero point vibration energy, E_v :

$$E_v = Q \left[0.056 + 0.039 \exp \left(\frac{4 - A_2}{2.5} \right) \right]; \quad Q > 0, \quad A_2 \geq 4. \quad (1)$$

The relationship (1) and the equations from reference [5] (where by misprint the numerical coefficient of K_{ov} was written 0.1296 instead of 0.2196) was used [16] to get a new table super-

seding tables 2 of reference [7] and table 6 of reference [15] and will be used in the following, to estimate the half lives for new decay modes :

$$A_Z \rightarrow A_1 Z_1 + A_2 Z_2 + A_3 Z_3 + \dots \quad (2)$$

by emission of several heavy ions ($A_2, Z_2, A_3, Z_3, \dots$) simultaneously. The daughter (heavy fragment) is ($A_1 Z_1$).

Like the diproton [25-27], dineutron [28-30] and trineutron [31] the complex (A'_2, Z'_2), where $A'_2 = A_2 + A_3 + \dots$ and $Z'_2 = Z_2 + Z_3 + \dots$ is not a stable nucleus, but one can imagine a mechanism in which the particles during formation pass the potential barrier and after tunnelling they move apart [32]. Of course, in this case, the released energy $Q = M - (M_1 + M_2 + M_3 + \dots)$ will be shared between more than 2 fragments and the kinetic energy spectrum of the emitted particles will be more complicated than a simple « line » obtained when a single HI is emitted.

The group of HI has usually, the mass defect larger than the mass defect of the corresponding single nuclide, leading to smaller Q -value and consequently to longer half lives (smaller emission rates). On the contrary, for ^8Be (which is known to fission in two alpha particles) the opposite is true. Hence one can expect slightly decreased half lives for 2 α emission in comparison with ^8Be radioactivity, which were estimated [6-9] to be rather good.

The results for some of the most favourable cases are presented in table I. Also the branching ratios relative to α decay are plotted in figure 1 for 2 α and 3 α radioactivities, and in figure 2 for the groups : $\alpha + ^{12}\text{C}$, $\alpha + ^{13}\text{C}$ and $\alpha + ^{14}\text{C}$. The dotted line is drawn at the position of the magic number of neutrons (126) of the daughter.

Heavy-ion branching ratios as low as 10^{-13} have turned out to be detectable experimentally. Since the predictions for the 2 α mode in isotopes of Ac, Th, Pa are of the same order of magnitude, it seems conceivable that a detection method can be devised, although competition with ^8Be and even ^{12}C is to be envisaged. Other predicted processes such as the emission of 3 α and $\alpha + \text{HI}$ will be very much lower in intensity unless much more favourable combinations are found. The best chance of seeing these processes seems to be from the decay of excited levels (5, 8) such as in beta-delayed heavy-ion emission.

Table I. — *Emission of multiple heavy ions from some parent nuclides compared with other competing processes.*

Parent nucleus	$\log T_i$ (s)	$\log T_\alpha$ (s)	Emitted multiple HI				Single HI in competition		
			Group	Q (MeV)	$\log T$ (s)	$\log (T/T_\alpha)$	HI	Q (MeV)	$\log T$ (s)
^{219}Ac	- 5.15	- 5.15	2 α	18.4	9.6	14.7	^8Be	18.3	9.8
^{220}Ac	- 1.59	- 0.97		17.5	11.6	12.6	^8Be	17.4	11.9
^{220}Th	- 5.01	- 5.01		18.5	10.0	15.0	^8Be	18.4	10.2
^{221}Th	- 2.77	- 2.54		17.8	11.6	14.2	^{12}C	33.3	11.7
^{222}Pa	- 2.24	- 1.94		18.1	11.6	13.5	^{12}C	33.9	11.4
^{223}Pa	- 2.19	- 1.84	3 α	26.7	26.2	28.1	^{12}C	34.0	11.3
^{225}Pa	0.26	0.41		$\alpha + ^{12}\text{C}$	40.2	28.2	^{15}N	40.2	15.4
^{225}Th	2.68	3.07		$\alpha + ^{13}\text{C}$	33.5	31.7	^{14}C	31.7	16.9
^{226}Th	3.27	3.39		$\alpha + ^{14}\text{C}$	39.5	30.8	^{18}O	45.7	18.9
^{221}Ra	1.45	1.92		$\alpha + ^9\text{Be}$	20.9	42.2	^{14}C	32.4	13.8
^{232}Pu	3.16	4.01	2(^{12}C)	60.1	48.3	44.3	^{26}Mg	78.4	20.8
^{233}Am	2.56	3.60	2(^{12}C)	61.4	47.5	43.9	^{26}Mg	79.5	20.8
^{235}Np	7.53	12.66	2(^{14}C)	56.0	59.4	46.8	^{28}Mg	77.1	21.8
^{236}Pu	7.96	8.10	2(^{14}C)	58.6	55.7	47.6	^{28}Mg	79.7	19.8

Fig. 1. — Branching ratios relative to the α decay for 2 α and 3 α radioactivities versus the neutron number of the parent nucleus.

Fig. 2. — Branching ratios relative to the α decay for multiple HI emissions : $\alpha + {}^{12}\text{C}$, $\alpha + {}^{13}\text{C}$ and $\alpha + {}^{14}\text{C}$.

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