Heavy cluster decay of trans-zirconium "stable" nuclides

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By using the analytical superasymmetric fission model it is shown that all "stable" nuclei lighter than lead with $Z > 40$ are metastable relative to the spontaneous emission of nuclear clusters. An even-odd effect is included in the zero point vibration energy. Half-lives in the range 10^{40}–10^{50} s are obtained for $Z > 62$. The region of metastability against these new decay modes is extended beyond that for α decay and in some cases, in the competing region, the emission rates for nuclear clusters are larger than for α decay.

During the last few years advances in studies of many nuclear decay modes have gained considerable interest. Recently, these have been reviewed by Hamilton *et al.*[1] We have used (see Refs. 2–4, and references therein) several methods to show that nuclei heavier than α particles ($A_2 > 4$) and lighter than fission fragments ($A_2 < 70$) are spontaneously emitted from various parent nuclides (A,Z) leading to the daughters (A_1,Z_1). A review paper presenting our early work will be published elsewhere.[5]

There is, already, experimental evidence concerning two of more than 140 new decay modes:[6,7] (1) ^{14}C spontaneous emission[8–12] from ^{223}Ra and[11] from ^{222,224}Ra and (2) ^{24}Ne radioactivity[13] of ^{232}U and[14] of ^{231}Pa.

The experimental data are in agreement with the half-lives and the branching ratios relative to α decay calculated[5–7,15] (see also Refs. 16 and 17) in the framework of the analytical superasymmetric fission model (ASAFM)[3,18] and with the branching ratios computed by Shi and Swiatecki[19] using a proximity-plus-Coulomb potential.

Up to now only the region of parent nuclides with $Z > 82$ have been investigated. The purpose of this paper is to extend the domain for nuclides lighter than lead, pointing out that all the so-called "stable" nuclides with atomic numbers $Z > 40$, are, in fact, metastable with respect to several new cluster decay modes.

In order to estimate the half-lives, T' and T, relative to nuclear cluster emission we shall use ASAFM[7] with two values of the zero point vibration energy E_v. This energy enters crucially the formula for the lifetime against cluster emission

$$T=\frac{h\ln 2}{2E_v}\exp\left(\frac{2}{\hbar}\int_{R_a}^{R_b}\{2\mu[E(r)-Q']\}^{1/2}dr\right)\ , \qquad (1)$$

$$Q'=Q+E_v\ ,$$

where the standard notations[7] are used for the reduced mass, μ, the potential interaction energy $E(r)$ and $E(R_a)=E(R_b)=Q'$. We choose on the one hand,

$$E_v=Q\left[0.056+0.039\exp\left(\frac{4-A_2}{2.50}\right)\right];\ Q>0;\ A_2>4\ , \qquad (2)$$

which leads the half-life T, regardless of the odd (o) or even (e) character of the neutron (N) and proton (Z) numbers of the parent nuclide, and on the other hand, with

$$E_v'=E_v\times\begin{cases}1.105, & e\text{-}e\\ 0.947, & e\text{-}o\\ 1.000, & o\text{-}e\\ 0.789, & o\text{-}o\end{cases}\ \text{parent}\ , \qquad (3)$$

leading to the half-life T', one can obtain better agreement for α decay of 380 emitters. Hence, T' and T are the half-lives with or without the even-odd effect taken into account, respectively. A similar even-odd effect was observed[20] for ^{14}C radioactivity of Ra isotopes[11] and of ^{225}Ac: an enhanced cluster emission rate from e-e nuclei, or equivalently a hindrance from o-e, e-o, and o-o parents.

The released energy, Q, is computed with the new version of the mass table.[21] We do not consider the relatively small angular momentum carried away by the emitted cluster if the parent or daughter nuclei have a finite spin, because we have shown previously[7] that the hindrance introduced by the corresponding centrifugal barrier can be ignored, if the cluster is not too small.

Figure 1 shows that from the energetical point of view, spontaneous cluster emission is allowed in a larger region of nuclei than that for α decay. For example, the neutron deficient nucleus ^{67}Se, which is stable relative to α decay, can be split into ^{27}Si$+^{40}$Ca ($Q=0.37$ MeV), ^{28}Si$+^{39}$Ca ($Q=1.91$ MeV), ^{31}S$+^{36}$Ar ($Q=2.42$ MeV), and ^{32}S$+^{35}$Ar ($Q=2.20$ MeV). For $Z > 40$, all the nuclei tabulated by Wapstra and Audi,[21] including the "stable" ones (colored in

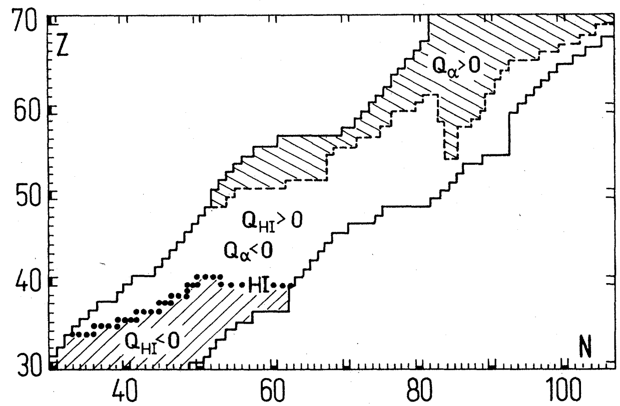

FIG. 1. The lower limits of the regions where α decay (dashed line) and various cluster radioactivities (dotted line) are allowed from energetical point of view.

black on the chart of nuclei[22]) are metastable with respect to these new decay modes.

Consequently, it makes sense to search for the most probable decay modes of 156 nuclides with $Z=41-83$, which are listed in Ref. 22 or other charts and tables, without any specification for the half-life. However, if the lifetime of a nucleus is long enough, $T>T_{max}$, one can from a practical point of view, consider the nuclides to be stable. The questions are, what is T_{max}, which decay channel determines it, and can it be measured? Indeed, measurements of lifetime have reached new limits. For example, half-lives of the order of 10^{25} s have been measured for the spontaneous fission of some actinides.

In Table I only some of the "stable" parent nuclei with $T<10^{50}$ s for cluster emission with $Z_2 \leq 28$ are listed. A more complete table containing also ^{162}Er, ^{171,172,174,176}Yb, ^{175}Lu, $^{176-179}$Hf, ^{180}Ta, ^{190}Os, ^{193}Ir, $^{194-196}$Pt, $^{198-201}$Hg, and ^{203}Tl, and many other radioactive nuclei will be published elsewhere. Alpha decay half-lives, T_{α}, are estimated with our semiempirical formula.[3,5]

One can see that $T_{\alpha}<10^{30}$ s is expected for ^{151}Eu, ^{176}Hf, ^{180}W, and ^{184,187}Os. One has $T<10^{42}$ s for ^{16}O emission from ^{156}Dy, ^{48}Ca emission from ^{184}W, ^{185}Re, and ^{184}Os, and for ^{49}Ca emission from ^{187}Os. Usually the daughter neutron number is magic or almost magic, $N_1 \simeq 82$, and the daughter proton number is not very far from $Z_1 \simeq 50$. These effects are similar with those observed[7,18] in the trans-lead region for $N_1 \simeq 126$ and $Z_1 \simeq 82$. But in this region one can meet cluster emission rates several times larger than for α particles. For example, ^{16}O from ^{154}Gd, ^{32}Si from ^{169}Tm, ^{48}Ca from ^{176}Yb, ^{180}Hf, ^{181}Ta, and ^{183,184}W, ^{50}Ca from ^{186}W, ^{58}Cr from ^{192}Os, ^{68}Ni from ^{198}Pt and ^{202}Hg, and ^{62}Fe from ^{197}Au.

In conclusion, according to our estimates in the framework of ASAFM the so-called "stable" nuclei with $Z>60$ are expected to decay spontaneously, by emission of clusters like ^{12}C, ^{16}O, ^{30,32}Si, ^{48,50}Ca, and ^{68}Ni with half-lives $T>10^{40}$ s, leading to daughters with $Z_1=50-58$ and $N_1 \simeq 78-82$.

TABLE I. Some "stable" nuclides with half-life T in respect to heavy cluster emission shorter than 10^{50} s.

Nuclide	Emitted heavy ion	Daughter Z_1	N_1	Q (MeV)	Q_{α} (MeV)	$\log T_{\alpha}$ (s)	$\log T$ (s)	$\log T'$ (s)	$\log\left(\frac{T}{T_{\alpha}}\right)$	$\log\left(\frac{T'}{T'_{\alpha}}\right)$
^{150}Sm	^{12}C	56	82	11.21	1.45	35.8	48.8	48.3	13.0	12.5
^{151}Eu		57	82	12.57	1.96	25.7	42.7	42.7	17.0	17.0
^{154}Gd	^{16}O	56	82	19.29	0.92	60.4	48.5	48.0	−11.9	−12.4
^{156}Dy		58	82	22.29	1.76	32.2	41.1	40.5	8.8	8.3
^{169}Tm	^{32}Si	55	82	49.36	1.20	54.7	48.3	48.3	−6.4	−6.4
^{168}Yb	^{30}Si	56	82	51.13	1.95	32.1	45.5	44.6	13.3	12.5
^{170}Yb	^{32}Si	56	82	51.58	1.74	37.1	45.9	45.0	8.8	7.9
^{180}Hf	^{48}Ca	52	80	79.64	1.28	54.3	44.0	42.8	−10.3	−11.5
^{181}Ta		53	80	81.68	1.52	47.6	43.6	43.6	−3.9	−3.9
^{180}W		54	78	83.86	2.51	25.9	43.3	42.1	17.4	16.2
^{182}W		54	80	84.09	1.77	40.7	42.6	41.4	1.9	0.7
^{183}W		54	81	84.35	1.68	46.2	42.0	42.7	−4.2	−3.6
^{184}W		54	82	84.94	1.66	43.9	40.9	39.7	−3.0	−4.2
^{186}W	^{50}Ca	54	82	83.48	1.12	64.9	43.9	42.7	21.0	−22.2
^{185}Re	^{48}Ca	55	82	86.95	2.19	32.8	40.7	40.7	7.8	7.8
^{184}Os		56	80	88.87	2.97	21.2	40.8	39.6	19.5	18.3
^{187}Os	^{49}Ca	56	82	88.34	2.72	27.2	41.6	42.3	14.5	15.1
^{188}Os	^{52}Ti	54	82	94.75	2.14	34.4	42.8	41.5	8.4	7.1
^{189}Os	^{53}Ti	54	82	94.27	1.97	41.9	43.8	44.5	1.9	2.5
^{192}Os	^{58}Cr	52	82	98.57	0.36	161.6	47.4	46.0	−114.2	−115.6
^{191}Ir	^{56}Cr	53	82	102.39	2.08	37.1	44.4	44.4	7.4	7.4
^{192}Pt	^{56}Cr	54	82	105.41	2.41	31.2	43.2	41.8	12.0	10.6
^{198}Pt	^{68}Ni	50	80	113.74	0.09	399.3	48.3	46.7	−351.0	−352.6
^{197}Au	^{62}Fe	53	82	111.54	0.95	83.6	47.1	47.1	−36.5	−36.5
^{196}Hg	^{60}Fe	54	82	115.99	2.04	40.6	43.7	42.2	3.1	1.6
^{202}Hg	^{68}Ni	52	82	118.52	0.13	317.5	48.7	47.1	−268.7	−270.4

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