Cluster- decays studies of rare-earth nuclei and associated shell effects

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Introduction

Since the discovery of ^{14}C-decay from ^{223}Ra by Rose and Jones [1] in 1984, many other ^{14}C-decays from other radioactive nuclei ^{221}Fr, $^{(221,222,224,226)}$Ra,^{223,225}Ac and ^{226}Th and some 12 to 13 neutron-rich clusters, such as ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg and ^{32,34}Si, have been observed experimentally for the ground-state decays of translead ^{226}Th to^{242}Cm parents [2], which all decay with the doubly closed shell daughter ^{208}Pb (Z=82, N=126) or its neighboring nuclei. Theoretically, such an exotic natural radioactivity of emitting particles (nuclei)heavier than alpha-particle was already predicted in 1980 by Sandulescu, Poenaru and Greiner [3] on the basis of the quantum mechanical fragmentation theory (QMFT) proposed by one of us (RKG) and others. Todate, ^{34}Si is the heaviest cluster observed with the longest decay half-life ever measured ($\log_{10}T_{1/2}$(s)=29.04) from ^{238}U parent . Keeping in mind the doubly magic nature of the ^{208}Pb daughter, a second island of heavy-cluster radioactivity was predicted by Poenaru, Greiner and collaborators on the basis of analytical superasymmetric fission model (ASAFM), and by Gupta and collaborators on preformed cluster model (PCM)[4], in the decays of some neutron-deficient rare-earth nuclei in to ^{100}Sn (Z=N=50) daughter or a neighboring nucleus. Furthermore, Gupta and collaborators predicted another doubly closed ^{132}Sn (Z=50,N=82) daughter radioactivity, for decays of some selective neutron-rich rare-earth nuclei (single isotopes of Ba to Gd parents). More recently, a new shell closure at N=90 is predicted for the ^{140}Sn isotope on the basis of shell model calculations [5]. In this paper, heavy cluster emissions to many more rare-earth parents (329 cases) with ^{50}Sn always as the daughter product are considered. Specifically, we have considered the emission of various isotopes of C, O, Ne,Mg, Si, S, Ar, Ca, Ti, Cr, Fe and Ni, respectively, from neutron-deficient to neutron-rich Ba, Ce, Nd, Sm, Gd, Dy, Er, Yb, Hf, W, Os and Pt parents, with a view to look for ^{100}Sn and ^{132}Sn radioactivities, as well as any other new Sn radioactivity with new shell closures in neutrons. Since the cluster decays are more probable with daughters as magic nuclei, the decay half-lives are expected to drop (be minimum) for the magic daughters.

Preformed Cluster Model

The preformed cluster model (PCM) [4 uses the dynamical collective coordinates of mass and charge asymmetries η and η_z on the basis of Quantum Mechanical Fragmentation Theory. The decay constant λ in PCM is defined as

$$\lambda = \frac{\ln 2}{T_{1/2}} = P_0 \nu_0 P \qquad (1)$$

Here P_0 is the cluster preformation probability and P is the barrier penetrability which refer, respectively, to the η- and R- motions. ν_0 is the barrier assault frequency. P_0 are the solutions of the stationary Schrodinger equation in η,

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V_R(\eta)\right\}\psi^{(\nu)}(\eta)=E^{(\nu)}\psi^{(\nu)}(\eta) \qquad (2)$$

Which on proper normalization are given as

$$P_0 = \sqrt{B_{\eta\eta}}\left|\psi^{(0)}\left(\eta\left(A_i\right)\right)\right|^2\left(2/A\right) \qquad (3)$$

The fragmentation potential ($V_R(\eta)$ in eq (2) is calculated simply as the sum of Coulomb interaction, the nuclear proximity potential and the ground state binding energies of two nuclei:

$$V\left(R_a,\eta\right) = -\sum_{i=1}^{2} B(A_i,Z_i) + \frac{Z_1 Z_2 e^2}{R_a} + V_P \qquad (4)$$

With B's taken from the 2003 experimental compilation of Audi et al and from the 1995 calculations of Moller et al. Thus, full shell effects are contained in our calculations that come from the experimental and/or calculated binding energies. The WKB tunneling probability calculated is P= P_iP_b with

$$P_i = \exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_i}\{2\mu[V(R)-V(R_i)]\}^{1/2}dR\right]$$

$$P_b = \exp\left[-\frac{2}{\hbar}\int_{R_i}^{R_b}\{2\mu[V(R)-Q]\}^{1/2}dR\right]$$

These integrals are solved analytically for R_b, the second turning point, defined by $V(R_b)$=Q-value for the ground- state decay.

The assault frequency ν_0 is given siply as

$$\nu_0 = \left(\frac{2E_2}{\mu}\right)^{1/2} \Big/ R_0 \qquad (7)$$

With $E_2=(A_1/A)Q$, the kinetic energy of lighter fragment, for the Q- value shared between the two products as inverse of their masses.

Calculation and Results

The preformed cluster model (PCM) is used for the cluster decay calculations with $_{50}$Sn as a daughter nucleus always from various parents of Ba to Pt region.

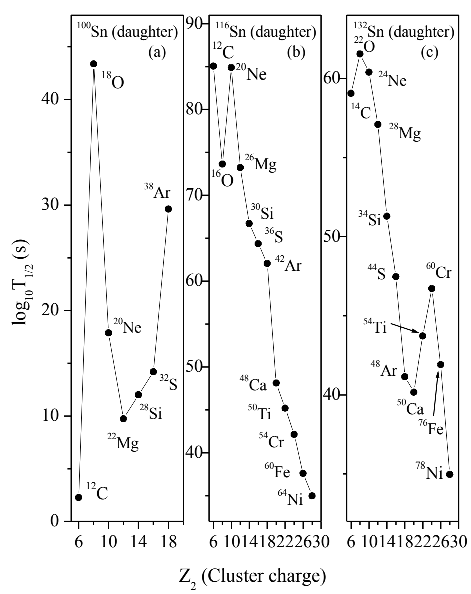

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Fig. 1 The half-life of most probable clusters emitted from various Ba to Pt parents with (a) ^{100}Sn (b) ^{116}Sn and (c) ^{132}Sn daughter, plotted as a function of cluster proton number Z_2.

Thus the ^{100}Sn and ^{132}Sn-daughter radioactivities is studied to look for the most probable clusters, emitted from the rare-earth parents, and the presence of any new neutron magicity. The most probable clusters, respectively, with ^{100}Sn and ^{132}Sn daughters, are predicted to be ^{12}C from ^{112}Ba and ^{78}Ni from ^{210}Pt parent. Further possibilities with ^{100}Sn and ^{132}Sn daughters are also noticeable in ^{22}Mg and ^{50}Ca clusters emitted from ^{122}Sm and ^{182}Yb parents, respectively, as the second best new cases. In addition, a new shell is indicated at N_1=66 with ^{116}Sn-daughter due to ^{64}Ni cluster emitted from ^{180}Pt parents.

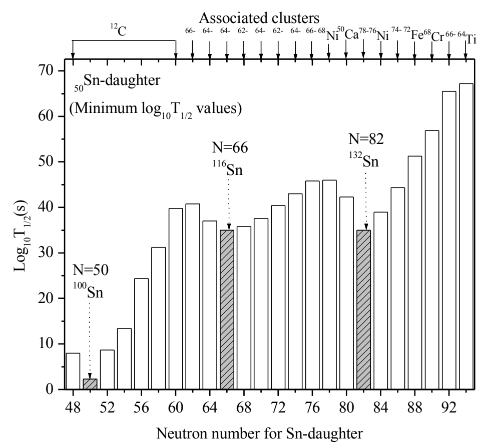

Fig. 2 Histogram of $\log_{10}T_{1/2}$ (s) versus Sn-daughter neutron number N_1 for the most probable clusters emitted from various Ba to Pt parents.

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