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Cluster decay in the superallowed α decay region

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The emissions of α particles and protons are the dominant decay channels in the neutron-deficient nuclei corresponding to the *sdg* major shell. The possibility of cluster emission is explored here. It is shown that the cluster decay mode has a small yet sizable branching ratio.

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Lower *sdg* shell nuclei are interesting testing grounds for nuclear models, including algebraic models [1]. Experimentally, they provide a wealth of information, such as the evolution of spin orbit potential with isospin [2], making this region all the more important. Nuclides close to light Sn isotopes are known to possess very interesting properties, including superallowed α emission [3] and spontaneous proton emission [4]. They are under active theoretical (see, e.g., Refs. [1–4]) and experimental investigations [5].

In addition to α and proton emission, one of the nuclei in this region, ^{114}Ba, is known to have a small ^{12}C emission branch. The Q value, branching ratio, and hence half-life against spontaneous ^{12}C emission have been measured and reported in the literature [6]. The nucleus ^{114}Ba has 58 neutrons and is just two units away from the $N = Z$ line, implying that the nucleus is highly neutron deficient (the stable Ba isotopes are $^{130,132,134\text{–}138}$Ba). This simple observation naturally leads to a very important question: Are there any other nuclides in the *sdg* shell that may have a significant cluster emission branch, in addition to the α decay branch? The present Rapid Communication attempts to answer this question.

The pioneering work on spontaneous cluster emission from certain nuclei by Sandulescu and coworkers opened up another possible avenue to investigate the nuclear structure and structure models [7]. This prediction was established by Rose and coworkers [8] through a very difficult and painstaking experiment. A number of such spontaneous cluster emission events from a variety of parent nuclei were reported in the literature afterward (see, for a summary, Ref. [9]).

On the other hand, the theoretical description of cluster emission is a very challenging task. A number of such investigations with a variety of approaches of varying degree of sophistication have been carried out (see, for example, Refs. [10–15]). The formalism reported in Ref. [15] proposes to treat the cluster as a point particle moving in a Gamow state under an effective cluster-daughter interaction potential. The cluster is assumed to be preformed here. In this context, it is worthwhile to point out that it has recently been concluded that the description of clusterization is beyond what mean-field approaches, like the shell model, can achieve [16].

The beauty of the formalism reported in Ref. [15] is that it leads to an exact decay width from a given Gamow state of the potential well [17]. It has been shown there that the method successfully describes all the known cluster emission processes, within at the most one order of magnitude. This result is very encouraging and implies that the method can be applied with confidence to the exploration of the hitherto unknown cluster emission processes. In this work, we therefore employ the formalism developed in Ref. [15] to investigate cluster as well as α emission processes from lower *sdg* shell nuclei. In a nutshell, the approach amounts to a description of a cluster state as a Gamow state built on a given effective potential. The decay width can then be obtained by matching the outgoing cluster wave function (obtained using the code GAMOW [18]) with the corresponding Coulomb wave function. Further theoretical and computational details can be found in Ref. [15].

In the present investigation, we choose proton-deficient even-even Te, Xe, and Ba isotopes, namely, $^{108\text{–}118}$Te, $^{110\text{–}122}$Xe, and $^{114\text{–}126}$Ba. The clusters are assumed to be ^{4}He, ^{10,12,14}Be, $^{10\text{–}20}$C, and $^{14\text{–}20}$O. For a given parent, the cluster is chosen in such a way that the daughter nucleus will have at least 48 protons, and that one- and two-neutron and proton separation energies are positive (i.e., the corresponding states are bound). Besides, it is required that the emission is allowed, i.e., that the corresponding Q value is positive. The binding energies of parent, daughter, and clusters have been taken from the mass evaluation [19]. In the absence of measured mass for a specific nuclide, its binding energy is adopted from the trace-formula-inspired mass model [20], which is quite precise throughout the periodic table. The results thus obtained are presented in Table I. It should be noted that only emission events corresponding to half-lives less than 10^{30} s have been listed here. This is because longer half-lives imply that branching ratios would be too small and the cascade of emitted α particles would overwhelm any detection of the cluster.

The calculated half-lives are close to the corresponding experimental ones when available. The cluster decay branches turn out to be small. Considering that in measured cluster emission processes in transactinide nuclei the dominant α decay mode may be more than 10 orders of magnitude larger than the cluster mode [15], the ratios obtained here seem to be well within experimental reach.

It is also interesting to analyze the formation probabilities of the various clusters. In our cluster treatment, where the cluster is considered as a particle decaying through a single channel,

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TABLE I. The calculated values of $\log_{10} T_{1/2}$ for even-even cluster emitters. The Q values and the cluster formation probabilities (P_c) are also presented for completeness.

Parent	Daughter	Cluster	Q value (MeV)	$\log_{10} T_{1/2}$ (Calc.)	$\log_{10} T_{1/2}$ (Expt.)	Cluster formation probability (P_c)
^{108}Te	^{104}Sn	^{4}He	3.416	1.266	0.632	9.1×10^{-4}
^{110}Te	^{106}Sn	^{4}He	2.696	6.843	5.792	7.4×10^{-4}
^{112}Te	^{108}Sn	^{4}He	2.076	13.877		6.3×10^{-4}
^{114}Te	^{110}Sn	^{4}He	1.526	23.499		5.4×10^{-4}
^{110}Xe	^{106}Te	^{4}He	3.876	−0.241	−0.838	8.6×10^{-4}
^{110}Xe	^{98}Cd	^{12}C	15.722	15.252		1.1×10^{-8}
^{112}Xe	^{108}Te	^{4}He	3.336	3.103	2.352	7.3×10^{-4}
^{112}Xe	^{100}Cd	^{12}C	14.172	20.325		6.6×10^{-9}
^{114}Xe	^{110}Te	^{4}He	2.726	8.070		6.2×10^{-4}
^{114}Xe	^{102}Cd	^{12}C	12.582	26.558		3.7×10^{-9}
^{116}Xe	^{112}Te	^{4}He	2.096	15.399		5.2×10^{-4}
^{118}Xe	^{114}Te	^{4}He	1.386	29.190		4.3×10^{-4}
^{114}Ba	^{110}Xe	^{4}He	3.536	3.057	1.689	6.3×10^{-4}
^{114}Ba	^{102}Sn	^{12}C	18.982	8.915	>4.10	1.7×10^{-8}
^{114}Ba	^{98}Cd	^{16}O	26.410	13.461		1.5×10^{-11}
^{116}Ba	^{112}Xe	^{4}He	3.145	5.880		5.7×10^{-4}
^{116}Ba	^{104}Sn	^{12}C	17.171	13.480		8.9×10^{-9}
^{116}Ba	^{100}Cd	^{16}O	24.469	17.642		6.7×10^{-12}
^{118}Ba	^{114}Xe	^{4}He	2.585	11.049		4.9×10^{-4}
^{118}Ba	^{106}Sn	^{12}C	15.281	19.177		4.5×10^{-9}
^{118}Ba	^{102}Cd	^{16}O	22.319	22.988		2.8×10^{-12}
^{120}Ba	^{116}Xe	^{4}He	1.736	23.377		3.9×10^{-4}
^{120}Ba	^{108}Sn	^{12}C	13.182	27.020		2.2×10^{-9}

the formation probability is equivalent to the spectroscopic factor. The formation probability is given in our case by the square of the wave function integrated between a lower limit L_b and an upper one L_u. The lower limit is the touching radius, i.e., the radius of the daughter nucleus plus the radius of the cluster. The upper limit is the radius of the daughter nucleus plus twice the radius of the cluster. We have checked that this integral is virtually independent of the upper limit for values of this limit larger than L_u, as it should be.

The corresponding results are shown in Table I.

One sees, as expected, that the α-particle formation probability P_α in a given isotope is always much larger than the corresponding heavy-cluster probability P_c. For instance, in the mother nucleus ^{116}Ba it is $P_\alpha = 5.7 \times 10^{-4}$, while $P_{^{12}C} = 8.9 \times 10^{-9}$ and $P_{^{16}O} = 6.7 \times 10^{-12}$. Also as expected, the formation probability decreases strongly as the cluster becomes heavier. It is interesting to compare this with the formation probabilities of α and heavier clusters in the region above ^{208}Pb. As an example, the α formation probability in ^{222}Ra is 3.9×10^{-4}, whereas that for ^{14}C formation turns out to be 4.8×10^{-11}. One thus sees that the α formation probability is larger in the superallowed Sn region than in nuclei above ^{208}Pb.

In summary, we have evaluated cluster decay from nuclei lying in the superallowed α decay region, i.e., in the light tin region, by applying a theory which includes a microscopic treatment of the cluster center-of-mass motion, as described in Ref. [15]. The advantage of this approach is that the decay width is independent of the matching point distance. As usual in radioactive decay processes, the most important quantity in determining the decay width, and hence the half-life, is the cluster Q value, i.e., the binding energies. However, those quantities are not known in many of the cases in this highly unstable region. We evaluated those energies by using a highly reliable formalism [20]. We thus found that the branching ratio $B_c = T_{1/2}(\text{cluster})/T_{1/2}(\alpha)$ of cluster to α decay can vary from a factor $10^{3.6}$ (^{12}C decay from ^{120}Ba) to $10^{18.5}$ (^{12}C decay from ^{114}Xe). Considering that cluster decays with values of B_c larger than 10^{10} have been measured in the actinide region, one can conclude that it may be possible to perform such measurements even in the light tin region.

We have also found that the formation probability of a cluster decreases strongly as the cluster becomes heavier, as expected.

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