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Distinction between pre-formed cluster emission and heavy ion decay by fission

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Abstract. For studying cluster radioactivity in the actinide region as well as trans-tin region two types of models are used: the pre-cluster formation model and the unified fission model. In the case of the actinide region, the cluster-like shapes are preferred for very high asymmetry while fissioning shapes are more suitable for less asymmetry and symmetry (the line of demarcation being around $A_e = 31$). In this work this line of demarcation is studied in the case of the trans-tin region. The results of this study show that the transition from cluster mode to fission mode takes place at $A_e = 16$.

Keywords. Cluster radioactivity; pre-formed cluster emission; heavy ion decay by fission; comparison.

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1. Introduction

The spontaneous emission of fragments heavier than alpha particle termed as cluster radioactivity has now become an experimentally confirmed reality. Theoretically, such emissions were first predicted by Sandulescu, Poenaru and Greiner [1]. The first experimental observation was made by Rose and Jones [2]. Encouraged by this, researchers tried to detect other novel modes of radioactive decay in which heavy nuclei disintegrate by emission of intermediate mass fragments. Theoretically, the interest in such decays lies in the estimation of lifetimes and branching ratios with respect to alpha decays. The lifetimes for the observed cluster radioactivity of radioactive nuclei have been estimated using various models and compared with the experimental data. These models can be classified as the fission models, where only the barrier penetrabilities are calculated, and the preformed cluster models, where the cluster is assumed to be formed before it penetrates the barrier and its preformation probability is also included in the calculations. The physics of the two approaches is apparently different, though it has been possible to look for some similarities between them [3].

The purpose of this work is to compare the cluster mode and fission mode of cluster radioactivity to find the transition point from one mode to the other in the case of trans-tin region using our model. In section two, we give the description of our model applicable for treating cluster radioactivity from trans-tin region. The transition from the cluster mode to fission mode in actinide region is discussed in the third section. Extension to trans-tin region is discussed in §4. Finally §5 contains conclusion.

2. Our model

In order to study such cluster radioactivity, we have developed a model (CYEM) [4] in two sphere approximation in which the zero-point vibration energy is explicitly included without violating the conservation of energy and the nuclear inertial mass coefficient dependent on the centre of mass distance has been used. We have already demonstrated the success of this model by applying it to the cases of ^{14}C, ^{24}Ne [4] and also extended [5] this model for the emission of fragments heavier than ^{24}Ne from uranic and trans-uranic nuclei. Recently, we have also extended [6,7] this model for the newly predicted trans-tin region incorporating the most important cluster deformation. In the case of newly discovered trans-tin cluster radioactivity the daughter nuclei are formed around the doubly magic ^{100}Sn, the deformations of the clusters are very large and hence they have to be incorporated in the lifetime calculations.

In our earlier version of the model [8], we have treated the parent and the daughter nuclei spheroid, keeping the cluster as spherical. But in this work the parent and the emitted cluster are considered to be spheroid, keeping the daughter as spherical. If the emitted cluster has a deformation, say quadrupole deformation only, while the daughter nucleus is spherical and if the Q-value of the reaction is taken as the origin, the potential for the post-scission region as a function of the centre of mass distance r of the fragments is given by

$$V(r) = V_c(r) + V_n(r) - V_{df}(r) - Q. \tag{1}$$

Here, V_c is the Coulomb potential between a spheroidal emitted cluster and spherical daughter, V_n is the nuclear interaction energy due to finite range effects of Krappe *et al*; and V_{df} is the change in the nuclear interaction energy due to quadrupole deformation β_2 of the emitted cluster.

The Coulomb potential between the emitted fragments is taken as the interaction of a spheroidal emitted cluster and a spherical daughter. For a prolate spheroidal emitted cluster with longer axis along the fission direction, Pik-Pichak obtained

$$V_c(r) = \frac{3}{2}\frac{Z_d Z_e e^2 \nu}{r}\left(\frac{1-\nu^2}{2}\ln\frac{\nu+1}{\nu-1} + \nu\right) \tag{2}$$

and for an oblate spheroidal emitted cluster with shorter axis along the fission direction,

$$V_c(r) = \frac{3}{2}\frac{Z_d Z_e e^2}{r}\left(\nu(1+\nu^2)\arctan\nu^{-1} - \nu^2\right). \tag{3}$$

For the overlapping region, we approximate the potential barrier by a third-order polynomial in r having the form [4]

$$V(r) = -E_v + [V(r_t) + E_v]\left\{s_d\left(\frac{r-r_i}{r_t-r_i}\right)^2 - s_e\left(\frac{r-r_i}{r_t-r_i}\right)^3\right\}, \quad r_i \le r \le r_t \tag{4}$$

where

$$r_t = a_e + R_d. \tag{5}$$

Here, a_e is the semi-major or minor axis of the spheroidal cluster depending on the prolate or oblate shape of the emitted cluster; and ri is the distance between the centres of mass of the daughter and the emitted particle portions in the spheroidal parent nucleus.

Expressing the energies in MeV, lengths in fm and time in seconds, for calculating the lifetime of the decay system we use the formula

$$T = \frac{1.433 \times 10^{-21}}{E_v}[1 + \exp(K)]. \tag{6}$$

The action integral K is given by

$$K = K_L + K_R, \tag{7}$$

where

$$K_L = \frac{2}{\hbar}\int_{r_a}^{r_t} [2B_r(r)V(r)]^{1/2}\,\mathrm{d}r \tag{8}$$

and

$$K_R = \frac{2}{\hbar}\int_{r_t}^{r_b} [2B_r(r)V(r)]^{1/2}\,\mathrm{d}r. \tag{9}$$

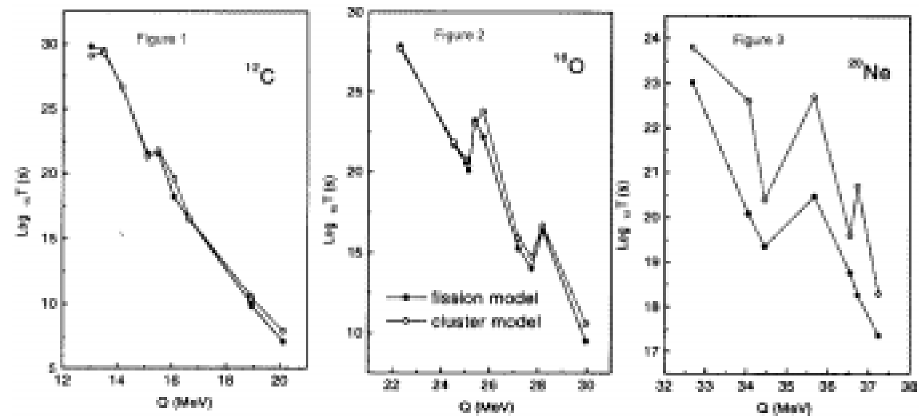
The limits of integration r_a and r_b are the two appropriate zeros of the integrand which are found numerically.

3. Transition from cluster mode to fission mode in actinide region

Poenaru *et al* have discussed the applicability of the cluster mode or the fission mode for studying cluster radioactivity in the actinide region and have found out that the transition from one mode to other takes place around $A_e = 31$. They have considered the parametrisation of two intersecting spheres with constant radius R_e of the light fragment (cluster mode) or with constant volume V_e of the light fragment (fission mode). They have concluded that cluster mode is preferred for studying cluster radioactivity for $A_e < 31$, the fission mode is more suitable for $A_e > 31$ [9].

4. Extension to trans-tin region

We have applied our model to study the emission of ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si [10] etc from the trans-tin region and compared with that of Poenaru *et al* [11]. In the figures 1–3, we give the life times for the decay of lighter to heavier clusters where the deviation of the results obtained by our fission model and the cluster model is found to become large after ^{16}O emission.



Figures 1–3. Lifetimes for the decay of lighter to heavier clusters.

5. Conclusion

Even though the preformed cluster model can be used for cluster radioactivity, still there is a distinction between cluster mode and fission mode. Thus we conclude that fission model is more apt for all cluster decays while the pre-cluster model is quite applicable for the lighter clusters.

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