Cluster radioactive-decay using the Relativistic mean field theory within the preformed cluster model

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Introduction

Cluster radioactivity is the spontaneous emission of clusters heavier than α-particle. Since its first theoretical prediction [1] in 1980 and experimental confirmation [2] in 1984, this phenomenon is now established for some 26 decays with light to heavy (^{14}C to ^{34}Si) clusters from various actinides (^{221}Fr to ^{242}Cm). Theoretically, two types of models have been advanced, namely i) Unified fission models (UFM), such as the analytic super-asymmetric fission model (ASAFM) [1], and ii) the Preformed cluster models (PCM), like that of Gupta and collaborators based on collective potential energy surfaces [3]. The two models differ from each other for their non-inclusion or inclusion of the pre-formation/ spectroscopic factor(s) of the cluster(s) being born before penetrating the confining interaction barrier. Some effort has also gone in understanding it on the mean-field Hatree-Fock-Bogoliubov theory [4], treating it as an asymmetric fission process.

In this paper, based on PCM, for the first time we use the relativistic mean field (RMF) theory, which is already shown [5] to support the clustering effects in various heavy parents with observed cluster decays. For the present study, we have chosen the parents ^{222}Ra, ^{226,228}Th, ^{230,232,234}U, ^{236,238}Pu, and ^{242}Cm which decay, respectively, in to ^{14}C, $^{18.20}$O, ^{22,24,26}Ne, ^{28,30}Mg, and ^{34}Si clusters, having always the doubly magic ^{208}Pb as the daughter nucleus.

Methodology

The decay constant λ (or the decay half-life time $T_{1/2}$= ln2/λ), in PCM is defined as [3]

$$\lambda_{PCM} = \nu_0 P_0 P, \qquad (1)$$

which in UFM is simply given by [1]

$$\lambda_{UFM} = \nu_0 P, \qquad (2)$$

where ν_0 is the assault frequency with which the cluster hits the barrier. P_0 is the pre-formation probability of the cluster, and P is the WKB penetrability of preformed cluster in R-motion. An empirical estimate of the pre-formation factor $P_0^{(emp)}$ (= $\lambda_{Expt}/\lambda_{UFM}$) can also be obtained [3].

In order to obtain the nuclear interaction potential $V_n(R)$, the double folding procedure [6] is used to fold the density-dependent M3Y interaction potential (DDM3Y) with the RMF calculated nuclear densities of the cluster and daughter nuclei. Then, the total interaction potential $V(R) = V_n(R) + V_C(R)$, where $V_C(R)$ is the Coulomb interaction potential. This allows us to calculate the penetration probability P of the cluster, and hence calculate λ_{UFM} and $P_0^{(emp)}$.

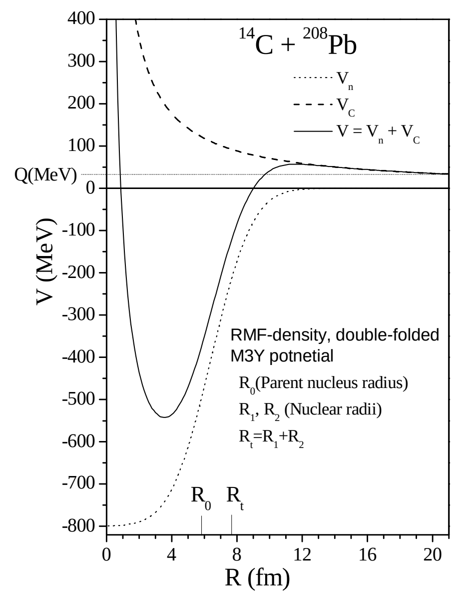

Fig. 1 *The RMF densities double folded M3Y potential V_n , Coulomb V_C and total interaction potential V as a function of the radial separation between the cluster and daughter nuclei.*

Results and Discussions

In Fig. 1, the total interaction potential V(R) between the preformed cluster ^{14}C and daughter nucleus ^{208}Pb is shown as a solid line. The strong attractive part, the nuclear potential V_n (the dotted line), is the double folded DDM3Y and the repulsive part is the Coulomb potential V_C (the dashed line). The total interaction potential V(R) is used for calculating the penetrability P, in the following.

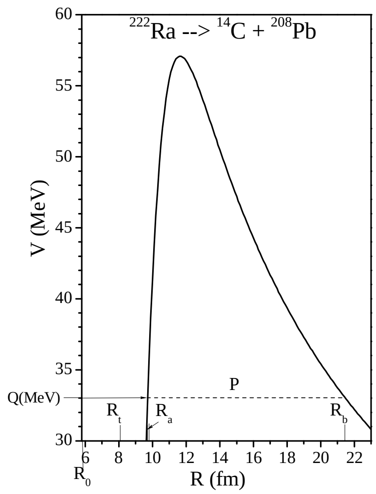

Fig. 2 *Same as Fig. 1 for the total interaction potential V(R), illustrating the penetration process of the cluster with an energy equal to Q-value of the decay.*

Fig. 2 illustrates the decay path for WKB penetration probability P through the total interaction potential V (R) for ^{14}C cluster decay of ^{222}Ra with an energy Q. For turning points R_a and R_b, $V(R_a) = V(R_b)$ = Q-value. The calculated P and the empirically estimated $P_0^{(emp)}$ are given in Table 1 for the measured cluster decays from different parent nuclei having the daughter ^{208}Pb in each case. The $P_0^{(emp)}(C)$ for clusters is given in terms of the α-particle $P_0^{(emp)}(\alpha)$, i.e., as $P_0^{(emp)}(C)/\ P_0^{(emp)}(\alpha)$. It is relevant to mention here that for the α-decays of all the parent nuclei mentioned above, we obtain very large $P_0^{(emp)}(\alpha)$ in comparison to the corresponding $P_0^{(emp)}(C)$ values for cluster decays. Note in Table 1 that the $P_0^{(emp)}(C)/\ P_0^{(emp)}(\alpha)$ decreases as the size of the cluster increases, in the line with previous studies based on PCM [3].

Table1: *The WKB penetrability P and the ratio $P_0^{(emp)}(C)/\ P_0^{(emp)}(\alpha)$ for various cluster decays ^{14}C, $^{18.20}O$, $^{22,24,26}Ne$, $^{28,30}Mg$, and ^{34}Si with ^{208}Pb as the daughter product of parents ^{222}Ra, $^{226,228}Th$, $^{230,232,234}U$, $^{236,238}Pu$, and ^{242}Cm, respectively. The impinging frequency $\nu_0 \sim 10^{21}$ s^{-1} in each case. The Q_{value} is calculated by using the experimental binding energies [7].*

Cluster Decay	**Q_{value}** (MeV)	**P**	**$P_0^{(emp)}$**(C)/ **$P_0^{(emp)}$**(α)
^{14}C	33.050	2.933×10^{-25}	9.197×10^{-07}
^{18}O	45.727	2.540×10^{-29}	4.315×10^{-07}
^{20}O	44.723	1.541×10^{-31}	1.821×10^{-10}
^{22}Ne	61.388	3.154×10^{-29}	3.792×10^{-10}
^{24}Ne	62.311	2.696×10^{-28}	2.920×10^{-13}
^{26}Ne	59.465	1.659×10^{-32}	1.246×10^{-13}
^{28}Mg	79.670	1.802×10^{-26}	3.631×10^{-16}
^{30}Mg	76.824	7.262×10^{-30}	9.970×10^{-17}
^{34}Si	96.511	1.090×10^{-25}	3.101×10^{-18}

Summary and Conclusions

The present study based on RMF formalism, using the double folded M3Y interaction, shows the importance of pre-formation factor P_0 for the process of cluster radioactive-decay, which has so far been explored on the PCM based on Quantum Mechanical Fragmentation theory [3]. Though at present the factor P_0 is adjusted only empirically, it will be highly interesting to see how this quantity can be treated within the RMF theory. Work in this direction is in progress.

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