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Cluster Radioactivity in ^{127}I

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Abstract Using the preformation cluster model of Gupta and collaborators we have studied all the possible cluster decay modes of ^{127} I. The calculated half-lives are compared with recently measured lower limits of cluster decay half-lives (for the clusters like ^{24}Ne, ^{28}Mg, ^{30}Mg, ^{32}Si, ^{34}Si, ^{48}Ca and ^{49}Sc) of ^{127}I. Our calculated half-life values lies well above the experimentally measured lower limits and the trend of the values also matches with experimental ones.

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1. INTRODUCTION

A new kind of exotic radioactive decay mode, in between α-decay and spontaneous fission called cluster decay or cluster radioactivity or heavy particle decay apart from the three basic decay modes (α-decay, β-decay and γ-emission) was predicted theoretically in 1980 [1]. Later in 1984 Rose and Jones [2] observed experimentally the emission of ^{14}C from ^{223}Ra with branching ratio of $(8.5\pm2.5)\times10^{-10}$ relative α-particle. Subsequently other authors [3, 4] also observed the same cluster ^{14}C from same radioactive parent ^{223}Ra. A few years after the above observations, several other decay modes like ^{20}O, ^{23}F, ^{24,26}Ne, ^{28,30}Mg and ^{32,34}Si from different radioactive parent nuclei like ^{221}Fr, $^{221-224,226}$Ra, ^{225}Ac,^{228,230,232}Th, ^{231}Pa, $^{230,232-236}$U, ^{237}Np, ^{236,238,240}Pu, ^{241} and ^{242}Cm were observed by various experimental groups in all around the world with branching ratio relative to α-decay from 10^{-9} to 10^{-16} [5, 6]. All the emitted clusters are heavier than α-particle but lighter than lightest fission fragment observed. The daughter nuclei observed are always double magic nucleus ^{208}Pb (N=126 and Z=82) or its neighbouring nuclei, which implies that cluster decay process associated itself with the closed shell behaviour of emitted daughter nucleus. Simultaneously it has also been studied extensively using various models after its experimental verification.

In general there exists two kinds of models for explaining the observed decay modes and for predicting new decay modes. In one kind of model, the α-particle as well as the heavy cluster (or clusters) was assumed to be pre-born in a parent nucleus before they could penetrate the barrier with the available Q-value. These models are in general called as ”Preformed Cluster Models” (PCM) [7–11]. In such a model, clusters of different sizes are considered to be preformed in the parent nucleus with different probabilities. In the other model, only Gamow’s idea of barrier penetration is used i.e.

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without considering the cluster being or not being preformed in the parent nucleus. These models are in general called as "Unified Fission Models" (UFM) [12–16].

Several semi-empirical formulae were also proposed to calculate the partial half-lives of cluster decay modes in trans-lead region. A semi-empirical formula with only three parameters to calculate logarithm of half-lives of cluster decay modes was proposed by one of us [17]. Recently a scaling law has been given by Horoi et al. to calculate the logarithm half-lives cluster decay modes [18]. Apart from the trans-actinide region, it was theoretically predicted that the trans-tin region as fertile region to observe the heavy particle decay due to the closed shell behaviour of Sn nucleus [19–25]. Based on different theoretical models Ba and Ce isotopes were predicted as cluster emitters to emit ^{12}C and ^{16}O clusters respectively leaving Sn as daughter nuclei. Later ^{12}C emission is reported experimentally from ^{112}Ba nucleus and from ^{114}Ba with upper limit for the half-lives as > 3.63 s, 1.70×10^4 s and >4.10 s. Recently a new semi-empirical formula is proposed by us [26] which is a modified form of [17] to calculate the logarithm half-lives of ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg and ^{28}Si clusters from various isotopes of Ba, Ce, Nd, Sm and Gd respectively. Very recently Bernabei et al. [27] measured the new upper limits of the half-lives of ^{24}Ne, ^{28}Mg, ^{30}Mg, ^{32}Si, ^{34}Si, ^{48}Ca and ^{49}Sc cluster radioactivity in ^{127}I parent nucleus. In the present work we have theoretically studied all the possible cluster decay modes of ^{127}I using PCM proposed by R. K. Gupta and co-workers [7–9].

2. PREFORMATION CLUSTER MODEL

Preformation Cluster Model (PCM) of R. K. Gupta and co-workers [7–9] is developed by adapting the Gamow's theory of α-decay but, instead of square well potential, a more realistic nuclear interaction potential is used and also a preformation probability P_0 is associated with the size of the cluster. The clusters of different sizes are having different preformation probabilities, which decreases with the increasing size of cluster. Thus the half-life and decay constant (λ) in PCM is defined as

$$T_{1/2} = \frac{ln2}{\lambda} \quad and \quad \lambda = P_0 P_\nu . \tag{1}$$

with P is the barrier penetration probability, P_0 is the preformation probability and ν is the assault frequency calculated as in [7–9]. In PCM of R. K. Gupta and co-workers the preformation probability is a theoretically calculated quantity by solving the Schrdinger equation of the motion in mass asymmetry (charge asymmetry) coordinate, at fixed R (defined later) and is essentially based on the nuclear structure information of the decay process. The mass and charge asymmetry is defined as

$$\eta = \frac{A_1 - A_2}{A} \quad and \quad \eta_z = \frac{Z_1 - Z_2}{Z} \tag{2}$$

where A and Z are the mass and charge numbers of the parent nucleus. A_i and Z_i with i=1,2 corresponds to the mass and charge numbers of daughter and cluster respectively. The preformation probability P_0 is obtained by solving the following Schrodinger equation

$$\left[-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V_R(\eta)\right]\psi^{\nu}(\eta)=E^{\nu}\psi^{\nu}(\eta), \tag{3}$$

Using a similar equation such as shown above one can solve the penetration probability P in R co-ordinate for fixed η as

$$\left[-\frac{\hbar^2}{2\sqrt{B_{RR}}}\frac{\partial}{\partial R}\frac{1}{\sqrt{B_{RR}}}\frac{\partial}{\partial R}+V_R(R)\right]\psi^{\nu}(R)=E^{\nu}\psi^{\nu}(R), \tag{4}$$

with $R=C_1+C_2$. C_i(i=1,2) is the Sussman's central radius which is related to the effective sharp radius R_i by (b∼1 fm)

$$C_i=R_i\left(1-\frac{b^2}{R_i^2}\right) \tag{5}$$

where the sharp effective radius is given as $R_i=1.28A_i^{2/3}-0.76+0.8A_i^{-1/3}$. The collective potential or the fragmentation potential V(η) appearing in Eq.3 is calculated as at fixed eta in R-coordinate (R-motion).

$$V(\eta)=\sum_{i=1}^{2}B_i(A_i,Z_i)+V_C+V_P \tag{6}$$

where B_i(i=1,2) corresponds to the binding energy of the daughter and cluster respectively. V_C and V_P are the coulomb and proximity potential calculated as in [7–9]. The scattering potential appearing in Eq.4 is simply the sum of coulomb and proximity potential calculated at fixed eta in R-coordinate (R-motion)

The Q-values of the decay modes are,

$$Q=M-\sum_{i=1}^{2}m_i \tag{7}$$

where M is the mass excess of the parent nucleus and m_i with i = 1,2 corresponds to the mass excesses (taken from [29]) daughter and cluster respectively, expressed in MeV.

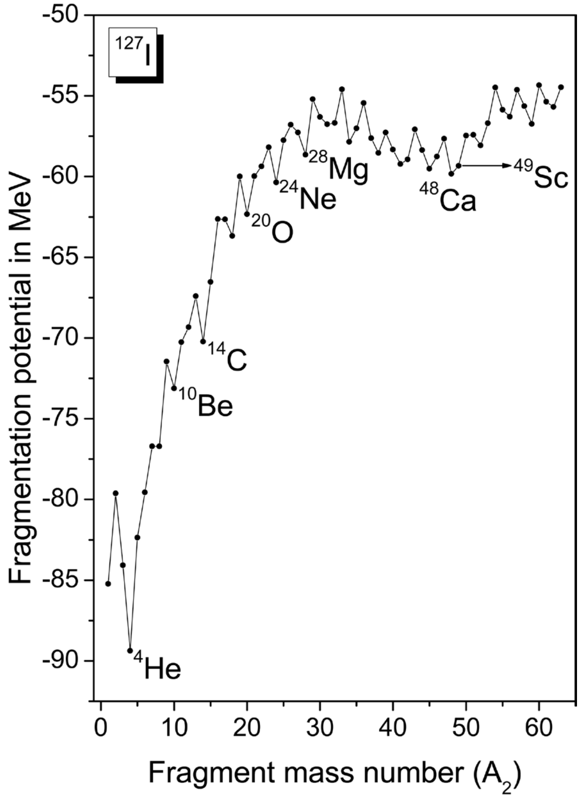

Figure 1: The calculated fragmentation potential using Eq. 6 for ^{127}I. The clusters with local minima are labelled.

3. CALCULATIONS AND RESULTS

In the present work we have studied the all possible cluster decay modes in ^{127}I. Figure 1 presents the charge minimized fragmentation potential from Eq. 6 According to quantum mechanical fragmentation theory the minimum in the fragmentation potential gives rise to the maximum in the probability to observe the particular decay mode. The fragmentation potential increases with the increasing mass number of the clusters, but there are some local minima in the potential energy surface for the clusters like ^{4}He, ^{10}Be, ^{14}C, ^{20}O, ^{24}Ne, ^{28}Mg, ^{48}Ca, and ^{49}Sc in which ^{10}Be, ^{14}C, ^{20}O, ^{24}Ne, ^{28}Mg clusters are already observed in trans-lead region. Also there exist a small cold valley in the near symmertic region and having minimum in the potential double magic cluster ^{48}Ca (N=28, Z=20), and its neighbour nucleus cluster ^{48}Ca (N=28, Z=20), and its neighbour nucleus ^{49}Sc. Figure 2 presents the calculated

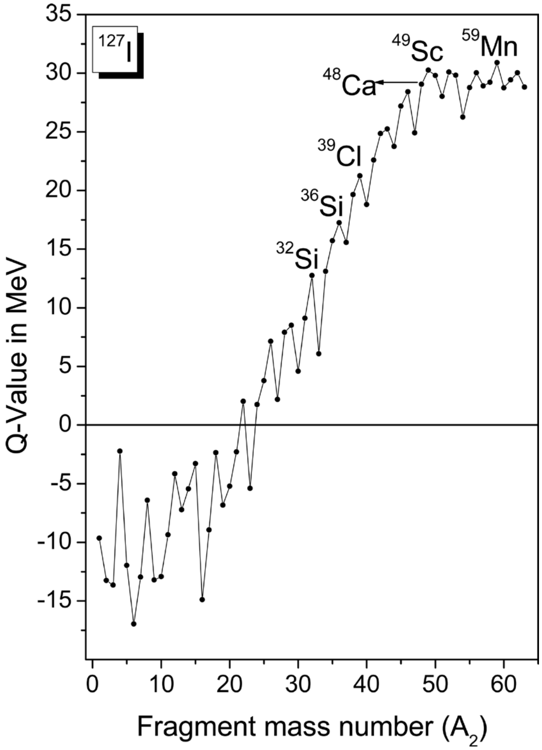

Figure 2: The calculated Q-values of cluster decay modes of ^{127}I using Eq. 7. The Q-values are positive only beyond the cluster with mass number 22. The clusters with local maxima are labelled.

Q-values which is the available energy for the clusters to penetrate the potential barrier. The maximum in the Q-value increases the penetration probability which increases the probability to observe the particular decay mode. Though the smaller clusters like ^{10}Be, ^{14}C, ^{20}O, ^{24}Ne has minimum in potential energy their Q-value are very low. The Q-value systematics prefers the heavier clusters (^{48}Ca, and ^{49}Sc) in near symmetric region to observe such cluster radioactivity.

The Penetration probability is calculated only for the clusters having positive Q-values and is presented in Figure 3. The clusters like ^{26}Mg, ^{43}K, ^{46}Ca, ^{50}Ti, ^{53}V, and ^{56}Cr has the maximum in the penetration probability. Figure 4(a) presents the calculated preformation probability P_0 for the complete mass asymmetry involved, as mentioned earlier the preformation probability decreases with increase of mass number of the clusters. There exist large fluctuations and increase in the P_0 for

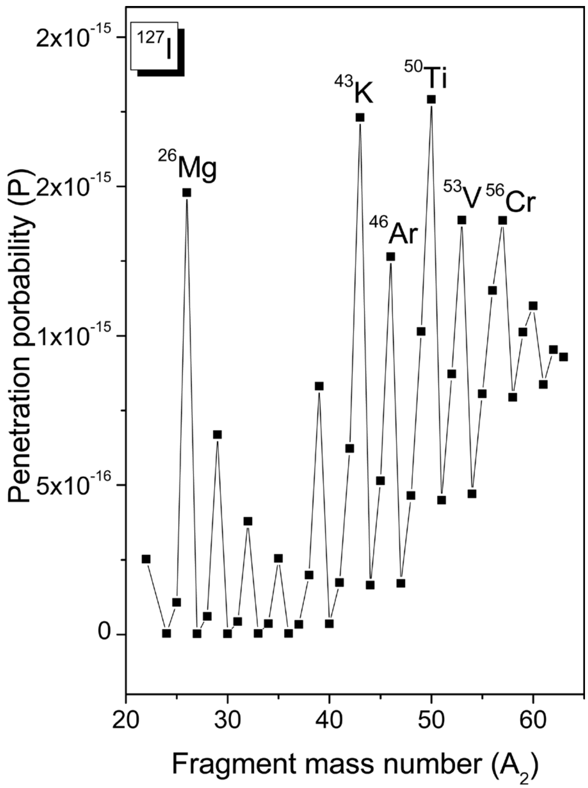

Figure 3: The calculated penetration probability (P) only for the cluster decay modes ^{127}I. having positive Q-values. The clusters having minima in P are labelled

the clusters in the near symmetric mass region and has maximum probability for the ^{48}Ca (N=28, Z=20), and its neighbour nucleus ^{49}Sc. For clear vision of the fluctuations near symmetric mass region, it is enlarged and presented in Figure 4 (b).

The decay constant and logarithm of half-lives all possible cluster decay modes of ^{127}I, with positive Q-values are calculated, presented in Figure 5 and 6 respectively. It is clear from the figure 5 the decay constant reflects the combined effect of penetration probability and preformation probability since the assault frequency is merely a constant varies in between 10^{20} and 10^{22}. The decay constant prefer the clusters that posses maximum in both the penetration probability and preformation probability. The log $T_{1/2}$ values also prefer the same clusters that are preferred by the decay constant

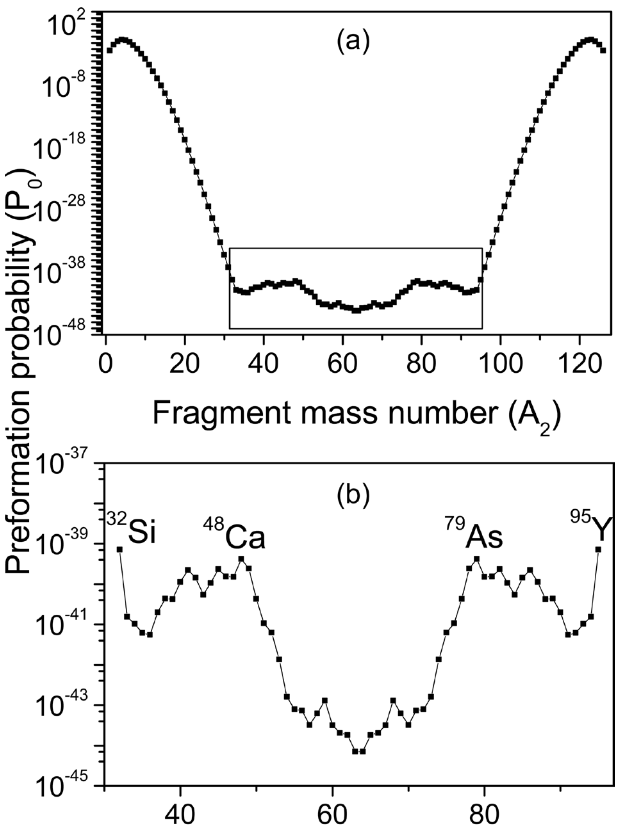

Figure 4: (a) The calculated preformation probability (P_0) for the whole mass asymmetry involved in ^{127}I. (b) The rectan-gularly marked portion in (a) is enlarged for clear vision of preformation probability (P_0) for clusters in near symmetric region. The clusters with maximum P_0 and their complementary daughters in this region are labelled.

since log $T_{1/2}$ is derived from the decay constant. The clusters (^{24}Si, ^{28}Mg, ^{30}Mg, ^{32}Si, ^{34}Si, ^{48}Ca, and ^{49}Sc) for which limits of cluster decay half-lives is measured in the recent experiment [27] is labelled in both figure 5 and 6. Figure 7 presents comparison of our calculated cluster decay half-lives with the measured lower limits of cluster decay half-lives of ^{127}I. Our calculated half-lives lies well above the experimental lower limit for the clusters ^{30}Mg, ^{32}Si, ^{34}Si, ^{48}Ca, and ^{49}Sc. The trend of the variation of cluster decay half-lives for heavier clusters (^{32}Si, ^{34}Si, ^{48}Ca, and ^{49}Sc) matches with the measured half-lives.The calculated half-lives lies below the measured lower limit for clusters ^{24}Ne and ^{28}Mg and this may be due to the very lesser Q-values.

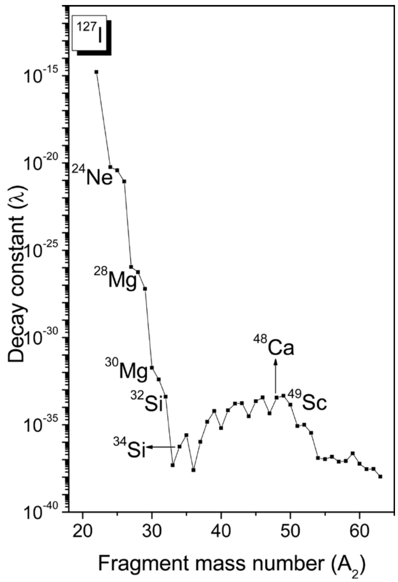

Figure 5: The calculated decay constant (λ) using Eq.1 for the possible cluster decay modes of ^{127}I, with positive Q-values. The clusters for which the experimental lower limits of half-lives measured in [27] are labelled.

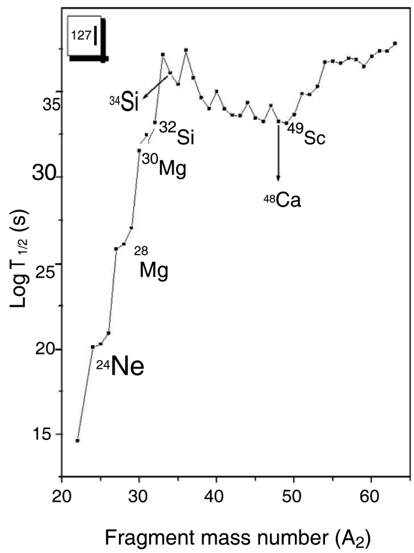

Figure 6: The calculated log values of half-life for the possi-ble cluster decay modes of ^{127}I, with positive Q-values. The clusters for which the experimental lower limits of half-lives measured in [27] are labelled.

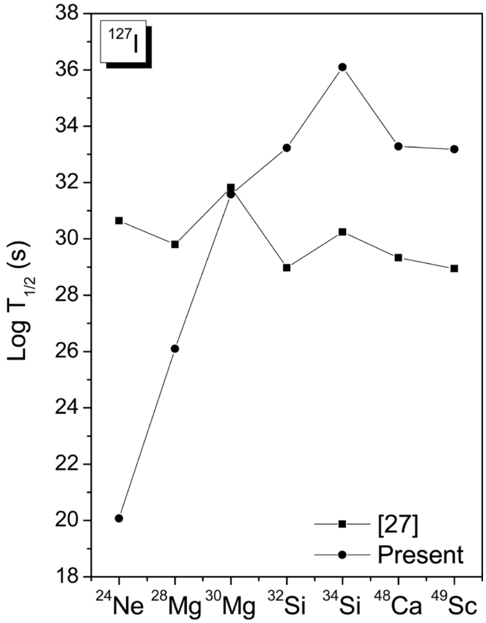

Figure 7: The calculated logarithm of half-lives, expressed in seconds, are compared with the experimentally measured [27] lower limits of possible cluster decay modes of ^{127}I.

Table 1: The table shows log values of our calculated cluster decay half-lives using PCM and log values of experimentally measured lower limits of cluster decay half-lives of ^{127} I.

Cluster decay modes	**$\log_{10} T_{1/2}$(s)**	
	present	**Ref.[27]**
^{127}I→ ^{24}Ne + ^{103}Tc	20.07	30.65
^{127}I→ ^{28}Mg + ^{99}Nb	26.10	29.80
^{127}I→ ^{30}Mg + ^{97}Nb	31.58	31.82
^{127}I→ 32Si + ^{95}Y	33.23	28.98
^{127}I→ 34Si + ^{93}Y	36.10	30.24
^{127}I→ ^{48}Ca + ^{79}As	33.28	29.33
^{127}I→ ^{49}Sc + ^{78}Ge	33.18	28.95

4. SUMMARY

Summarizing in this work, we have studied the cluster decay half-lives of all possible cluster decay modes of ^{127}I nucleus using preformation cluster model. The calculated cluster decay half-lives of different clusters (^{24}Si, ^{28}Mg, ^{30}Mg, ^{32}Si, ^{34}Si, ^{48}Ca, and ^{49}Sc) emitted from ^{127}I are compared with the experimentally measured lower limits. Our calculated cluster decay half-lives lies well above the experimental lower limit except for two lighter clusters (^{24}Si and ^{28}Mg). The trend of the calculated values also matches with the experimental values for the heavy clusters ^{30}Mg, ^{32}Si, ^{34}Si, ^{48}Ca, and ^{49}Sc.

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