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Study of Cluster Emission in Ra Isotopes using Modified Universal Decay Law

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Cluster radioactivity was first predicted by Sandulescu *et al.* in 1980 [1]; these clusters were heavier than α particles and lighter than fission fragments. However, the experimental proof of this decay was given by Rose and Jones in 1984 [2]: ^{14}C emitted from ^{223}Ra. Till now, many clusters decay from light to heavy clusters (^{14}C to ^{32}Si) have been observed from various trans-lead nuclei (Fr, Ra, etc.) resulting the corresponding daughter as magic (Z=82) or neighboring nuclei which indicate the importance of this particular (Z>82) region in cluster radioactivity [3].

The half-lives of cluster decay are sensitive to the disintegration energy (Q−value), which is given by:

$$Q = B.E.(d) + B.E.(c) - B.E.(p) + k[Z_p^{\epsilon} - Z_d^{\epsilon}]$$

where B.E.(p), B.E.(d) and B.E.(c) are the binding energies of the parent nucleus, daughter nucleus, and emitted cluster, respectively. The term $k[Z_p^{\epsilon} - Z_d^{\epsilon}]$ indicates screening effect caused by the surrounding electrons around the nuclei [4] with k=8.7 eV [8.7 × 10^{-6}MeV] and ϵ=2.517 for Z $\geq$ 60.

Although, cluster decay half-lives can be estimated with the help of various models [5] but there are also various formulas which are capable to calculate the cluster decay half-lives accurately [6]. In 2009, Qi, proposed a formula for the calculation of half lives of α and cluster emission. This is also known as universal decay law [8] which was recently modified by Soylu and Qi [9] by adding angular momentum (l) and isospin (I) dependent terms, named as MUDL and represented as,

$$\begin{aligned} log_{10}T_{1/2}(Sec.) \;=\; & aZ_cZ_d\sqrt{\frac{\mu}{Q}} + b\sqrt{\mu Z_cZ_d} \\ & \sqrt{(A_d^{1/3} + A_c^{1/3})} + c + d \\ & \sqrt{\mu Z_cZ_d(A_d^{1/3} + A_c^{1/3})} \\ & \sqrt{l(l+1)} + e\sqrt{I(I+1)} \end{aligned}$$

In this formula, Z_c and Z_d are the proton number of cluster and daughter nucleus, respectively. μ is reduced mass defined as $A_dA_c/(A_d + A_c)$. Coefficients of MUDL are given as: a = 0.2760038, b = -0.2414764, c = -42.3417001, d = 0.0011798, and e = 49.66757757.

In the present work, we have attempted to find various clusters which have the chances of emission from Ra (Z=86) isotopes (126≤N≤147) considering the proton shell closure effect. Therefore, we have calculated cluster decay half-lives for various clusters (isotopes of C: Z=6) from Ra isotopes by using MUDL formula given above. For these theoretical estimates, the disintegration energies (Q-values) are used from WS4 mass model [10], which are found to be more precise than other widely used theories, as shows in our previous work [11]. Consequently, we have found the significant probability of $^{12-16}$C emission from $^{220-224}$Ra, respectively.

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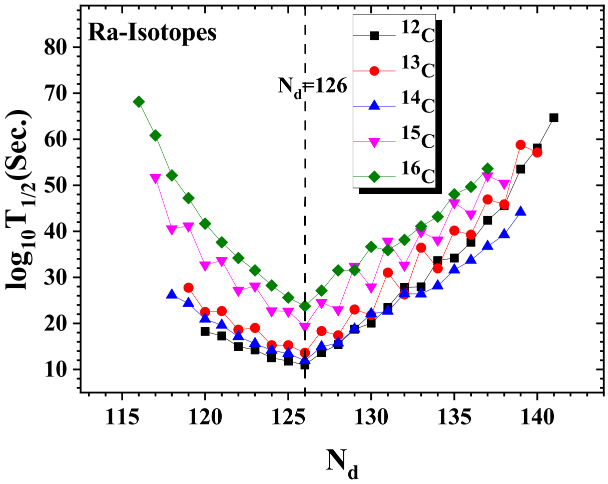

FIG. 1: Variation of half-lives of $^{12-16}$C cluster emissions from Ra isotopes (126≤N≤147) as a function of neutron number of daughter nuclei. These half-lives are calculated by using MUDL formula.

For this study, the logarithmic half-lives of unknown cluster emissions (isotopes of C) from Ra isotopes (126≤N≤147) are plotted in Fig. 1 (up to 10^{70} Sec.) where the minima correspond to ^{208}Pb daughter i.e., doubly magic (Z=82, N=126). These minima provide us the most probable clusters having chances of emission from the respective isotopes. Our main results (most probable clusters) are tabulated in Table I and are within the experimental reach, which are also found in the close match with the recent predictions of Refs. [12, 13].

TABLE I: The calculated logarithmic half-lives of highly probable clusters emitted from Ra isotopes (126≤N≤147) using MUDL formula.

Parent nucleus	Daughter nucleus	Emitted cluster	Q (MeV)	l	$\log_{10}T_{1/2}$ (Sec.)
^{220}Ra	^{208}Pb	^{12}C	32.13	0	10.98
^{221}Ra	^{208}Pb	^{13}C	31.70	3	13.63
^{222}Ra	^{208}Pb	^{14}C	33.16	0	11.90
^{223}Ra	^{208}Pb	^{15}C	29.22	2	19.38
^{224}Ra	^{208}Pb	^{16}C	26.99	0	23.75

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