Decay Properties of the Nuclei with Neutron Number N=126: A Stretch of the r-Process Pathway

A. Shrivastava[1] *, R. Sharma[2], and G. Saxena[3,4]
[1]*Dayalbagh Educational Institute, Agra - 282005, INDIA*
[2]*Department of Physics, S.S. Jain Subodh P.G.(Autonomous) College, Jaipur-302004, INDIA*
[3]*Department of Physics (H&S), Govt. Women Engineering College, Ajmer-305002, INDIA*
[4]*Department of Physics, Faculty of Science, University of Zagreb, Bijenička c. 32, 10000 Zagreb, Croatia*
** Email: shriapra@gmail.com*

The half-lives of neutron-rich nuclei on the astrophysical r-process path are of primary importance for its full understanding. The r-process description is also affected by various inputs of nuclear properties such as masses, β-decay rates, (n, γ) and (γ, n) reaction cross sections, etc. [1,2]. Scarce experimental data on r-process nuclei, contribute to the difficulties in understanding the astrophysical scenario. The Radioactive Ion Beam (RIB) facilities have enabled the production and measurement of several waiting-point nuclei directly on the r-process path from N=50 to N=82. From astrophysical point of view, the β-decay half-lives are much important for nuclei synthesis (thus star elements abundance) and evolution of stars. It is the competition between β-decay rates and neutron capture rates that determines by which way (rapid neutron capture process (r-process) or the slow neutron capture process (s-process)), the heavier nuclei in universe are produced. Thus, the β-decay half-lives of the waiting point nuclei are very important because it is the key to understand the third r-process peak of heavy nuclei with mass numbers A ~ 195.

The nuclei which are directly in the path of the r-process along N = 126, approximately from Gadolinium (Z=64) to tantalum (Z=73), could not be accessed experimentally yet. Nevertheless, one can try to measure neutron-rich nuclei in the higher Z neighborhood, on both sides of the N = 126 shell closure, and use such information as a benchmark for theoretical models. Nuclei around the waiting point nuclei are still completely unexplored. The present goal of this work is to estimate half-lives and decay modes of unknown isotones of N=126.

In the present work, inspired from recent experimental and theoretical studies on the nuclei with N=126, we have investigated the decay modes such as β^--decay, β^+/EC-decay, α-decay, Cluster Decay (CD) and Spontaneous Fission (SF) for N=126 isotones within the range 64≤Z≤98 by the calculation of half-lives using several empirical formulas.

For the weak decay we adopted an empirical formula given by Fiset and Nix [3] to estimate the β-decay half-lives, whereas for the α-decay half-lives we used QF formula [4]. Additionally, for the cluster decay and spontaneous fission we used UDL formula [5] and modified Bao formula [6], respectively.

Half-lives for electron capture and beta decay are calculated as:

$$T_{EC}(s) = \frac{9m_e^2}{2\pi(aZ_k)^{2s+1}\rho[Q_{EC}-(1-s)m_e]^3} \times \left(\frac{2R_0}{\hbar c/m_e}\right)^{2s+2} \times \frac{\Gamma(2s+1)}{1+s} \times 10^{6.5}$$

$$T_\beta(s) = \frac{540m_e^5}{\rho\left(w_\beta^6 - m_e^6\right)} \times 10^{5.0}$$

α-decay half-lives are calculated by the following formula:

$$\log_{10} T_{1/2}^{QF}(s) = a\sqrt{\mu}\left(\frac{Z^{0.6}}{\sqrt{Q_\alpha}}\right)^2 + b\sqrt{\mu}\left(\frac{Z^{0.6}}{\sqrt{Q_\alpha}}\right) + c + dl(l+1)$$

Cluster decay (CD) half-lives are obtained by:

$$\log_{10} T_{1/2}^{CD}(s) = aZ_cZ_d\sqrt{\frac{\mu}{Q}} + b\left[\mu Z_cZ_d\left(A_c^{\frac{1}{3}} + A_d^{\frac{1}{3}}\right)\right]^{\frac{1}{2}} + c$$

half-lives for spontaneous fission (SF) calculated by using the below expression:

$$\log_{10} T_{1/2}^{SF}(s) = c_1 + c_2\left(\frac{Z^2}{(1-kl^2)A}\right) + c_3\left(\frac{Z^2}{(1-kl^2)A}\right)^2 + c_4 E_{s+p}$$

Descriptions of these formulas are given in above mentioned references. For the Q-values we have used WS4 [7] mass model which has found with lesser root mean square error value compared to several other models as described in Ref. [8].

Table 1: Calculated EC half-lives (in seconds) for nuclei with Z=94-98 and N=126.

Z	A	Q_{EC}	$\log_{10}T_{EC}$
94	220	5.48	3.42
95	221	8.01	2.64
96	222	6.62	3.10
97	223	9.09	2.40
98	224	18.55	1.66

Table 2: Calculated β−decay half-lives (in seconds) for nuclei with Z=64-68 and N=126.

Z	A	Q_{β^-}	$\log_{10}T_{\beta^-}$
64	190	12.45	-0.39
65	191	13.69	-0.86
66	192	11.27	-0.14
67	193	12.50	-0.63
68	194	9.99	0.16

Table 1 and Table 2 indicate that the higher Q-value (MeV) corresponds to lower half-lives can help to deduce r-process nucleosynthesis in neutron-rich nuclei.

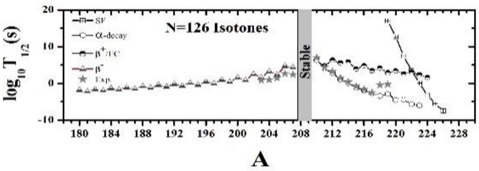

Fig. 1 The comparison of half-lives of β^-, EC, α decays and SF for N=126 isotones.

Fig.1 embedded with the half-lives of various decays which shows that the used empirical formulas agree well with the experimental half-lives. Towards neutron rich side, β^- decay dominates over any other decay where towards neutron deficient side there is a clear competition of EC with that of α-decay which needs further investigation. However, the chances of spontaneous fission are very unlikely due to its more half-life compared to other decays.

We have also found probable clusters such as He, Be, C, O, Ne, Mg, Si, S, Ar as well as heavy clusters such as ^{48}Ca, ^{56}Ti, ^{62}Cr, ^{68}Fe, ^{74}Ni and ^{80}Zn emitted from Parent nuclei ^{256}No, ^{264}Rf, ^{270}Sg, ^{276}Hs, ^{282}Ds, and ^{288}Cn respectively and

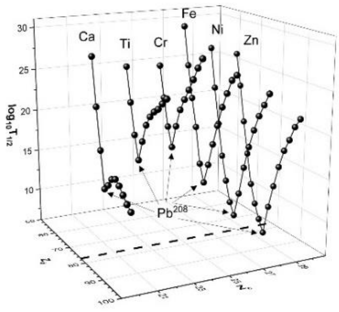

Fig. 2 Cluster decay half-lives for N=126 isotones as daughter nuclei for various mentioned clusters.

also found that minima of various decays correspond to daughter nuclei ^{208}Pb which is doubly magic nuclei (Z=82, N=126) as shown in fig.2. These half-lives of cluster decays are also compatible and require more attention on theoretical front.

In this paper we have calculated the half-lives to prove the competition between decay modes. The half-lives are found consistent with the experimental values, as a result various mentioned empirical formulas can be utilized to estimate half-lives for other unknown isotones of N=126. The prediction of the β−decay half-lives of some unknown neutron-rich nuclei in N=126 isotones are expected to be crucial for future nuclear and astrophysical studies, especially for the 3rd r-process peak.

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