Proton Radioactivity in the Medium Mass Region using an Empirical Formula

A. Jain[1,2],[*] Pranali Parab[3], G. Saxena[4], and Mamta Aggarwal[3]
[1]*Department of Physics, School of Basic Sciences, Manipal University Jaipur, Jaipur - 303007, India*
[2]*Department of Physics, St. Wilfred P.G. College, Jaipur-302020, India*
[3]*Department of Physics, University of Mumbai, Vidhyanagari, Mumbai, 400098, Maharashtra, India and*
[4]*Department of Physics (H&S), Govt. Women Engineering College, Ajmer - 305002, India*

Introduction

Proton radioactivity offers insights into nuclei beyond the proton drip line. To investigate ground-state proton emitters, focus is placed on nuclei with half-lives of few μs and larger, consistent with current techniques. Consequently, research has shifted toward heavier elements (Z > 50) [1]. Validating proton radioactivity experimentally is essential. An experiment investigating high-spin states in ^{119}Cs and ^{121}La, using ^{32}S to bombard a ^{92}Mo target, showed a prolate-to-oblate shape transition based on TRS calculations [2]. So, the region 50 < Z < 65 is crucial for proton emitters. Theoretically, proton decay half-lives can be estimated through several semi-empirical or analytical formulas and models [3].

The half-lives of proton radioactivity primarily depend on the disintegration energy (Q-value); however, nuclear deformation also plays a significant role, influencing the half-lives [4]. In this work, we have investigated proton radioactivity within the region 50 < Z < 65 using our newly fitted empirical formula [5]. While this formula was initially developed for 2p-radioactivity and accounts for nuclear deformation, it has demonstrated excellent performance in describing proton radioactivity, as discussed in this study. After validating the accuracy of this formula, we have applied it to predict the half-lives of unknown proton emitters. The experimental and theoretical data used in this analysis were sourced from NUBASE2020 [6] and the WS4 mass model [7], respectively.

*Electronic address: `jainakshay311@gmail.com`

Formalism

The proton and two-proton decay half-lives for various nuclei can be determined using a semi-empirical relation that explicitly incorporates the Q-value, reduced mass μ, angular momentum l and quadrupole deformation β. This relation is given as:

$$log_{10}T_{1/2} = a + b\sqrt{\mu}\sqrt{Z_d A^{1/3}} + c\sqrt{\mu}\left(\frac{Z_d}{\sqrt{Q}}\right) + d\sqrt{l(l+1)} + e|\beta|^p \quad (1)$$

In this expression, the parameters a, b, c, d, e, and p are assigned values of -9.3533, -0.0224, 0.0892, 0.0649, 35.8126 and 3, respectively. The symbols Z_d, A, and l represent the proton number of the daughter nucleus, the mass number of the parent nucleus, and the angular momentum carried by the emitted proton, respectively.

Results and discussion

To begin, we have validated our formula in the region 50 < Z < 65 for proton decay. Fig. 1 presents a comparison between the proton decay half-lives predicted by our formula and the experimental values for 11 potential proton emitters with the error bars. As evident in Fig. 1, all data points closely align with the experimental results, demonstrating the accuracy of our formula. As the mass number increases, the half-lives also increase, indicating that proton decay predominantly occurs in the lower mass region.

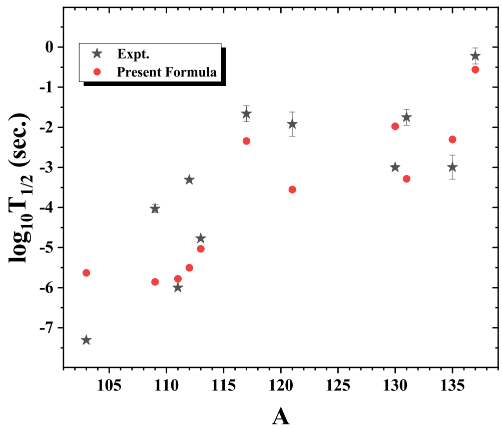

FIG. 1: Comparison of logarithmic half-lives of proton decay calculated by present formula (red circles) with the experimental data (black stars) for the region 50 < Z < 65. Error bars also mentioned.

In the subsequent phase of this study, we have extended our investigation to unexplored regions in the range 50 < Z < 65, located near the proton drip line. This exploration is purely theoretical, with data obtained from the WS4 mass model [7]. Through a systematic analysis, we have identified five potential proton emitters within this medium-mass region (50 < Z < 65). These nuclei exhibit prolate deformation, as reflected by their positive β values, and possess nonzero angular momentum. Notably, their calculated logarithmic half-lives are within reach of current experimental techniques, as demonstrated in Table I.

While the Q-value plays a dominant role in determining proton decay half-lives, the contributions of β and l cannot be overlooked. The l is calculated using the spin and parity assignments of the parent and daughter nuclei, which are extracted from NUBASE2020 [6] and the Ref. [8]. Angular momentum (l) is determined in accordance with the selection rules provided by Denisov *et al.* [9]. These factors, in combination, contribute to a comprehensive understanding of the proton decay process in this region.

Accurate prediction of proton decay half-lives aids in understanding nuclear structure and stability, especially near the drip line, where experimental data are often scarce.

TABLE I: Half-life of theoretical proton emitter candidates obtained using the present formula where Q_p and β taken from WS4 mass model [7]. The l is calculated by using spin and parity of parent and daughter nuclei,which are taken from NUBASE2020 [6] and from [8].

Proton Emitter	Q (MeV)	l	β	$\log_{10}T_{1/2}$ (sec.)
^{105}Sb	0.32	2	0.05	-1.76
^{115}Cs	0.20	4	0.19	2.20
^{118}La	0.55	1	0.25	-2.27
^{123}Pr	0.36	2	0.27	-0.40
^{139}Tb	0.24	1	0.22	2.15

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