Theoretical Investigation of Decay Properties of Nuclei

A. Jain[1]*
Supervisor: S. K. Jain[1]; Co-Supervisor: G. Saxena[2]
[1]*Department of Physics, School of Basic Sciences,*
Manipal University Jaipur, Jaipur - 303007, India and
[2]*Department of Physics (H&S), Govt. Women Engineering College, Ajmer - 305002, India*

In nature, an unstable nucleus attains stability by emitting basic decay particles such as α-particles [1], β-particles, protons, or even two-proton (2p) particles, or through nuclear fission. A newly recognized decay mode, known as cluster decay, serves as an intermediate process between α-decay and fission [2]. This phenomenon has been both theoretically predicted and experimentally confirmed in heavy nuclei. The lifetimes of all these mentioned decay modes can range from mere seconds to several years. One of the significant challenges in theoretical studies lies in accurately formulating models to describe both basic and exotic decays across a wide spectrum of nuclear masses, where lifetimes span such extreme durations.

In this thesis, an attempt has been made to address the challenges in studying decay modes by employing newly fitted or modified empirical and semi-empirical formulas. The non-linear least-squares fitting is performed using the Levenberg-Marquardt algorithm through the $scipy.optimize.curve_fit$ library, as described in Wood's work [3]. These formulas incorporate critical factors such as angular momentum (l), isospin (I), and deformation (β). Using these modified formulas, the logarithmic half-lives of various decay phenomena—including α decay, cluster decay, proton/2p decay, β decay, and spontaneous fission (SF)-are calculated. Additionally, the study explores several nuclear properties such as magicity, nuclear structure, radius, and density. This study has been done from light mass to superheavy region.

α-decay is a dominant mode for unstable medium, heavy, and superheavy nuclei (SHN). This study proposes a new four-coefficient formula (QF) based on 398 experimental values for α-decay. Additionally, three empirical formulas-Horoi, Sobiczewski, and Manjunatha-are modified by incorporating l and I dependnet terms (NMHF, NMSF, and NMMF) [4], showing excellent agreement with experimental half-lives for both favored and unfavored α-decays across all (Z, N) combinations. The QF formula predicted half-lives for 724 favored and 635 unfavored transitions using experimental Q-values [5], with significantly lower RMSE and mean deviation. Using precise WS4 mass model Q-values [6], probable α-decay chains for Z=120 isotopes are identified, and the NMHF, NMSF, and NMMF formulas predicted half-lives for Z=121–124 isotopes. The study also estimated α-decay half-lives from isomeric states in heavy and SHN. The calculated half-lives are found to closely match the experimental ranges, offering valuable insights for future experimental investigations into isomeric states.

Cluster decay is a rare but notable phenomenon, primarily observed in the trans-lead region. In this study, six widely used formulas for calculating cluster decay half-lives are modified, similar to the approach for α-decay, using a dataset of 61 experimental values for fitting. The modified formulas show reduced χ^2 per degree of freedom, lower RMSE, and improved statistical parameters compared to their original versions. Among these, the modified Balasubramaniam *et al.* (MBKAG) formula [7] is the most accurate. Using this improved formula, cluster decay half-lives for isotopes involving elements such as Be, B, C, N, O, F, Ne, Na, Mg, and Si are systematically

---

*Electronic address: `jainakshay311@gmail.com`

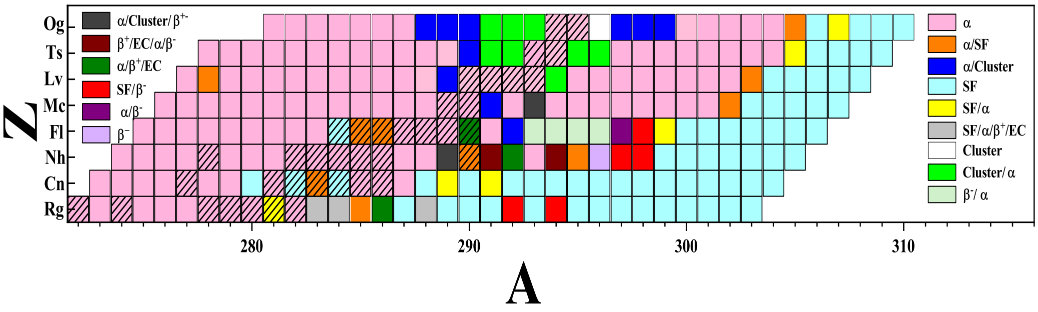

FIG. 1: A chart of the nuclei ($111 \leq Z \leq 118$), along with their likely decay modes.

predicted in the trans-lead region.

A refined relation, $(aZ_c + b)(Z_d/Q)^{1/2} + (cZ_c + d)$, has been developed for estimating half-lives of cluster and α-decays with the influence of I and l, named as ITM formula [8]. This formula accurately reproduces experimental half-lives in the trans-tin, trans-lead, and superheavy regions. A systematic study of isotopes with $56 \leq Z \leq 120$ shows strong competition among cluster emission, α-decay, SF, and β-decay, with notable emission of clusters from C to Sr, influenced by shell effects. The proposed formula effectively predicts half-lives across the periodic table, from trans-tin to SHN.

Proton emission is a radiative decay process where a proton is ejected from the nucleus, with proton and 2p-decay being key in the light mass region. This thesis presents a semi-empirical formula that predicts half-lives for known and potential proton and 2p emitters near the proton drip line, incorporating nuclear deformation for $Z < 82$. The formula accurately estimates measured values and reliably predicts other emitters. For proton-rich nuclei without experimental data, theoretical values from relativistic mean-field (RMF) calculations are used. Additionally, 2p-decay correlations with 2p-halo and deformation are explored, showing shape coexistence with a predominance of prolate shapes [10].

Finally, we have compared various decay modes to explore the potential for synthesizing new isotopes [9]. The study examines possible decay modes from the lower mass region to SHN, with Fig. 1 showcasing the results for $111 \leq Z \leq 118$ as a representative example. This research is crucial for advancing the understanding of astrophysical phenomena and guiding future experiments.

AJ acknowledges SERB for fellowship under the project CRG/2019/001851 and the ITS grant (ITS/2022/001826) to attend the research program in Spain. I sincerely appreciate the unwavering support provided by Manipal University Jaipur throughout my academic journey.

References

[1] Y.T. Oganessian, *et al.*: PRC **74**, 044602 (2006).

[2] R. Bonetti and A. Guglielmetti: Rom. Rep. Phys. **59**, 301 (2007).

[3] A. Matt Wood: ”Python and Matplotlib Essentials for Scientists and Engineers”, Morgan and Claypool Publishers (2015).

[4] P.K. Sharma *et al.*, NPA, **1016**, 122318 (2021).

[5] G. Saxena *et al.*, Phys. Scr. **96**, 125304 (2021).

[6] Ning Wang *et al.*, PLB **734**, 215 (2014).

[7] A. Jain *et al.*, NPA **1031**, 122597 (2023).

[8] G. Saxena and A. Jain, EPJA **59**, 189 (2023).

[9] A. Jain *et al.*, Phys. Scr. **98**, 085304 (2023).

[10] G. Saxena *et al.*, JPG **50** 015102 (2023).