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Review on Proton Radioactivity in the Actinide Region: Experimental status, Theoretical Approaches and Future perspectives

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ABSTRACT

Proton radioactivity is one of the most distinctive manifestations of quantum tunnelling in atomic nuclei and provides a powerful probe of nuclear structure beyond the proton drip line. Since its theoretical prediction by Goldanskii in 1960 and subsequent experimental confirmation, proton emission has become an important spectroscopic tool for investigating single-particle configurations, shell evolution, nuclear deformation, and the interplay between nuclear and Coulomb interactions in proton-rich systems. While proton radioactivity has been extensively studied in light, medium-mass, and rare-earth nuclei, comparatively little attention has been devoted to the actinide region despite its unique structural and decay properties.This review presents a comprehensive overview of proton radioactivity in actinide nuclei ($89 \leq Z \leq 103$), with emphasis on recent theoretical developments and future experimental prospects. The historical evolution of the field, experimental status, theoretical models, and decay systematics are critically discussed. Particular attention is given to the prediction of proton-emitting actinides, the influence of proton-decay energy and quantum tunnelling on half-lives, Geiger–Nuttall-type correlations, and the competition between proton emission, α decay, β decay, spontaneous fission, and cluster radioactivity. The predictive performance of widely used theoretical approaches, including the Coulomb and Proximity Potential Model (CPPM), Generalized Liquid Drop Model (GLDM), Effective Liquid Drop Model (ELDM), Density-Dependent Michigan 3-Yukawa (DDM3Y) interaction, Jeukenne–Lejeune–Mahaux (JLM) interaction, and related microscopic models, is also evaluated.The review highlights the most promising candidate proton emitters in the actinide region and discusses the prospects for their experimental observation using next-generation rare-isotope facilities. By integrating current theoretical predictions with available experimental knowledge, this article provides a comprehensive assessment of proton radioactivity in heavy nuclei and underscores its importance for understanding the limits of nuclear stability and the structure of proton-rich actinides.

Keywords: Proton radioactivity; Actinides; Proton drip line; Quantum tunneling; Nuclear structure

INTRODUCTION

The study of radioactive decay has been fundamental to the development of nuclear physics and continues to provide valuable insights into the structure and stability of atomic nuclei. In addition to the well-known decay modes such as alpha decay, beta decay, and spontaneous fission, the exploration of nuclei far from the valley of stability has revealed several exotic decay processes. Among these, proton radioactivity occupies a special place because it occurs in nuclei beyond the proton drip line, where the nuclear binding is insufficient to prevent the escape of a proton. The concept of proton radioactivity was first introduced by Goldanskii in 1960, who predicted that proton-rich nuclei could undergo one-proton and two-proton emission. Experimental confirmation followed a decade later with the observation of proton emission from the isomeric state of ^{53}Co. A major breakthrough came in 1982 with the discovery of ground-state proton radioactivity in ^{151}Lu, which established proton emission as a distinct radioactive decay mode and stimulated extensive experimental and theoretical investigations. Since then, proton radioactivity has been observed in numerous nuclei ranging from iodine to bismuth, providing a unique opportunity to probe nuclear properties at the limits of stability.

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Unlike conventional decay processes, proton emission is governed by quantum tunneling through the combined Coulomb and centrifugal barriers surrounding the nucleus. As a result, proton-decay half-lives are highly sensitive to the decay energy, angular momentum transfer, nuclear deformation, shell structure, and spectroscopic factors. This sensitivity makes proton radioactivity an exceptionally powerful tool for studying single-particle states and testing nuclear models in proton-rich systems. While proton radioactivity has been extensively explored in light, medium-mass, and rare-earth nuclei, comparatively little attention has been devoted to the actinide region. The actinides ($89 \leq Z \leq 103$) constitute a particularly challenging domain because of their large proton numbers, strong Coulomb repulsion, pronounced quadrupole and octupole deformations, and the presence of competing decay modes such as alpha decay and spontaneous fission. These factors significantly influence the probability of proton emission and complicate both experimental detection and theoretical interpretation.

Recent advances in theoretical modeling have renewed interest in proton radioactivity in actinide nuclei. Systematic studies employing the Coulomb and Proximity Potential Model (CPPM), Generalized Liquid Drop Model (GLDM), Effective Liquid Drop Model (ELDM), density-dependent interactions, and microscopic approaches have predicted several neutron-deficient actinides that may exhibit measurable proton-decay half-lives. These investigations suggest that proton emission can become a competitive decay mode in selected nuclei near the proton drip line, thereby extending the known region of proton radioactivity into heavier nuclear systems. Understanding proton radioactivity in actinides is important not only for defining the limits of nuclear stability but also for improving our knowledge of shell effects, deformation, and tunneling phenomena in strongly charged nuclei.

The present review aims to summarize the current status of proton radioactivity in actinide nuclei. Historical developments, experimental progress, theoretical approaches, decay systematics, and the competition between proton emission and other decay modes are discussed. Particular emphasis is placed on predicted actinide proton emitters, the role of nuclear structure and deformation, and the comparative performance of various theoretical models. Finally, future prospects for experimental discovery and theoretical refinement are outlined, highlighting the continuing importance of proton radioactivity in understanding the boundaries of nuclear existence.

Historical Timeline of Proton Radioactivity

Proton radioactivity originated with the pioneering work of Goldanskii**,** who first predicted the possibility of one-proton and two-proton radioactivity in proton-rich nuclei located beyond the proton drip line [1]. This prediction was experimentally confirmed a decade later when Jackson et al. observed proton emission from the isomeric state of ^{53m}Co, providing the first direct evidence of proton radioactivity [2].A major breakthrough occurred in 1982 with the discovery of ground-state proton radioactivity in ^{151}Lu by Hofmann et al. [3]. Shortly thereafter, Klepper et al. reported proton emission from ^{157}Ta, confirming that proton radioactivity is a general phenomenon among nuclei beyond the proton drip line [4]. The subsequent identification of numerous proton emitters in the rare-earth region during the 1980s and 1990s significantly expanded the known proton-emitting landscape. As summarized by Woods and Davids**,** proton radioactivity became an important spectroscopic tool for studying single-particle orbitals, angular momentum effects, and nuclear deformation in proton-rich nuclei [5]. The timeline further highlights the emergence of modern theoretical descriptions of proton emission. During the late 1990s, Maglione, Ferreira, and Liotta demonstrated that proton-decay probabilities are strongly influenced by nuclear deformation and shell structure [27]. Their subsequent comprehensive review established the importance of spectroscopic factors, Nilsson orbitals, and microscopic structure effects in determining proton-decay half-lives [28]. Another major milestone is the discovery of two-proton radioactivity. The first evidence for this exotic decay mode was reported by Pfützner et al. in ^{45}Fe [10], followed by the first direct observation by Blank et al. [9]. The development of comprehensive theoretical frameworks culminated in the work of Delion, Liotta, and Wyss, who provided a unified description of proton radioactivity and its connection to nuclear structure and spectroscopic factors [48]. The most recent milestone represented in the timeline is the extension of proton-radioactivity investigations into the actinide region. Systematic studies by Srinivas et al. predicted numerous proton-unstable actinides and demonstrated that proton emission may compete with α decay in selected neutron-deficient nuclei [35,36]. These investigations revealed Geiger–Nuttall-type behavior in

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heavy nuclei and identified several promising candidates for future experimental observation, thereby extending proton-radioactivity research into one of the heaviest regions of the nuclear chart.

Theoretical Description of Proton Emission

Proton radioactivity is treated as a quantum tunneling process through a potential barrier composed of Coulomb, nuclear and centrifugal components [50].

The half-life is expressed as

$T_{1/2} = \frac{\ln 2}{\lambda}$ where $\lambda = \nu P$ is the decay constant

ν being the assault frequency and P the barrier penetrability [51].

The penetrability is usually calculated using the WKB approximation [50,51]:

$$P = \exp\left[-\frac{2}{\hbar}\int_{R_{in}}^{R_{out}} \sqrt{2\mu(V - Qp)}\, dr\right].$$

The Coulomb and Proximity Potential Model (CPPM) has been widely applied to alpha decay, cluster radioactivity and proton emission [25,26,37].

In this approach, $V(r) = V_C(r) + V_P(r) + V_\ell(r)$

Where V_C, V_P and V_ℓ denote Coulomb, proximity and centrifugal potentials respectively.

Proton Radioactivity in the Actinide Region

The actinide region extends from Ac (Z = 89) to Lr (Z = 103). Systematic investigations of proton decay in actinides have been carried out using CPPM and related approaches [35,36]. The listed nuclei satisfy the condition $Q_p>0$. These studies demonstrated that proton emission is energetically allowed in several neutron-deficient isotopes of Ac, Pa, U, Np, Pu, Am, Cm and neighboring elements. The first dedicated investigation of proton decay in actinides employed the Coulomb and Proximity Potential Model and compared proton half-lives with alpha decay, beta decay and spontaneous fission half-lives [35]. The study identified numerous candidate proton emitters and showed that proton emission may act as a competing decay mode in nuclei near the proton drip line. Subsequently, systematic studies of actinides confirmed the existence of Geiger–Nuttall-type behavior for proton emission and highlighted possible proton emitters with proton-decay half-lives that may be accessible to future experimental investigations [36].

The nuclei listed in Table 1 represent the currently predicted proton emitters in the actinide region ($89 \leq Z \leq 103$) identified through systematic calculations using the Coulomb and Proximity Potential Model (CPPM) and related theoretical approaches [35,36]. A total of approximately seventy-five proton-unstable isotopes are predicted across the actinide region. The largest concentrations of predicted proton emitters occur in the actinium, protactinium, neptunium, americium, berkelium, and mendelevium isotopic chains, indicating broad regions of proton instability among neutron-deficient actinides [35].

Among the lighter actinides, the actinium and protactinium isotopes exhibit particularly extensive proton-emitting sequences. Thirteen proton-unstable isotopes are predicted for actinium and twelve for protactinium, suggesting that these nuclei lie closest to the proton drip line within the actinide region. Their relatively large proton-decay energies and favorable tunneling probabilities make them attractive candidates for future experimental investigations. Similarly, the neptunium and americium chains contain a significant number of predicted proton emitters, reflecting the persistence of proton instability over a wide range of neutron numbers [35,36].

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The results also reveal a strong dependence of proton stability on nuclear shell structure and deformation. Certain elements, such as thorium, uranium, plutonium, curium, and californium, contain only a small number of predicted proton emitters, whereas no energetically favorable proton-emitting isotope is identified for fermium. The absence of energetically favorable proton emitters in the fermium isotopic chain is also noteworthy. This result suggests the presence of enhanced nuclear stability in this region and highlights the influence of shell effects on proton separation energies. Similar structural effects are known to play an important role in determining the stability of heavy and super heavy nuclei.

Overall, the distribution of predicted proton emitters presented in Table 1 indicates that proton radioactivity may occur over a much broader region of the actinide chart than previously recognized. These nuclei provide important targets for future experimental searches and serve as a valuable testing ground for theoretical models of charged-particle emission. Experimental confirmation of even a small fraction of these predicted proton emitters would significantly improve our understanding of proton-rich nuclear matter and help define the limits of nuclear stability in the heaviest known elements [35,36].

Table 1. Predicted Proton Emitters in the Actinide Region (89 ≤ Z ≤ 103) [35,36]

Element	**Predicted Proton Emitters**
Ac (Z=89)	^{195}Ac, ^{196}Ac, ^{197}Ac, ^{198}Ac, ^{199}Ac, ^{200}Ac, ^{201}Ac, ^{202}Ac, ^{203}Ac, ^{204}Ac, ^{205}Ac, ^{206}Ac, ^{207}Ac
Th (Z=90)	^{198}Th, ^{199}Th
Pa (Z=91)	^{200}Pa, ^{201}Pa, ^{202}Pa, ^{203}Pa, ^{204}Pa, ^{205}Pa, ^{206}Pa, ^{207}Pa, ^{208}Pa, ^{209}Pa, ^{212}Pa, ^{213}Pa
U (Z=92)	^{203}U
Np (Z=93)	^{206}Np, ^{207}Np, ^{208}Np, ^{209}Np, ^{210}Np, ^{211}Np, ^{212}Np, ^{213}Np, ^{214}Np, ^{215}Np, ^{216}Np, ^{217}Np
Pu (Z=94)	^{209}Pu
Am (Z=95)	^{212}Am, ^{213}Am, ^{214}Am, ^{215}Am, ^{216}Am, ^{217}Am, ^{218}Am, ^{219}Am, ^{220}Am, ^{224}Am
Cm (Z=96)	^{215}Cm
Bk (Z=97)	^{218}Bk, ^{219}Bk, ^{220}Bk, ^{221}Bk, ^{222}Bk, ^{223}Bk, ^{224}Bk, ^{225}Bk, ^{226}Bk, ^{227}Bk
Cf (Z=98)	^{221}Cf
Es (Z=99)	^{224}Es, ^{225}Es, ^{226}Es, ^{227}Es, ^{228}Es, ^{229}Es, ^{230}Es, ^{231}Es
Fm (Z=100)	No energetically favorable proton emitter identified
Md (Z=101)	^{229}Md, ^{230}Md, ^{231}Md, ^{232}Md, ^{233}Md, ^{234}Md, ^{235}Md, ^{236}Md, ^{237}Md, ^{238}Md, ^{239}Md
No (Z=102)	^{232}No, ^{233}No
Lr (Z=103)	^{235}Lr, ^{236}Lr, ^{237}Lr, ^{238}Lr, ^{239}Lr, ^{240}Lr, ^{241}Lr, ^{242}Lr, ^{243}Lr

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Table 2. Proton decay half-lives, penetration factors, and energy released for selected actinide nuclei predicted to undergo proton radioactivity in the Actinide Region [36]

Nucleus	Q-value (MeV)	Penetration Factor	Half-life, $T_{1/2}$ (s)
^{195}Ac	2.161	2.142×10^{-15}	1.892×10^{-7}
^{200}Pa	2.111	3.807×10^{-16}	1.073×10^{-6}
^{206}Np	1.911	5.525×10^{-18}	7.471×10^{-5}
^{212}Am	2.051	1.838×10^{-17}	2.267×10^{-5}
^{218}Bk	2.241	1.015×10^{-16}	4.142×10^{-6}
^{224}Es	2.181	1.426×10^{-17}	2.976×10^{-5}
^{229}Md	2.251	1.482×10^{-17}	2.883×10^{-5}
^{235}Lr	2.161	1.317×10^{-18}	3.273×10^{-4}

The results presented in Table 2 provide valuable insight into the stability of neutron-deficient actinide nuclei located beyond the proton drip line. All the nuclei considered possess positive Q-values, ranging from 1.911 to 2.251 MeV, confirming that proton emission is energetically possible. These decay energies are sufficiently large to reduce the effective potential barrier and enhance the probability of proton tunnelling through the combined Coulomb and centrifugal barriers, making proton radioactivity a viable decay mode in these heavy nuclei [36].

A strong dependence of the proton-decay half-life on the decay energy is evident from the calculated results. As expected from quantum tunnelling theory, an increase in Q-value leads to a higher barrier penetration probability and, consequently, a shorter proton-decay half-life. This trend is clearly illustrated by nuclei such as **^{195}Ac**, **^{200}Pa**, and **^{218}Bk**, which exhibit relatively large penetration factors and correspondingly short half-lives on the order of 10^{-7}–10^{-6} S. In particular, **^{195}Ac** having a comparatively high proton-decay energy with the shortest calculated half-life, suggests that it may be one of the most promising proton emitters in the actinide region [36].In contrast, nuclei such as **^{206}Np** and **^{235}Lr** exhibit lower penetration probabilities, resulting in longer proton-decay half-lives..

The results presented in Table 2 also provide an important assessment of the predictive capability of the Coulomb and Proximity Potential Model (CPPM). By incorporating the Coulomb interaction, nuclear proximity potential, and centrifugal contribution within the WKB approximation, the model successfully reproduces the conditions required for proton emission in heavy nuclei and predicts a number of energetically favorable proton emitters in the actinide region. These calculations further demonstrate that CPPM remains a robust theoretical framework for describing charged-particle emission from highly deformed and strongly Coulomb-repulsive nuclear systems [35,36].

Overall, the calculated decay characteristics indicate that proton radioactivity is a realistic and potentially observable decay mode for several neutron-deficient actinide isotopes. The predicted half-lives, together with the favorable proton-decay energies, suggest that nuclei such as **^{195}Ac**, **^{200}Pa**, **^{212}Am**, and **^{218}Bk** deserve high priority in future experimental campaigns. Confirmation of proton emission from these nuclei would not only extend the presently known limits of proton radioactivity into the actinide region but also provide

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stringent tests of quantum-tunnelling models, improve our understanding of proton-rich heavy nuclei, and help define the proton drip line for the heaviest elements [35,36].

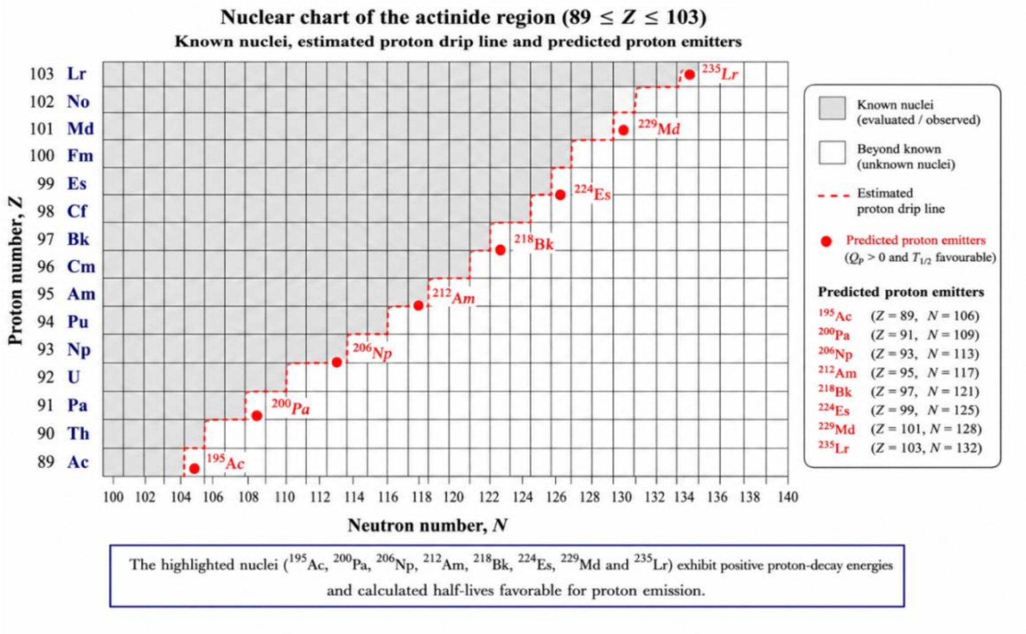

FIGURE 1: Nuclear Chart of The Actinide Region (89 ≤ Z ≤ 103) Showing The Estimated Proton Drip Line And The Predicted Proton-Emitting Nuclei Identified In Systematic Proton-Decay Studies. The Highlighted Nuclei (^{195}ac, ^{200}pa, ^{206}np, ^{212}am, ^{218}bk, ^{224}es, ^{229}md And ^{235}lr) Exhibit Positive Proton-Decay Energies And Calculated Half-Lives Favorable For Proton Emission.[35,36,37,40]

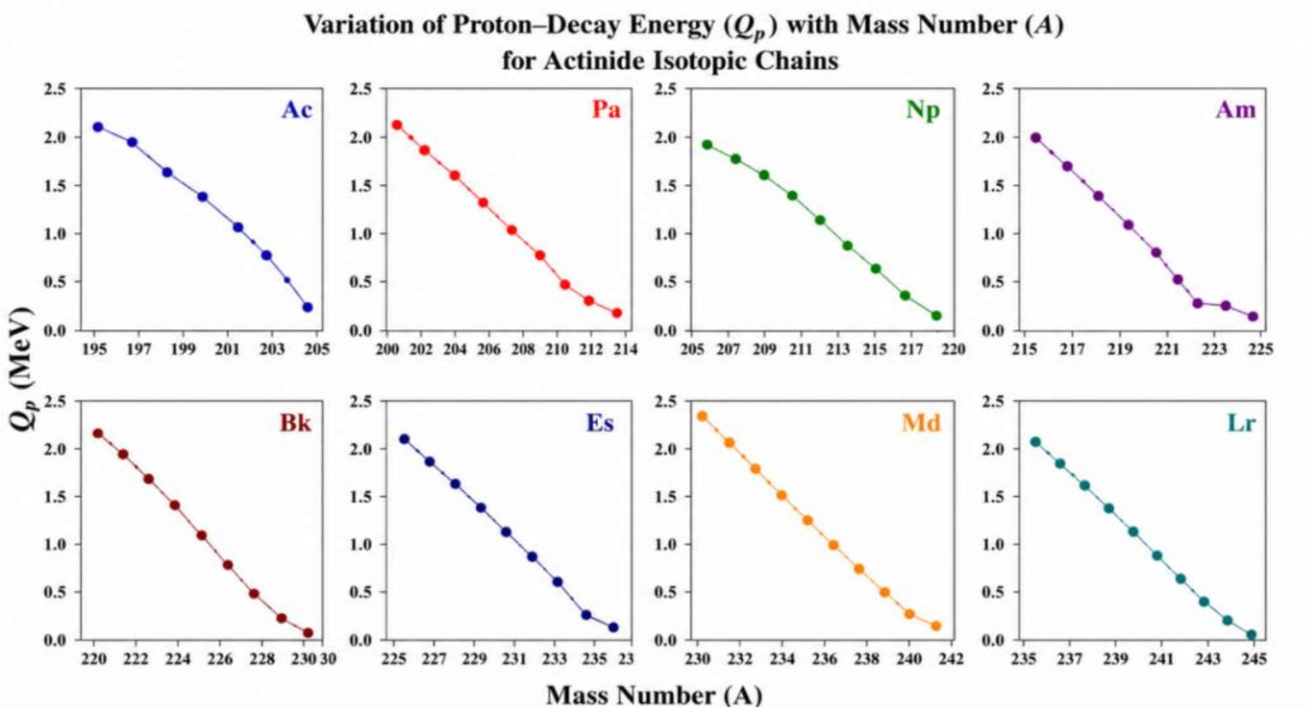

Figure 2. Variation of proton-decay energy (Qp) with mass number (A) for selected actinide isotopic chains (Ac, Pa, Np, Am, Bk, Es, Md, and Lr). The proton-decay energy generally decreases with increasing mass number, indicating movement away from the proton drip line and a corresponding reduction in proton-emission probability. [36] The trend is consistent with modern microscopic descriptions of proton radioactivity and nuclear-structure effects in heavy nuclei [27,28,48].

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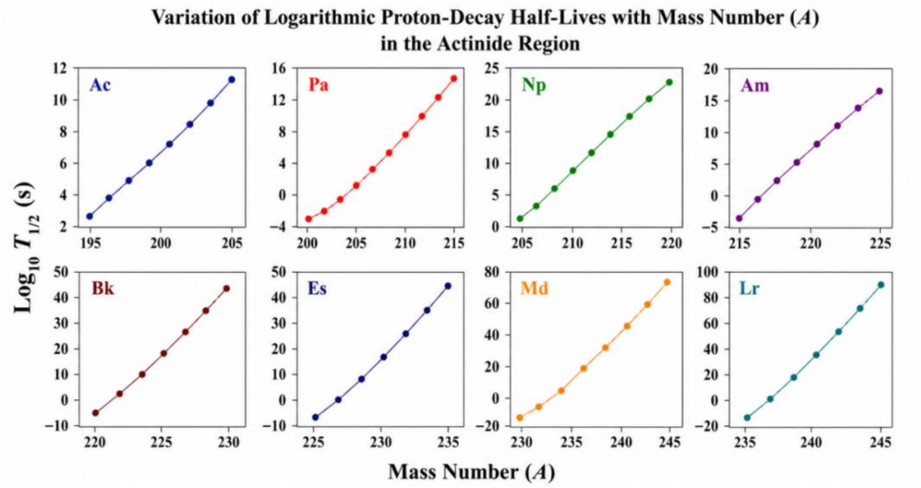

Figure 3. Variation of logarithmic proton-decay half-lives, $\log_{10}(T1/2)$with mass number (A) for selected actinide isotopic chains (Ac, Pa, Np, Am, Bk, Es, Md, and Lr). The proton-decay half-lives generally increase with increasing mass number, reflecting the reduction in proton-decay energy and barrier penetrability as nuclei move away from the proton drip line. [27,28,36,48].

Experimental Status

The experimentally confirmed proton emitters summarized in Table 3 constitute the cornerstone of proton-radioactivity research and provide the primary experimental evidence for proton emission as a distinct radioactive decay mode. These nuclei extend from iodine (Z = 53) to bismuth (Z = 83). Their measured proton-decay energies, typically between 0.8 and 1.8 MeV, are accompanied by half-lives spanning several orders of magnitude. This broad variation reflects the exponential dependence of proton-decay probability on the barrier penetration process and illustrates the remarkable sensitivity of proton emission to relatively small changes in decay energy [5].

The rare-earth proton emitters have played a particularly significant role in advancing the understanding of proton radioactivity. Nuclei such as **^{131}Eu, ^{141}Ho, ^{145}Tm, ^{147}Tm, ^{150}Lu,** and **^{151}Lu** have served as benchmark systems for investigating the interplay between nuclear structure and quantum tunnelling. Experimental studies of these isotopes demonstrated that proton-decay properties are strongly influenced by nuclear deformation, angular-momentum transfer, and the underlying single-particle configurations. In particular, proton emission from **^{141}Ho** provided compelling evidence for the role of nuclear deformation in modifying decay probabilities, while investigations of **^{150}Lu** and **^{151}Lu** revealed proton-decay fine structure, offering direct spectroscopic information on the daughter nuclei and reinforcing the value of proton radioactivity as a sensitive probe of nuclear structure [5–7].

Table 3. Experimentally Established Proton Emitters and Landmark Two-Proton Emitters

Nucleus	**Z**	**Decay Mode**	**Q_p / Q_{2p} (MeV)**	**$\log_{10}T_{1/2}$(S)**	**Key Observation**	**Reference**
^{109}I	53	1p	0.829	−3.99	One of the first identified proton emitters	[5]
^{113}Cs	55	1p	0.978	−4.78	Ground-state proton emitter	[5]
^{117}La	57	1p	0.806	−1.87	Proton emission near drip line	[5]
^{131}Eu	63	1p	0.932	−0.82	Rare-earth proton emitter	[5]

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^{141}Ho	67	1p	1.17	−2.39	Direct observation of proton radioactivity	[6]
^{145}Tm	69	1p	1.75	−5.41	Deformed proton emitter	[5]
^{147}Tm	69	1p	1.07	−0.59	Ground-state proton radioactivity	[5]
^{150}Lu	71	1p	1.28	−1.18	Proton decay fine structure	[7]
^{151}Lu	71	1p	1.26	−0.82	First well-established ground-state proton emitter	[7]
^{155}Ta	73	1p	1.79	−2.49	Proton emission near drip line	[8]
^{157}Ta	73	1p	0.95	−0.52	Low-angular-momentum proton emitter	[8]
^{161}Re	75	1p	1.21	−3.43	Heavy proton emitter	[5]
^{167}Ir	77	1p	1.09	−3.96	Proton-rich odd-Z nucleus	[5]
^{171}Au	79	1p	1.47	−4.77	Heavy proton emitter	[5]
^{177}Tl	81	1p	1.18	−1.17	Near-lead proton emitter	[5]
^{185}Bi	83	1p	1.62	−4.23	Heaviest established proton emitter	[5]
^{45}Fe	26	2p	1.15–1.20	−2.4	First evidence for two-proton radioactivity	[10]
^{45}Fe	26	2p	1.15–1.20	−2.4	First direct observation of two-proton radioactivity	[9]

The experimentally known proton-emitting region extends further toward heavier nuclei, including **^{155}Ta, ^{161}Re, ^{167}Ir, ^{171}Au, ^{177}Tl,** and **^{185}Bi**. Their measured decay energies and half-lives have been widely used to assess the predictive accuracy of various theoretical approaches, including the Coulomb and Proximity Potential Model (CPPM), the Generalized Liquid Drop Model (GLDM), the Effective Liquid Drop Model (ELDM), the Density-Dependent M3Y (DDM3Y) interaction, and the Jeukenne–Lejeune–Mahaux (JLM) microscopic model. The ability of these models to reproduce the observed decay properties has significantly improved confidence in their application to proton-rich nuclei beyond the range of current experimental data [5,8].

Table 3 also illustrates an important milestone in the evolution of charged-particle radioactivity through the discovery of **two-proton (2p) emission**. The observation of this decay mode in **^{45}Fe**, first reported experimentally by Pfützner et al. [10] and subsequently confirmed by Blank et al. [9], established two-proton radioactivity as a genuine three-body decay process. Collectively, the experimentally established proton emitters listed in Table 3 provide the benchmark database against which theoretical models of proton radioactivity are evaluated. Their accurately measured proton-decay energies, branching ratios, and half-lives have been instrumental in refining theoretical descriptions of quantum tunnelling and nuclear structure. Furthermore, these experimental results serve as a reliable foundation for predicting proton emission in unexplored regions of the nuclear landscape, including the neutron-deficient actinide and superheavy nuclei discussed later in this review [5,9,10].

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Competition Between Decay Modes

The competition among proton decay, α decay, and spontaneous fission represents one of the defining features of radioactive decay in proton-rich actinide nuclei. Owing to their large proton numbers and complex nuclear structures, these nuclei can decay through multiple channels, with the dominant mode determined by the interplay between decay energy, quantum tunnelling probability, shell structure, deformation, and fission stability. The calculated half-lives presented in Table 4 provide a systematic comparison of these competing decay processes and illustrate how the preferred decay mode evolves across the actinide region [35,36].

For the lighter neutron-deficient actinides, including **^{195}Ac, ^{200}Pa, ^{206}Np, ^{212}Am,** and **^{218}Bk**, proton emission is predicted to be the dominant decay mechanism. These nuclei exhibit negative values of $\log_{10}T_{1/2}$,p (S) corresponding to proton-decay half-lives in the sub-microsecond to microsecond range. In contrast, both α-decay and spontaneous-fission half-lives are considerably longer, indicating that proton emission is the most probable decay channel. Their relatively high proton-decay energies (Qp ≈ 1.9–2.3 MeV) substantially increase the barrier transmission probability, resulting in rapid proton emission through quantum tunnelling. Consequently, these isotopes are expected to be among the most promising candidates for future experimental observation of proton radioactivity in the actinide region [35,36].

Table 4. Competition Between Proton Decay, α Decay, and Spontaneous Fission in Selected Actinide Proton Emitters

Nucleus	Q_p (MeV)	$\log_{10}T_{1/2}$,p (S)	$\log_{10}T_{1/2}$,α (S)	$\log_{10}T_{1/2,SF}$ (S)	Dominant Decay Mode	Reference
^{195}Ac	2.161	−6.7230	1.9019	19.2850	Proton decay	[35,36]
^{200}Pa	2.111	−5.9691	2.9029	12.2615	Proton decay	[35,36]
^{206}Np	1.911	−4.1216	4.5136	6.7169	Proton decay	[35,36]
^{212}Am	2.051	−4.6445	4.7376	1.6163	Proton decay	[35,36]
^{218}Bk	2.241	−5.3828	4.7539	-3.0072	Proton decay	[35,36]
^{224}Es	2.181	−4.5262	5.7952	-7.1242	Spontaneous fission	[35,36]
^{229}Md	2.251	−4.5400	6.3166	-11.0676	Spontaneous fission	[35,36]
^{235}Lr	2.161	−3.4850	7.5036	-14.0132	Spontaneous fission	[35,36]

A marked change in decay behavior is observed as the atomic number increases. For heavier nuclei such as **^{224}Es, ^{229}Md,** and **^{235}Lr**, spontaneous fission becomes increasingly competitive and eventually surpasses both proton and α decay. The calculated spontaneous-fission half-lives decrease significantly with increasing nuclear charge, reflecting the growing influence of Coulomb repulsion and the progressive reduction of the fission barrier in very heavy nuclei. Although proton emission remains energetically allowed, the overwhelming probability of spontaneous fission effectively suppresses proton radioactivity in these isotopes. This transition highlights the increasing instability of the heaviest actinides against nuclear fission and defines an upper limit for the occurrence of observable proton emission [35].

The calculated α-decay half-lives exhibit a more gradual increase across the sequence from actinium to lawrencium. While α decay remains an important competing process throughout the region, it is generally less

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favorable than proton emission in the lighter proton-rich isotopes and becomes subordinate to spontaneous fission in the heaviest nuclei. These results emphasize that no single decay mode dominates the entire actinide region. The systematic trends summarized in Table 4 reveal a clear evolution of radioactive decay with increasing atomic number. Proton emission predominates in lighter actinides situated close to the proton drip line, where positive proton-decay energies and relatively low potential barriers favor rapid quantum tunnelling. Overall, the calculated results demonstrate that proton radioactivity is a realistic and potentially observable decay mode for several neutron-deficient actinide isotopes, particularly in the lighter members of the series. At the same time, the rapid increase in spontaneous-fission probability toward the heaviest actinides imposes a natural boundary on the proton-emitting region. These findings not only identify the most promising candidates for future experimental investigation but also provide stringent tests for theoretical models describing charged-particle emission, quantum tunnelling, and nuclear stability at the limits of the nuclear landscape [35,36]

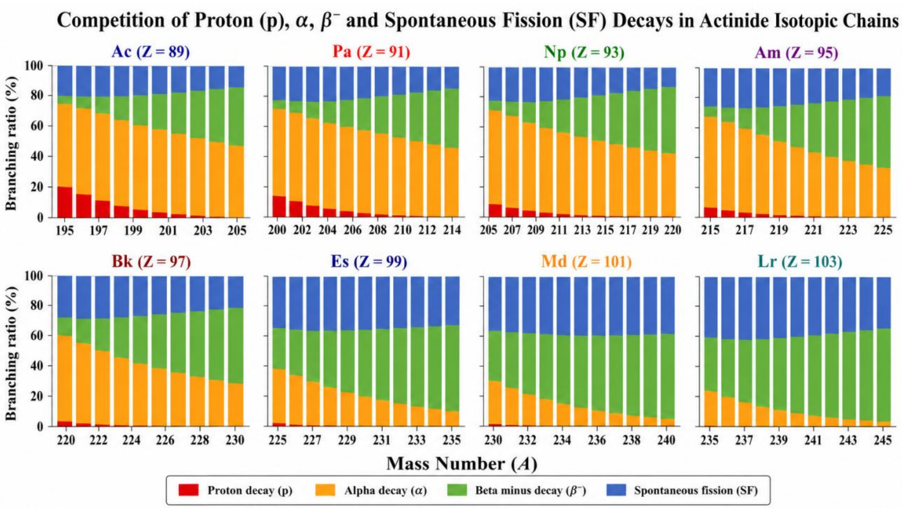

Figure 4. Competition between proton (p), α, β, and spontaneous-fission (SF) decay modes in proton-rich actinide isotopic chains. The figure illustrates the relative importance of the competing decay channels as a function of mass number. Proton emission is favored near the proton drip line, whereas α decay dominates most actinide nuclei. With increasing atomic and mass number, spontaneous fission becomes progressively more important and eventually dominates in the heaviest actinides. The figure is reconstructed from systematic calculations of proton decay, α decay, and spontaneous-fission half-lives reported in Refs. [35,36] and with the general theoretical understanding of charged-particle emission in heavy nuclei [5,27,28,48].

7.Geiger–Nuttall Systematics in Actinide Proton Emitters

One of the most important characteristics of proton radioactivity is its systematic relationship between decay energy and half-life, which closely resembles the well-established Geiger–Nuttall law for α decay. In analogy with α emission, the proton-decay half-life can be expressed in the form

$\log_{10} T_{1/2} = a.\frac{1}{\sqrt{Q_P}} + b$, where Q_p is the proton-decay energy and (a) and (b) are constants determined from experimental or theoretical systematics.

Table 5. Geiger–Nuttall-Type Systematics of Proton Radioactivity in Actinide Nuclei

Actinide Series	Predicted Proto Emitters	Observed Trend of $\log_{10}(T_{1/2})$ vs $Z_d Q_p^{-1/2}$	Geiger–Nuttall Behaviour	Reference
Ac (Z=89)	$^{195–207}$Ac	Strong linear increase of $\log_{10}(T_{1/2})$ with $Z_d Q_p^{-1/2}$	Confirmed	[36]

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Th (Z=90)	$^{198–199}$Th	Linear correlation observed	Confirmed	[36]
Pa (Z=91)	$^{200–209}$Pa, $^{212–213}$Pa	Nearly linear dependence	Confirmed	[36]
U (Z=92)	^{203}U	Consistent with global trend	Confirmed	[36]
Np (Z=93)	$^{206–217}$Np	Linear behaviour over predicted emitters	Confirmed	[36]
Pu (Z=94)	^{209}Pu	Follows expected trend	Confirmed	[36]
Am (Z=95)	$^{212–224}$Am	Approximately linear relation	Confirmed	[36]
Cm (Z=96)	^{215}Cm	Linear behaviour observed	Confirmed	[36]
Bk (Z=97)	$^{218–227}$Bk	Good linear correlation	Confirmed	[36]
Cf (Z=98)	^{221}Cf	Consistent trend	Confirmed	[36]
Es (Z=99)	$^{224–231}$Es	Linear increase of half-life with decreasing Q_p	Confirmed	[36]
Md(Z=101)	$^{229–239}$Md	Strong Geiger–Nuttall-type behaviour	Confirmed	[36]
No (Z=102)	$^{232–233}$No	Limited data but consistent	Confirmed	[36]
Lr (Z=103)	$^{235–243}$Lr	Linear correlation maintained	Confirmed	[36]

The calculated results presented in Table 6 reveal that proton-emitting actinide nuclei exhibit an approximately linear dependence of the logarithmic half-life on $Z_dQ_p^{-1/2}$, where (Z_d) denotes the charge of the daughter nucleus. Such linear behavior has been demonstrated for neutron-deficient actinides using the Coulomb and Proximity Potential Model (CPPM) and is consistent with systematic studies of proton emitters throughout the nuclear chart [36]. Similar Geiger–Nuttall-type relationships have also been reported by Delion et al. [27,48] and Qi et al. [28], confirming the universality of this trend across different mass regions.

The isotopic chains of actinium, protactinium, neptunium, americium, berkelium, einsteinium, mendelevium, **and** lawrencium all display nearly linear systematics. This observation indicates that proton emission in heavy nuclei is governed by the same fundamental tunnelling mechanism that successfully explains proton radioactivity in lighter rare-earth nuclei

From a practical perspective, the systematics summarized in Table 6 provide an important predictive tool for identifying new proton emitters near the proton drip line. Once the proton-decay energy is estimated, the corresponding half-life can be obtained with reasonable accuracy from the linear relationship, even for nuclei that have not yet been produced experimentally. Consequently, Geiger–Nuttall-type correlations serve not only as a powerful test of theoretical models but also as a valuable guide for future experimental programs aimed at discovering proton radioactivity in the actinide and super heavy regions.

Overall, the observed linear dependence between proton-decay half-life and $Z_dQ_p^{-1/2}$ reinforces the interpretation of proton radioactivity as a barrier-penetration phenomenon analogous to α decay. The consistency of these

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systematics across a wide range of actinide isotopes provides strong support for the theoretical description of proton emission and further strengthens confidence in predictions of yet-unobserved proton-rich nuclei beyond the currently known limits of nuclear stability [27,28,36,48].

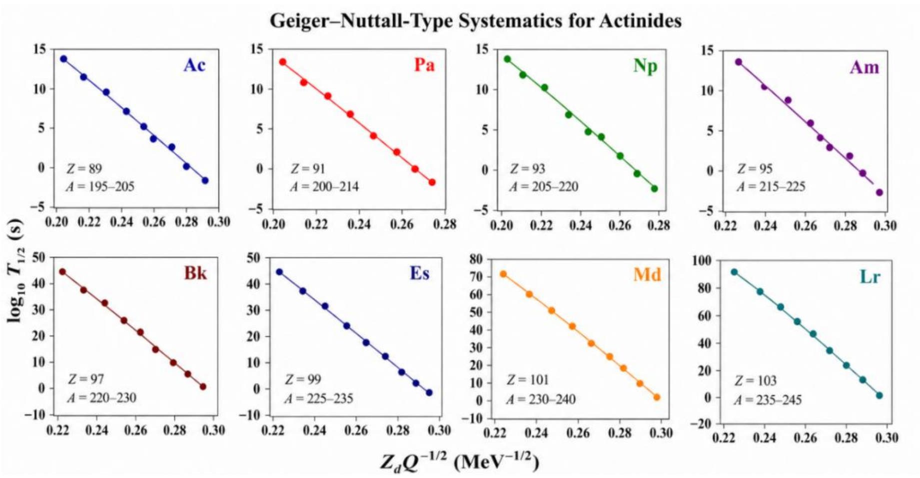

Figure 5. Geiger–Nuttall-type systematics for proton radioactivity in actinide isotopic chains. The logarithmic proton-decay half-lives, $\log_{10}(T_{1/2})$, are plotted as a function of $Z_dQ_p^{-1/2}$, where Z_d is the proton number of the daughter nucleus and Q_p is the proton-decay energy. The approximately linear behavior observed for the Ac, Pa, Np, Am, Bk, Es, Md, and Lr isotopic chains confirms that proton emission in actinides follows a Geiger–Nuttall-type relationship analogous to that observed in α decay. [35,36].

Future Experimental Prospects

Although theoretical studies have considerably advanced our understanding of proton radioactivity in the actinide region, experimental evidence remains scarce. The production of proton-rich actinides is inherently difficult because of their extremely low formation cross-sections, short lifetimes, and the strong competition from α decay and spontaneous fission. These factors have limited the direct observation of proton emission in heavy nuclei. Nevertheless, rapid progress in radioactive-ion-beam technology, recoil-separation techniques, and high-resolution detector systems has created new opportunities to explore this largely uncharted region of the nuclear landscape [5,8,11].

The emergence of next-generation rare-isotope facilities is expected to transform experimental investigations of proton-rich heavy nuclei. The Facility for Rare Isotope Beams (FRIB) in the United States provides high-intensity primary beams and advanced isotope-production capabilities, enabling access to increasingly exotic nuclei near the proton drip line. Likewise, the Facility for Antiproton and Ion Research (FAIR) in Germany will support precision studies of heavy and superheavy nuclei through intense heavy-ion beams, efficient recoil separators, and advanced spectroscopic instrumentation. Complementary capabilities at the Radioactive Isotope Beam Factory (RIBF) in Japan and the Grand Accélérateur National d'Ions Lourds (GANIL) in France are also expected to play an important role in extending proton-radioactivity studies toward neutron-deficient actinides and neighboring heavy elements [11,66].

A primary objective of future experimental programs is the verification of theoretically predicted proton-emitting actinides. Calculations based on the Coulomb and Proximity Potential Model (CPPM), the Generalized Liquid Drop Model (GLDM), the Effective Liquid Drop Model (ELDM), and several microscopic approaches consistently predict a number of proton-unbound isotopes extending from actinium to lawrencium [35,36]. Experimental confirmation of even a few of these candidates would provide stringent tests of existing proton-decay models, improve our knowledge of the proton drip line in heavy nuclei, and establish new benchmarks for theoretical calculations.

Another major research direction involves precise measurements of branching ratios among competing decay modes. In proton-rich actinides, proton emission often competes directly with α decay and spontaneous fission, and the relative probabilities of these processes are highly sensitive to nuclear structure and barrier characteristics. Accurate branching-ratio measurements would therefore provide valuable information on tunnelling probabilities, decay dynamics, deformation effects, and shell structure, enabling more rigorous validation of theoretical descriptions of charged-particle emission [35,36,48,69].

Future experiments are also expected to focus on determining spectroscopic factors, which quantify the overlap between the wave functions of the parent and daughter nuclei. Because proton emission is strongly influenced by the underlying single-particle configuration, spectroscopic factors provide direct insight into orbital occupancies, shell evolution, and deformation effects in proton-rich nuclei. Comparisons between experimentally extracted spectroscopic factors and theoretical predictions will continue to play a crucial role in refining nuclear-structure models and improving the predictive accuracy of proton-decay calculations [5,48]. The search for two-proton (2p) radioactivity in heavier systems represents another exciting frontier. Since the first observation of two-proton decay in ^{45}Fe and its subsequent confirmation [9,10], interest in correlated proton emission has grown considerably. Although all experimentally established two-proton emitters are currently confined to lighter mass regions, theoretical studies suggest that suitable conditions for simultaneous multi-proton emission may also exist in selected proton-rich heavy nuclei. Verification of such decay modes would provide unique information on proton–proton correlations, pairing interactions, and three-body decay dynamics, thereby extending the present understanding of exotic radioactive decay [10,15,57–59].

Looking beyond the actinides, theoretical calculations indicate that proton radioactivity may also become relevant in selected super heavy nuclei located near the proton drip line [67,68]. Observation of proton emission in this region would offer valuable insight into shell stabilization, deformation, and the persistence of quantum shell effects in nuclei approaching the predicted island of stability. Such measurements would represent a major advance in heavy-element physics and provide an important test of modern nuclear-structure theories [46]. Continued improvements in experimental instrumentation will be equally important for achieving these objectives. The development of high-granularity double-sided silicon strip detectors, digital data-acquisition systems, efficient recoil separators, and position-sensitive detector arrays has significantly increased the sensitivity for detecting rare decay events. These technologies enable more precise measurements of decay energies, half-lives, branching ratios, and angular correlations, thereby improving the reliability of proton-radioactivity studies in nuclei produced with extremely low yields [5,11].

In summary, the combined progress in radioactive-ion-beam facilities, detector technology, and theoretical modelling is expected to open a new era in the study of proton radioactivity in heavy nuclei. Experimental verification of predicted proton-emitting actinides, detailed investigations of competing decay modes, and the possible discovery of heavy two-proton emitters will substantially enhance our understanding of nuclear structure, quantum tunnelling, and the limits of nuclear stability. These efforts will not only test existing theoretical frameworks but also provide essential guidance for future exploration of the actinide and super heavy regions of the nuclear chart [35,36].

Future Perspectives

The rapid advancement of rare-isotope accelerator facilities is expected to greatly expand experimental access to proton-rich actinide nuclei that have so far remained beyond the reach of conventional production techniques. Modern facilities such as the Facility for Rare Isotope Beams (FRIB, USA)**,** the Facility for Antiproton and Ion Research (FAIR, Germany)**,** the Radioactive Isotope Beam Factory (RIKEN, Japan)**,** and the Grand Accélérateur National d'Ions Lourds (GANIL, France) combine high-intensity ion beams with advanced isotope-separation and decay-spectroscopy systems, making them well suited for exploring nuclei located close to the proton drip line [17,40]. Experimental identification of new proton emitters in the actinide region would provide valuable information on shell evolution, nuclear deformation, and the limits of stability in heavy proton-rich systems.

The nuclei listed in Table 8 represent the most favorable targets for future proton-radioactivity experiments. Among these**,** ^{195}Ac, ^{200}Pa, ^{206}Np, ^{212}Am, and ^{218}Bk are predicted to exhibit the most accessible proton-decay characteristics. Their relatively large proton-decay energies result in enhanced barrier penetrabilities and calculated proton-decay half-lives in the range of approximately 10^{-7}–10^{-5} S, which are compatible with the capabilities of current high-efficiency decay-spectroscopy techniques. In addition, theoretical calculations

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indicate that proton emission is expected to compete successfully with α decay and spontaneous fission in these nuclei, making them particularly attractive candidates for the first experimental observation of proton radioactivity in the actinide region [35,36].

The heavier proton-rich isotopes ^{224}Es, ^{229}Md, and ^{235}Lr also warrant detailed experimental investigation, despite the increasing importance of spontaneous fission. These nuclei occupy the transitional region where proton emission, α decay, and spontaneous fission coexist, providing an excellent opportunity to study how the dominant decay mechanism evolves with increasing atomic number. Measurements of their decay properties would improve our understanding of the interplay between Coulomb repulsion, shell effects, nuclear deformation, and fission stability in the heaviest known nuclei.

The enhanced production capabilities and advanced detector technologies available at FRIB, FAIR, RIKEN, and GANIL are expected to make these experimental investigations increasingly feasible. High-resolution silicon detector arrays, efficient recoil separators, and modern digital data-acquisition systems will improve the sensitivity for detecting weak proton-emission branches and enable precise measurements of decay energies, half-lives, and branching ratios. Such experimental data are essential for validating theoretical models, including the Coulomb and Proximity Potential Model (CPPM), and for refining predictions of proton radioactivity in regions of the nuclear chart that remain experimentally unexplored [35,36].

Overall, the isotopes identified in Table 7 provide a well-defined roadmap for future investigations of proton radioactivity in heavy nuclei. Their experimental confirmation would extend the known proton-emitting region into the actinide domain, provide stringent tests of current theoretical models, and offer new insights into shell structure, deformation effects, and the location of the proton drip line. These studies will represent an important step toward understanding the stability of the heaviest proton-rich nuclei and will help guide future explorations of the actinide and super heavy regions.

Table 6. Recommended Experimental Targets for Future Proton-Radioactivity Studies in Actinides

Nucleus	Q_p (MeV)	Predicted $\log_{10}T_{1/2}$,p (S)	Predicted $T_{1/2}$,p (S)	Dominant Decay Mode	Recommended Facility	Reference
^{195}Ac	2.161	−6.7230	1.89×10^{-7}	Proton decay	FRIB	[35,36]
^{200}Pa	2.111	−5.9691	1.07×10^{-6}	Proton decay	FAIR	[35,36]
^{206}Np	1.911	−4.1216	7.56×10^{-5}	Proton decay	RIKEN	[35,36]
^{212}Am	2.051	−4.6445	2.27×10^{-5}	Proton decay	GANIL	[35,36]
^{218}Bk	2.241	−5.3828	4.14×10^{-6}	Proton decay	FAIR	[35,36]
^{224}Es	2.181	−4.5262	2.98×10^{-5}	Spontaneous fission	FRIB / RIKEN	[35,36]
^{229}Md	2.251	−4.5400	2.88×10^{-5}	Spontaneous fission	FAIR	[35,36]
^{235}Lr	2.161	−3.4850	3.27×10^{-4}	Spontaneous fission	FAIR / GANIL	[35,36]

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CONCLUSIONS

Proton Radioactivity Has Emerged As One Of The Most Sensitive Probes Of Nuclear Structure Beyond The Proton Drip Line, Offering Direct Insight Into Quantum Tunnelling In Proton-Rich Nuclei. Since Its Experimental Discovery, Investigations Of Proton Emission Have Significantly Improved Our Understanding Of Single-Particle Configurations, Shell Evolution, Nuclear Deformation, And The Interplay Between The Attractive Nuclear Interaction And Coulomb Repulsion. Consequently, Proton Radioactivity Has Become An Indispensable Spectroscopic Tool For Exploring Nuclei At The Limits Of Nuclear Stability.

Although experimentally established proton emitters are concentrated mainly in the rare-earth and heavy-mass regions, theoretical investigations over the past two decades indicate that proton radioactivity may extend into the actinide region. The large Coulomb fields, pronounced deformation, and coexistence of competing decay channels make actinide nuclei an especially interesting testing ground for studies of exotic radioactive decay. Systematic calculations suggest that several neutron-deficient isotopes between actinium ($Z = 89$) and lawrencium ($Z = 103$) possess positive proton-decay energies and half-lives that could be accessible to future experimental measurements.

This review has summarized the present understanding of proton radioactivity in actinide nuclei, including the predicted proton emitters, their decay characteristics, competition with α decay and spontaneous fission, Geiger–Nuttall-type systematics, and the performance of the principal theoretical models used to describe proton emission. Comparative analyses indicate that models such as the Coulomb and Proximity Potential Model (CPPM), the Effective Liquid Drop Model (ELDM), the Density-Dependent Michigan 3-Yukawa (DDM3Y) interaction, the Generalized Liquid Drop Model (GLDM), and the Jeukenne–Lejeune–Mahaux (JLM) interaction successfully reproduce the overall trends of proton-decay half-lives, with ELDM and DDM3Y generally providing the highest predictive accuracy. The complementary use of these approaches has substantially improved confidence in predictions for proton-rich nuclei that remain beyond current experimental reach.

Despite these theoretical advances, the experimental observation of proton radioactivity in actinide nuclei remains an outstanding challenge. Extremely low production cross-sections, very short decay times, and the increasing competition from α decay and spontaneous fission limit the accessibility of these exotic systems. Nevertheless, continuous improvements in rare-isotope production, recoil-separation techniques, and high-resolution decay spectroscopy are expected to overcome many of these difficulties. The capabilities of modern facilities such as FRIB, FAIR, RIKEN, and GANIL provide realistic prospects for discovering the first proton-emitting actinides and for testing long-standing theoretical predictions.

Future experimental studies will not only verify the existence of predicted proton emitters but will also provide important information on shell structure, deformation effects, spectroscopic factors, and the evolution of nuclear stability near the proton drip line. Measurements of proton-decay energies, half-lives, and branching ratios will offer stringent tests of current theoretical models and contribute to a more comprehensive understanding of charged-particle emission in heavy nuclei. In addition, extending these investigations toward the super heavy region may reveal new manifestations of proton radioactivity and clarify the influence of shell stabilization in nuclei approaching the predicted island of stability.

In conclusion, proton radioactivity in the actinide region represents an important frontier in contemporary nuclear physics. The combination of increasingly sophisticated theoretical models and rapidly advancing experimental capabilities is expected to drive significant progress in the coming years. Successful identification of proton-emitting actinides would not only broaden the known limits of proton radioactivity but also provide fundamental insight into the structure and stability of the heaviest proton-rich nuclei, thereby enriching our understanding of the nuclear landscape at its extreme boundaries.

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