

Decay dynamics of helium-cluster dinuclear systems in the spontaneous fission of ^{252}Cf

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DOI: 10.63907/ansa.v2i1.74

Received: 10 February 2026

Abstract

The decay dynamics of helium-cluster dinuclear systems (DNS) in the spontaneous fission of ^{252}Cf have been systematically investigated within the framework of the TNS and DNS model, with particular focus on the catalytic role of external Coulomb fields from foil materials. The analysis demonstrates a pronounced and monotonic decrease in decay barrier heights as DNS systems approach foil nuclei, with the effect exhibiting clear dependence on both the atomic number of the foil material and the specific composition of the DNS. Calculations of half-lives using the WKB approximation confirm the dramatic consequences of this barrier modification. These results provide a quantitative theoretical foundation for understanding the experimentally observed catalysis of foil materials on the decay of fissile fragments.

1 Introduction

Nuclear fission represents one of the most complex nuclear processes, typically resulting in binary division of heavy nuclei. However, recent experimental evidence has revealed more exotic decay modes, including binary and ternary fission processes [1–15]. Particularly intriguing is the phenomenon of collinear cluster tripartition (CCT), where three fragments are emitted in near-collinear geometry [7].

The conventional understanding of ternary fission involves the emission of light charged particles (LCPs), predominantly alpha particles, with probabilities of approximately $2 - 4 \times 10^{-3}$ per binary fission [15]. These long-range alpha (LRA) particles typically emerge with energies around 16 MeV and exhibit angular distributions predominantly perpendicular to the fission axis. Recent experimental investigations employing solid-state degrader foils (C, Al, Ti, Ni, Cu, Ta) have uncovered a remarkable related phenomenon [6–10]. These studies have revealed more complex scenarios involving delayed break-up processes and shape isomer states in fission fragments.

The interaction of fission fragments with solid-state foils has emerged as a powerful probe for investigating nuclear structure and decay dynamics. Experimental observations using double-hit coincidence techniques have demonstrated that some fission fragments undergo binary break-up while passing through foils, with characteristic delay times of about 400 ns [9]. These time scales suggest the involvement of shape isomer states with lifetimes significantly longer than typical nuclear reaction times.

The Coulomb field of the foil material appears to play a crucial role in inducing these break-up processes. Theoretical considerations based on dinuclear system models [5] suggest that the external Coulomb field can lower potential barriers and facilitate transitions between different nuclear configurations. This is particularly relevant for highly deformed shape isomers, where the deformation energy stored in the system may be comparable to the fission barrier.

Recent experiments have revealed mass-asymmetric break-up channels, including the remarkable ${}^4\text{He}-{}^{128}\text{Sn}$ partition observed in multiple experimental configurations [9–11]. The consistency of these observations across different experimental setups, including COMETA, LIS, and VEGA spectrometers, provides compelling evidence for the reliability of these findings.

This article presents a theoretical investigation of specific trinuclear system (TNS) configurations in the spontaneous fission of ${}^{252}\text{Cf}$ that lead to the formation of helium-cluster dinuclear systems (DNS). We focus on two particularly probable decay pathways:

- ${}^{252}\text{Cf} \rightarrow {}^{134}\text{Te} + {}^{118}\text{Pd} \rightarrow \text{DNS}({}^4\text{He} + {}^{130}\text{Sn}) + {}^{118}\text{Pd}$
- ${}^{252}\text{Cf} \rightarrow {}^{122}\text{Cd} + {}^{130}\text{Sn} \rightarrow \text{DNS}({}^4\text{He} + {}^{118}\text{Pd}) + {}^{130}\text{Sn}$

These DNS configurations (${}^{134}\text{Te} + {}^{118}\text{Pd}$ and ${}^{122}\text{Cd} + {}^{130}\text{Sn}$) are located in the minimum of the DNS driving potential of ${}^{252}\text{Cf}$ [4], making their occurrence more probable than other configurations. The presence of magic ${}^{130}\text{Sn}$ nuclei in these systems enhances their stability and favors their formation. We investigate the decay dynamics of these metastable DNS under the influence of the Coulomb field from various foil materials (Al, Cu, Ta), calculating the modifications to their potential energy landscapes and the resulting changes in their half-lives. Our results provide a quantitative theoretical foundation for understanding the experimentally observed catalytic effect of foil materials on the decay of fission fragments and offer new insights into the role of shell effects in ternary fission processes.

2 Model

The calculations presented in this work are performed within the framework of the TNS and DNS model, which provides a robust description of clusterization and decay dynamics in spontaneous fission isomers [3, 4]. In this model, the total potential energy of a DNS, U_{DNS} , is defined as:

$$U_{\text{DNS}} = V_{\text{int,DNS}} + Q_{\text{DNS}},$$

where the interaction potential $V_{\text{int,DNS}}$ is composed of nuclear and Coulomb parts. The Coulomb interaction is calculated using the Wong formula [16], while the nuclear interaction is computed via the double-folding procedure with Migdal's forces, as detailed in Ref. [17]. It should be noted that for He clusters, a modified nuclear density parameter was employed in the present calculations, differing from the standard value used for other light clusters in the original formulation. The half-lives are determined using the WKB approximation [18], with the excitation energy of the system being taken into account. For a complete description of the model formalism, parameters, and underlying assumptions, the reader is referred to Ref. [3, 4].

For light nuclei such as the He particle, the Gaussian distribution provides the most accurate description:

$$\rho_{\alpha}(r) = A_{\alpha} \left(\frac{\gamma^2}{\pi} \right)^{3/2} \exp(-\gamma^2 r^2) \quad (1)$$

where $\gamma = 0.671 \text{ fm}^{-1}$. The width parameter γ is obtained by minimizing the total energy in the density functional approach [5]. The parameter A_{α} is a normalization constant. For the ${}^4\text{He}$ cluster, integrating the density over all space yields the mass number, which fixes $A_{\alpha} = 4$.

3 Interaction of DNS and foil nucleus

The analysis of the interaction between the DNS and the foil nucleus was conducted following the methodology established in Ref. [4]. In the present work, the specific DNS configurations under investigation were ${}^4\text{He} + {}^{130}\text{Sn}$ and ${}^4\text{He} + {}^{118}\text{Pd}$, which were considered to interact with Al, Cu and Ta foil nuclei. The kinetic energies of the DNSs were determined from energy and momentum conservation laws to be 110.96 MeV for the ${}^4\text{He} + {}^{130}\text{Sn}$ system and 122.52 MeV for the ${}^4\text{He} + {}^{118}\text{Pd}$ system. These energies are far below the Coulomb barriers between the DNS and the foil nuclei, therefore the total interaction potential was calculated considering only the Coulomb interaction.

The maximum approach distances, $R_{\text{max.app.}}$, for head-on collisions were determined to be 44.9 fm, 53.8 fm and 61.4 fm for the ${}^4\text{He} + {}^{130}\text{Sn}$ system with Al, Cu and Ta foils, respectively. For the ${}^4\text{He} + {}^{118}\text{Pd}$ system, the corresponding distances were 32.9 fm with Al, 40.5 fm with Cu and 78.3 fm with Ta. The modification of the DNS interaction potential by the Coulomb field of the foil nucleus is illustrated in Fig. 1, where a significant distortion of the potential pocket is observed as the distance to the foil decreases.

This distortion of the potential energy landscape leads to a substantial and systematic lowering of the decay barrier for the DNS, a phenomenon that is critically

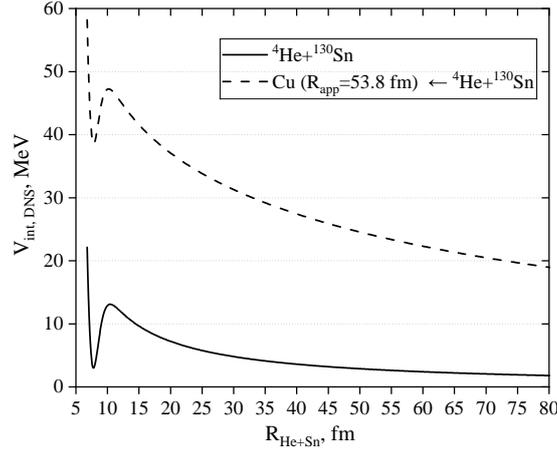


Figure 1: Modification of the interaction potential for the DNS ${}^4\text{He} + {}^{130}\text{Sn}$ by the Coulomb field of Cu foil nuclei.

dependent on both the atomic number of the foil material and the specific composition of the DNS. The dependence of the decay barrier height on the distance between the DNS and the foil is illustrated in Figs. 2 and 3 for the Al, Cu, and Ta foils. A pronounced and monotonic decrease in the barrier height is observed as the DNS approaches the foil nucleus for all systems. The magnitude of this effect exhibits a clear hierarchy based on the Coulomb strength of the foil: the Ta foil ($Z=73$), possessing the highest atomic number, induces the most significant barrier suppression, followed by Cu ($Z=29$), and then Al ($Z=13$). For instance, the decay barrier for the ${}^4\text{He} + {}^{130}\text{Sn}$ system is lowered from its nominal value nearly 10.1 MeV to approximately 9.1 MeV, 8.7 MeV, and 8.4 MeV at the point of closest approach to the Al, Cu, and Ta foils, respectively. An even more dramatic reduction

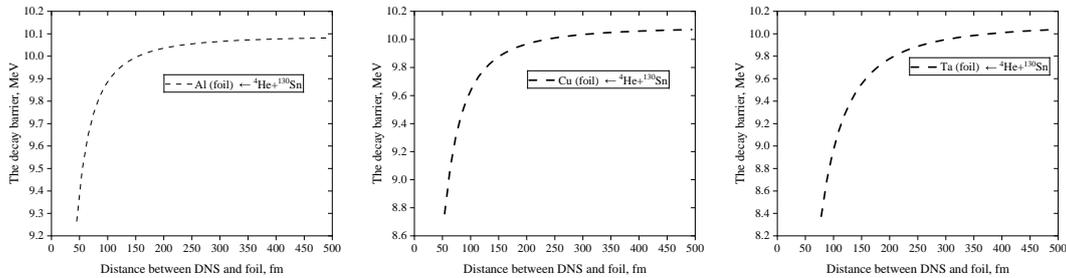


Figure 2: Change of the decay barrier for the DNS ${}^4\text{He} + {}^{130}\text{Sn}$ as a function of the distance to the Al, Cu and Ta foil nucleus.

is observed for the ${}^4\text{He} + {}^{118}\text{Pd}$ system, where the barrier decreases from more than 10.2 MeV to about 9 MeV, 8.2 MeV, and 7.8 MeV for the same foils. This systematic reduction in the potential barrier under the influence of an external Coulomb field is the fundamental mechanism that catalyzes the subsequent decay of the metastable dinuclear systems.

The half-lives of the asymmetric DNSs were calculated as a function of excitation energy using the WKB approximation, following the averaging procedure over the excitation energy spectrum detailed in Ref. [4, 18]. The results, presented in Figs. 4 and 5, demonstrate a dramatic catalytic effect induced by the foil's Coulomb field that exhibits strong dependence on both the foil material and DNS composition.

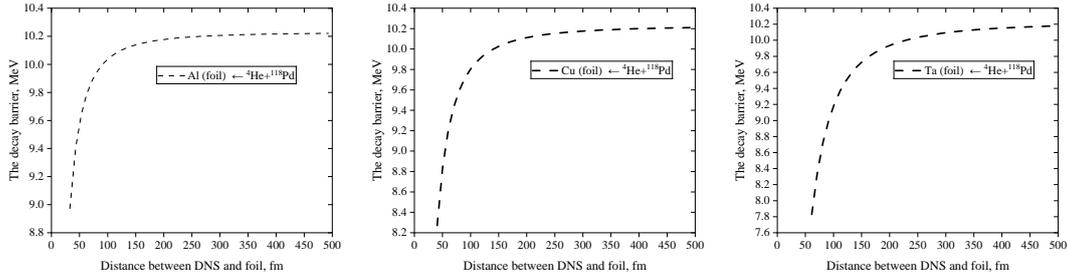


Figure 3: Change of the decay barrier for the DNS ${}^4\text{He} + {}^{118}\text{Pd}$ as a function of the distance to the Al, Cu and Ta foil nucleus.

For the ${}^4\text{He} + {}^{130}\text{Sn}$ system, the half-life at zero excitation energy decreases from approximately 10 s in free space to about 10^{-12} s, 10^{-14} s, and 10^{-16} s when approaching Al, Cu, and Ta foils, respectively, representing reduction factors of 10^{13} , 10^{15} , and 10^{17} . Even more strikingly, the ${}^4\text{He} + {}^{118}\text{Pd}$ system shows an even

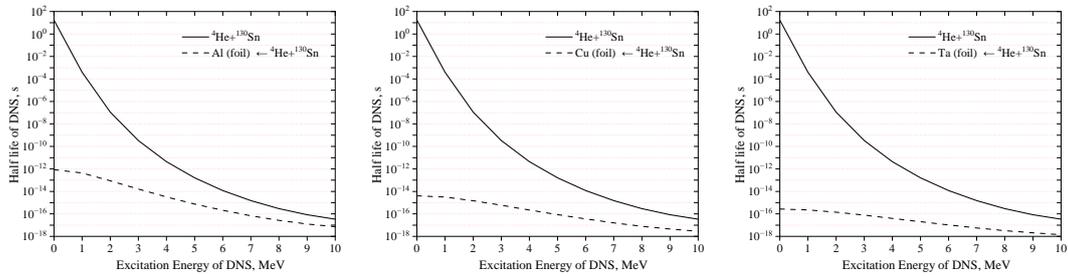


Figure 4: Half-life of the DNS ${}^4\text{He} + {}^{130}\text{Sn}$ as a function of excitation energy with (dashed lines) and without (solid lines) interaction with Al, Cu and Ta foils.

greater sensitivity to the external field, with half-lives dropping from around 10^{14} s in isolation to approximately 10^{-13} s, 10^{-16} s, and 10^{-17} s near Al, Cu, and Ta foils, corresponding to reduction factors of 10^{27} , 10^{30} , and 10^{31} . This systematic trend reveals that the catalytic effect strengthens with increasing atomic number of the foil material and is more pronounced for the ${}^4\text{He} + {}^{118}\text{Pd}$ system compared to ${}^4\text{He} + {}^{130}\text{Sn}$. Across all systems and excitation energies up to 10 MeV, the presence

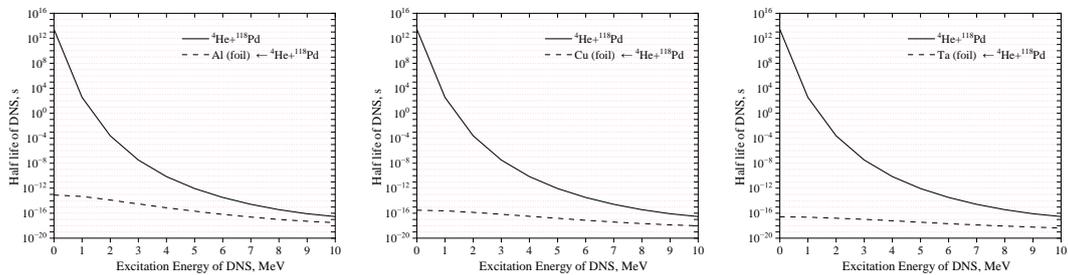


Figure 5: Half-life of the DNS ${}^4\text{He} + {}^{118}\text{Pd}$ as a function of excitation energy with (dashed lines) and without (solid lines) interaction with Al, Cu and Ta foil.

of foil nuclei accelerates the decay process by many orders of magnitude, effectively transforming metastable systems with half-lives ranging from seconds to years into extremely short-lived states with half-lives of femtoseconds to nanoseconds. These

computational results provide a quantitative theoretical foundation for interpreting the experimentally observed secondary decay of fission fragments [8] with characteristic delay times on the order of picoseconds when traversing material foils.

4 Conclusions

In the present work, the decay dynamics of helium-cluster dinuclear systems formed in the spontaneous fission of ^{252}Cf has been systematically investigated within the framework of the TNS and DNS model, with particular focus on the catalytic role of external Coulomb fields from foil materials. This study reveals that the potential energy landscape of DNS configurations undergoes substantial and systematic modifications when interacting with foil nuclei, leading to dramatic acceleration of decay processes.

The analysis demonstrates a pronounced and monotonic decrease in decay barrier heights as DNS systems approach foil nuclei, with the effect exhibiting clear dependence on both the atomic number of the foil material and the specific composition of the DNS. For the $^4\text{He} + ^{130}\text{Sn}$ system, the decay barrier is suppressed from its nominal value of approximately 10.1 MeV to 9.1 MeV, 8.7 MeV, and 8.4 MeV at the point of closest approach to Al, Cu, and Ta foils, respectively. An even more significant reduction is observed for the $^4\text{He} + ^{118}\text{Pd}$ system, where the barrier decreases from over 10.2 MeV to about 9.0 MeV, 8.2 MeV, and 7.8 MeV for the same foils. This systematic barrier suppression, which strengthens with increasing atomic number of the foil material, represents the fundamental mechanism enabling the catalytic decay of metastable dinuclear systems.

Calculations of half-lives using the WKB approximation confirm the dramatic consequences of this barrier modification. For the $^4\text{He} + ^{130}\text{Sn}$ system at zero excitation energy, the half-life decreases from approximately 10 s in free space to about 10^{-12} s, 10^{-14} s, and 10^{-16} s when approaching Al, Cu, and Ta foils, representing reduction factors of 10^{13} , 10^{15} , and 10^{17} , respectively. The $^4\text{He} + ^{118}\text{Pd}$ system exhibits even greater sensitivity, with half-lives dropping from around 10^{14} s in isolation to approximately 10^{-13} s, 10^{-16} s, and 10^{-17} s near Al, Cu, and Ta foils, corresponding to reduction factors of 10^{27} , 10^{30} , and 10^{31} . This transformation of metastable systems with half-lives ranging from seconds to years into extremely short-lived states with half-lives of picoseconds to femtoseconds provides a quantitative theoretical foundation for interpreting experimental observations of secondary fission fragment decay [8].

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