Influence of the Coulomb Field of Foil Nuclei on Half-Lives of Cluster States in Fission Fragments

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Experimental Puzzle: Mass Loss in Foils

Key Experimental Observation

- Primary fission fragments of ^{252}Cf lose mass (up to $\approx$ 20 amu) when passing through degrader foils (Ti, Al, Cu, Pt)
- Time delay $\approx$ 400 ns suggests metastable states
- Only 10^{-4}–10^{-5} of primary products undergo break-up

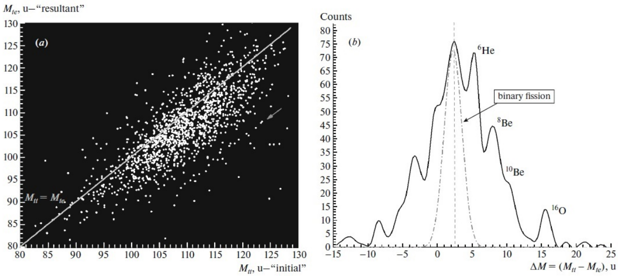


Figure: Mass spectra before and after Cu foil (adapted from Pyatkov et al., Phys. At. Nucl. **87**, S419 (2024))

Model

Sequential Ternary Fission

$$^{252}\mathrm{Cf} \to \mathrm{DNS} \to \mathrm{TNS}$$

Example Channels

- $^{252}\mathrm{Cf} \to {}^{122}\mathrm{Cd} + {}^{130}\mathrm{Sn} \to {}^{14}\mathrm{C} + {}^{108}\mathrm{Mo} + {}^{130}\mathrm{Sn}$
- $^{252}\mathrm{Cf} \to {}^{122}\mathrm{Cd} + {}^{130}\mathrm{Sn} \to {}^{20}\mathrm{O} + {}^{102}\mathrm{Zr} + {}^{130}\mathrm{Sn}$

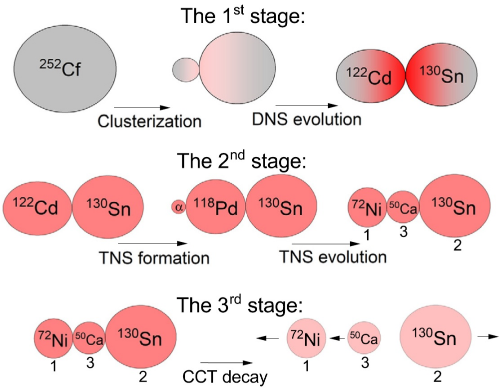


Figure: Schematic of TNS decay process

Potential Energy

DNS Potential Energy

$$U_{\text{DNS}} = V_{12} + Q_{\text{DNS}}$$

where $Q_{\text{DNS}} = B_1 + B_2 - B_{\text{CN}}$

Interaction Potential

$$V_{12} = V_N + V_C$$

- Nuclear part V_N: Double-folding with density-dependent forces
- Coulomb part V_C: Includes quadrupole deformations

TNS Potential Energy

$$U_{\text{TNS}} = V_{123} + Q_{\text{TNS}} = V_{12} + V_{23} + V_{13} + Q_{\text{TNS}}$$

Dinuclear and Trinuclear System

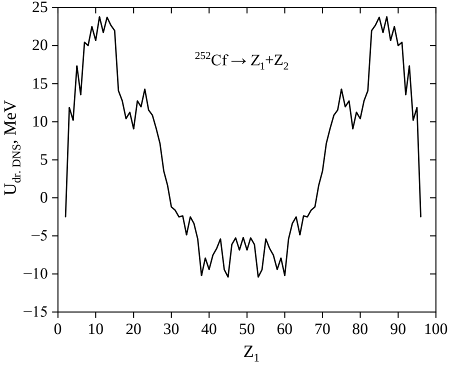


Figure: Driving potential for ^{252}Cf showing preferred DNS configurations

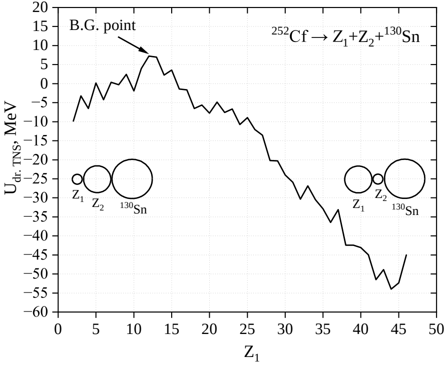


Figure: Driving potential showing preferred TNS configurations

Interaction between DNS and the third nucleus as a foil in the Coulomb field

Key Mechanism

- External Coulomb field modifies V_{12}
- Lowers decay barrier
- Dramatically increases decay probability

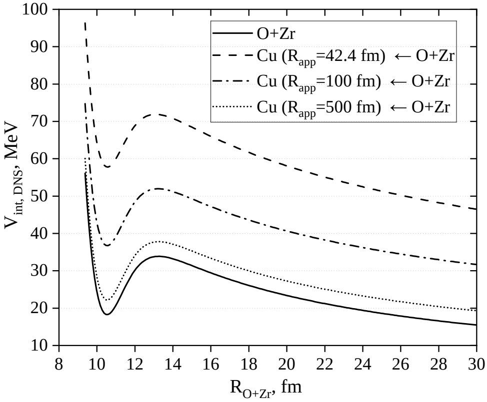
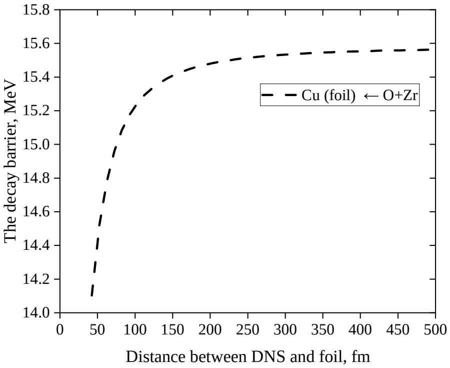
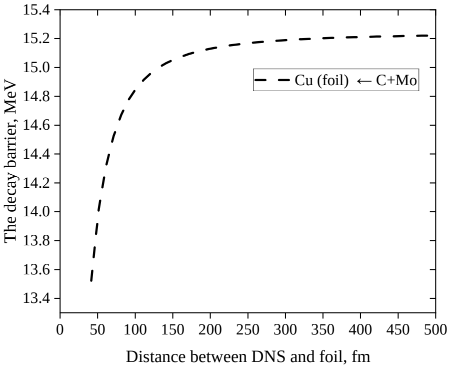


Figure: DNS interaction with foil nucleus (Cu)

Modification of the Decay Barrier





Closest Approach Distances

- Cu $\leftarrow$ C+Mo: $R_{\text{app.}} = 41.4$ fm
- Cu $\leftarrow$ O+Zr: $R_{\text{app.}} = 42.4$ fm

WKB Tunneling Formalism

Tunneling Probability

$$P(E) = \frac{1}{1 + \exp\left(\frac{2}{\hbar}\int_{R_{\text{in}}}^{R_{\text{out}}} \sqrt{2\mu(V_{12}(R) - V_{12}(R_{12}^m) - E)}dR\right)}$$

Energy Averaging

$$P_{\text{av}}(E_x) = \int_0^{E_x} W(E)P(E)dE$$

with $W(E) = \frac{\exp(-E/T_{\text{DNS}})}{T_{\text{DNS}}(1-\exp(E_x/T_{\text{DNS}}))}$

Half-Life Calculation

$$T_{1/2}(E_x) = \frac{\pi \log 2}{\omega_0 P_{\text{av}}(E_x)}$$

where $\omega_0 = \sqrt{V''(R - R_{\text{min}})/\mu}$

Half-life of DNS

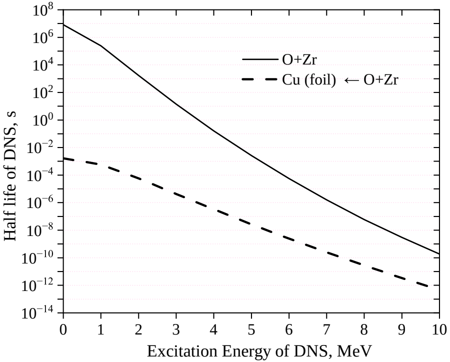


Figure: Half-life of DNS O+Zr as function of excitation energy with and without Cu foil interaction

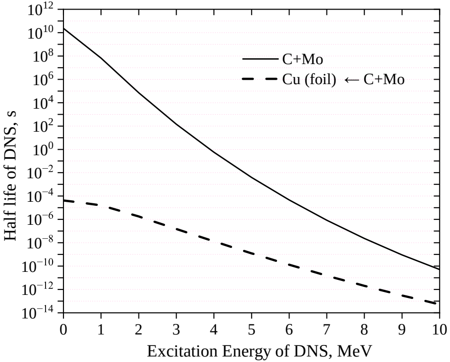


Figure: Half-life of DNS C+Mo as function of excitation energy with and without Cu foil interaction

Quantitative Results

DNS System	Reduction Factor	$R_{app.}$ (fm)	E_{kin} (MeV)
$^{14}C + ^{108}Mo$	10^{15}–10^{3}	41.4	117.62
$^{20}O + ^{102}Zr$	10^{10}–10^{2}	42.4	115.84

Table: Summary of DNS decay parameters and foil effects

Key Findings

- Half-life reduction is **asymmetry-dependent**
- More asymmetric DNS show stronger effect

Summary & Conclusions

Mechanism for Experimental Observation

- Proposed theoretical model explaining **mass loss** of ^{252}Cf fission fragments in degrader foils
- DNS examples: $^{14}\mathrm{C} + {}^{108}\mathrm{Mo}$ and $^{20}\mathrm{O} + {}^{102}\mathrm{Zr}$

Key Finding: Coulomb Field Catalysis

- Foil nucleus Coulomb field **lowers DNS decay barrier**
- Dramatically enhances decay via **quantum tunneling**

Publication Status

This work has been **submitted to Physics Letters B**

Outlook & Future Work

Next Steps

- Kinetic energy profiles of DNS fragments post-foil
- Angular distribution of DNS break-up events
- Extend to other foil materials and DNS configurations
- Investigate orientation effects more systematically
- Compare with additional experimental data

Broader Implications

- Novel method to study nuclear isomers
- Insight into cluster states in heavy nuclei
- Connection to ternary fission dynamics

References

- Kalandarov et al., Phys. Lett. B **850**, 138522 (2024)
- Pyatkov et al., Phys. At. Nucl. **87**, S419 (2024)
- Pyatkov et al., Phys. Rev. C **96**, 064606 (2017)
- Pyatkov et al., Eur. Phys. J. A **45**, 29 (2010)
- Audi et al., Nucl. Phys. A **729**, 337 (2003) - Mass data
- Wong, Phys. Rev. Lett. **31**, 766 (1973) - Coulomb interaction
- Raman et al., At. Data Nucl. Data Tables **78**, 1 (2001) - Deformations
- Migdal, *Theory of Finite Fermi Systems* (1967) - Nuclear forces
- Wentzel, Z. Phys. **38**, 518 (1926) - WKB method

Thank you for your attention!

- AYSS-2025 Conference Organizers

Questions?

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