# Catalysis of Fission Isomer Decay in the Coulomb Field of a Foil Nucleus for Ternary System of $^{252}$Cf

*F.O. Otakhonov*[a,1], *Sh.A. Kalandarov*[a,2], *A.A. Shoymardonov*[b,3]

[a] BLTP Joint Institute for Nuclear Research, 141980 Dubna, Russia

[b] Tashkent state university of economics, 100066, Tashkent, Uzbekistan

В этой работе мы исследуем распад изомеров, образующихся при спонтанном делении $^{252}$Cf. В рамках модели тройной ядерной системы (ТЯС), мы описываем образование ТЯС и её распад, с последующим образованием изомера, в виде двойной ядерной системы (ДЯС). Изменение периодов полураспада ДЯС мы рассчитываем, используя квантово-механический туннельный подход. Наши расчеты показывают значительный каталитический эффект внешнего кулоновского поля на процесс распада ДЯС. Наши результаты дают прямое и количественное объяснение экспериментальным наблюдениям, которые опубликованы в работе [1]. Эта работа устраняет разрыв между теоретическими предсказаниями и экспериментальными наблюдениями, обеспечивая всестороннее понимание этого удивительного явления ядерного распада.

In this work, We investigate the decay of fission isomers formed in spontaneous fission of $^{252}$Cf. In the framework of TNS model, we describe the formation of the TNS and its decay, with subsequent formation of fission isomer as a dinuclear system. The modification of DNS half-lives we calculate using a quantum-mechanical tunneling approach. Our calculations reveal a dramatic catalytic effect of the external Coulomb field on the decay process of DNS. Our results provide a direct and quantitative explanation for the experimental observations reported by [1]. This work bridges the gap between theoretical predictions and experimental observations, providing a comprehensive understanding of this fascinating nuclear decay phenomenon.

PACS: 24.10.Pa, 24.60.Dr,24.75.+i

## 1. Introduction

Recent experiments on spontaneous fission of $^{252}$Cf reveal a remarkable phenomenon: when fragments traverse metallic foils, a small fraction undergoes delayed secondary decay with time delays up to 400 ns [1–3]. This indicates the existence of stable fission isomers whose decay is catalyzed by the foil material. The observed mass loss in fragment spectra provides further evidence for this catalytic process.

The collinear cluster tripartition (CCT) process, involving three-fragment emission with magic nuclei, finds natural explanation in the trinuclear system (TNS) model [4]. This framework describes how primary ternary fission can leave residual dinuclear systems (DNS) in metastable states. The foil's

[1]E-mail: otaxonov@theor.jinr.ru
[2]E-mail: shuhrat@theor.jinr.ru
[3]E-mail: a.shoymardonov@tsue.uz

Coulomb field then distorts the DNS potential, lowering decay barriers and exponentially enhancing tunneling probabilities.

We investigate this Coulomb catalysis for two $^{252}$Cf ternary channels that are experimentally observed as distinct from binary fission modes [1–3]:

- $^{252}\text{Cf} \rightarrow ^{98}\text{Sr} + ^{154}\text{Nd} \rightarrow DNS(^{8}\text{Be} + ^{90}\text{Se}) + ^{154}\text{Nd}$
- $^{252}\text{Cf} \rightarrow ^{154}\text{Nd} + ^{98}\text{Sr} \rightarrow DNS(^{26}\text{Ne} + ^{128}\text{Sn}) + ^{98}\text{Sr}$

These probe different aspects: $^{8}$Be represents light cluster emission, while $^{128}$Sn involves magic stability. Our calculations demonstrate dramatic half-life reductions, providing quantitative explanation for experimental observations and confirming the TNS-DNS mechanism for fission isomer decay.

## 2. Model

The theoretical framework for this investigation is based on the TNS and DNS concepts, which have been successfully applied to describe cluster decay and collinear cluster tripartition [4, 5]. The formation and subsequent decay of fission isomers are considered within a sequential decay scenario.

The process begins with spontaneous fission of $^{252}$Cf into primary fragments. The $^{98}\text{Sr} + ^{154}\text{Nd}$ pair lies in a driving potential minimum [4], making it a probable primary DNS configuration. From this stable state, light cluster emission forms trinuclear systems which are given previously. We assume that this leads to the formation of the fission isomers, specifically the $\text{DNS}(^{8}\text{Be} + ^{90}\text{Se}) + ^{154}\text{Nd}$ and $\text{DNS}(^{26}\text{Ne} + ^{128}\text{Sn}) + ^{98}\text{Sr}$ configurations.

The secondary DNS ($^{8}$Be+$^{90}$Se or $^{26}$Ne+$^{128}$Sn) become the stable fission isomers whose decay is catalyzed by the foil.

The stability and decay properties of the DNS are determined by its potential energy landscape. The total potential energy $U_{\text{DNS}}(R)$ is calculated as the sum of the interaction potential $V_{\text{int}}(R)$ and the $Q$-value, where $Q_{\text{DNS}} = B_1 + B_2 - B_{\text{CN}}$ accounts for mass excess differences using experimental values [6].

The interaction potential combines nuclear and Coulomb components. The nuclear part is computed using the double-folding formalism with density-dependent Migdal forces [7], while the Coulomb interaction incorporates quadrupole deformations [8] via the Wong formula [9]. The DNS resides in a potential pocket at $R_m \approx R_1 + R_2 + 0.5$ fm, stabilized against decay by a barrier $B_f$.

The secondary DNS is localized in a potential pocket at a distance $R_m \approx R_1 + R_2 + 0.5$ fm, prevented from decay by a barrier $B_f$.

The fission isomers, represented by the secondary DNS, fly towards the detector with kinetic energies determined from the TNS decay kinematics. For both channels considered, these energies are below the Coulomb barrier between the DNS and the Cu foil nucleus. Therefore, the interaction is purely Coulombic.

The total potential energy of the DNS in the presence of the foil nucleus Cu is modified as:

$$U_{\text{total}}(R, D) = U_{\text{DNS}}(R) + V_{C,\text{foil}}(D), \tag{1}$$

where $D$ is the distance between the center-of-mass of the DNS and the Cu nucleus. The term $V_{C,\text{foil}}(D)$ is the Coulomb potential between the DNS and the Cu nucleus. This external field distorts the potential landscape of the DNS, effectively lowering its decay barrier $B_f$ as the distance $D$ decreases.

The decay of the metastable DNS is treated as a quantum tunneling process through the potential barrier. The half-life is calculated using the Wentzel-Kramers-Brillouin (WKB) approximation. The probability $P$ for tunneling at an excitation energy $E$ is given by:

$$P(E) = \left[1 + \exp\left(\frac{2}{\hbar}\int_{R_{\text{in}}}^{R_{\text{out}}} \sqrt{2\mu[V_{\text{int}}(R) - V_{\text{int}}(R_m) - E]}dR\right)\right]^{-1}, \tag{2}$$

where $\mu$ is the reduced mass of the DNS, and $R_{\text{in}}$, $R_{\text{out}}$ are the classical turning points.

To account for the thermal population of excitation energies in the DNS, we define a temperature $T_{\text{DNS}} = \sqrt{E_x/a}$ using the Fermi gas model, with a level density parameter $a = A_{\text{DNS}}/8$. The excitation-energy averaged tunneling probability is then:

$$P_{\text{av}}(E_x) = \frac{\sum_{i=0}^{n} \exp(-i\delta E_x/T_{\text{DNS}})\, P(i\delta E_x)}{\sum_{i=0}^{n} \exp(-i\delta E_x/T_{\text{DNS}})}, \tag{3}$$

where $n = E_x/\delta E_x$ and $\delta E_x$ is a small energy step. The half-life of the DNS is finally obtained as:

$$T_{1/2}(E_x) = \frac{\pi \ln 2}{\omega_0\, P_{\text{av}}(E_x)}. \tag{4}$$

Here, $\omega_0 = \sqrt{V''(R_m)/\mu}$ is the frequency of zero-point oscillations in the potential well. The external Coulomb field of the Cu foil enters this calculation by modifying the interaction potential $V_{\text{int}}(R)$ in the tunneling integral, leading to a significant decrease in $T_{1/2}$ as the DNS approaches the foil.

## 3. Results

The external Coulomb field catalyzes DNS decay by lowering potential barriers (Fig. 1), with dramatic differences between the two systems. For $^{8}$Be+$^{90}$Se, the close approach distance ($R_{app} = 23.6$ fm) enables strong Coulomb interaction, reducing the barrier to 3.7 MeV. In contrast, the larger separation for $^{26}$Ne+$^{128}$Sn ($R_{app} = 65.6$ fm) results in only moderate barrier reduction to 0.85 MeV.

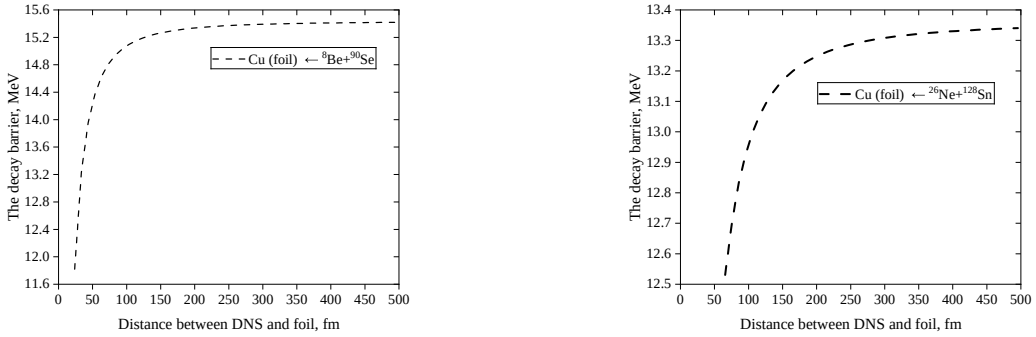


Fig. 1. Modification of the decay barrier height for the asymmetric DNS as a function of the distance to the Cu foil nucleus. The arrows indicate the calculated distance of closest approach, $R_{app}$.

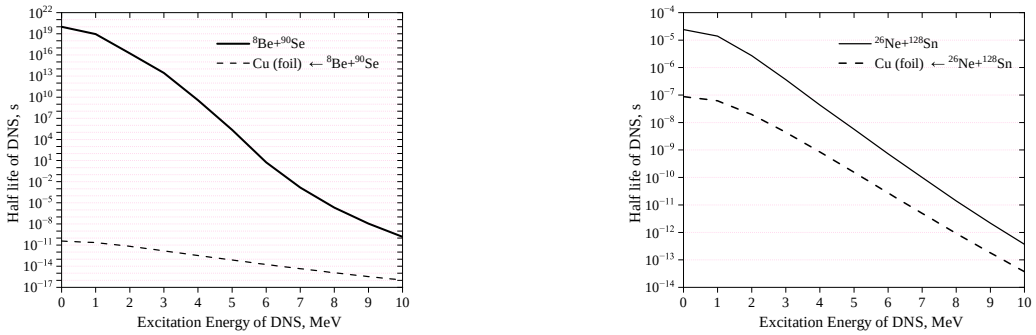


Fig. 2. Half-life of DNS (Be+Se and Ne+Sn) as a function of excitation energy with(dashed lines) and without (solid lines) interaction with a Cu foil.

This differential barrier lowering explains the observed half-life reductions (Fig. 2). The $^{8}$Be+$^{90}$Se system experiences dramatic catalysis (half-life reduction from $\sim 10^{30}$ to $\sim 10^{6}$ times) due to the close approach, while $^{26}$Ne+$^{128}$Sn shows minimal effect (reduction from $\sim 10^{3}$ to $\sim 10^{2}$ times) owing to the larger separation.

The picosecond-scale traversal time through the foil provides sufficient duration for the strong Coulomb field to disrupt $^{8}$Be+$^{90}$Se at close approach, explaining the experimental mass loss and delayed fission observed in [1]. The differential response confirms the crucial role of approach distance in Coulomb catalysis of fission isomer decay.

## 4. Conclusion

Our investigation of Coulomb-catalyzed decay in two $^{252}$Cf ternary channels reveals a crucial dependence on approach distance. The $^{8}$Be+$^{90}$Se system, with its close approach of 23.6 fm, experiences dramatic catalysis with half-life reductions of 30 orders of magnitude. In contrast, the $^{26}$Ne+$^{128}$Sn system, with its larger 65.6 fm separation, shows only moderate 3-order reduction due to weaker Coulomb interaction.

The picosecond traversal time through the foil provides sufficient duration for close-approach systems like $^{8}$Be+$^{90}$Se to undergo complete disruption, while more distant configurations remain largely unaffected. This differential response explains the selective mass loss and delayed fission patterns observed experimentally.

These results establish the TNS-DNS model with Coulomb catalysis as the definitive mechanism for foil-induced fission isomer decay, with approach distance being the critical parameter determining catalytic efficiency.

## REFERENCES


1. *Pyatkov Y.V., Kamanin D.V., others.* Manifestation of the $N = 32$, 34 Subshell Closures in the Ternary Decays of Heavy Nuclei // Phys. Atom. Nucl. — 2024. — V. 87. — P. 418–426.

2. *Pyatkov Y.V., Kamanin D.V., Kopach Y.N., Alexandrov A.A., Alexandrova I.A., Borzakov S.B., Voronov Y.N., Zhuchko V.E., Kuznetsova E.A., Panteleev T., Tyukavkin A.N.* Collinear Cluster Tripartition Channel in the Reaction $^{235}$U$(n_{\rm th}, f)$ // Phys. Atom. Nucl. — 2010. — V. 73, no. 8. — P. 1309–1316.

3. Search for Collinear Tripartition of the $^{252}$Cf Nucleus / Yu. V. Pyatkov, D. V. Kamanin, E. A. Sokol, A. A. Alexandrov, I. A. Alexandrova, S. V. Khlebnikov, S. V. Mitrofanov, Yu. E. Penionzhkevich, Yu. V. Ryabov, V. G. Tishchenko, S. R. Yamaletdinov // Proceedings of the International Conference on Dynamical Aspects of Nuclear Fission. — 2001. — P. 229–233.

4. *Kalandarov S.A., Tashkhodjaev R.B., Ganiev O.K.* Formation mechanism of decay fragments in spontaneous ternary fission of heavy nuclei // Phys. Lett. B. — 2024. — V. 850. — P. 138522.

5. *Adamian G.G., Antonenko N.V., Jolos R.V., Ivanova S.P., Melnikova O.I.* Potential Energy of Dinuclear System // Physics of Atomic Nuclei. — 1994. — V. 57, no. JINR-E4-93-377. — P. 1870–1880.

6. *Audi G., Wapstra A.H., Thibault C.* The AME2003 atomic mass evaluation // Nucl. Phys. A. — 2003. — V. 729. — P. 337–676.

7. *Migdal A.B.* Theory of Finite Fermi Systems and Applications to Atomic Nuclei // Libri Ricevuti e Recensioni. — 1967. — V. 66.

8. *Raman S., Jr. C.W.N., Tikkanen P.* Transition probability from the ground to the first-excited 2+ state of even-even nuclides // At. Data Nucl. Data Tables. — 2001. — V. 78, no. 1. — P. 1–128.

9. *Wong C.Y.* Interaction Barrier in Charged-Particle Nuclear Reactions // Phys. Rev. Lett. — 1973. — V. 31. — P. 766–769.