Induced decay of binary fission fragments during their passage through a solid foil

F.O. Otakhonov
Sh.A. Kalandarov, G.G. Adamian, N.V. Antonenko

Bogoliubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research, Dubna, Russia

Joint Workshop on Physics of Strong Interacting Systems

October 18-23, 2026, Nanjing, China

Outline

1. Introduction
2. Theoretical model: TNS and DNS
3. Influence of foil Coulomb field
4. Additional excitation from collective vibrations
5. Discussion and conclusions

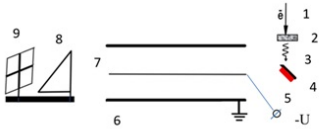
Experimental motivation

VEGA Setup (JINR):

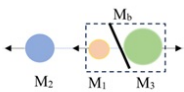
- Source: MT-25 microtron ($e^- \rightarrow \gamma$)
- Target: ^{242}Pu on Ti backing (1.5 μm)
- EGS: focusing $\pm 1.5^\circ$
- MCP (start), PIN diodes (stop + energy)

Kinematics (two-stage decay):

1. Binary fission: $M_2 + M_b$ (into foil)
2. M_b breaks up in Ti foil $\rightarrow$ LCP (M_1)+M_3
3. LCP (M_1) emitted **backward** and registered



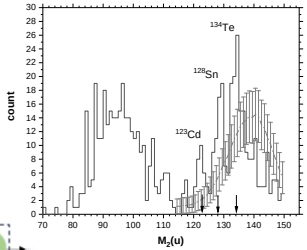
a)



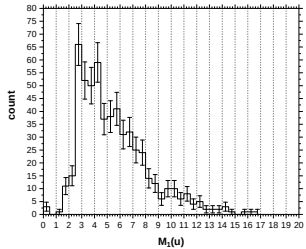
b)

Results:

- Excess of M_2 at ^{128}Sn, ^{134}Te (magic nuclei)
- LCP masses 3–16 u
- Yield: 10^{-3} per binary fission
  $\Rightarrow 10^3\times$ higher than conventional polar α



Mass spectrum of M_2

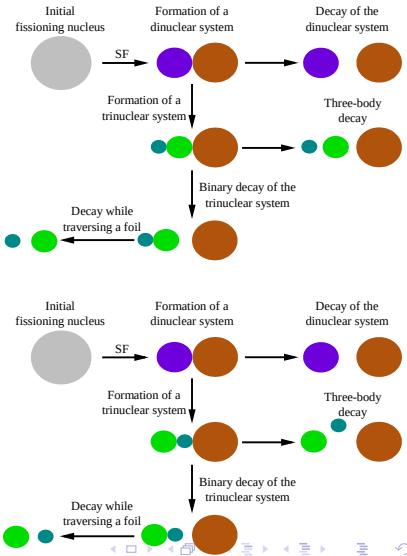


Mass spectrum of LCP M_1

Formation of cluster states in fission fragments

- During fission, a **trinuclear system (TNS)** may form[a].
- After the first binary decay of TNS, a **dinuclear system (DNS)** remains – the shape-isomer/cluster state.
- Example: $^{252}Cf \rightarrow {}^{122}Cd + {}^{130}Sn \rightarrow {}^{20}O + {}^{102}Zr + {}^{130}Sn$;
  remaining DNS – $^{20}O+{}^{102}Zr$;
  $^{235}U \rightarrow {}^{104}Mo + {}^{131}Sn \rightarrow {}^{100}Zr + {}^{4}He + {}^{131}Sn$;
  remaining DNS – $^{100}Zr + {}^{4}He$.

[a] Sh.A. Kalandarov et al., Phys. Lett. B **850**, 138522 (2024)



Potential energy of DNS

- Total potential energy of DNS:

$$U_{\mathbf{DNS}} = V_{\mathbf{12}} + Q_{\mathbf{DNS}}, \qquad Q_{\mathbf{DNS}} = B_{\mathbf{1}} + B_{\mathbf{2}} - B_{\mathbf{CN}}.$$

where B_i are mass excesses and $B_{\mathbf{CN}}$ is that of the compound nucleus.

- Interaction potential $V_{\mathbf{12}} = V_N + V_C$ [1]:

$$V_C(R_{\mathbf{12}}, Z_{\mathbf{1}}, Z_{\mathbf{2}}) = \frac{Z_{\mathbf{1}} Z_{\mathbf{2}} e^2}{R_{\mathbf{12}}} + \frac{Z_{\mathbf{1}} Z_{\mathbf{2}} e^2}{R_{\mathbf{12}}^3} \sqrt{\frac{20}{9\pi}} \left(R_{\mathbf{01}}^2 \beta_{\mathbf{1}} + R_{\mathbf{02}}^2 \beta_{\mathbf{2}} \right) + \frac{7 Z_{\mathbf{1}} Z_{\mathbf{2}} e^2}{3\pi R_{\mathbf{12}}^3} \left(R_{\mathbf{01}}^2 \beta_{\mathbf{1}}^2 + R_{\mathbf{02}}^2 \beta_{\mathbf{2}}^2 \right).$$

where $R_{\mathbf{12}}$ is the relative distance between the centers of the fragments, $R_{\mathbf{0}i} = r_{\mathbf{0}i} A_i^{\mathbf{1/3}}$ and quadruple deformation parameters in 2^+ state β_i.

- Nuclear part (double-folding)

$$V_N(R_{\mathbf{12}}) = \int \rho_{\mathbf{1}}(\mathrm{r}) F_{\mathbf{eff}}(\mathrm{r}, R_{\mathbf{12}}) \rho_{\mathbf{2}}(\mathrm{r} - \mathrm{R}_{\mathbf{12}})\, d\mathrm{r}\,:$$

$$F_{\mathbf{eff}}(\mathrm{r}, R_{\mathbf{12}})^{\mathbf{2}} = C_{\mathbf{0}} \left[F_{\mathbf{in}} + (F_{\mathbf{ex}} - F_{\mathbf{in}}) \frac{\rho_{\mathbf{0}} - \rho(\mathrm{r}, R_{\mathbf{12}})}{\rho_{\mathbf{0}}} \right]; \quad \rho(\mathrm{r}, R_{\mathbf{12}}) = \rho_{\mathbf{1}}(\mathrm{r}) + \rho_{\mathbf{2}}(\mathrm{r} - \mathrm{R}_{\mathbf{12}})$$

with $C_{\mathbf{0}} = 300$ MeV·fm$^{\mathbf{3}}$, $F_{\mathbf{in}} = 0.09$, $F_{\mathbf{ex}} = -2.59$, $\rho_{\mathbf{0}} = 0.17$ fm$^{\mathbf{-3}}$;

- Fermi density distribution:

$$\rho_i(r) = \frac{\rho_{\mathbf{0}}}{1 + \exp\left[(r - R_i(\theta_i))/a_{\mathbf{0}i}\right]}, \quad R_i(\theta_i) = R_{\mathbf{0}i} \left(1 + \beta_i Y_{\mathbf{20}}(\cos\theta_i)\right);$$

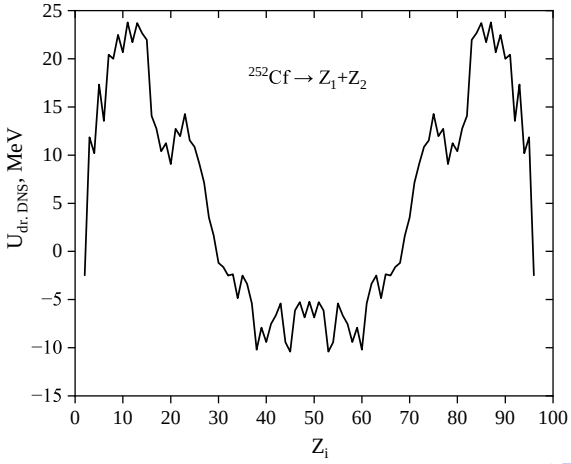
where $r_{\mathbf{0}i}$ and $a_{\mathbf{0}i}$ depend on fragment mass (light clusters: $r_{\mathbf{0}i} = 1.02$–1.16 fm, $a_{\mathbf{0}i} = 0.49$–0.56 fm; heavy nuclei: $r_{\mathbf{0}i} = 1.16$ fm, $a_{\mathbf{0}i} = 0.56$ fm) and Legendre polynomial $Y_{\mathbf{20}}$

[1] C. Y. Wong, Phys. Rev. Lett. 31, 766 (1973)

[2] A.B. Migdal, Theory of Finite Fermi Systems (Interscience, 1967):

DNS driving potential

- The driving potential for ^{252}Cf shows minima near $Z = 38$–48 (light group) and $Z = 50$–60 (heavy group) – consistent with asymmetric fission.



TNS driving potential

- Total potential energy of TNS:

$$U_{\mathrm{TNS}} = V_{12} + V_{23} + V_{13} + Q_{\mathrm{TNS}}, \quad Q_{\mathrm{TNS}} = B_1 + B_2 + B_3 - B_{\mathrm{CN}}$$

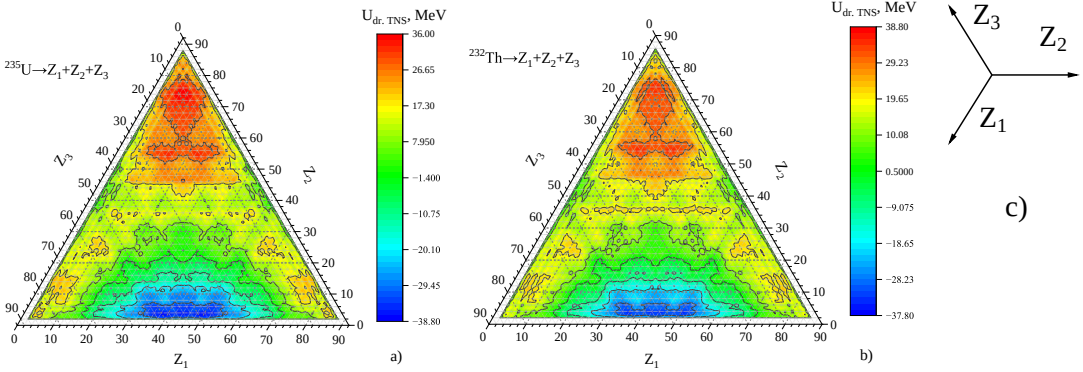


Figure: Driving potential for TNS (Dalitz-like plot).

Kinetic energy distribution and closest approach

After TNS decay, the DNS and the third fragment (e.g., Sn) separate. From conservation of momentum and energy:

$$\begin{cases} V_{\text{TNS}}(R_{12}^m, R_{23}^b) & = V_{12}(R_{12}^m) + E_{\text{kin}}^{\text{DNS}} + E_{\text{kin}}^3 \\ m_{\text{DNS}}\, v_{\text{DNS}} & = -m_3\, v_3, \end{cases}$$

where R_{12}^m is the minimum distance in DNS, R_{23}^b is the top of the barrier between DNS and fragment 3. The closest approach distance R_{app} between DNS and foil nucleus in a head-on collision is found from momentum and energy conservation:

$$\begin{cases} E_{\text{kin}}^{\text{DNS}} = V_{C_1 - foil}(R_{\text{app}}) + V_{C_2 - foil}(R_{12}^m + R_{\text{app}}) + E_{\text{kin}}^{\text{DNS*}} + E_{kin}^{foil}, \\ (m_1 + m_2) v_{\text{DNS}} = (m_1 + m_2) v_{\text{DNS}}^* + m_{foil}\, v_{foil}. \end{cases}$$

For the systems studied:

$$R_{\text{app}}(\text{Cu} \leftarrow \text{C+Mo}) = 41.4 \text{ fm}, \quad R_{\text{app}}(\text{Cu} \leftarrow \text{O+Zr}) = 42.4 \text{ fm}.$$

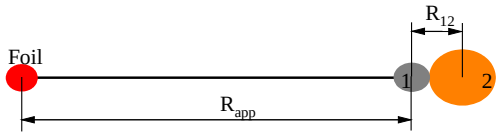
[2] F.O. Otakhonov et al., Phys. Lett. B **872**, 140088 (2026)

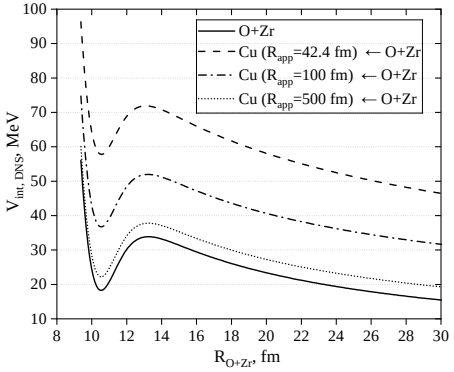
Interaction of DNS with a foil nucleus

- The total potential felt by the DNS in the field of a foil nucleus at a distance $R_{\mathbf{app}}$ is

$$V_{\mathbf{total}}(R_{12}, R_{\mathbf{app}}) = V_{12}(R_{12}) + V_{C_{\mathbf{1}-foil}}(R_{\mathbf{app}}) + V_{C_{\mathbf{2}-foil}}(R_{12} + R_{\mathbf{app}}).$$

- DNS (e.g. ^{20}O+^{102}Zr) passes near a foil nucleus (Cu, Ti)[3].
- At closest approach $R_{\mathbf{app}}$, the Coulomb field modifies the DNS interaction potential.
- The barrier for the decay of DNS is lowered.





[3]F.O. Otakhonov et al., Phys. Lett. B **872**, 140088 (2026)

Barrier height reduction

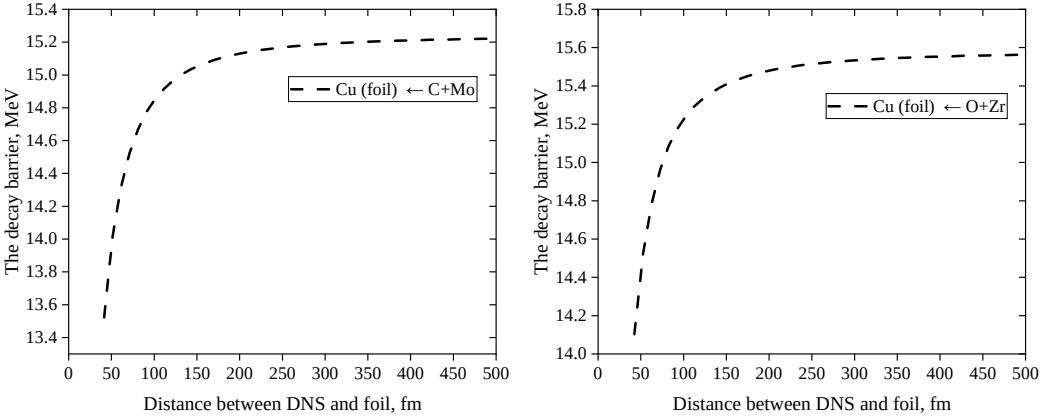


Figure: Changing the decay barrier of DNS (C+Mo and O+Zr) according to the distance between DNS and Cu foil.

[3]F.O. Otakhonov et al., Phys. Lett. B **872**, 140088 (2026)

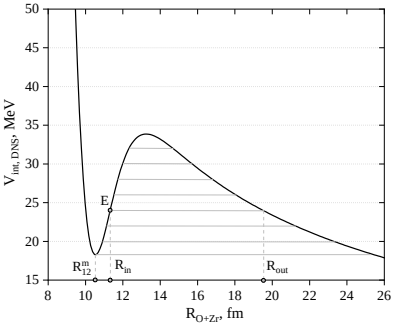
Half-life calculations (WKB method)

The excitation energy E_x dependent averaged tunneling probability:

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

where:

- The probability that the DNS possesses a specific internal energy E ($0 \le E \le E_x$) is described by a normalized Boltzmann distribution $W(E) = \frac{\exp(-E/T_{DNS})}{T_{DNS}(1-\exp(-E_x/T_{DNS}))}$ and the temperature is given by the Fermi gas model $T_{\mathrm{DNS}} = \sqrt{E_x/a}$, with the level density parameter $a = (A_1 + A_2)/8$.
- For a fixed energy E, the tunneling probability through the barrier is given by the WKB approximation $P = \frac{1}{1+\exp\left(\frac{2}{\hbar}\int_{R_{\mathbf{in}}}^{R_{\mathbf{out}}} \sqrt{2\mu(V_{\mathbf{12}}(R)-V_{\mathbf{12}}(R^m_{\mathbf{12}})-E)}\,dR\right)}$ where R_{in} and R_{out} are the classical turning points (depend on E).
- The half-life is obtained from the oscillation frequency ω_0 in the potential pocket $T_{1/2} = \frac{\pi \ln 2}{\omega_0 P_{\mathbf{av}}}$, $\omega_0 = \sqrt{\frac{V''_{\mathbf{12}}(R^m_{\mathbf{12}})}{\mu}}$.



Half-life modification by Cu foil

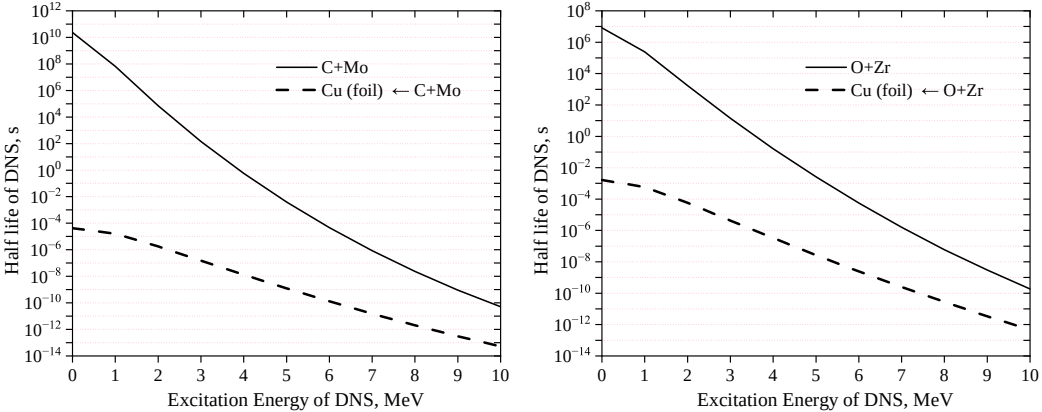
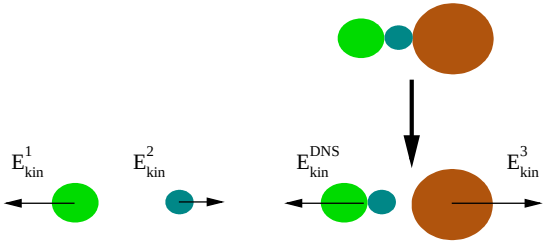


Figure: Half-life with (dashed) and without (solid) Coulomb field of Cu.
Reduction factors: 10^{15}–10^{3} (C+Mo) and 10^{10}–10^{2} (O+Zr) for $E_x = 0$–10 MeV.

[3] F.O. Otakhonov et al., Phys. Lett. B **872**, 140088 (2026)

Experimental observation of low-energy LCP from fission fragments

Low-energy light charged particles (LCP) detected with masses $M \approx 3$–16 u, mostly α particles.



Half-life of ^{100}Zr+α with Ti foil

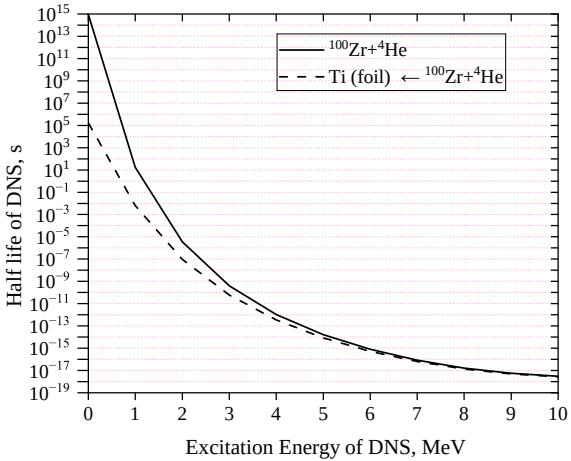


Figure: Half-life with (dashed) and without (solid) Coulomb field of Ti.

Dynamics in the Coulomb field

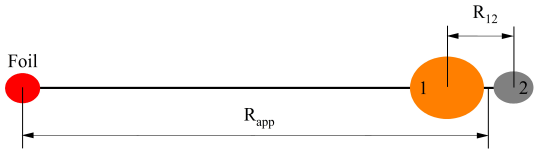
$$\hbar\lambda = 1MeV \text{ (friction strength)}, \quad \mu_{12} = \frac{A_1 A_2}{A_1 + A_2}, \quad \mu_{12Foil} = \frac{(A_1 + A_2)A_{\text{foil}}}{A_1 + A_2 + A_{\text{foil}}}.$$

Incident energy: $E_{\text{cm}} = \dfrac{A_{\text{foil}}}{A_1 + A_2 + A_{\text{foil}}} E_{\text{kDNS}}$, $v_{\text{CM}} = \sqrt{2E_{\text{cm}}/(\mu_{12Foil})}$.

Equations of motion (collinear):

$$\mu_{12}\ddot{R_{12}} = -\lambda\mu_{12}\dot{R_{12}} - \frac{A_2}{A_1 + A_2} \frac{Z_1 Z_{\text{foil}} e^2 (R_{app} + \frac{A_2}{A_1+A_2} R_{12})}{|R_{app} + \frac{A_2}{A_1+A_2} R_{12}|^3} + \frac{A_1}{A_1 + A_2} \frac{Z_2 Z_{\text{foil}} e^2 (R_{app} - \frac{A_1}{A_1+A_2} R_{12})}{|R_{app} - \frac{A_1}{A_1+A_2} R_{12}|^3} - \frac{dV_{\text{DNS}}}{dR_{12}},$$

$$\mu_{12Foil}\ddot{R_{app}} = \frac{Z_1 Z_{\text{foil}} e^2 (R_{app} + \frac{A_2}{A_1+A_2} R_{12})}{|R_{app} + \frac{A_2}{A_1+A_2} R_{12}|^3} + \frac{Z_2 Z_{\text{foil}} e^2 (R_{app} - \frac{A_1}{A_1+A_2} R_{12})}{|R_{app} - \frac{A_1}{A_1+A_2} R_{12}|^3}.$$



Energy dissipation during traversal

- In the experiment with Ti foil, the DNS ^{100}Zr + ^{4}He experiences different Coulomb forces on Zr and ^{4}He from the Ti nucleus.
- This leads to **collective vibrations** of the DNS.
- Vibrations damp in time, converting energy into intrinsic excitation.
- Friction force $-\lambda\mu_{12}\dot{R_{12}}$ converts relative motion into internal excitation.
- Dissipated energy in one encounter with a foil nucleus:

$$\Delta E_{\text{encounter}} = \int \lambda\mu_{12}|\dot{R_{12}}|^2 dt \approx \lambda\mu_{12}\sum_i (\Delta R_{12_i})^2.$$

- For ^{100}Zr+^{4}He system and Ti foil: $\Delta E_{\text{encounter}} = 0.00016$ MeV per nucleus.
- Foil thickness corresponds to about 10 000 Ti nuclei along the path.
- Total energy gain: $E_{\text{dis,total}} \approx 10\,000 \times 0.00016 = 1.6$ MeV.

Half-life of ^{100}Zr+α with Ti foil

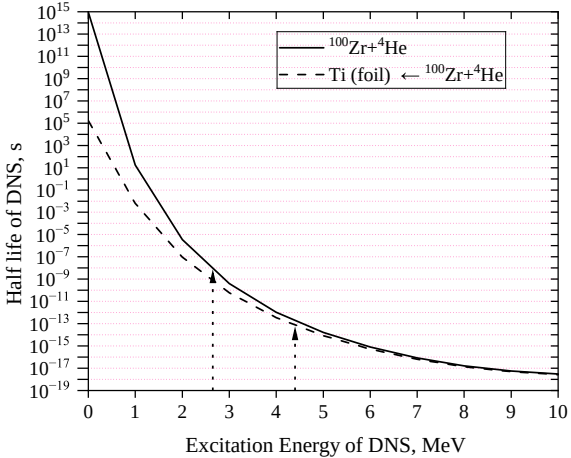


Figure: Half-life of DNS ^{100}Zr+^{4}He as function of E_x. Without foil, $T_{1/2} = 10^{-8}$ s at $E_x \approx 2.8$ MeV. With foil, at $E_x \approx 4.4$ MeV, $T_{1/2} < 10^{-13}$ s (transit time).

Discussion and conclusions

- The Coulomb field of the Ti foil **lowers the decay barrier** (direct effect).
- Additionally, it induces **collective vibrations** that increase the excitation energy of DNS.
- These effects together leads the DNS halflife time to be less than traversal time ($\sim 10^{-13}$ s).

Thank you!

Questions and comments are welcome.

Impact parameter distribution

- The interaction strength between DNS and a foil nucleus strongly depends on the impact parameter b.
- Only almost head-on collisions ($b \approx 0$) lead to a significant lowering of the decay barrier.
- For a uniform flux of DNS hitting the foil, the probability to have a closest approach distance in the interval $[R_i, R_{i+1}]$ is proportional to the area of the corresponding ring:

$$\Delta S_i = \pi \left(R_{i+1}^2 - R_i^2 \right).$$

- The total area (normalisation) is $S_{\text{tot}} = \sum_i \Delta S_i$.
- If P_i is the probability of decay for that interval (extracted from detailed trajectory calculations), the overall decay probability is

$$P_{\text{decay}} = \frac{1}{S_{\text{tot}}} \sum_i \Delta S_i \, P_i.$$