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Multinucleon transfer reactions with relativistic TDDFT

Dandan Zhang 张丹丹

Institute of Theoretical Physics, Chinese Academy of Sciences

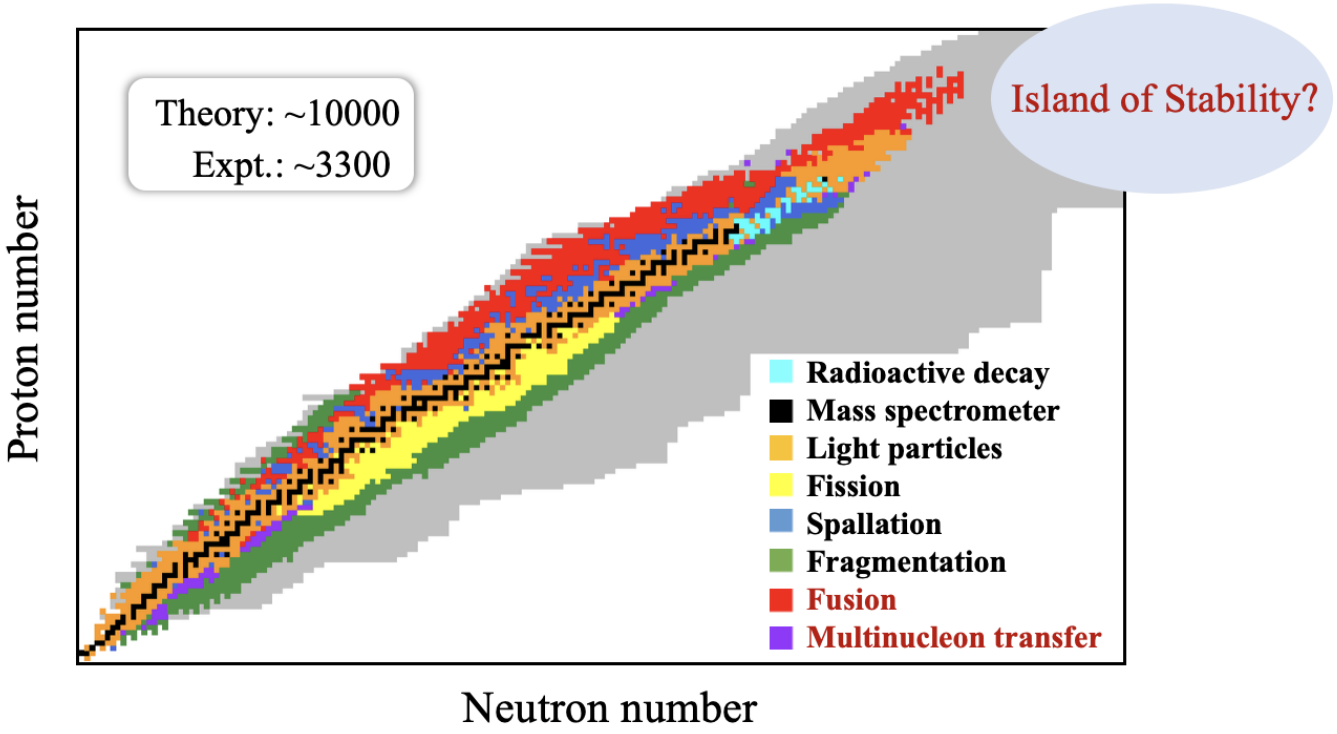
Oct. 20, 2026

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- Introduction
- Relativistic time-dependent density functional theory
- Multinucleon transfer reaction
- Summary and outlook

Heavy-ion reactions

- Heavy-ion reactions, induced by ions heavier than α particles, are one of the important methods for synthesizing new nuclides.



Thoennessen, *The Discovery of Isotopes* (2016)
Xia et al., ADNDT 121, 1 (2018)

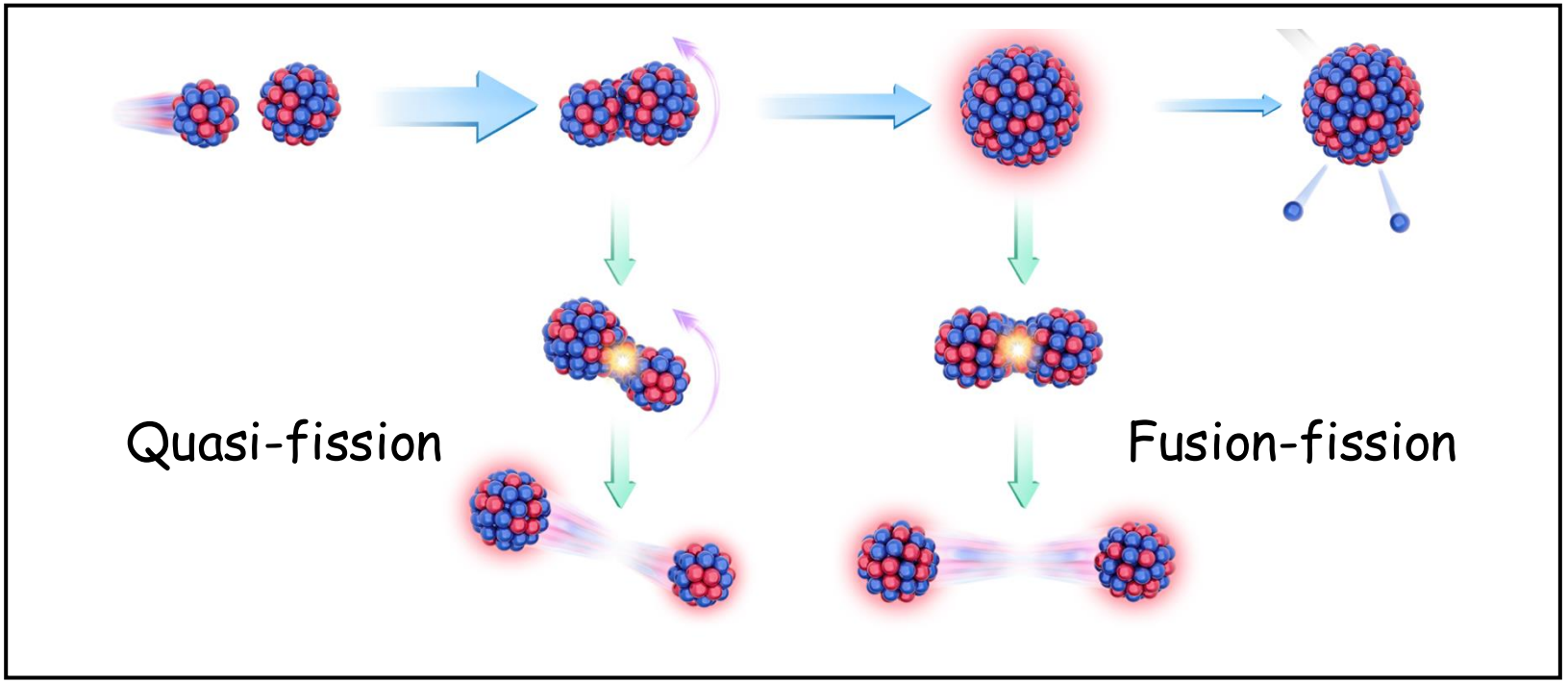
- Fusion: synthesizing superheavy nuclei (SHN).
- Multinucleon transfer (MNT) reactions: synthesizing neutron-rich nuclei.

Jiang, **DDZ**, Zhou. Physics 54, 599 (2025)

Fusion: Neutron-deficient superheavy nuclei

- Fusion is the only successful method for synthesizing SHN to date.
- All the superheavy nuclei produced via fusion are neutron-deficient.
- It meets the challenge of the low cross-section when synthesizing new elements.

Münzenberg et al., EPJA 59, 21 (2023); Oganessian, EPJA 60, 227 (2024); Zhang et al., NST 36, 204 (2025)

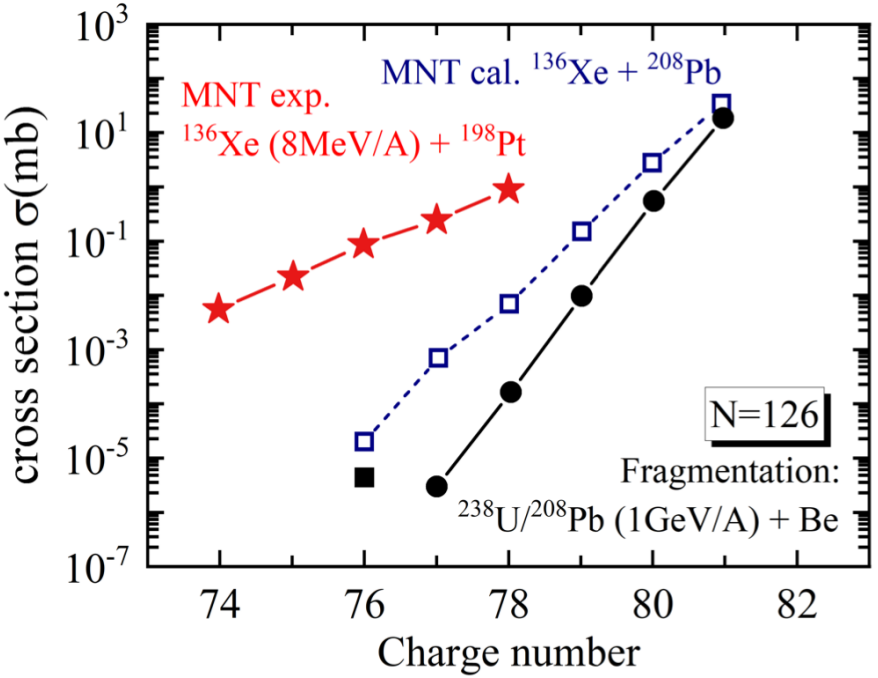


Jiang, **DDZ**, Zhou. Physics 54, 599 (2025)

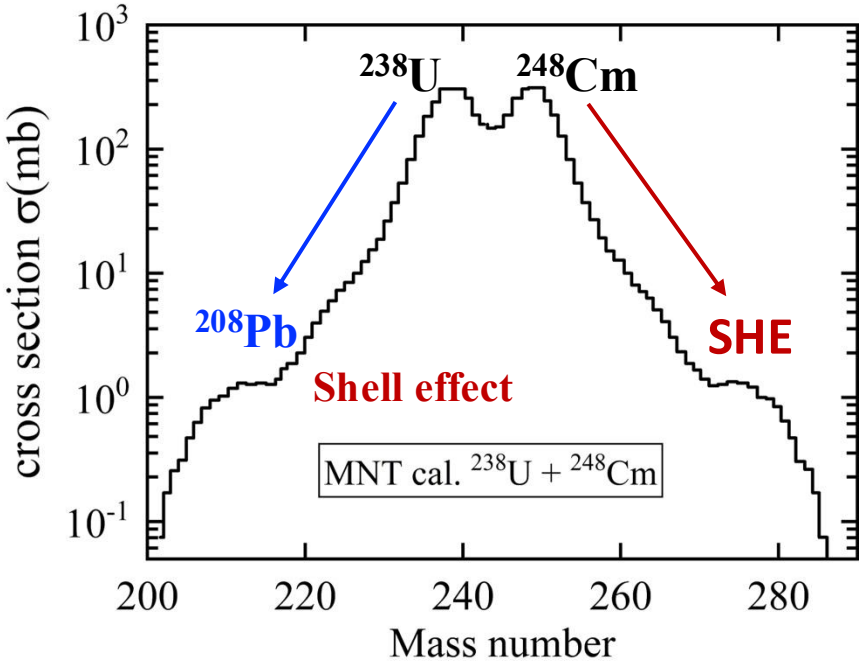
MNT: Neutron-rich nuclei

- Recently, the MNT reaction has been suggested as a possible pathway for the synthesis of neutron-rich heavy and superheavy nuclei
  - ✓ Neutron-rich region around $N = 126$
  - ✓ Possible reaction mechanism

Complex mass and angular distributions!



Zagrebaev and Greiner, PRL 101,122701 (2008)
Watanabe et al., PRL 115,172503 (2015)



Zagrebaev and Greiner, JPG 34, 2265 (2007)
Zagrebaev and Greiner, PRC 87, 034608 (2013)

Theoretical models for MNT reactions

- The multinucleon transfer process is a complex quantum many-body dynamical problem. A broad range of theoretical approaches has been developed:

  - ✓ Coupled channels — Thompson, Comput. Phys. Rep. 7, 167 (1988); Scamps & Hagino, PRC 92, 054614 (2015) …
  - ✓ Dinuclear System Model — Adamian, Antonenko, and Scheid, NPA 618, 176 (1997); Adamian et al., NPA 633, 409 (1998); Adamian et al., PRC 81, 024604 (2010); Feng, PRC 95, 024615 (2017); Zhu et al., JPG 42, 085102 (2015) …
  - ✓ GRAZING Model — Winther, NPA 572, 191 (1994); Yanez and Loveland, PRC 91, 044608 (2015);Wen et al., PRC 99, 034606 (2019) …
  - ✓ Langevin Model — Zagrebaev and Greiner, PRL 101, 122701 (2008); Zagrebaev and Greiner, PRC 78, 034610 (2008); Zhu, PLB 849, 138423 (2024); Dai et al., PRC 109, 024617 (2024) …
  - ✓ Quantum Molecular Dynamics — Wang et al., PRC 65, 064608 (2002); Li et al., PRC 93, 014618 (2016); Zhao et al., PRC 92, 024613 (2015) …
  - ✓ Time-Dependent Density Functional Theory (TDDFT) — Simenel, PRL 105, 192701 (2010); Sekizawa and Yabana, PRC 88, 014614 (2013); Wu and Guo, PRC 100, 014612 (2019), Zhang et al., PRC 109, 024614 (2024);
  - ✓ Stochastic Mean-Field / TDRPA — Li et al., PRC 110, 034611 (2024); Zhang et al., PLB 869, 139828 (2025) …
  - ✓ Other approaches — Simenel, PRL 106, 112502 (2011); Ayik et al., PRC 97, 054618 (2018); Yilmaz et al., PRC 98, 034604 (2018); Sekizawa and Ayik, PRC 102, 014620 (2020); Gao, Sekizawa, and Zhu, PRC 112, 014602 (2025);…

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Relativistic TDDFT

- Relativistic TDDFT has been developed and applied to a series of nuclear dynamical phenomena.

Ren, Zhao, and Meng, PRC 102, 044603 (2020)
Ren, Zhao, and Meng, PLB 801, 135194 (2020)
Ren, Zhao, and Meng, PRC 105, L011301 (2022)
Ren, Zhao, Vretenar, Nikšić, Zhao, Meng, PRC 105, 044313 (2022)
Ren, Vretenar, Nikšić, Zhao, Zhao, Meng, PRL 128, 172501 (2022)

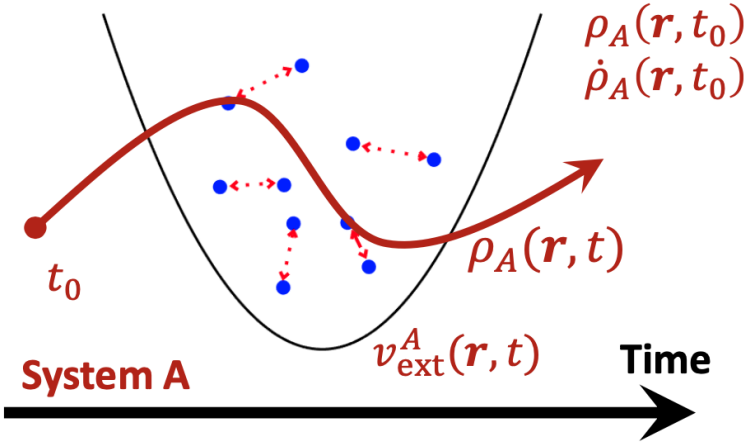
Li, Vretenar, Ren, Nikšić, Zhao, Zhao, Meng, PRC 107, 014303 (2023)
Li, Vretenar, Nikšić, Zhao, Meng, PRC 110, 034302 (2024)
Li, Zhao, Meng, PLB 856, 138877 (2024)
DDZ, Vretenar, Nikšić, Zhao, Meng, PRC 109, 024614 (2024)
DDZ, Li, Vretenar, Nikšić, Ren, Zhao, Meng, PRC 109, 024316 (2024)
DDZ, Vretenar, Nikšić, Zhao, Meng, PLB 869, 139828 (2025)
DDZ, Li, Vretenar, Nikšić, Ren, Zhao, Meng, PRC 114, 014628 (2026)

- **Idea:** Transforming the time-dependent many-body problem to a time-dependent one-body problem.

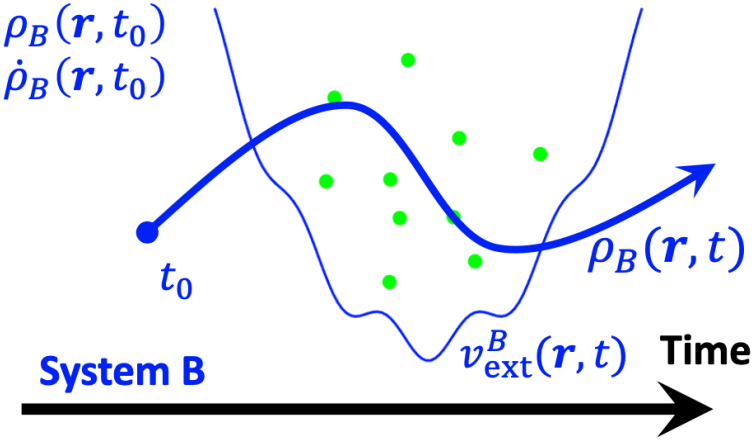
Runge and Gross, PRL 52, 997(1984)
Leeuwen, PRL 82, 3863(1999)

Initial condition:

$$\rho_A(\boldsymbol{r}, t_0) = \rho_B(\boldsymbol{r}, t_0)$$
$$\dot{\rho}_A(\boldsymbol{r}, t_0) = \dot{\rho}_B(\boldsymbol{r}, t_0)$$



Time-dependent many-body problem

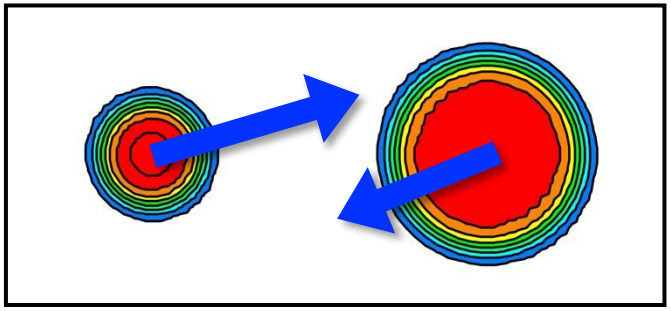


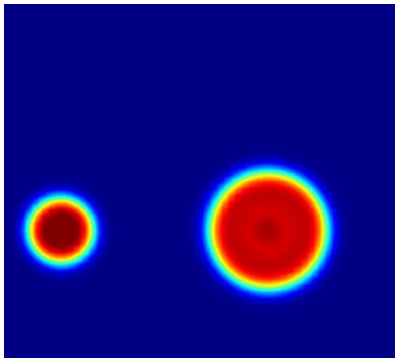
Time-dependent one-body problem

Figure is taken from Z. X. Ren

Particle number and angular momentum projection

- TDDFT gives the most probable reaction path, and the wavefunction of reaction products typically lacks well-defined quantum numbers (particle number, spin)





- We extended relative TDDFT to include particle number projection and angular momentum projection.

DDZ, Vretenar, Nikšić, Zhao, Meng, PRC 109, 024614 (2024)
DDZ, Vretenar, Nikšić, Zhao, Meng, PLB 869, 139828 (2025)

Particle number projection

Particle number projection operator:

$$\hat{P}_n^V = \frac{1}{2\pi}\int d\theta\, e^{i\theta(n-\hat{N}_V)}.$$

$$P(n) = \langle\Psi|\hat{P}_n^V|\Psi\rangle, \quad P(n) = \frac{\langle\Psi|\hat{P}_n^V\hat{P}_N|\Psi\rangle}{\langle\Psi|\hat{P}_N|\Psi\rangle}.$$

Angular momentum projection

Angular momentum projection operator:

$$\hat{P}_{MK}^S = \frac{2S+1}{16\pi^2}\int d\Omega \left(D_{MK}^S(\Omega)\right)^* \hat{R}(\Omega).$$

$$P(S,K) = \langle\Psi|(\hat{P}_{MK}^S)^+\hat{P}_{MK}^S|\Psi\rangle = \langle\Psi|\hat{P}_{KK}^S|\Psi\rangle.$$

Simenel, PRL 105, 192701 (2010); Sekizawa and Yabana, PRC 88,014614 (2013)

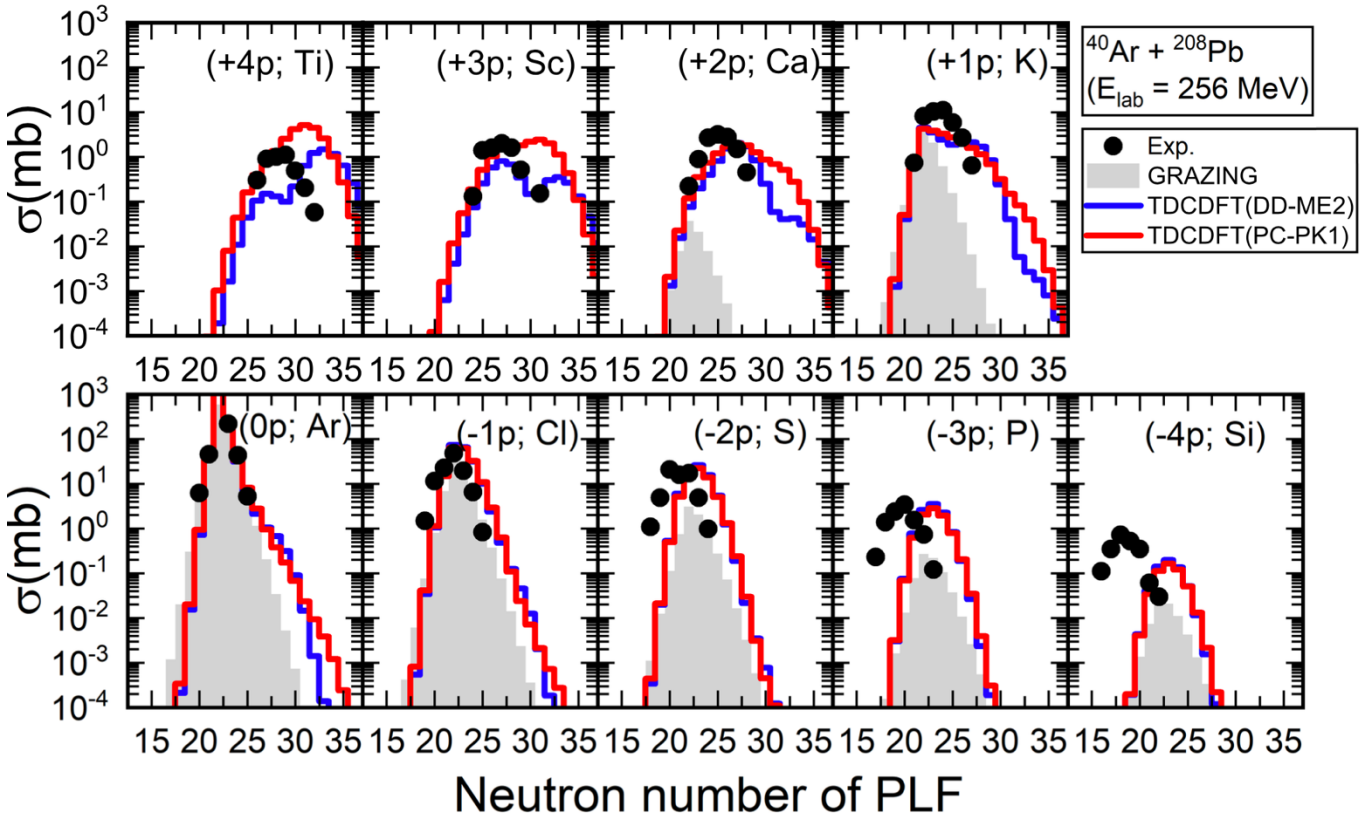
Scamps et al., PRC 108, L061602 (2023)

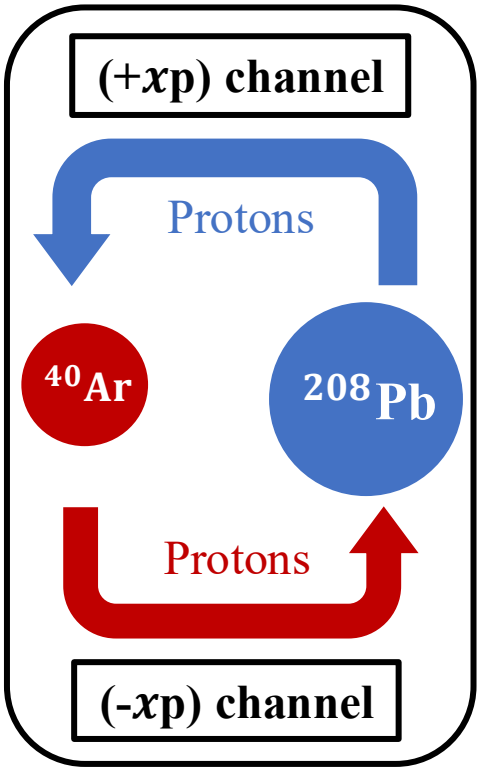
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  - ✓ Mass distribution: cross-section
  - ✓ Spin distribution
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Multinucleon transfer cross-sections

- For the MNT reaction ^{40}Ar + ^{208}Pb,





D. D. Zhang, D. Vretenar, T. Nikšić, P. W. Zhao, and J. Meng, Phys. Rev. C 109, 024614 (2024)

De-excitation: Yang, **DDZ**, Vretenar, Li, Niksic, Zhao, Meng, PRC 113, 044626 (2026)

- ✓ Relativistic TDDFT gives a reasonable description of the cross-section.
- ✓ The inclusion of the de-excitation process would improve the results.

Fragment intrinsic spins and their correlations

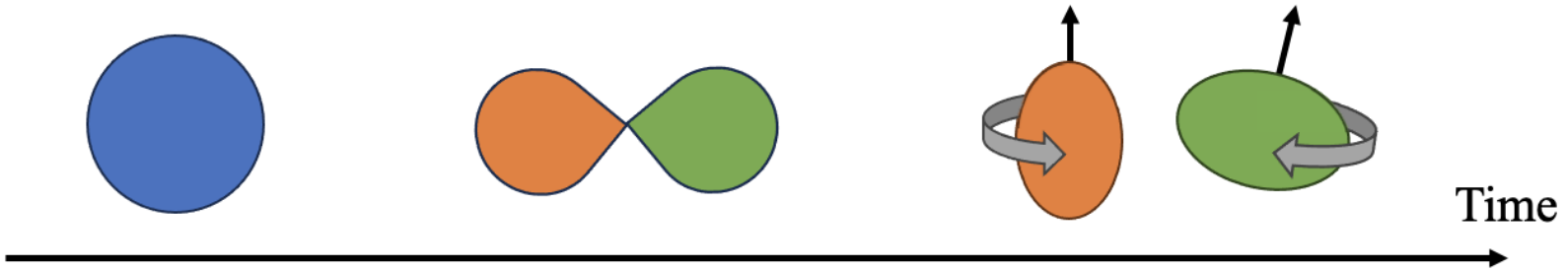
- In a system that consists of two fragments, the conservation of angular momentum requires

$$J = S^L + S^H + \Lambda.$$

S^L, S^H: spins of two fragments. Λ: orbital angular momentum.

- The spontaneous fission of even-even nuclei ($J = 0$) is a typical case.

The generation of spins and their correlations.

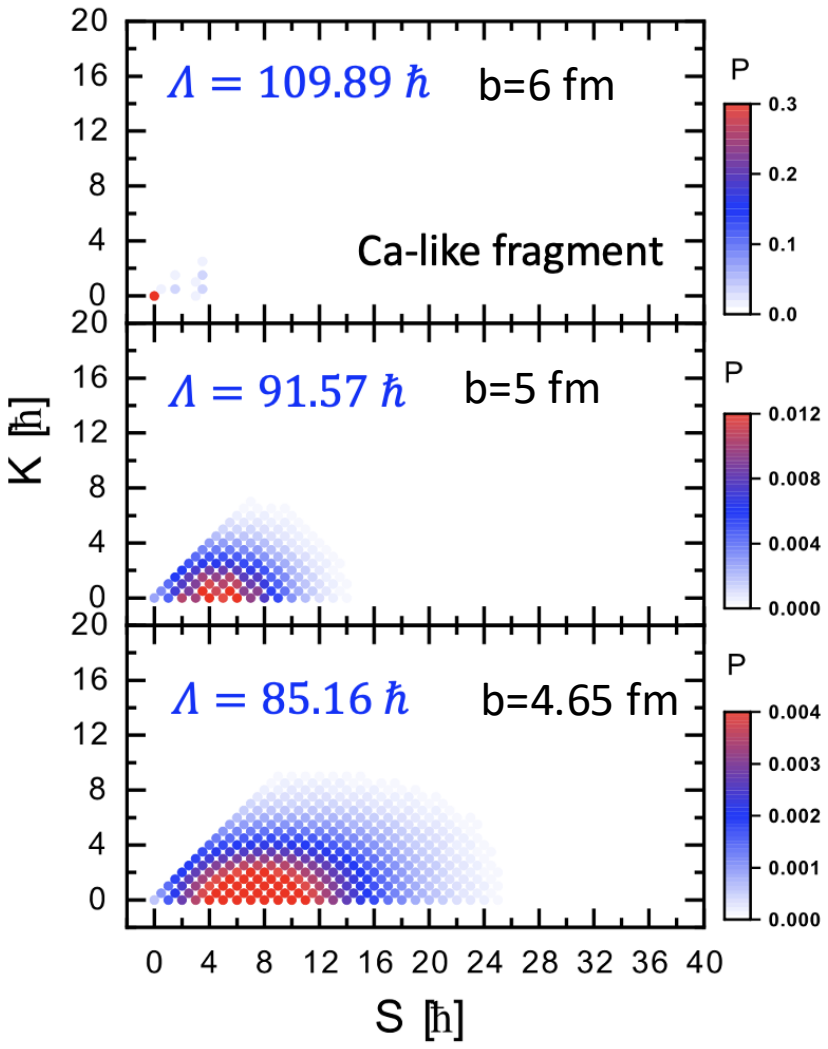


The fragment intrinsic spins and their correlations in fission have attracted broad interest.

Wilson et al., Nature 590, 566 (2021)
Bulgac et al., PRL 126, 142502 (2021); Bulgac et al., PRL 128, 022501 (2022); Scamps et al., PRC 108 L061602 (2023)

- **Lack such investigations in reactions** (more complex and challenging).

Spin distributions in the MNT reactions ^{40}Ca + ^{208}Pb



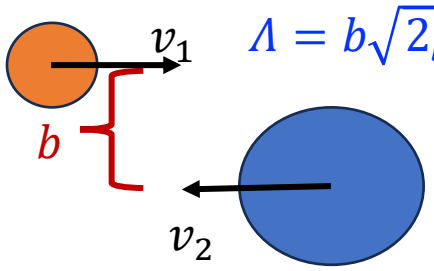
$$J = S^L + S^H + \Lambda.$$

At the beginning, $J = 0 + 0 + \Lambda$

Almost no nucleon transfer

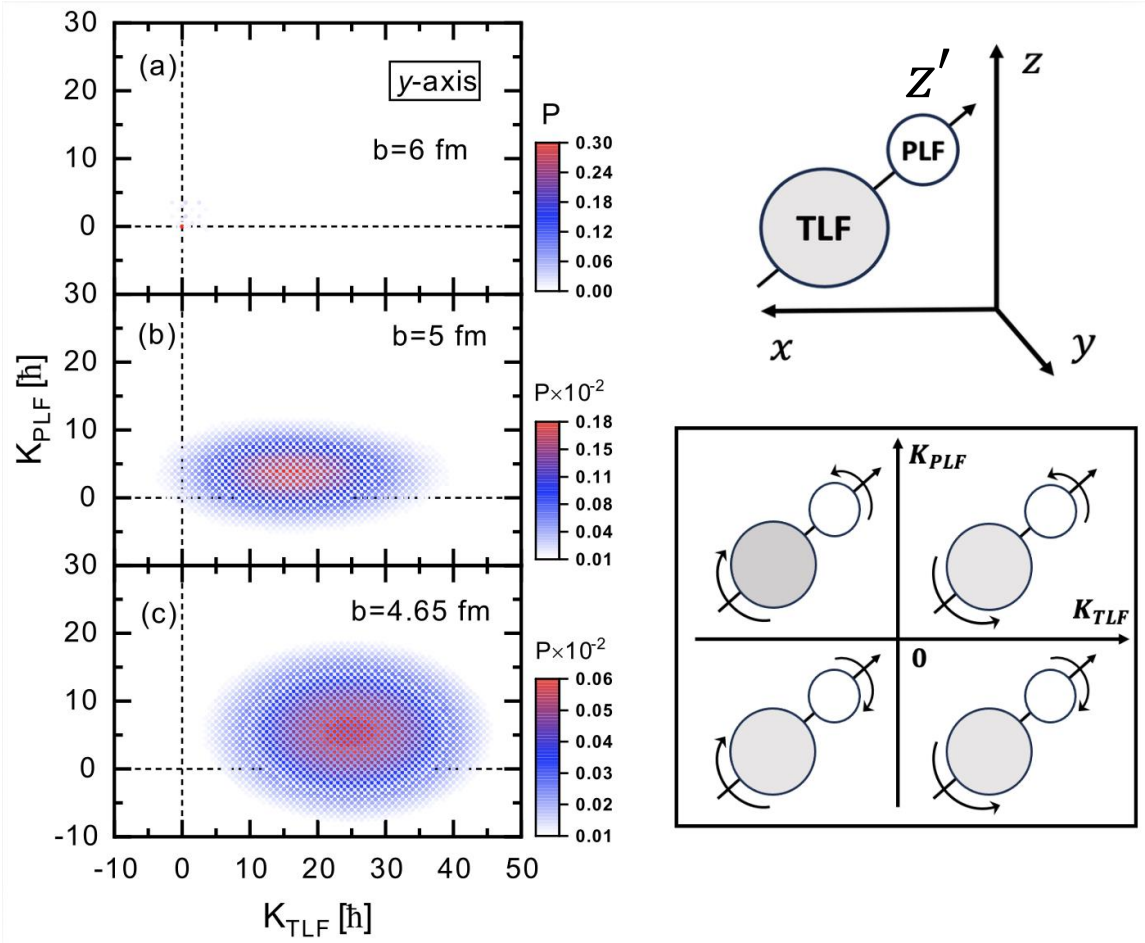
- ✓ The spins are generated.
- ✓ The orbital angular momentum is converted into intrinsic spin.

Nucleon transfer



DDZ, Vretenar, Nikšić, Zhao, Meng, PLB 869, 139828 (2025)

The joint spin distribution of two fragments (y-axis)



Joint spin distribution:

$$P(K_{\mathrm{PLF}}, K_{\mathrm{TLF}}) = \langle \Psi | \hat{P}_{K_P} \hat{P}_{K_T} | \Psi \rangle.$$

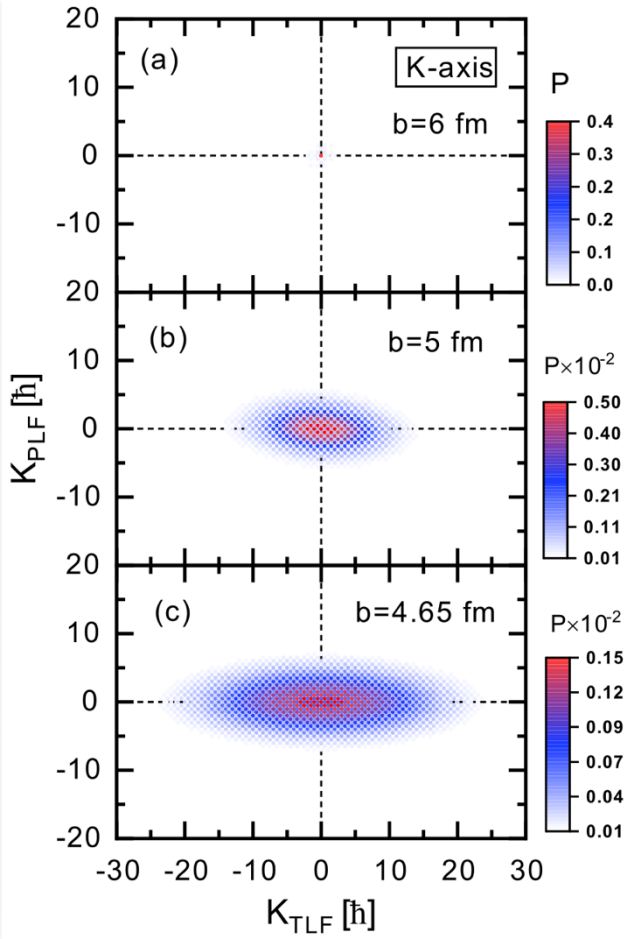
$K_{\mathrm{PLF}} K_{\mathrm{TLF}} > 0$, wriggling

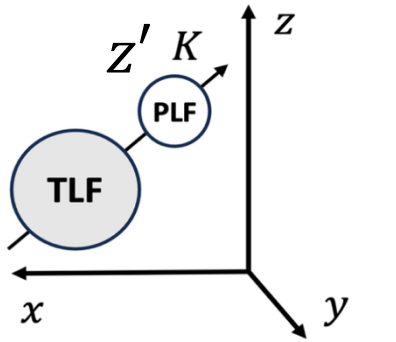
$K_{\mathrm{PLF}} K_{\mathrm{TLF}} < 0$, bending

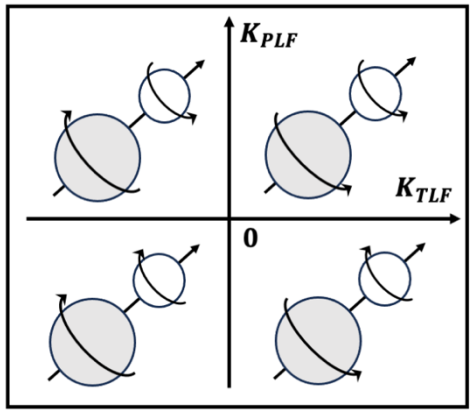
Various collective rotational modes are revealed.

DDZ, Vretenar, Nikšić, Zhao, Meng, PLB 869, 139828 (2025)

The joint spin distribution of two fragments (z'-axis)







Joint spin distribution:

$$P(K_{\mathrm{PLF}}, K_{\mathrm{TLF}}) = \langle \Psi | \hat{P}_{K_P} \hat{P}_{K_T} | \Psi \rangle.$$

$K_{\mathrm{PLF}} K_{\mathrm{TLF}} > 0$, titling

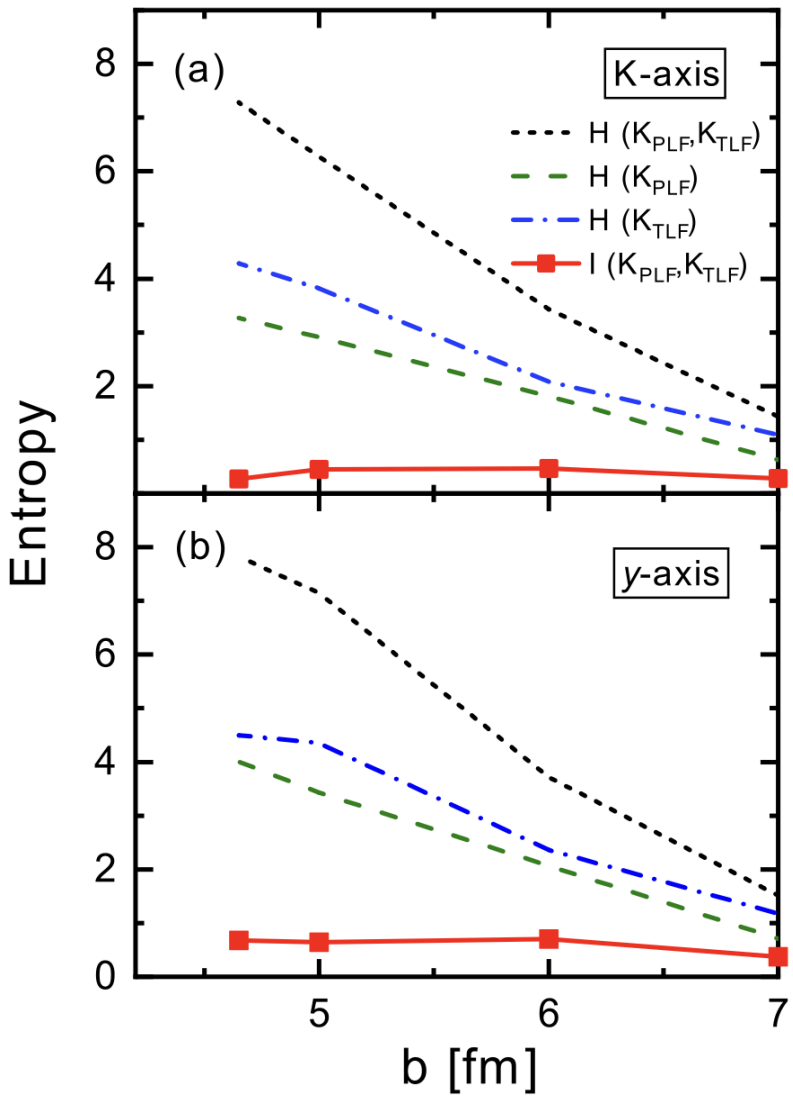
$K_{\mathrm{PLF}} K_{\mathrm{TLF}} < 0$, twisting

Various collective rotational modes are revealed.

DDZ, Vretenar, Nikšić, Zhao, Meng, PLB 869, 139828 (2025)

How to quantify the correlations between the two fragments' spins?

The correlations between two fragments



Mutual information I(A, B)

$$I(A,B) = H(A) + H(B) - H(A,B).$$

$$H(A) = -\sum_A P(A)\ln\big(P(A)\big).$$

$$H(A,B) = -\sum_{A,B} P(A,B)\ln\big(P(A,B)\big).$$

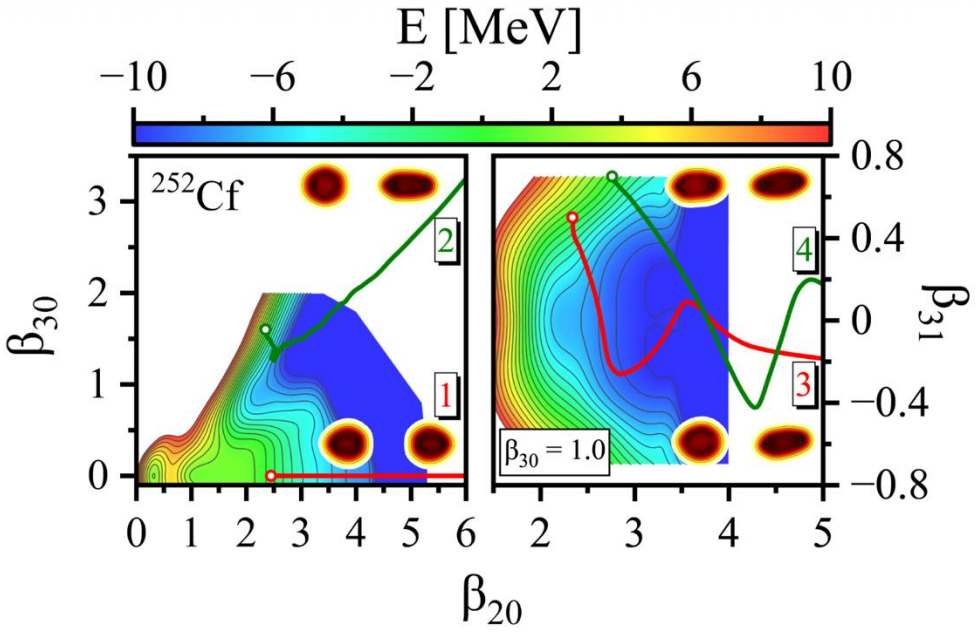
The smaller mutual information indicates fewer correlations.

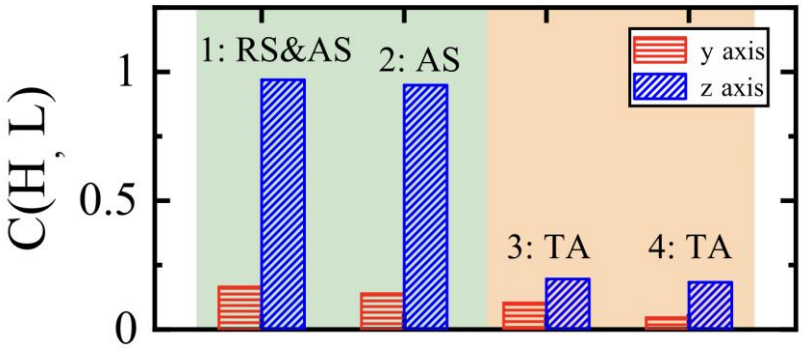
The spins of the two fragments are correlated, but the correlations are rather weak.

DDZ, Vretenar, Nikšić, Zhao, Meng, PLB 869, 139828 (2025)

Correlations in fission

Correlation indicator: $C(A,B) = \dfrac{I(A,B)}{\sqrt{H(A)H(B)}}$





RS&AS: Reflection and axial symmetries
AS: Axial symmetries
TA: Triaxial Asymmetries

B. Li, **D. D. Zhang**, et al., Phys. Rev. Lett. 136, 252502 (2026)

Breaking axial symmetry reduces spin-spin correlations of fission fragments.

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Summary and outlook

- Relativistic TDDFT is extended to include particle-number and angular-momentum projection, then applied to the MNT reaction.

  ✓ Mass distribution

  DDZ, Vretenar, Niksic, Zhao, Meng PRC 109, 024614 (2024)
  DDZ, Li, Vretenar, Niksic, Zhao, Meng, PRC 109, 024316 (2024)
  DDZ, Li, Vretenar, Niksic, Zhao, Meng, PRC 114, 014628 (2026)
  Yang, **DDZ**, Vretenar, Li, Niksic, Zhao, Meng, PRC 113, 044626 (2026)

  ✓ Spin distribution

  DDZ, Vretenar, Niksic, Zhao, Meng, PLB 869, 139828 (2025)
  Li, **DDZ**, Vretenar, Niksic, Zhao, Meng, PRL 136, 252502 (2026)

- MNT reaction: What candidate reaction conditions are needed to synthesize new superheavy and neutron-rich nuclei?

  ✓ Xe+Pt, Xe+Pb, Xe+U

  ✓ U+Bi, U+U, U+Cm

  Mass distribution
  Angular distribution
  Reaction mechanism
  ….
  In progress

Collaborators

- Institute of Theoretical Physics, China: Yi-Ming Jiang, Shan-Gui Zhou
- Nankai University, China: Zhengxue Ren
- Peking University, China: Bo Li, Jie Meng, Yaochen Yang, Pengwei Zhao
- University of Zagreb, Croatia: Tamara Nikšić, Dario Vretenar

Thanks for your attention!