59th Zakopane Conference on Nuclear Physics, 2026

Generation of Spin in Fission Fragments from Microscopic Theory

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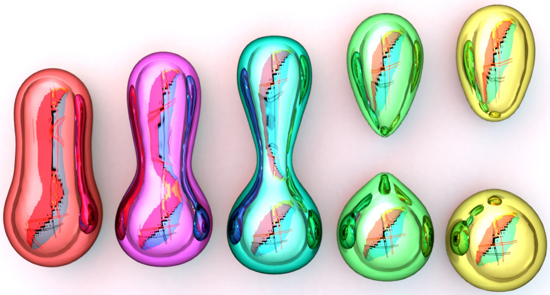
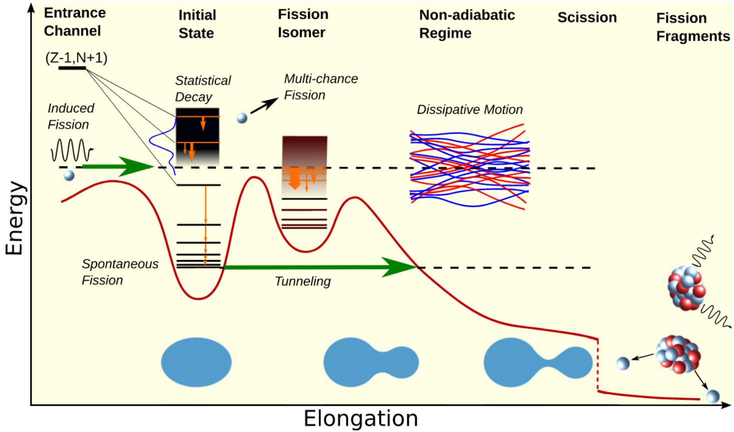
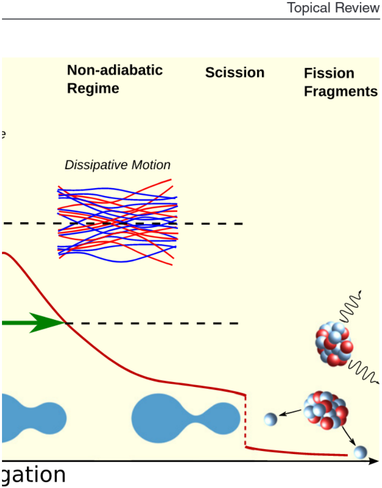


J. Phys. G: Nucl. Part. Phys. **47** (2020) 113002 Topical Review

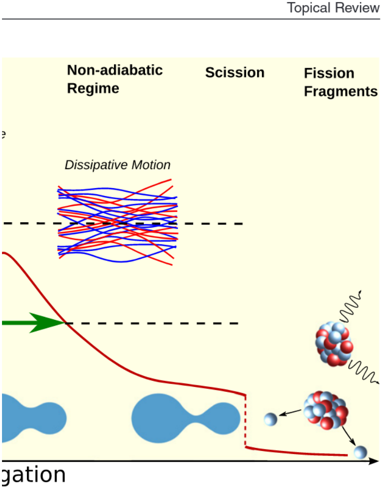



Topical Review
Non-adiabatic Regime
Scission
Fission Fragments
Dissipative Motion
gation

What do we want to understand ?

- Charge and mass distribution
- Connection with structure
- Odd-even effects
- Charge polarization
- Spin-Parity of the fragments

$\rightarrow P(N, Z, J^{\pi}, E^{*})$



TDHFB equations

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} U \\ V \end{pmatrix} = \begin{pmatrix} h(t) & \Delta(t) \\ -\Delta^*(t) & -h^*(t) \end{pmatrix}\begin{pmatrix} U \\ V \end{pmatrix}$$

Strengths

- Self-consistent mean field + pairing
- Functional and no other adjustable parameters.
- One-body dissipation
- Large-amplitude collective motion

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Strengths

- Self-consistent mean field + pairing
- Functional and no other adjustable parameters.
- One-body dissipation
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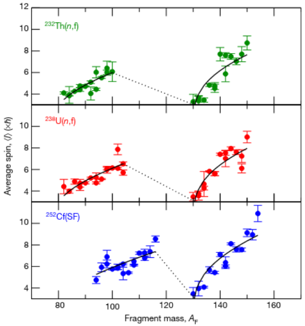
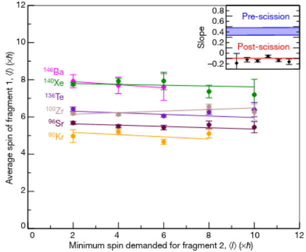
Limitations

- Missing quantum and statistic fluctuations
- Broken symmetries (projection needed)
- Computationally expensive

Spin of the fragments

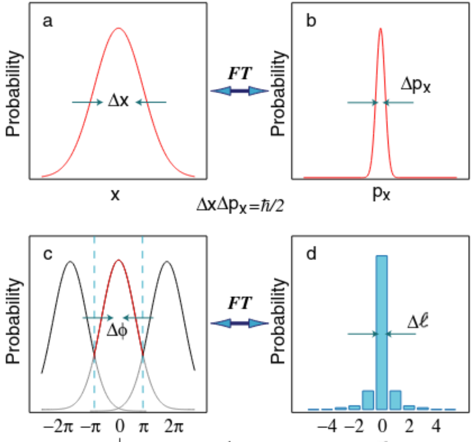


Correlations



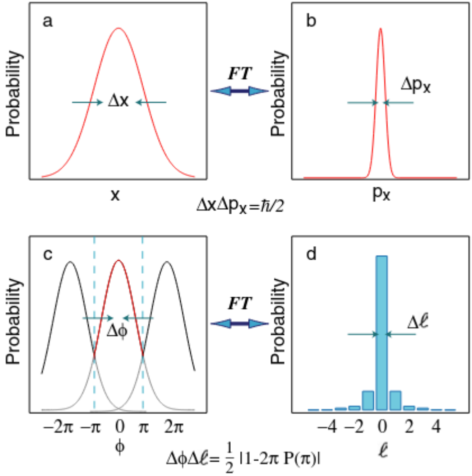
J. N. Wilson, Nature, 590, 566 (2021)

- The average spin follows a sawtooth shape
- No correlations between the spins of the fragments



$\Delta\phi\Delta\ell = \frac{1}{2}\,|1\text{-}2\pi\, P(\pi)|$

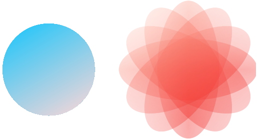
S. Franke-Arnold, et al. New Journal of Physics 6, 103 (2004)



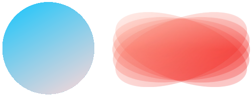
S. Franke-Arnold, et al. New Journal of Physics 6, 103 (2004)

Orientation pumping mechanism

Isotropic potential at scission

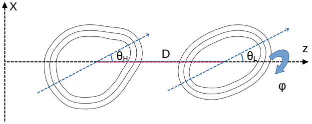


Confining potential at scission



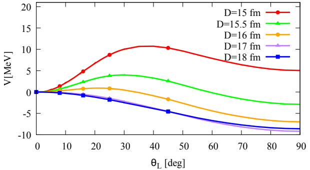
L. Bonneau, P. Quentin, and I. N. Mikhailov, PRC 75, 064313 (2007).

For $\Delta\Theta = 1^\circ$, $\Delta L = 29\hbar$.



Potential as a function of the light fragment angle

$^{132}Sn+^{108}Ru$

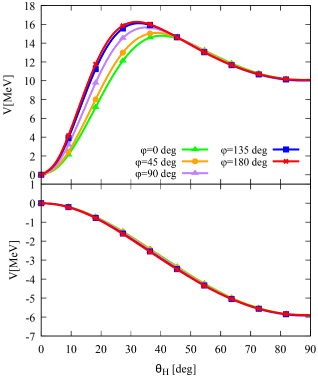


Two torques :

- attractive nucleus-nucleus torque
- repulsive Coulomb torque

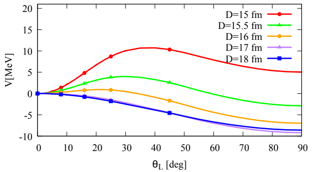
Potential as a function of the light fragment angle

$^{144}Ba+^{96}Sr$. D=15.5 and 20 fm



The azimuthal angle doesn't have an important role.

Frozen Hartree-Fock potential



Two torques :

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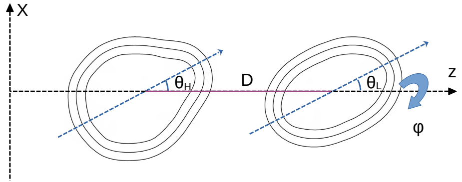
4 degrees of freedom

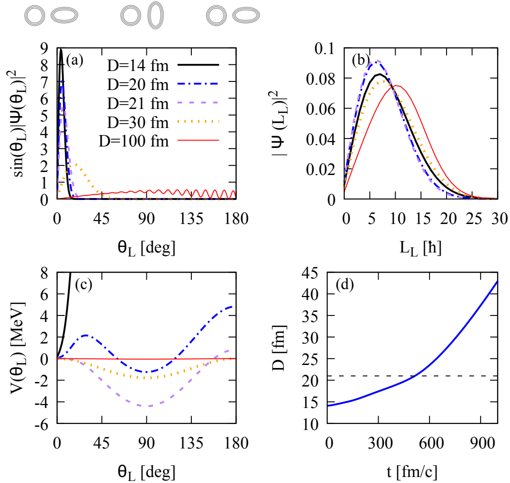


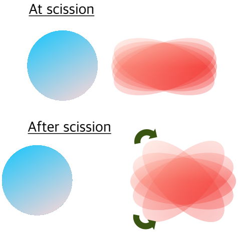
Hamiltonian

$$\hat{H}(D) = \frac{\hbar^2}{2I_H}\hat{L}_H^2 + \frac{\hbar^2}{2I_L}\hat{L}_L^2 + \frac{\hbar^2}{2I_\Lambda(D)}\hat{\Lambda}^2 + \hat{V}(\hat{\Theta}_H, \hat{\Theta}_L, \hat{\varphi}, D)$$

Solved in basis $|L_H, m, L_L, -m\rangle$
Important : assume cold rigid fragments

G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616(2023).
Similar to the orientation pumping mechanism model Mikhailov, I. N., and Quentin, P. Physics Letters B, 462(1-2), 7-13 (1999)





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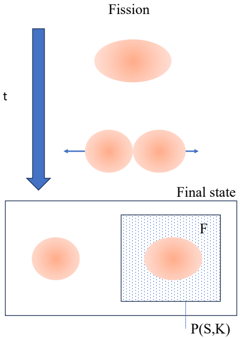


Projection method

Projection on the spin and K number (Projection of the spin on the fission axis)

$$\hat{P}^{S}_{MK} = \frac{(2S+1)}{16\pi^2} \int d\Omega \mathcal{D}^{S*}_{MK}(\Omega)\, e^{i\alpha \hat{S}_z} e^{i\beta \hat{S}_y} e^{i\gamma \hat{S}_z},$$

$$P(S_F, K_F) = \langle \Psi | \hat{P}^{S_F}_{K_F K_F} | \Psi \rangle,$$

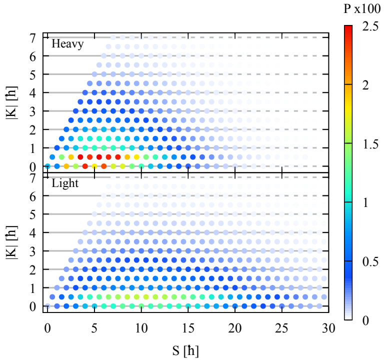
Calculation of the overlap : G. F. Bertsch and L. M. Robledo, PRL 108, 042505 (2012)

$$\langle \Psi | \hat{R} | \Psi \rangle = \frac{(-1)^n}{\prod_{\alpha}^{n} v_{\alpha}^2} \mathrm{pf} \begin{bmatrix} V^T U & V^T R^T V^* \\ -V^\dagger R V & U^\dagger V^* \end{bmatrix}$$

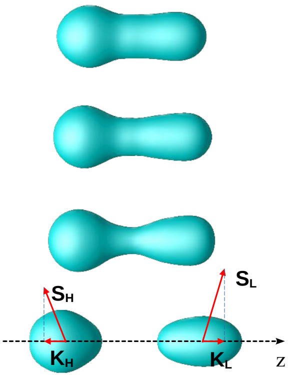
Optimized Pfaffian calculation : M. Wimmer, ACM Trans. Math Softw. 38, 30 (2012).

Spin distribution in the fragments

Obtained using 3-angle projection operator

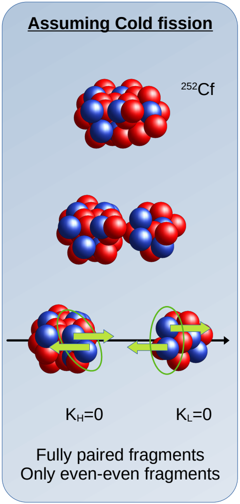


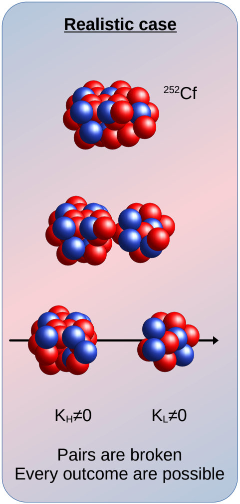
Geometry of the reaction

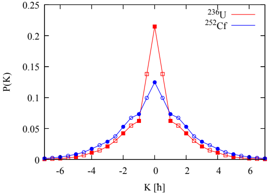


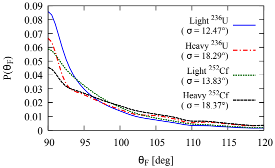
G.scamps, I. Abdurrahman, M. Kafker, A. Bulgac, and I. Stetcu, PRC 108 (6), L061602

Pair breaking mechanism ?









$$\cos\theta_F = \frac{K_F}{\sqrt{S_F(S_F+1)}}$$

G.scamps, I. Abdurrahman, M. Kafker, A. Bulgac, and I. Stetcu, PRC 108 (6), L061602.

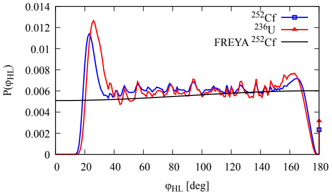
Opening angle distribution

$$\varphi_{HL} = \arccos\left(\frac{\Lambda(\Lambda+1) - S_H(S_H+1) - S_L(S_L+1)}{2\sqrt{S_H(S_H+1)S_L(S_L+1)}}\right)$$

$$P(\Lambda, S_H, S_L) = \sum_{k_H k_L} \langle\Psi|\hat{P}^{\Lambda}_{0,0}\hat{P}^{S_H}_{K_H K_H}\hat{P}^{S_L}_{K_L K_L}|\Psi\rangle.$$

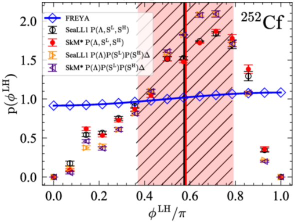
$$P(\Lambda, S_H, S_L) = \sum_{K_H K_L K'_H K'_L} (-1)^{K'_H - K_H + K'_L - K_L}$$

$$C^{\Lambda,0}_{S_H,-K_H,S_L,-K_L} C^{\Lambda,0}_{S_H,-K'_H,S_L,-K'_L} \langle\Psi|\hat{P}^{S_H}_{K_H K'_H}\hat{P}^{S_L}_{K_L K'_L}|\Psi\rangle$$



G.scamps, I. Abdurrahman, M. Kafker, A. Bulgac, and I. Stetcu, PRC 108 (6), L061602.

One angle projector :



Uncertainty principle in TDDFT

Can we understand the generation of spin in TDDFT with the uncertainty principle ?

TDHFB framework

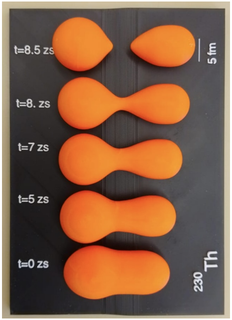
- Gogny-TDHFB code
- Gogny D1S interaction
- Hybrid basis :
  - 2D harmonic oscillator (x, y)
  - 1D spatial mesh (z)

Fissioning nuclei

- ^{230}Th
- ^{240}Pu
- ^{250}Cf

Asymmetric fission region
Heavy fragment influenced by octupole deformation

Y. Hashimoto, Time-dependent hartree-fock-bogoliubov calculations using a lagrange mesh with the gogny interaction, PRC 88, 034307 (2013).



Conceptual difficulty

- Unlike position, angular variables are **periodic**.
- Mean values and fluctuations of an angle are not uniquely defined.
- Restrict to well-oriented wave packet

Orientation–angular momentum uncertainty

$$\Delta\theta\, \Delta L_x > \frac{1}{2}, \qquad (L_x \text{ in units of } \hbar)$$

Analogous relation for L_y.

Gaussian orientation state and spin distribution

Gaussian wave packet :

$$\Psi(\theta, \varphi) = \mathcal{N} \exp\left[-\frac{\theta^2}{4\sigma_\theta^2}\right]$$

Spin cut-off distribution :

$$P(L) = \frac{2L+1}{\mathcal{Z}} \exp\left[-\frac{L(L+1)}{2\sigma_L^2}\right]$$

Heisenberg-type relation :

$$\sigma_\theta\, \sigma_L = \frac{1}{2}$$

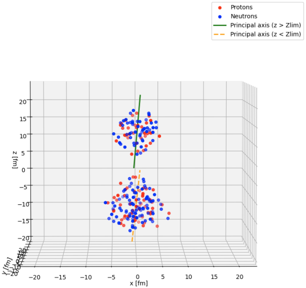
Second difficulty : composite nuclei

- In collective Hamiltonian models, angle wave packets are well defined.
- In microscopic approaches, there is no direct access to angular fluctuations.

Proposed approach

- Sample nucleon positions from the Bogoliubov vacuum.
- Markov Chain Monte Carlo sampling (`NucleoScope`).
- Determine principal axis event-by-event.

Principal axis determination



Examples for ^{230}Th.
Red/blue dots : proton/neutron distributions.
Lines : fragment principal axes.

Nucleoscope paper : A. Bernard *et al.*, Eur. Phys. J. A 62, 112 (2026)

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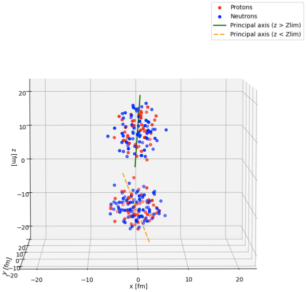

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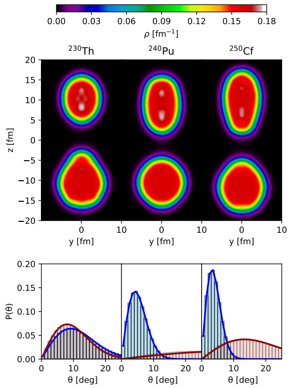
Distribution of θ

- For each sampled event, principal axis of each fragment is computed.
- Obtain θ = angle between fragment axis and global z-axis.
- Construct full probability distribution $P(\theta)$.
- Expectation value $\langle\theta\rangle = 0$ due to symmetry.
- Standard deviation σ_θ characterizes the angular fluctuation.

Physical meaning

- Reflects uncertainty in fragment orientation.
- Geometric definition mainly sensitive to quadrupole deformation.
- Can be used for spin-cutoff estimations.

Angular distribution figure



Angular distribution $P(\theta)$ for light (blue) and heavy (red) fragments. Fitted curves illustrate approximate Gaussian behavior.

Angular distribution

$$f(\theta) = \mathcal{N}^2 \sin(\theta) \exp\left[-\frac{\theta^2}{2\sigma_\theta^2}\right]$$

- Excellent agreement with Gaussian form
- Angular fluctuations are Gaussian
- Larger quadrupole deformation $\Rightarrow$ narrower distribution

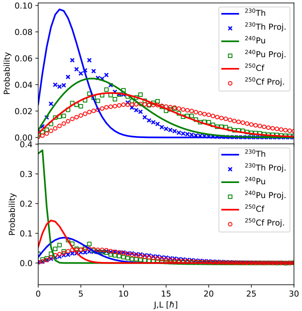
From σ_θ to spin

$$\sigma_\theta \, \sigma_L = \frac{1}{2}$$

- Extract σ_θ
- Deduce spin cut-off σ_L
- Build spin distribution

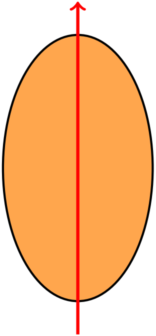
Spin distribution

$$P(L) = \frac{2L+1}{\mathcal{Z}} \exp\left[-\frac{L(L+1)}{2\sigma_L^2}\right]$$



Projection results vs. spin cut-off formula (light : top, heavy : bottom).
$\rightarrow$ Partial reproduction of the spin distribution

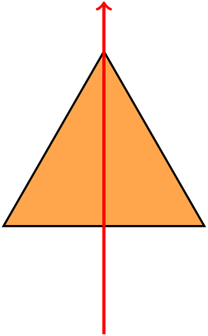
Prolate deformation



$Q_2 > 0$

Principal axis well defined

Triangular (octupole) configuration



$Q_2 = 0$

Orientation still defined but principal axis isotropic

Overlap of rotated many-body states

$$\langle\Psi|e^{i\alpha\hat{J}_z}e^{i\theta\hat{J}_y}e^{i\gamma\hat{J}_z}|\Psi\rangle \simeq \exp\left[-\frac{\theta^2}{8\sigma_\theta^2}\right]$$

- Gaussian approximation for small rotations
- Width σ_θ characterizes angular localization

Physical meaning

- Many-body state localized in rotational space
- Does **not** rely on geometric definition of orientation
- Orientation angle and angular momentum are conjugate variables

Spin fluctuations

Spin cut-off distribution :

$$P(J) = \frac{2J+1}{\mathcal{Z}}\exp\left[-\frac{J(J+1)}{2\sigma_J^2}\right]$$

$$\sigma_\theta\,\sigma_J = \frac{1}{2}$$

Spin Cut-off Parameters from Different Approaches

Nucleus	Frag.	σ_L (uncert. with principal axis)	σ_J (overlap)	σ_J (projection)
^{230}Th	L	2.90	5.74	5.81
	H	3.37	7.84	7.88
^{240}Pu	L	6.79	9.32	9.37
	H	0.75	4.67	4.93
^{250}Cf	L	9.00	12.18	12.27
	H	2.12	6.50	6.63

Key result

- Spin cut-off parameters extracted from :
  - angular fluctuations + uncertainty relation
  - Gaussian overlap fit
  - exact angular-momentum projection
- **very good agreement** between overlap and exact projection.
- Error with the principal axis method (miss higher order deformation).

G. Scamps, A. Guilleux, D. Regnier, A. Bernard, Uncertainty Principle and Angular Momentum Generation in Microscopic Fission Models, arXiv :2512.02207 [nucl-th].

Spin-parity distribution

Fission as a quantum transition

$$(J_0, \pi_0) \to (J_1, \pi_1) + (J_2, \pi_2) + L$$

$$\boldsymbol{J}_0 = \boldsymbol{J}_1 + \boldsymbol{J}_2 + \boldsymbol{L}$$

$$\pi_0 = \pi_1 \pi_2 (-1)^L$$

Conservation rules are not constraining

State-of-the-art models of fragment decay assume a simple, equiprobable partition between positive and negative parities

Fragment parity projection

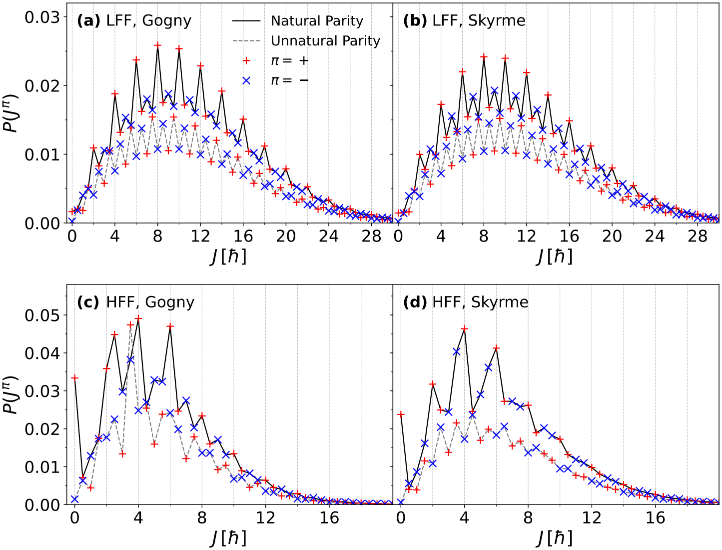
$$\hat{P}_F^{\pi} = \frac{1}{2}(1 + \pi \hat{\Pi}_F)$$

$$P_F(J, K, \pi, N, Z) = \langle \Psi | \hat{P}_F^N \hat{P}_F^Z \hat{P}_{KK,F}^J \hat{P}_F^{\pi} | \Psi \rangle$$

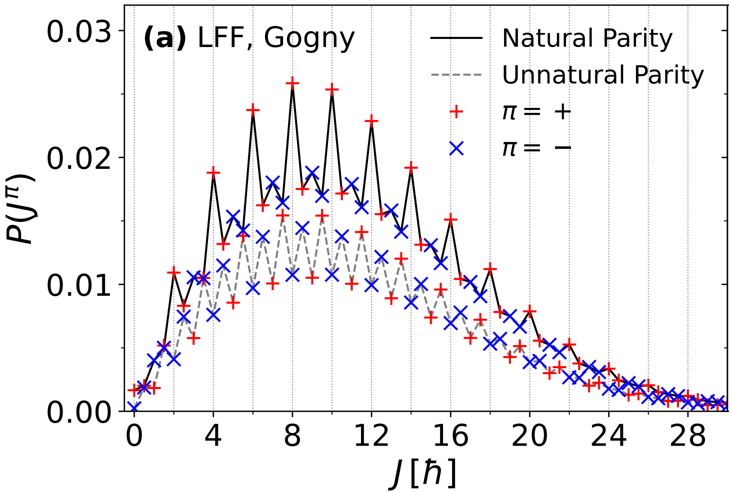
Fragment quantum numbers obtained by simultaneous projections

+ comparison Skyrme Skm* (P. Marević, A. Bjelčić, N. Schunck) - Gogny D1S

Fragment spin–parity ^{240}Pu



G. Scamps, P. Marević, A. Bjelčić, N. Schunck, *Microscopic Spin-Parity Distributions of Fission Fragments*, arXiv :2607.24156 [nucl-th]



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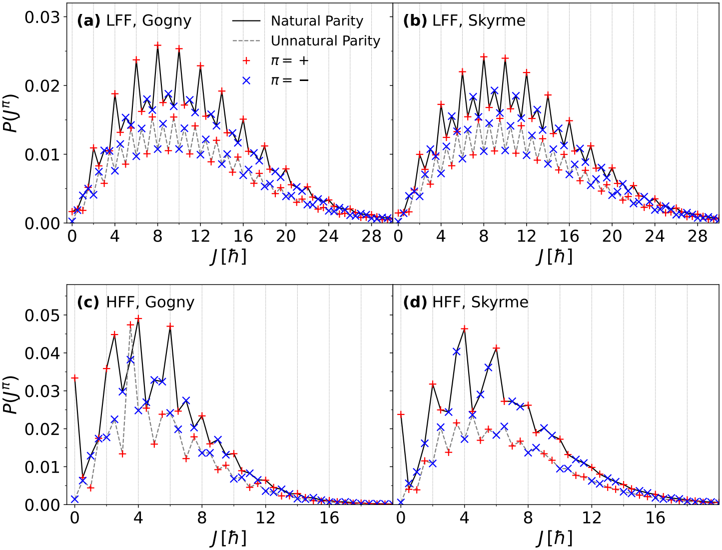
Fragment spin–parity ^{240}Pu



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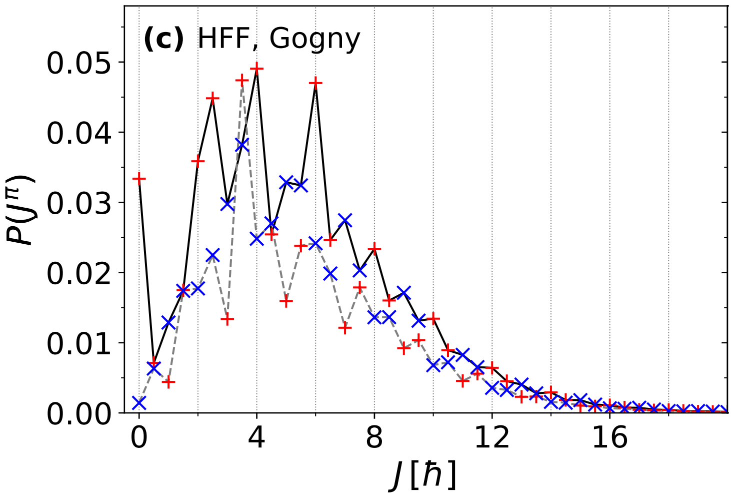

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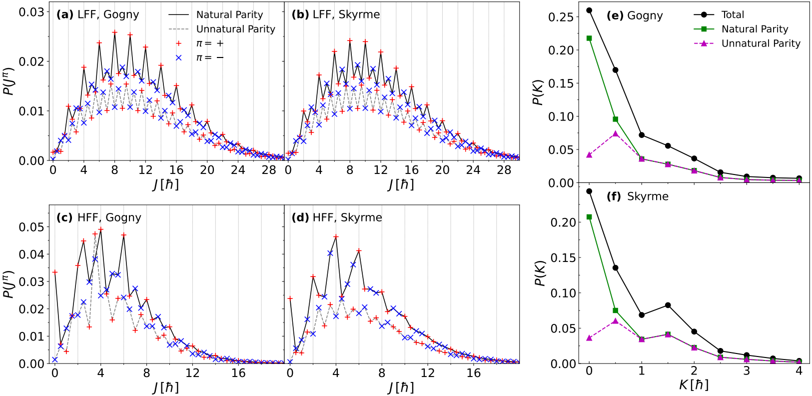
Nuclear structure	Symmetry	Allowed spins	Parity pattern
Spherical even-even	Full rotational symmetry	$J = 0$ and $K = 0$ (ground state)	0^+
Quadrupole-deformed	Axial symmetry + reflection	$J = 0, 2, 4, \ldots$ and $K = 0$	$\pi = +$ (natural)
Octupole-deformed	Broken reflection symmetry	$J = 0, 1, 2, 3, \ldots$ and $K = 0$	Alternating $\pi = (-1)^J$ (natural)
Pair breaking (q.p. excitation)	Broken pairing symmetry	All J and K accessible	Natural + unnatural

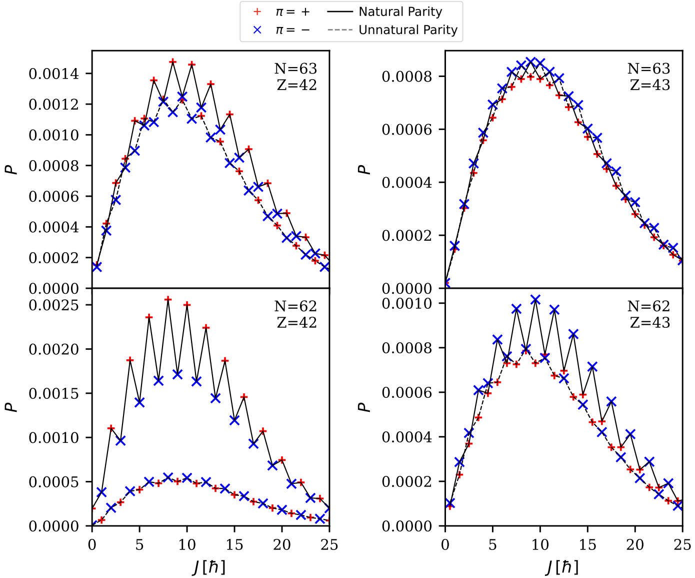
Symmetry breaking $\longrightarrow$ characteristic spin–parity signatures

Fragment spin–parity and K distributions



G. Scamps, P Marević, A. Bjelčić, N. Schunck, Microscopic Spin-Parity Distributions of Fission Fragments, arXiv :2607.24156 [nucl-th]

Light fragment spin–parity



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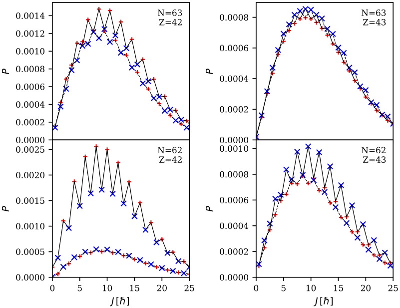
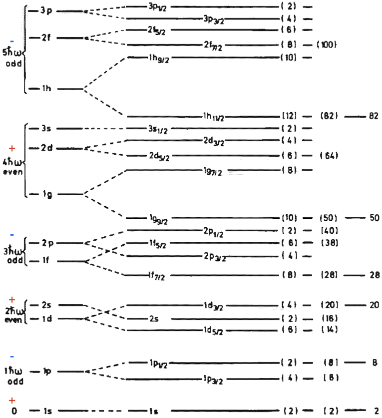
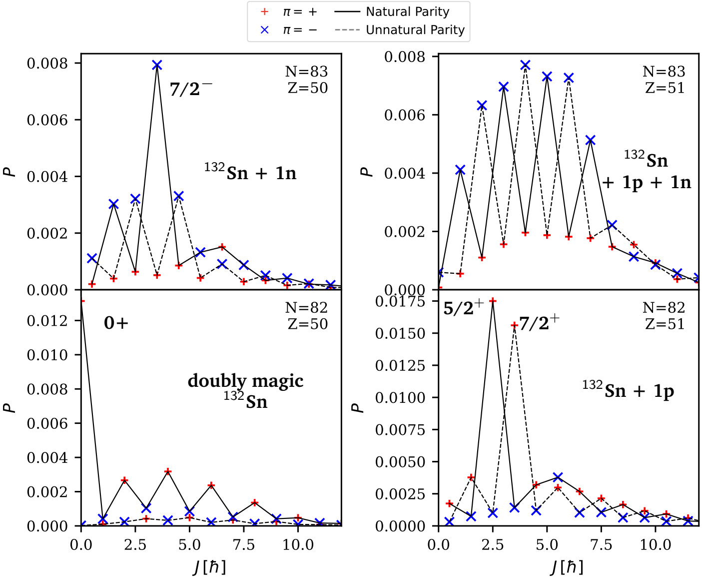




Ring and Schuck, The Nuclear Many-Body Problem

Heavy fragment spin–parity



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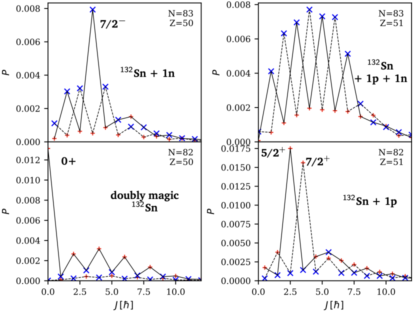

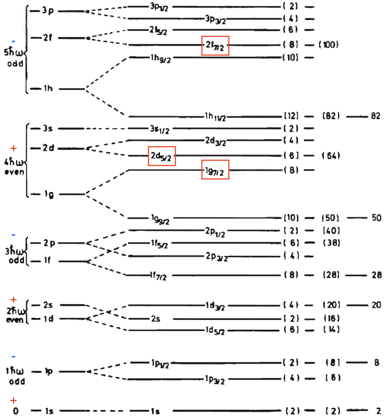

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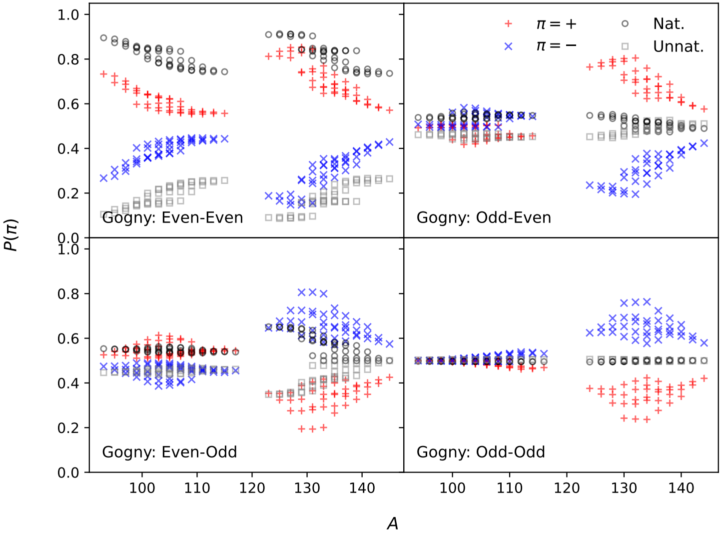

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Conclusion

- **Complete spin–parity characterization**

$$P(J, K, \pi, N, Z)$$

  of fission fragments obtained with projection operators using Gogny D1S and Skyrme SkM* EDFs.

- **Origin of fragment angular momentum**
  - Light fragments : dominated by collective quantum fluctuation.
  - Heavy fragments : microscopic structure and single-particle effects become important.

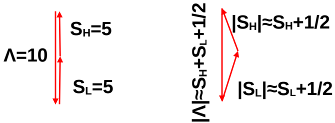
- **Role of pair breaking**
  - Generates non-zero K components.
  - Explains unnatural-parity configurations.

- **Impact for fission observables**
  - Current de-excitation models assume random parity.
  - Including parity distributions may modify simulated observables.

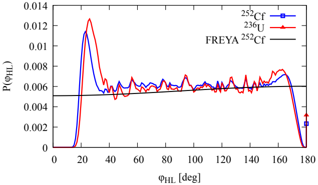
Thank you for your attention

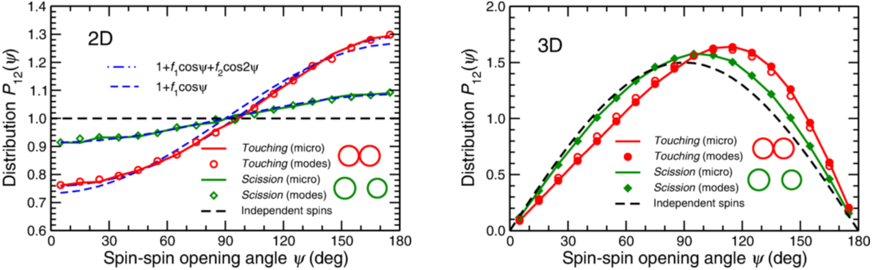
Thanks to my collaborators : George Bertsch, Alice Bernard, David Regnier, Antoine Guilleux, Aurel Bulgac, Ionel Stetcu, Ibrahim Abdurrahman, Matthew Kafker, Petar Marević, Nicolas Schunck, Antonio Bjelčić, Yukio Hashimoto

Non alignement of the spins



To get a 5 degrees angle between two spins require spins of 262 $\hbar$ and 6565 $\hbar$ for 1 degree



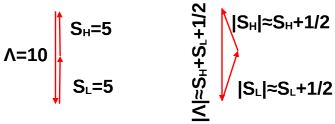


J. Randrup, Phys. Rev. C 106, L051601 (2022).

Question

- How the quantal effects change this picture ?
- How the geometry change the opening angle distribution assuming no correlation ?

Non alignement of the spins



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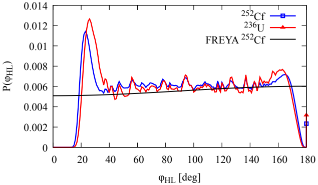
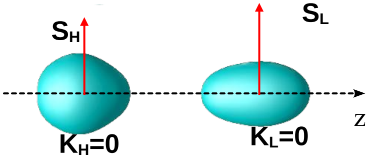
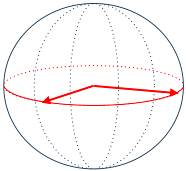


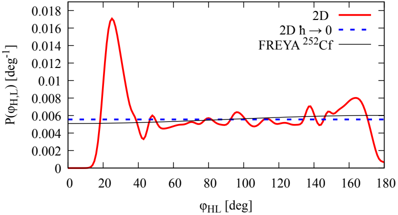
Opening angle distribution - 2D case





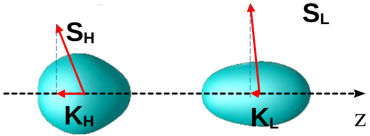
$$|\Psi\rangle = \sum_{S_H, K_H, S_L, K_L} c_{S_H, K_H, S_L, K_L} |S_H, K_H, S_L, K_L\rangle,$$

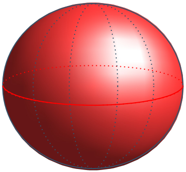
$$|c_{S_H, K_H, S_L, K_L}|^2 \propto \delta_{K_H,0}\delta_{K_L,0}(2S_H+1)e^{\frac{-S_H(S_H+1)}{2\sigma_H^2}} \times (2S_L+1)e^{\frac{-S_L(S_L+1)}{2\sigma_L^2}}.$$



G. Scamps, PRC 109, L011602 (2024).

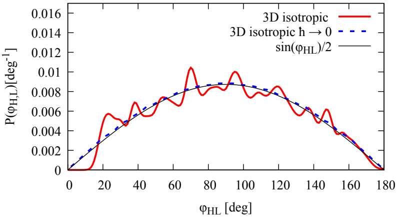
Opening angle distribution - 3D uniform case





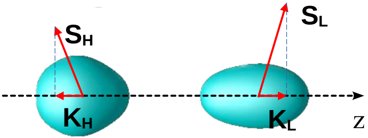
$$|\Psi\rangle = \sum_{S_H, K_H, S_L, K_L} c_{S_H, K_H, S_L, K_L} |S_H, K_H, S_L, K_L\rangle,$$

$$|c_{S_H, K_H, S_L, K_L}|^2 \propto e^{\frac{-S_H(S_H+1)}{2\sigma_H^2}} e^{\frac{-S_L(S_L+1)}{2\sigma_L^2}}.$$



G. Scamps, PRC 109, L011602 (2024).

Opening angle distribution - 3D with total spin S=0



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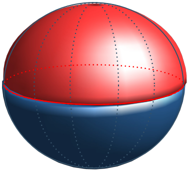
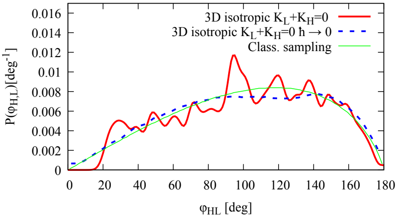
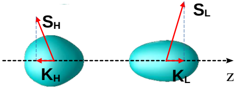
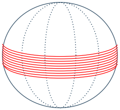
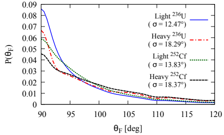




G. Scamps, PRC 109, L011602 (2024).







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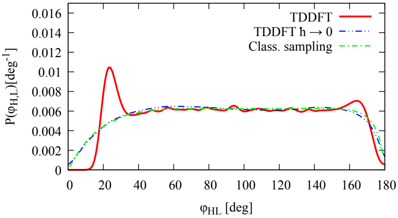
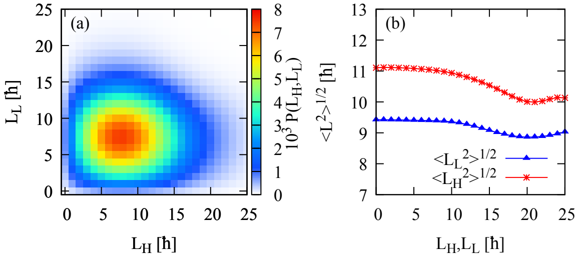
$|c_{S_H, K_H, S_L, K_L}|^2$ From TDDFT



TDDFT shows an intermediate case between 2D and 3D.
G. Scamps, PRC 109, L011602 (2024).

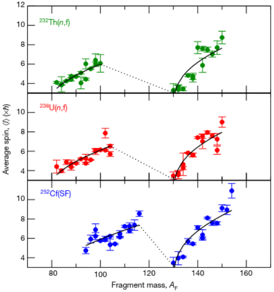
Correlation between the angular momentum

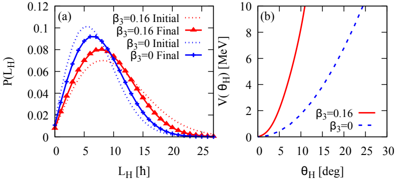


$^{144}Ba + ^{96}Sr$

- No or small correlation observed in the magnitude of the angular momentum.
- More angular momentum for the heavy fragment

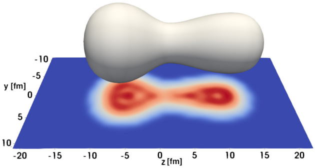
Effect of octupole deformation





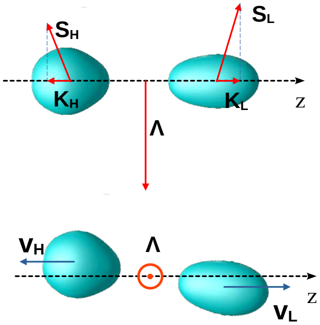
G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616 (2023).

Mechanism



- Pear-shaped deformation plays an important role at scission. G. Scamps C. Simenel, Nature 564, pages 382–385 (2018)
- Octupole deformation makes the angular potential stiffer which increase the zero-point motion $\rightarrow$ more angular momentum

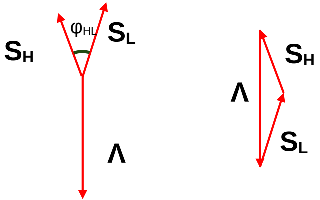
Orbital angular momemtum



In spontaneous fission of a 0^+ state

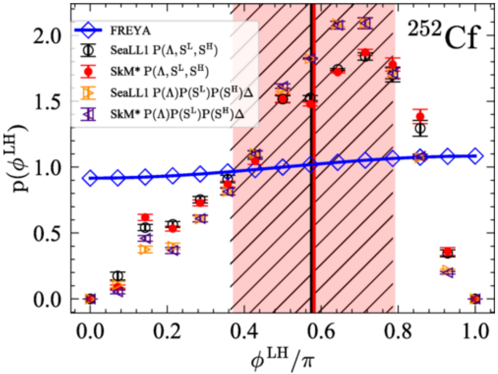
$$\mathbf{S_H} + \mathbf{S_L} + \mathbf{\Lambda} = \mathbf{0},$$

Triangular rule :

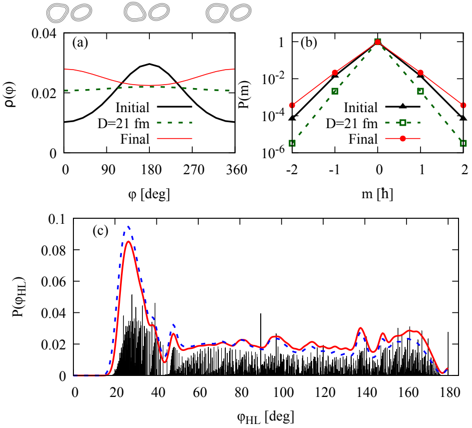


$$\cos(\varphi_{HL}) = \left(\frac{\Lambda(\Lambda+1) - S_H(S_H+1) - S_L(S_L+1)}{2\sqrt{S_H(S_H+1)S_L(S_L+1)}} \right)$$

TDDFT (in 2022) vs Freya



A. Bulgac, I. Abdurrahman, K. Godbey, and I. Stetcu, Phys. Rev. Lett. 128, 022501(2022).

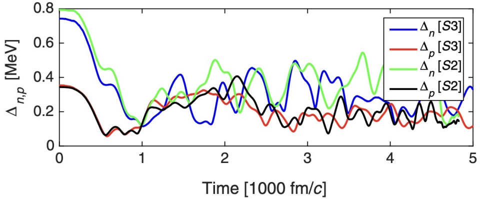


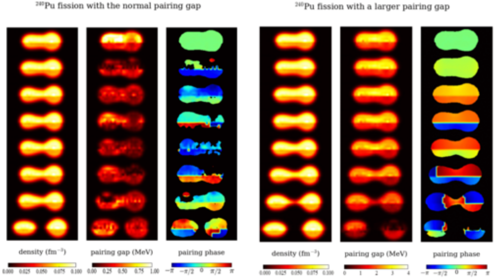
G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616 (2023).

Geometry

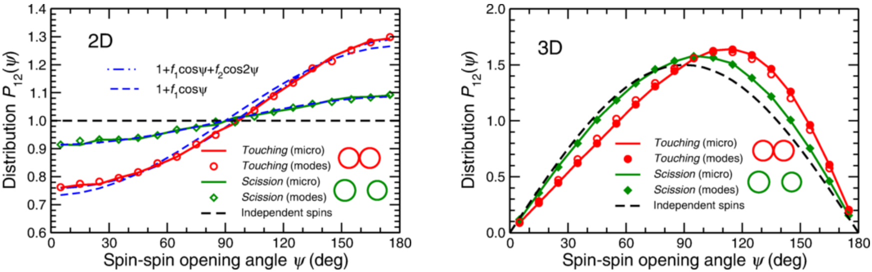
- Small azimuthal correlation
- Spins are perpendicular to the fission axis
- Complex pattern in the opening angle, different from previous model

Vanishing pairing during dynamics ?





A. Bulgac, P. Magierski, Kenneth J. Roche, and I. Stetcu, PRL 116, 122504 (2016).
A. Bulgac, S. Jin, K. J. Roche, N. Schunck, and I. Stetcu, PRC 100, 034615 (2019).



J. Randrup, Phys. Rev. C 106, L051601 (2022).

Question

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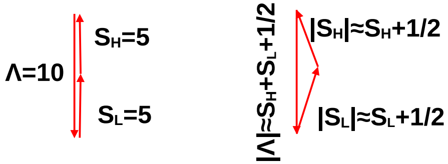
Opening angle distribution - why the spins can not be aligned ?

Non alignement of the spins



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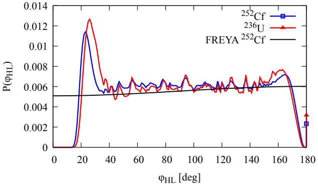

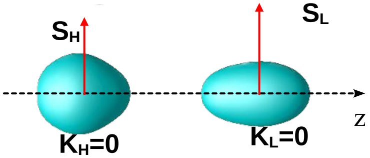

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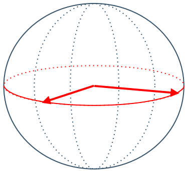

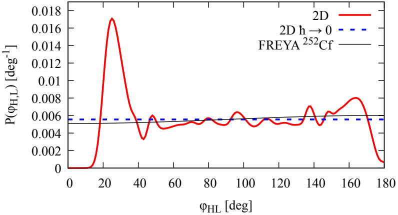

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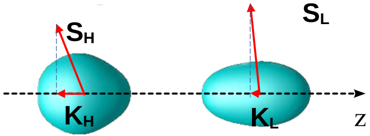

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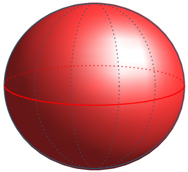

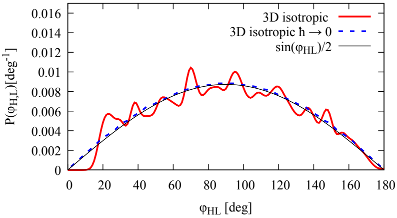

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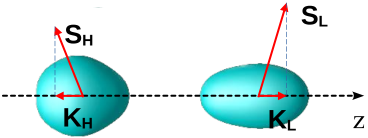
Opening angle distribution - 3D with total spin S=0



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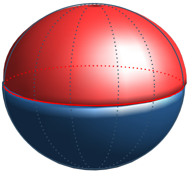
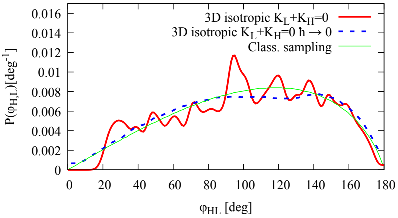
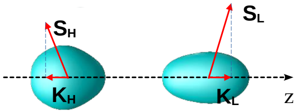




G. Scamps, PRC 109, L011602 (2024).

Opening angle distribution - 3D from TDDFT



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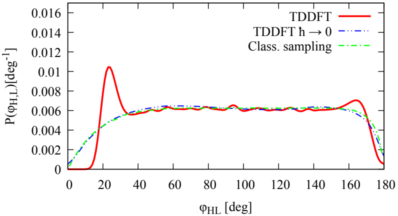

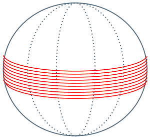

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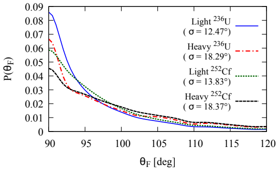

Main points

- Orientation-pumping (uncertainty principle) mechanism at scission
- Additional effect of the Coulomb torque
- Internal excitation (breaking of pairs)
- Spins are mainly perpendicular to the fission axis
- Uncorrelated magnitude and orientation of the spins
- Dependence of the mechanism with the deformation (quadrupole and octupole)

Outlook

- TD-GCM with rotated fragments
- Rotated fission system

Thank you