

Fragment spin generation and scission mechanism in rapidly rotating fission

Yu Qiang,^{1,2} Zhibo Li,² and Junchen Pei^{2,3,*}

¹Hangzhou International Innovation Institute, Beihang University, Hangzhou 311115, China

²School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

³Southern Center for Nuclear-Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences, Huizhou 516000, China



(Received 28 February 2026; revised 17 July 2026; accepted 10 August 2026; published 15 September 2026)

The generation of fission fragment spin as a probe of scission mechanism remains a question of considerable interests. We present here microscopic calculations of rapidly rotating fission of the compound nucleus ^{240}Pu under varying initial conditions within the time-dependent density functional theory framework. The obtained spin ratio of light to heavy nascent fragments is unchanged up to high spins but diminished as excitation energies increase, indicating sawtooth structures in fragment spins would fade away at high excitations rather than high angular momentum. Results also show elongated neck configurations and nonaxially symmetric deformations of fragments owing to rapid rotations. These findings offer insights into the scission mechanism of rapidly rotating compound nuclei with strong fragment spin polarizations.

DOI: [10.1103/f2ws-57py](https://doi.org/10.1103/f2ws-57py)

Introduction. Nuclear scission in the final stages of fission is not a trivial splitting along the fission axis, as indicated by considerable fragment spins about $7\hbar$ generated even in spontaneous fission [1]. This is distinctly different from the controllable separation between clouds of atoms [2]. In 2021, an accurate measurement of fission fragment (FF) intrinsic spins shows surprising sawtooth structures of fragment spin distributions as a function of fragment masses [3]. The similar sawtooth structures have been observed in distributions of neutron multiplicities, which is related to the energy partition between binary fragments [4–6]. Furthermore, the experiment found no spin correlations between fragments and FF spins are likely to be generated after scission. Subsequently, strong interests have been motivated, however, the generation of FF spin and the scission mechanism are still under debates [7–16].

The deeper understanding of nuclear scission is crucial for the application needs of high quality multiple post-fission data. The intuitive modeling of nuclear scission as a random rupture in the neck has been widely adopted in descriptions of FF yields [17,18]. The microscopic time-dependent density functional theory (TDDFT) reveals that the scission is a fast nonadiabatic process so that quantum entanglement between two separated fragments is persistent, impacting the partition of particles and energies between fragments [19,20]. The FF spin can be generated by specific fragment rotational modes at scission [21], mainly the bending and wriggling modes in which FF spins are perpendicular to the fissioning axis [22,23]. In this respect, TDDFT calculations claim the bending mode is predominated [12], in contrast to the wriggling mode by FREYA as a Monte Carlo modeling [24].

However, a latest TDDFT calculation adopting the full angular momentum projection reveals that the twisting mode along the fissioning axis is also frequently activated [14].

The FF spins inherited from initial angular momentum of compound nuclei (CN) have usually not been taken into account in existing models, as they focus on fissioning nuclei with low angular momentum [9,12,14,25]. FF spins with low initial excitation energies and low angular momentum are determined by fluctuation spins at scission [26]. However, it is of interests to know the scission mechanism of rapidly rotating nuclei, and consequently the partition of angular momentum between fragments, with both the inherited and the rest spins. The fission dynamics is much related to excitation energies, leading to enhanced viscosity [27] and the fade away of sawtooth structures [6,19,28]. Both TDDFT and FREYA results show that the dependence of FF spin on the angular momentum of CN is weak and is more related to excitation energies [11,26]. However, a recent measurement of isomeric yield ratios pointed out that FF spin comes from the fission process and also CN angular momentum [29,30]. Therefore, it is vital for theoretical studies to disentangle the influences of angular momentum and excitation energies on FF spin and scission by systematical variations of initial conditions.

The fission under rapid rotation is a very violent nonequilibrium nonadiabatic process [31], inducing strong spin alignment or polarizations between fragments and CN. In this respect, the microscopic real-time dynamical approach is suitable. TDDFT has been demonstrated to be a promising framework for descriptions of the later phase of fission after the saddle point [27,32–36]. Even far from the equilibrium, the partition of energies, angular and linear momentum, and particles between nascent fragments can be self-consistently determined by importing the random fluctuation mechanism and combining the projection technique based on the TDDFT

*Contact author: pei@pku.edu.cn

framework. [19,37–40]. Currently, within the TDDFT framework, the FF intrinsic spins are obtained by applying angular momentum projections (AMP) on each fragment in the partial space. However, only very low or zero angular momentum has been considered in earlier theoretical studies [11,12,14]. Experimentally, the rapidly rotating fission can be studied by the fusion reactions induced by light projectiles such as α [30], ^{16}O and ^{32}S [57]. Besides, the high angular momentum is also relevant for heavy-ion reactions such as quasi-fission and multi-nucleon transfer reactions [41,42]. The aim of this Letter is to study the generation of FF spins and the scission mechanism across a wide range of initial angular momentum and excitation energies based on TDDFT, which has been a missing piece for a long time.

Methods. The dynamical fission process after the saddle point of ^{240}Pu is studied within the TDDFT framework, specifically, the time-dependent Hartree-Fock + BCS (TD-BCS) approach [36,43]. With a finite-temperature HF + BCS solution as an initial start for TD-BCS evolutions, the dynamical pairing effect and the thermal excitation are self-consistently included [27,28]. The initial wave functions are obtained by deformation constrained HF + BCS calculations at finite temperature [44,45]. The initial deformation ($\beta_2 = 2.3$, $\beta_3 = 1.0$) is adopted at zero temperature. At finite temperatures with high viscosity, a slightly larger initial deformation of (2.6, 1.2) is chosen to reach the scission. Then the TD-BCS equation is solved as in Ref. [46] using the modified SKY3D code [47]. In this work, the Skyrme force SkM* has been adopted [48], which has widely been used in fission studies. Although other forces like UNEDF1 and SLy4 are also suitable, they only result in minor changes in dynamical evolutions [34]. Besides, the mixing-type density dependent pairing interaction is adopted in our approach [49]. The pairing strengths are $V_p = 480$ and $V_n = 450 \text{ MeV fm}^{-3}$ for protons and neutrons, respectively.

Next the angular momentum of CN is obtained by an initial rotation of the system at the beginning of the evolution. The system is rotated along the y axis which is perpendicular to the splitting direction. The driven rotation of the single-particle Hamiltonian is applied continuously for 30 fm/c at the beginning. After the initial boost, the system is evolved to the splitting with the conservation of energies and angular momentum. The Hamiltonian is written as

$$\hat{h}_q = U_q(\vec{r}) - \nabla \cdot [B_q(\vec{r})\nabla] + i\vec{W}_q \cdot (\vec{\sigma} \times \nabla) + \vec{S}_q \times \vec{\sigma} - \frac{i}{2}[(\nabla \times \vec{A}_q) + 2\vec{A}_q \cdot \nabla], \quad (1)$$

where the mean-field potential $U_q(\vec{r})$, effective mass $B_q(\vec{r})$, spin-orbit potential $\vec{W}_q(\vec{r})$, and the time-odd terms $\vec{S}_q, \vec{A}_q$ are all set to rotate in a constant speed, and q denotes the isospin of neutron and proton. For each time step t_i , the coordinate $\vec{r}$ of $[U_q, B_q, \vec{W}_q, \vec{S}_q, \vec{A}_q]$ rotates as

$$\vec{r}(t_i) = (x_i, y_i, z_i) \rightarrow (x_i + z_i \cos(\omega\Delta t), y_i, z_i - x_i \sin(\omega\Delta t)). \quad (2)$$

The angular momentum can be adjusted by the rotating speed ω . Such an initial rotation method is similar to the cranking Hartree-Fock method, which has been applied previously in

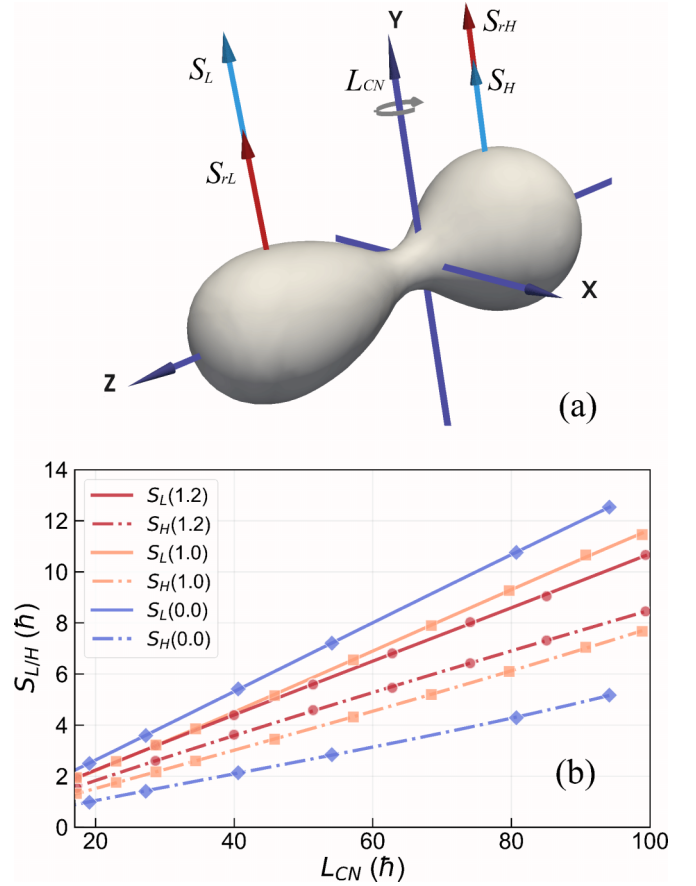


FIG. 1. (a) Illustration of FF spin $S_{L/H}$ of a rotating CN with angular momentum L_{CN} along the y axis, in which inherited spins are denoted as S_{rL} and S_{rH} for light and heavy fragments, respectively. (b) Calculated expectation values of spins of light and heavy FF as a function of L_{CN} of ^{240}Pu , with initial temperatures $T = 0.0, 1.0$, and 1.2 MeV . Note that calculated spins at low L_{CN} are not shown, see the text.

TDHF studies [50,51]. However, the cranking TDHF calculation is difficult to incorporate pairing effects and particularly the initial thermal excitations. Both the total energy and angular momentum of the CN system increase rapidly by the initial boost and then become stable. To our knowledge, this work presents the first microscopic self-consistent study of CN fission dynamics at rapid rotations and high excitations.

Results. The fission evolutions of ^{240}Pu based on TD-BCS with varying initial excitation energies and angular momentum have been studied in a controllable way. In our approach, the energy boosted by the initial rotation is almost collective rotation energy. To study CN fission with energy dependencies, initial configurations with temperatures at $T = 0.0, 1.0, 1.2 \text{ MeV}$ are adopted for TD-BCS evolutions.

The orientations of FF spins and the CN rotation are illustrated in Fig. 1(a). The FF spin along the y axis can be calculated by $\langle J_y \rangle$, when two fragments are well separated [52]. The obtained $\langle J_x \rangle$ and $\langle J_z \rangle$ are basically zero in all cases. Note that AMP should be applied to obtain FF spin when CN has a low angular momentum. Under rapid rotations, the obtained expectation value of FF spin in a given direction

is close to the peak of angular momentum distributions, as confirmed by cranking HF plus AMP calculations [53,54]. As demonstrated in studies of quasifission fragment spins [41], the expectation value of the angular momentum perpendicular to the reaction plane encapsulates most of the system's spin at high spins. The application of AMP at thermal excitations is too complicated. Thus the present study focuses on the fission of CN at rapid rotations, and our method is not applicable at low initial angular momentum.

The calculated FF spin at different initial excitation energies and angular momentum are shown in Fig. 1(b). Because our method is not suitable at low initial angular momentum, the calculated FF spins are displayed only for $L_{CN} \geq 20\hbar$. It can be seen that both heavy and light fragment's average spins increase almost linearly with the increasing angular momentum of CN. The spin of light fragment S_L is larger than that of the heavy fragment S_H , being consistent with the sawtooth structures [3]. The spin ratio of light to heavy fragments is unchanged up to high spins but reduced as the temperature increases. Finally the spins of two fragments become close at high temperatures. This implies the fade away of sawtooth structures of FF spin at high excitations rather than at high angular momentum of CN.

It has been pointed out [22] that FF spins can be decomposed into two parts: the rigid rotation inherited from CN and the rest motion, referred to as spin-depolarizing modes, including bending, wriggling, tilting, and twisting modes. This intriguing semiclassical picture has stimulated strong interests in the generation of FF spin. The depolarizing spin is also called fluctuation spin in other studies [8,26]. To be consistent with this picture, the rigid rotation of fragments inherited from CN can be estimated according to the moments of inertia,

$$\frac{L_{CN}}{\mathcal{I}_{CN}} = \frac{S_{rH}}{\mathcal{I}_H} = \frac{S_{rL}}{\mathcal{I}_L}, \quad (3)$$

where $\mathcal{I}_{CN}$, $\mathcal{I}_H$, and $\mathcal{I}_L$ denote the moments of inertia of CN, the heavy and light fragments, respectively. The rotation inertia can be calculated with the rigid-body inertia assumption, since nuclear superfluidity disappears quickly as CN angular momentum and excitation energies increase [45,55]. It was known that the momentum of inertia is close to the rigid-body value at high spins [56]. Furthermore, while the moments of inertia are approximate, their ratios are more accurate. Note that FF spin inherits only a very small portion of the CN angular momentum, since each FF inertia is much smaller than the CN inertia, as displayed in Table I. Generally the heavy fragment has a larger rigid inertia and a higher inherited spin than the light fragment. The S_{rH} is even higher than the S_H . This is different from the final partition of FF spin in Fig. 1. In contrast to spontaneous fission, where the intrinsic FF spin is governed by the depolarizing spin, the scenario at high angular momentum is characterized by a combined contribution from inherited spin and depolarizing spin. From this decomposition, our results are consistent with the bending mode at low excitation energies.

The scission configuration can be significantly altered by the rapid rotation of CN, impacting multiple post-scission

TABLE I. Calculated rigid rotation spins inherited from CN for the heavy S_{rH} and light S_{rL} fragments of ^{240}Pu . Results for CN at different temperatures T (MeV) and angular momentum L_{CN} ($\hbar$) are displayed. E^* (MeV) denotes associated total excitation energies including rotational energies.

$E^*(T)$	L_{CN}	S_{rH}	S_{rL}
1.8(0.0)	27.6	2.52	2.05
10.9(0.0)	68.6	6.08	5.13
21.0(0.0)	95.2	8.26	6.90
20.9(1.0)	28.8	2.69	1.96
30.7(1.0)	68.7	6.32	4.65
41.1(1.0)	99.3	8.94	6.58
34.4(1.2)	28.8	2.76	1.91
40.6(1.2)	63.0	5.94	4.13
52.6(1.2)	99.3	9.13	6.43

observables. In Fig. 2, it is shown that TKE of fragments increase with the increasing L_{CN} , explaining the trend observed in the heavy-ion induced fission [57]. We also see that TKE decreases significantly with increasing initial E^* , owing to enhanced dissipation and elongated neck at high excitations [27]. As a probe of the distance between fragments at scission, the Coulomb energies pre-scission are also shown in Fig. 2. However, it shows that the Coulomb energies decrease significantly as L_{CN} increases. This indicates the rapid CN rotation leads to elongated neck configurations. In non-rotating fission, the Coulomb energy is the major part of TKE. Therefore, the increasing TKE as a function of L_{CN} is attributed to relative rotational energies between fragments instead of the Coulomb energy. Or say that a large portion of the collective rotational motion of CN is converted into the relative motion between fragments or TKE after the scission.

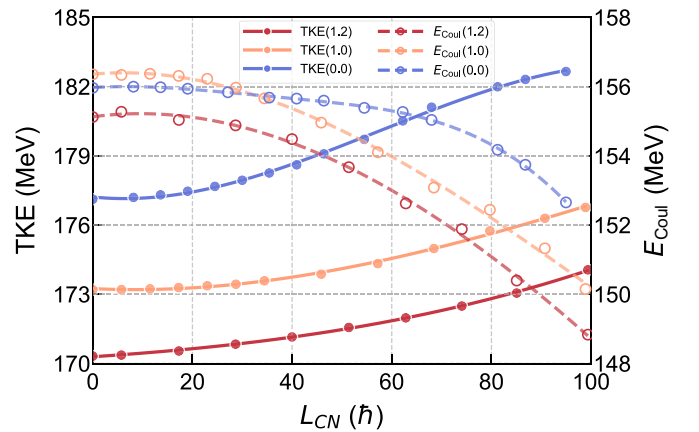


FIG. 2. Total kinetic energy (TKE) and extracted Coulomb energy E_{Coul} between fission fragments as a function of L_{CN} at initial temperatures of 0.0, 1.0, 1.2 MeV. The Coulomb energy is determined when the neck reaches the same number of particles in neck $N_c = 2.0$ for comparison. The N_c refers to the particles contained in a region of 1 fm at the location of the thinnest scission neck. The solid lines denote TKE (the left vertical coordinate) and the dash-dotted lines denote the Coulomb energy (the right vertical coordinate). All energies are given in MeV.

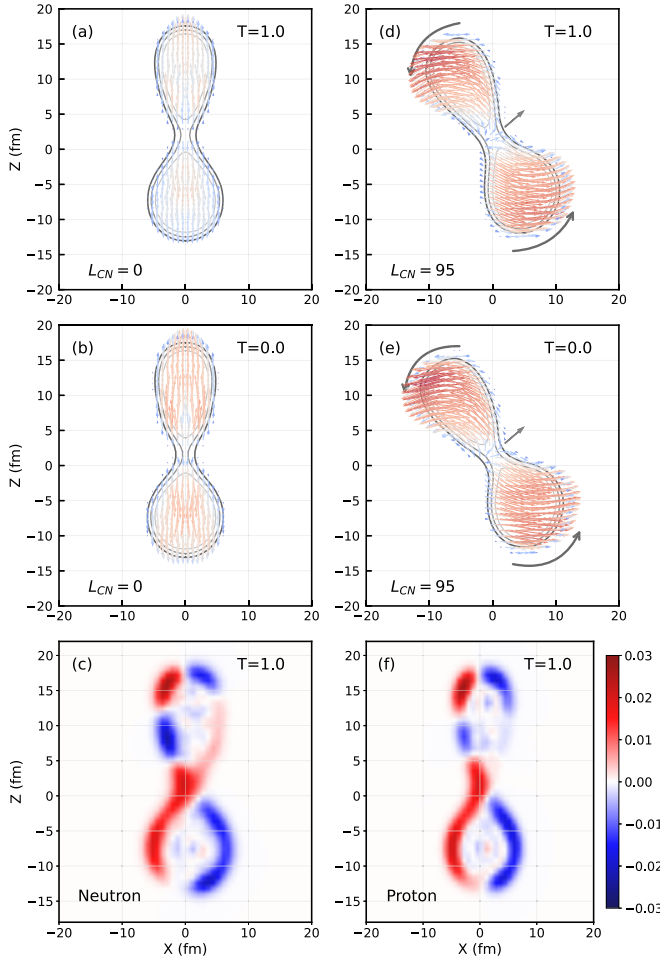


FIG. 3. Calculated current density distributions $\vec{j}(\mathbf{r})$ at scission for different initial temperatures T (in MeV) and angular momenta L_{CN} (a) for $T = 1.0$, $L_{CN} = 0$; (b) for $T = 0.0$, $L_{CN} = 0$; (d) for $T = 1.0$, $L_{CN} = 95\hbar$; and (e) for $T = 0.0$, $L_{CN} = 95\hbar$. Neck currents show scission nucleons emitted perpendicular to the fission axis. Density contours are shown with quadrupole deformation $\beta_2 = 4.0$ for comparison. The density differences (units in fm^{-3}) in neutrons (c) and protons (f) between $L_{CN} = 95\hbar$ and 0 are also shown.

To illustrate the scission configurations with varying initial angular momentum and excitation energies, Fig. 3 shows the evolution of pre-scission current density $\vec{j}(\mathbf{r})$. The currents, related to velocity fields, exhibit violent fission dynamics at rapid rotation. Without initial rotations, the scission neck becomes thicker at higher excitation energies due to enhanced viscosity [58]. As shown in density contours, it can be seen that neck sizes become thicker under rapid rotations irrespective of initial temperatures. The neck is particularly thicker under highly excited rapid rotations. These neck sizes are determined at the same quadrupole deformation $\beta_2 = 4.0$ for comparison. The thicker neck size allows an elongated scission configuration and consequently the decreased Coulomb energy, being consistent with Fig. 2. This can be understood that the strong centrifugal effect leads to a violent nonadiabatic splitting that stretches the neck.

Experimentally, the widths of fragment mass distributions increase at high excitation energies and high angular momentum [57], demonstrating the influences of thicker and elongated neck configurations. Furthermore, we see clearly that there are scission currents with a polarized direction being perpendicular to the fission axis at high spins. This indicates possible subsequent scission neutrons emitted in the direction perpendicular to the fission axis at high L_{CN} . An earlier study shows that at low excitations, scission neutrons emitted in roughly equal numbers in the equatorial plane and along the fission axis [59,60]. Thus scission neutron emissions in rapidly rotating fission can be verified by light projectile nuclei induced fission. Besides, as evidenced by density contours at $L_{CN} = 95\hbar$, the fragments show pronounced non-axially symmetric deformations [61]. Figures 3(c) and 3(f) displays the density differences between rapid rotation and zero rotation by aligning their fission axis, which also demonstrates clearly the breaking of axially symmetric shapes owing to rapid rotations. Note that the fragment shapes are related to the distortion energies, and also the sharing of excitation energies and intrinsic spins [62,63].

Conclusion. We have self-consistently incorporated initial rotation and thermal excitations into microscopic real-time descriptions of nuclear fission process, offering insights into the scission mechanism and the generation of FF spin. For fission of ^{240}Pu under rapid rotation, the light FF spin is larger than the heavy FF spin, and the spin ratio is unchanged with increasing CN angular momentum. However, the partition of FF spin is dependent on excitation energies and the spins of two fragments become close at high excitation energies, indicating the disappearance of sawtooth structures in FF spins at high excitations rather than high angular momentum. The FF spin is a combined contribution from inherited spin and depolarizing spin. Actually the heavy fragment inherits more angular momentum with a larger moment of inertia.

The obtained TKE and the inherited angular momentum also shows that most of the CN angular momentum is converted into relative motion between fragments, explaining the increasing TKE as CN angular momentum increases in experiments. However, the Coulomb energies before scission decrease with increasing angular momentum. This is consistent with elongated scission deformations under rapid rotations, explaining experimental observations of increased widths of fragment mass distributions and TKE distributions in heavy-ion induced fission. In addition, the fragments exhibit considerable nonaxially symmetric shapes owing to rapid rotations. This work demonstrates that the violent nonequilibrium nonadiabatic scission under rapid rotations can significantly impact post-fission observables.

Acknowledgments. We thank useful discussions with F. R. Xu and H. M. Jia. This work was supported by the National Key R & D Program of China (Grant No. 2023YFA1606403) and the National Natural Science Foundation of China under Grants No.12475118 and No. 12335007.

Data availability. The data that support the findings of this article are openly available [64].

- [1] J. B. Wilhelmy, E. Cheifetz, R. C. Jared, S. G. Thompson, H. R. Bowman, and J. O. Rasmussen, Angular momentum of primary products formed in the spontaneous fission of ^{252}Cf , *Phys. Rev. C* **5**, 2041 (1972).
- [2] P. Colciaghi, Y. Li, P. Treutlein, and T. Zibold, Einstein-Podolsky-Rosen experiment with two Bose-Einstein condensates, *Phys. Rev. X* **13**, 021031 (2023).
- [3] J. Wilson *et al.*, Angular momentum generation in nuclear fission, *Nature (London)* **590**, 566 (2021).
- [4] J. Terrell, Neutron yields from individual fission fragments, *Phys. Rev.* **128**, 2925 (1962).
- [5] C. Budtz-Jørgensen and H.-H. Knitter, Simultaneous investigation of fission fragments and neutrons in $^{252}\text{Cf}(\text{SF})$, *Nucl. Phys. A* **490**, 307 (1988).
- [6] M. Albertsson, B. G. Carlsson, T. Døssing, P. Möller, J. Randrup, and S. Åberg, Excitation energy partition in fission, *Phys. Lett. B* **803**, 135276 (2020).
- [7] I. Stetcu, A. E. Lovell, P. Talou, T. Kawano, S. Marin, S. A. Pozzi, and A. Bulgac, Angular momentum removal by neutron and γ -ray emissions during fission fragment decays, *Phys. Rev. Lett.* **127**, 222502 (2021).
- [8] J. Randrup and R. Vogt, Generation of fragment angular momentum in fission, *Phys. Rev. Lett.* **127**, 062502 (2021).
- [9] J. Randrup, Coupled fission fragment angular momenta, *Phys. Rev. C* **106**, L051601 (2022).
- [10] J. Randrup and R. Vogt, Refined treatment of angular momentum in the event-by-event fission model FREYA, *Phys. Rev. C* **89**, 044601 (2014).
- [11] A. Bulgac, I. Abdurrahman, S. Jin, K. Godbey, N. Schunck, and I. Stetcu, Fission fragment intrinsic spins and their correlations, *Phys. Rev. Lett.* **126**, 142502 (2021).
- [12] A. Bulgac, I. Abdurrahman, K. Godbey, and I. Stetcu, Fragment intrinsic spins and fragments' relative orbital angular momentum in nuclear fission, *Phys. Rev. Lett.* **128**, 022501 (2022).
- [13] A. Bulgac, Angular correlation between the fission fragment intrinsic spins, *Phys. Rev. C* **106**, 014624 (2022).
- [14] G. Scamps, I. Abdurrahman, M. Kafker, A. Bulgac, I. Stetcu, *et al.*, Spatial orientation of the fission fragment intrinsic spins and their correlations, *Phys. Rev. C* **108**, L061602 (2023).
- [15] G. Scamps, Quantal effect on the opening angle distribution between the spins of the fission fragments, *Phys. Rev. C* **109**, L011602 (2024).
- [16] J. Randrup, D. Thomas, and R. Vogt, Probing fission fragment angular momenta by photon measurements, *Phys. Rev. C* **106**, 014609 (2022).
- [17] U. Brosa, S. Grossmann, and A. Muller, Nuclear scission, *Phys. Rep.* **197**, 167 (1990).
- [18] B. D. Wilkins, E. P. Steinberg, and R. R. Chasman, Scission-point model of nuclear fission based on deformed-shell effects, *Phys. Rev. C* **14**, 1832 (1976).
- [19] Y. Qiang, J. C. Pei, and K. Godbey, Quantum entanglement in nuclear fission, *Phys. Lett. B* **861**, 139248 (2025).
- [20] H. Y. Shang, Y. Qiang, and J. C. Pei, Energy partition between entangled fission fragments, *Nucl. Sci. Tech.* **36**, 211 (2025).
- [21] J. R. Nix and W. J. Swiatecki, Studies in the liquid-drop theory of nuclear fission, *Nucl. Phys.* **71**, 1 (1965).
- [22] R. P. Schmitt and A. J. Pacheco, Equilibrium treatment of spin-depolarizing modes in mass asymmetric heavy-ion systems, *Nucl. Phys. A* **379**, 313 (1982).
- [23] T. Døssing and J. Randrup, Dynamical evolution of angular momentum in damped nuclear reactions: (I). Accumulation of angular momentum by nucleon transfer, *Nucl. Phys. A* **433**, 215 (1985).
- [24] R. Vogt and J. Randrup, Observational consequences of angular momentum in fission, *EPJ Web Conf.* **322**, 07001 (2025).
- [25] P. Marevic, N. Schunck, J. Randrup, and R. Vogt, Angular momentum of fission fragments from microscopic theory, *Phys. Rev. C* **104**, L021601 (2021).
- [26] T. Døssing, S. Åberg, M. Albertsson, B. G. Carlsson, and J. Randrup, Angular momentum in fission fragments, *Phys. Rev. C* **109**, 034615 (2024).
- [27] Y. Qiang and J. C. Pei, Energy and pairing dependence of dissipation in real-time fission dynamics, *Phys. Rev. C* **104**, 054604 (2021).
- [28] Y. Qiang, J. C. Pei, and P. D. Stevenson, Fission dynamics of compound nuclei: Pairing versus fluctuations, *Phys. Rev. C* **103**, L031304 (2021).
- [29] D. Gjestvang *et al.*, Examination of how properties of a fissioning system impact isomeric yield ratios of the fragments, *Phys. Rev. C* **108**, 064602 (2023).
- [30] S. Cannarozzo *et al.*, Disentangling the influence of excitation energy and compound nucleus angular momentum on fission fragment angular momentum, *Phys. Rev. C* **111**, L031601 (2025).
- [31] R. Choudhury, Recent studies in heavy ion induced fission reactions, *Pramana - J. Phys.* **57**, 585 (2001).
- [32] P. Goddard, P. Stevenson, and A. Rios, Fission dynamics within time-dependent Hartree-Fock: Deformation-induced fission, *Phys. Rev. C* **92**, 054610 (2015).
- [33] A. Bulgac, P. Magierski, K. J. Roche, and I. Stetcu, Induced fission of ^{240}Pu within a real-time microscopic framework, *Phys. Rev. Lett.* **116**, 122504 (2016).
- [34] A. Bulgac, S. Jin, K. J. Roche, N. Schunck, and I. Stetcu, Fission dynamics of ^{240}Pu from saddle to scission and beyond, *Phys. Rev. C* **100**, 034615 (2019).
- [35] G. Scamps and C. Simenel, Impact of pear-shaped fission fragments on mass-asymmetric fission in actinides, *Nature (London)* **564**, 382 (2018).
- [36] G. Scamps, C. Simenel, and D. Lacroix, Superfluid dynamics of ^{258}Fm fission, *Phys. Rev. C* **92**, 011602(R) (2015).
- [37] Y. Tanimura, D. Lacroix, and S. Ayik, Microscopic phase-space exploration modeling of ^{258}Fm spontaneous fission, *Phys. Rev. Lett.* **118**, 152501 (2017).
- [38] A. Bulgac, Fission-fragment excitation energy sharing beyond scission, *Phys. Rev. C* **102**, 044609 (2020).
- [39] A. Bulgac, S. Jin, and I. Stetcu, Unitary evolution with fluctuations and dissipation, *Phys. Rev. C* **100**, 014615 (2019).
- [40] D. Lacroix and S. Ayik, Stochastic quantum dynamics beyond mean field, *Eur. Phys. J. A* **50**, 95 (2014).
- [41] G. Scamps, Microscopic study of spin transfer in near-barrier nuclear reactions, *Phys. Rev. C* **110**, 054605 (2024).
- [42] H. Lee, P. McGlynn, and C. Simenel, Shell effects in quasifission in reactions forming the ^{226}Th compound nucleus, *Phys. Rev. C* **110**, 024606 (2024).
- [43] C. Simenel and A. S. Umar, Formation and dynamics of fission fragments, *Phys. Rev. C* **89**, 031601(R) (2014).
- [44] P.-G. Reinhard, B. Schuetrumpf, and J. A. Maruhn, The axial Hartree-Fock + BCS code SkyAx, *Comput. Phys. Commun.* **258**, 107603 (2021).

- [45] A. L. Goodman, Finite-temperature HFB theory, *Nucl. Phys. A* **352**, 30 (1981).
- [46] S. Ebata, T. Nakatsukasa, T. Inakura, K. Yoshida, Y. Hashimoto, and K. Yabana, Canonical-basis time-dependent Hartree-Fock Bogoliubov theory and linear-response calculations, *Phys. Rev. C* **82**, 034306 (2010).
- [47] J. A. Maruhn, P.-G. Reinhard, P. D. Stevenson, and A. S. Umar, The TDHF code Sky3D, *Comput. Phys. Commun.* **185**, 2195 (2014).
- [48] J. Bartel, P. Quentin, M. Brack, C. Guet, and H.-B. Håkansson, Towards a better parametrisation of Skyrme-like effective forces: A critical study of the SkM force, *Nucl. Phys. A* **386**, 79 (1982).
- [49] J. Dobaczewski, W. Nazarewicz, and M. V. Stoitsov, Nuclear ground-state properties from mean-field calculations, *Eur. Phys. J. A* **15**, 21 (2002).
- [50] L. Guo, J. A. Maruhn, P.-G. Reinhard, and Y. Hashimoto, Conservation properties in the time-dependent Hartree Fock theory, *Phys. Rev. C* **77**, 041301(R) (2008).
- [51] T. Ichikawa, K. Matsuyanagi, J. A. Maruhn, and N. Itagaki, High-spin torus isomers and their precession motions, *Phys. Rev. C* **90**, 034314 (2014).
- [52] A. Bulgac, S. Jin, and I. Stetcu, Nuclear fission dynamics: Past, present, needs, and future, *Front. Phys.* **8**, 63 (2020).
- [53] D. Baye and P. H. Heenen, Angular momentum projection on a mesh of cranked Hartree-Fock wave functions, *Phys. Rev. C* **29**, 1056 (1984).
- [54] H. Zdunick, W. Satuła, J. Dobaczewski, and M. Kosmulski, Angular momentum projection of cranked Hartree-Fock states: Application to terminating bands in $A \sim 44$ nuclei, *Phys. Rev. C* **76**, 044304 (2007).
- [55] W. Nazarewicz, R. Wyss, and A. Johnson, Structure of superdeformed bands in the $A \approx 150$ mass region, *Nucl. Phys. A* **503**, 285 (1989).
- [56] B. R. Mottelson and J. G. Valatin, Effect of nuclear rotation on the pairing correlation, *Phys. Rev. Lett.* **5**, 511 (1960).
- [57] B. G. Glagola, B. B. Back, and R. R. Betts, Effects of large angular momenta on the fission properties of Pt isotopes, *Phys. Rev. C* **29**, 486 (1984).
- [58] K. T. R. Davies, A. J. Sierk, and J. R. Nix, Effect of viscosity on the dynamics of fission, *Phys. Rev. C* **13**, 2385 (1976).
- [59] I. Abdurrahman, M. Kafker, A. Bulgac, and I. Stetcu, Neck rupture and scission neutrons in nuclear fission, *Phys. Rev. Lett.* **132**, 242501 (2024).
- [60] P. Carpentier, N. Pillet, D. Lacroix, N. Dubray, and D. Regnier, Construction of continuous collective energy landscapes for large amplitude nuclear many-body problems, *Phys. Rev. Lett.* **133**, 152501 (2024).
- [61] G. Scamps, Microscopic description of the torque acting on fission fragments, *Phys. Rev. C* **106**, 054614 (2022).
- [62] R. Han, M. Warda, A. Zdeb, and L. M. Robledo, Scission configuration in self-consistent calculations with neck constraints, *Phys. Rev. C* **104**, 064602 (2021).
- [63] G. Scamps and G. Bertsch, Generation, dynamics, and correlations of the fission fragments' angular momenta, *Phys. Rev. C* **108**, 034616 (2023).
- [64] Y. Qiang, Detailed data for Figs. 1, 2, and 3, <https://github.com/qyqyff420/TDBCS-rotating-fission>.