LA-UR-26-23929

Exploring Real-Time Nuclear Dynamics: Mean Field and Beyond

Nuclear theory for astrophysics: Bridging bound-state and continuum physics

Outline

- ❖ theoretical overview
- ❖ applications to fission dynamics
  - select fission fragment properties (fragmentation, TKE)
  - angular momenta of fission fragments
  - scission neutrons
  - even-odd and odd-odd fission dynamics
- ❖ eGCM
- ❖ quantum computing for nuclear dynamics
- ❖ summary and outlook

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18 May 2026 — 22 May 2026, Trento, Italy

Applications of the TD-DFT formalism

- Nuclear physics:
  - induced fission
  - neutron-induced reactions
  - heavy-ion collisions
  - pairing vibrations
  - electromagnetic response
- Neutron star crust: dynamics of vortices, vortex pinning mechanism
- Cold atoms physics, optical lattices

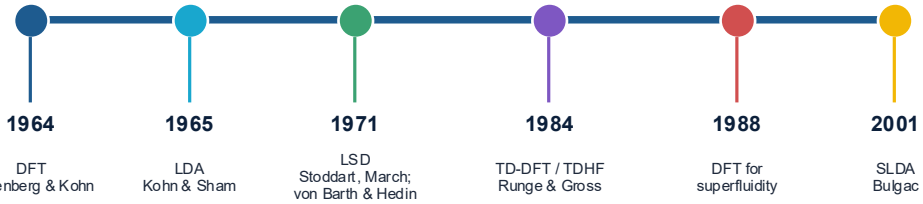
Limitations:
- only one-body observables can be described accurately
- average quantities (unless going to stochastic implementation)
- the results depend on how good the functional is: (fission) dynamics can help
- neglects two-body collisions
- large computational resources necessary

DFT to superfluid dynamics

Kohn recognition

Nobel Prize in Chemistry, 1998, for foundational DFT work.

A concise lineage from ground-state density functionals to time-dependent superfluid DFT



System	T_c[eV]
Dilute Fermi gases	10^{-12}-10^{-9}
Liquid ^{3}He	10^{-7}
Metals, composite materials	10^{-3}-10^{-2}
Nuclei, neutron stars	10^{5}-10^{8}

Densities

rho(r), tau(r), nu(r)
normal + anomalous channels

→

Energy functional

E[rho, tau, nu]
optimized variationally

Minimization

delta E = 0
with constraints

HFB-like equations

quasiparticle amplitudes
u and v

SLDA: static superfluid local density approximation →

TD-SLDA: time-dependent evolution of superfluid dynamics

small-amplitude limit: QRPA

DFT for the Unitary Fermi Gas

A universal, strongly interacting benchmark for the superfluid density functional theory

Zero range + infinite scattering length

At unitarity, the system has no intrinsic interaction length scale. Apart from m and $\hbar$, its behavior is set only by the average interparticle separation.

Why it matters

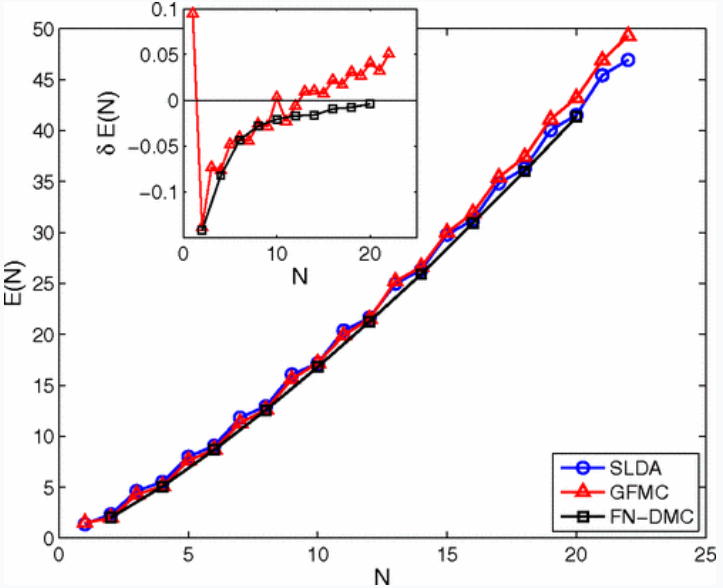
- Similar to dilute neutron matter in neutron-star crusts
- Routinely created in table-top cold-atom laboratories
- Known precisely from theory and experiment
- A rare real system where DFT can be built and tested end-to-end

$$\mathcal{E}(\mathbf{r}) = \alpha\frac{\tau(\mathbf{r})}{2} + \beta\frac{3(3\pi^2)^{2/3}n^{5/3}(\mathbf{r})}{10} + \gamma\frac{|\nu(\mathbf{r})|^2}{n^{1/3}(\mathbf{r})},$$

$$n(\mathbf{r}) = 2\sum_k |v_k(\mathbf{r})|^2, \quad \tau(\mathbf{r}) = 2\sum_k |\nabla v_k(\mathbf{r})|^2,$$

$$\nu(\mathbf{r}) = \sum_k v_k^*(\mathbf{r})u_k(\mathbf{r}),$$

Bulgac, Phys. Rev. A 76, 040502(R) (2007)



Excellent agreement: DFT vs. GFMC / FN-DMC

Dynamics in DFT

Reformulation of exact quantum-mechanical evolution for many-body systems when the observables of interest are single-particle properties.

Density mapping theorem

Theorem 4.—The exact time-dependent density of the system can be computed from

$$n(\vec{r}\,t) = \sum \phi_j^*(\vec{r}\,t)\phi_j(\vec{r}\,t), \tag{15}$$

where the single-particle orbitals $\phi_j(\vec{r}\,t)$ fulfill the time-dependent Schrödinger equation

$$(i\partial/\partial t + \tfrac{1}{2}\nabla^2)\phi_j(\vec{r}\,t) = v_{\text{eff}}[\vec{r}\,t; n(\vec{r}\,t)]\phi_j(\vec{r}\,t) \tag{16}$$

with an effective one-particle potential given by

$$v_{\text{eff}}[\vec{r}\,t, n(\vec{r}\,t)] = v(\vec{r}\,t) + \int d^3r'\, n(\vec{r}\,'t)\, w(\vec{r}, \vec{r}\,') + \delta A_{\text{xc}}/\delta n(\vec{r}\,t). \tag{17}$$

Superfluid / TD-SLDA evolution equation

$$\begin{pmatrix} h(\vec{r},t) + V_{ext}(\vec{r},t) - \mu & \Delta(\vec{r},t) + \Delta_{ext}(\vec{r},t) \\ \Delta^*(\vec{r},t) + \Delta^*_{ext}(\vec{r},t) & \mu - h^*(\vec{r},t) - V^*_{ext}(\vec{r},t) \end{pmatrix} \begin{pmatrix} u_k(\vec{r},t) \\ v_k(\vec{r},t) \end{pmatrix} = i\hbar \begin{pmatrix} \dot{u}_k(\vec{r},t) \\ \dot{v}_k(\vec{r},t) \end{pmatrix}$$

Foundational papers

- **73** **1973 Rajagopal & Callaway**
  Phys. Rev. B 7, 1912
- **78** **1978 Peuckert**
  J. Phys. G 11, 4945
- **84** **1984 Runge & Gross**
  Phys. Rev. Lett. 52, 997

Key message

The exact many-body time evolution can be recast through a time-dependent effective one-particle problem, enabling DFT-based dynamics.

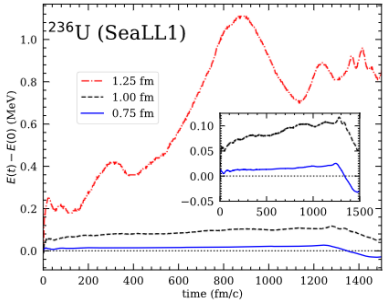
Numerical implementation of the dynamics with DFT

Unitary gas: A. Bulgac and K. Roche, J. Phys. Conf. Series **125** (2008) 012064
Nuclear physics: S. Jin, K. Roche, I. Stetcu, I. Abdurrahman, and A. Bulgac, Comp. Phys. Commun. **269,** 108130 (2021)

Time evolution realized with the multistep predictor-modifier-corrector Adams-Bashford-Milne (ABM) method:
✓ two applications of h per time step (few operations, does not involve matrix multiplication)
✓ sixth order method (very accurate)
✓ very stable numerically for long time intervals

Derivatives are calculated using FFTW
MPI+CUDA implementation
Very efficient I/O for Check-Point Restart

Energy conservation



SciDAC 2008 IOP Publishing
Journal of Physics: Conference Series **125** (2008) 012064 doi:10.1088/1742-6596/125/1/012064

Time-dependent density functional theory applied to superfluid nuclei

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Computer Physics Communications
www.elsevier.com/locate/cpc

The LISE package: Solvers for static and time-dependent superfluid local density approximation equations in three dimensions ☆,☆☆

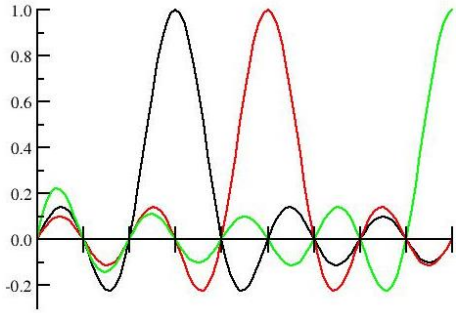
Shi Jin [a], Kenneth J. Roche [b,a], Ionel Stetcu [c,*], Ibrahim Abdurrahman [a], Aurel Bulgac [a]
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https://github.com/lanl/lise

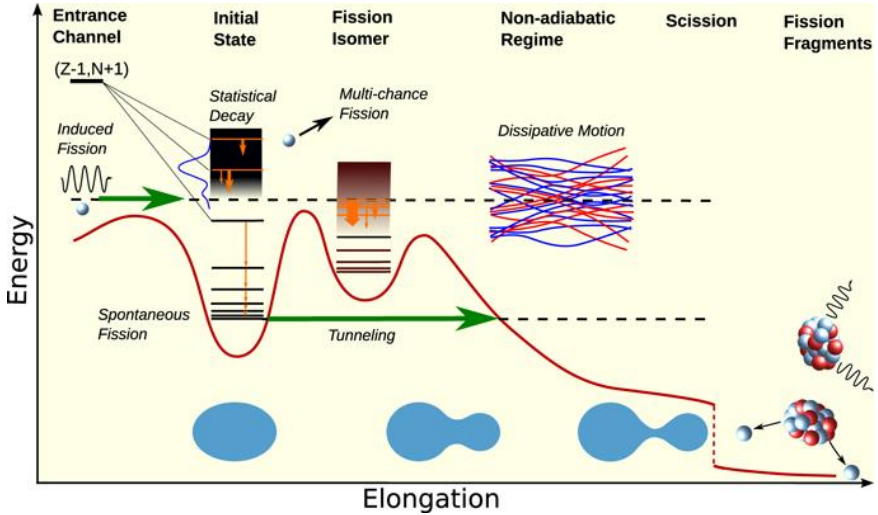
Lattice representation

- quasiparticle wavefunctions represented on a lattice
- periodic boundary conditions
- N_x, N_y, N_z spatial points (dimension $4N_xN_yN_z$)
- derivatives computed with FFT
- good description of the relevant DOF for E>0
- exponential convergence when box size and momentum cutoff properly chosen
- (almost) unique ability to describe correctly all components of the quasiparticle wavefunctions

$$\varphi_i(x) = \frac{1}{N} e^{-\frac{i\pi(x-x_i)}{Na}} \frac{\sin\frac{\pi(x-x_i)}{a}}{\sin\frac{\pi(x-x_i)}{Na}}$$



Theorist's view of the fission process



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IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 47 (2020) 113002 (58pp)
https://doi.org/10.1088/1361-6471/abab4f

Topical Review

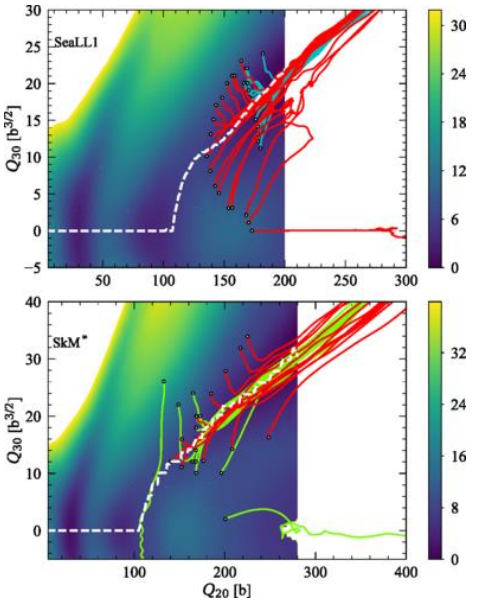
Future of nuclear fission theory

Michael Bender[1], Rémi Bernard[2,3], George Bertsch[4], Satoshi Chiba[5], Jacek Dobaczewski[6,7,8], Noël Dubray[3,9], Samuel A Giuliani[10], Kouichi Hagino[11], Denis Lacroix[12], Zhipan Li[13], Piotr Magierski[14], Joachim Maruhn[15], Witold Nazarewicz[16], Junchen Pei[17], Sophie Péru[3,9], Nathalie Pillet[3,9], Jørgen Randrup[18], David Regnier[3,9], Paul-Gerhard Reinhard[19], Luis M Robledo[20,21], Wouter Ryssens[22], Jhilam Sadhukhan[23,24], Guillaume Scamps[25], Nicolas Schunck[26], Cédric Simenel[2], Janusz Skalski[27], Ionel Stetcu[28], Paul Stevenson[29], Sait Umar[30], Marc Verriere[26,28], Dario Vretenar[31], Michał Warda[32] and Sven Åberg[33]

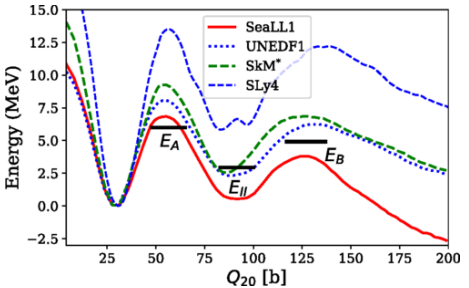
- Slow process from compound to outer barrier
- Faster, but still slow and dissipative motion from saddle to scission

Fission simulations

- Evolution until outer barrier: slow and adiabatic
- Start the calculation the nucleus just outside the outer barrier
- Dynamics: relatively slow, dissipative (non-adiabatic)
- Evolve in time until full separation (at least 30 fm)
- Calculate properties of the FFs:
  - Mass, Charge, TKE
  - Excitation energy sharing
  - Perform different projections (angular momentum)
- Shown ^{240}Pu
  - Also available ^{236,239}U, ^{241,243}Pu, ^{238}Np, ^{252}Cf (sf).

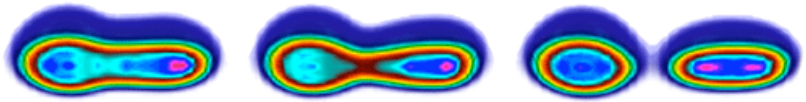


NEDF	$E^*_{\rm ini}$	TKE	$N_{\rm H}$	$Z_{\rm H}$	$N_{\rm L}$	$Z_{\rm L}$	$E^*_{\rm H}$	$E^*_{\rm L}$	TXE	TKE+TXE	$\tau_{s\to s}$ (fm/c)
SeaLL1-1asy	7.9(1.7)	177.8(3.1)	83.4(0.4)	53.2(0.4)	62.9(0.5)	41.1(0.4)	17.1(3.0)	20.3(2.0)	37.4(3.1)	215.2(2.5)	2317(781)
SeaLL1-2asy	2.6(1.8)	178.0(2.3)	82.9(0.4)	52.9(0.2)	63.3(0.5)	41.5(0.3)	19.5(3.8)	14.0(1.9)	33.5(5.1)	211.5(3.3)	1460(176)
SeaLL1-sy	9.2	147.1	77.5	48.9	68.8	45.4	45.2	29.0	74.2	221.3	10103
SkM*-1asy	8.2(3.0)	174.5(2.5)	84.1(0.9)	53.0(0.5)	61.8(0.9)	40.9(0.5)	16.6(3.1)	14.9(2.3)	31.5(3.8)	206.0(2.4)	1214(448)
SkM*-1sy	9.6	149.0	73.4	47.2	72.6	46.7	29.4	28.5	57.9	206.9	3673
SkM*-2asy	8.1(0.2)	182.8(4.4)	82.6(1.0)	52.4(0.6)	63.6(1.0)	41.7(0.5)	14.3(3.9)	13.0(3.0)	27.3(3.4)	210.1(1.8)	1349(309)

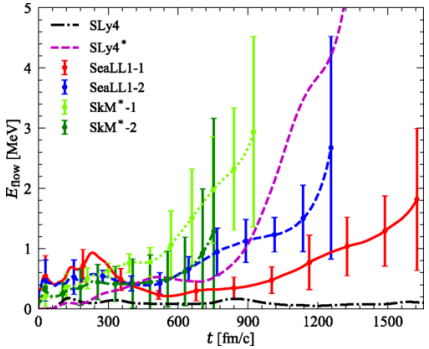


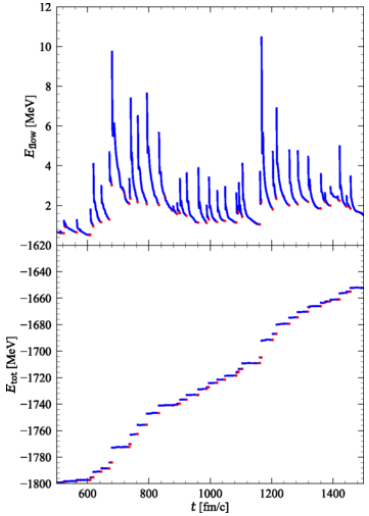
Bulgac et al, Phys. Rev. Lett. **116**, 122504 (2016)
Bulgac et al, Phys. Rev. C **100**, 034615 (2019)

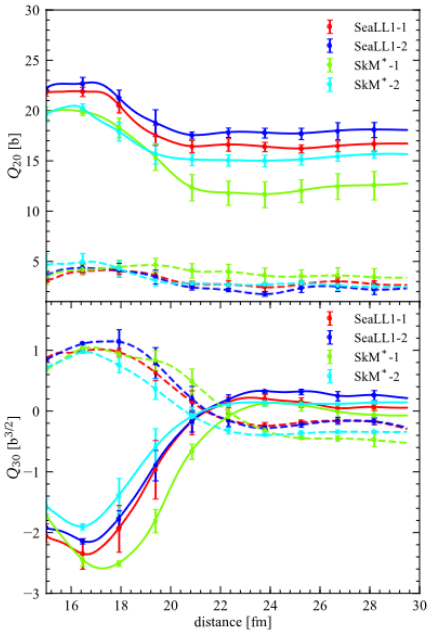
Lessons learned from fission dynamics



- Slow evolution, non-adiabatic
- Most of the potential energy is transformed into heat (excitation of the nucleus)
- It takes some time after the separation for the FF shape to stabilize: questions the properties extracted before full separation
- Pairing still survives in the fission fragments even though their excitation energy is large



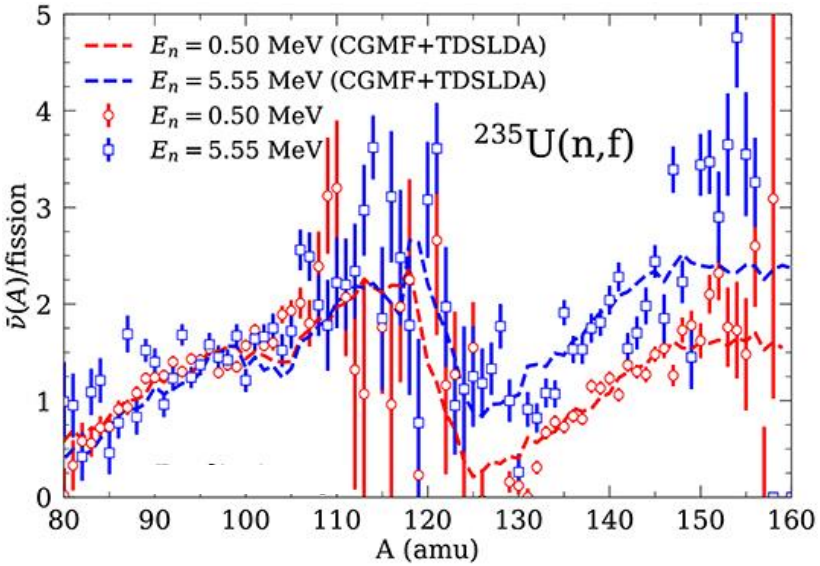




Bulgac et al, Phys. Rev. C **100**, 034615 (2019)

Guide to phenomenological models

Excitation energy sharing extracted from TDDFT calculations as a function of incident neutron energy, parameterized, and included in CGMF



Bulgac, Jin, Stetcu, Front. Phys. **8**, 63 (2020)

Fission fragment spin distributions

PHYSICAL REVIEW LETTERS **126,** 142502 (2021)

Fission Fragment Intrinsic Spins and Their Correlations

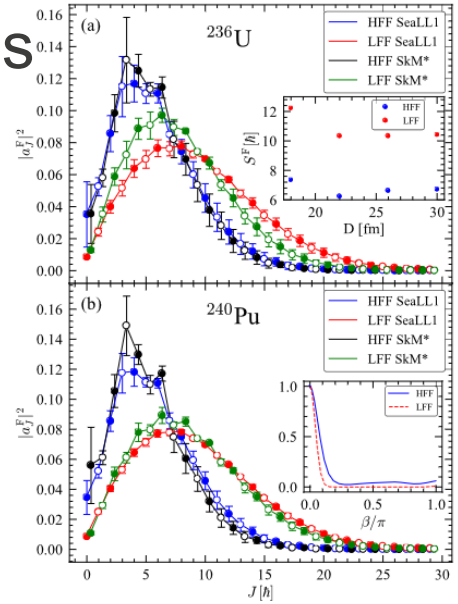
Aurel Bulgac,[1] Ibrahim Abdurrahman,[1] Shi Jin,[1] Kyle Godbey,[2] Nicolas Schunck,[3] and Ionel Stetcu[4]
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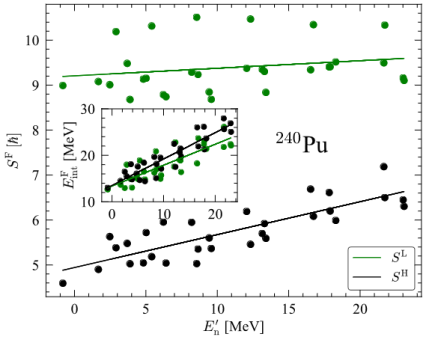
(Received 24 December 2020; revised 5 February 2021; accepted 11 March 2021; published 7 April 2021)

Nucleus	NEDF	S^L	S^H	β_2^L	β_2^H
^{236}U	SeaLL1	10.5 (0.6)	6.8(0.7)	0.67(0.07)	0.09(0.04)
^{236}U	SkM*	8.6(0.6)	6.3(0.7)	0.46(0.10)	0.09(0.03)
^{240}Pu	SeaLL1	10.4(0.3)	6.7(0.5)	0.62(0.04)	0.06(0.03)
^{240}Pu	SkM*	9.4(0.4)	5.8(0.5)	0.54(0.06)	0.06(0.03)

Nucleus	NEDF	$\langle\Phi\vert J_x^L J_x^H\vert\Phi\rangle$	$\langle\Phi\vert J_y^L J_y^H\vert\Phi\rangle$	$\langle\Phi\vert J_z^L J_z^H\vert\Phi\rangle$
^{236}U	SeaLL1	−1.16(0.63)	−1.16(0.63)	−2.63(0.47)
^{236}U	SkM*	−0.48(0.71)	−0.48(0.71)	−1.62(0.30)
^{240}Pu	SeaLL1	−0.72(0.65)	−0.72(0.65)	−4.43(0.92)
^{240}Pu	SkM*	−0.90(0.57)	−0.90(0.57)	−1.80(0.52)

- Light fragment has on average higher spins that the heavy fragment (light fragment is more deformed)
- FF spins approximately perpendicular to each other
- Mostly bending and twisting modes
- Relaxation is important, otherwise the spin is too large.
  - Larger spins have been obtained by Marevic et al., Phys. Rev. C **104**, L021601 (2021)





Inclusion of relative angular momentum

PHYSICAL REVIEW LETTERS **128,** 022501 (2022)

Fragment Intrinsic Spins and Fragments' Relative Orbital Angular Momentum in Nuclear Fission

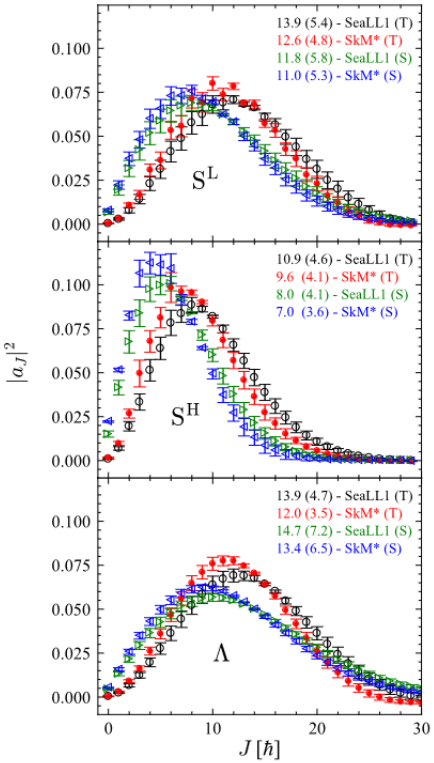
Aurel Bulgac,[1] Ibrahim Abdurrahman,[1] Kyle Godbey,[2] and Ionel Stetcu[3]
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(Received 20 August 2021; revised 16 September 2021; accepted 23 December 2021; published 12 January 2022)

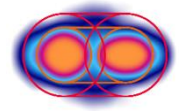
Key result: FF spins are correlated due to the relative angular momenta. This is in contradiction with:

- FREYA, which finds the spins uncorrelated
- (Apparently) Wilson et al., Nature **590**, 566 (2021)
  - Integrating out the relative angular momentum does produce practically uncorrelated spins Bulgac, PRC **106**, 014624 (2022)
  - Correlations can be lost after the neutron evaporation: Stetcu et al, Phys. Rev. Lett. **127**, 222502 (2021)

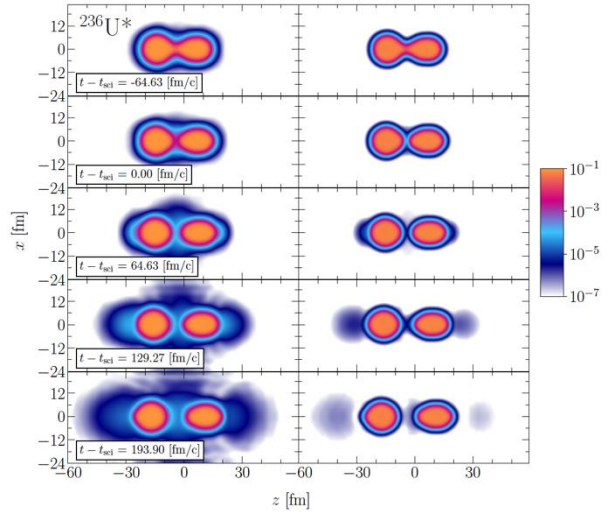
$$\sum_{\Lambda} S_3(S_L, S_H, \Lambda) \approx S_1(S_L) \cdot S_1(S_H)$$

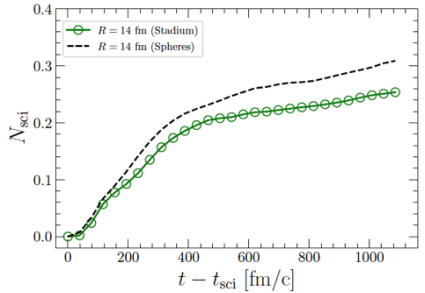


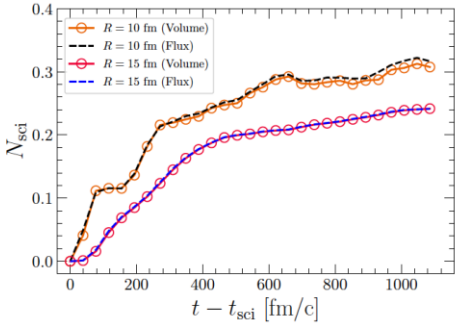
Scission neutrons



- Scission neutrons have been introduced by Bohr and Wheeler in 1939
- This has been a hotly debated topic over the years, even the same authors claiming at one point that all neutrons are emitted at scission and later on about half.
- Very difficult to investigate as it requires large computational resources to allow the observation of the scission neutrons
  - We used either 48x48x120 or 48x48x100 point lattices
  - Required some of the biggest machines to run
  - Larger boxes are still required
- Their clear experimental confirmation remains challenging



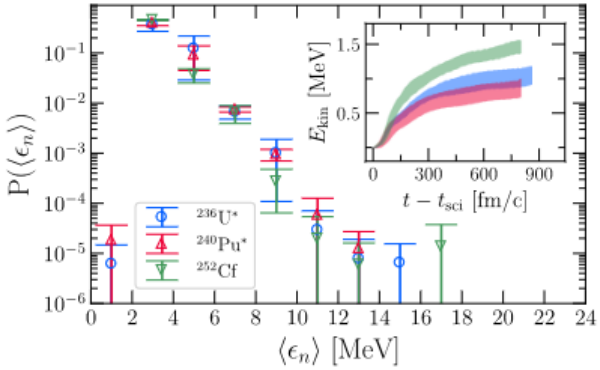




Abdurrahman et al., PRL **132**, 242501 (2024)

Properties of scission neutrons

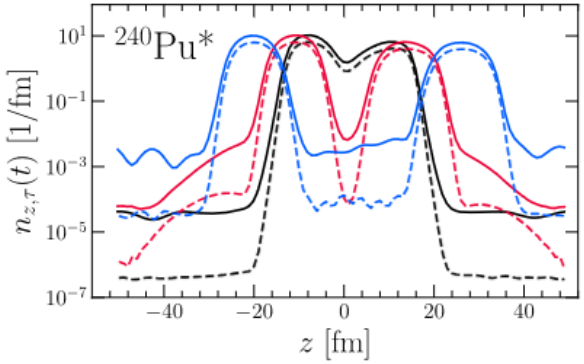
- The total number of emitted neutrons is about 0.30±0.05, 0.26±0.05, and 0.55±0.02 per fission event for ^{236}U, ^{240}Pu, and ^{252}Cf, respectively
- This corresponds to roughly 9%–14% of the total emitted prompt neutrons (estimates are conservative)
- Carjan et al estimated an upper bound of 25-50% of scission neutrons.
- Roughly equal number of perpendicular and longitudinal scission neutrons emitted
- The average kinetic energies of the SNs are given by 3.51±0.25 MeV, 3.42±0.27 MeV, and 2.67±0.24 MeV for 236U, 240Pu, and 252Cf, respectively
- Faster than typically considered prompt neutrons

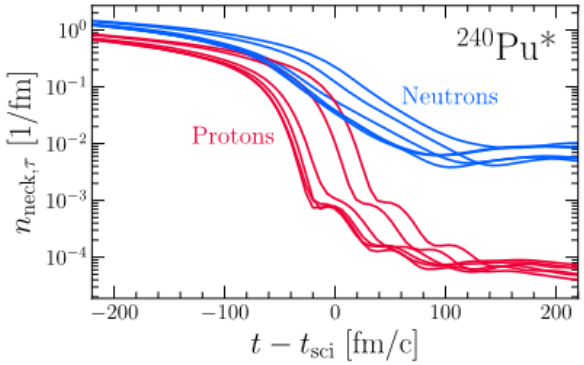


Abdurrahman et al., PRL **132**, 242501 (2024)

Emission mechanism and neck rupture

- Neck rupture behavior is universal for large class of asymmetric fission trajectories.
  - The number density decays exponentially, with a decay time of τ ≈ 35.0 ± 2.2 fm/c for neutrons and 15.3 ± 0.3 fm/c for protons.
  - It is not random, once a wrinkle forms at the outer saddle it does not move.
  - Still needs to be tested for symmetric or close to symmetric fission and more nuclear systems.
- Catapult mechanism, suggested by Mädler in 1984, is responsible for longitudinal emission.





Even-odd and odd-odd nuclei

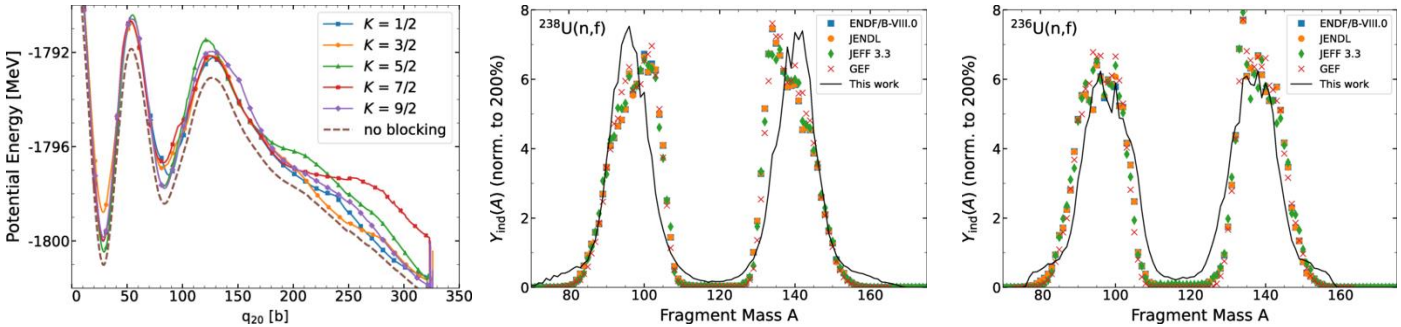
- Blocking approximation for even-odd and odd-odd systems
- Odd-mass and odd-odd nuclei break time-reversal invariance
- Not too many studies available in the literature

PHYSICAL REVIEW C **107**, 044312 (2023)

Editors' Suggestion

Microscopic calculation of fission product yields for odd-mass nuclei

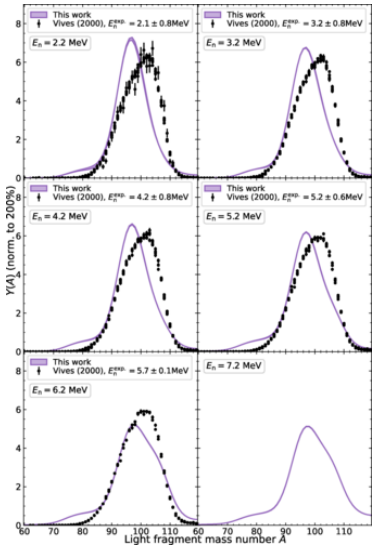
N. Schunck,[1,*] M. Verriere,[1] G. Potel Aguilar,[1] R. C. Malone,[1] J. A. Silano,[1] A. P. D. Ramirez,[1] and A. P. Tonchev[1,2]



Post-neutron emission (FREYA)

TDGCM+GOA

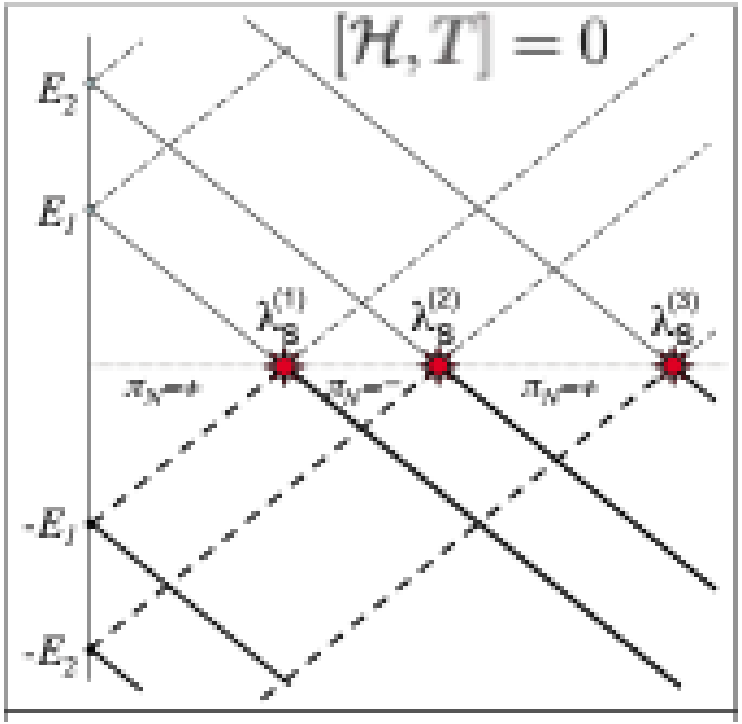
(adiabatic approximation)



Pre-neutron emission

Self-Consistent Odd Solutions

- Typical HFB:
  - Energy density functional defines defines HFB Hamiltonian.
  - Hamiltonian is diagonalized to obtain quasi-particle wavefunctions (qpwfs).
  - **Qpwfs with positive energies are selected.**
  - Qpwfs generate densities, which generate potentials, which generate a new Hamiltonian.
  - All steps are repeated until convergence.
- For HFB extended to odd systems, the two quasi-particle states above and below the Fermi surface are swapped.
  - States are chosen so the sign of the expectation value of the sigma z operator is fixed.
- Leads to:
  - Breaking of time-reversal invariance.
  - Time odd terms.
  - Triaxial ground states.

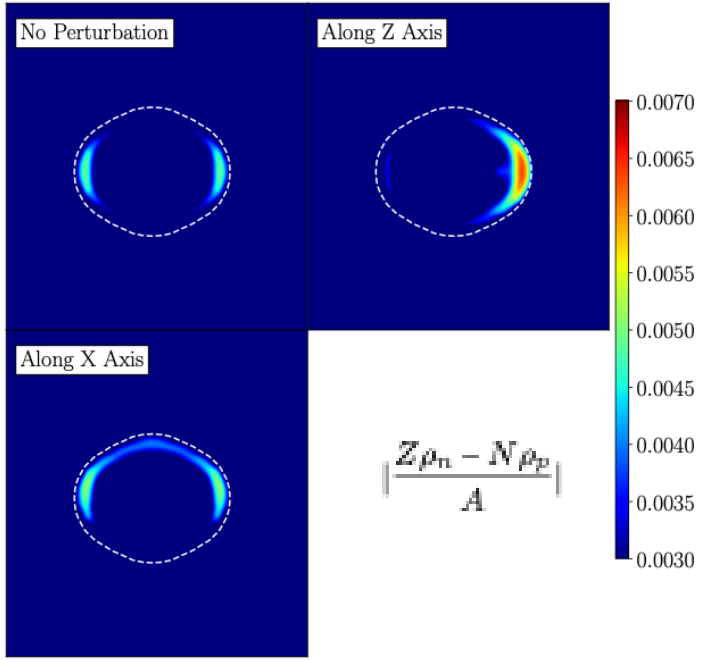


Source: Bertsch et. al. Phys. Rev. A. **79**, 043602 (2009).

Curtesy I. Abdurrahman

Static Polarizabilities of Odd Actinides

- We found very little difference in the polarizability of ^{241}Pu, treating it as an even or odd system.
- In DFT, the IVGDR only depends on the one body densities.
- Ground state deformations, as well as pairing, will likely have a strong influence in the polarizability (still needs to be investigated).
- We might find pronounced differences for odd vs even nuclei in regions of the nuclear chart with sharp shape transitions.
- We plan to also extract the polarizability of ^{238}Np (odd-odd).



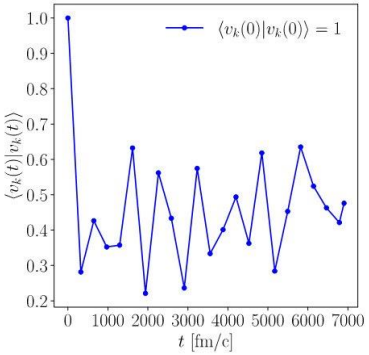
Nucleus	Treatment	E_{tot} [MeV]	Q_{xx} [b]	Q_{yy} [b]	Q_{zz} [b]	Δ_p [MeV]	Δ_n [MeV]	α_E	α_{Ex}	α_{Ey}	α_{Ez}
^{241}Pu	Even	-1815.7	-14.82	-14.82	29.65	0.62	0.92	3.34	3.06	3.06	3.90
^{241}Pu	Odd	-1815.2	-14.80	-14.78	29.58	0.66	0.82	3.35	3.07	3.07	3.91
^{239}U	Even	-1803.82	-14.34	-14.34	28.68	0.69	0.93	-	-	-	-
^{239}U	Odd	-1803.26	-14.31	-14.30	28.61	0.71	0.88	3.44	3.19	3.19	3.95

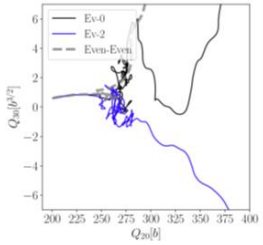
Preliminary

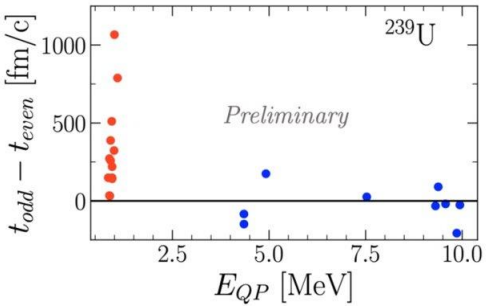
Curtesy I. Abdurrahman

Odd systems in TDDFT

- Time-reversal symmetry explicitly broken (no approximations)
- Fission fragments properties, TKE and TXE quite similar to even and odd mass nuclei.
- **Pauli blocking is not a good approximation for time-dependent phenomena or large amplitude collective motion.**







Some of the scission times are very long

PHYSICAL REVIEW LETTERS **135,** 062501 (2025)

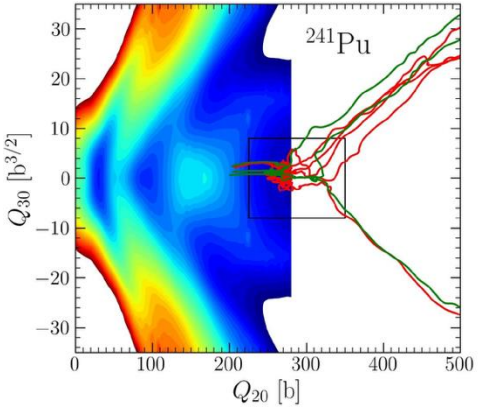
Time-Dependent Density Functional Theory Description of ^{238}U(n,f), ^{240,242}Pu(n,f), and ^{237}Np(n,f) Reactions

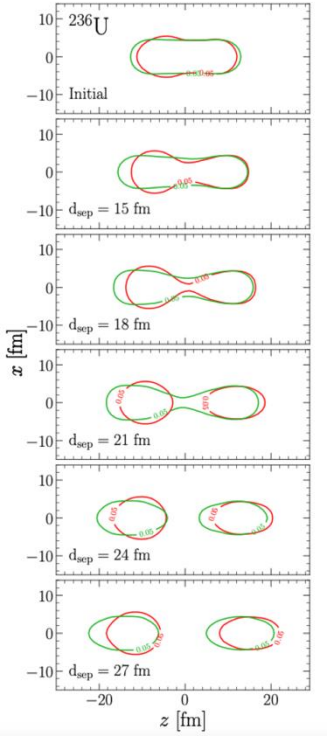
Aurel Bulgac,[1] Ibrahim Abdurrahman,[2] Matthew Kafker,[1] and Ionel Stetcu[2]
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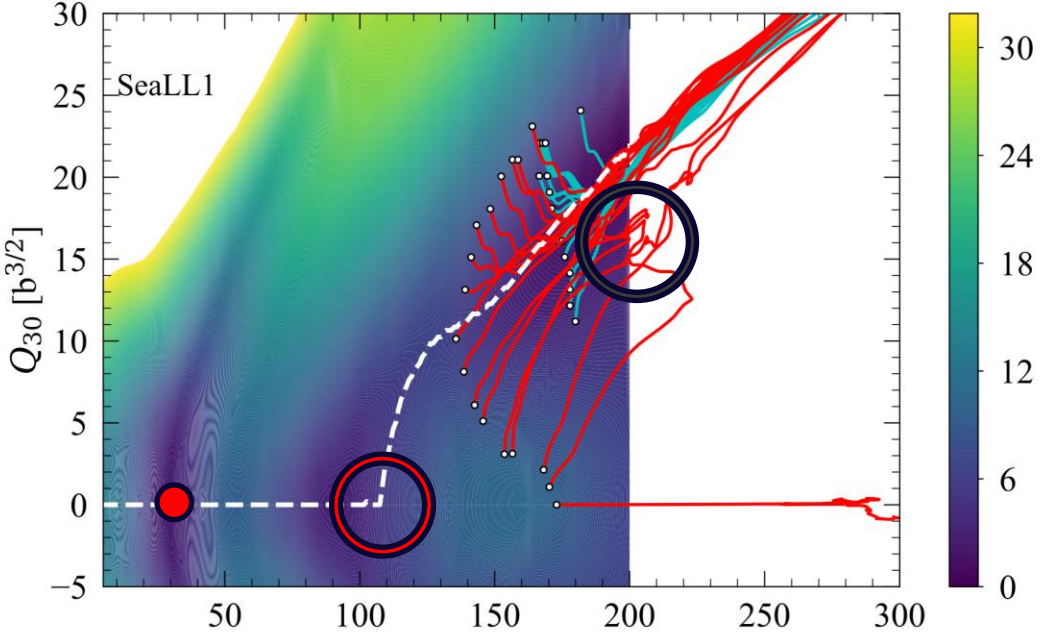
“Confused” trajectories

- Trajectories starting from more symmetric configurations still fission asymmetrically, but rupture at larger separation distances.
  - ➢ Leads to lower TKE.
  - ➢ Could explain experimentally observed decrease in TKE as the system’s initial excitation energy is increased.
- For these trajectories, small differences in the initial conditions can lead to vastly different outcomes
- HFF emerges much more deformed in these cases





What TDDFT cannot do?



- The lines are TDDFT ^{239}Pu(n_{th},f) induced fission trajectories, which are known for decades to have a pure classical character (exactly as the two rays considered in describing interference).

- Unlike GCM or TDGCM, where configurations representing various nuclear shapes are all "cold," along the TDDFT a nucleus which undergoes a non-equilibrium evolution and it heats up on its way from the saddle to scission.

- All these TDDFT trajectories in reality originate at the fat red bullet, where an absorbed thermal neutron leads to the formation of the compound nucleus according to N. Bohr, Nature,137, 344 (1936).

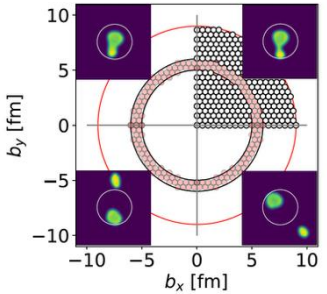
- It is desirable to treat these trajectories as in a many-slit interference experiment, which eventually lead to interference fringes on the "screen," which in this case is a fission fragment detector.

- The sum over all individual trajectories with appropriate weights leads to a many-nucleon wave function.

- The length of the path in the action integral $\int \sum_n p_n \, dq_n$ varies from one trajectory to another, as the collective velocity depends on the profile of the potential energy surface in the collective space (Q_{20}, Q_{30})

One very promising solution to these problems is obtained within **the enhanced Generator Coordinate Method (eGCM).**

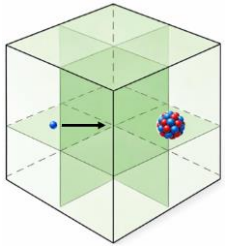
First results using eGCM



- **First continuum eGCM implementation for heavy-ion MNT:** enhanced Generator Coordinate Method application to $^{48}\mathrm{Ca} + ^{208}\mathrm{Pb}$, going beyond TDHF and earlier GCM variants by mixing many TDDFT trajectories at many times.
- **Qualitatively new reaction outcome:** Unlike TDHF, where all simulated trajectories separate, eGCM predicts formation of a long-lived compound-like nucleus.
- **Strong many-body configuration mixing:** The eGCM wave function becomes highly complex after contact, with much larger mixing than allowed in earlier GCMR-style treatments.
- **Compound-nucleus behavior emerges microscopically:** The eGCM spectrum shows signatures consistent with quantum-chaotic compound-nucleus dynamics, supporting a Bohr-like compound-nucleus picture.
- **Much broader transfer distributions than TDHF:** eGCM predicts substantial proton and neutron transfer, mainly toward the heavy fragment, even in periferral collisions.
- **Central interpretation: quantum interference and entanglement among eGCM components play a major role.** Destructive interference can stabilize the compound-like configuration and give it a very long lifetime, a behavior absent from mean-field TDHF.
- **Main limitation:** The work addresses the early formation and evolution of the compound-like system, but not its later fission or quasi-fission decay, which is needed for direct experimental comparison

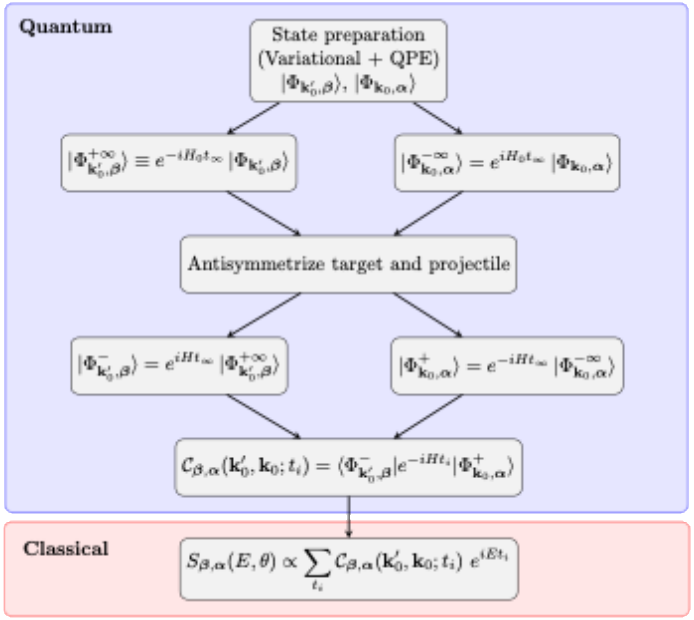
Kafker and Bulgac, **arXiv: 2604.21845** (2026)

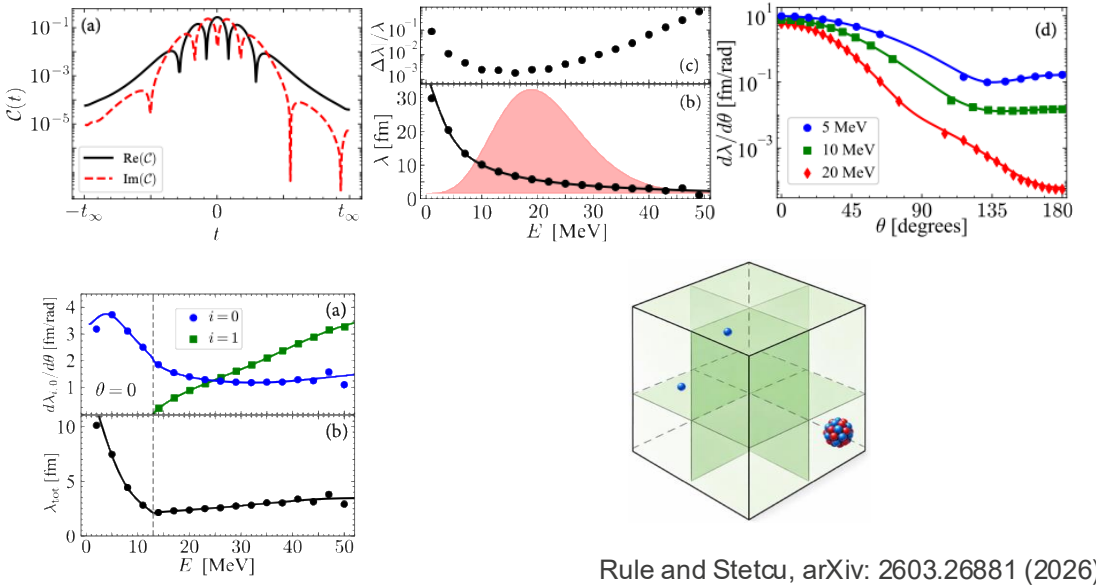
Quantum computing is on the way



Quantum-classical algorithm for reaction cross sections

- Uses wave packets to localize the target and projectile far from each other
- Envisioned for first quantization implementation
- Computes the *S* matrix → cross section (total, elastic, inelastic)





Rule and Stetcu, arXiv: 2603.26881 (2026)

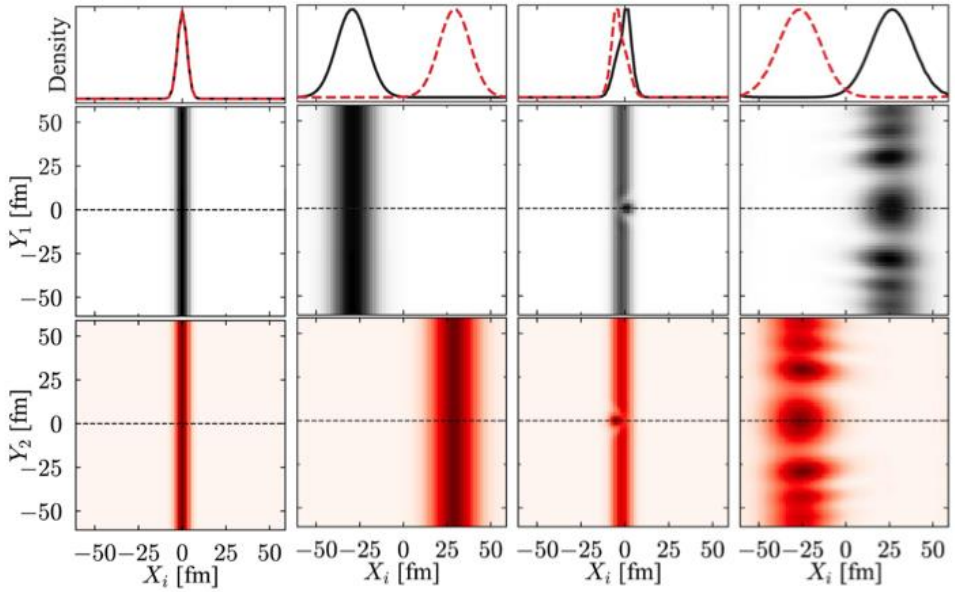
Scattering state preparation

Use Moller operators to construct incoming/outgoing scattering states

$$\Omega_{\pm} \equiv \lim_{t \to \mp\infty} e^{iHt} e^{-iH_0 t}$$

$$|\Psi^{\pm}_{\mathbf{k},\boldsymbol{\alpha}}\rangle = \frac{k_z}{2\pi\mu\eta(k_z)} \sqrt{\frac{\mu}{k}} \int_{-\infty}^{+\infty} dt\; e^{-iHt} |\Phi^{\pm}_{\mathbf{k}_0,\boldsymbol{\alpha}}\rangle\, e^{iEt}$$

$$S_{\beta k',\alpha k} = \langle \Psi^{-}_{\beta,k'} | \Psi^{+}_{\alpha,k} \rangle$$

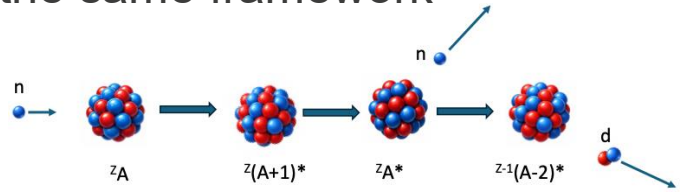


Tannor and Weeks, *J. Chem. Phys.* 98, 3884

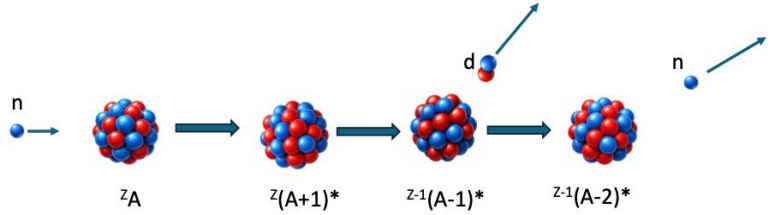
Rule and Stetcu, arXiv: 2603.26881 (2026)

Beyond 2→2 reactions

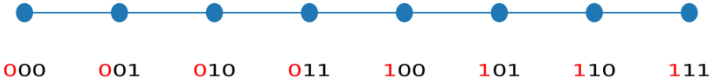
- More products in the final state: treat them as successive emissions within the same framework



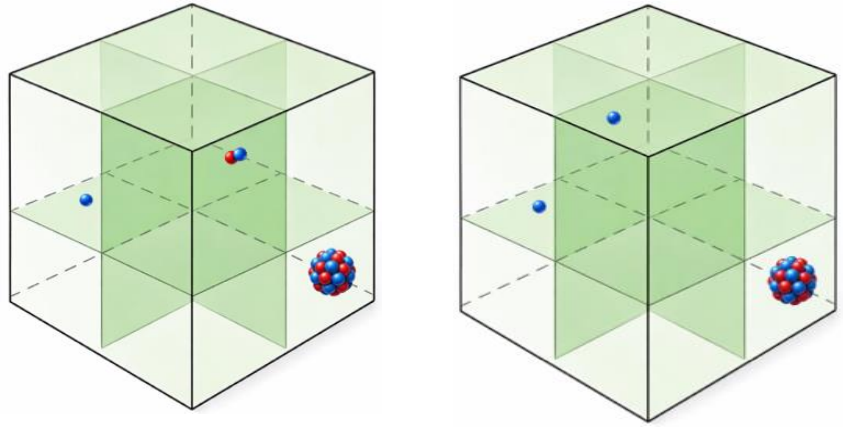
and



- Or search for products far from the nucleus by *measuring* only select qubits that place the particles on a distinctly different region



read most left qubit, can tell whether the particle is in the first or second half of the box



Summary

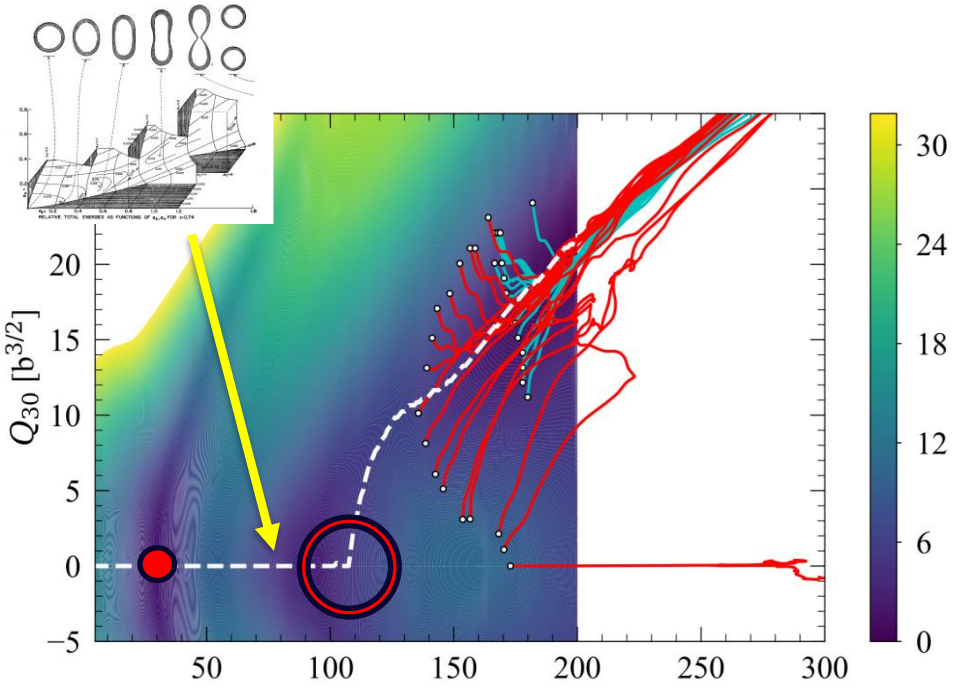
- TDDFT is a versatile method that can be applied to
  - Linear response: electromagnetic response
  - Nuclear reactions: fission, heavy-ion collisions
  - Other fields in nuclear physics and condensed matter
- Results are sensitive to pairing correlations
  - Can help finding the right density functional
- We have elucidated several aspects of the fission dynamics:
  - Dissipative character from saddle to scission
  - Non-Markovian character (long memory)
  - Strong evidence for scission neutrons, including properties like their angular dependence and energy spectrum
  - Universal character of neck rupture dynamics (not random)
  - Generation of angular momenta
  - Odd-odd and even-odd nuclei: Pauli blocking approximation not adequate for the dynamics
- Future plans:
  - Exploration of more heavy-ion reactions in eGCM
  - Extension of eCGM to pairing (fission)
  - Quantum computing

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What is eGCM?

$$E \oint_{Q'} \langle \Phi(Q)|\Phi(Q')\rangle f(Q') = \oint_{Q'} \langle \Phi(Q)|H|\Phi(Q')\rangle f(Q').$$

Hill and Wheeler, Phys. Rev. 89, 1102 (1952)



$$E \oint_{Q',t'} \langle \Phi(Q,t)|\Phi(Q',t')\rangle f(Q',t') = \oint_{Q',t'} \langle \Phi(Q,t)|H|\Phi(Q',t')\rangle f(Q',t')$$

$$|\Psi_E\rangle = \oint_{Q,t} |\Phi(Q,t)\rangle f(Q,t).$$

- Q labels the "slits" (white dots)
- t is the "time" along a given TDDFT trajectory $|\Phi(Q,t)\rangle$ starting on the rim of the outer fission barrier at Q
- Unlike in GCM, in eGCM for $t > 0$ the nuclei are excited dynamically

$|\Psi_E\rangle$ Correlated many-nucleon wave function

eGCM can be used for many nuclear reactions!
In particular, for multi-nucleon transfer in heavy-ions reactions.