Exotic Three-Body Decay in Open Quantum Systems

Simin Wang (S. M. Wang)

Fudan University

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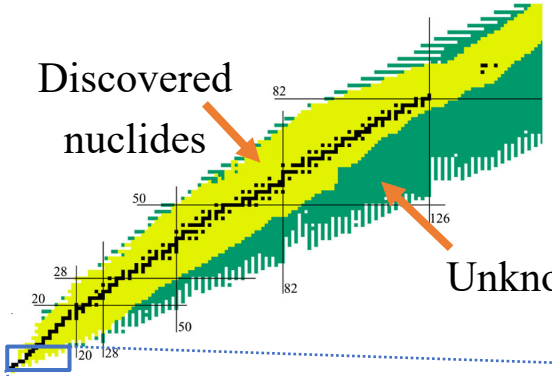
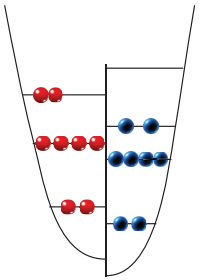
Collaborators: W. Nazarewicz, M. Pfützner, I. Mukha,
R. J. Charity, L. G. Sobotka, A. Volya, Z. H. Li …

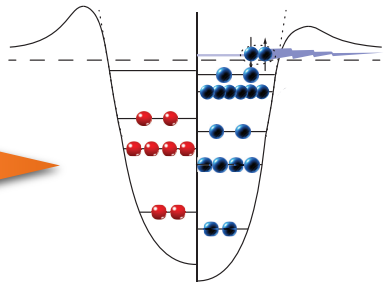
Rich phenomena towards the dripline

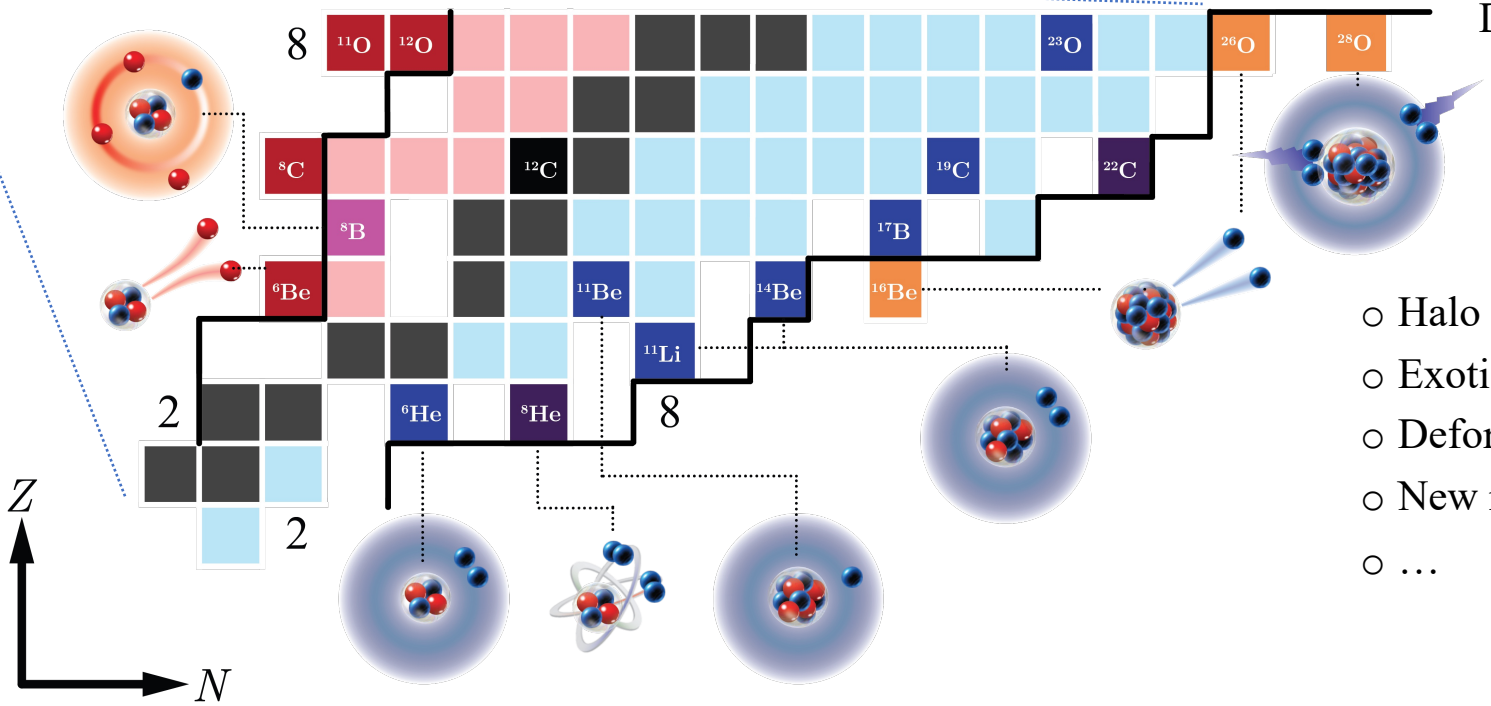


Closed quantum system



Open quantum system

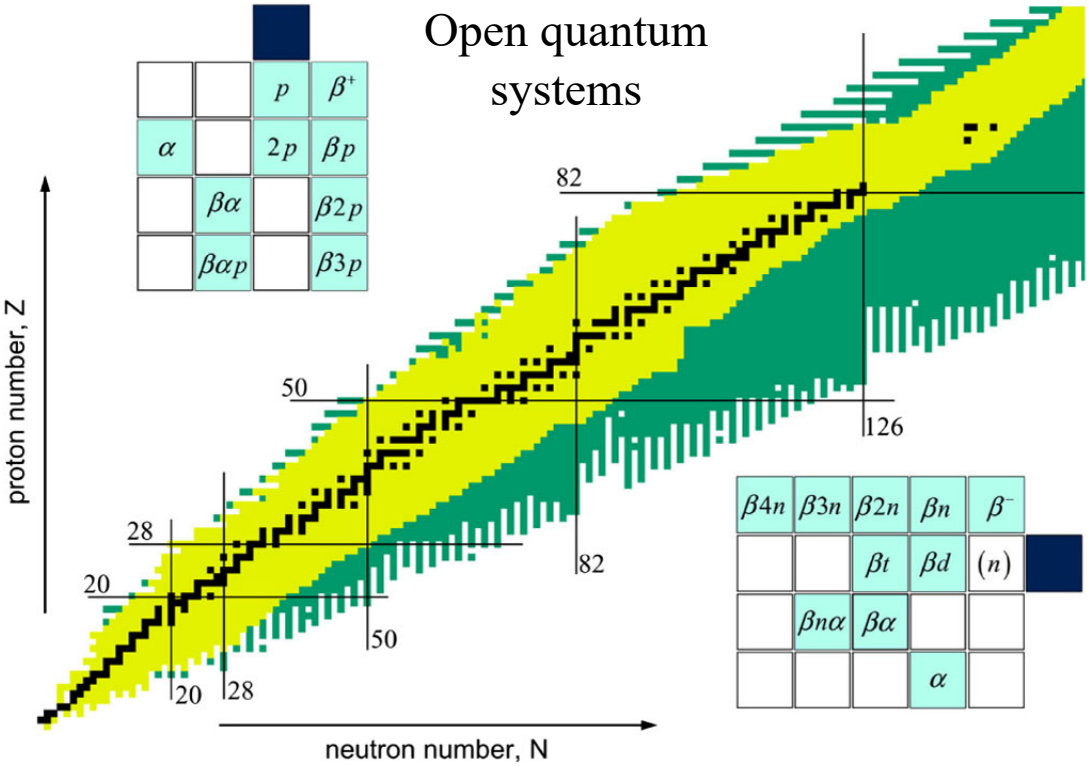




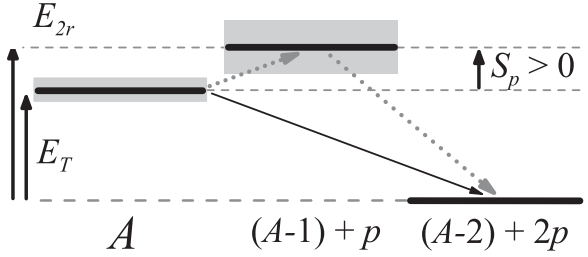
Dripline

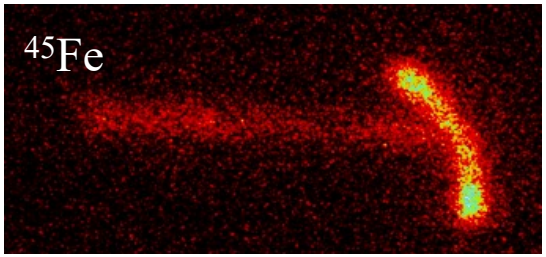
- Halo & clustering
- Exotic decay
- Deformation
- New magic number
- …

Exotic two-proton (2*p*) decay



- **2*p* decay**





g.s. 2*p* emitters: ^{45}Fe, ^{48}Ni, ^{16}Ne, ^{6}Be ...

other cases: ^{17}Na*, ^{22}Mg*, ^{28}S*, ^{22}Al ($\beta 2p$) ...

Y.B. Zeldovich, Sov. Phys. JETP 11, 812 (1960)

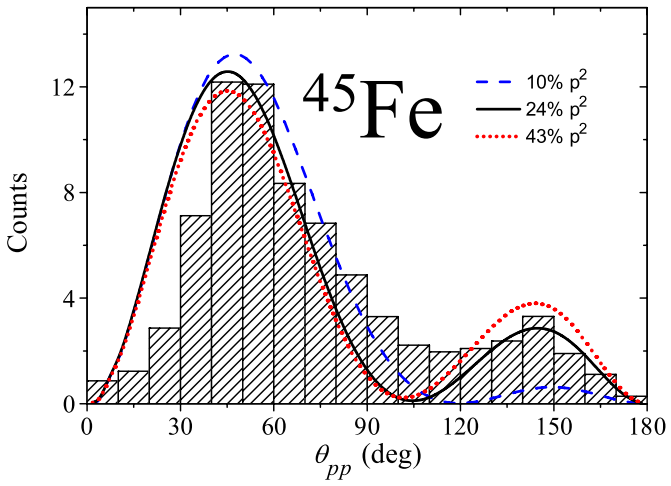
V. Goldansky, Nucl. Phys. 19, 482 (1960)

J. Giovinazzo *et al.*, Phys. Rev. Lett. 89, 102501 (2002)

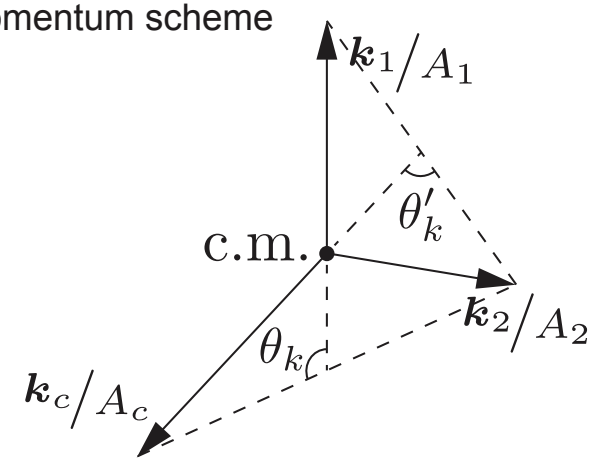
K. Miernik *et al.*, Phys. Rev. Lett. 99, 192501 (2007)

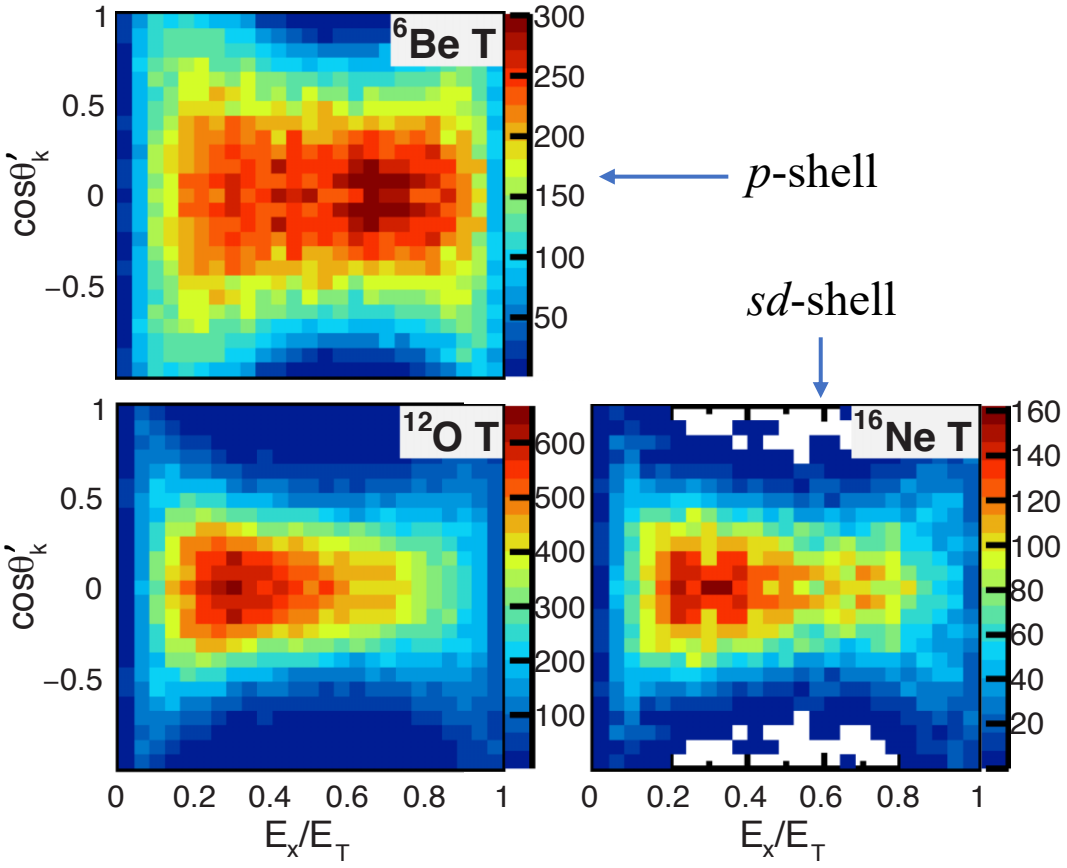
Asymptotic nucleon-nucleon correlation

K. Miernik *et al.* PRL 99, 192501 (2007)



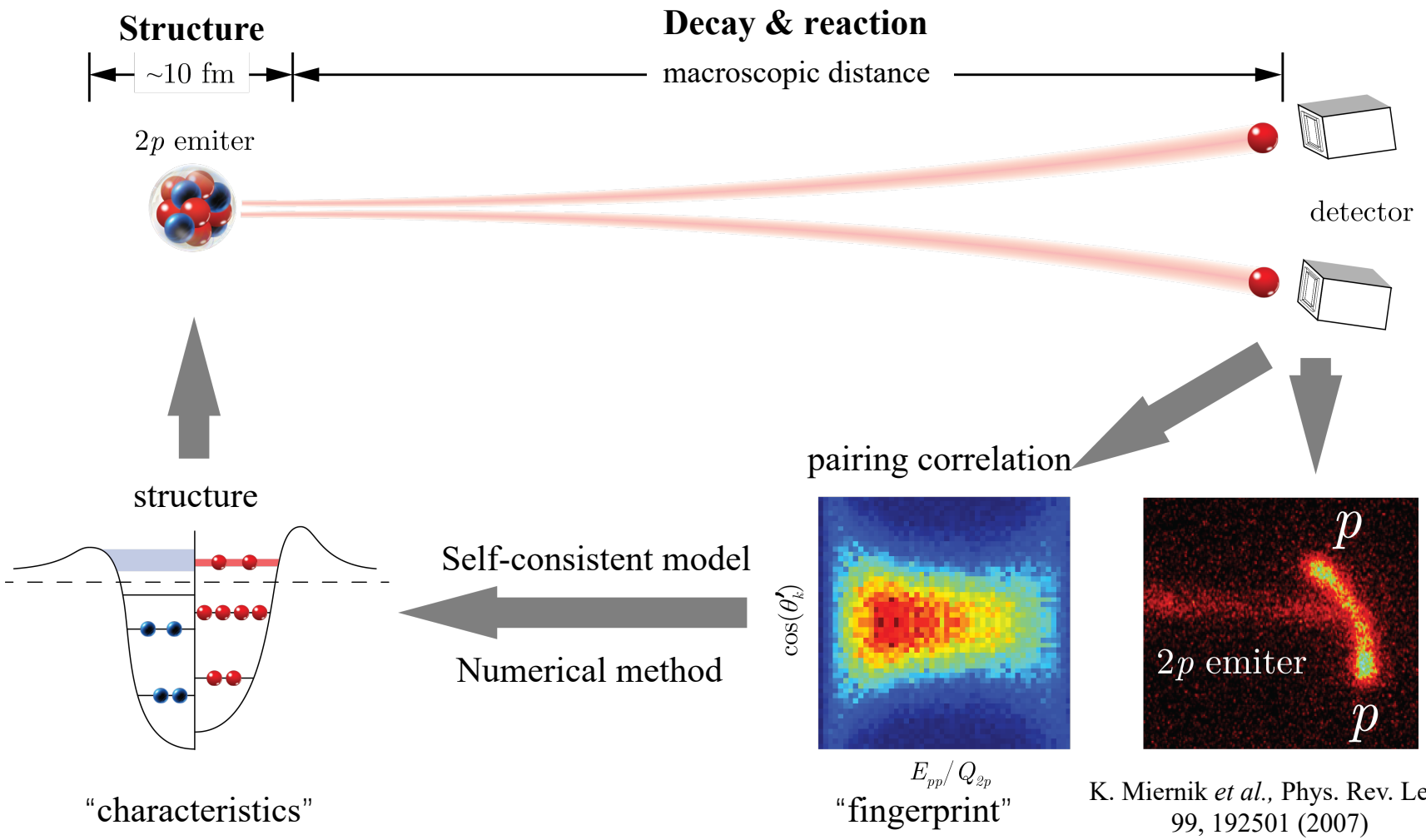
Momentum scheme





T.B. Webb *et al.* Phys. Rev. C 100, 024306 (2019)

Structure ⟷ Asymptotic observables



K. Miernik *et al.*, Phys. Rev. Lett. 99, 192501 (2007)

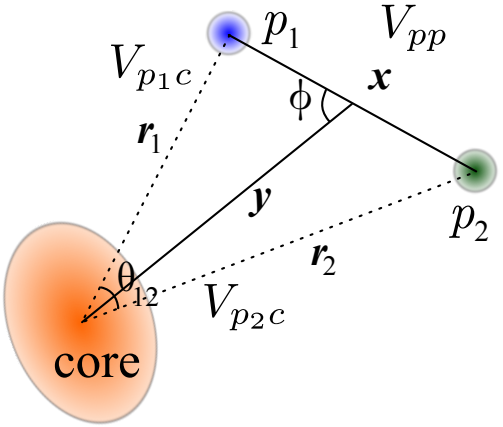
Gamow coupled-channel (GCC) method

- The 3-body **Hamiltonian** can be written as:

$$\hat{H} = \sum_{i=1}^{3} \frac{\hat{\vec{p}}_i^{\,2}}{2m_i} + \sum_{i=1}^{2} V_{p_i c} + V_{pp} + \hat{H}_{\rm core} - \hat{T}_{\rm c.m.}$$

- **Total wave-function** $\Psi^{J\pi} = \sum_{J_p \pi_p j_c \pi_c} \left[\Phi^{J_p \pi_p} \otimes \phi^{j_c \pi_c} \right]^{J\pi}$

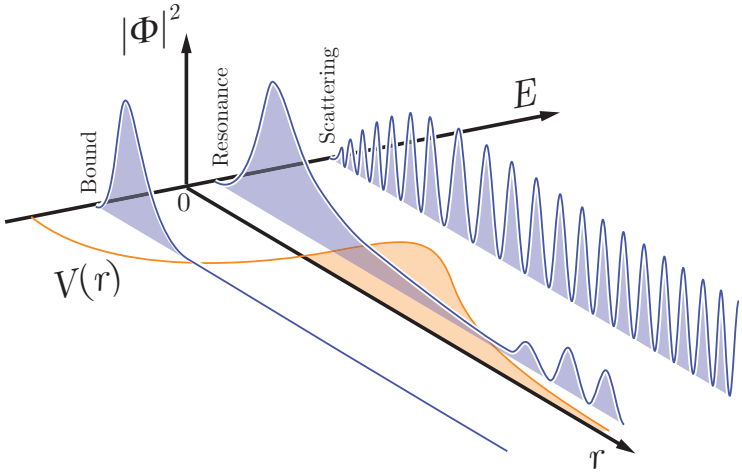
valence protons — deformed core



1. **Jacobi coordinates**
   a) No spurious center-of-mass motion
   b) Correct 3-body asymptotic behavior
2. **Berggren basis**
   a) Bound, scattering, and Gamow states
   b) Structure and decay information

Bottom line: to analyze how nuclear structure impacts decay properties.

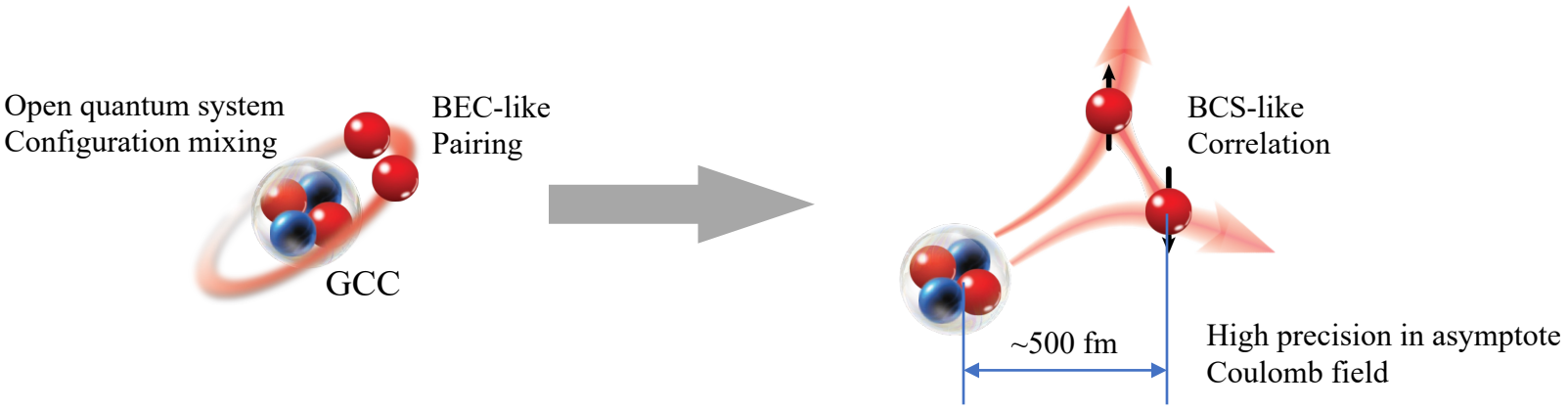
Berggren basis



SW and W. Nazarewicz, Phys. Rev. Lett. 120, 212502 (2018)

Time dependent (TD) approach

Dynamics and mechanism of $2p$ decay



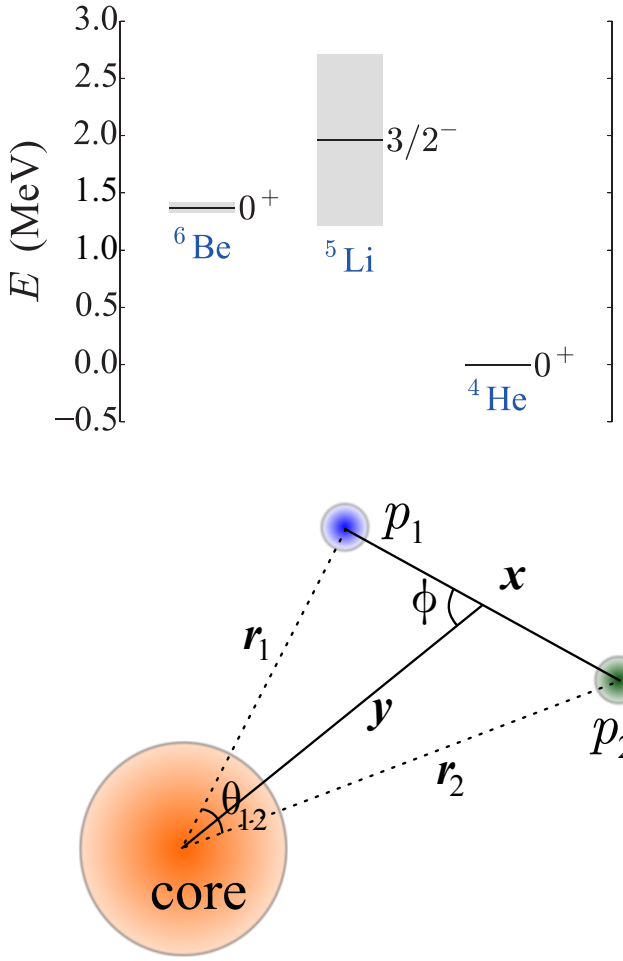
- **Time evolution operator**

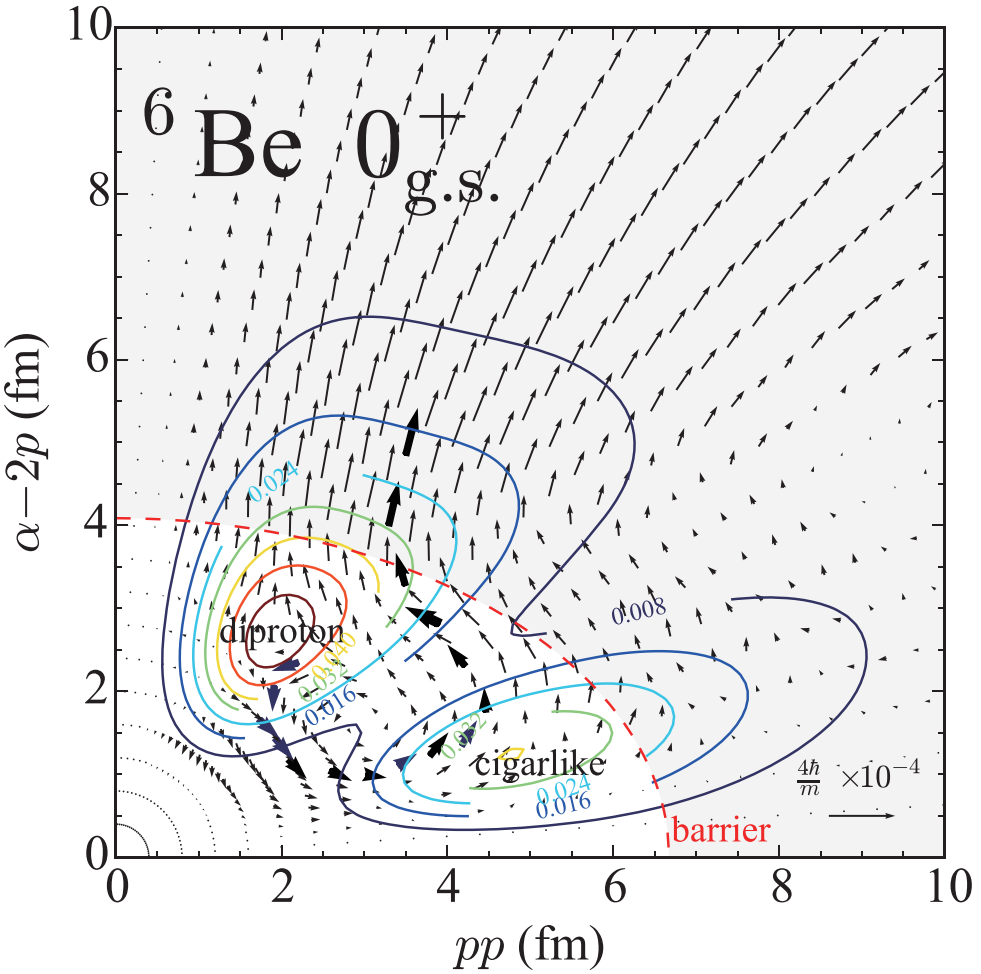
$$e^{-i\frac{\hat{H}}{\hbar}t} = \sum_{n=0}^{\infty}(-i)^n\,(2-\delta_{n0})\,J_n(t)T_n(\hat{H}/\hbar)$$

  - Time propagator can be expanded with Chebyshev polynomials.
  - Configuration mixing and proper asymptotic behavior.

SW and W. Nazarewicz, Phys. Rev. Lett. 126, 142501 (2021)

Ground-state of ^{6}Be

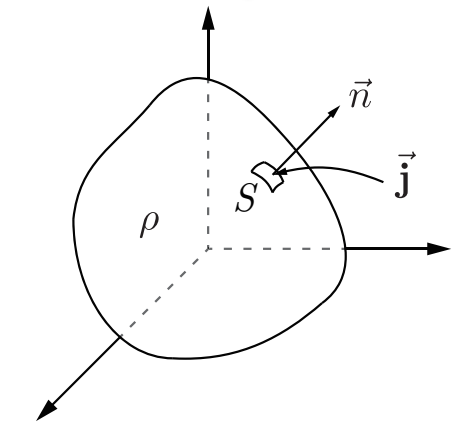




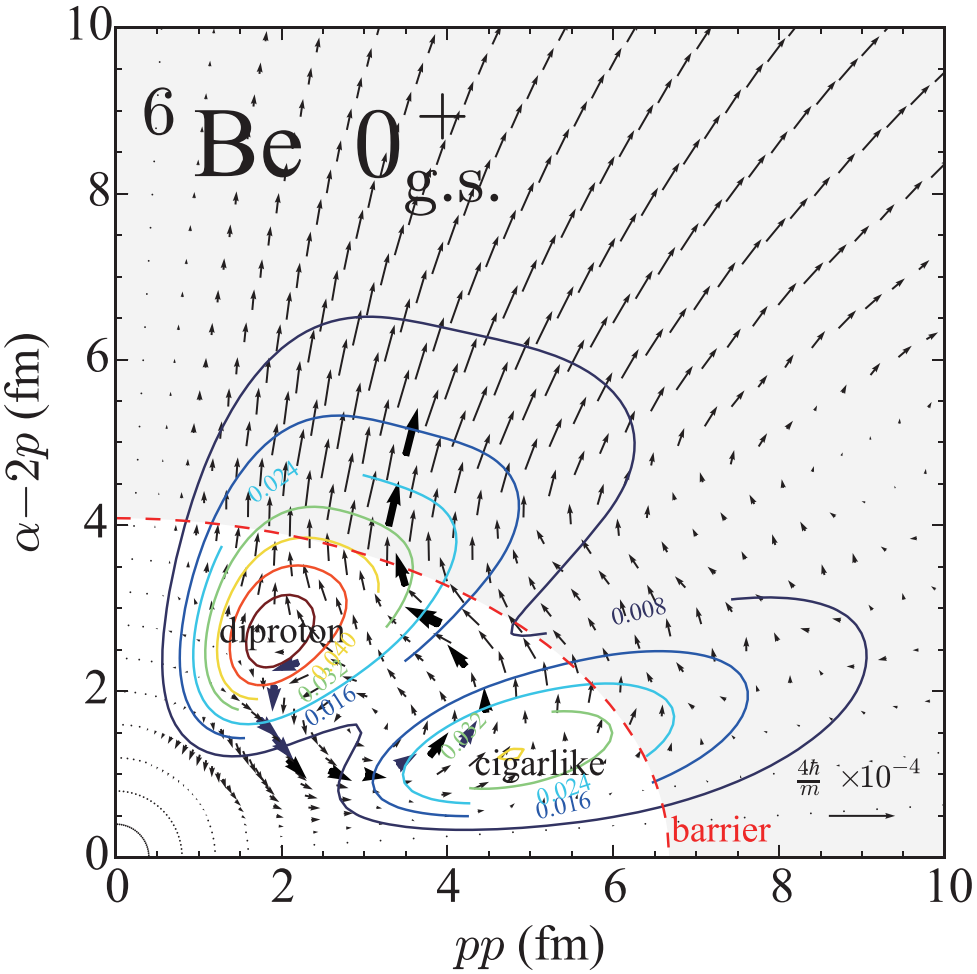
SW *et al.*, Phys. Rev. C 99, 054302 (2019)

Ground-state of ^{6}Be

Probability current

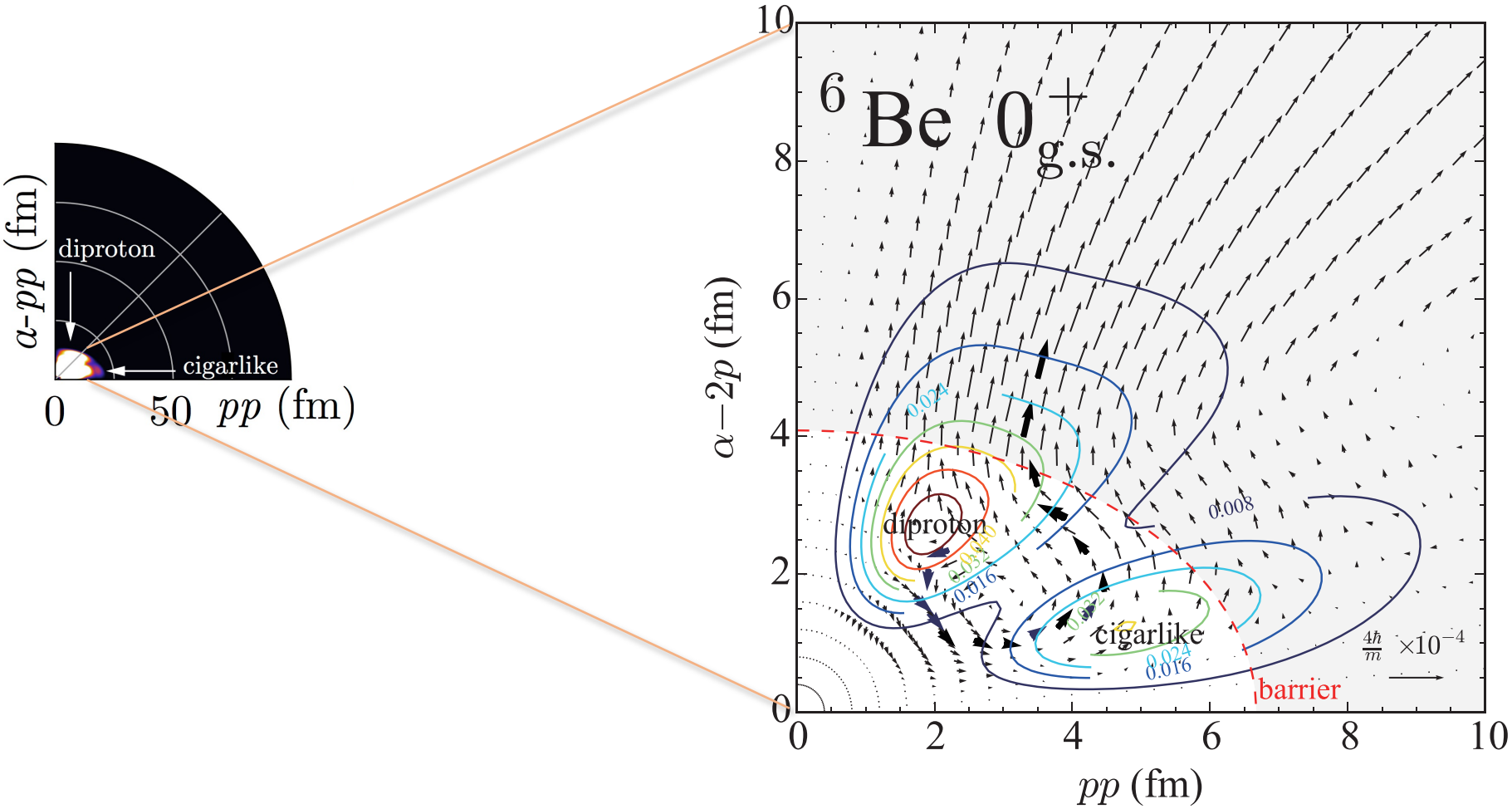


$$\iiint \frac{\partial \rho}{\partial t}\,\mathrm{d}V = -\oiint \vec{\mathbf{j}}\cdot\vec{n}\,\mathrm{d}S$$



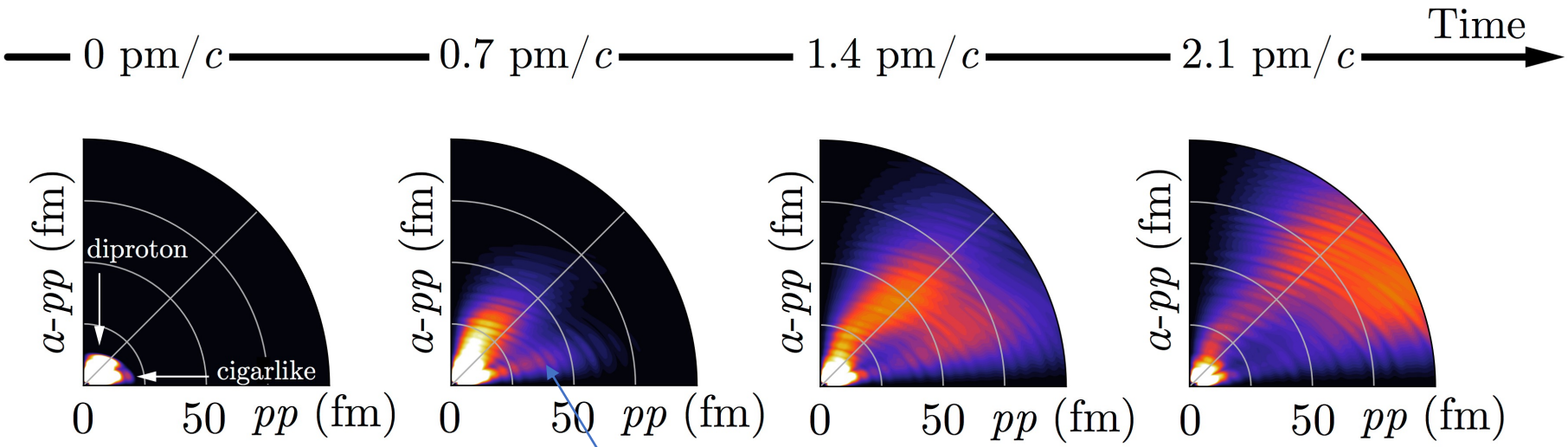
SW *et al.*, Phys. Rev. C 99, 054302 (2019)

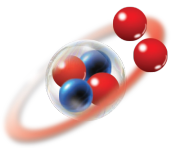
Ground-state of ^{6}Be



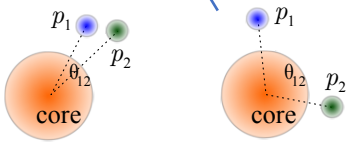
SW *et al.*, Phys. Rev. C 99, 054302 (2019)

$2p$ decay in ^{6}Be

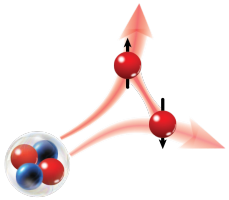




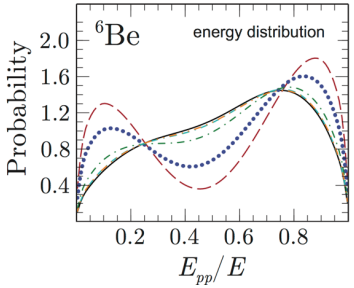
Protons inside nucleus



Two types of tunneling:
1. diproton (primarily)
2. cigarlike



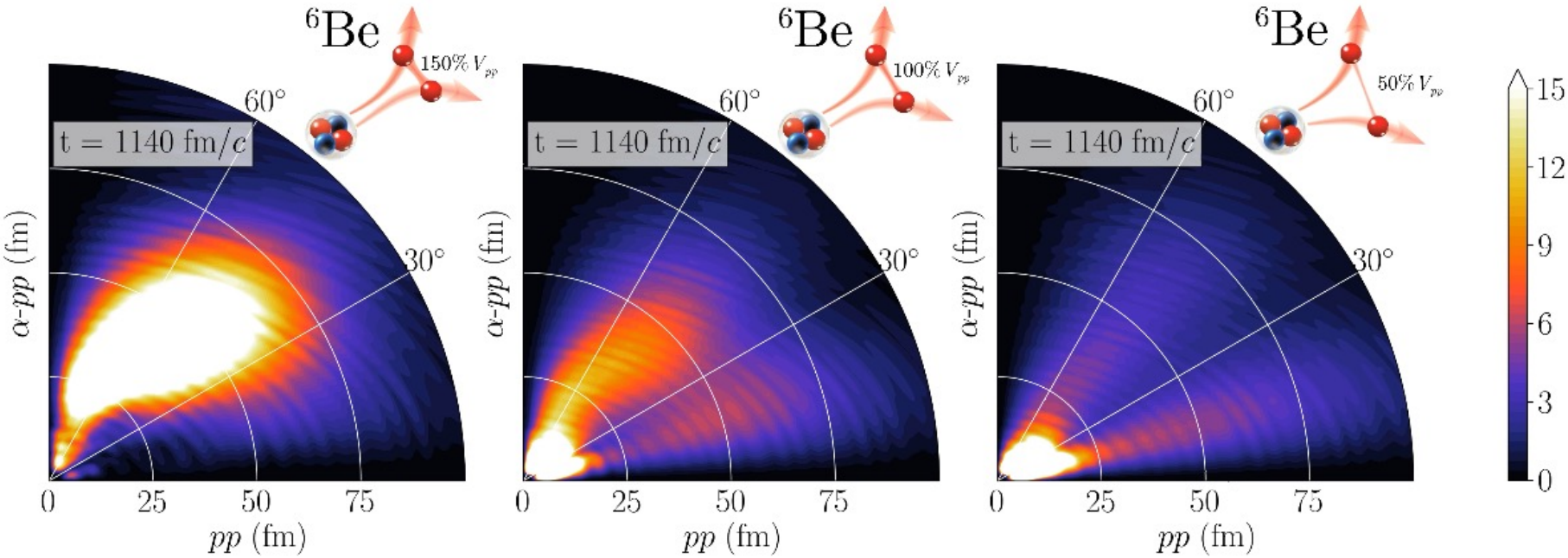
Diproton branch bends due to Coulomb repulsion



Asymptotic correlation begin to converge

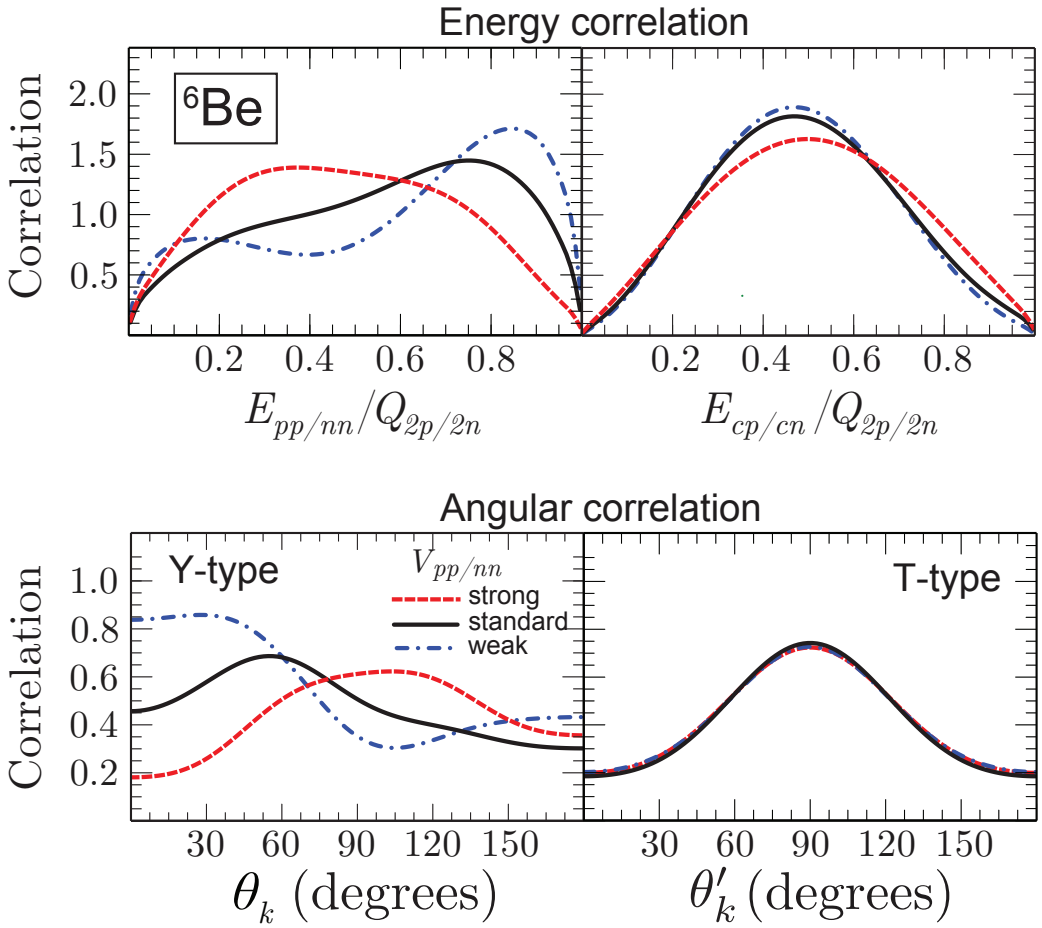
SW and W. Nazarewicz, Phys. Rev. Lett. 126, 142501 (2021)

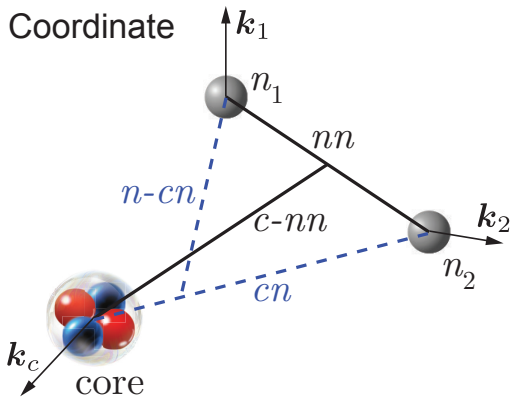
Decay dynamics depends on pairing

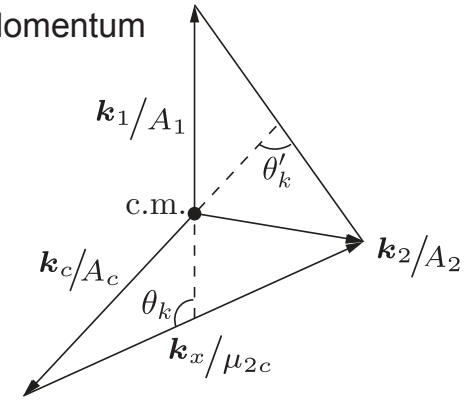


- The decay dynamics as well as correlation strongly depend on the pairing strength.
- Strong pairing results in a larger decay width, which indicates that pairing will benefit the 2p tunneling.

Asymptotic correlations



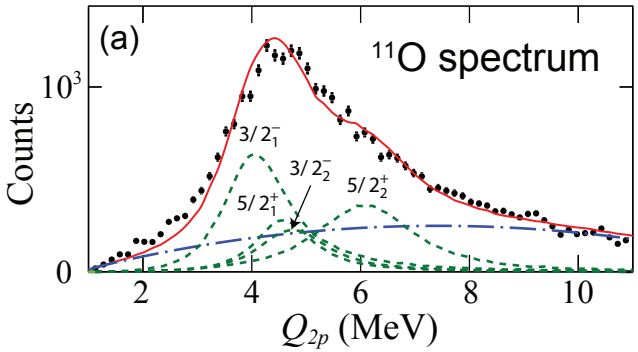




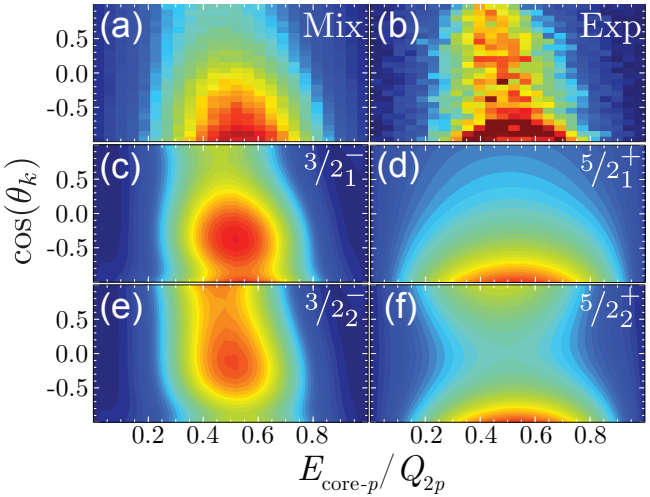
- E_{pp} and Y-type angular correlations are strongly impacted by nucleon-nucleon interaction.

Predicted spectrum and correlation of ^{11}O

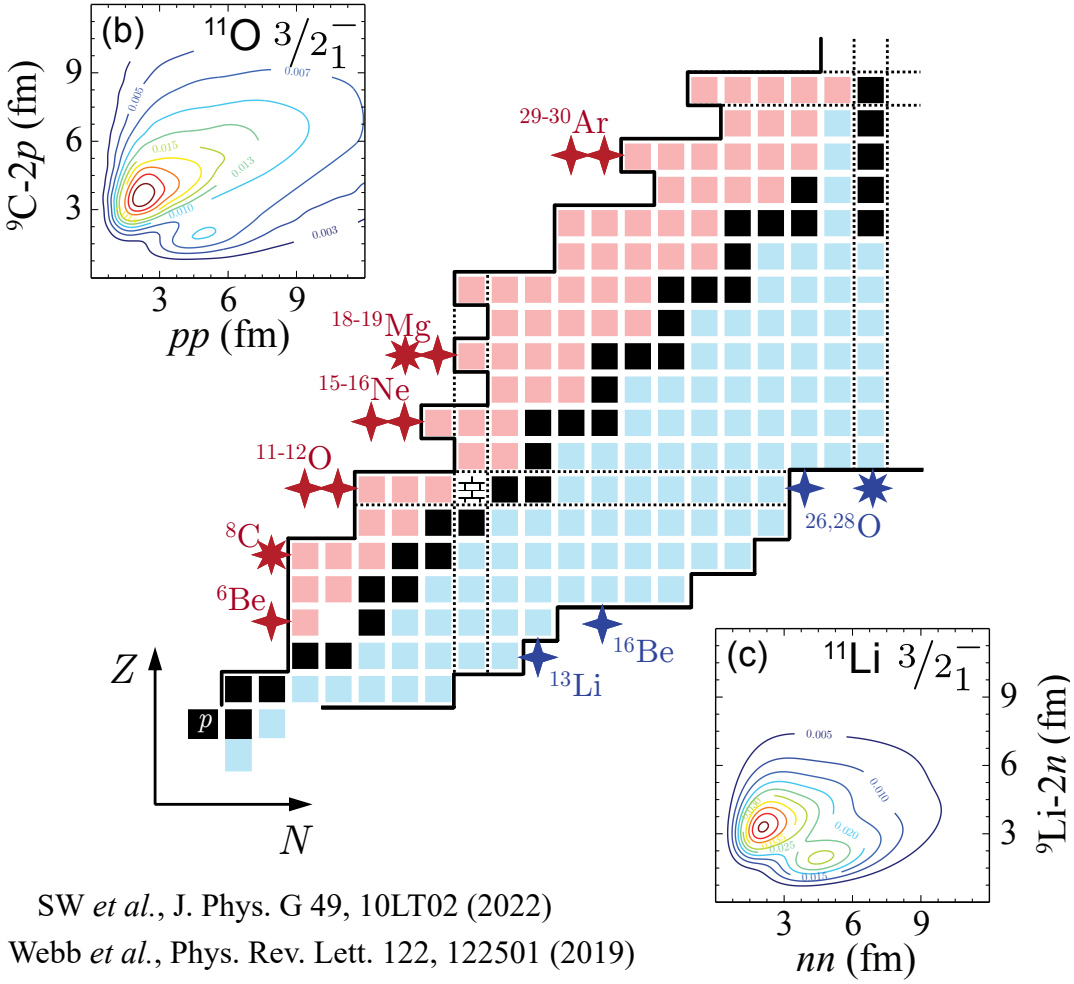
Measured spectrum of ^{11}O



Asymptotic correlation of ^{11}O



Density distribution

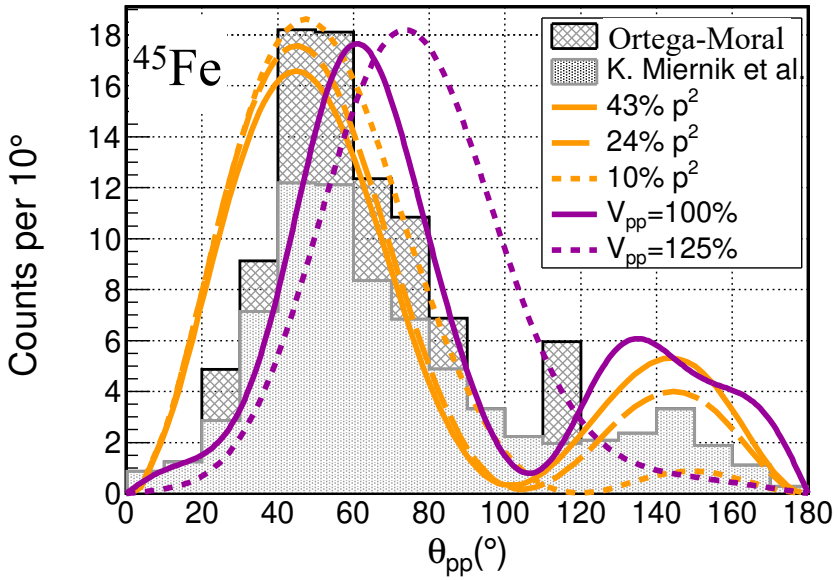


SW *et al.*, J. Phys. G 49, 10LT02 (2022)

T. Webb *et al.*, Phys. Rev. Lett. 122, 122501 (2019)

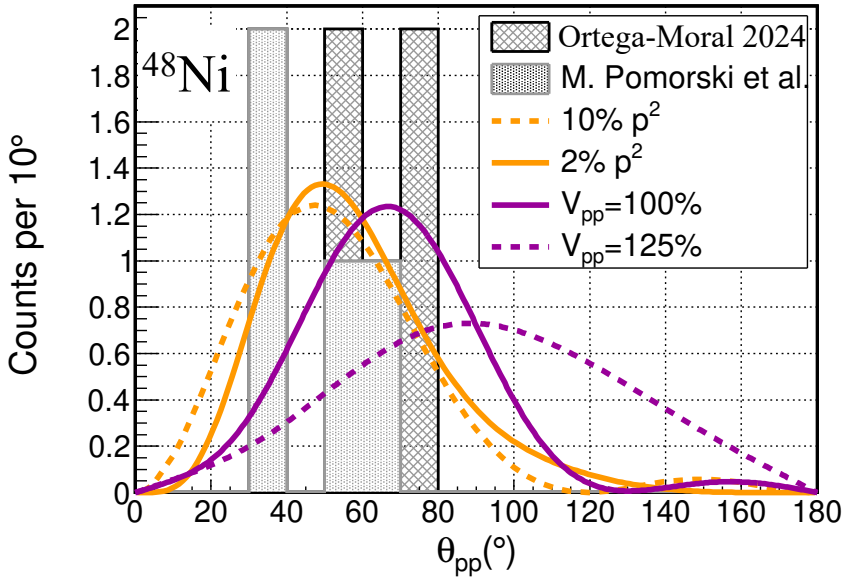
Asymptotic correlation of ^{45}Fe and ^{48}Ni

Angular correlation of ^{45}Fe



$f^2_{7/2}$	$p^2_{3/2}$	$p^2_{1/2}$	$f^2_{5/2}$	$s^2_{1/2}$
80.0%	11.2%	2.6%	2.5%	0.3%

Angular correlation of ^{48}Ni



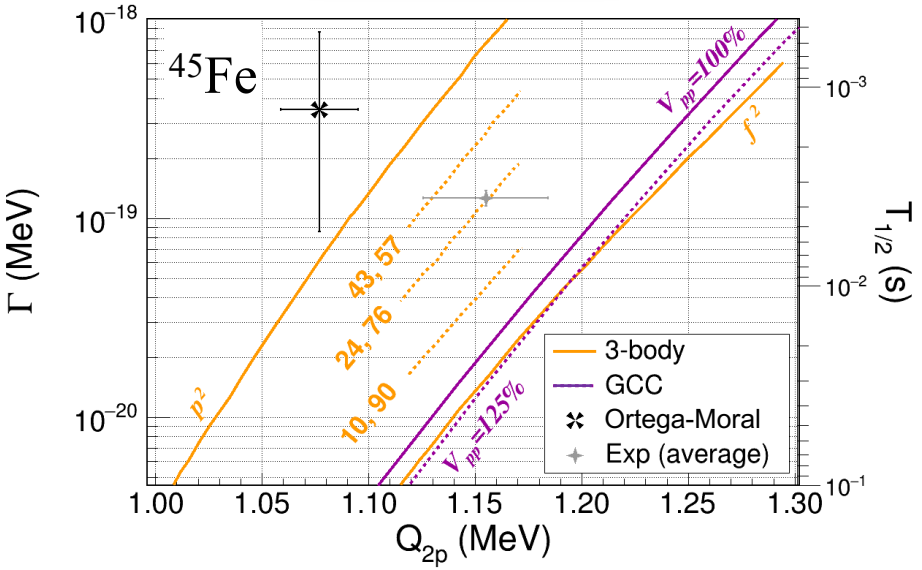
$f^2_{7/2}$	$p^2_{3/2}$	$p^2_{1/2}$	$f^2_{5/2}$	$s^2_{1/2}$
91.6%	4.7%	1.0%	1.0%	0.1%

- Closed shell behavior for ^{48}Ni.
- In accord with results of CI and 3-body model.

A. O. Moral, SW *et al.*, arXiv:2504.14607 (2025)

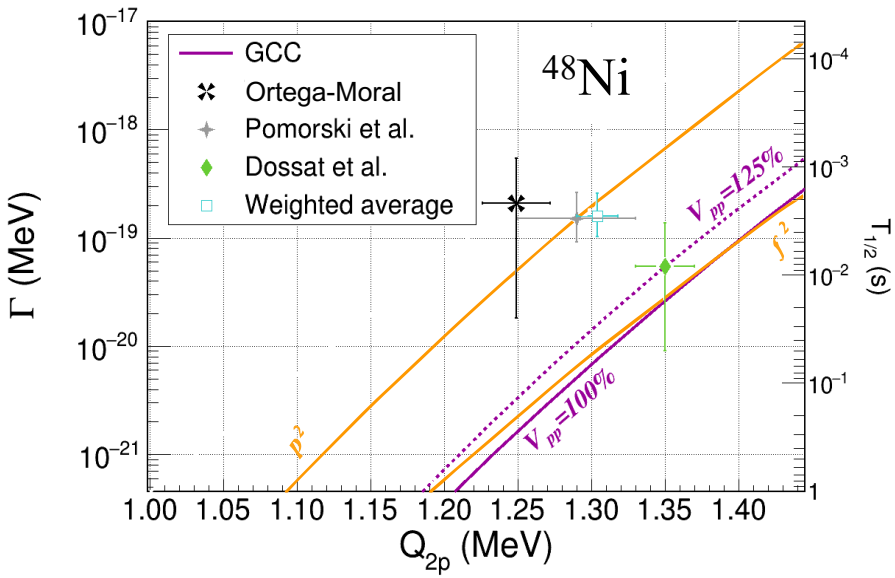
Half-lives of ^{45}Fe and ^{48}Ni

Half-live of ^{45}Fe



Q_{2p}^{Exp} (keV)		Q_{2p}^{Cal} (keV)		
Ortega-Moral	Average	Brown	Ormand	Cole
1083.9(6)	1155(29)	1154(94)	1279(181)	1218(49)

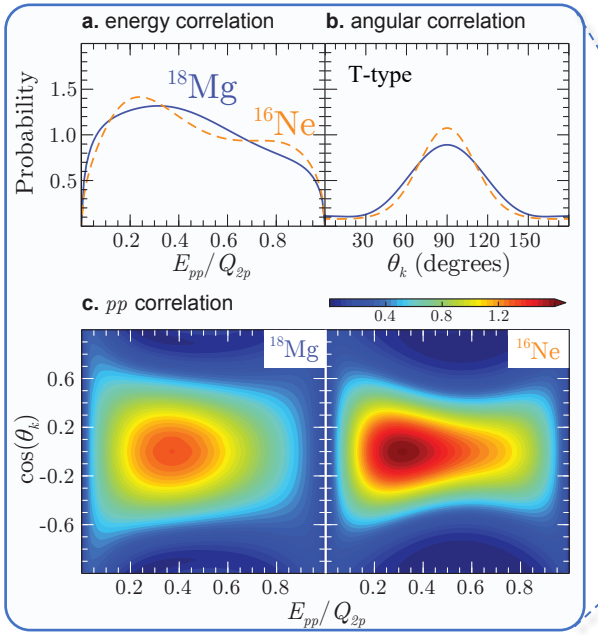
Half-live of ^{48}Ni



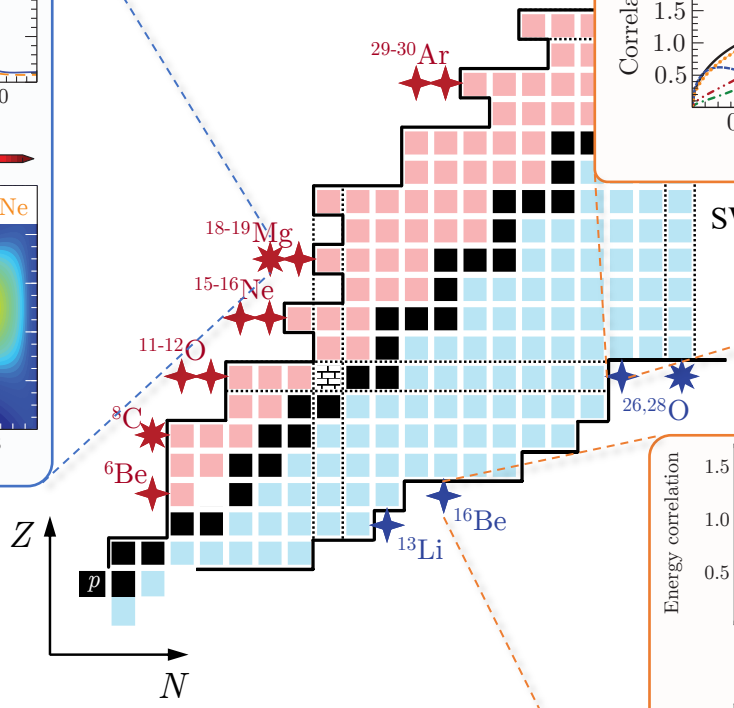
Q_{2p}^{Exp} (keV)		Q_{2p}^{Cal} (keV)		
Ortega-Moral	Pomorski	Brown	Ormand	Cole
1249(23)	1290(40)	1360(130)	1290(330)	1350(60)

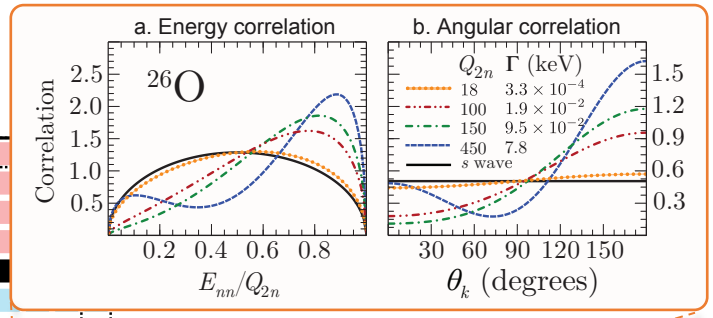
- Latest experiment suggests lower decay energies and shorter half-lives.
- The half-lives are sensitive to the decay energies and corresponding configurations.

Correlations in light-mass nuclei



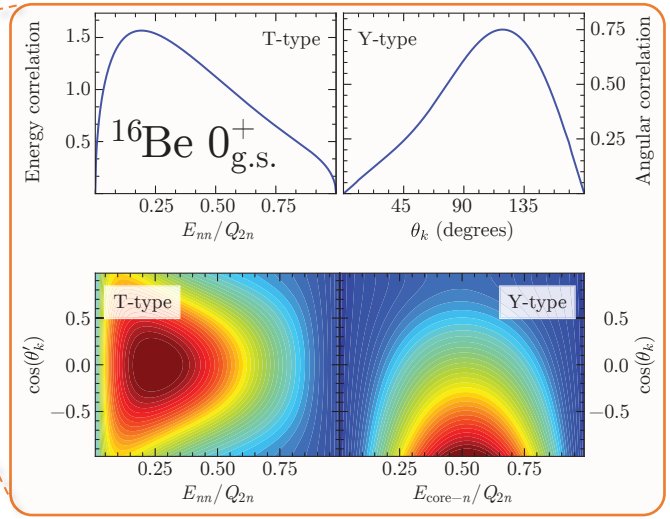
L. Zhou, SW *et al.*,
Nucl. Sci. Tech. 35, 107 (2024)





SW *et al.*, J. Phys. G 49, 10LT02 (2022)

Y. R. Lin and SW



- $4p$ ($2p$+$2p$) decay of ^{18}Mg.
- Multi-proton emissions.
- Correlation changes when $Q \rightarrow 0$.

Thank you for your attention!

Summary

- Time-dependent approach has been developed
  - To study the exotic 3-body decay dynamics
- Nucleon-nucleon correlations
  - Connection to nuclear inner structure
  - Ability to reveal 2*p* decay mechanism
- Continuum effect
  - Decay dynamics
  - More properties, such as SF & $B(E2)$

See Z. Xu's talk

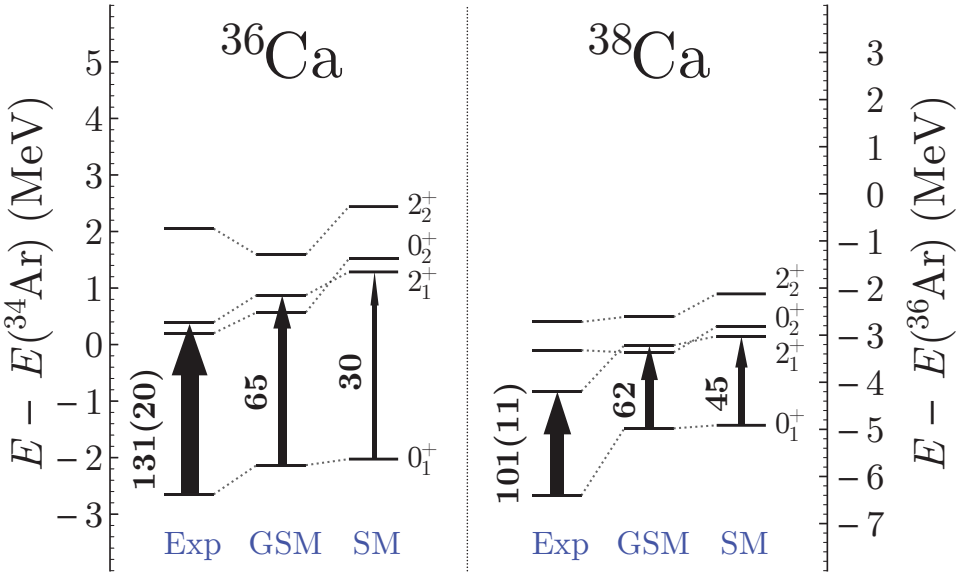
Acknowledgements

- W. Nazarewicz
- I. Mukha
- L. G. Sobotka
- Z. H. Li
- M. Pfützner
- R. J. Charity
- A. Volya
- …

Backup

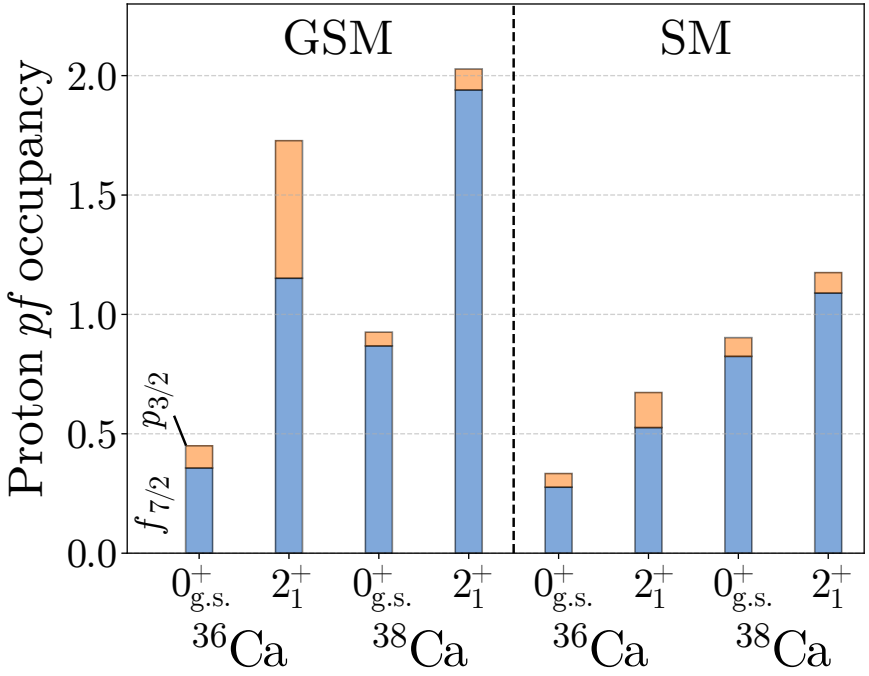
Rich phenomena towards the dripline

Spectra and $B(E2)$ values of ^{36,38}Ca



See Z. C. Xu's talk

Cross-shell excitations



Z. Xu, SW *et al.*, arXiv:2502.14106 (2025)

- Continuum enhances the cross-shell effect.
- p wave component is strongly impacted by the continuum.

Correlations of light-mass nuclei