



Revealing the Dynamics of Three-Body Decay

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Introduction Method 2p decay



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

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



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- \circ B(E2) is determined by transition density.
- \circ Transition density is extended due to the continuum.

 $Big(E2;0^+ o 2^+ig)=5e^2igg[\int_0^\infty
ho_2(r)r^4drigg]^2$





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Introduction Method 2p decay

Exotic two-proton (2p) decay



 E_{2r} E_{T} A (A-1) + p (A-2) + 2p

2p decay



g.s. 2*p* emitters: ⁴⁵Fe, ⁴⁸Ni, ¹⁶Ne, ⁶Be ... other cases: ¹⁷Na*, ²²Mg*, ²⁸S*, ²²Al (β2*p*) ...

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)



Introduction Method 2p decay Exotic structures Rare decay modes

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nucleon correlation

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

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ASY

Introduction Method 2p decay

Structure \leftrightarrow **Asymptotic observables**





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Theoretical status





Introduction Method 2p decay Theory status GCC TD

Gamow coupled-channel (GCC) method

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

Jacobi coordinates

Berggren basis

impacts decay properties.

$$\hat{H} = \sum_{i=1}^{3} \frac{\hat{\vec{p}}_{i}^{2}}{2m_{i}} + \sum_{i=1}^{2} V_{p_{i}c} + V_{pp} + \hat{H}_{\text{core}} - \hat{T}_{\text{c.m.}}$$

Total wave-function $\Psi^{J\pi} = \sum \left[\Phi^{J_p \pi_p} \otimes \phi^{j_c \pi_c} \right]^{J\pi}$ ٠ $J_p \overline{\pi_p j_c} \pi_c$ deformed core

No spurious center-of-mass motion

Proper 3-body asymptotic behavior

Bound, scattering, and Gamow states

Bottom line: to analyze how nuclear structure

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

Structure and decay information

 V_{pp} x p_2 V_{p_2c} core

valence protons







1.

2.

a)

b)

a)

b)

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Time dependent (TD) approach



- $\circ~$ Time propagator can be expanded with Chebyshev polynomials.
- Initial wave function is obtained by GCC, which includes configuration mixing and proper asymptote.
- $\,\circ\,$ Two-proton wave function has been propagated to over 500 fm.
- Green's functional method to benchmark

$$G(E) = \frac{1}{E - H} = -i \int_0^\infty dt \, \exp(iEt) \exp(-iHt)$$

 $\circ~$ Time propagator and Green's function can be connected by Fourier transformation.

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

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Introduction Method 2p decay Theory status GCC **TD**

Ground-state of 6Be



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



Introduction Method 2p decay **Dynamics** Correlation

Ground-state of 6Be



pp (fm)





Introduction Method 2p decay **Dynamics** Correlation

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 $\frac{4\hbar}{m} \times 10^{-4}$

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Ground-state of 6Be



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



Introduction Method 2p decay **Dynamics** Correlation

2p decay in ⁶Be



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



Introduction Method 2p decay **Dynamics** Correlation

Decay dynamics depends on pairing



 \circ The decay dynamics as well as correlation strongly depend on the pairing strength.

 \circ Strong pairing results in a larger decay width, which indicates that pairing will benefit the 2p tunneling.



Introduction Method 2p decay **Dynamics** Correlation

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Asymptotic correlations



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



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Energy dependence of the correlation in 6Be



I. A. Egorova et al., Phys. Rev. Lett. 109, 202502 (2012)

Deviates from Breit-Wigner due to the threshold proximity.
The threshold effect is channel-dependent.



Introduction Method 2*p* decay Lifetime Correlation

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Energy dependence of the correlation in ⁶Be



- \circ The weights of different components change as energy increases.
- o Result in a energy-dependent correlation.

SW, W. Nazarewicz, A. Volya, and Y.G. Ma, Phys. Rev. Res. 5, 023183 (2023)



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Non-exponential decay



The time evolution of a resonance contains exponential (resonant) and powered (scattering) decays.
When the decay width is large enough, scattering feature is dominated.

SW, W. Nazarewicz, A. Volya, and Y.G. Ma, Phys. Rev. Res. 5, 023183 (2023)



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Predicted spectrum and correlation of ¹¹O





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Asymptotic correlation of ⁴⁵Fe and ⁴⁸N 1.00 1.05 1.10



 $[\]circ$ Closed shell behavior for ⁴⁸Ni.

• In accord with results of CI and 3-body model.

Angular correlation of ⁴⁸Ni

 Q_{2n} (MeV)

1.15

1.20 1.25 1.30 1.35 1.40



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



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Half-lives of ⁴⁵Fe and ⁴⁸Ni



o Latest experiment suggests lower decay energies and shorter half-lives.

 \circ The half-lives are sensitive to the decay energies and corresponding configurations.



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Correlations in light-mass nuclei





Introduction Method 2p decay



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 2p decay mechanism
- Towards a comprehensive description
 - More microscopic description
 - Resonance & time evolution emulators

Acknowledgements



See S. König's talk





- 1. What's the difference between 2p and 2n decay?
- 2. Difference between complex scaling and Berggren basis
- 3. Correlations evolutions during the decay process
- 4. Any simultaneous multi-particle emissions?
- 5. Any 2*p* decay from excited states?
- 6. Is the decay dynamics depends on the production process?
- 7. Is the two-step 2n decay of ²⁸O have similar correlation, like the case of ¹⁸Mg?



Backup



Correlations in heavy-mass nuclei





Introduction Method 2*p* decay

Discovery of ¹¹O







Predicted spectrum and structure of ¹¹O





Predicted spectrum and structure of ¹¹O

Measured spectrum of ¹¹O (a) ¹¹O spectrum Counts 0 8 10 4 6 Q_{2p} (MeV) Updated spectrum of ¹¹O 300 trans. decay 250Counts 90 degrees 200 150100500 126 8 1020 (MeV)E

Asymptotic correlation of ¹¹O Mix (b) $_{0.5}$ (a) Exp 0.0-0.5 $_{0.5}$ (C) $3/2^{-1}_{1}$ (d) $5/2^+_1$ $\cos(\theta_k)$ 0.0 -0.5 $_{0.5}$ (e) $3/2^{-1}_{2}$ (f) $5/2^{+}_{2}$ 0.0-0.50.20.20.40.60.8 $0.4 \quad 0.6 \quad 0.8$ $E_{\text{core-}p}/Q_{2p}$



• The correlation and updated spectrum suggest multiple states in the broad resonance of ¹¹O.



Survival probability of resonant states



SW, W. Nazarewicz, A. Volya, and Y.G. Ma, Phys. Rev. Res., accepted (2023)



Observed 2*p* **emitters**





Lifetime of ⁶⁷Kr probes deformation evolution



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

- \circ 1/2[321] becomes available for the valence protons when β_2 close to -0.3, which dramatically increases the 2*p* decay width of ⁶⁷Kr. As a result, $T_{1/2}^{cal} = 24_{-7}^{+10} \text{ ms} (T_{1/2}^{exp} = 20 \pm 11 \text{ ms})$
- Decay primarily depends on small angular momentum components.



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Decay property of 54mNi



J. Giovinazzo et al., Nat. Comm. 12, 4805 (2021)

- Lifetime strongly depends on the decay energy and channels.
- Branching ratio is less than 10^{-21} for 2p decay.





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Short & mid → long range correlations



2p decay

TD



nucleon correlation

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

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ASY

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Structure \leftrightarrow **Asymptotic observables**



Method

2p decay

Correlation

Correlations of light-mass nuclei



 \mathbf{k}_1/A_1

 θ'_k

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