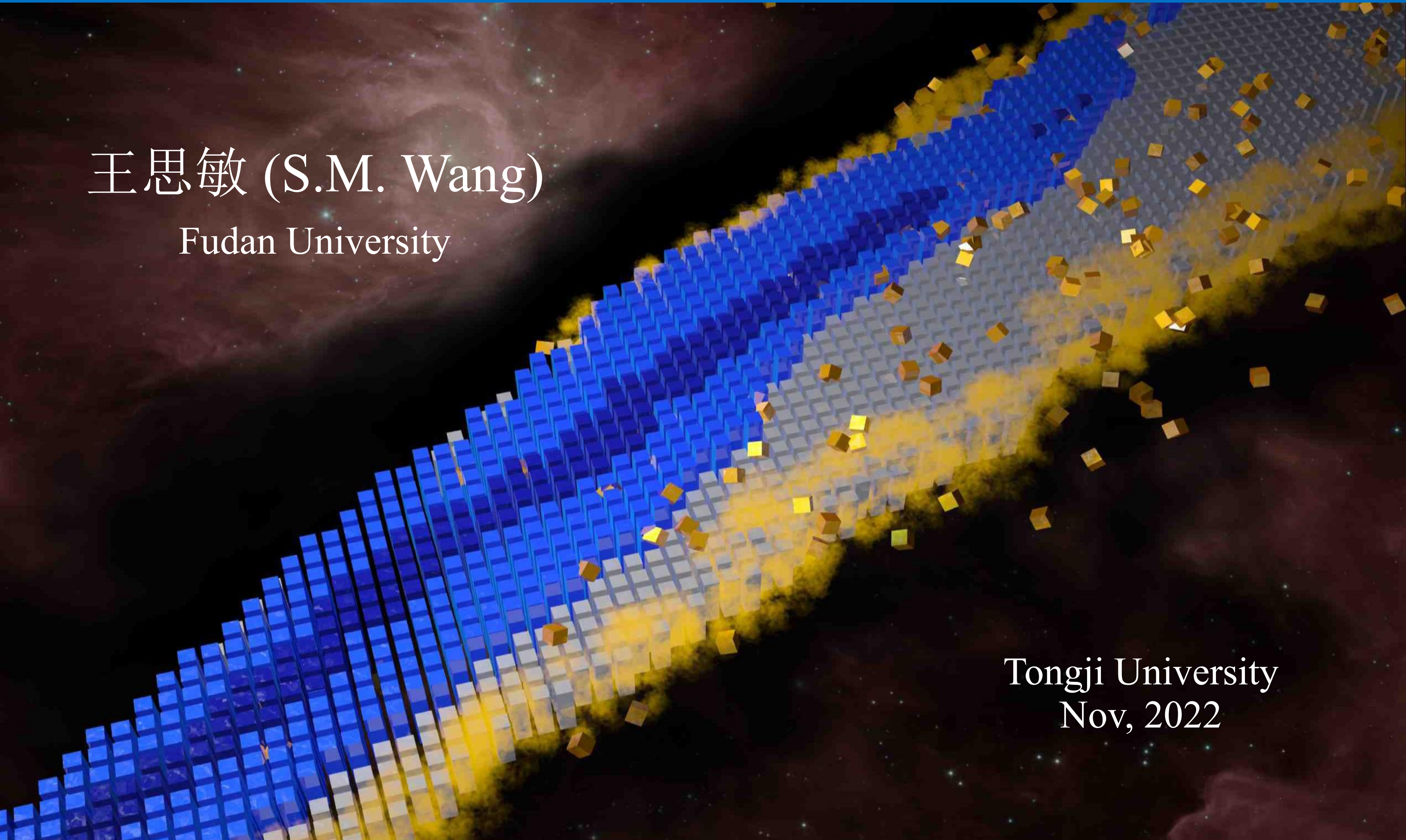
Recent progress in 2*p* radioactivity



王思敏 (S.M. Wang)
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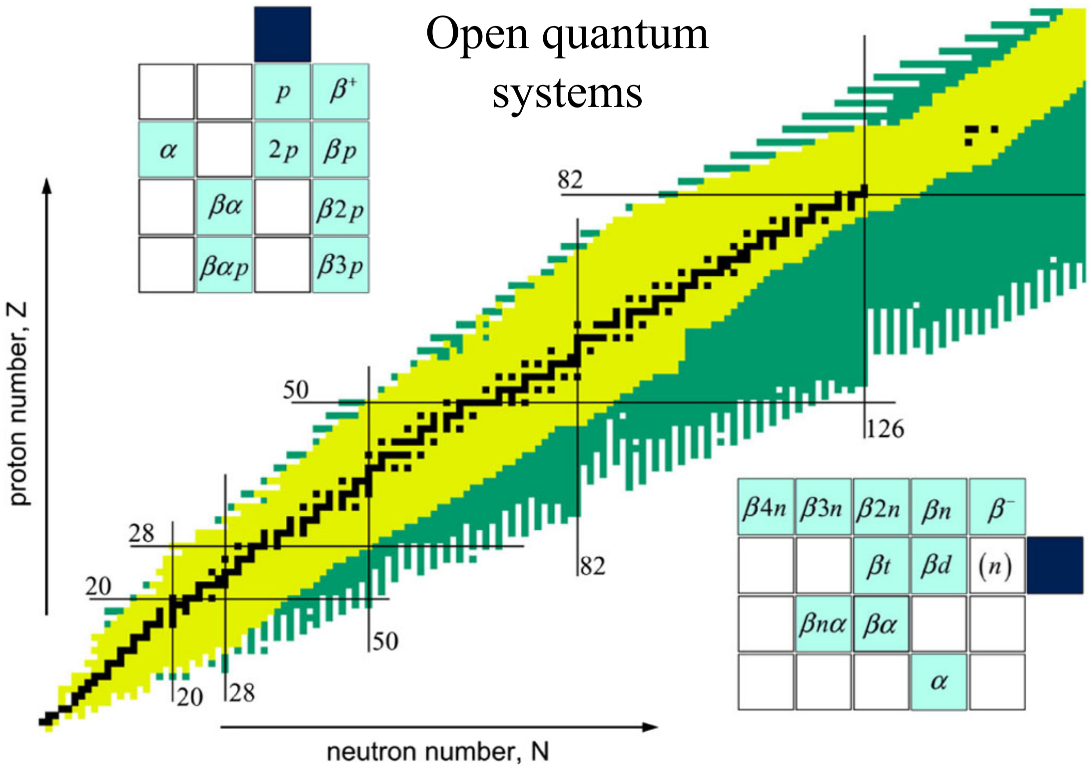
Nov, 2022

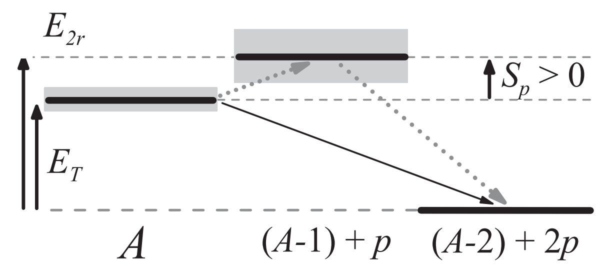
Outline

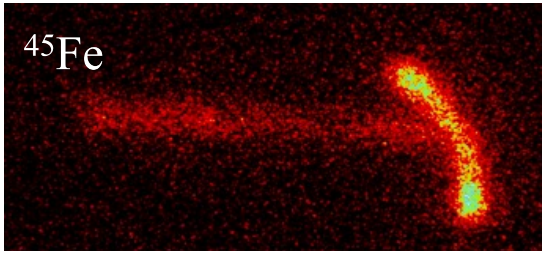
- Introduction
- The Models
  - Theoretical status
  - Our developments
- What can we learn from 2*p* decay
  - Structure
  - Continuum effect
  - Interplay between nuclear and Coulomb interactions
- Summary

Exotic decay modes



- **Two-proton (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 ($\beta 2p$) ...

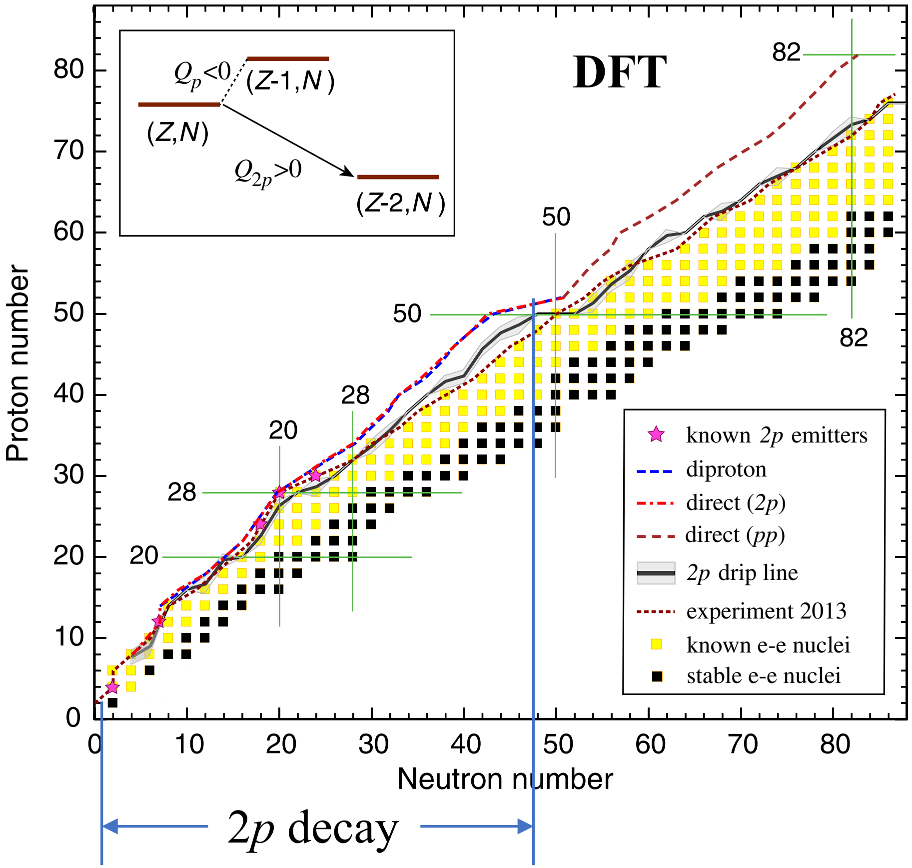
M. Pfützner *et al.*, RMP 84, 567 (2012)

V. Goldansky, NP 19, 482 (1960)

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

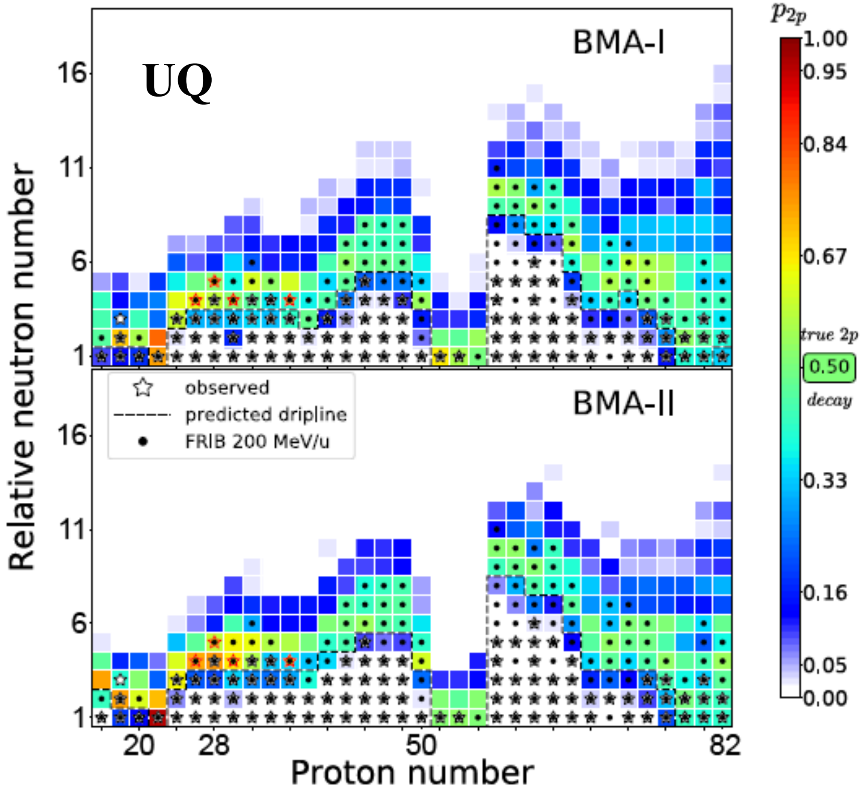
Two-proton (2*p*) decay candidates

- **Theoretical predictions of 2*p* decay**



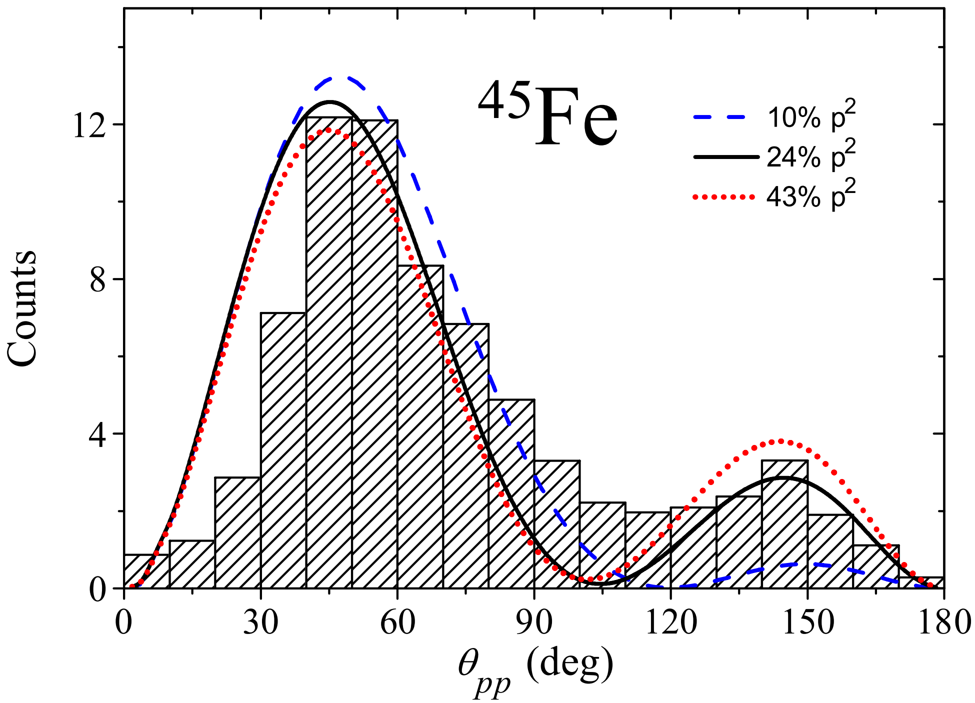
E. Olsen, *et al.* PRL 11 (2013) 139903

- **Probability of 2*p* emitter**

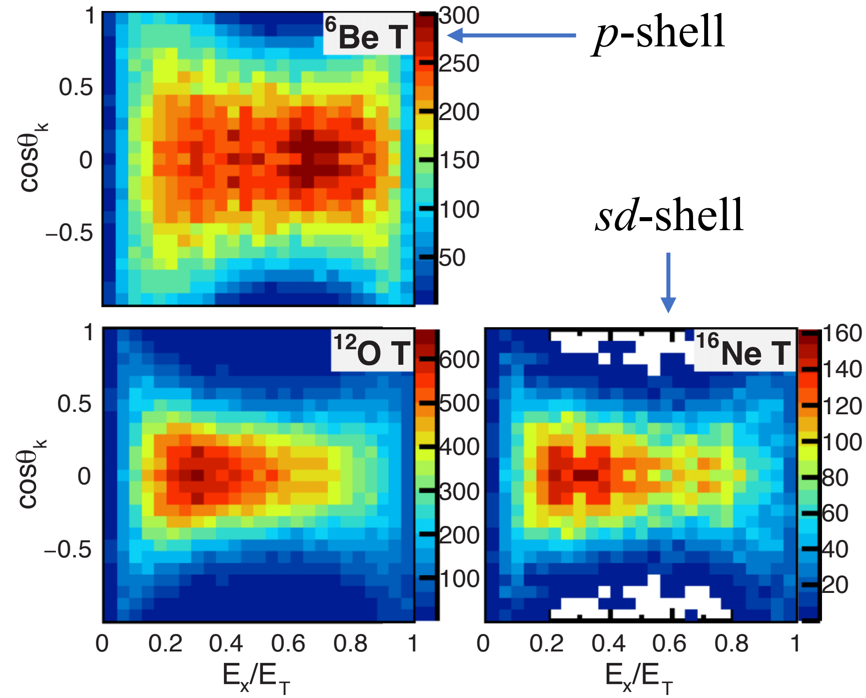


L. Neufcourt *et al.* PRC 101, 014319 (2020)

nucleon-nucleon correlation



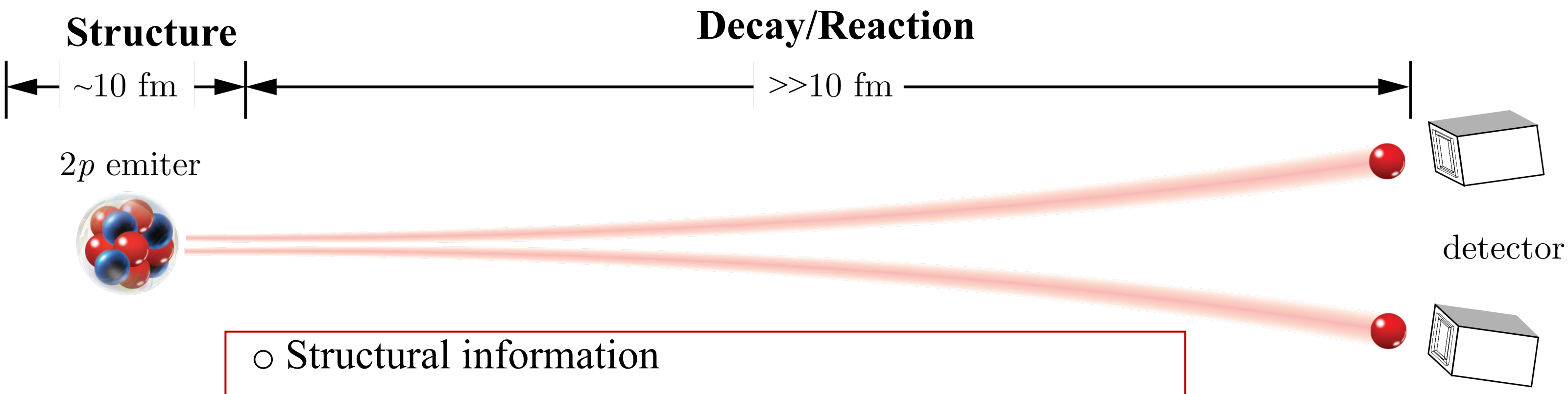
K. Miernik *et al.* PRL 99, 192501 (2007)



T.B. Webb *et al.* PRL 99, 192501 (2007)

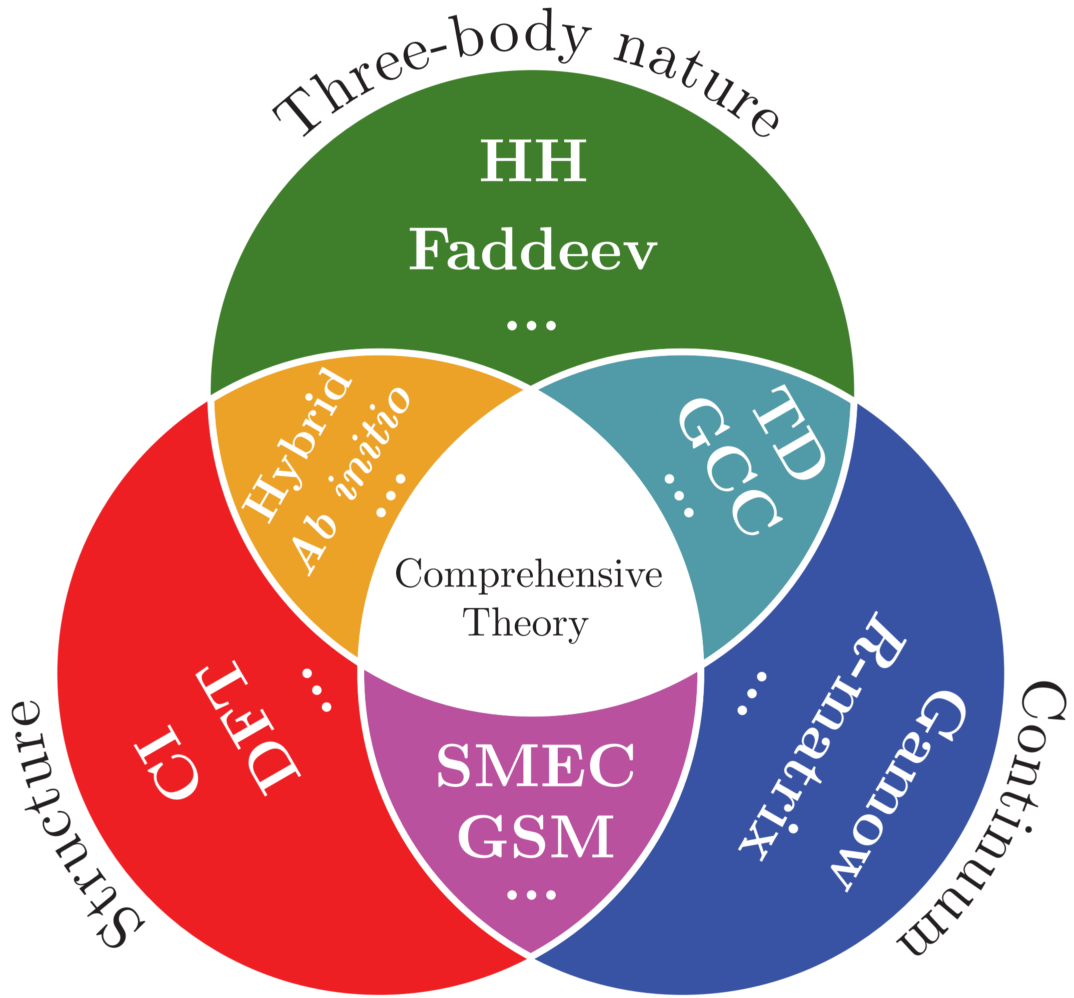
○ Different patterns of *pp* correlations, which boost the interest of 2*p*-decay studies.

What can we learn from 2*p* decay?



- ○ Structural information
- ○ Continuum effect
- ○ Interplay between nuclear and Coulomb interactions

Theoretical status

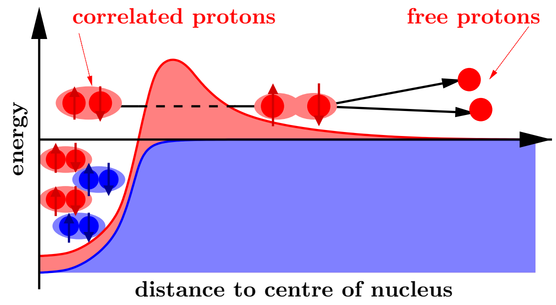


Theoretical status

- **Simplified model**
  - 2 protons form a pair and decay as a cluster

W. Nazarewicz, et al. PRC 53, 740 (1996)

B.A. Brown *et al.*, PRC 67, 041304 R (2003)

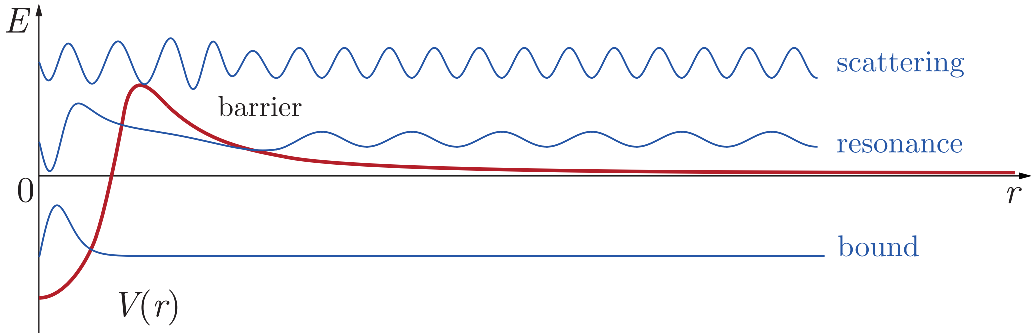


1. **Bound state** $\varphi_l(k,r) \xrightarrow[r\to\infty]{} C(k)e^{-kr}$
2. **Scattering state**

$$\varphi_l(k,r) \xrightarrow[r\to\infty]{} C^+(k)H^+(k,r) + C^-(k)H^-(k,r)$$

3. **Resonance (Gamow state)** with outgoing boundary conditions

$$\varphi_l(k,r) \xrightarrow[r\to\infty]{} C^+(k)H^+(k,r)$$



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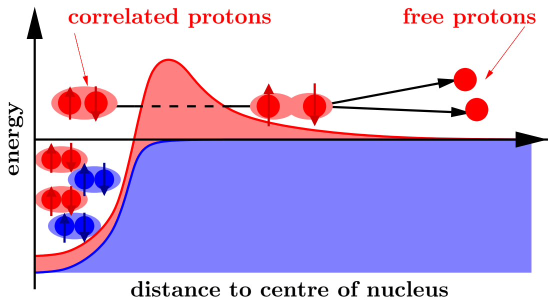
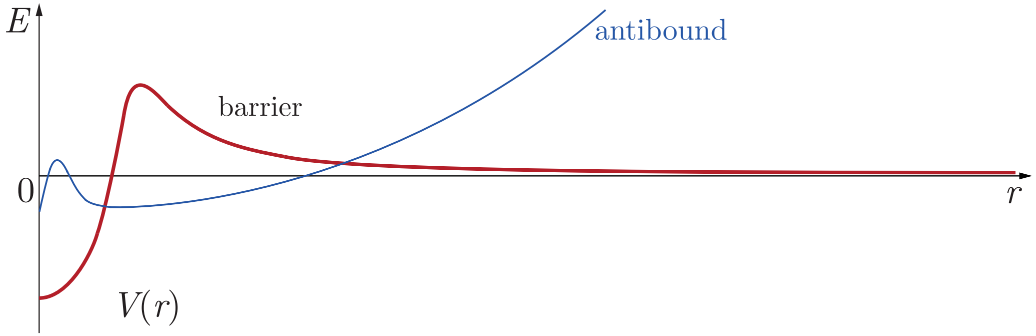


4. **Antibound (virtual) state**

$$\varphi_l(k,r) \xrightarrow[r\to\infty]{} C(k)e^{kr}$$

5. **Capturing state**

$$\varphi_l(k,r) \xrightarrow[r\to\infty]{} C^-(k)H^-(k,r)$$

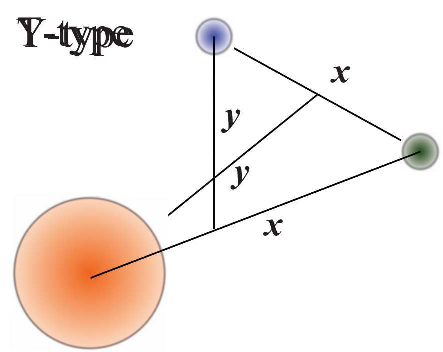


Theoretical status

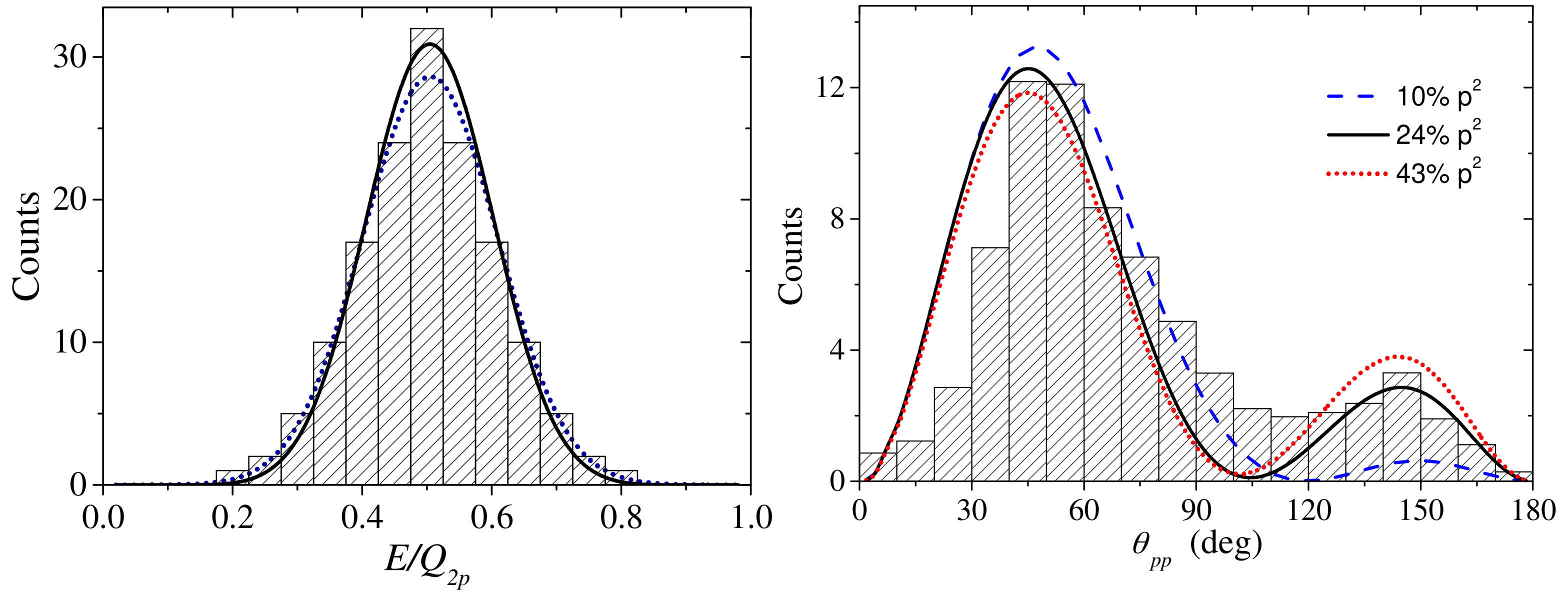
- **3-body model**
  - Correct asymptotic behavior
  - Frozen core: no core excitation or deformation

L.V. Grigorenko, PPN 40, 674 (2009)

Jacobi coordinates



Nucleon-nucleon correlations K. Miernik *et al.* PRL 99, 192501 (2007)



Theoretical status

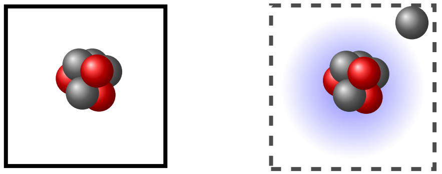
- **Configuration interaction**
  - Configuration mixing considered
  - Without the proper 3-body asymptotic behavior

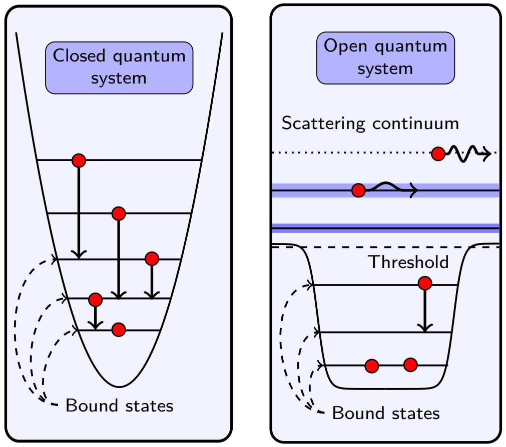
Hybrid model B. A. Brown *et al.*, PRC 100, 054332 (2019)

- CI + three-body

$$\Gamma_{2p} \approx \sum_{\ell} S(\ell^2)\Gamma(\ell^2)$$

Nucleus J^π	$T^{2p}_{1/2}$ Expt.	$T^{2p}_{1/2}$ without s^2 Incoherent	Coherent	$T^{2p}_{1/2}$ with s^2 Incoherent	Coherent
^{19}Mg $1/2^-$	4.0(15)			$0.73^{+1.5}_{-0.17}$	$0.20^{+0.40}_{-0.05}$
^{45}Fe $3/2^+$	3.6(4)	20(8)	6.6(26)	5.9(24)	1.8(7)
^{48}Ni 0^+	4.1(20)	5.1(29)	1.8(11)	1.3(6)	0.43(22)
^{54}Zn 0^+	1.9(6)	1.8(8)	0.9(4)	1.7(8)	0.6(3)
^{67}Kr $3/2^-$	20(11)	850(390)	320(140)	820(380)	250(110)
^{67}Kr $1/2^-$	20(11)	904(420)	290(130)	940(430)	360(160)





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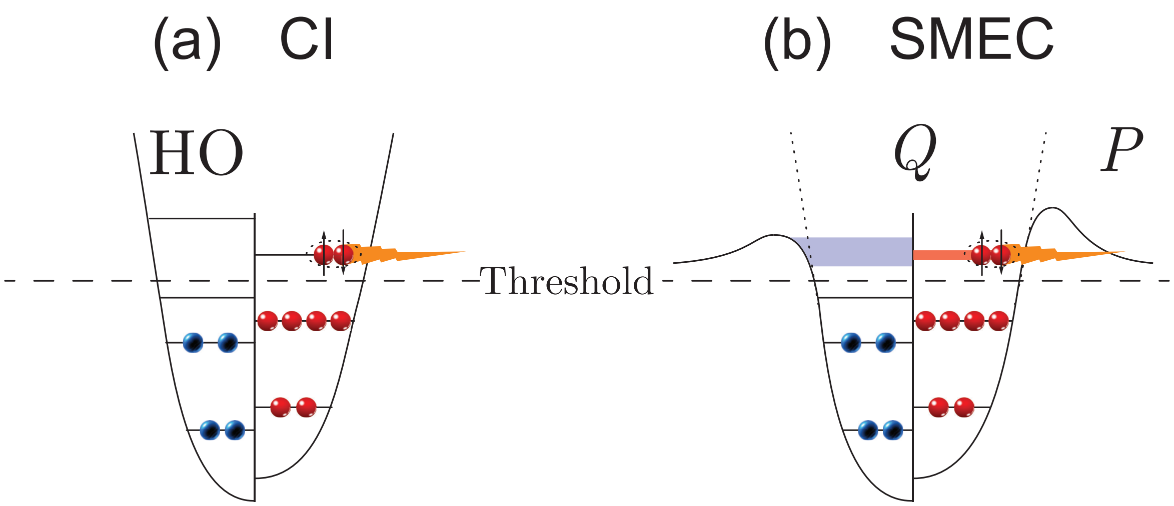
Shell-model embedded in the continuum (SMEC) J. Rotureau *et al.*, NPA 767, 13 (2006)

$$\mathcal{H}(E) = \hat{Q}H\hat{Q} + W_{QQ}(E)$$

$$W_{QQ}(E) = \hat{Q}H\hat{P}_1 \cdot \hat{G}_{P_1} \cdot \hat{P}_1 H\hat{Q}$$



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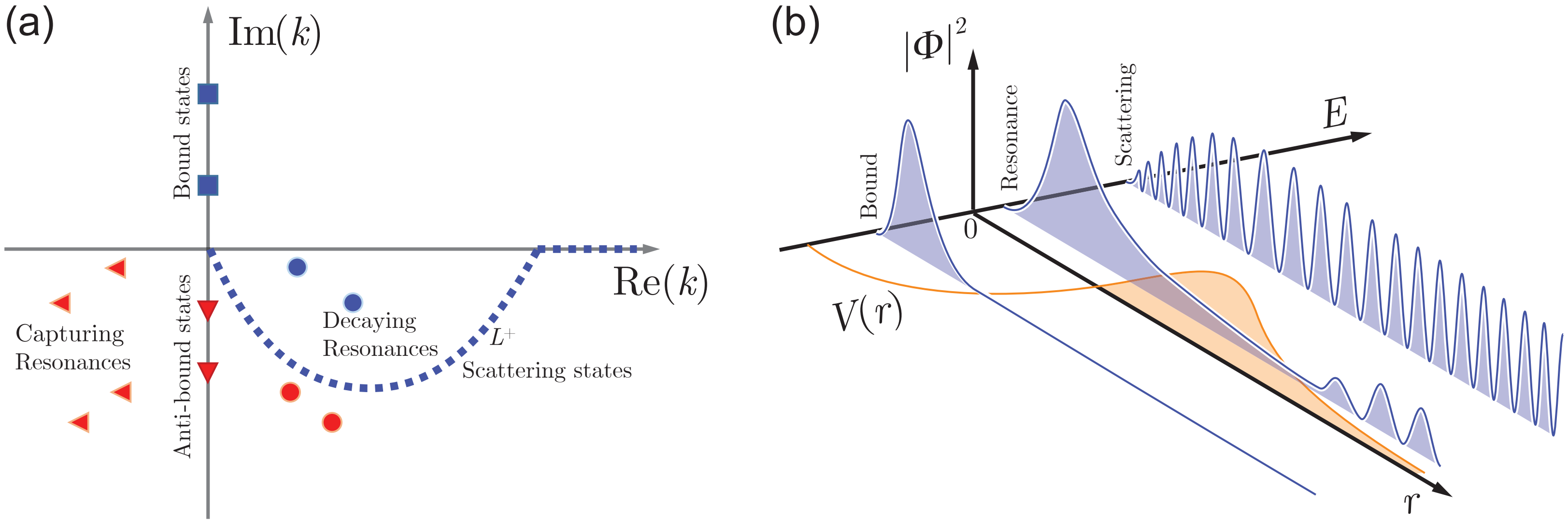
Gamow shell model (GSM) N. Michel *et al.*, PRC 103, 044319 (2021)

- CI + Berggren basis

$$\sum_{\mathfrak{n}} |u_{\mathfrak{n}}\rangle \langle u_{\mathfrak{n}}| + \int_{L^+} |u(k)\rangle \langle u(k)| \; dk = \hat{\mathbf{1}},$$



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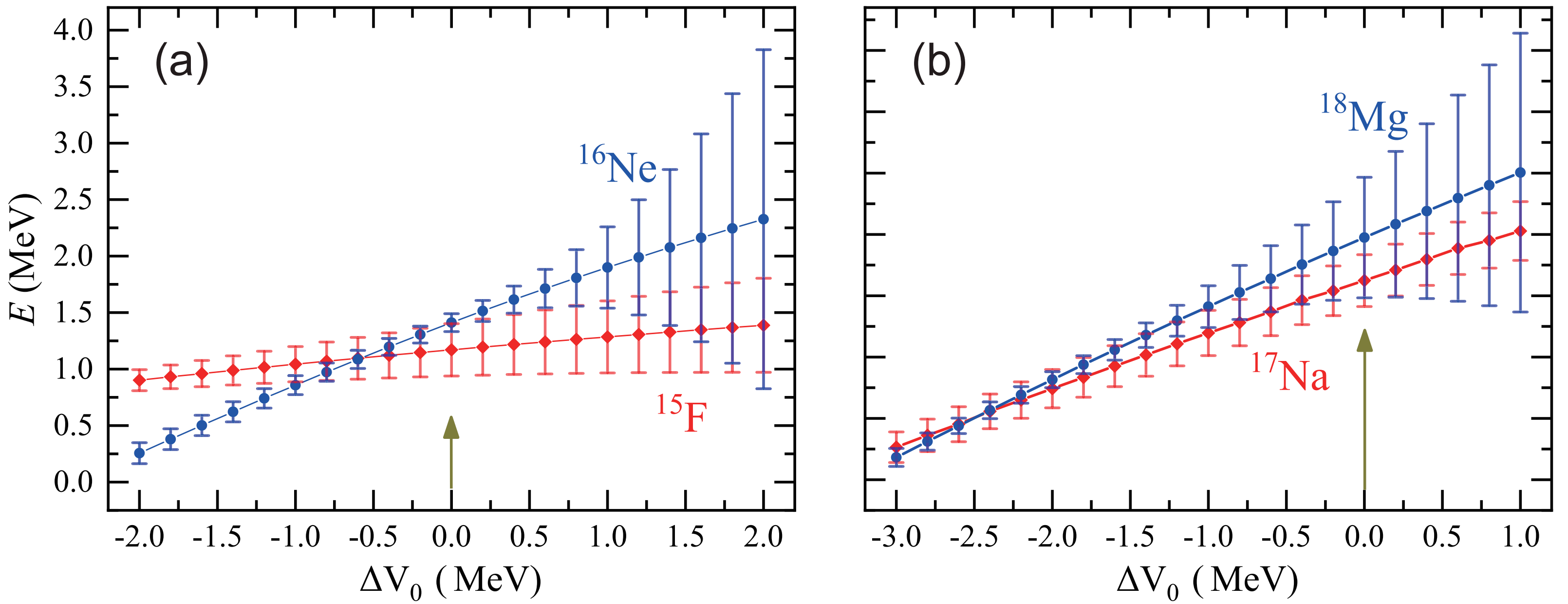

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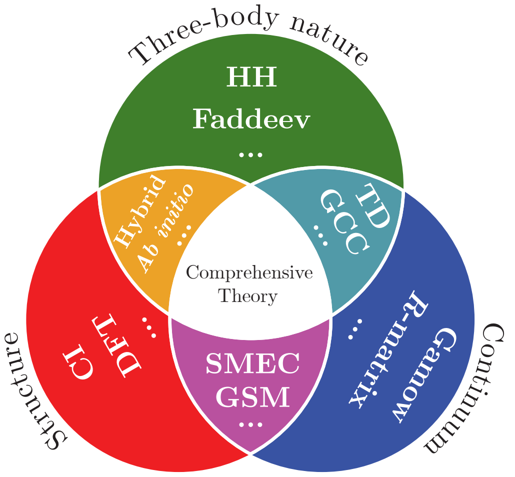
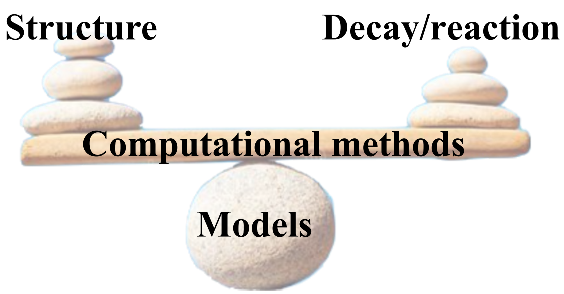


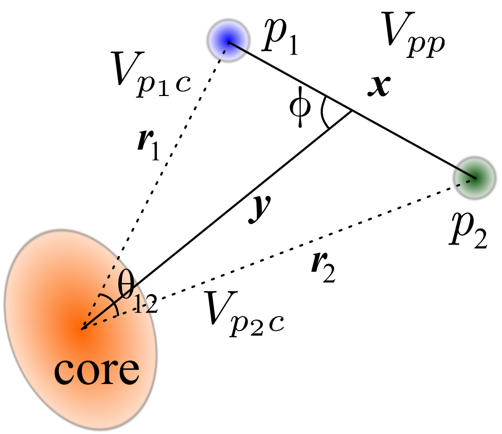


To understand the pairing correlation as well as the mechanism of 2*p* decay, the structure and decay aspects should be treated on the same footing.

Gamow coupled-channel (GCC) method

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

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



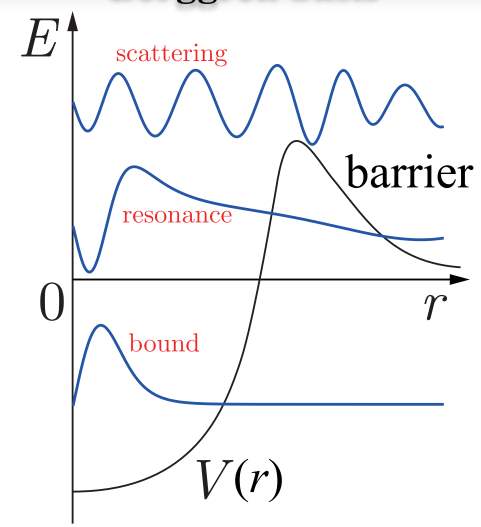
- **Total wave-function** $\Psi^{J\pi} = \sum_{J_p \pi_p j_c \pi_c} \left[\Phi^{J_p \pi_p} \otimes \phi^{j_c \pi_c} \right]^{J\pi}$

valence protons ($\Phi^{J_p \pi_p}$)

deformed core ($\phi^{j_c \pi_c}$) (New)

1. **Jacobi coordinates**
   a) No center-of-mass motion
   b) Correct 3-body asymptotic behavior
2. **Berggren basis** (New)
   a) Bound, scattering, and outgoing Gamow states
   b) Structure and decay information on the same footing

Berggren basis

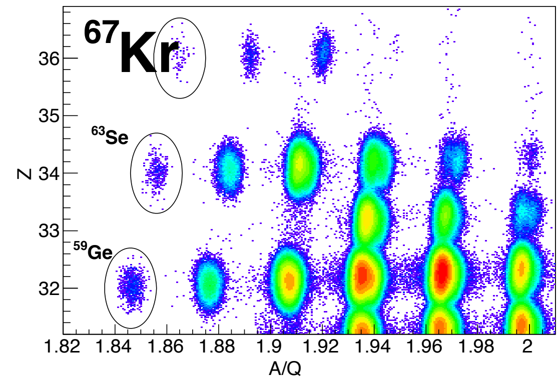


Bottom line: the objective of this work is to analyze how nuclear structure impacts decay properties and dynamics.

Puzzle of 2*p* decay in ^{67}Kr

- Experimentally, $T_{1/2}^{2p} = 20\ \mathrm{ms}$

  T. Goigoux *et al.*, PRL 117, 162501 (2016)



T. Goigoux *et al.*, PRL 117, 162501 (2016)

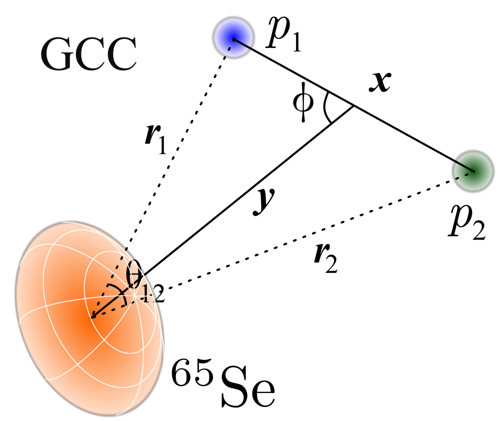
- Theoretically, $T_{1/2}^{2p} > 200\ \mathrm{ms}$ 3-body model, frozen core

  L. V. Grigorenko *et al.*, PRC 68, 054005 (2003)

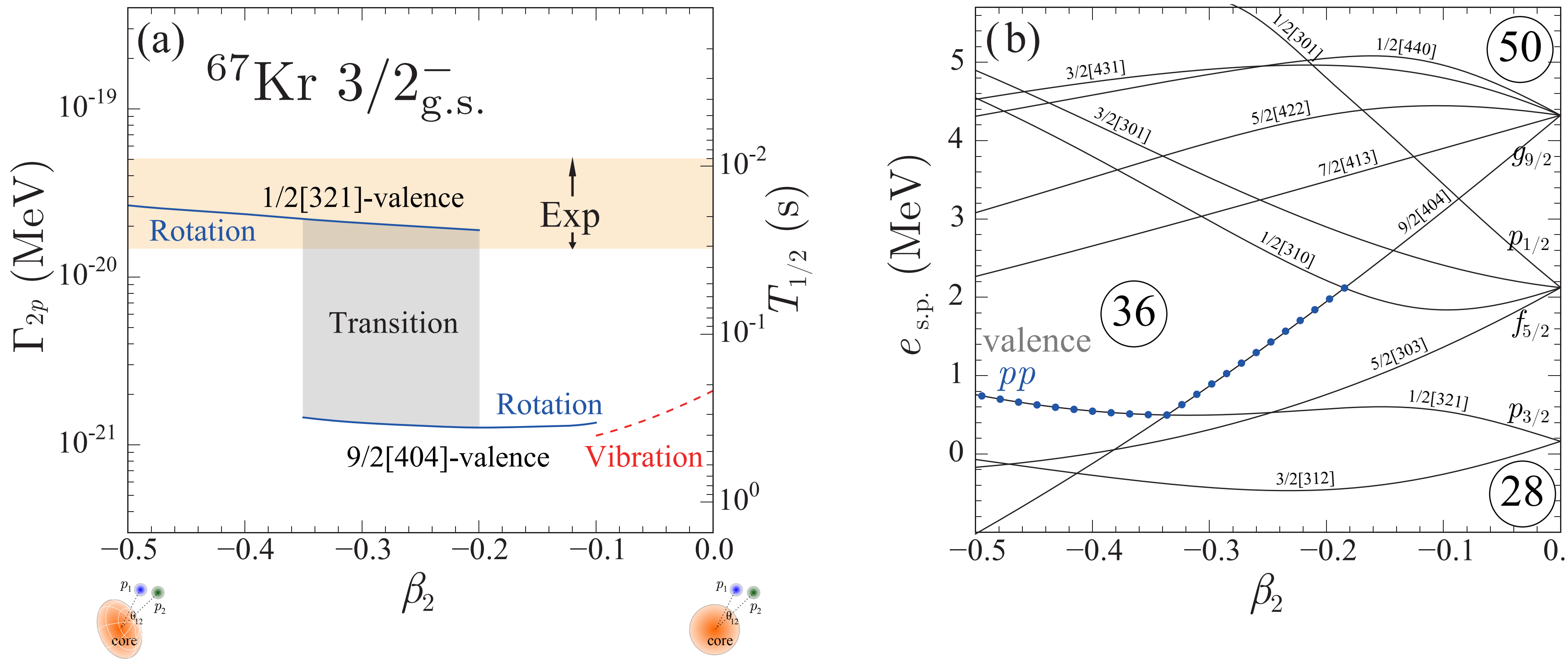
  $T_{1/2}^{2p} = 873\ \mathrm{ms}$ WKB method

  M. Goncalves *et al.*, PLB 774, 14 (2017)

- There might be deformation and configuration mixing.



Lifetime of ^{67}Kr as deformation evolution

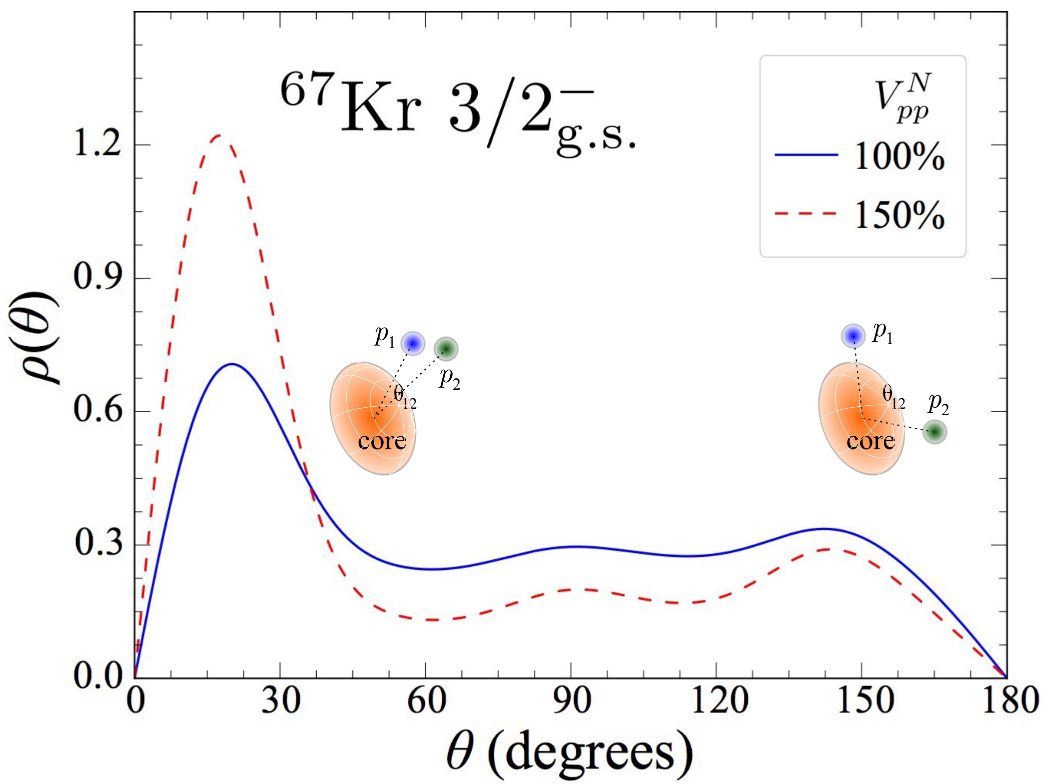


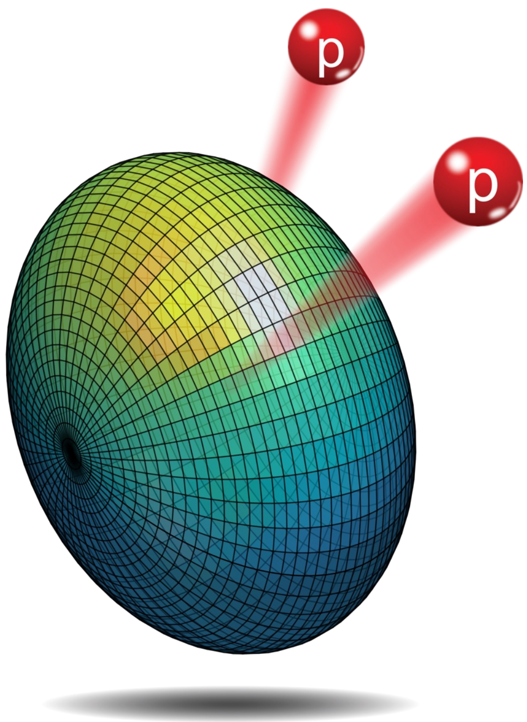
SW and W. Nazarewicz, PRL 120, 212502 (2018)

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

Diproton in ^{67}Kr

2*p* angular distribution

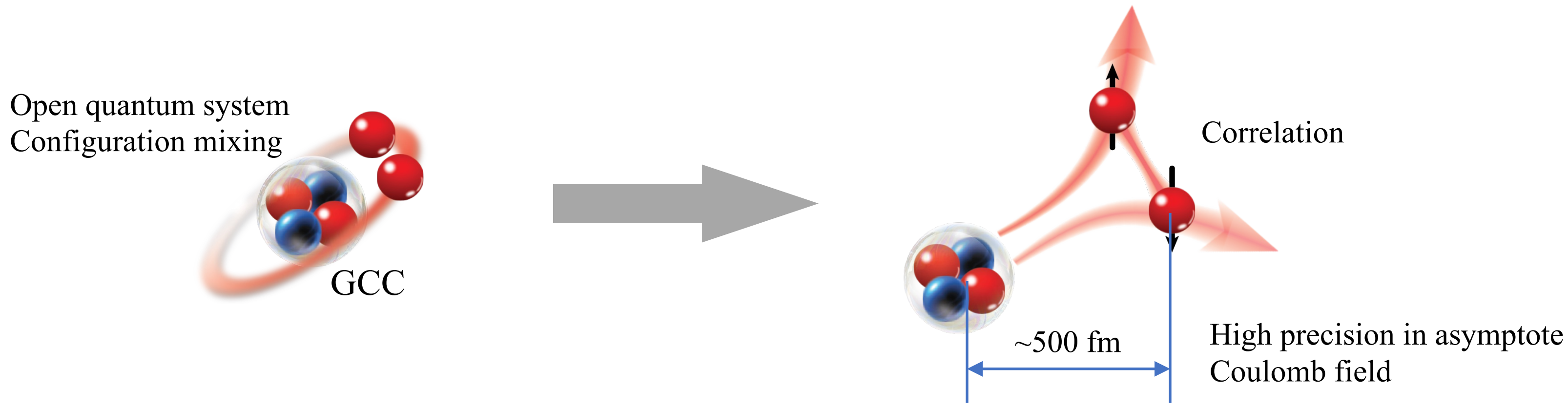




- Low-*l* continuum is crucial for deformed 2*p* decay.
- Diproton Cooper-pair benefits tunneling.

Time evolution

Our objective is to study the dynamics and mechanism of 2*p* decay

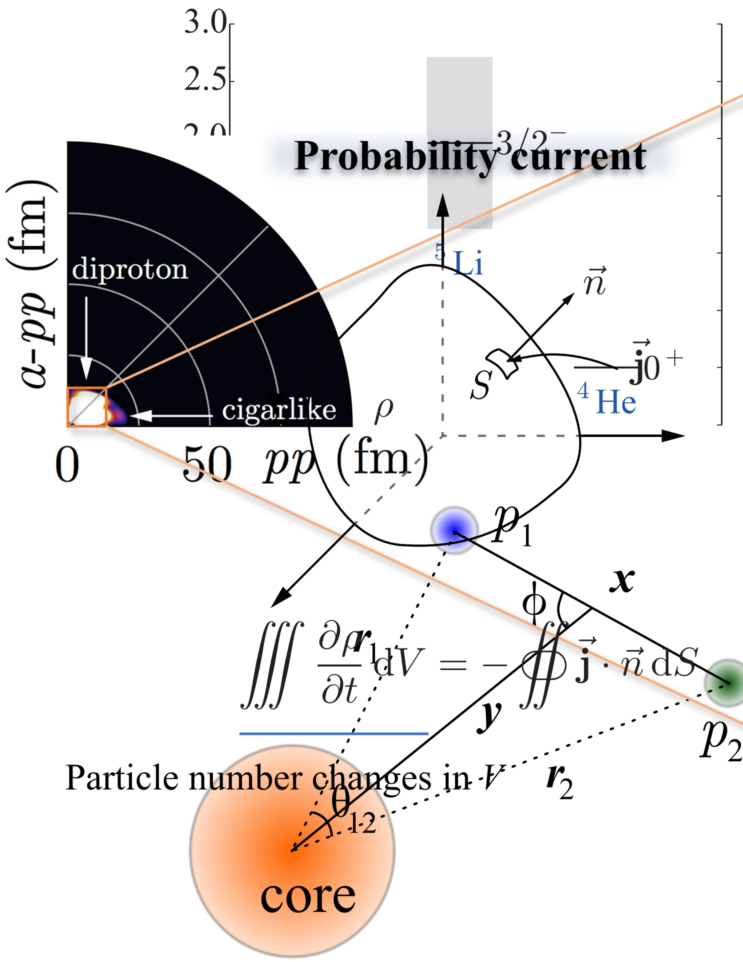


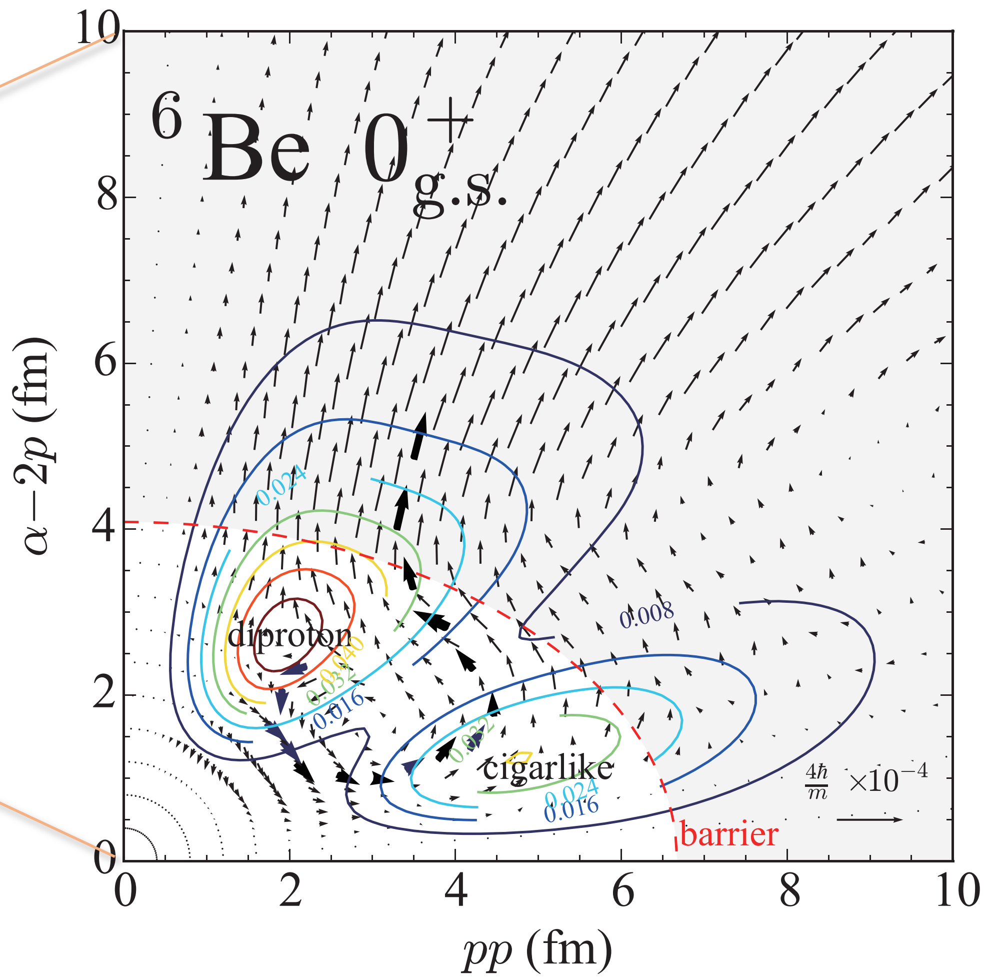
- **Time dependent approach**

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

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

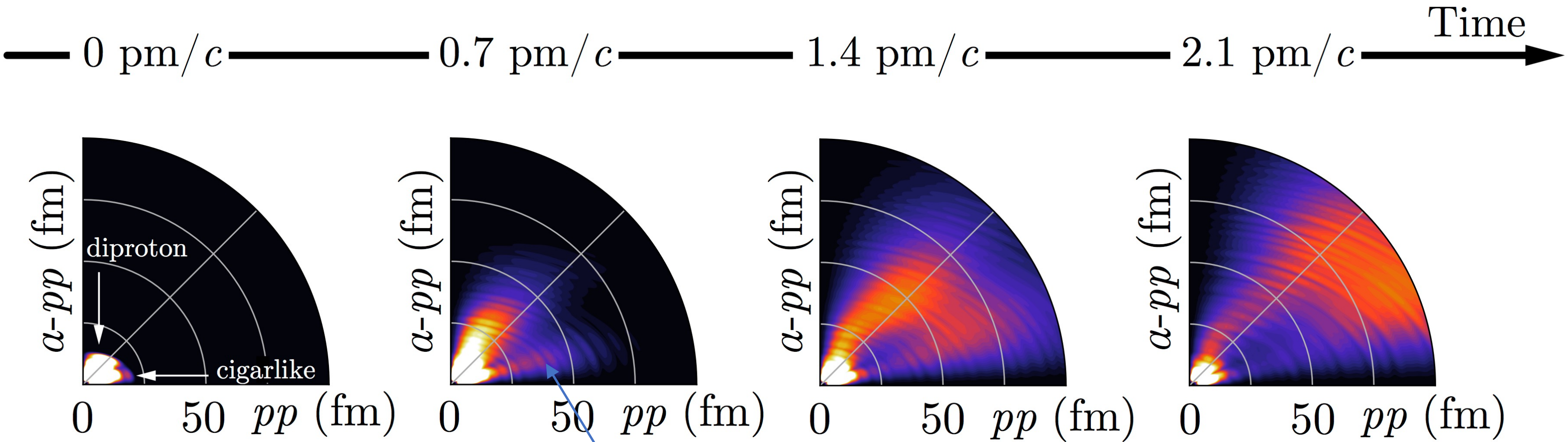
Ground-state of ^{6}Be

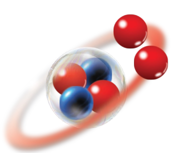




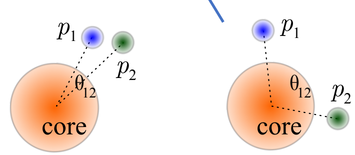
SW and W. Nazarewicz *et al.*, PRC 99, 054302 (2019)

2p decay in ^{6}Be

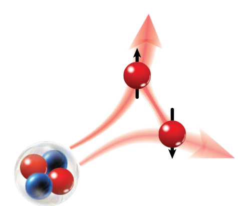




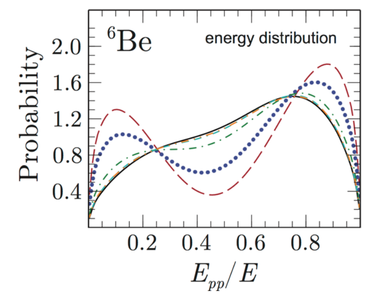
Protons inside nucleus



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



Diproton branch bends due to Coulomb repulsion

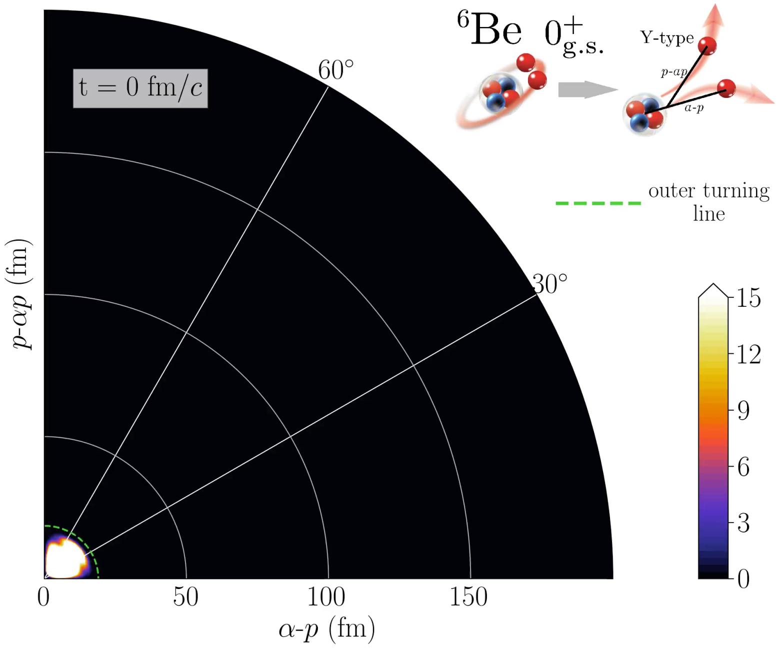


Asymptotic correlation begin to converge

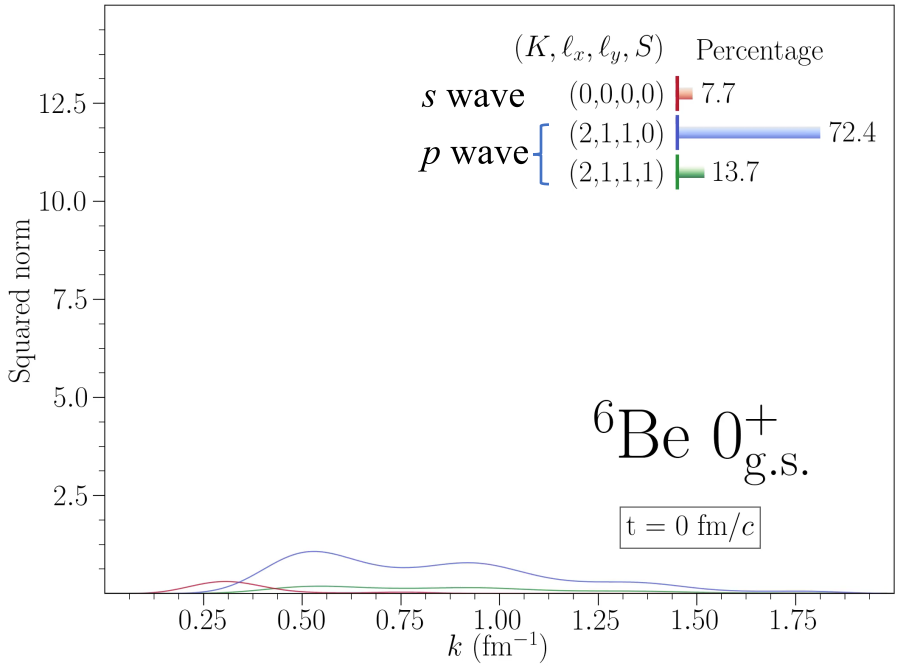
SW and W. Nazarewicz, PRL 126, 142501 (2021)

Density and configuration evolution

Density evolution in Jacobi-*Y* coordinate



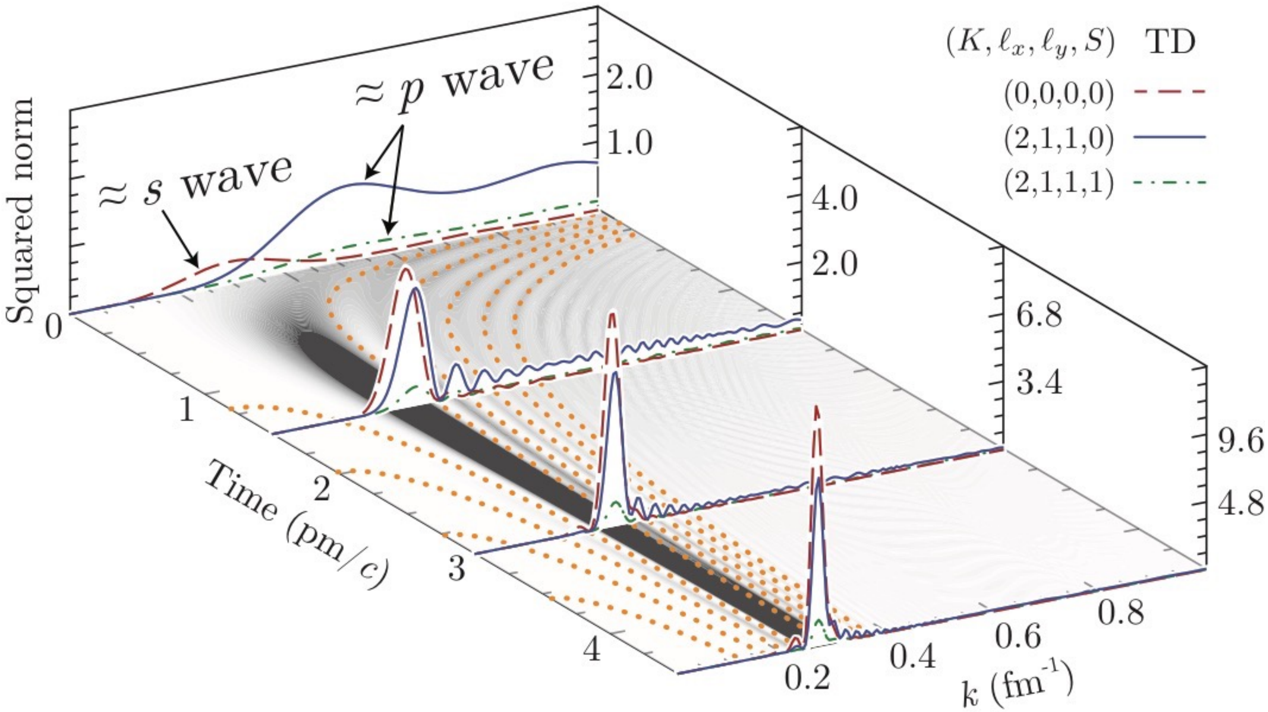
Configuration evolution of ^{6}Be



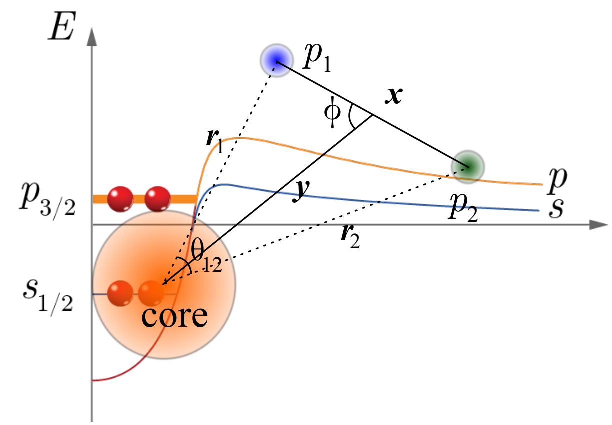
- Protons are emitted simultaneously.
- Gradual transition from *p* wave to *s* wave during the 2*p* decay process.

SW and W. Nazarewicz, PRL 126, 142501 (2021)

Configuration evolution of ^{6}Be



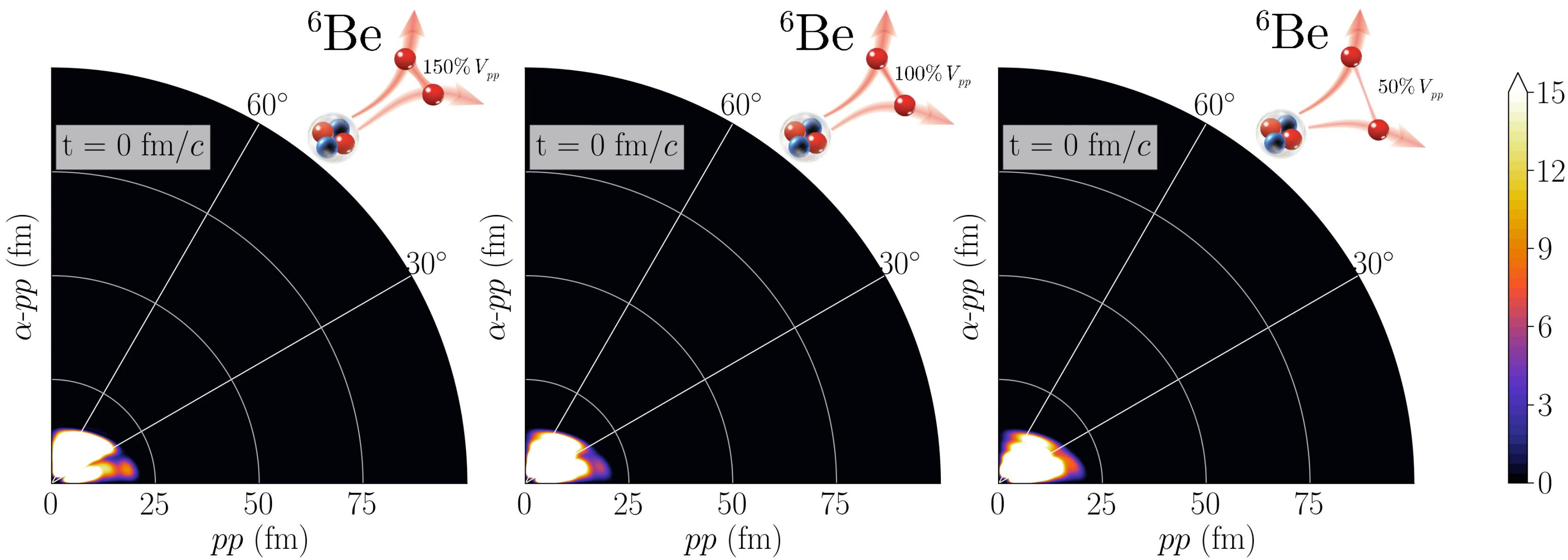
Jacobi	⬌	Single-particle
(ℓ_x, ℓ_y)	⬌	(ℓ_1, ℓ_2)
(0, 0) dinucleon	⬌	(s, s), (p, p), (d, d), (f, f)



- Dinucleon needs both positive- and negative-parity orbitals.
- Diproton structure forms a bridge from p wave to s wave.

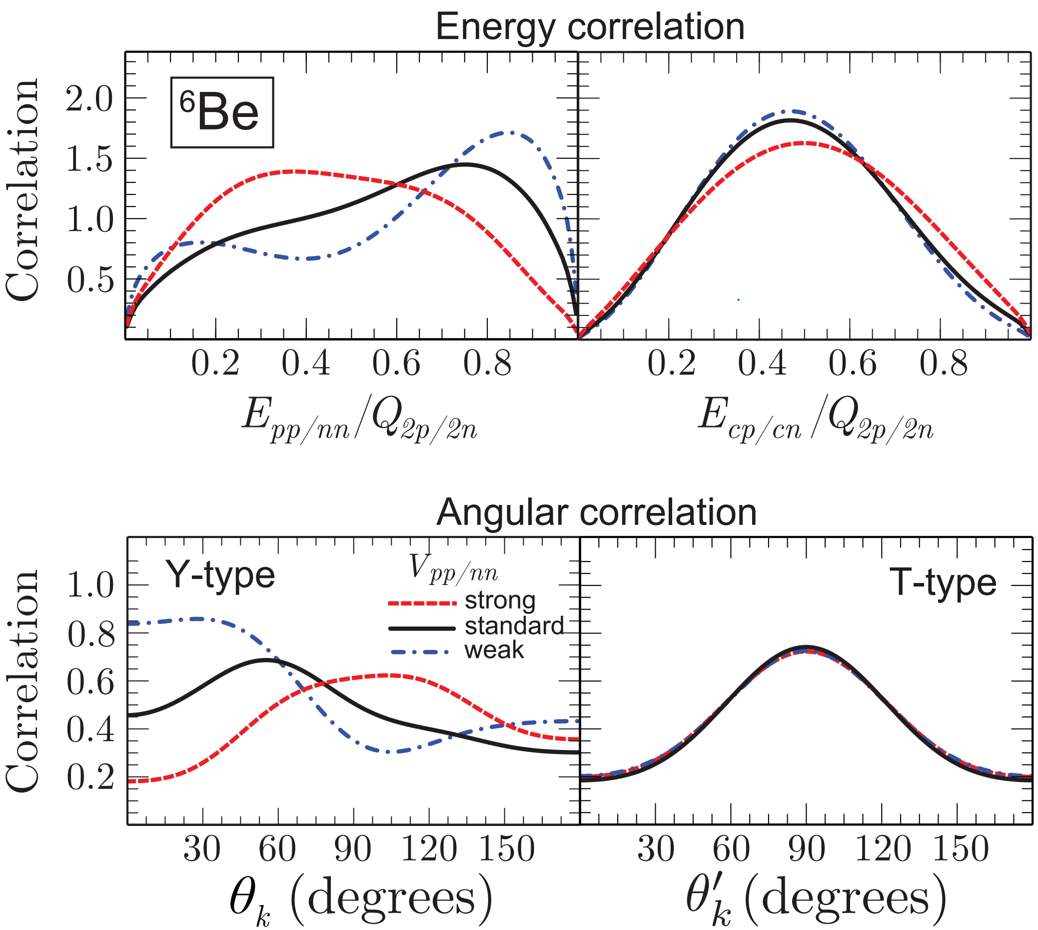
Decay dynamics with different pairing

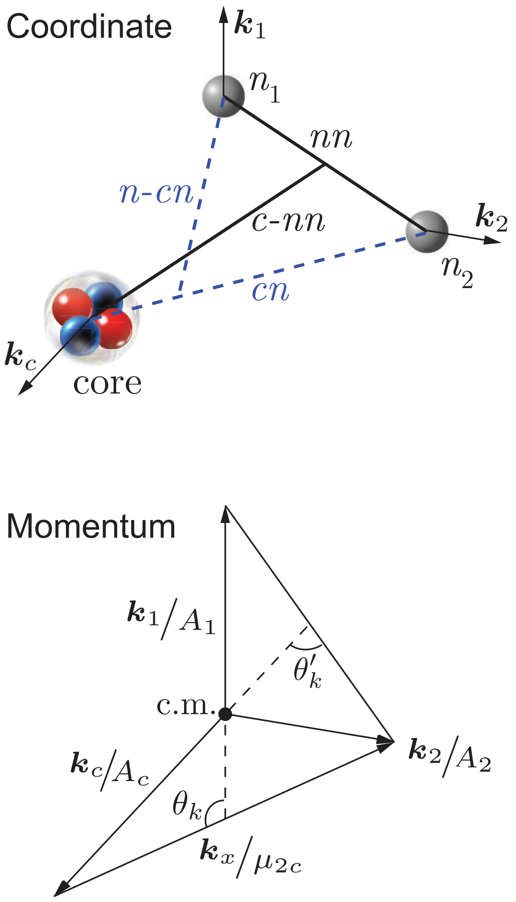
Strong pairing **Standard pairing** **Weak pairing**



- 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.

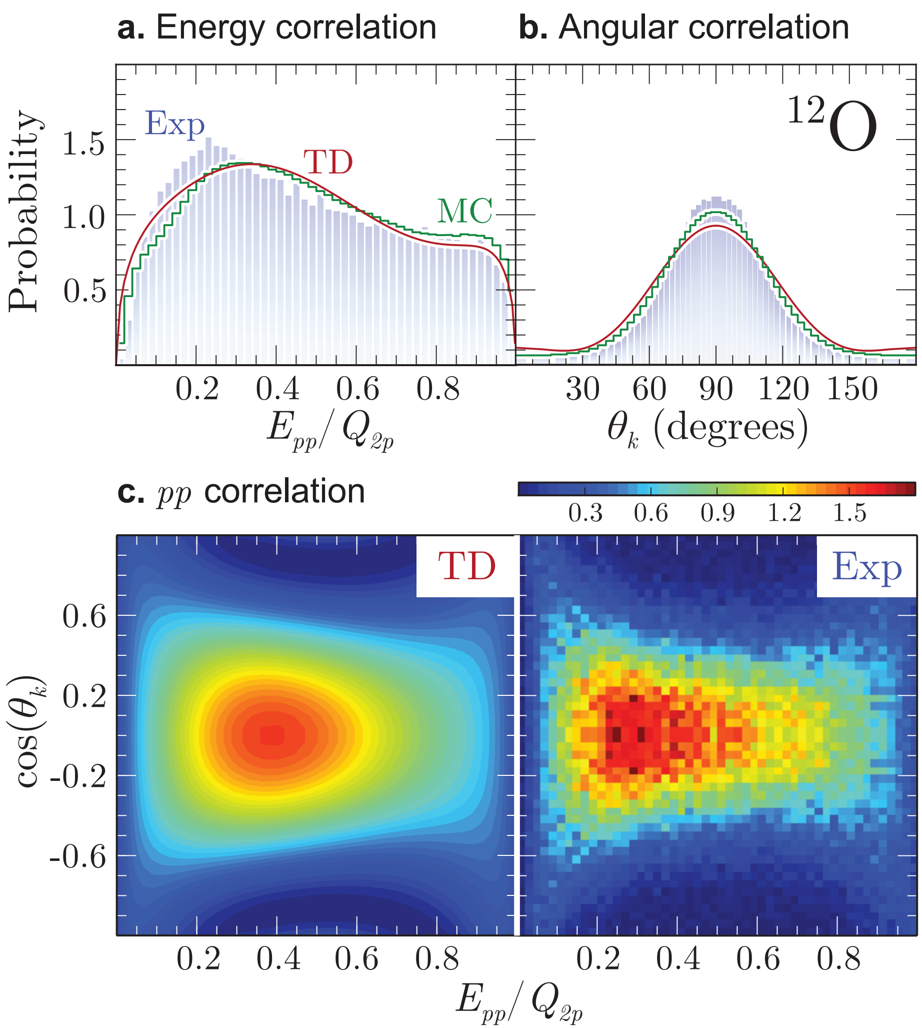
Asymptotic correlations

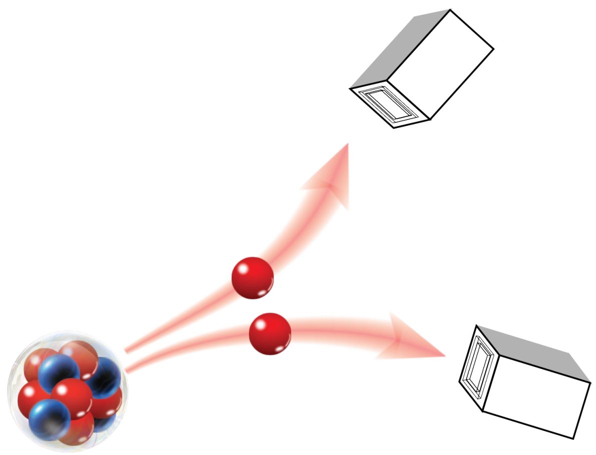




- E_{pp} and Y-type angular correlations are strongly impacted by nucleon-nucleon interaction.

Pairing correlation of ^{12}O





- Decipher nuclear structure information through nucleon-nucleon correlation.

  Correlation: 73% s-wave

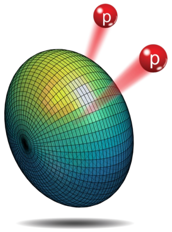
  ↓

  Structure $s(^{12}O) > s(^{6}Be)$

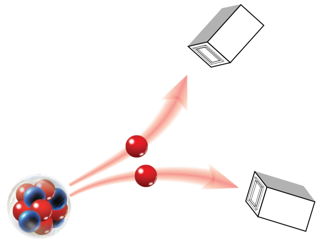
- Long-range correlation → Coulomb vs Nuclear

Summary

- What can we learn from 2*p* decay?
  - Structure:
    1. Deformation might change decay process
    2. Low-*l* orbitals are crucial for decay width



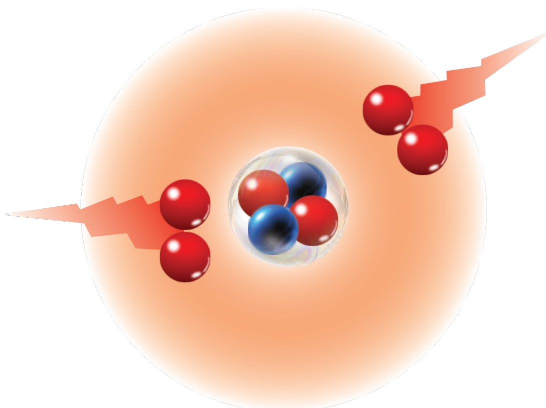
  - Continuum effect:
    1. Benefit for dinucleon/clustering
    2. Make a bridge for the transition among orbitals

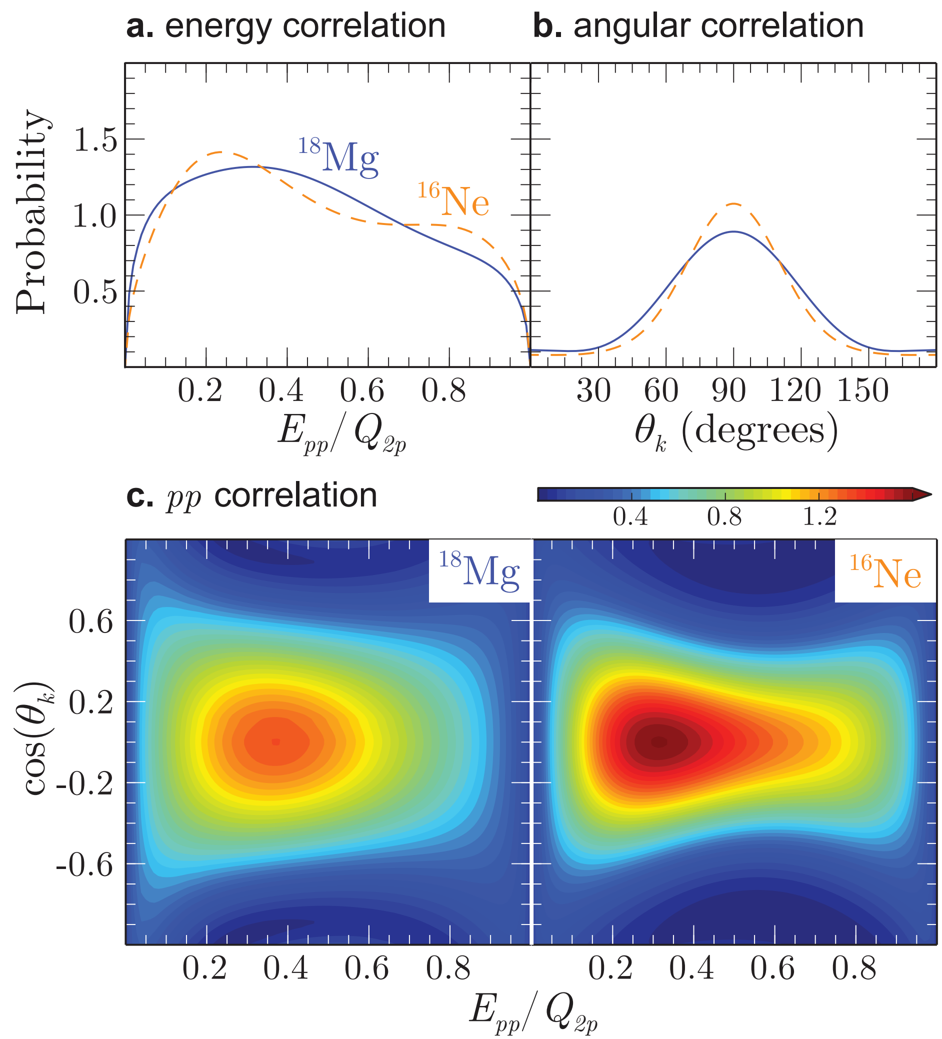


  - Pairing interaction
    1. Strongly impacts decay dynamics
    2. Manifests itself in asymptotic (E_{pp} and Jacobi-Y angular) correlations

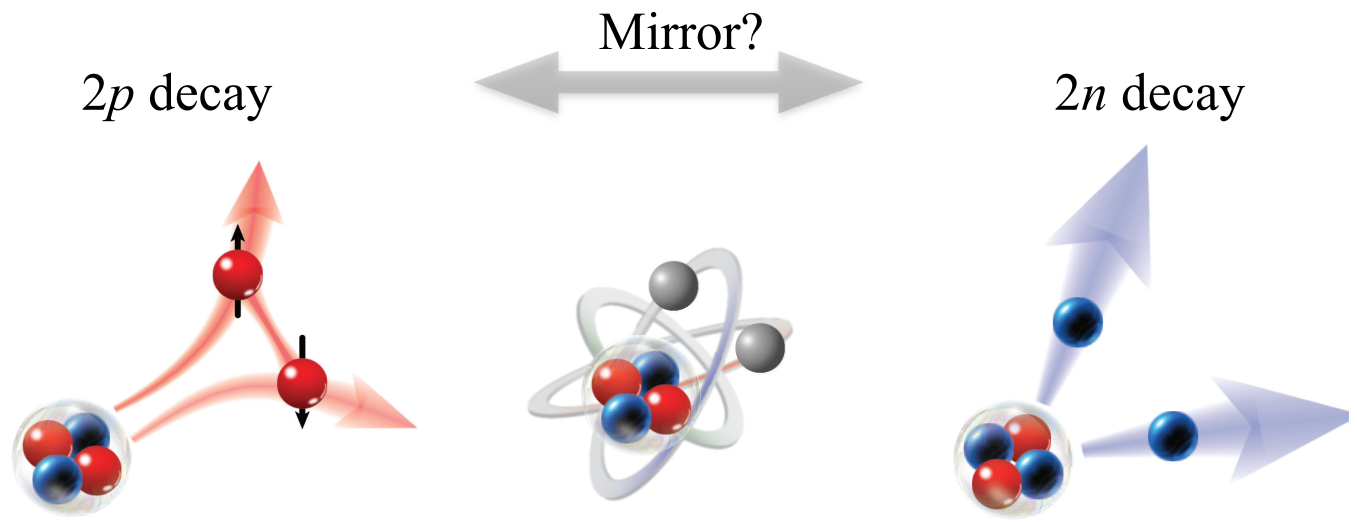
Perspectives: correlations of 2*p* decay

- Correlations needed: ^{48}Ni, ^{54}Zn, ^{67}Kr … .
- 2*p* + 2*p* decay: ^{8}C and ^{18}Mg?





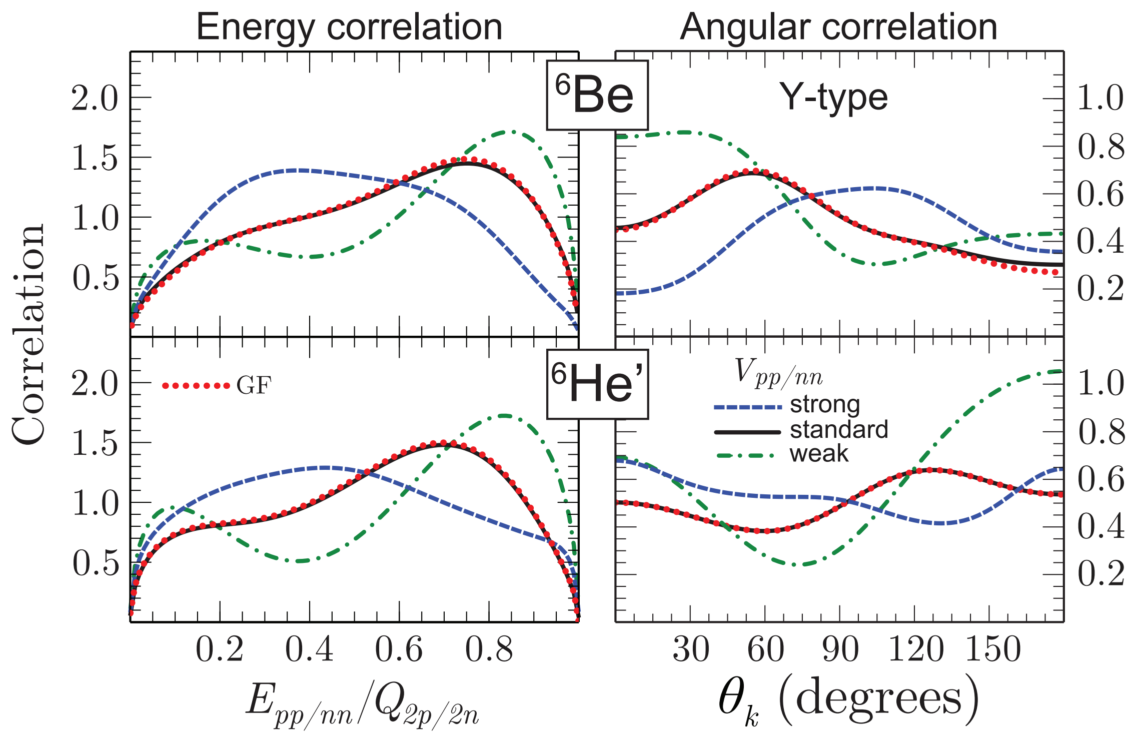
Perspectives: 2*n* decay

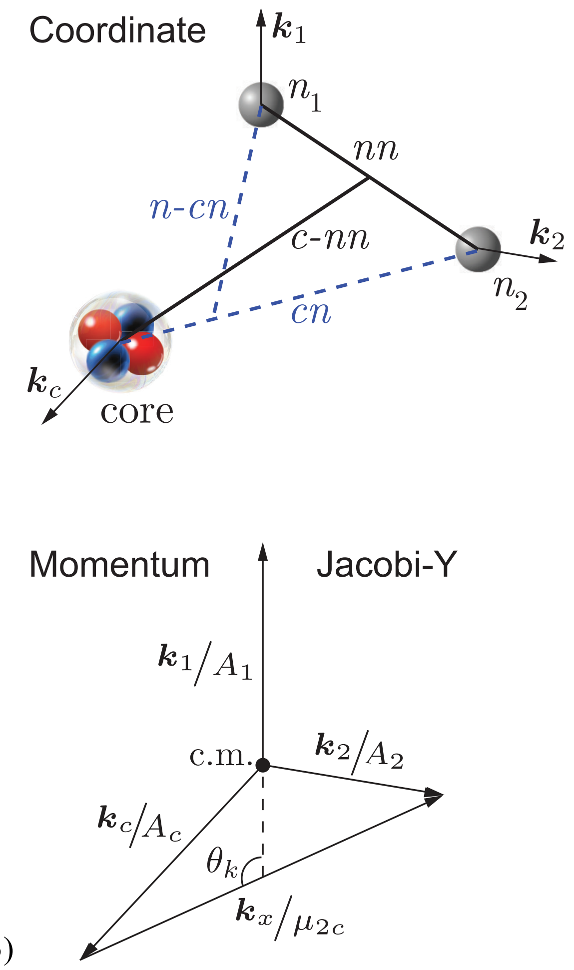


- The symmetry and asymmetry between 2*p* and 2*n* decays.
- Candidates: ^{16}Be, ^{26}O …

To be continued …

Asymptotic correlations: 2*p* vs 2*n*





- ***pp***: subthreshold resonance — L.P. Kok, PRL 45, 427 (1980)
  $k = 0.0647 - i0.0870$ fm^{-1}; $E = -140$ keV; $\Gamma = 934$ keV
- ***nn***: antibound state, $k = -i0.0559(33)$ fm^{-1} — V.A. Babenko, PAN 76, 684 (2013)

Thank you for your attention!

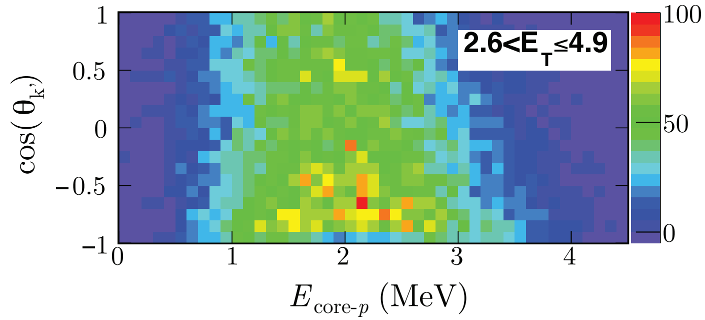
- Collaborations:
  - W. Nazarewicz (MSU)
  - F. R. Xu (PKU)
  - R.J. Charity (WU)
  - L.G. Sobotka (WU)
  - N. Michel (IMP)
  - J. Wylie (MSU)
  - M. Płoszajczak (GANIL)
  - …

FRIB UMASS LOWELL LUND UNIVERSITY IMP OAK RIDGE National Laboratory GANIL …

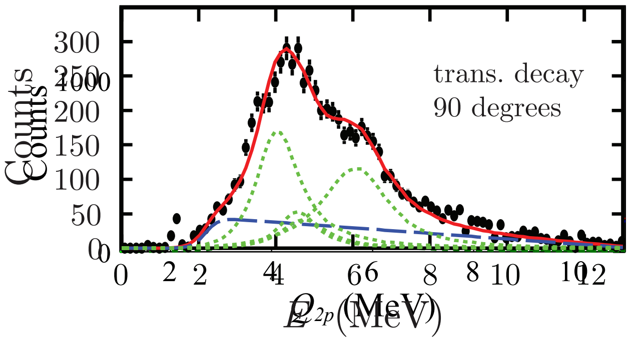
Backup slides

Asymptotic correlations of ^{11}O

Measured Jacobi-Y correlation of ^{11}O

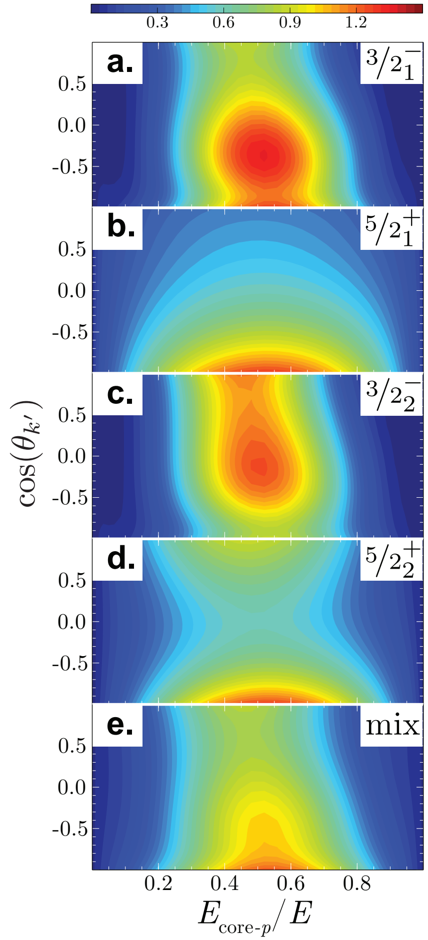


T. Webb *et al.*, in preparation



T. Webb, S.M. Wang *et al.*, PRC PRL, 044317 122 (2020) (2019)

Time-dependent calculation



- Distinct correlation patterns for different states.
- Useful tool to study inner structure.

Evolutions of pairing correlations