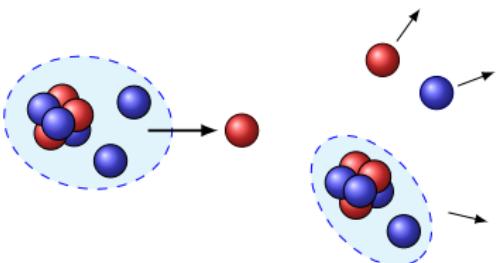
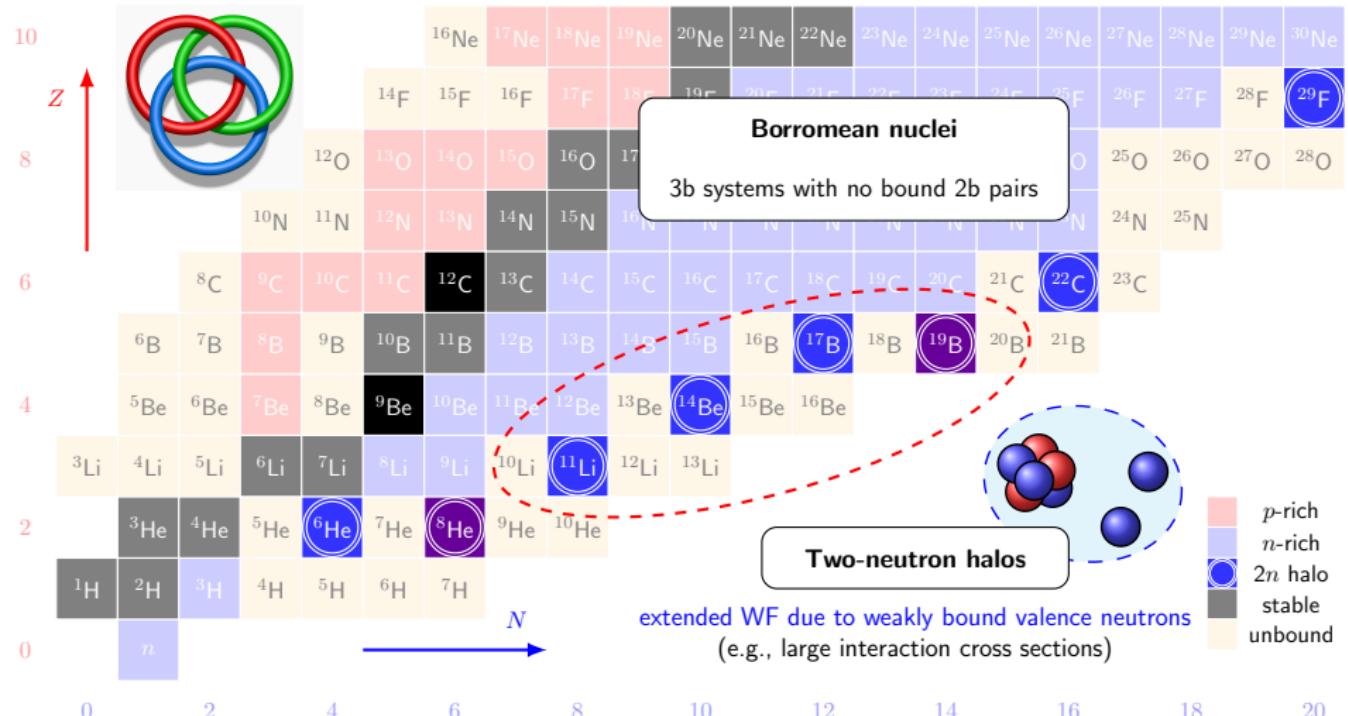


## Dineutron correlations in knockout reactions with Borromean halo nuclei

Jesús Casal

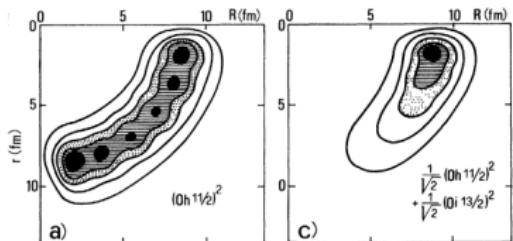
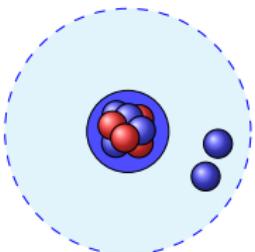
Universidad de Sevilla, Spain





## Dineutron?

  
 $S = 0, T = 1$   
 unbound



Strong spatial correlation at low neutron densities

The dineutron has minimum extension in the surface

*A. B. Migdal* (1973)

Spatially compact correlated  $n$ - $n$  pair at the surface of a nucleus  
*Sov. J. Nucl. Phys.* 238

*F. Catara et al.* (1984)

Mixing of different parities favors the dineutron localization  
*Phys. Rev. C* 29, 1091

*M. Matsuo* (2006)

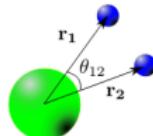
*Phys. Rev. C* 73, 044309

*K. Hagino et al.* (2007)

*Phys. Rev. Lett* 99, 022506

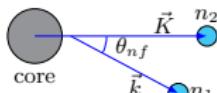
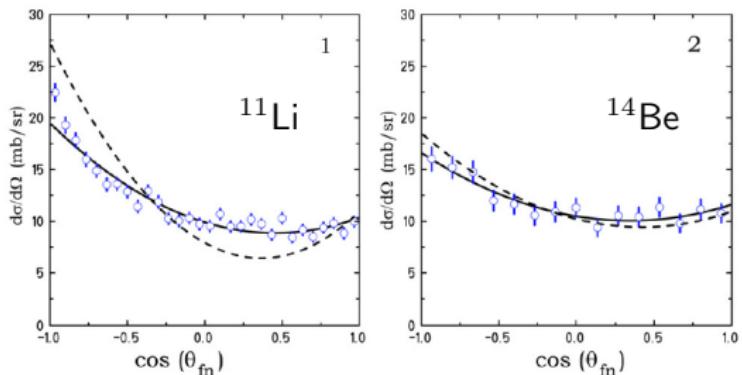
## (Some) Experimental evidences

- Coulomb dissociation;  $B(E1) \propto (1 + \langle \cos \theta_{12} \rangle)$   
*Nakamura et al.* [PRL 96, 252502 (2006)]:  $^{11}\text{Li}$   
 $\langle \theta_{12} \rangle < 90^\circ$  (coordinate space)



- 1n-knockout on carbon target

*Simon et al.* [PRL 83, 496 (1999), NPA 791, 267 (2007)];  $^{11}\text{Li}$ ,  $^{14}\text{Be}$   
 $\langle \theta_{nf} \rangle > 90^\circ$  (momentum space). Asymmetry  $\Rightarrow$  mixing ( $s$ ,  $p$ ,  $d$ )



More recently:

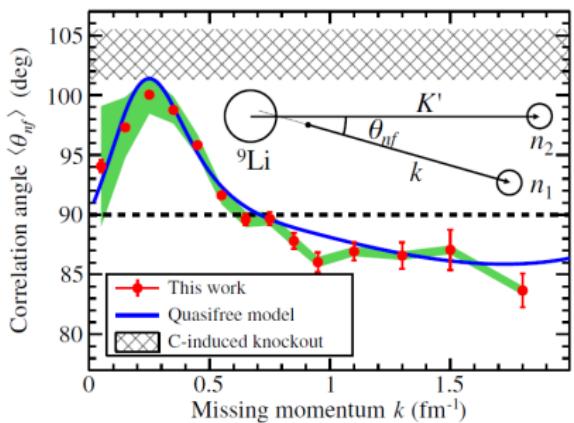
- *Y. Kubota et al.* [PRL 125, 252501 (2020)]

### Surface Localization of the Dineutron in $^{11}\text{Li}$

( $p, pn$ ) knockout at  $\sim 250$  MeV/nucleon [SAMURAI @ RIKEN]

average opening angle as a function of intrinsic neutron momentum

➢ explore the  $nn$  correlation at different neutron densities

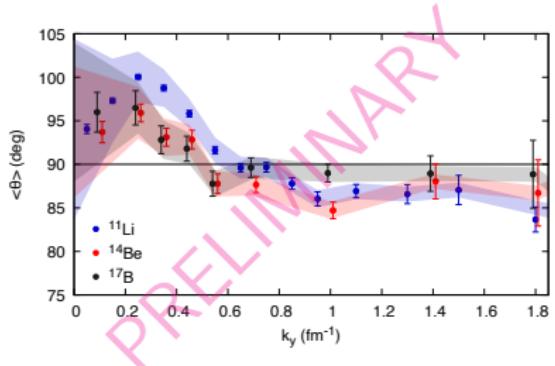


maximum at  $k \sim 0.3$  fm $^{-1}$   
(theory  $\Rightarrow r \sim 3.6$  fm)

⇒ large  $\theta_{nf}$ , i.e., dineutron,  
probed at the surface

## NEW experimental evidence!

Comparison  $^{11}\text{Li}$ ,  $^{14}\text{Be}$ ,  $^{17}\text{B}$ . RIKEN  $\sim 250$  MeV/nucleon (SAMURAI18)



- peak around  $k_y \sim 0.25 \text{ fm}^{-1}$  in all three nuclei
- larger for  $^{11}\text{Li}$  than  $^{14}\text{Be}$ ,  $^{17}\text{B}$
- different-parity mixing?  
core excitation?

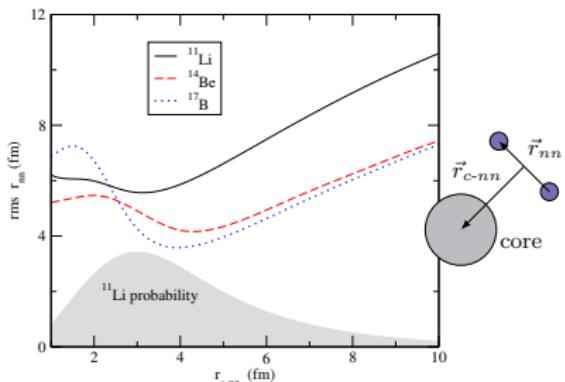
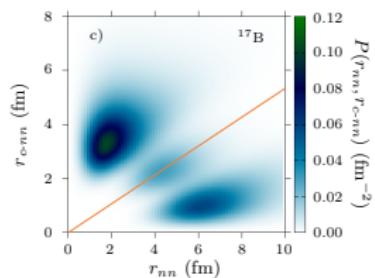
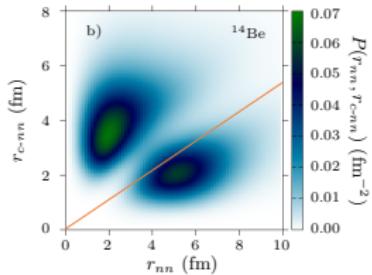
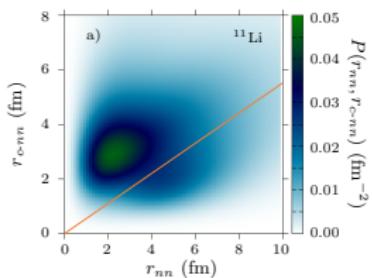
$$\Rightarrow \langle\theta\rangle_{max} = 100.0(2) [{}^{11}\text{Li}], 95.9(10) [{}^{14}\text{Be}], 96.4(19) [{}^{17}\text{B}] \text{ degrees}$$

First data **supporting universality of dineutron correlations**, with a somewhat larger signal at the surface of  $^{11}\text{Li}$

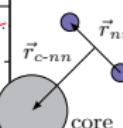
[A. Corsi, Y. Kubota, J.C. et al., submitted]

## ➤ Hyperspherical formalism to build $\Psi_{\text{g.s.}}(\mathbf{r}_{nn}, \mathbf{r}_{c-nn})$

e.g., Casal et al., PRC 88, 014327 (2013)



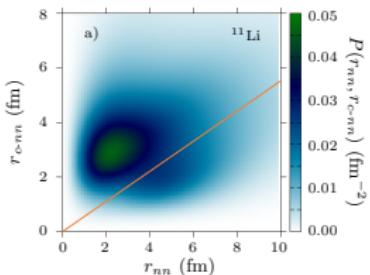
The minimum  $n$ - $n$  distance appears around the highest probability of presence (c.f. Hagino et al.)



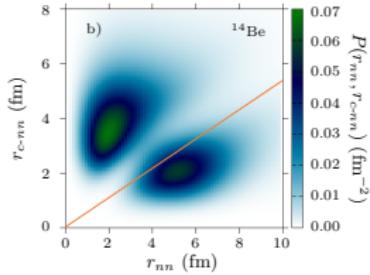
It corresponds to the surface (not the interior, not the halo tail)

## ➤ Hyperspherical formalism to build $\Psi_{\text{g.s.}}(\mathbf{r}_{nn}, \mathbf{r}_{c-nn})$

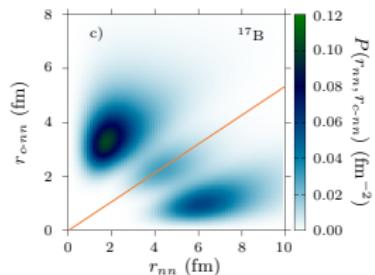
e.g., Casal et al., PRC 88, 014327 (2013)



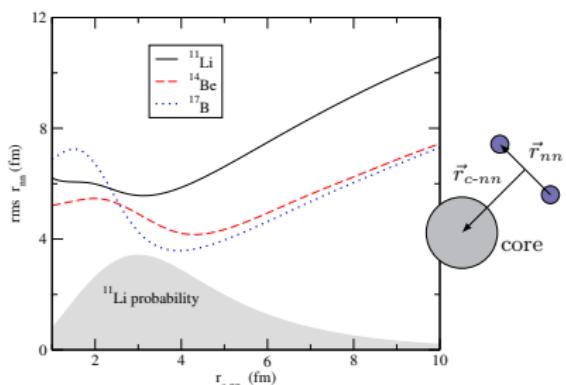
dominant *s*-wave  
large *p* admixture



dominant *p*-wave  
mixing with *s* and *d*  
core ex. ( $2^+$ , 20%)



*sd* shell  
small *p*-wave mix.

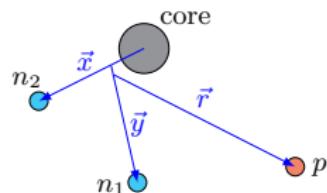


The minimum *n-n* distance appears around the highest probability of presence (c.f. Hagino et al.)

It corresponds to the surface (not the interior, not the halo tail)

PHYSICAL REVIEW C **104**, 024618 (2021)Opening angle and dineutron correlations in knockout reactions  
with Borromean two-neutron halo nucleiJ. Casal \* and M. Gómez-Ramos †

- Theory adapted from [Kikuchi *et al.*, PTEP **2016**(2016)103D03]  
⇒ eikonal sudden approximation
- Need three-body wave function for the Borromean projectile

hyperspherical formalism for  $\Phi_{\text{g.s.}}^{j\mu}(\mathbf{x}, \mathbf{y})$ *Zhukov et al.*, Phys. Rep. 231, 151 (1993)*Casal et al.*, PRC 88, 014327 (2013)

- (1): core +  $n$  state not distorted by the proton; (2): contact  $V_{pn}$

$$\mathcal{T} \propto \langle \phi_{\text{c-n}}(\mathbf{k}_x, \mathbf{x}) e^{i \mathbf{k}_y \cdot \mathbf{y}} | S(y) \Phi_{\text{g.s.}}^{j\mu}(\mathbf{x}, \mathbf{y}) \rangle = \tilde{\Phi}^{j\mu}(\mathbf{k}_x, \mathbf{k}_y)$$

$$\tilde{\Phi}^{j\mu} = \sum_{\eta} \omega_{\eta}(k_x, k_y) |\eta; j\rangle \quad |\eta; j\rangle = |l_x, j_x, I_c, j_2, l_y, j_1; j\rangle$$

$$\omega_{\eta}(k_x, k_y) = (4\pi)^2 \frac{i^{-l_x - l_y}}{k_x} \int dy \underbrace{\psi_{\eta}(k_x, y)}_{\langle 2b|3b \rangle \text{ structure overlaps!!}} j_{l_y}(k_y y) S(y) y$$

$S(y)$ : eikonal  $S$ -matrix

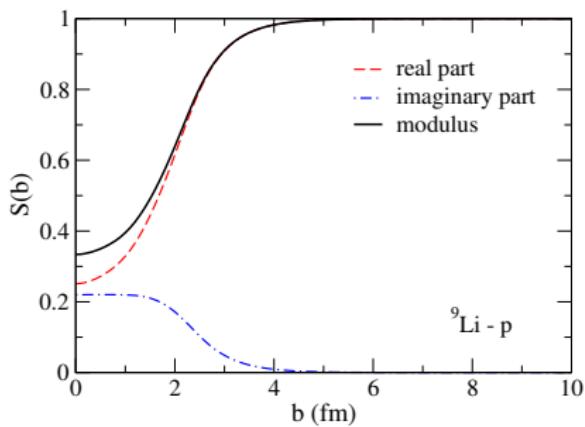
**Differential cross sections**  $(k_x, k_y, \theta)$ :

$$\begin{aligned} \sigma(k_x, k_y, \theta) \propto \sum_{\mu} \int \tilde{\Phi}^* \tilde{\Phi} &= \sum_{\eta\eta'} \omega_{\eta}(k_x, k_y) \omega_{\eta'}(k_x, k_y) C_{\eta\eta'} \delta_{I_c, I'_c} \\ &\times \sum_L D_{\eta\eta'}^L \begin{pmatrix} l_y & l'_y & L \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l_x & l'_x & L \\ 0 & 0 & 0 \end{pmatrix} P_L(\cos \theta) \end{aligned}$$

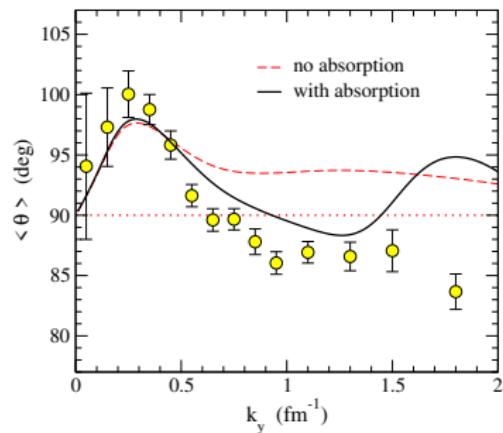
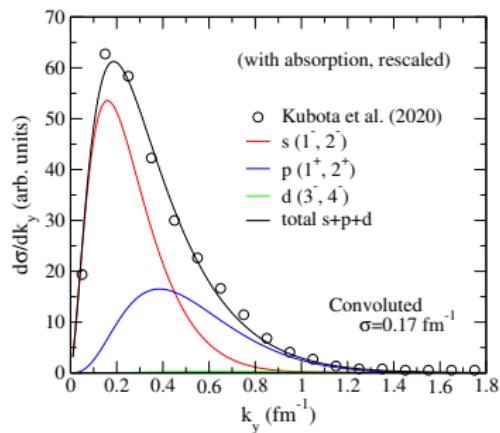
- Distributions in  $\cos \theta$  will be asymmetric only if  $\Phi_{\text{g.s.}}^{j\mu}$  contains different-parity core +  $n$  components.

## Absorption

- estimated via  $S(b) = \exp \left[ \frac{1}{i\hbar v} \int dz V(b, z) \right] = |S| e^{i\varphi}$
- Optical  $p$ -core potential  $V(b, z) = U + iW$   
 $N, M$  to scale real ( $V$ ) and imaginary ( $W$ ) parts:  $S(b) = |S|^M e^{i\varphi N}$



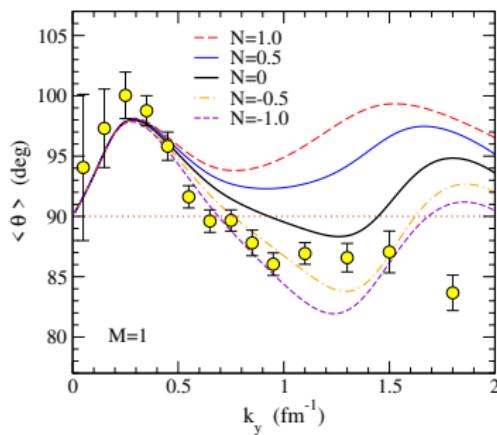
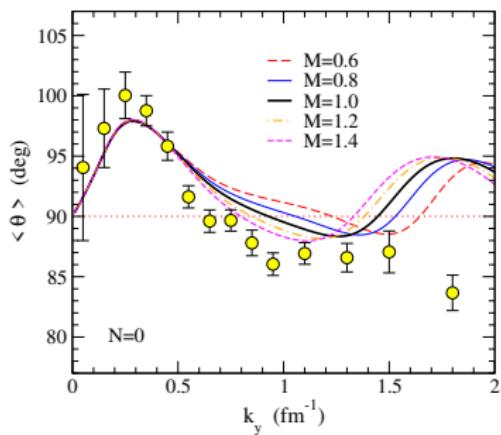
## $^{11}\text{Li}$ : Comparison with Kubota's data and $\langle\theta\rangle$ - $k_y$ correlations



- peak in the correlation plot  $\theta > \pi/2 \Rightarrow$  dineutron
- reasonable agreement with the data at small intrinsic momenta
- large intrinsic momenta **strongly sensitive to absorption**

J.C., M. Gómez-Ramos, PRC 104, 024618 (2021)

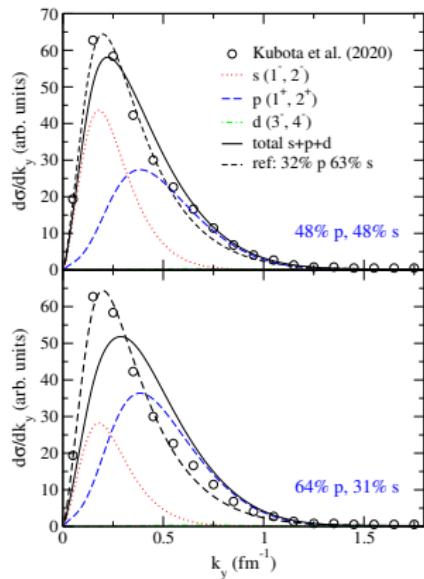
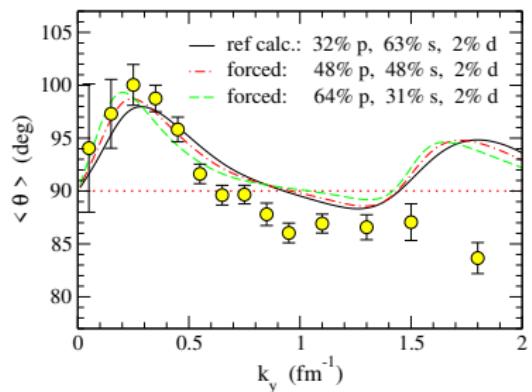
## Sensitivity to absorption (scaling $V = N^*U + iM^*W$ )



- high- $k_y$  (interior) heavily affected by absorption and distortion
- low- $k_y$  (surface) is very robust to changes in the reaction potential

J.C., M. Gómez-Ramos, PRC 104, 024618 (2021)

## Sensitivity to s.p. weights (rescaling structure overlaps)



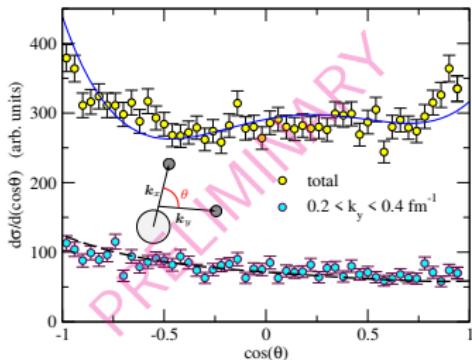
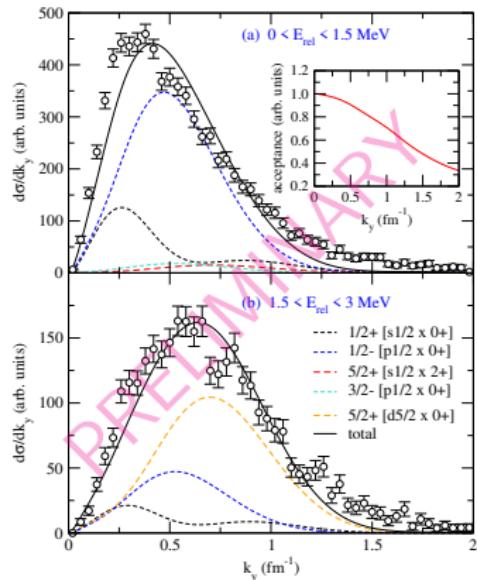
➤ moderate sensitivity to specific  $2s_{1/2}, 1p_{1/2}, 1d_{5/2}$  weights

... BUT momentum distributions not so well described

J.C., M. Gómez-Ramos, PRC 104, 024618 (2021)

# Intrinsic momentum and opening angle distributions for $^{14}\text{Be}$

$$(E_{\text{rel}} = E_{12\text{Be}-n})$$

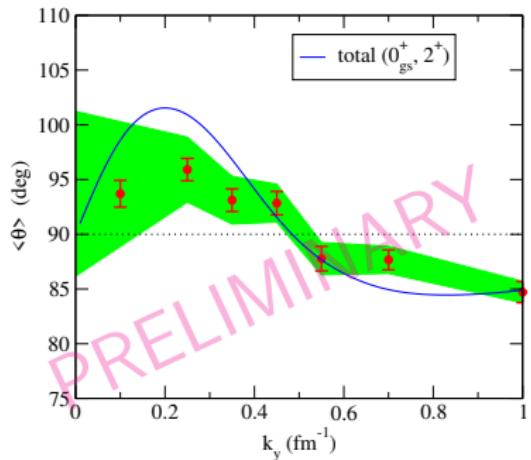


Asymmetry is not so evident in a  $k$ -inclusive measurement!

- rather good agreement with data for both observables
- small discrepancies might be due to missing components

[A. Corsi, Y. Kubota, J.C. et al., submitted]

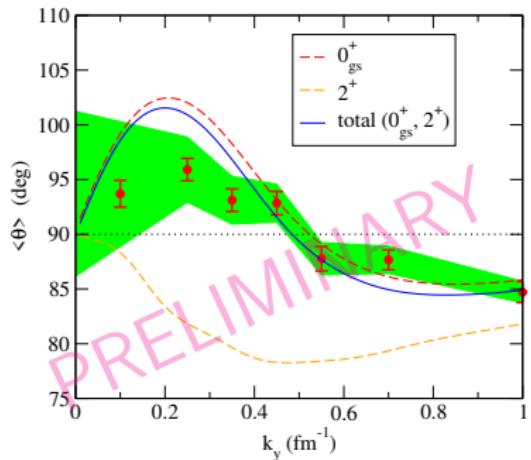
## Effect of core excitations for $^{14}\text{Be}$ correlations



➤ “raw” calculations overestimate the data

[A. Corsi, Y. Kubota, J.C. et al., submitted]

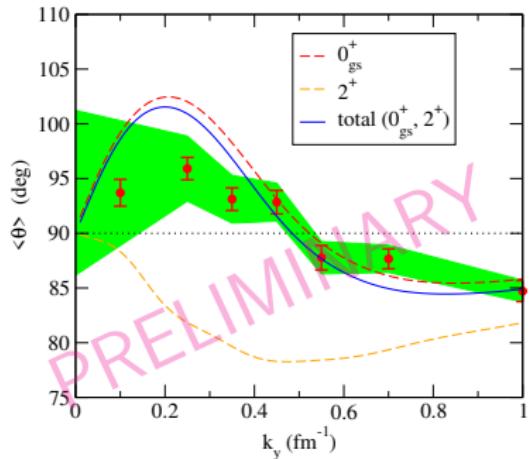
## Effect of core excitations for $^{14}\text{Be}$ correlations



- “raw” calculations overestimate the data
- core excitation ( $2^+$ ) gives “negative” correlations

[A. Corsi, Y. Kubota, J.C. et al., submitted]

## Effect of core excitations for $^{14}\text{Be}$ correlations

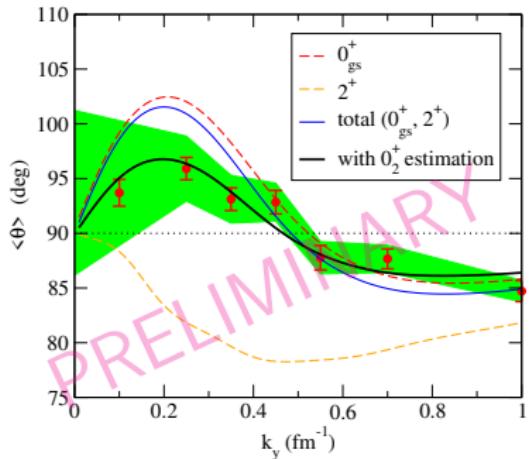


- “raw” calculations overestimate the data
- core excitation ( $2^+$ ) gives “negative” correlations

➤ estimation of the  $^{12}\text{Be}(0_2^+)$  isomer contribution ??  
Orthogonal partner of the  $^{12}\text{Be}(0_{\text{g.s.}}^+)$  (mixing with opposite sign)  
[A. O. Macchiavelli et al., Phys. Rev. C 97, 011302 (2018)]

[A. Corsi, Y. Kubota, J.C. et al., submitted]

## Effect of core excitations for $^{14}\text{Be}$ correlations



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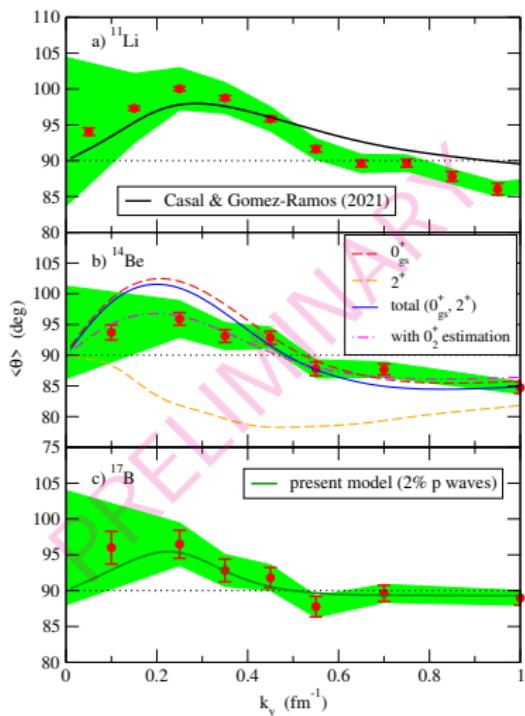
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Orthogonal partner of the  $^{12}\text{Be}(0_{\text{g.s.}}^+)$  (mixing with opposite sign)

[A. O. Macchiavelli et al., Phys. Rev. C 97, 011302 (2018)]

With  $P(0_2^+) \approx 16\%$  ⇒ good agreement with data

[A. Corsi, Y. Kubota, J.C. et al., submitted]

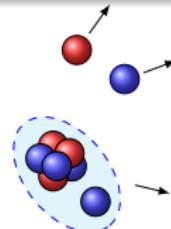


## Comparison $^{11}\text{Li}$ , $^{14}\text{Be}$ , $^{17}\text{B}$ and calculations

- Calculations capture the data trend for all three nuclei
- Theory and exp. agree that the dineutron signal appears in the surface

$^{17}\text{B}$  3b-model: adjusted to have *s*- and *d*-wave  $^{16}\text{B}$  states  
[features observed in PRL 126 (2021) 082501]

[A. Corsi, Y. Kubota, J.C. et al., submitted]



## Summary

### ➢ Borromean two-neutron halo nuclei

Exotic systems at the dripline; dynamics of valence neutrons

**Dineutron:** spatially compact  $n$ - $n$  correlation

### ➢ Structure probed via ( $p,pN$ ) knockout reactions

Very sensitive to partial-wave content

⇒ use three-body model for the projectile and  
a sudden eikonal model for the reaction

### ➢ Opening angle and momentum distributions compared to RIKEN data

$^{11}\text{Li}$ ,  $^{14}\text{Be}$ ,  $^{17}\text{B}$ ; max in  $\langle\theta\rangle$  appears at small  $k$

Asymmetry comes from mixing between different-parity states

The core seems to play an important role, at least for  $^{14}\text{Be}$

### ➢ Results support universality of dineutron correlations at the surface of Borromean halo nuclei

**Collaborators:**

M. Gómez-Ramos, A. M. Moro (Universidad de Sevilla)

A. Corsi (CEA Saclay), Y. Kubota (RIKEN) *for the SAMURAI18 collaboration*

**Funding:**

MSCA - IF - 2020

Grant agreement 101023609



Plan Estatal 2017-2020  
I+D+i Project No.

PID2020-114687GB-I00



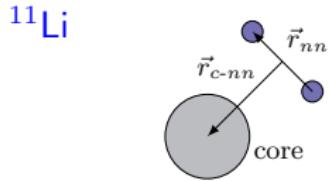
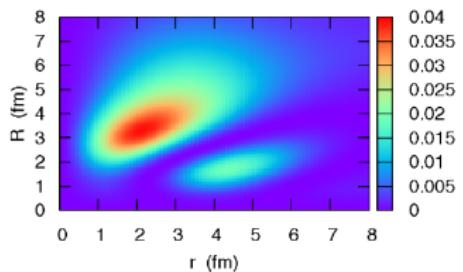
"Una manera de hacer Europa"

PAIDI P20\_01247

*M. Matsuo* (2006)

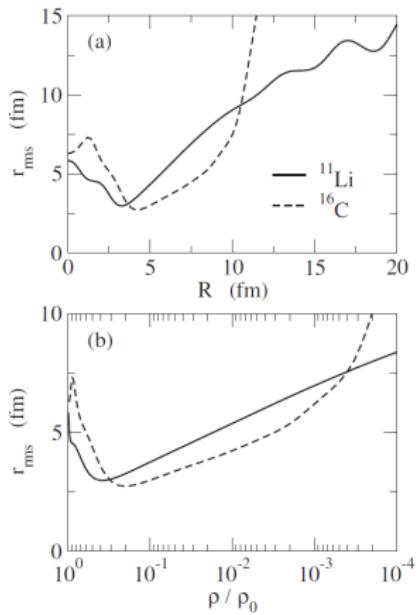
*"It is shown that the Cooper pair exhibits a strong spatial dineutron correlation over a wide range of neutron densities  $\rho/\rho_0 \approx 10^{-4} - 0.5$ "*  
Phys. Rev. C 73, 044309

*K. Hagino et al.* (2007)



Phys. Rev. Lett 99, 022506

*"... there exists such a well-pronounced radius in the surface where the Cooper pair has minimum extension and the highest probability of presence ..."*



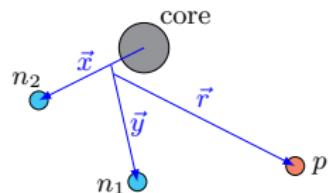
- eikonal sudden approximation  $\Rightarrow \chi_p = S(\mathbf{b})e^{i\mathbf{q}\cdot\mathbf{r}}$   
 $\mathbf{q}$ : momentum transferred to the knocked-out neutron
- (core +  $n$ ) state not distorted by the proton

$$\Psi^{3.b.(-)} = \phi_{c-n}(\mathbf{k}_x, \mathbf{x}) e^{i(\mathbf{k}_y + \mathbf{q}) \cdot \mathbf{y}}$$

- contact  $V_{pn} \Rightarrow S(\mathbf{b}) = S(\mathbf{b}_y)$  and approximate  $S(\mathbf{b}_y) \approx S(y)$

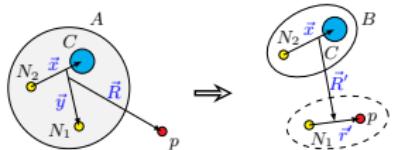
$$\mathcal{T} \propto \langle \phi_{c-n}(\mathbf{k}_x, \mathbf{x}) e^{i\mathbf{k}_y \cdot \mathbf{y}} | S(y) \Phi_{g.s.}^{j\mu}(\mathbf{x}, \mathbf{y}) \rangle = \tilde{\Phi}^{j\mu}(\mathbf{k}_x, \mathbf{k}_y)$$

$\Phi_{g.s.}^{j\mu}$ : gs WF of the core+ $n+n$  projectile  
 $\{\mathbf{x}, \mathbf{y}\}$ : Jacobi coordinates



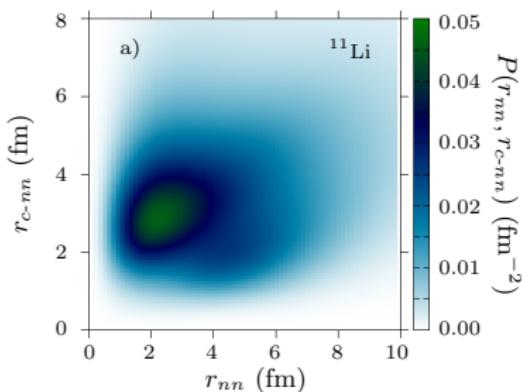
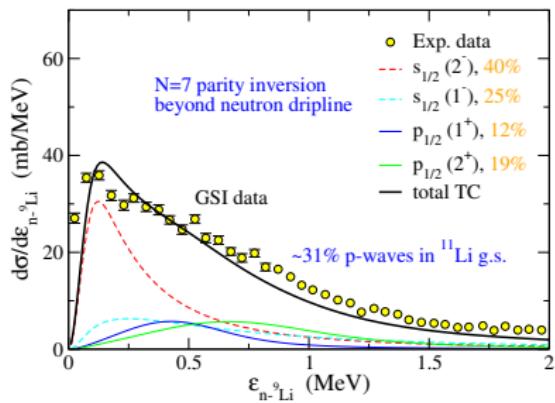
► “distorted” Fourier transform of the projectile g.s.

Previous work: Transfer to the Continuum (TC) for  $(p, pn)$   
 [M. Gómez-Ramos, J.C., A. M. Moro, PLB 772, 115 (2017)]



- Participant/Spectator approach
- Structure contained in 3b/2b overlaps

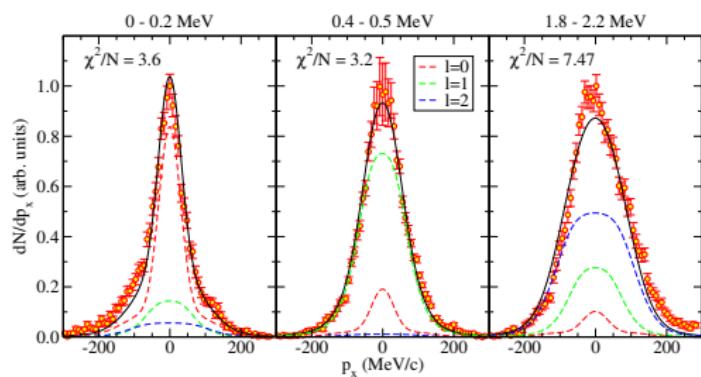
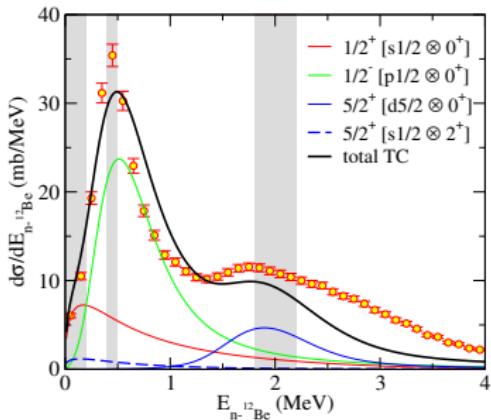
Applied to  $^{11}\text{Li}$ :  $3/2^-$  g.s.  
 ⇒ populate unbound  $^{10}\text{Li}$  states



3-body wf predicts dineutron conf.

Previous results for  $^{14}\text{Be}(p, pn)$ . Also TC

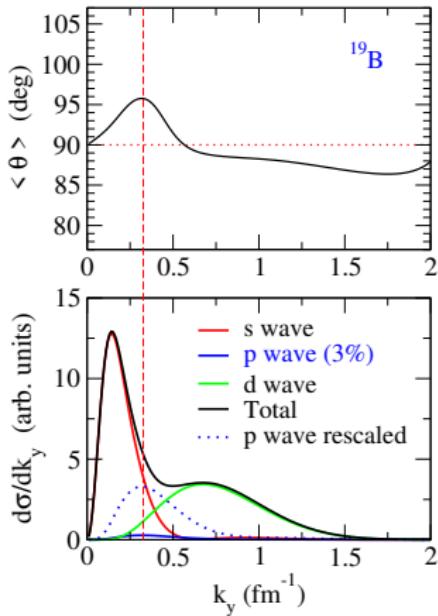
➢ populate  $^{13}\text{Be}$ . Relative-energy spectrum and momentum distributions  
[A. Corsi, Y. Kubota, J.C. et al., PLB 797, 134843 (2019)] RIKEN



- spectrum dominated by  $p$ -wave resonance
- significant mixing with  $s$ - and  $d$ -waves ⇒ asymmetry / dineutron!!
- model includes core excitation to the  $^{12}\text{Be}(2_1^+)$  state ( $\sim 20\%$  weight)

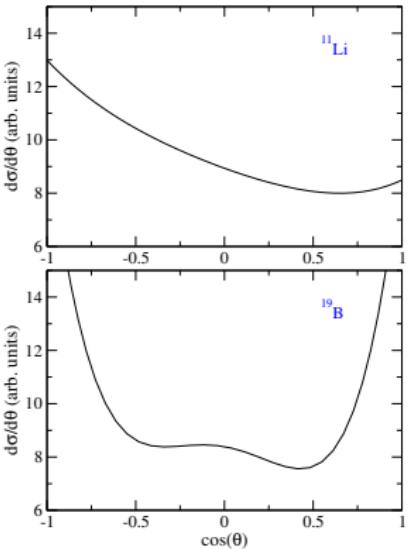
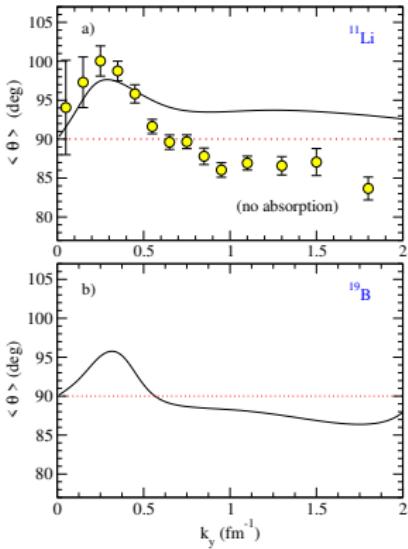
Correlation appears even for very small mixing!

E.g.:  $^{19}\text{B}$  (53%  $s_{1/2}$ , 39%  $d_{5/2}$ , 3%  $p$ -waves) [PRC 102 (2020) 051304(R)]

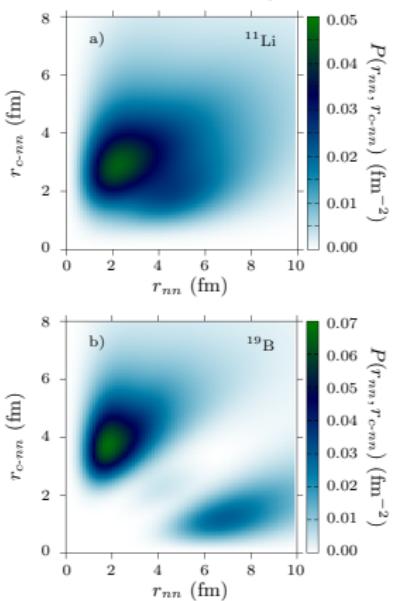


➤ It could be used to characterize small opposite-parity waves

## momentum space



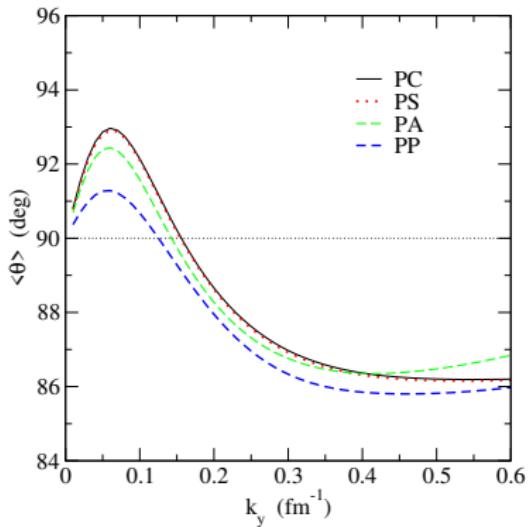
## coordinate space



- “dineutron peak” always appears in the correlation plot (peripherality)
- overall asymmetry gives a better measure of the amount of dineutron (e.g., total average  $\langle \theta \rangle$ )

## Effect of the Pauli treatment

E.g.:  ${}^6\text{He}$  ( ${}^4\text{He} + n + n$ ) [almost pure *p*-wave, small *s*-wave admixture]



PC: repulsive core  
PS: supersymmetric potential  
PA: adiabatic projection  
PP: projection operators

(see e.g., Thompson et al.  
PRC61(2000)024318)