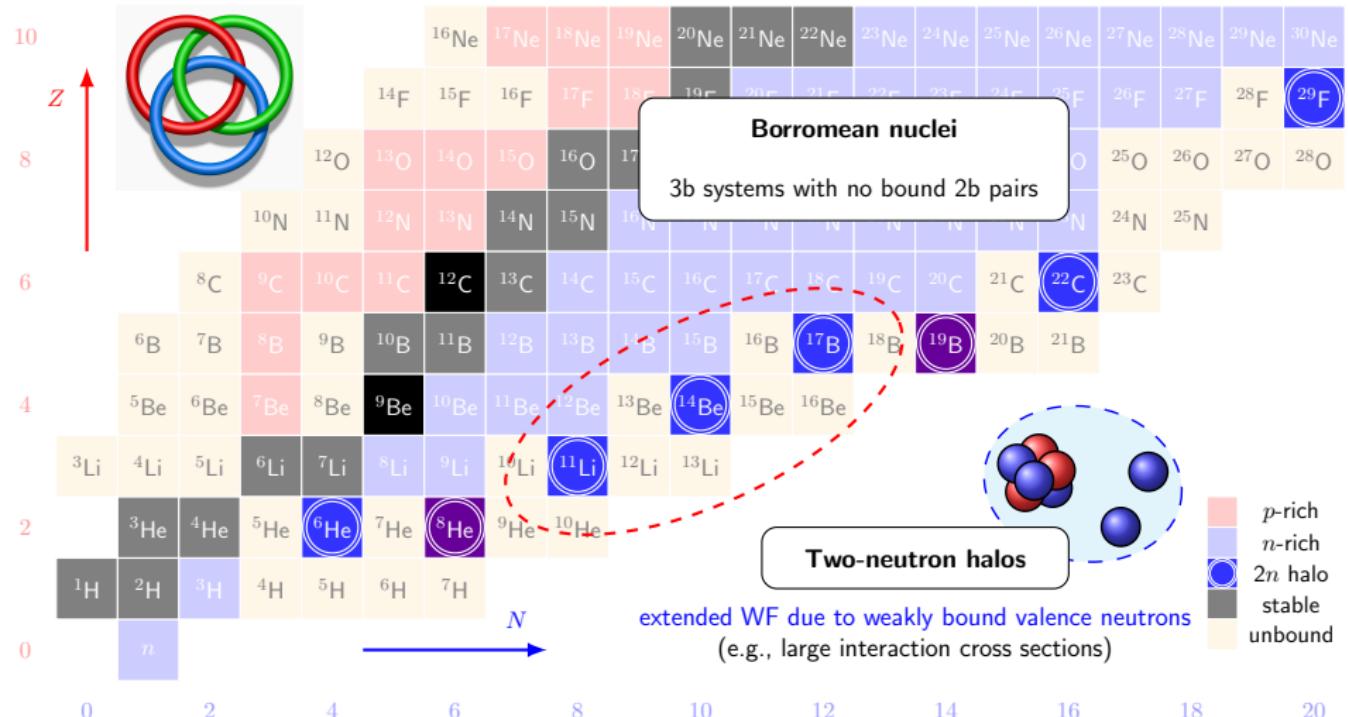


# Investigation of dineutron correlations at the surface of Borromean nuclei

**Jesús Casal**

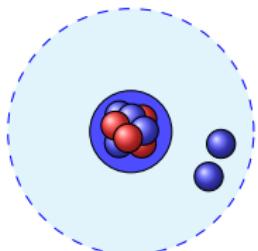
Universidad de Sevilla, Spain





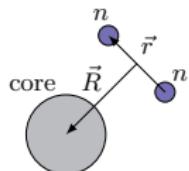
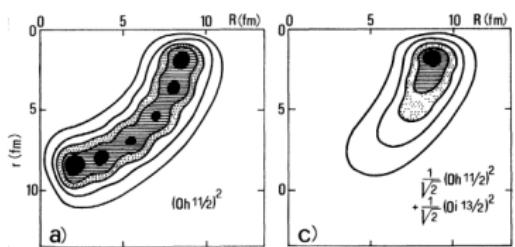
## Dineutron?

$S = 0, T = 1$   
unbound



*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)

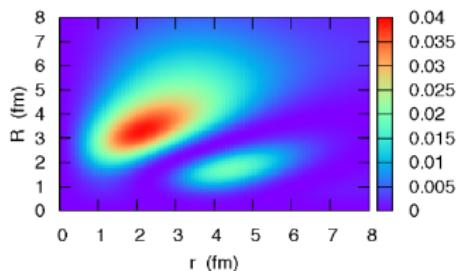
Mixing of different parities favors the dineutron localization

Phys. Rev. C 29, 1091

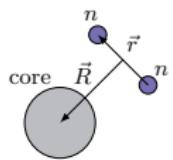
*M. Matsuo (2006)*

*"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)*

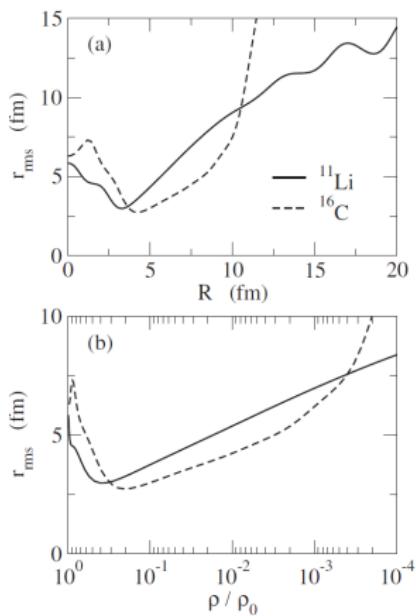


$^{11}\text{Li}$



Phys. Rev. Lett 99, 022506

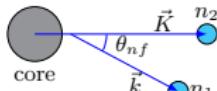
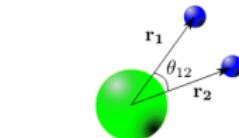
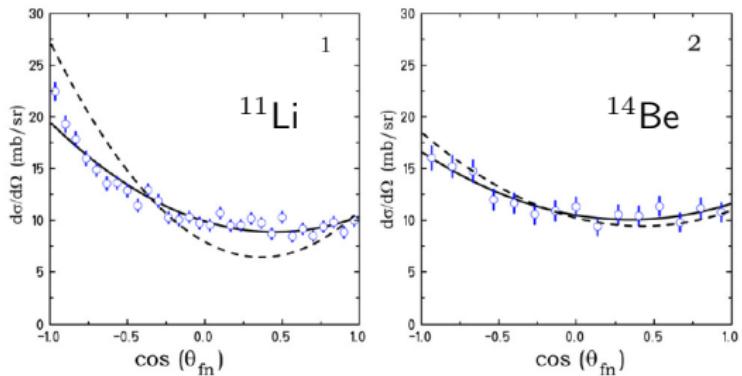
*"... there exists such a well-pronounced radius in the surface where the Cooper pair has minimum extension and the highest probability of presence . . ."*



## (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:

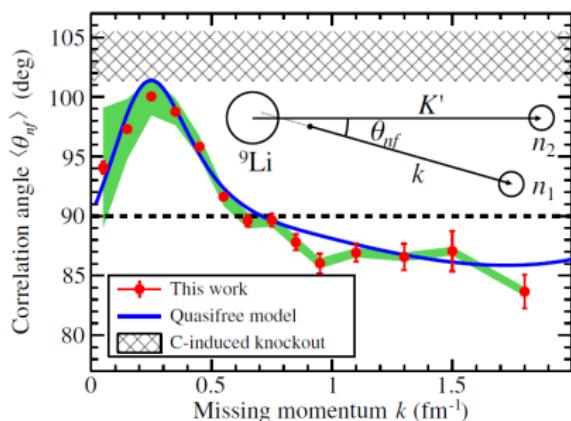
- *Y. Kubota et al.* [PRL 125, 252501 (2020)]

### 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



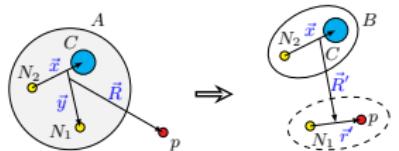
maximum at  $k \sim 0.3$  fm $^{-1}$   
(theory  $\Rightarrow r \sim 3.6$  fm)

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

... is this universal?

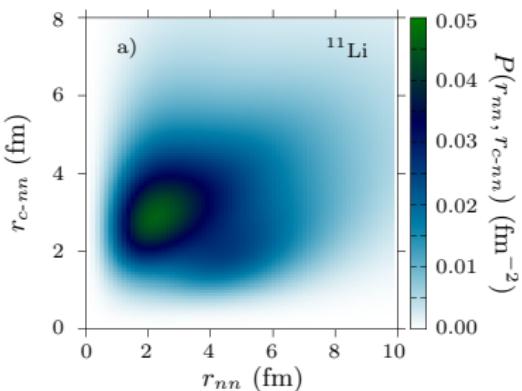
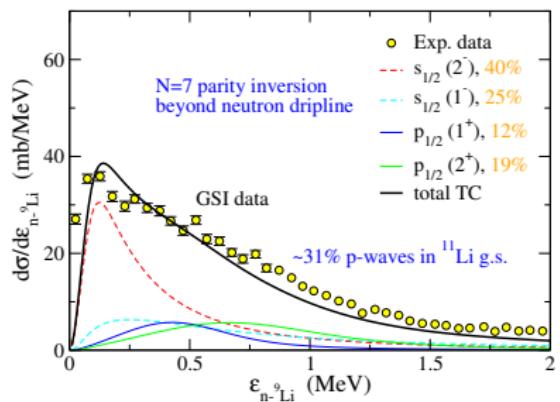
NEW RIKEN data ( $^{14}\text{Be}$ ,  $^{17}\text{B}$ )

Not for this talk, BUT: 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

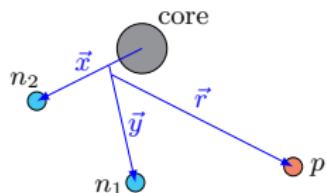
Applied to  $^{11}\text{Li}$ :  $3/2^-$  g.s.  
 ⇒ populate unbound  $^{10}\text{Li}$  states



3-body wf predicts dineutron conf.

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

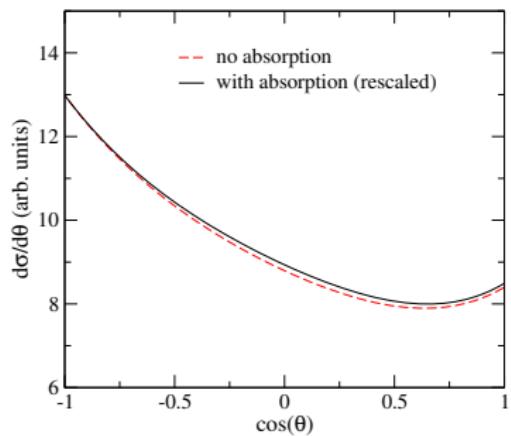
**Differential cross sections**  $(k_x, k_y, \theta)$ :

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

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

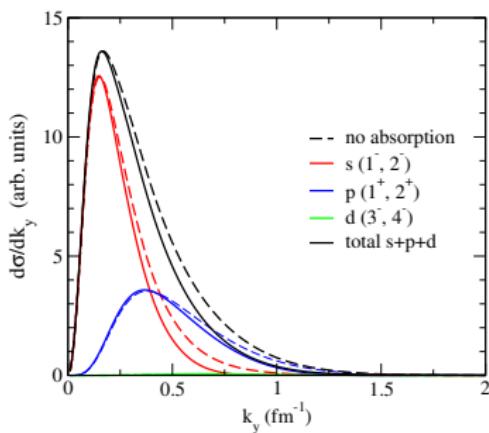
## Opening angle distribution

integrate  $k_x, k_y \rightarrow \theta$  dist.



## Intrinsic momentum distribution

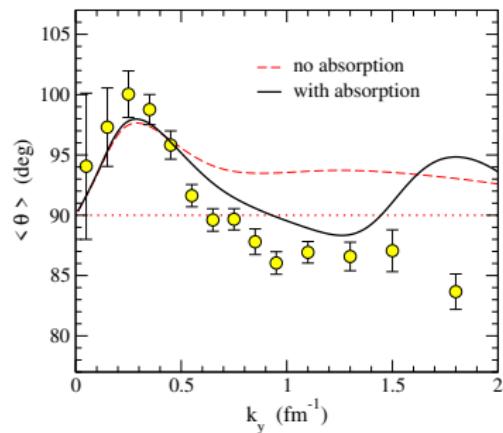
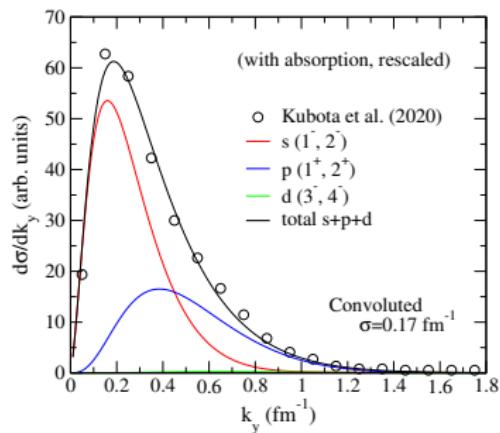
integrate  $k_x, \theta \rightarrow k_y$  dist.



- asymmetry in  $\theta$ -dist. comes from *s,p,d* mixing
- it favors  $\theta > 90$  deg. in momentum space

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

## Comparison with Kubota's data and $\langle \theta \rangle$ - $k_y$ correlations

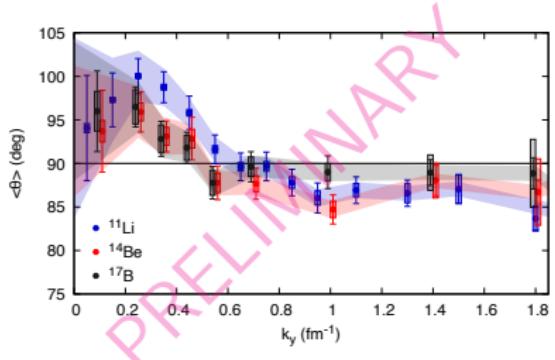


- peak in the correlation plot  $\theta > \pi/2 \Rightarrow$  dineutron
- reasonable agreement with the data at small intrinsic momenta
- large intrinsic momenta strongly sensitive to absorption

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

## NEW experimental evidence!

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



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

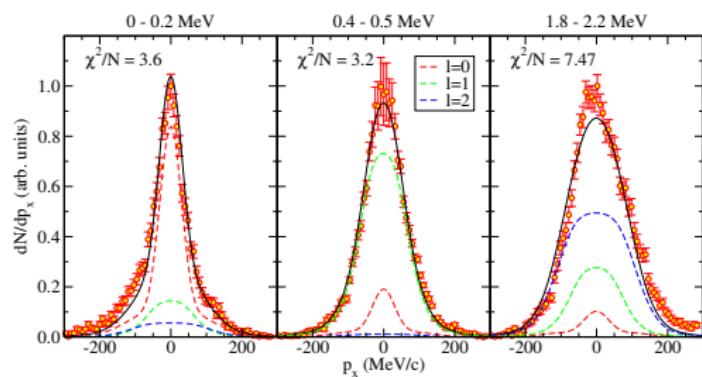
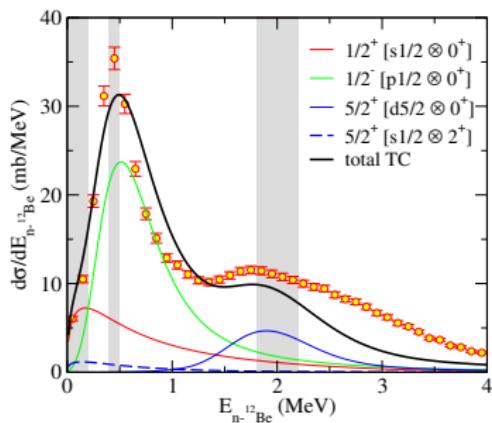
$$\Rightarrow \langle \theta \rangle_{0-0.4 \text{ fm}^{-1}} = 97.0(2) [^{11}\text{Li}], 93.8(5) [^{14}\text{Be}], 93.6(9) [^{17}\text{B}] \text{ degrees}$$

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]

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

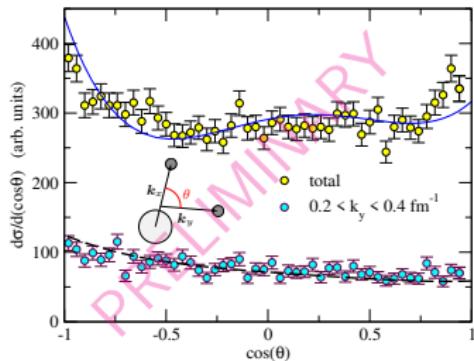
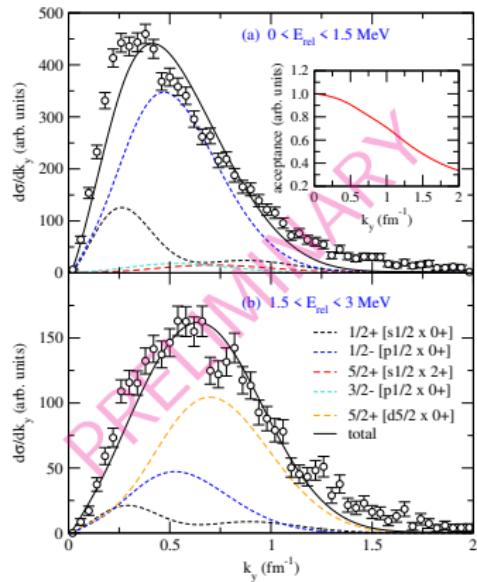
➢ populate  $^{13}\text{Be}$ . Relative-energy spectrum and momentum distributions  
 [A. Corsi, Y. Kubota, J.C. et al., PLB 797, 134843 (2019)] RIKEN



- 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)

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

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

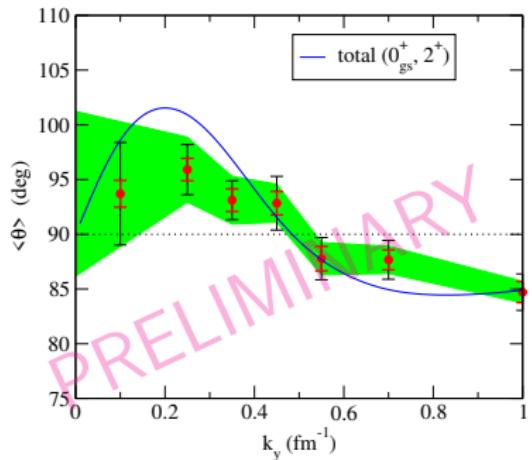


Asymmetry is not so evident in a  $k$ -inclusive measurement!

- 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]

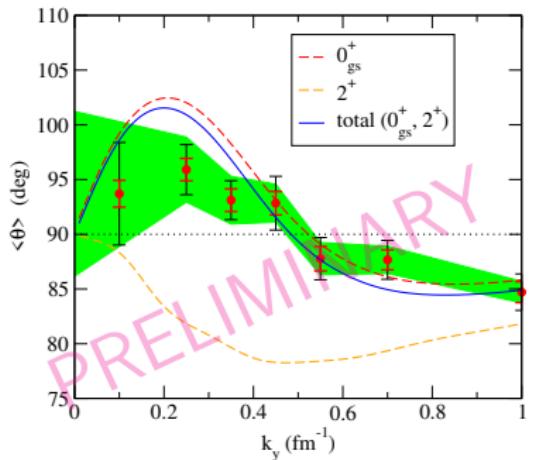
## Effect of core excitations for $^{14}\text{Be}$ correlations



➤ “raw” calculations overestimate the data

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

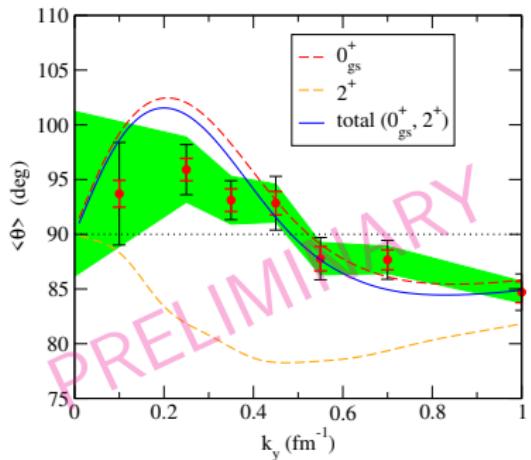
## Effect of core excitations for $^{14}\text{Be}$ correlations



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

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

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

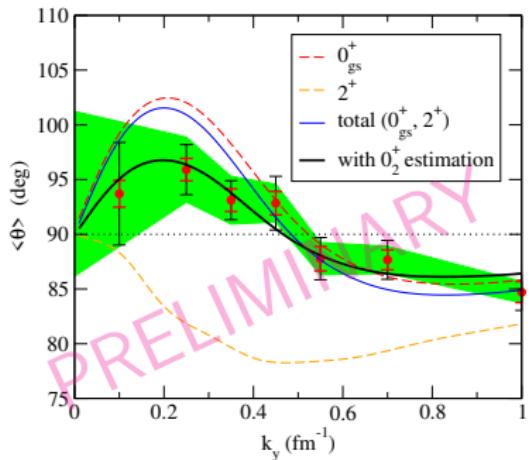


- “raw” calculations overestimate the data
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➤ estimation of the  $^{12}\text{Be}(0_2^+)$  isomer contribution ??  
 Orthogonal partner of the  $^{12}\text{Be}(0_{\text{g.s.}}^+)$  (mixing with opposite sign)  
 [A. O. Macchiavelli et al., Phys. Rev.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

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

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



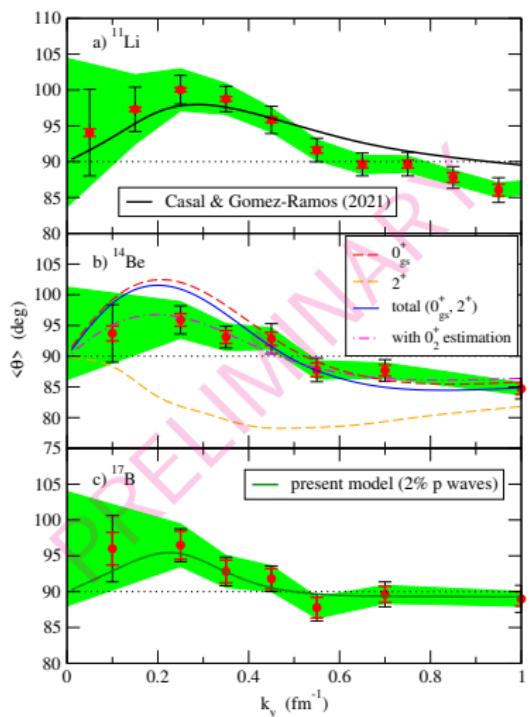
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 [A. O. Macchiavelli et al., Phys. Rev. C 97, 011302 (2018)]

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

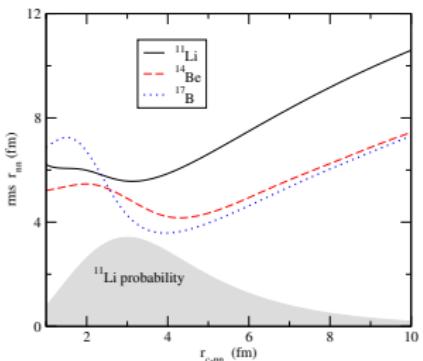
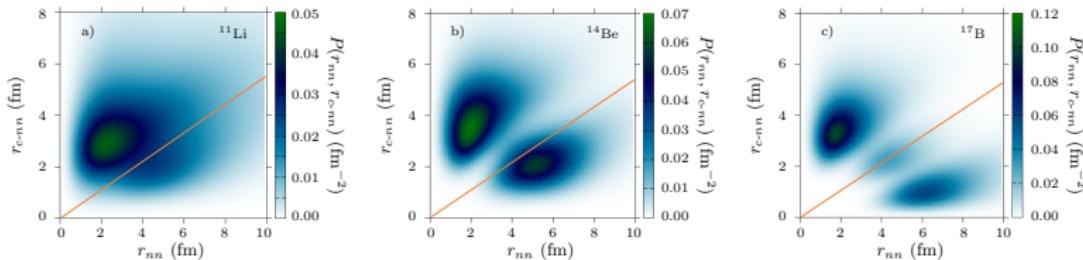
- Calculations capture the data trend for all three nuclei
- Theory and exp. agree that the dineutron signal appears in the surface\*

(even with small mixing;  $^{17}\text{B}$   
 ⇒ PRC104(2021)024618)

$^{17}\text{B}$  3b-model: adjusted to have  $s$ - and  $d$ -wave  $^{16}\text{B}$  states  
 (talk by Z. Yang tuesday morning)

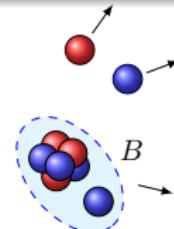
[A. Corsi, Y. Kubota, J.C. et al., submitted]

## \* Calculations in coordinate space



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)



## 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 indicate universality of dineutron correlations at the surface of Borromean halo nuclei (previously suggested by BCS and three-body calculations).

**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

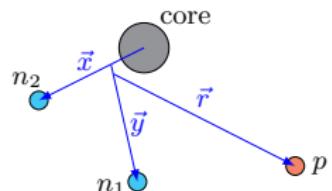
- eikonal sudden approximation  $\Rightarrow \chi_p = S(\mathbf{b})e^{i\mathbf{q}\cdot\mathbf{r}}$   
 $\mathbf{q}$ : momentum transferred to the knocked-out neutron
- (core +  $n$ ) state not distorted by the proton

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

- 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.

## 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  $V(b, z) = U + iW$   
Use  $N, M$  to scale real ( $V$ ) and imaginary ( $W$ ) parts, respectively:

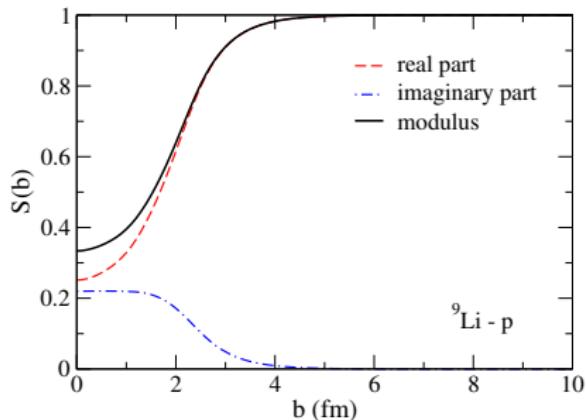
$$S(b) = |S|^M e^{i\varphi N}$$

If only  $W$  is considered ( $N = 0, M = 1$ ), the  $S$ -matrix is real

### Ingredients for the calculations ( $t\rho$ )

- >  ${}^9\text{Li}$  density from Hartree-Fock (code **OXBASH**)
- > Folding with effective (complex) NN interaction [Ray, PRC20(1979)1857]
- >  $S$ -matrix computed with **FrontHF** code (J. Tostevin, unpublished)

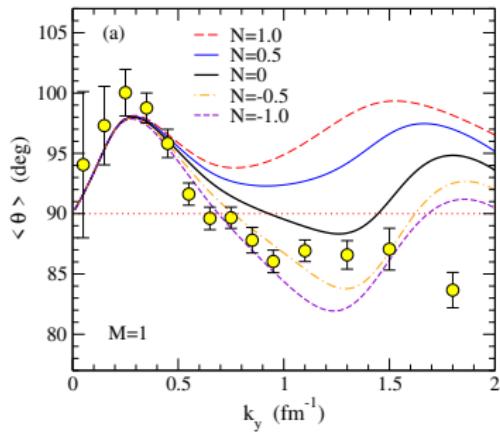
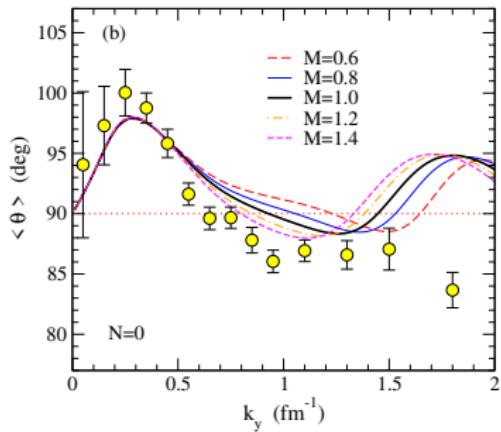
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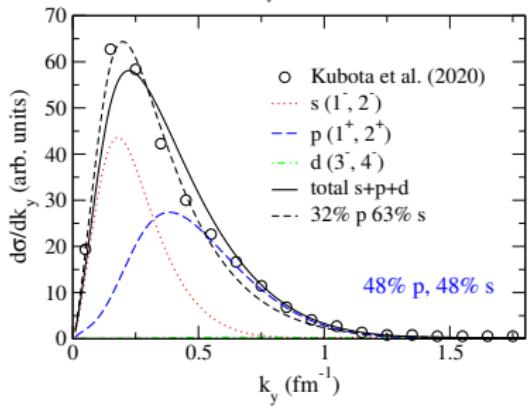
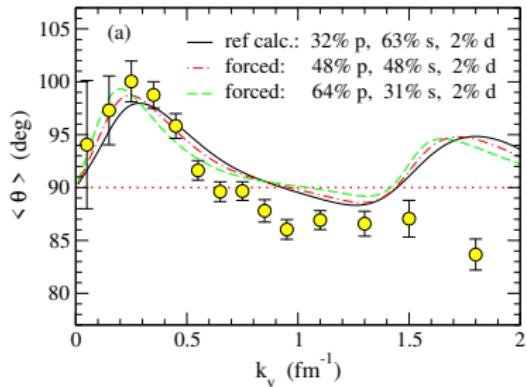
## Sensitivity to absorption (scaling $V = N^*U + iM^*W$ )



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

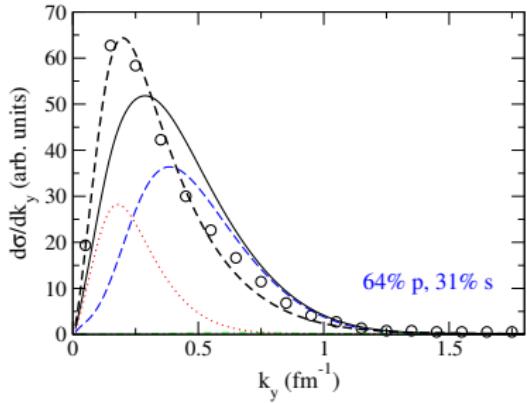
J.C., M. Gómez-Ramos, PRC 104, 024618 (2021)

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



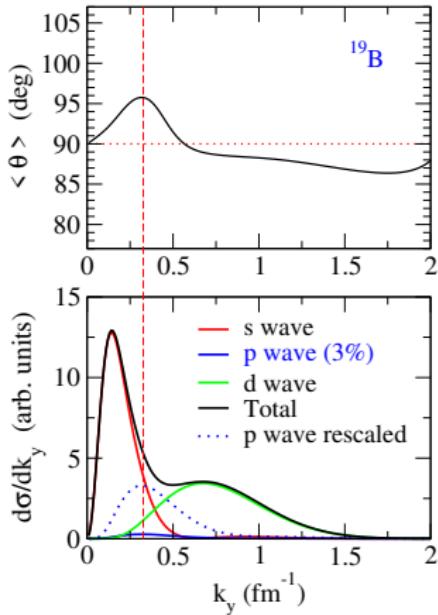
➢ moderate sensitivity to specific  $2s_{1/2}$ ,  $1p_{1/2}$ ,  $1d_{5/2}$  weights

... BUT momentum distributions not so well described



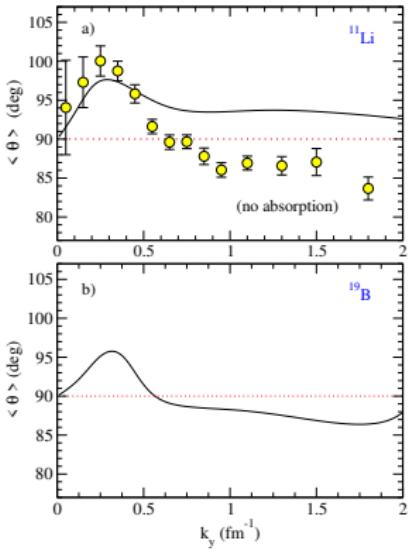
Correlation appears even for very small mixing!

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

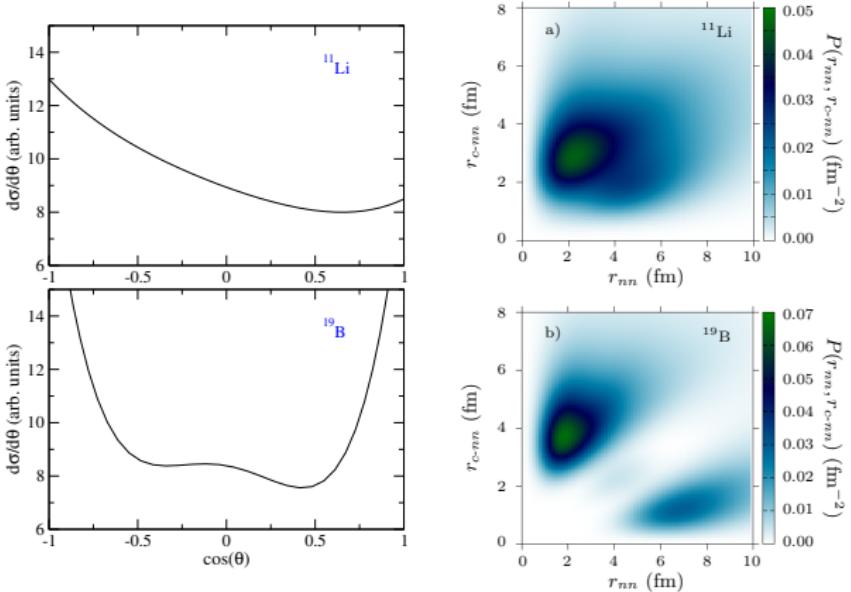


➤ It could be used to characterize small opposite-parity waves

### 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  $\langle \theta \rangle$ )