Searching for dineutron correlations in borromean halo nuclei

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Credits for the image: Ai Kubota

Borromean nuclei and dineutron correlation

Borromean nuclei= 3B system without 2B unbound subsystem

^{11}Li (^{9}Li+2n), ^{14}Be(^{12}Be+2n), ^{17}B(^{15}B+2n),…

Dineutron correlation is key to explain their binding

13C 4.94E+3	14C 8.17E+3	15C 1.21E+3	16C 4.25E+3	17C 7.33E+2	18C 4.18E+3	19C 5.76E+2	20C 2.98E+3	21C -6.80E+1	22C 1.03E+2
12B 3.36E+3	13B 4.87E+3	14B 9.69E+2	15B 2.77E+3	16B -8.30E+1	17B 1.46E+3	18B -5.00	19B 9.37E+1	20B -1.56E+3	21B -9.10E+2
11Be 5.01E+2	12Be 3.17E+3	13Be -5.10E+2	14Be 1.77E+3	15Be -1.80E+3	16Be 4.50E+2				
10Li -2.64E+1	11Li 3.95E+2	12Li -2.10E+2	13Li 1.00E+2						

S_n

number of protons

number of neutrons

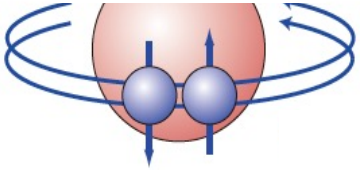
Theoretical predictions of dineutron correlation

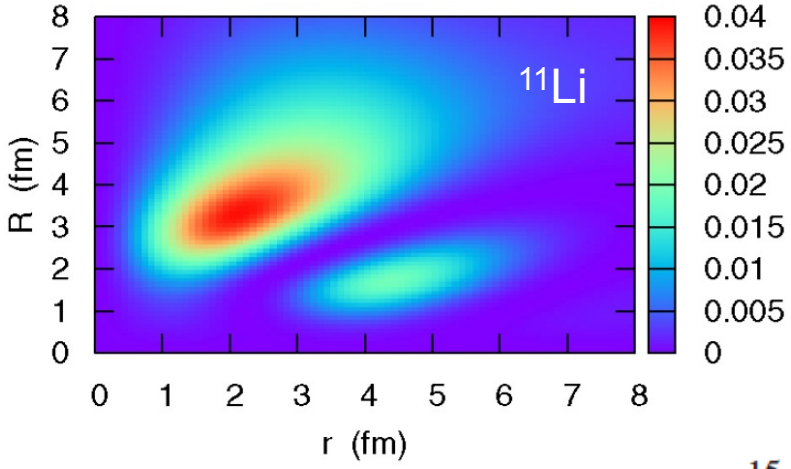
Due to pairing interaction between valence nucleons

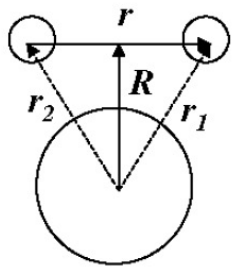
Responsible for the BEC behaviour in nuclear matter and dineutron correlation in nuclei

Matsuo, Phys. Rev. C73, 044309 (2006), Hagino et al., PRL 99, 022506 (2007)

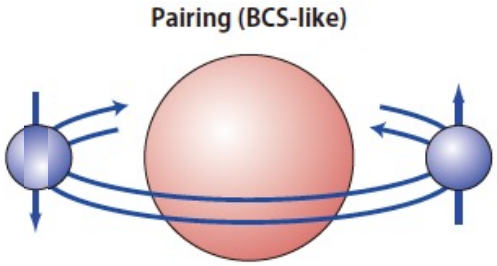
DI-NEUTRON (BEC LIKE)

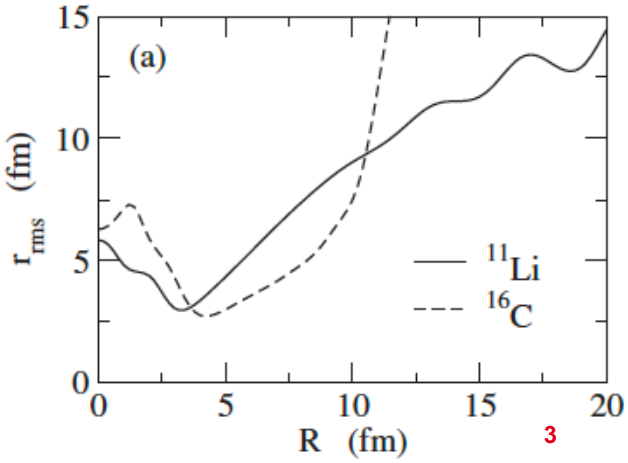






CIGAR (BCS LIKE)

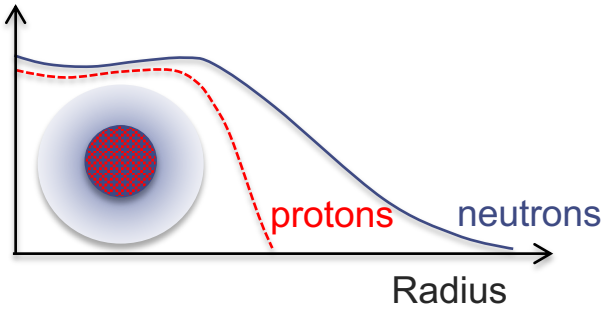


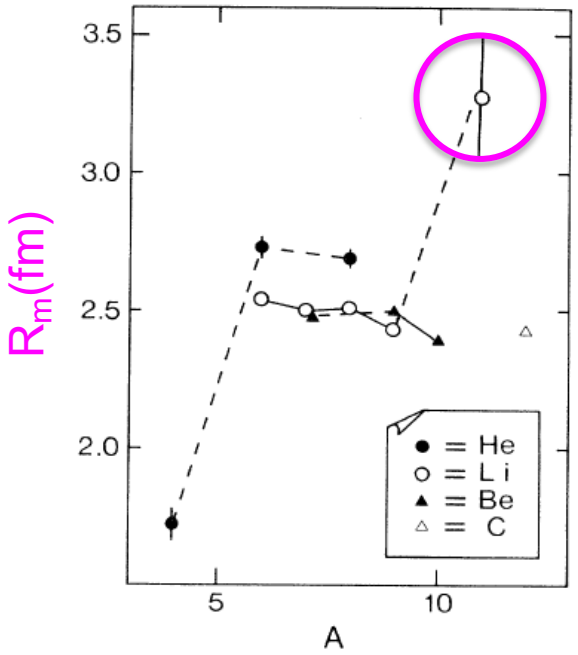


Experimental signature of dineutron correlation

- Increase of total reaction cross section ⇔ R_m: halo!

Tanihata et al., PRL 55 (1985)

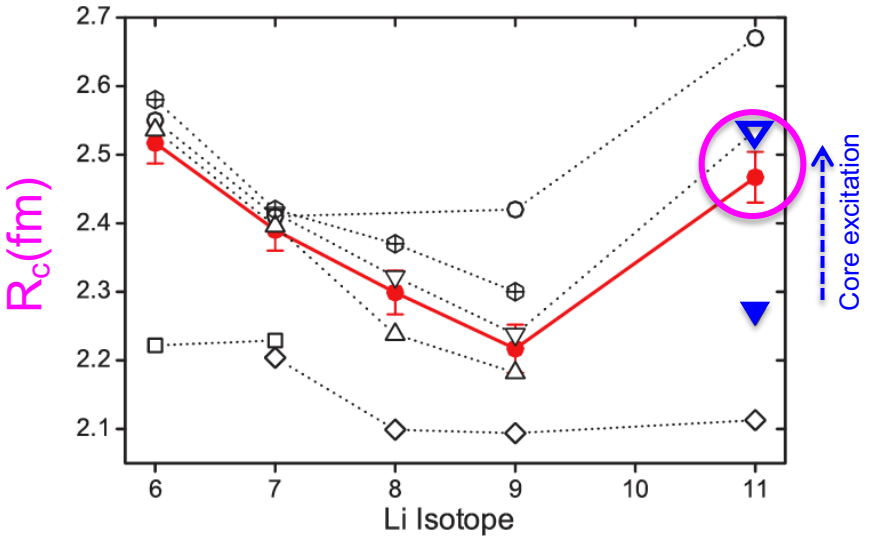




- ^{9}Li core excitation by the neutrons of the halo deduced from charge radii R_c(fm)

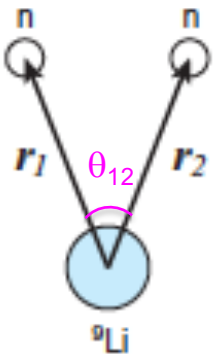
Sanchez et al, PRL 96 (2006)

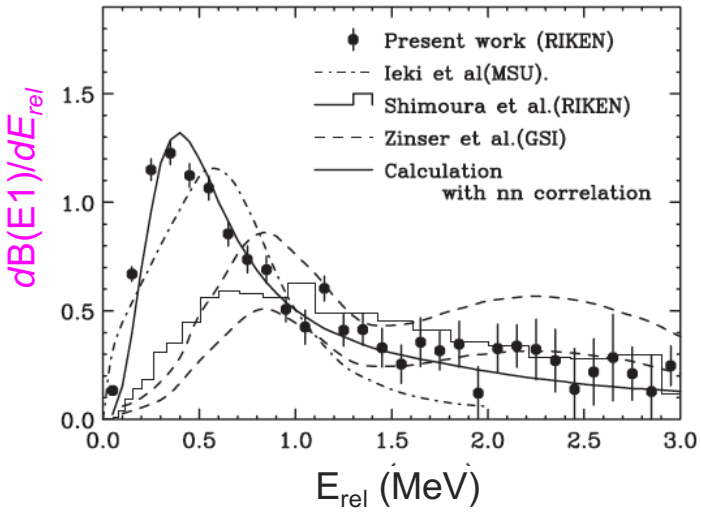
No direct information on correlations



Experimental signature of dineutron correlation

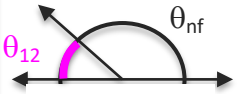
- Coulomb breakup cross section $dB(E1)/dE_{rel}$
  $B(E1) \sim \cos(\theta_{12})$
  $\Rightarrow$ $<\theta_{12}>=48^{+14}_{-18}$ degrees
  Nakamura *et al.*, PRL 96 (2006)



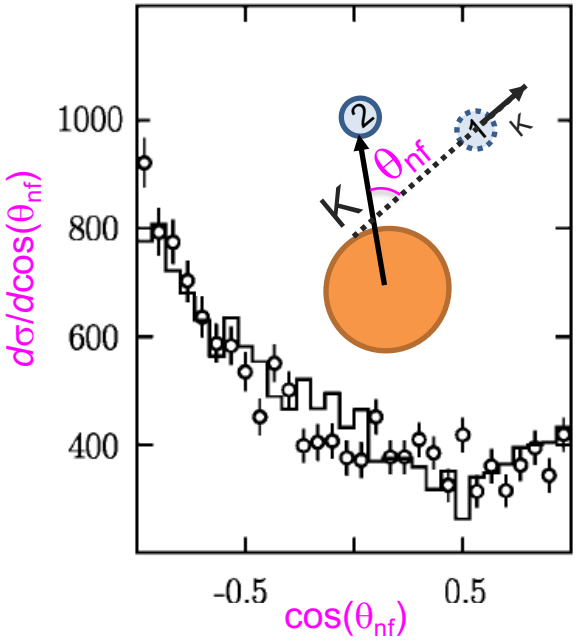


- Two-neutron transfer reactions
  Tanihata *et al.*, PRL 100 (2008)

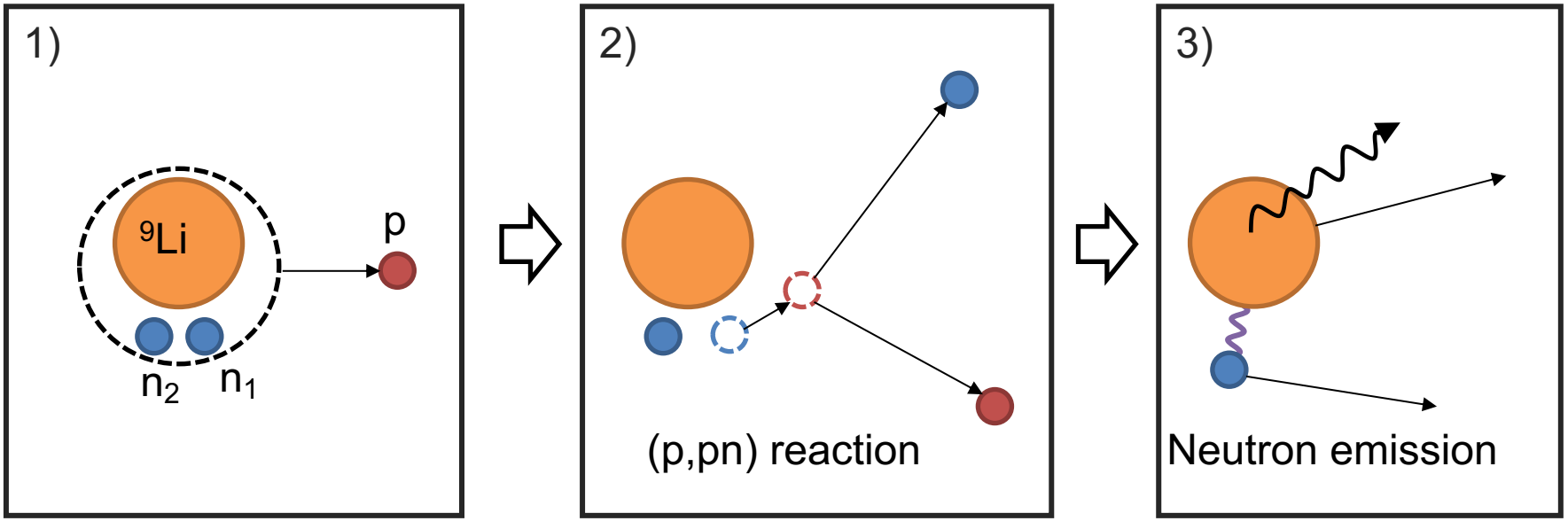
- Knockout reactions
  $\Rightarrow$ $<\theta_{nf}>=103.4(2.1)°$ degrees
  H.Simon *et al*, Phys. Rev. Lett. 83, 496 (1999); NPA 791 (2007)



- Different degree of dineutron in coulomb breakup and knockout
- No dependence on peripherality



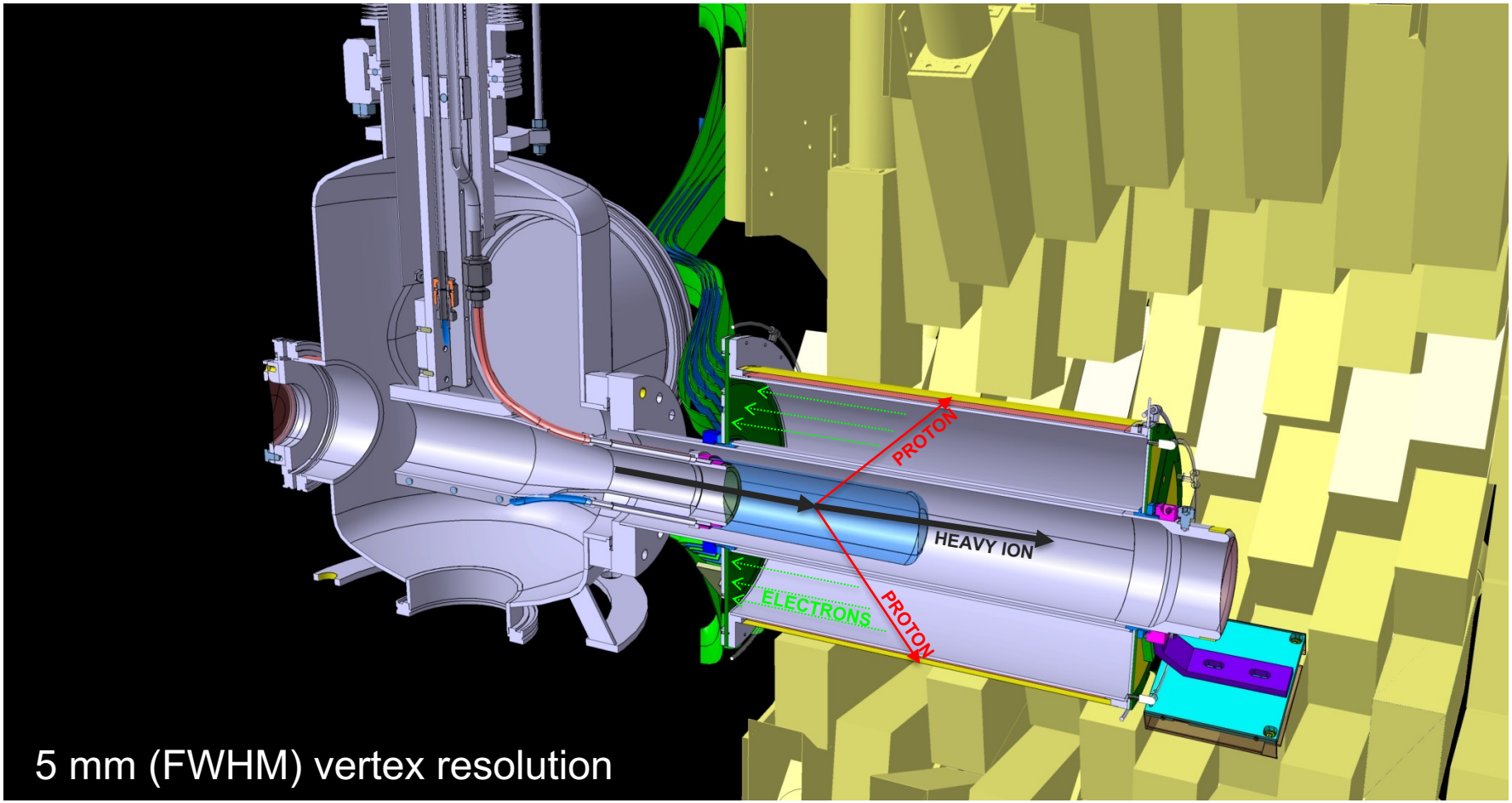
Dineutron correlation via Quasi-Free Scattering



- **QFS** on Hydrogen target ⇨ factorization of cross section via DWIA
- High momentum transfer ⇨ minimize Final State Interaction (FSI)
- **Kinematically complete** measurement
- Need high luminosity (10^5 pps ^{11}Li beam, 15-cm MINOS target)

The MINOS device

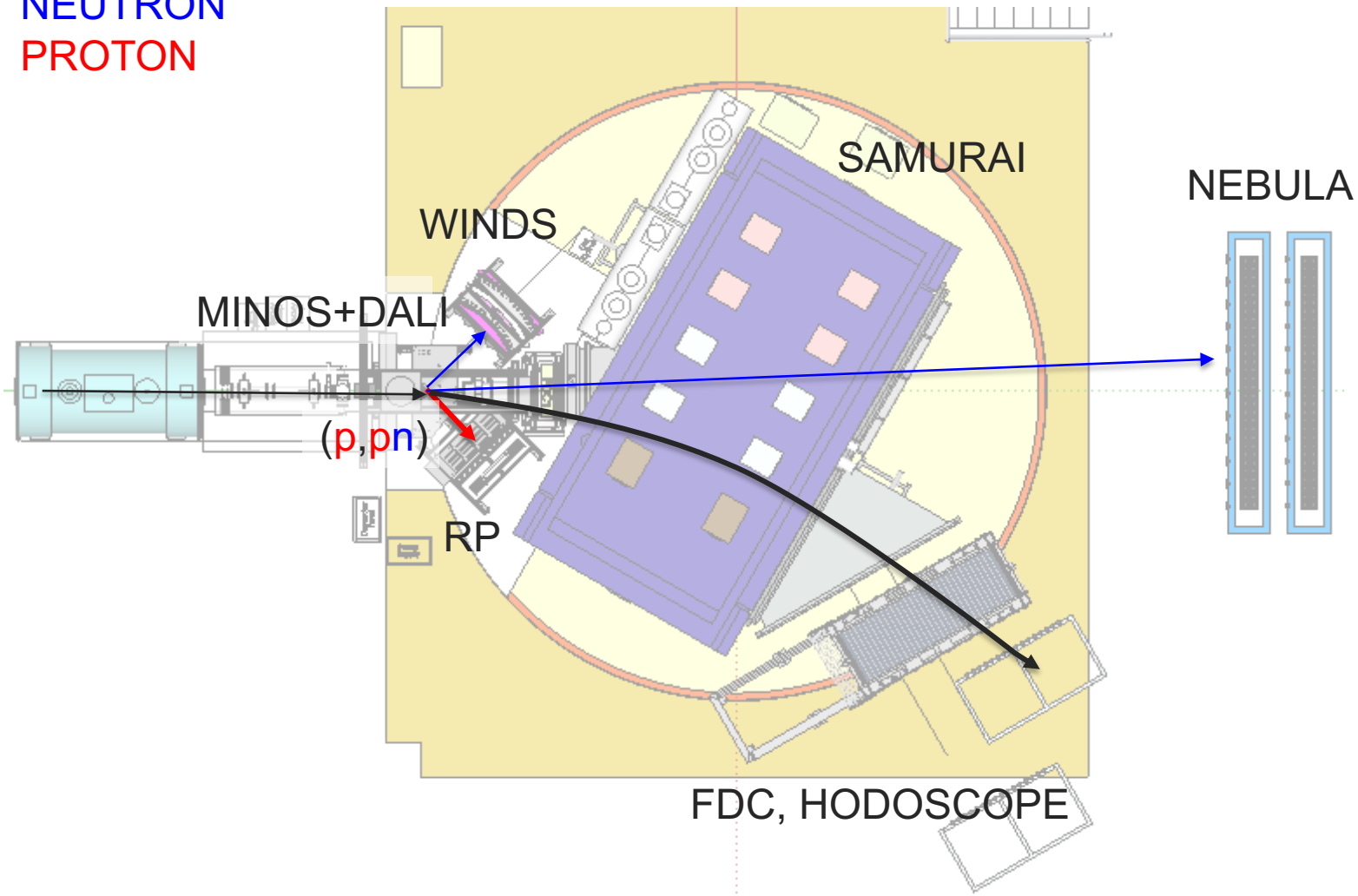
- Liquid Hydrogen Target (5-15 cm) + vertex tracker (time-projection chamber)
- Increase luminosity and preserve resolution in spectroscopy measurements



A.Obertelli, ERC Starting Grant 2010-2015
Developed at IRFU (2011-2013)
A.Obertelli et al., Eur. Phys. J. A (2014) 50

Dineutron correlation via Quasi-Free Scattering at RIBF

BEAM (^{11}Li, ^{14}Be), FRAGMENT (^{9}Li, ^{12}Be)
NEUTRON
PROTON



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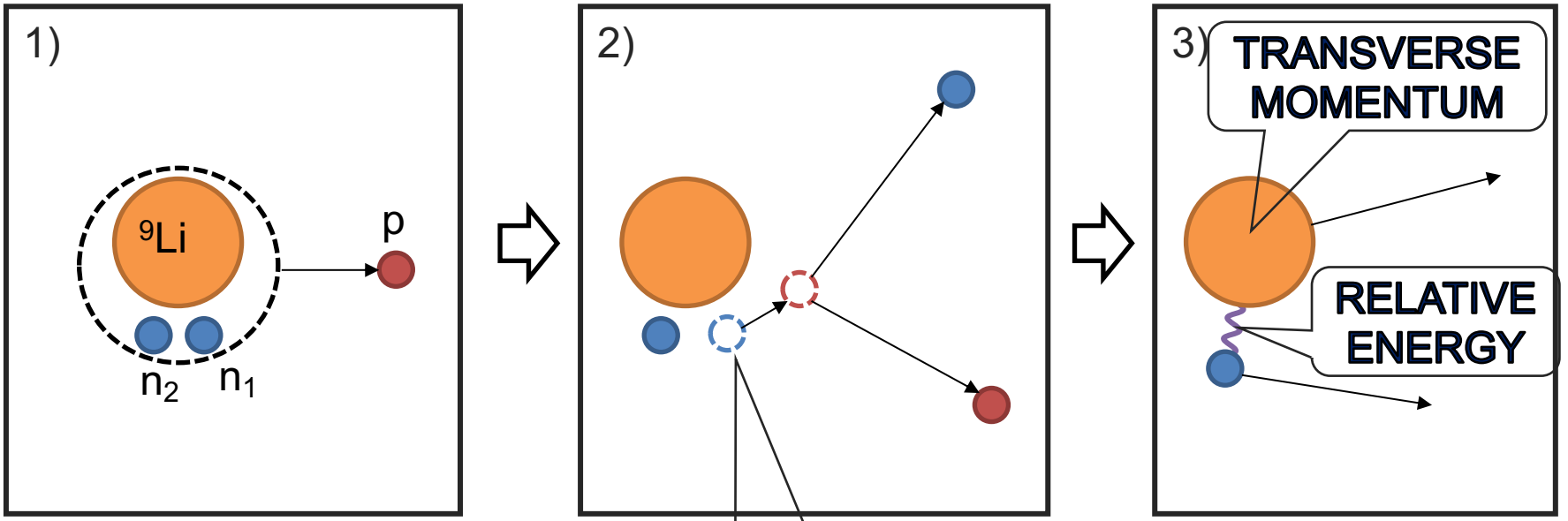
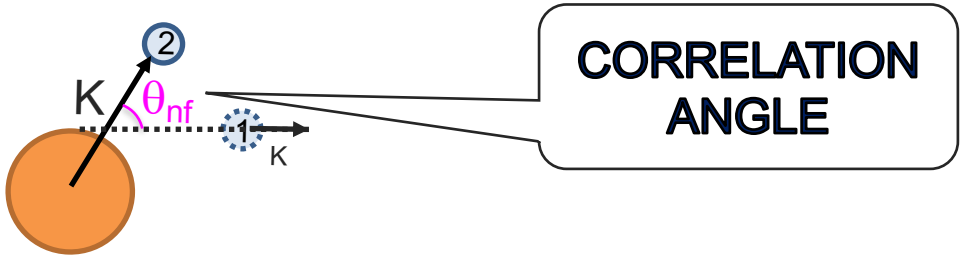
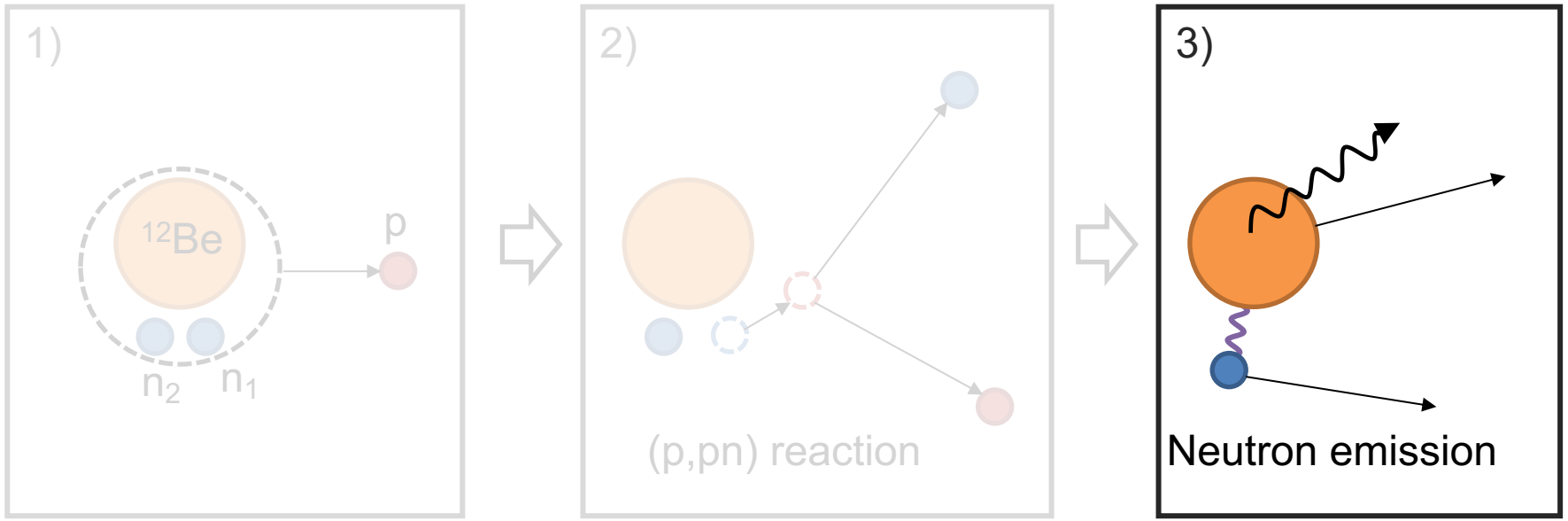
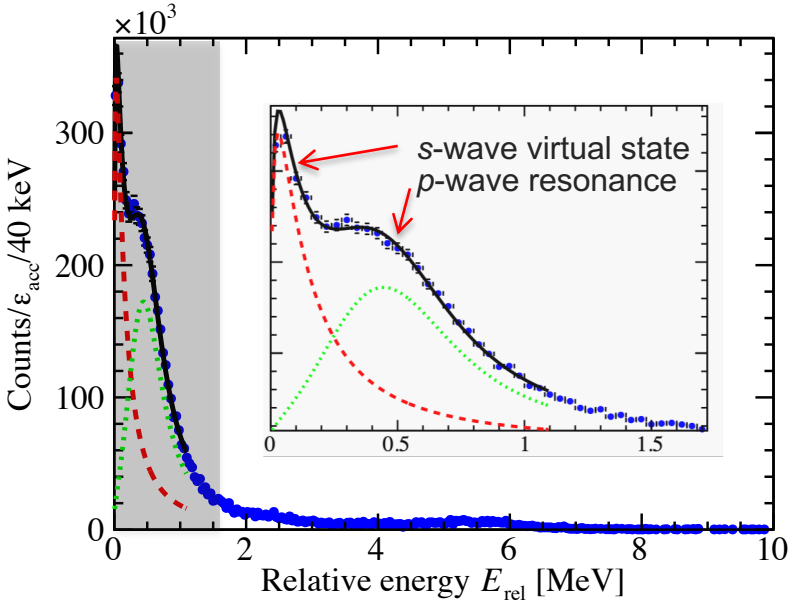


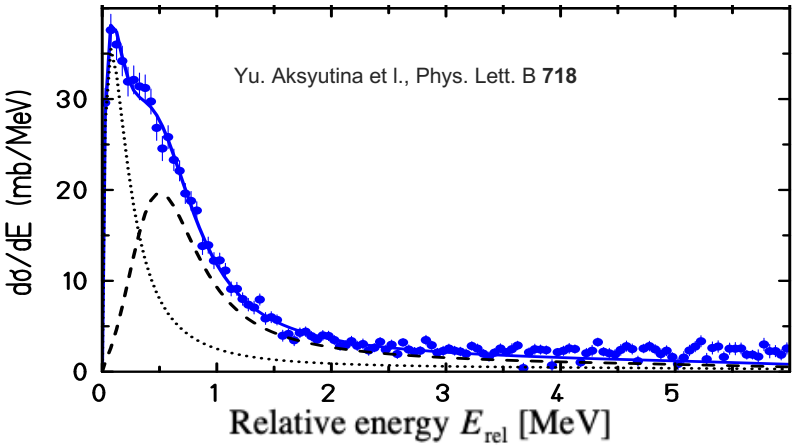


Focus on the decay of 10Li and 13Be



Structure of 10Li

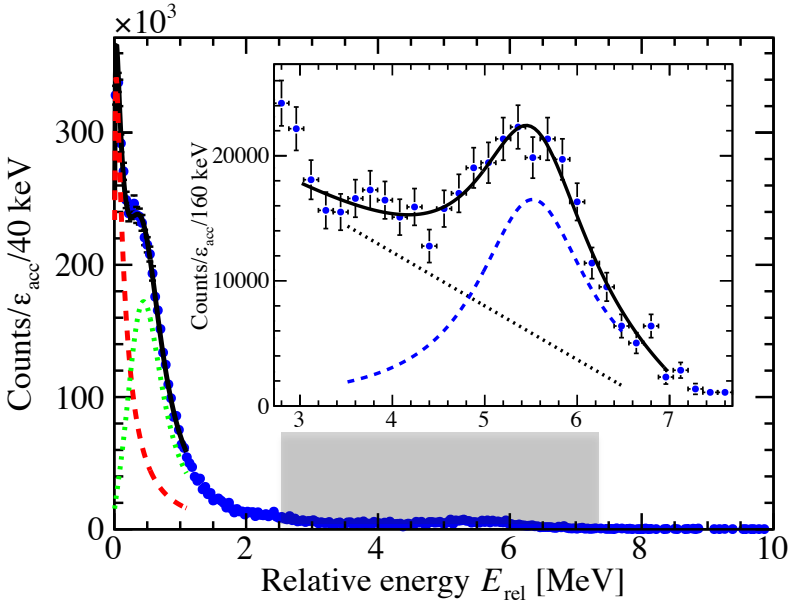




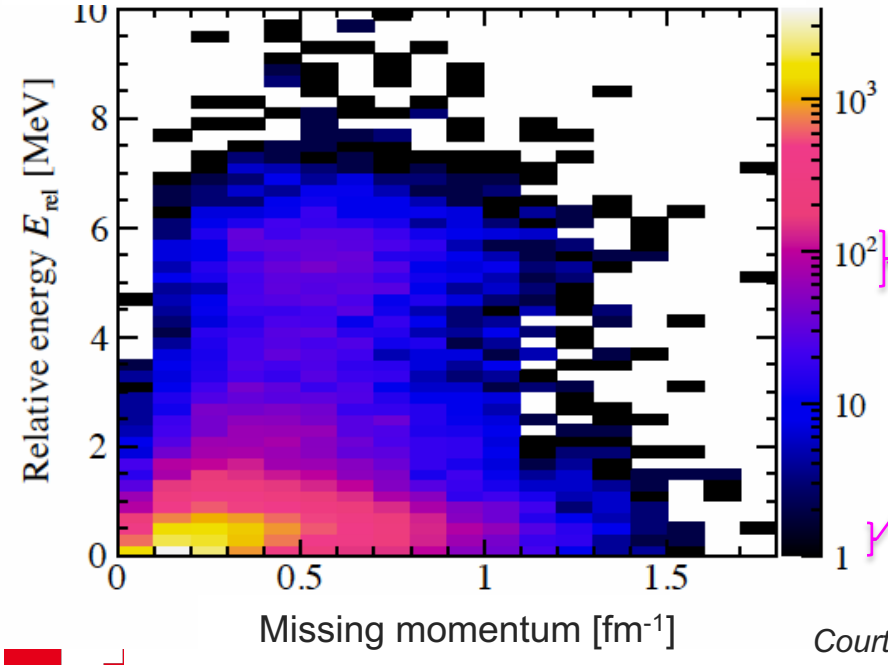
- ✓ *s-wave* virtual state and *p-wave* confirmed
- ✓ 2-3 times better resolution; statistics x 100

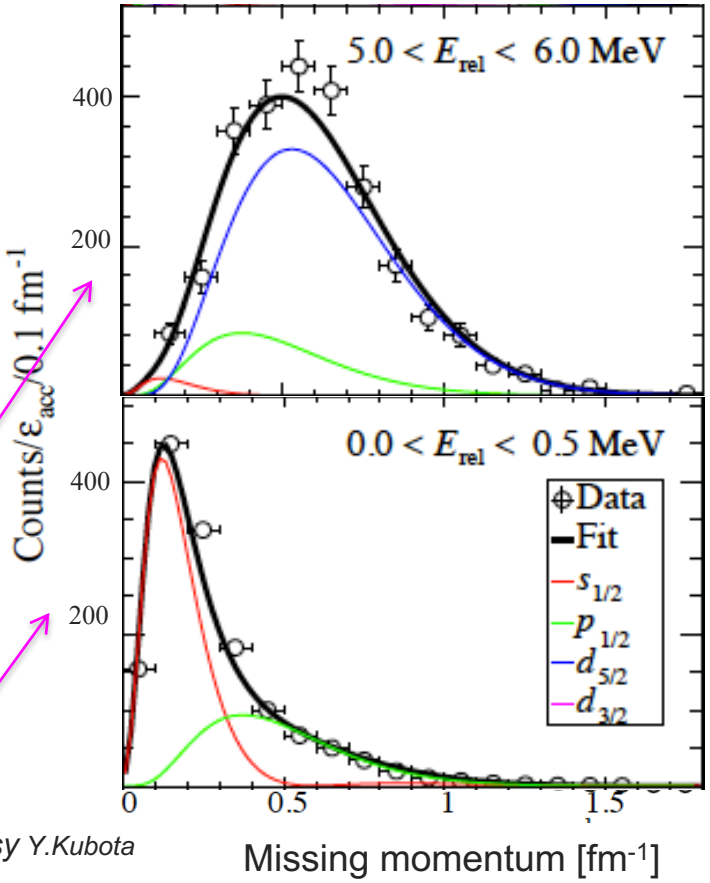
Courtesy Y.Kubota

Structure of 10Li



- ✓ *s-wave* virtual state and *p-wave* confirmed
- ✓ 2-3 times better resolution; statistics x 100
- ✓ new resonance:
  E_r = 5.52±0.04 MeV
  Γ = 0.72±0.10 MeV





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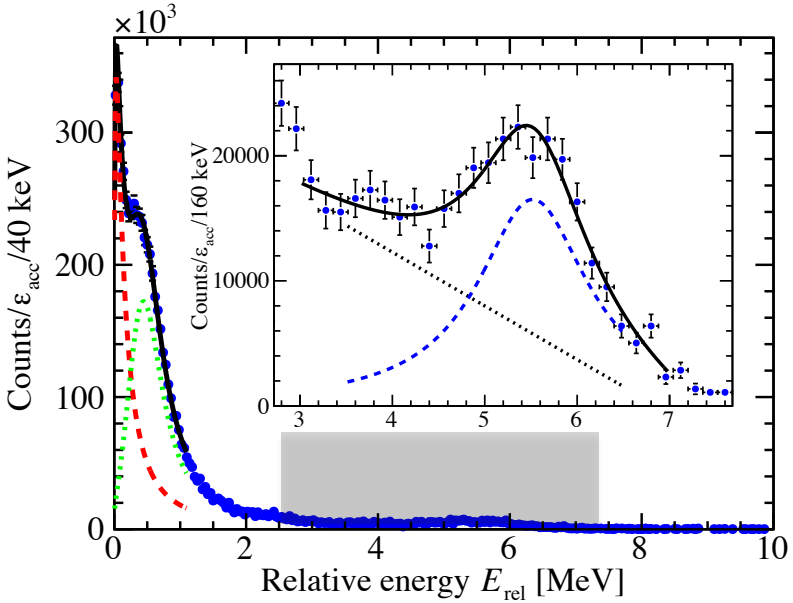
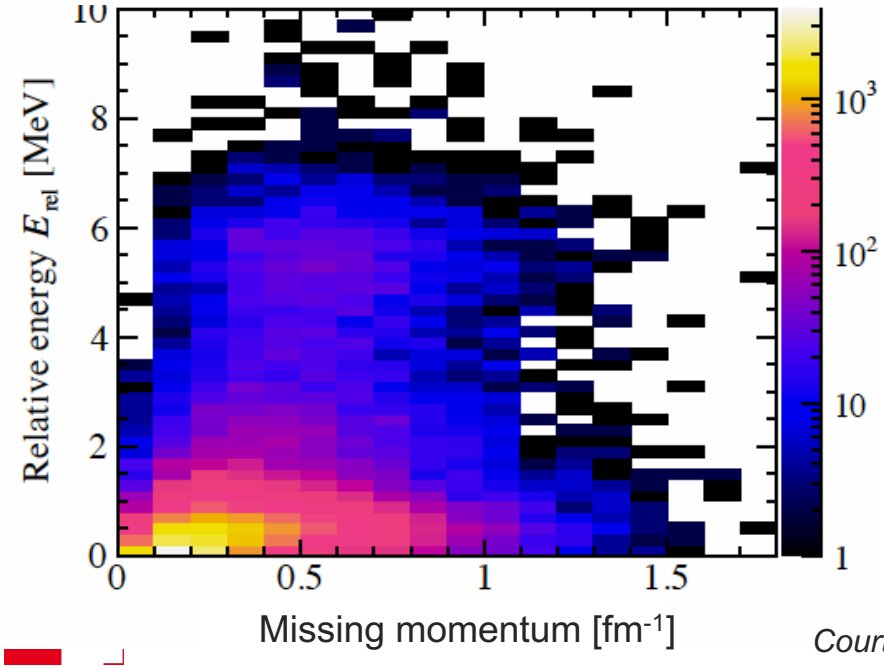
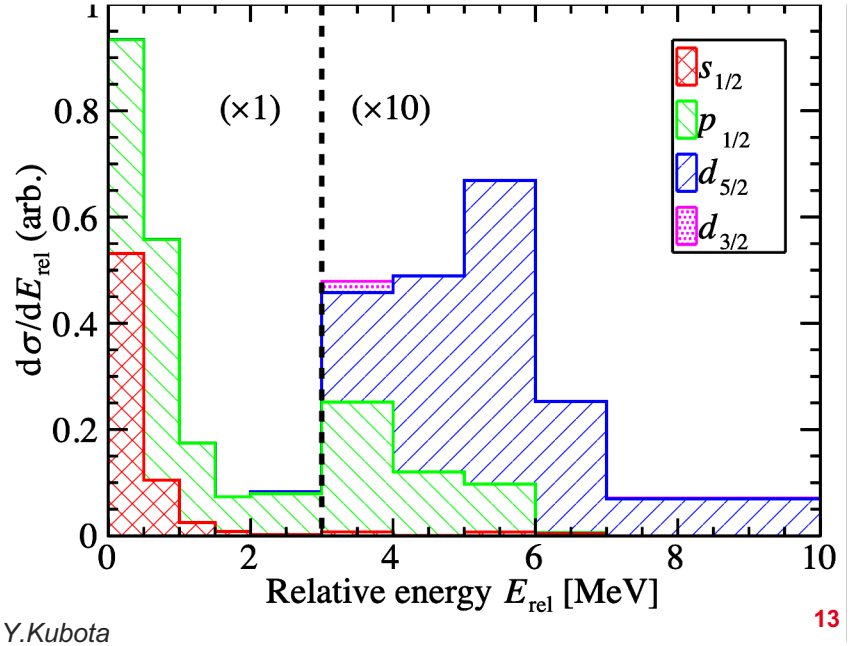


- ✓ s-wave virtual state and p-wave confirmed
- ✓ 2-3 times better resolution; statistics x 100
- ✓ new resonance:
  E_r = 5.52±0.04 MeV
  Γ = 0.72±0.10 MeV
- ✓ Multipole Decomposition Analysis of missing momentum spectrum suggests d-wave

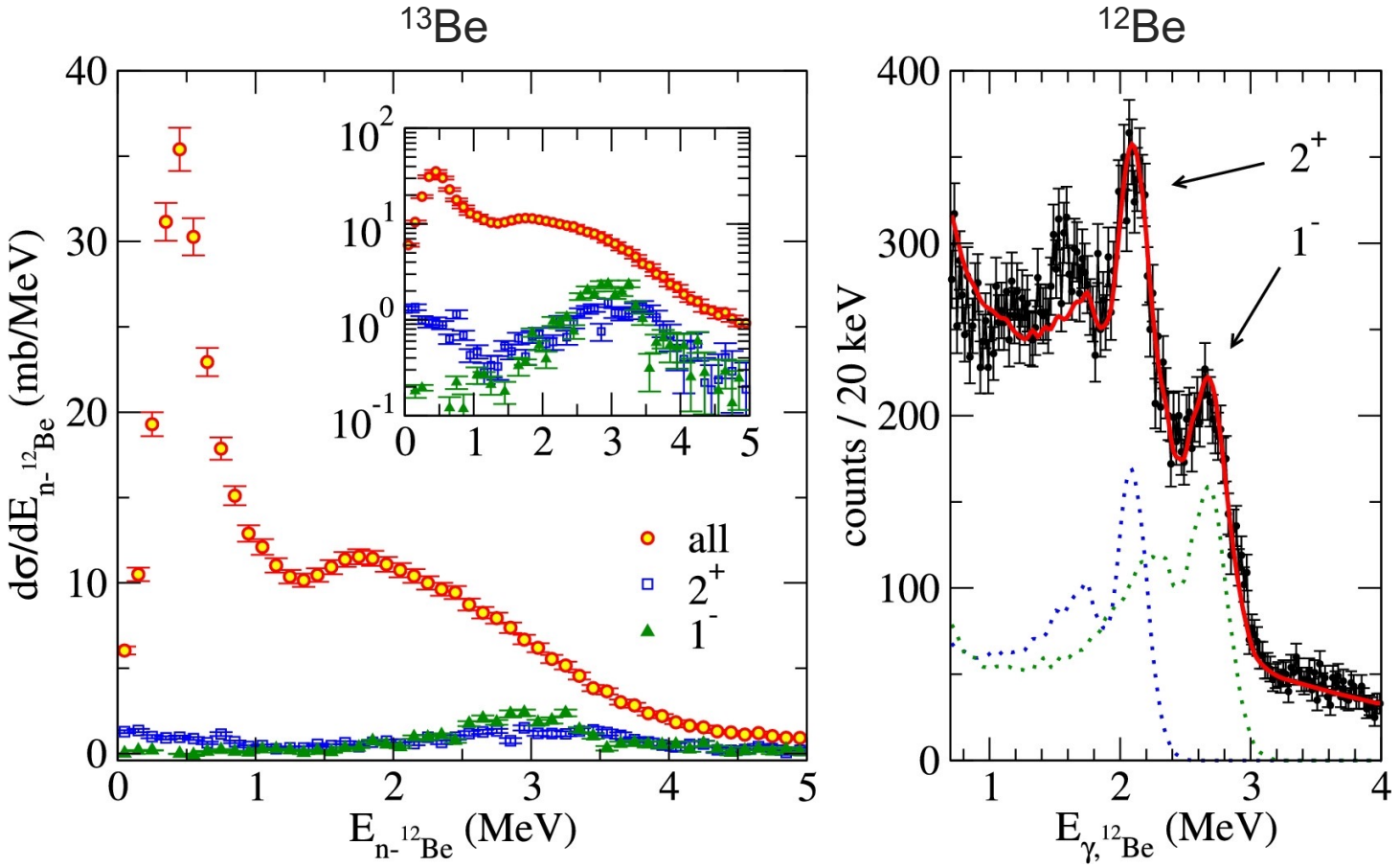




Courtesy Y.Kubota

Structure of 13Be

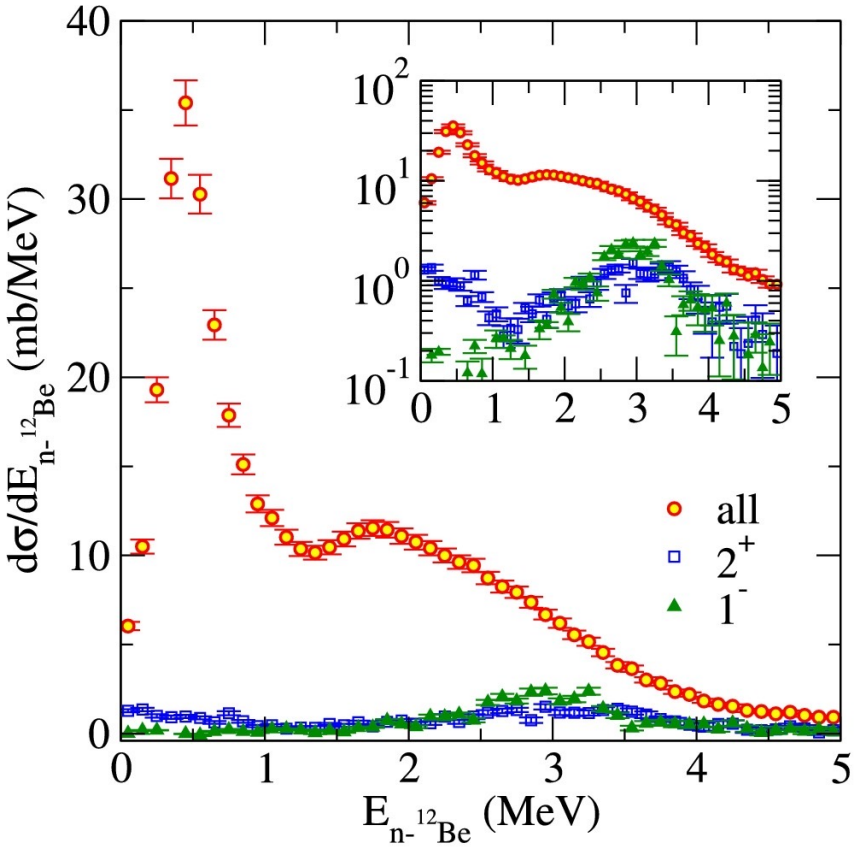
- Inconsistent interpretations of ^{13}Be spectrum in the literature
- Our experiment: gamma-n-^{12}Be coincidences with high statistics

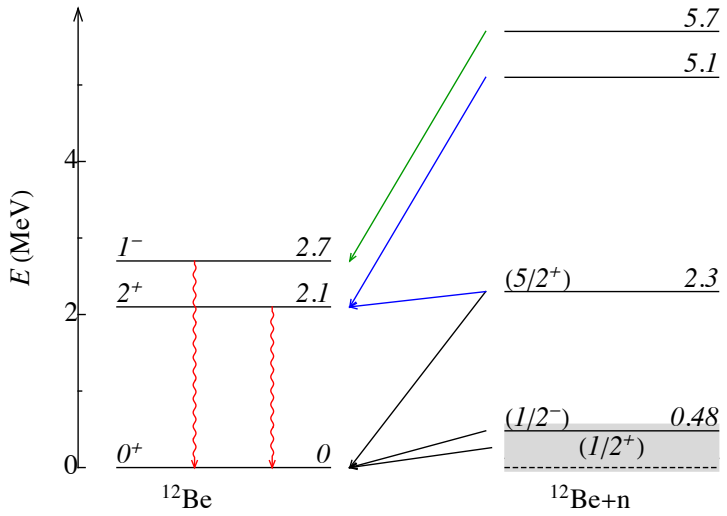


A.Corsi et al, Phys.Lett.B 797, 134843 (2019)

Structure of 13Be

- Inconsistent interpretations of ^{13}Be spectrum in the literature
- Gamma-n-^{12}Be coincidences with high statistics => level scheme
- Core excited contribution in the cross section is marginal



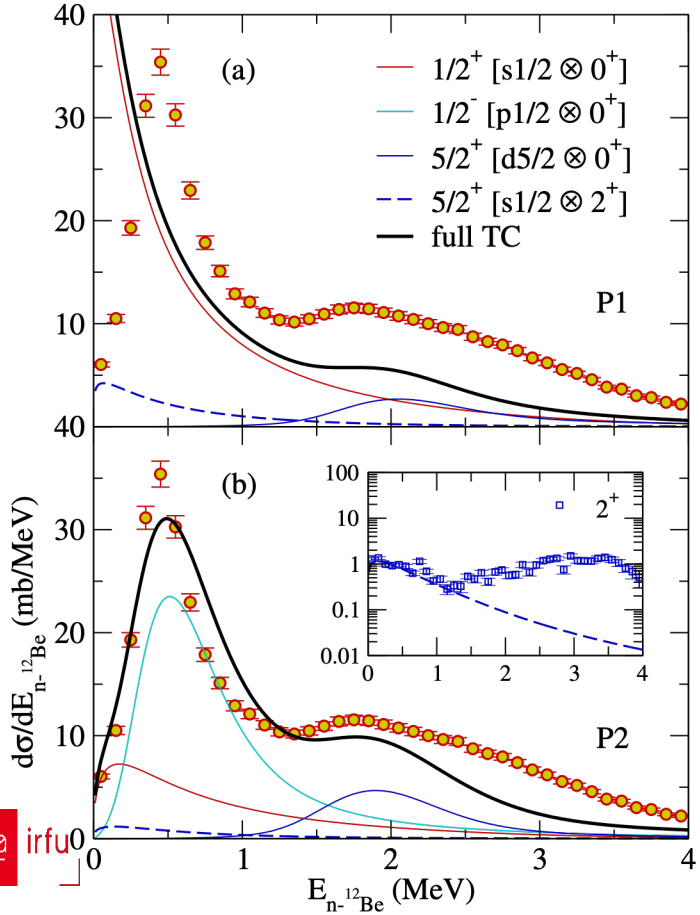


A.Corsi et al, Phys.Lett.B 797, 134843 (2019)

Structure of 13Be

Analysis with:

- 3B model + Transfer to the Continuum
  J.Casal, M.Gomez-Ramos, A.Moro
- core excitation of ^{12}Be taken into account via rotational model (only 2^+ state)
- different parametrizations for $V_{n\text{-}core}$
- **need to include *p-wave* to reproduce $E_{n\text{-}^{12}Be}$**



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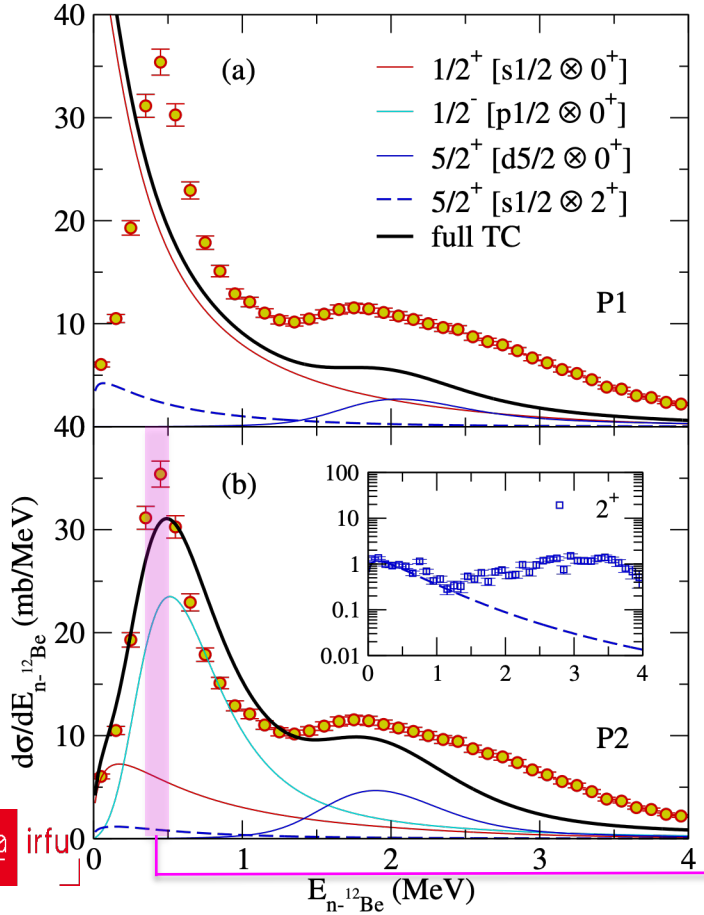

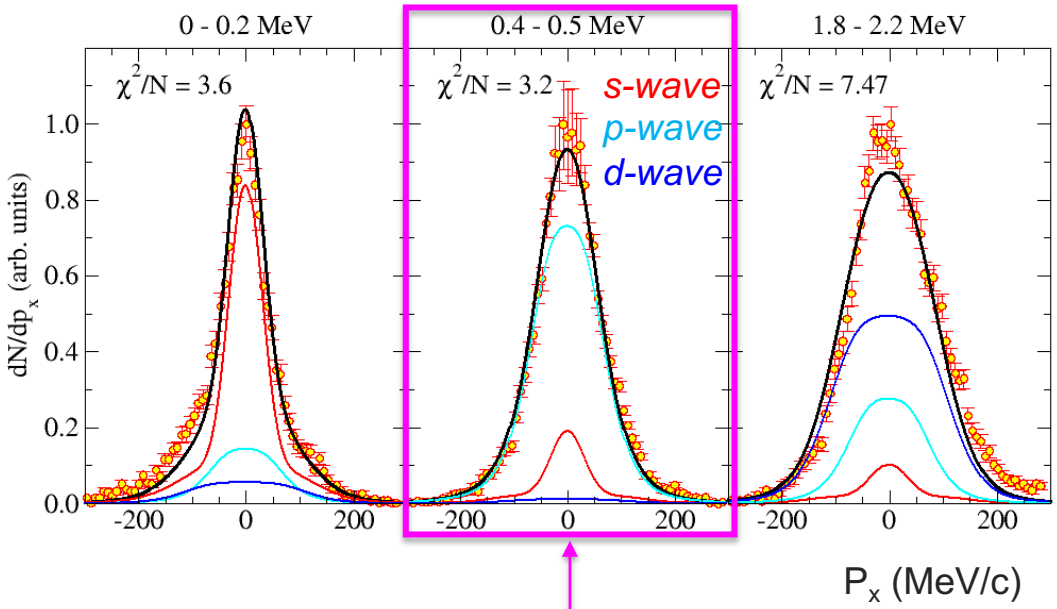

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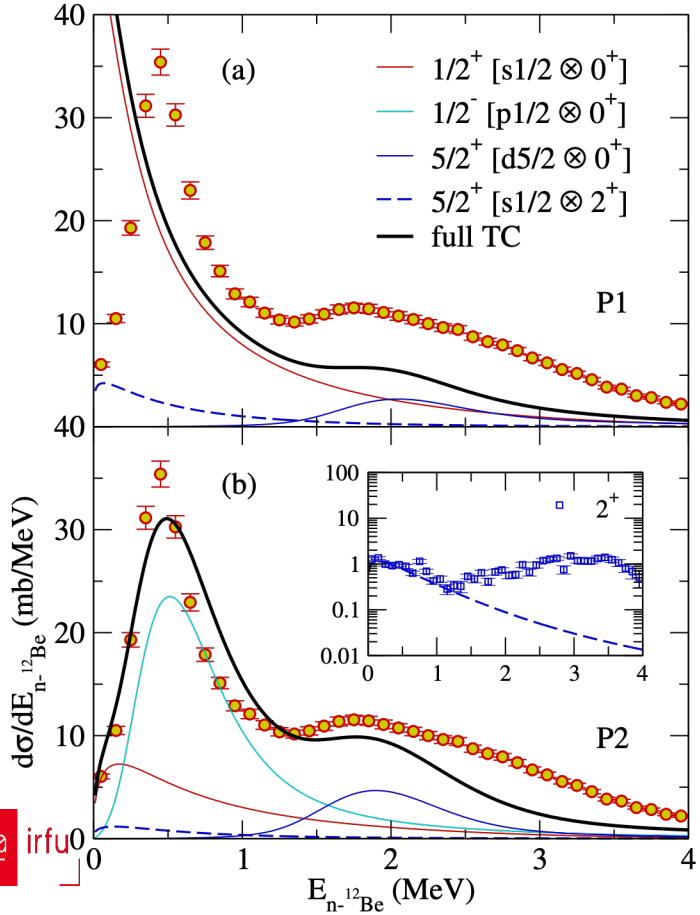
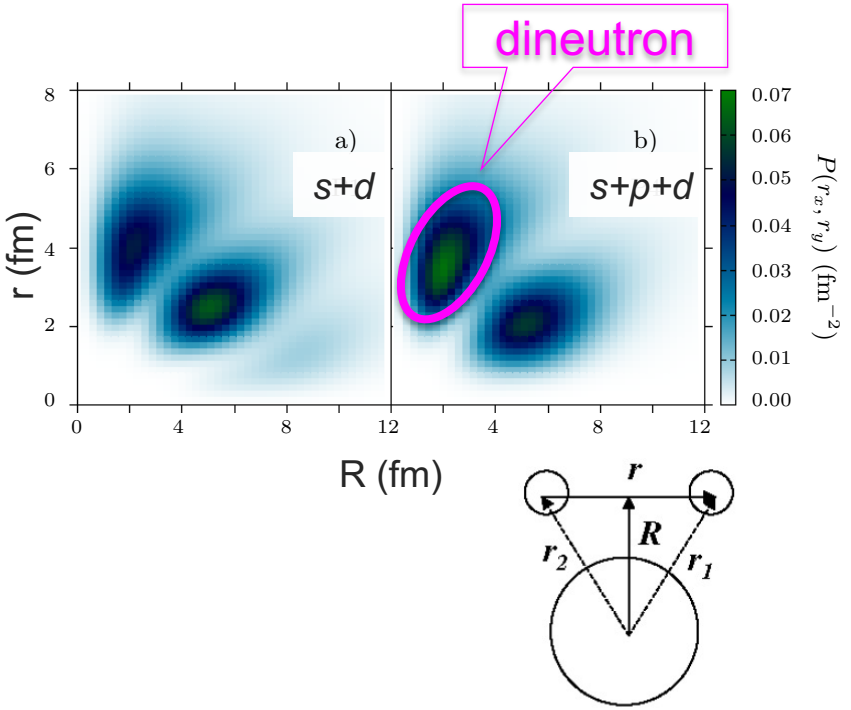


- ***p-wave* needed for dineutron correlation**



Structure of 13Be

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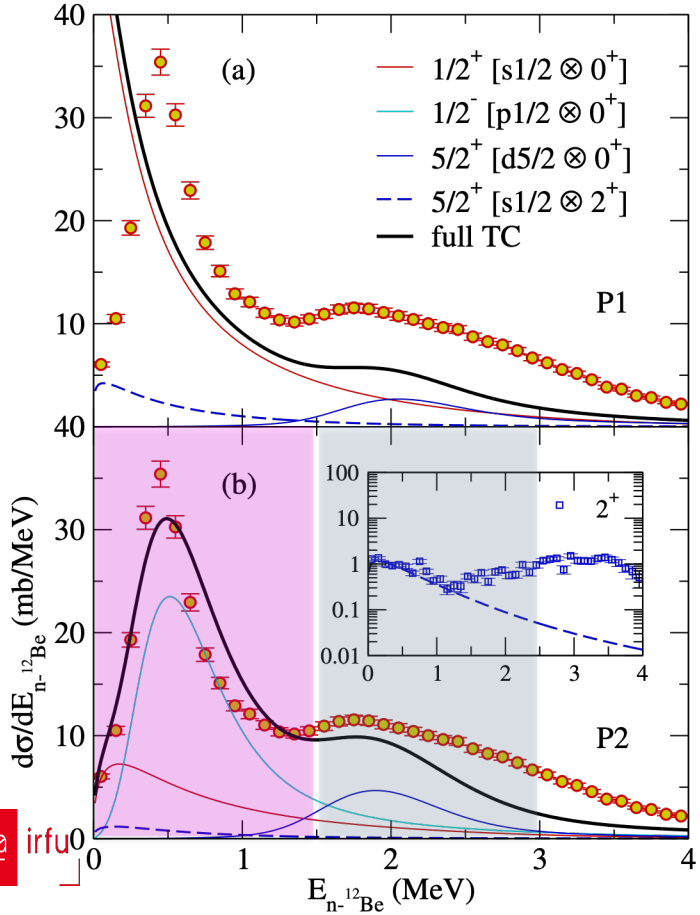
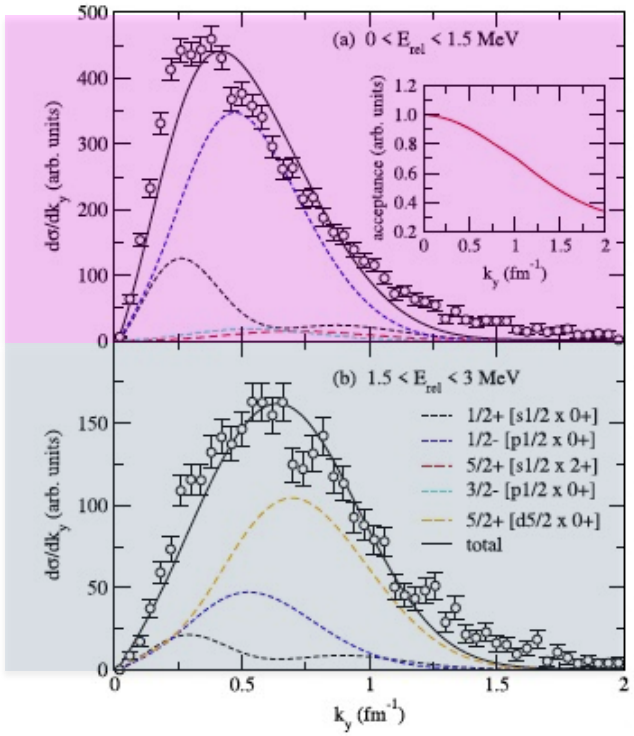
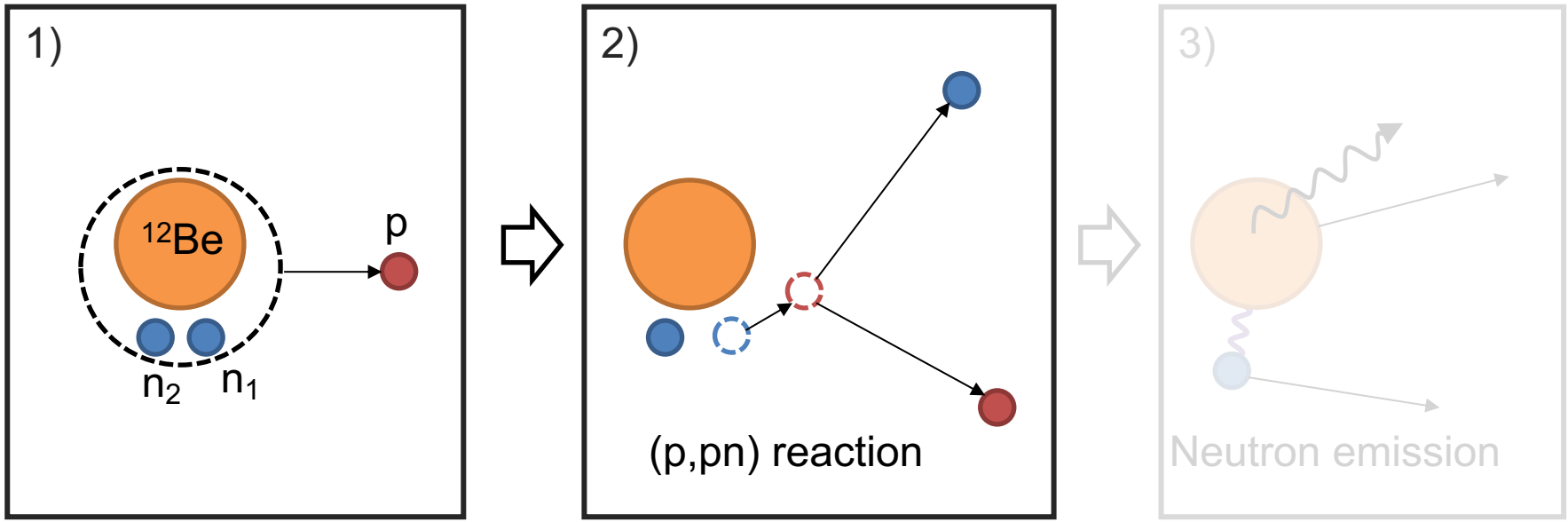
- 3B model + Transfer to the Continuum
  J.Casal, M.Gomez-Ramos, A.Moro
- core excitation of ^{12}Be taken into account via rotational model (only 2^+ state)
- different parametrizations for $V_{n\text{-}core}$
- can reproduce k_y distribution with the same s, p, d wave admixture





A.Corsi et al, Phys.Lett.B 797, 134843 (2019)

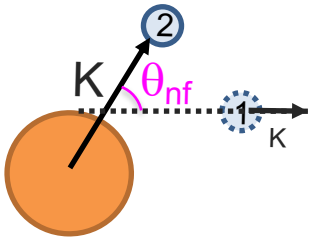
Focus on the (p,pn) reaction and dineutron

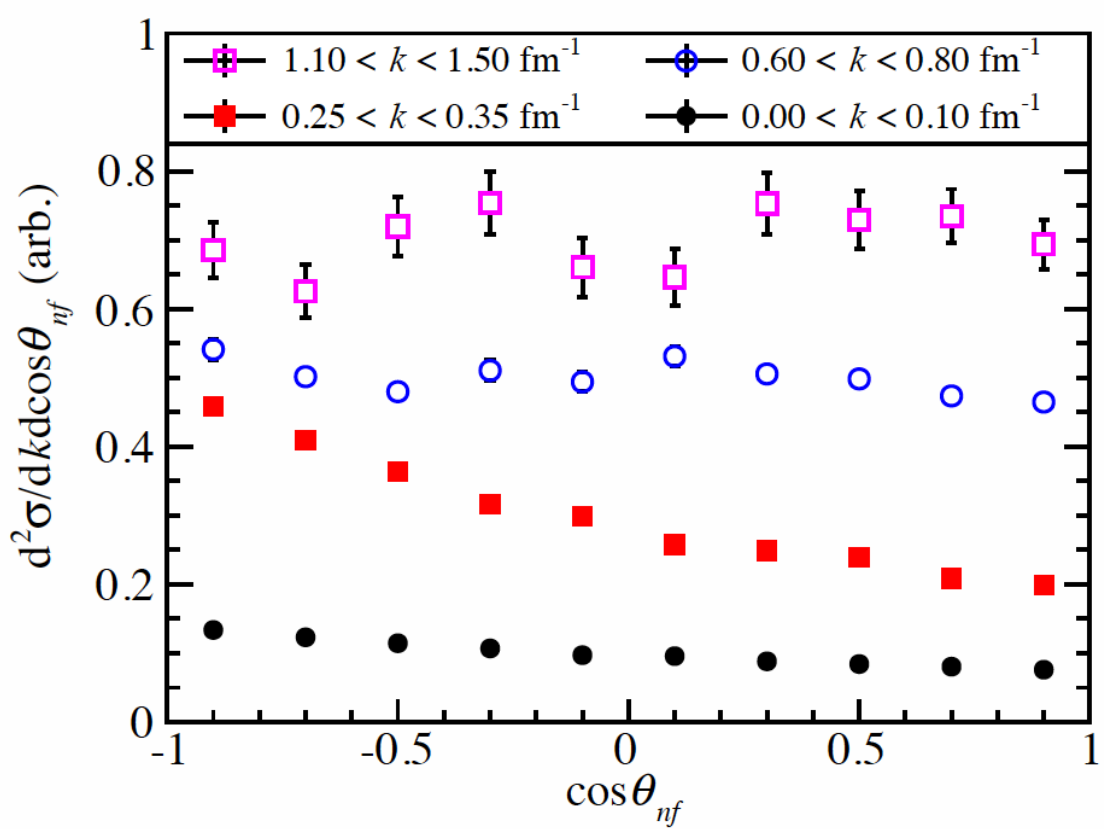


Dineutron correlation in 11Li

- Measure K' (^{9}Li-n_2 momentum) and k (n_1 missing momentum)
- Deduce the correlation angle in the momentum space
- Look at **correlation angle θ_{nf}** as a function of **missing momentum k** (peripherality)

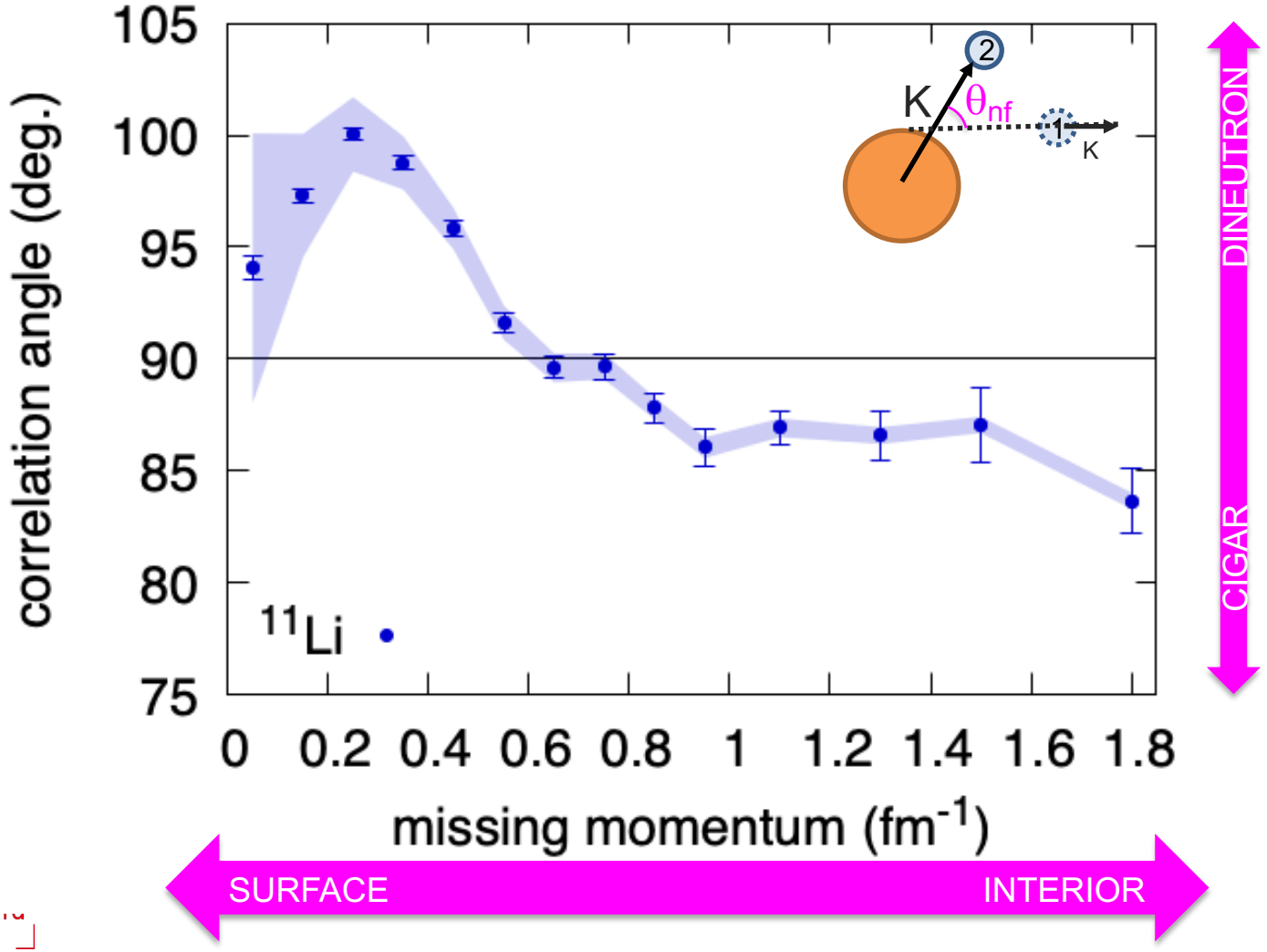
$$\cos\theta_{nf} = \frac{\boldsymbol{K'} \cdot \boldsymbol{k}}{|\boldsymbol{K'}||\boldsymbol{k}|}$$





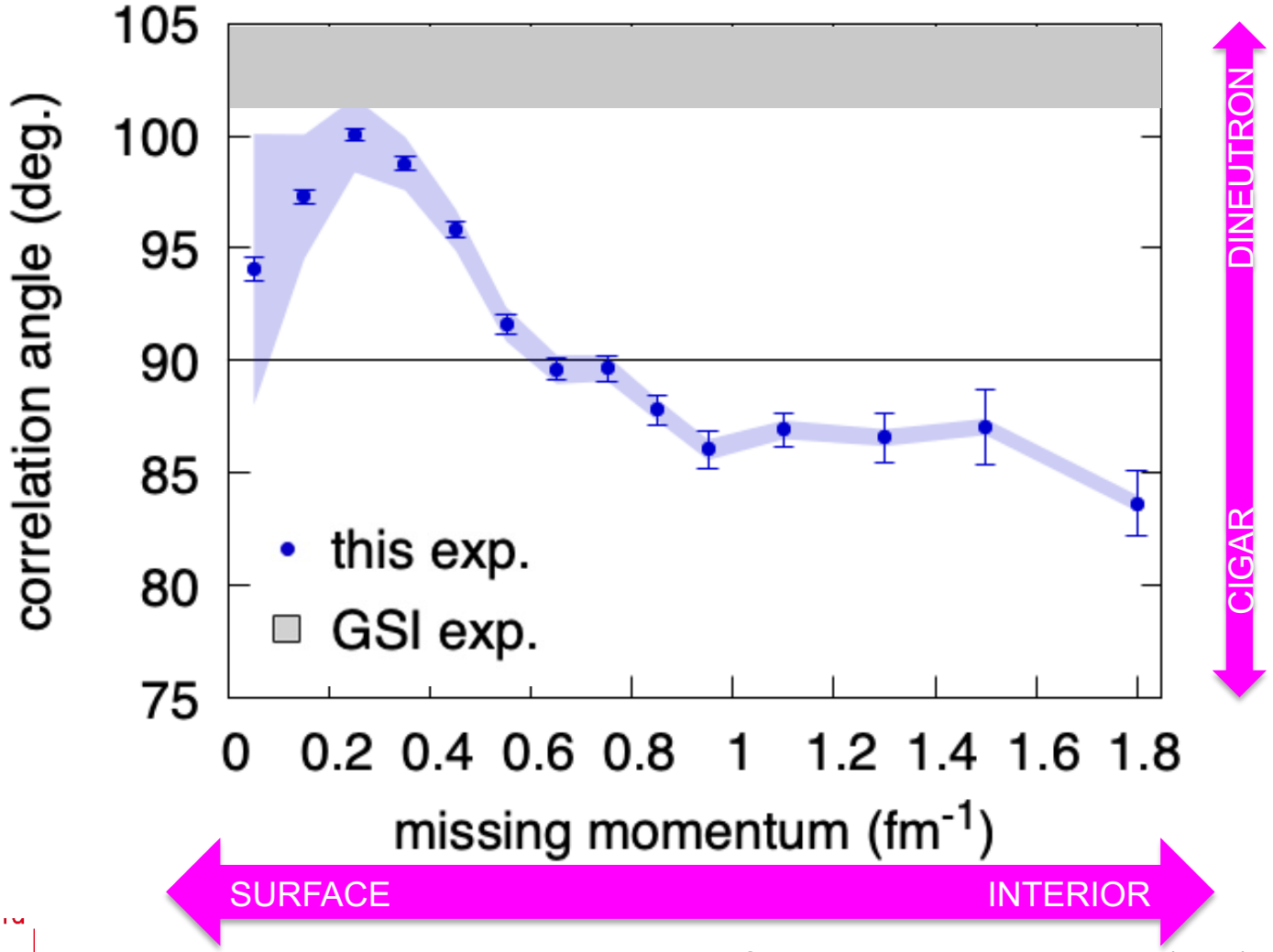
Dineutron correlation in 11Li

- Dineutron correlation develops **at the periphery** (missing momentum ~ 0.3 fm^{-1})



Dineutron correlation in 11Li

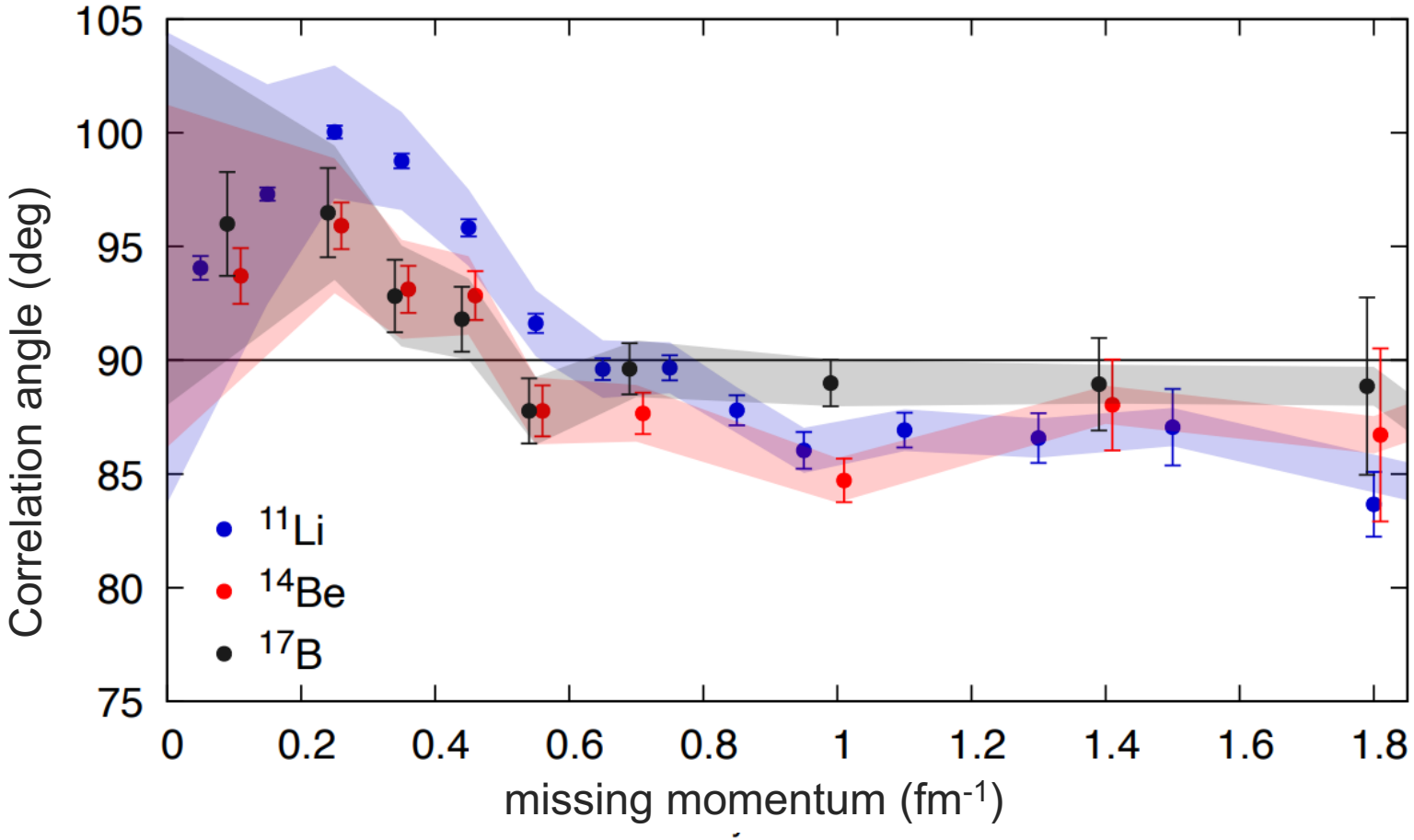
- Dineutron correlation develops at the periphery (missing momentum ~ 0.3 fm^{-1})
- Stronger dineutron correlation in GSI data (11Li+C). Carbon is a surface probe.



Y. Kubota, A.Corsi et al., Phys. Rev. Lett. 125 (2020) 252501

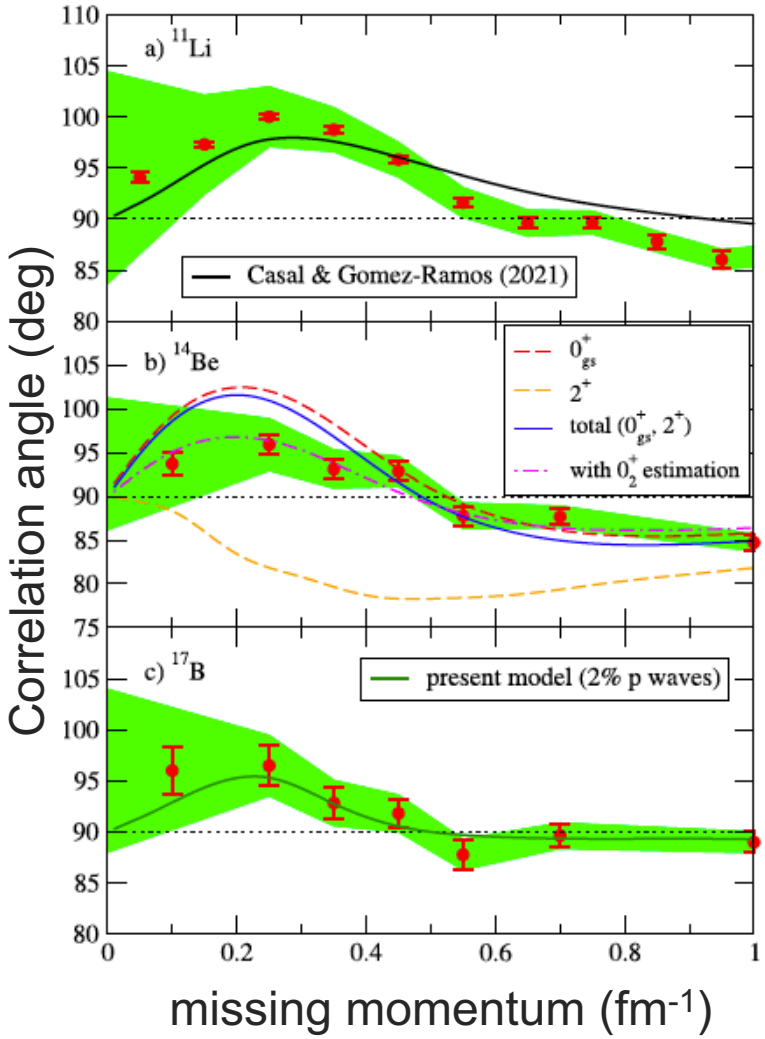
Dineutron correlation in 11Li, 14Be, 17B

- Dineutron correlation develops at the periphery (missing momentum ~ 0.3 fm^{-1})
- Similar correlation angle pattern in ^{14}Be and ^{17}B. **Universality?**



A.Corsi, Y.Kubota, J.Casal, M.Gomez-Ramos et al, Phys. Lett. B 840 (2023), 137875

Dineutron correlation in 11Li, 14Be, 17B



3B model + eikonal sudden approximation of (p,pN) reaction

J.Casal, M.Gomez-Ramos

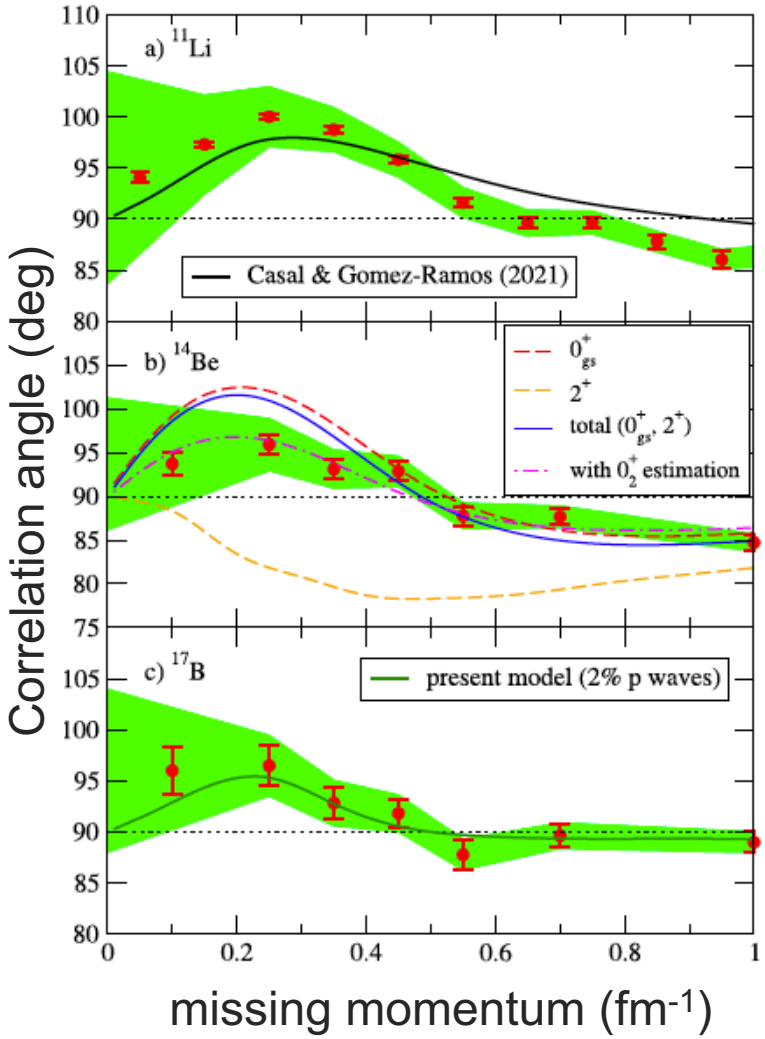
Mixture of s, p, and d waves in agrement with experimental observables from this and previous experiments

- 12Be+n, 15B+n relative energy
- 11Li Coulomb breakup,
- 14Be and 17B matter radii

Absorption dominates for missing momentum > 0.5 fm^{-1}

J.Casal, M.Gomez-Ramos et al, Phys. Rev. C 104, 024618 (2021)

Dineutron correlation in 11Li, 14Be, 17B



3B model + eikonal sudden approximation of (p,pN) reaction

J.Casal, M.Gomez-Ramos

Mixture of s, p, and d waves in agrement with experimental observables from this and previous experiments

- 12Be+n, 15B+n relative energy
- 11Li Coulomb breakup,
- 14Be and 17B matter radii

Absorption dominates for missing momentum > 0.5 fm^{-1}

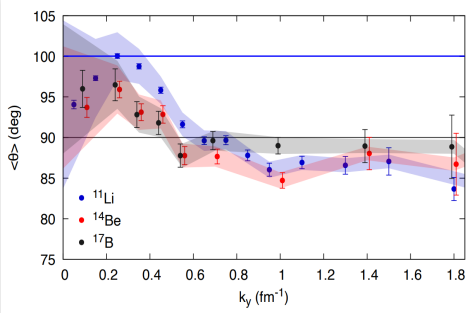
- ^{11}Li: well reproduced
- ^{14}Be: deviation maybe due to absence of ^{12}Be(0^+_2) state in 3B model. Improvement with 16% of 0^+_2
- ^{17}B: dineutron correlation driven by p wave

J.Casal, M.Gomez-Ramos et al, Phys. Rev. C 104, 024618 (2021)
A.Corsi, Y.Kubota, J.Casal, M.Gomez-Ramos et al, Phys. Lett. B 840 (2023), 137875

Dineutron correlation in 11Li, 14Be, 17B

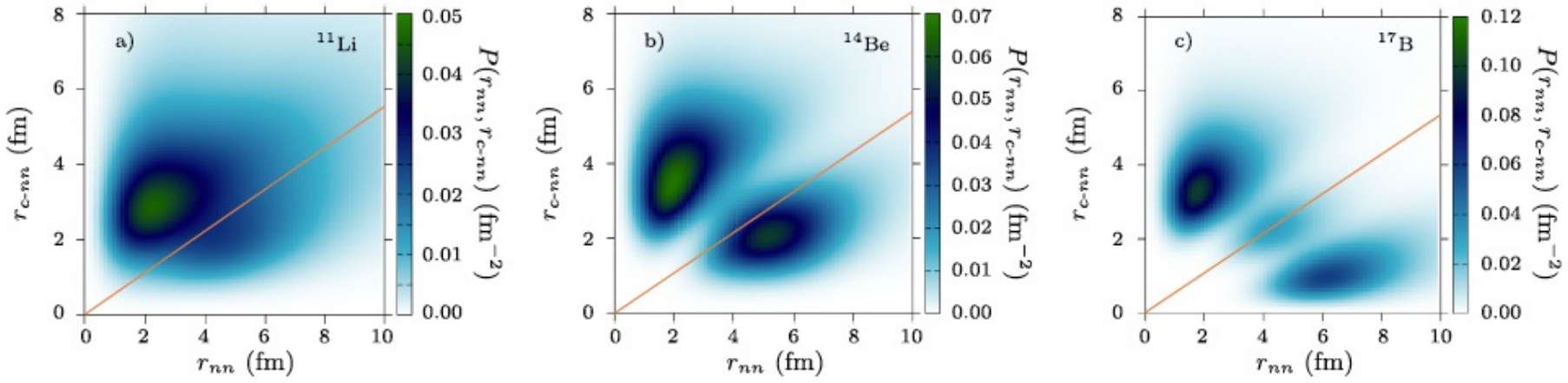
How to quantify the degree of dineutron correlation?

- experimental data (correlation angle)



- theory (benchmarked on data): $\chi = \frac{P_d - P_c}{P_d + P_c}$

χ=0.43 χ= 0.32 χ= 0.19



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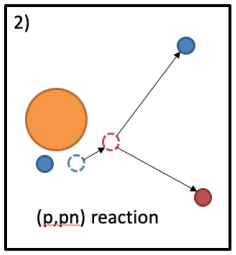
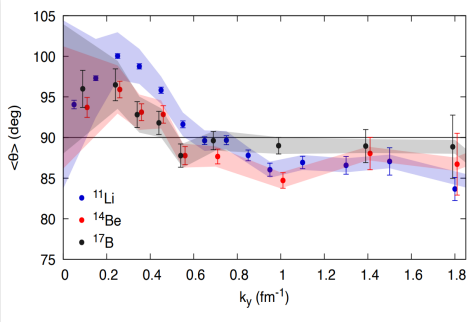
Conclusions and perspectives

- **QFS on Borromean nuclei** ^{11}Li, ^{14}Be, ^{17}B



- **New information on the spectroscopy of ^{10}Li, ^{13}Be**
  - ✓ new *d-wave* resonance at 5.5 MeV in ^{10}Li
  - ✓ dominance of *p-wave* at 0.5 MeV in ^{13}Be



- **Dineutron correlation**
  - ✓ dineutron as a function of peripherality for the first time
  - ✓ hint of universality of dineutron at nuclear periphery
  - ✓ better theoretical interpretation / more complex measurement

- **Theory**
  - Room for improvements in the description of 3B system