Experimental methods to study pairing in nuclei

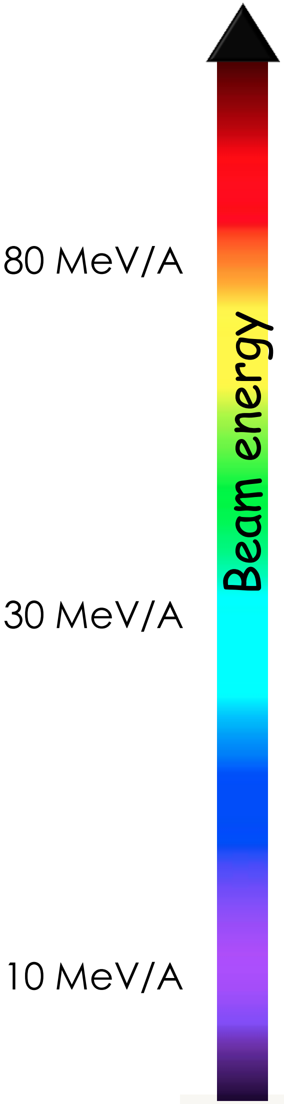
- ☐ **n-n pairing in light nuclei close to drip lines**
- ☐ **n-p pairing in N=Z nuclei**

M. Assié, IPN Orsay

n-n pairing in light nuclei close to drip-lines

- **Borromean nuclei**
- **Charge radius measurements**
- **Coulomb dissociation (E1 soft-dipole)**
- **Break-up methods**
- **Knock-out experiments**
- **Transfer methods**

Experimental studies of pairing



Reaction cross section : size, existence of a halo

Knockout: intrinsic momentum of removed nucleons

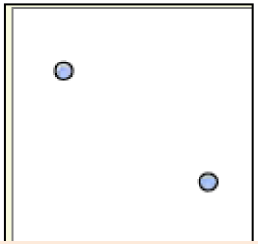
Coulomb/Nuclear BU : n-n correlation

Coulomb dissociation : Dipole response

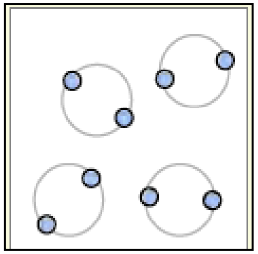
Transfer differential cross sections (1n, 2n): probe the wave function

The n-n pairing at the drip-line for light nuclei

unbound neutrons

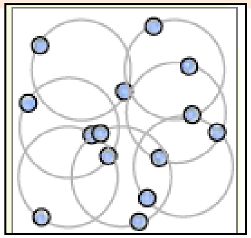


BEC-BCS



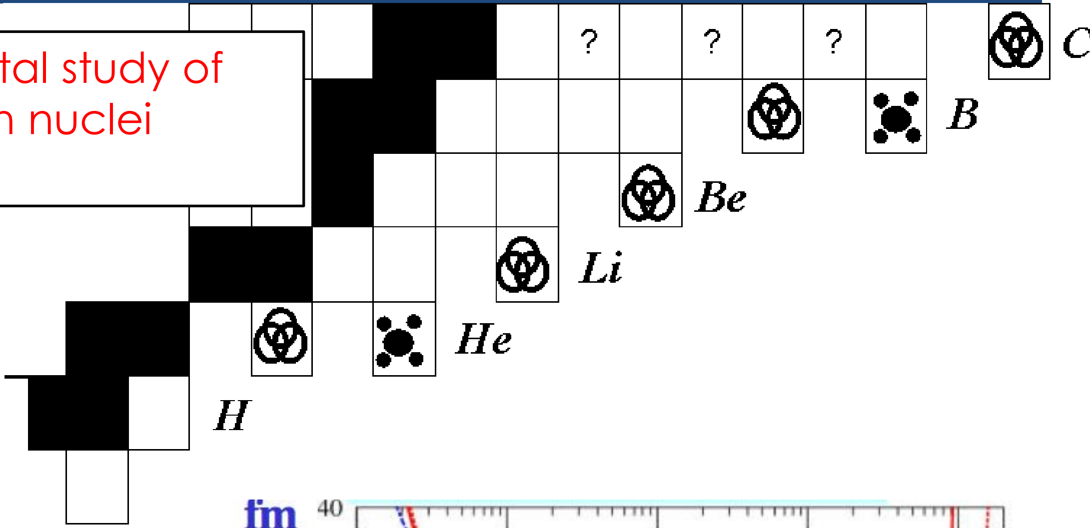
low density

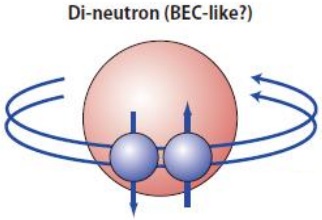
BCS

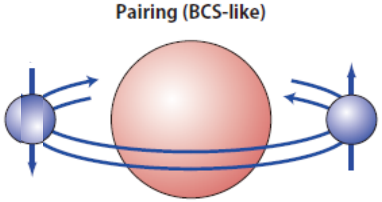


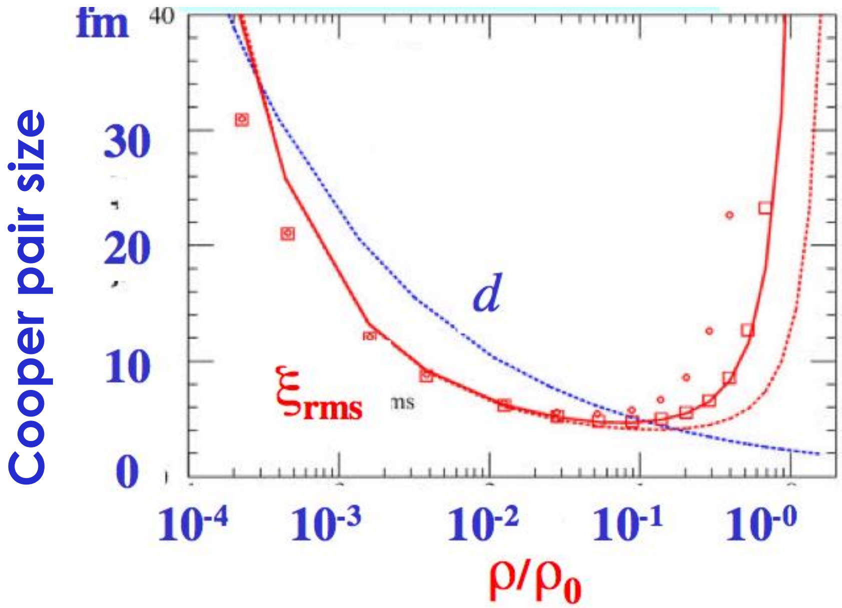
normal density

➙ Experimental study of borromean nuclei ^{6}He, ^{11}Li



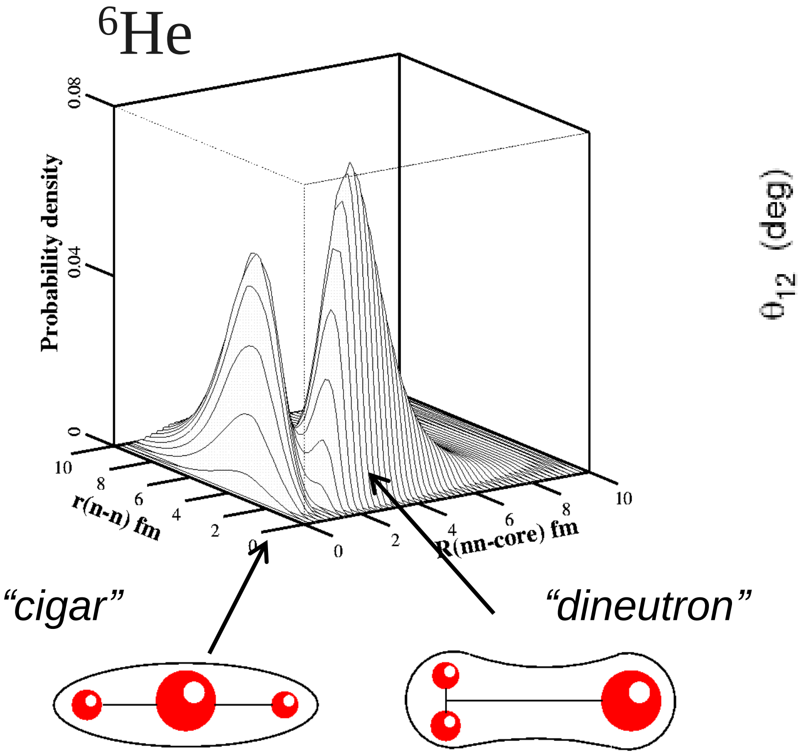




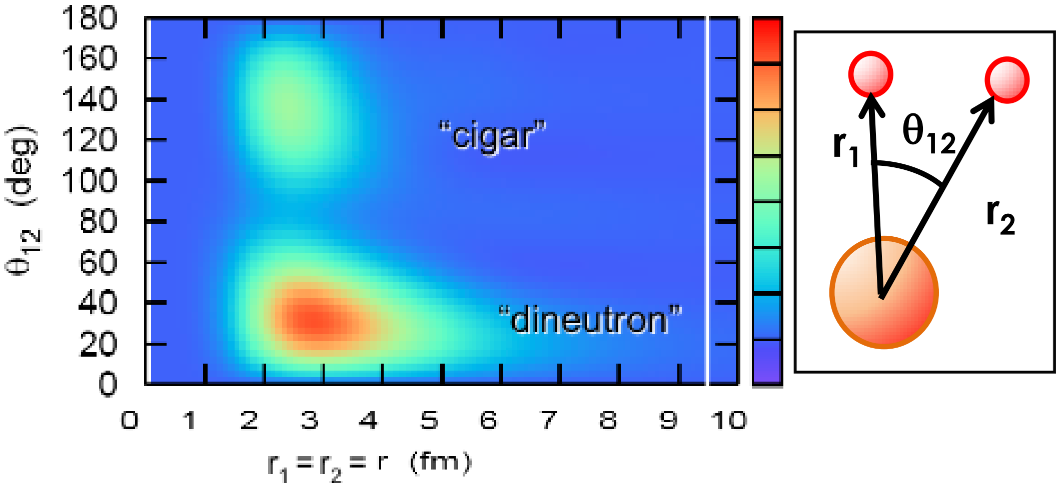


➟ ***M. Matsuo, PRC 73 (2006), N. Pillet et al, PRC (2007)***

The n-n pairing at the drip-line for light nuclei



➡ *Zhukov, Phys. Rep. (1993)*



➡ *K. Hagino, H. Sagawa, Phys. Rev. C 72 (2005).*

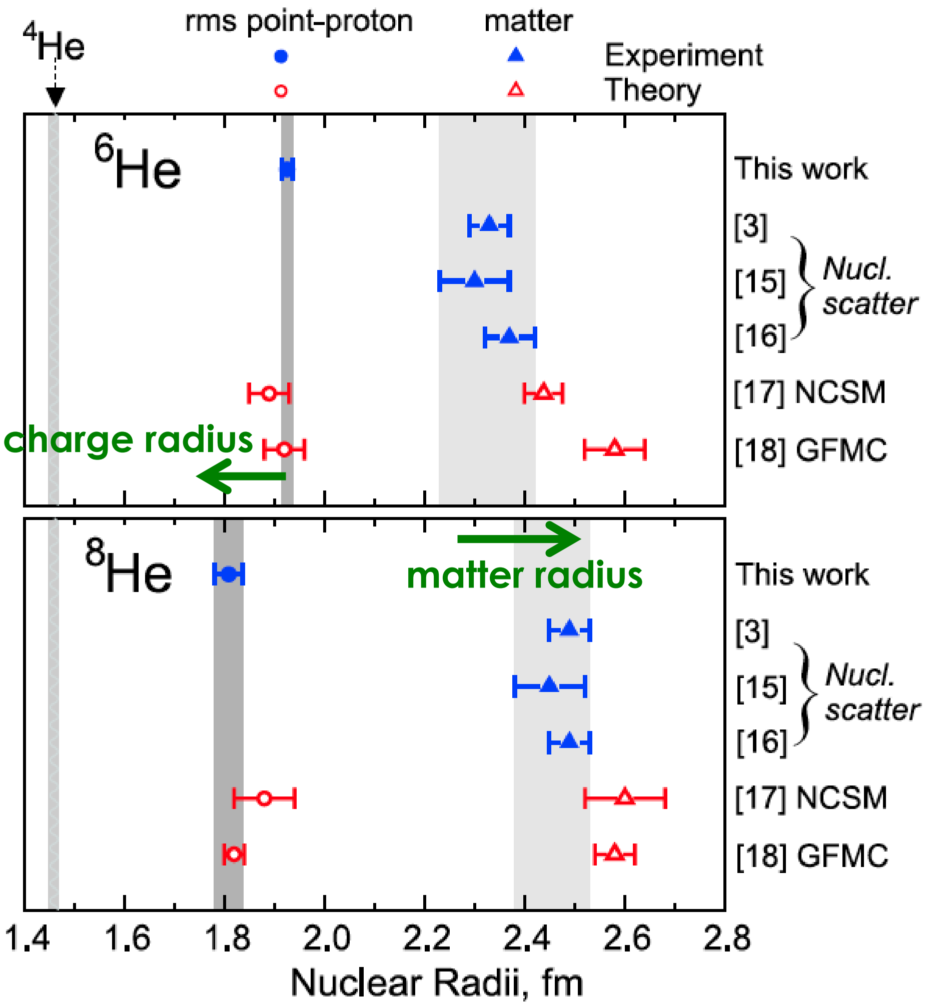
3-body model
density dependent contact interaction

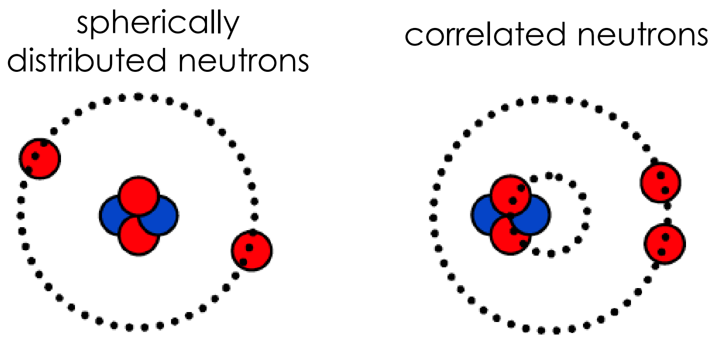
$r_{c\text{-}nn}$ = 3.6 fm ; r_{nn} = 4.6 fm

^{6}He $\langle\theta_{12}\rangle$=66.3°

^{11}Li $\langle\theta_{12}\rangle$=65.29°

Charge radius measurements





From ^{6}He to ^{8}He

- *matter radius* increases (neutrons added)
- *charge radius* decreases (neutrons spend more time close to each other → recoil motion of alpha core)

➡ ***P. Mueller, Phys. Rev. Lett. 99 (2007)***

➡ ***L.-B. Wang, Phys. Rev. Lett. 93 (2004).***

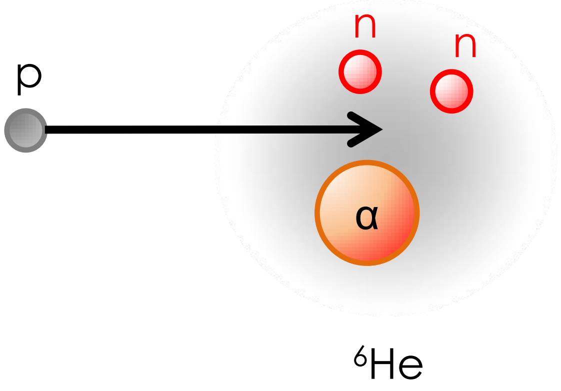
Radiative capture

^{6}He (p,γ) @ 40 A.MeV

λ_p= 0.7 fm

γ not sensitive to FSI

➞ **probe for clusterization in nuclei**

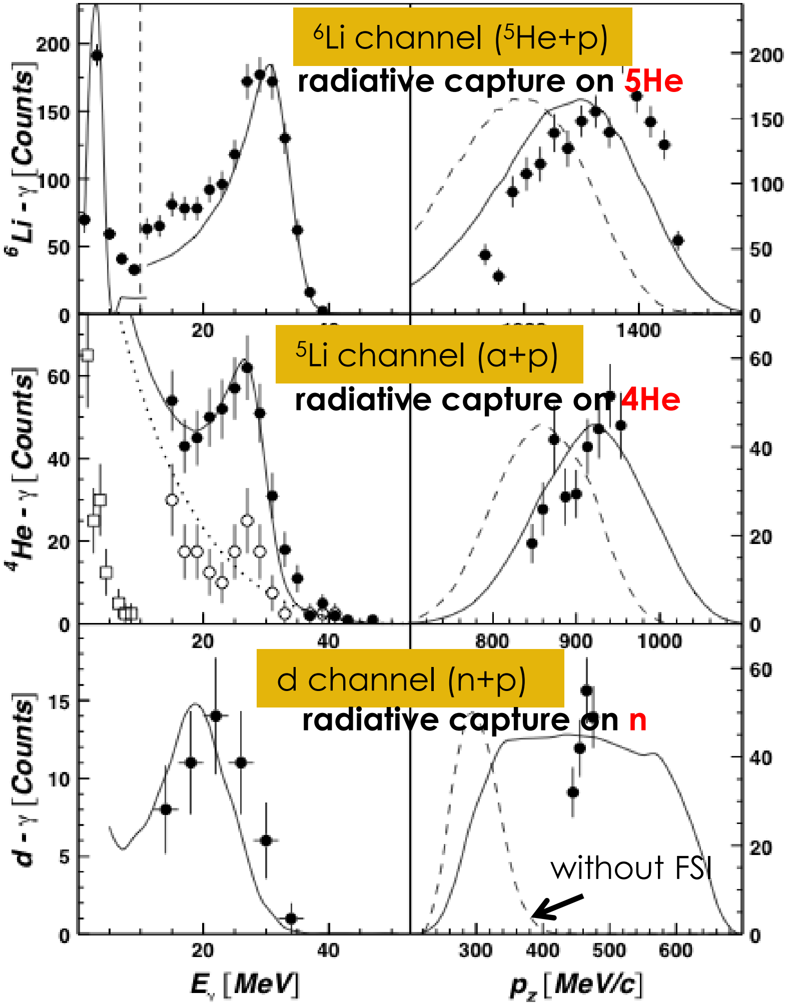


- Mainly **cigar configuration**

  (within the proton probe of 0.7fm)

- Use lower energy probe ?

➞ ***E. Sauvan, Phys. Rev. Lett. 87 (2001)***



^{6}Li channel (^{5}He+p)

radiative capture on 5He

^{5}Li channel (a+p)

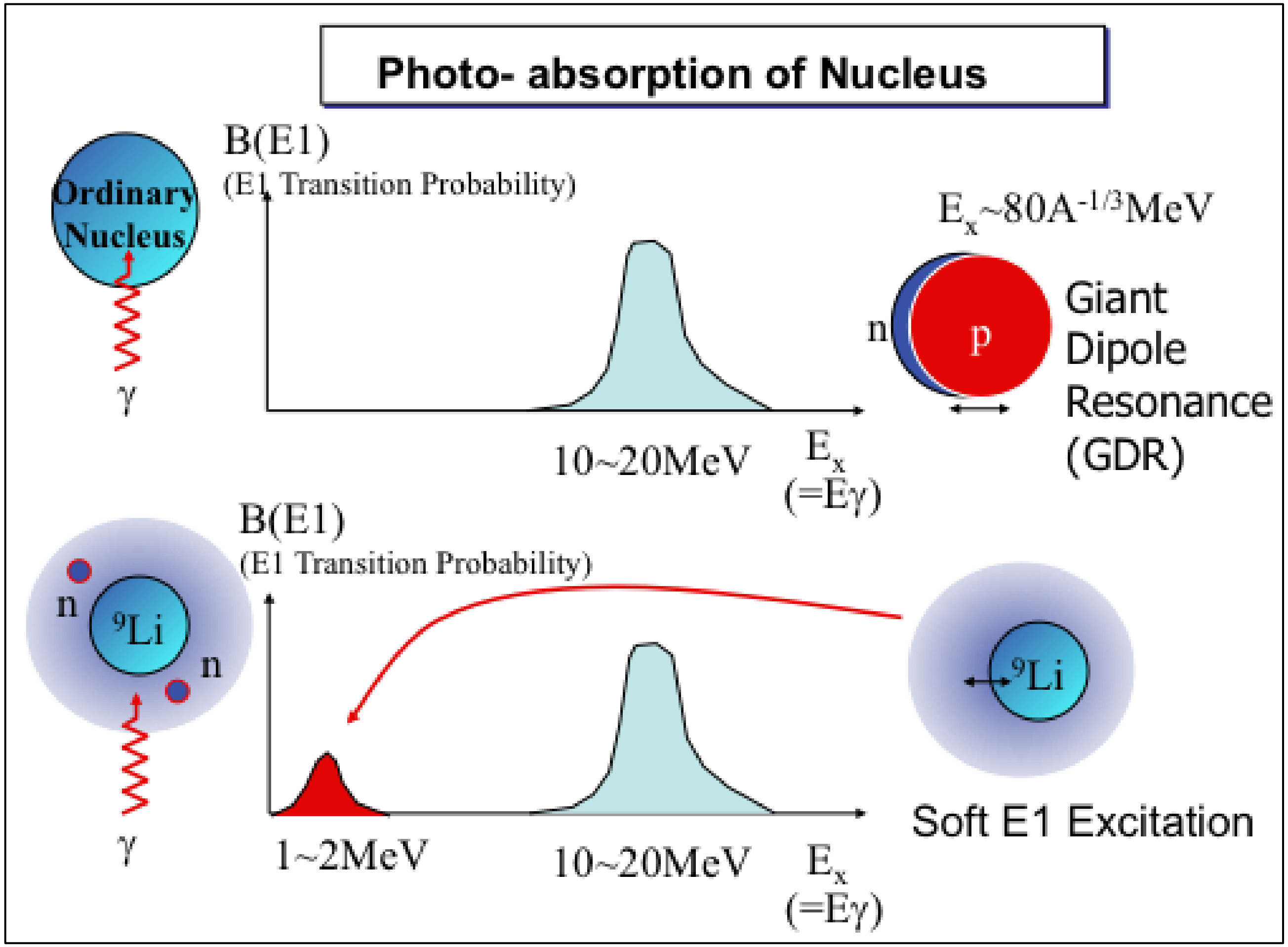
radiative capture on 4He

d channel (n+p)

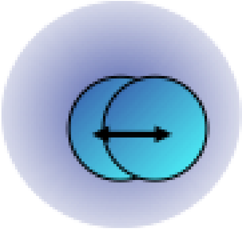
radiative capture on n

no **t+p** and **2n+p** channel observed

Coulomb dissociation B(E1)



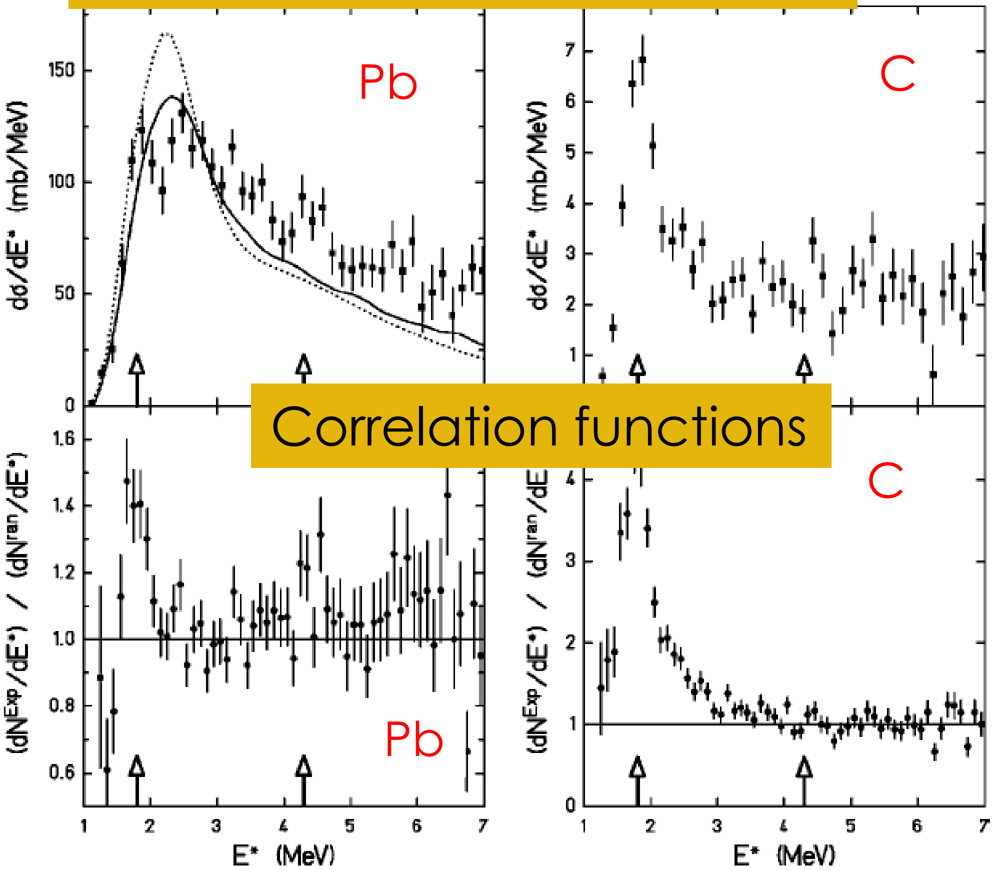
Soft Dipole Resonance



Slow Vibration
of core against halo

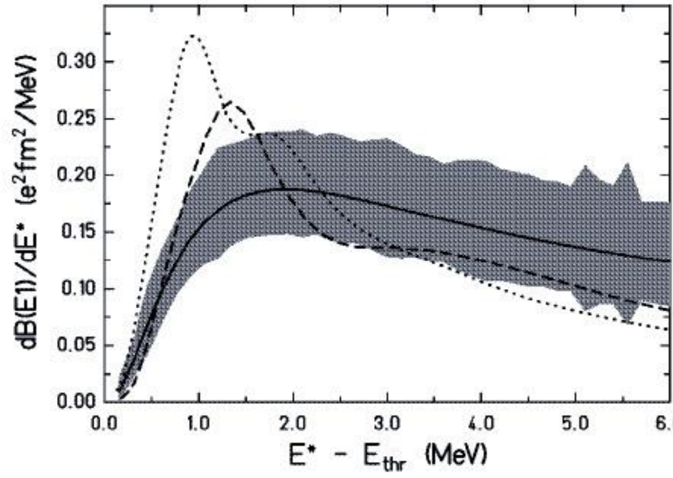
Coulomb dissociation B(E1)

Cross-sections on Pb and ^{12}C



Correlation functions

dB(E1)/dE* for ^{6}He



- equivalent photon method
- non-energy wieghted E1 cluster sum rule :

$$B(E1)=\frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2<r^2_{c,2n}>$$

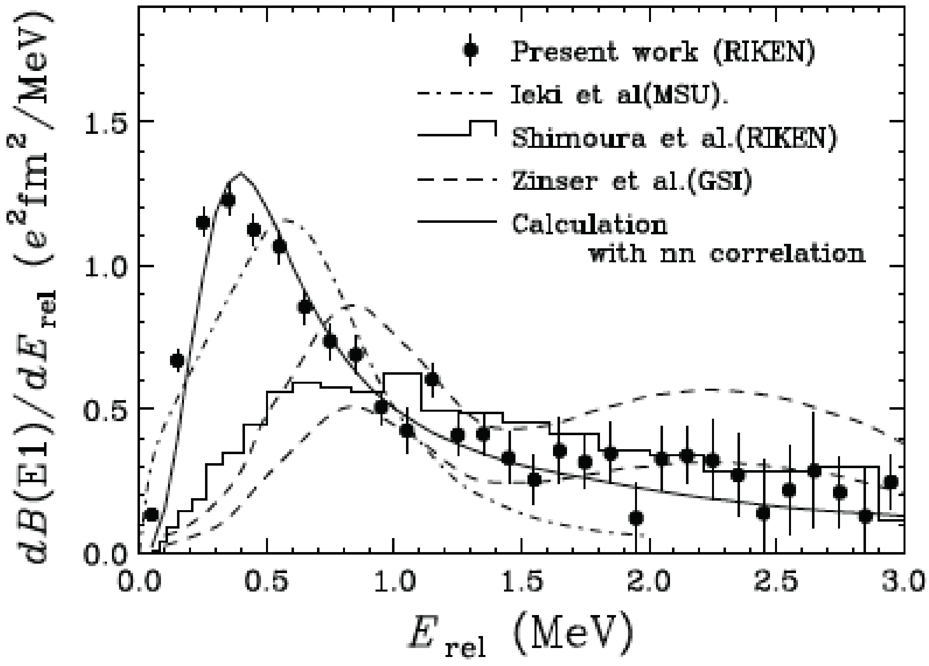
$$\sqrt{<r^2_{c,2n}>}=3.36(39)fm$$

$$<\theta_{12}>=83^{+20}_{-10}$$

➡ ***T. Aumann, Phys. Rev. C 59 (1999)***

Coulomb dissociation B(E1)

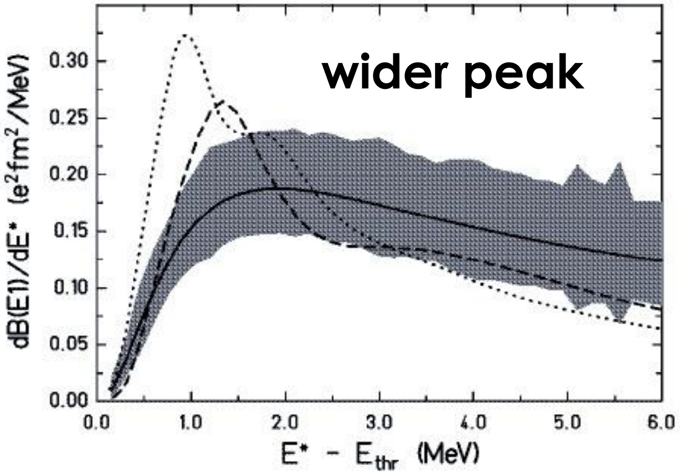
dB(E1)/dE for ^{11}Li



$$\sqrt{< r^2_{c,2n} >} = 5.01(32) fm$$

$$< \theta_{12} >= 48^{+14}_{-18}$$

dB(E1)/dE* for ^{6}He



- equivalent photon method
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$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 < r^2_{c,2n} >$$

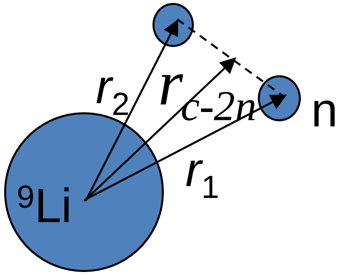
$$\sqrt{< r^2_{c,2n} >} = 3.36(39) fm$$

$$< \theta_{12} >= 83^{+20}_{-10}$$

➡ ***T. Nakamura, Phys. Rev. Lett 96 (2006)***

Coulomb dissociation B(E1)

^{11}Li $< \theta_{12} >= 48^{+14}_{-18}$ **^{6}He** $< \theta_{12} >= 83^{+20}_{-10}$



Simple two-neutron shell model

$$\left|\Psi(^{11}\mathrm{Li})\right\rangle = Core \otimes \left[\alpha\left|(1s)^2\right\rangle + \beta\left|(0p)^2\right\rangle\right]$$

Mixing of s(+ parity) and p(-parity) orbitals

$$\langle\cos\theta_{12}\rangle = \cancel{\alpha^2\left\langle(1s)^2\right|\cos\theta_{12}\left|(1s)^2\right\rangle} + \cancel{\beta^2\left\langle(0p)^2\right|\cos\theta_{12}\left|(0p)^2\right\rangle} + 2\alpha\beta\left\langle(0p)^2\right|\cos\theta_{12}\left|(1s)^2\right\rangle$$

$$= 2\alpha\beta\left\langle(0p)^2\right|\cos\theta_{12}\left|(1s)^2\right\rangle$$

If only $(1s)^2$ or $(0p)^2$ $\Longrightarrow$ $\langle\cos\theta_{12}\rangle = 0, \quad \langle\theta_{12}\rangle = 90^\circ$

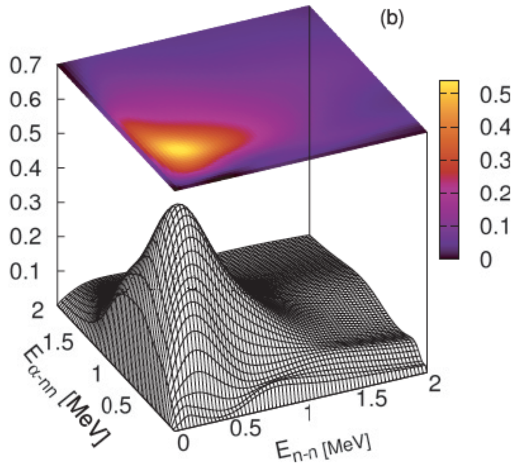
If full overlap $(1s)^2$ & $(0p)^2$ $\Longrightarrow$ $\langle\cos\theta_{12}\rangle = 1/\sqrt{3}, \quad \langle\theta_{12}\rangle = 55^\circ$

If 50% overlap integral $\Longrightarrow$ $\langle\cos\theta_{12}\rangle = 1/(2\sqrt{3}), \quad \langle\theta_{12}\rangle = 73^\circ$

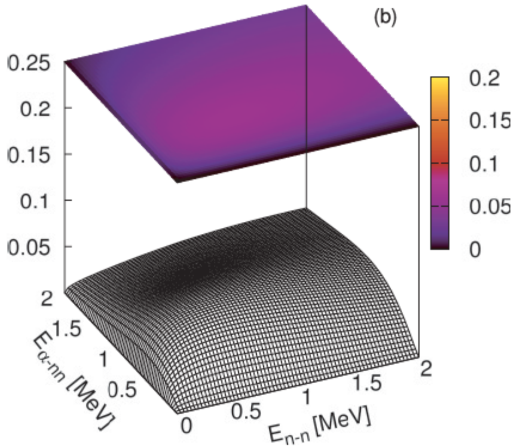
Mixture of different parity states is essential !

➡ T. Nakamura, Phys. Rev. Lett 96 (2006)

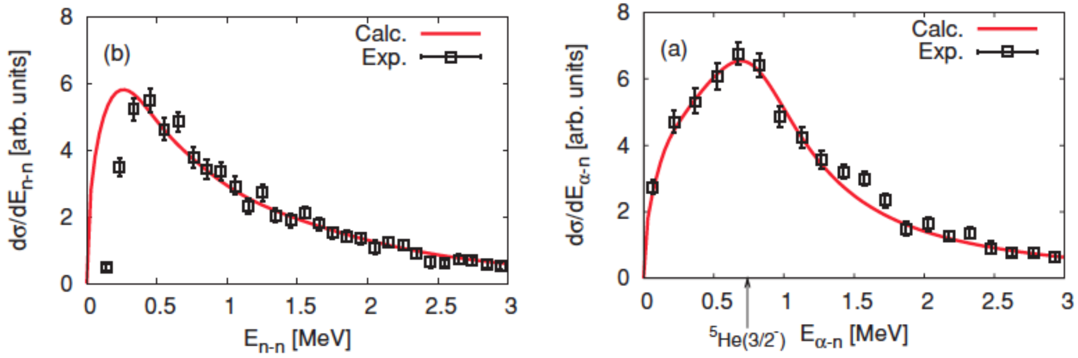
Coulomb dissociation B(E1) : limitation (^{6}He case)



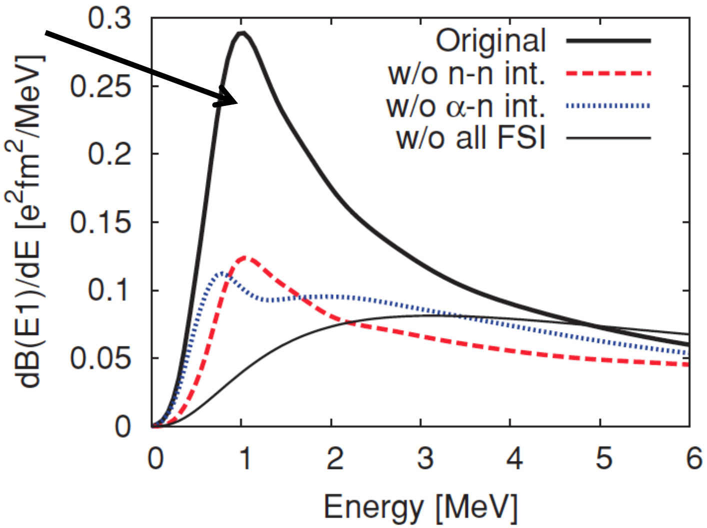
No nn g.s. correlation measurable !



→ *Y. Kikuchi, Phys. Rev. C 81 (2010)*



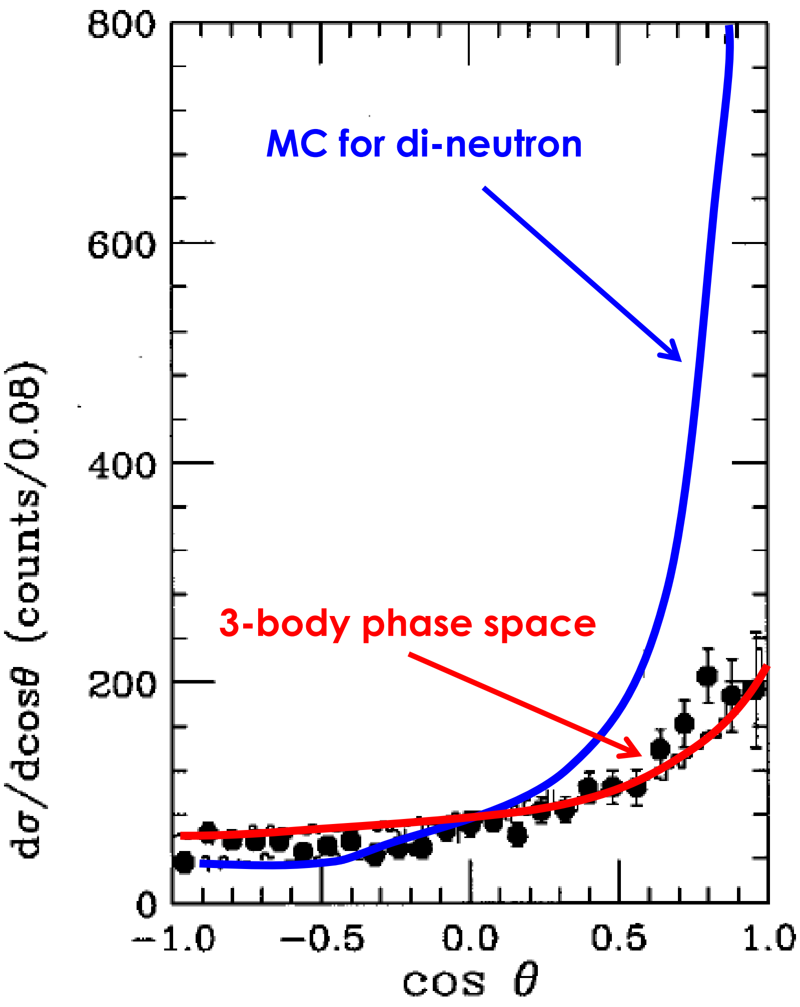
peak due to nn FSI
not nn initial



nn FSI and a-n FSI comparable and very important !
What for ^{11}Li ? (s component)

Coulomb dissociation : Angular correlations

Dissociation of ^{11}Li + ^{208}Pb @ 28 MeV/A



Conditions to observe initial correlations :

(1) $p_\gamma \ll p_{9Li}$ & $p_\gamma \ll p_n$

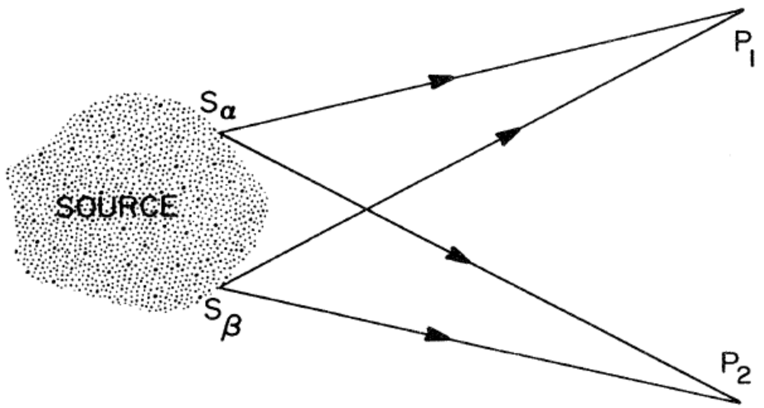
p_{9Li} ~30 MeV/c
p_n ~20 MeV/c
p_γ ~ 1 MeV/c

(2) sudden absorption of the γ

interaction time ~ 100 fm/c
rotation period of neutrons ~ 1000 fm/c

➡ ***K. Ieki et al, Phys. Rev. C (1993)***

Coulomb Break-up : Principle of intensity interferometry



experiment

$$C_{nn}(p_1,p_2) = \frac{\boxed{d^2n/dp_1dp_2}}{\boxed{(dn/dp_1)(dn/dp_2)}}$$

event mixing

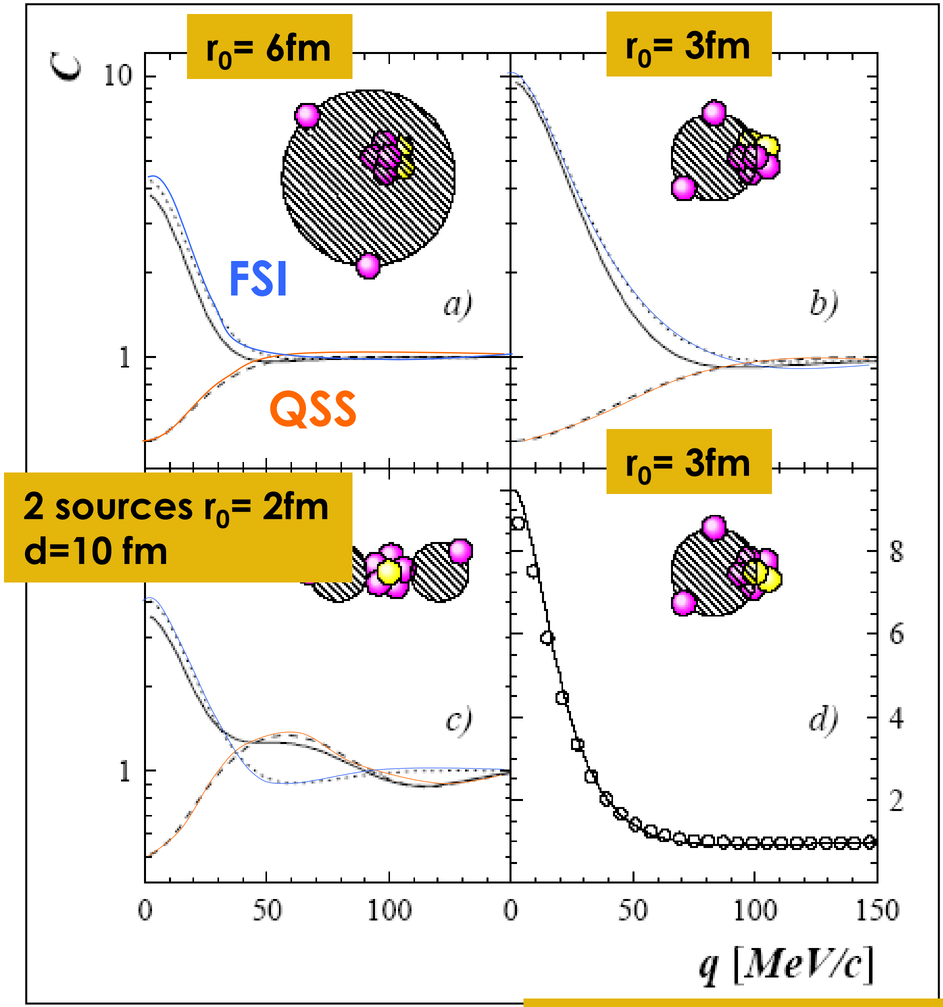
C_{nn} governed by **FSI**
(attractive for neutrons)
and **QSS**
(repulsive for fermions)

If the emission is simultaneous :
C_{nn} isolates n-n configurations

- **stellar interfeormetry: `**
  source = star
- **nuclear interferometry :**
  source= interaction region
  with evolution in time

➡ ***M. Marquès et al, Phys. Lett. B 476 (2000)***

Coulomb Break-up : Principle of intensity interferometry



Comparison with resonance of 50 fm/c

experiment

$$C_{nn}(p_1,p_2) = \frac{d^2n/dp_1dp_2}{(dn/dp_1)(dn/dp_2)}$$

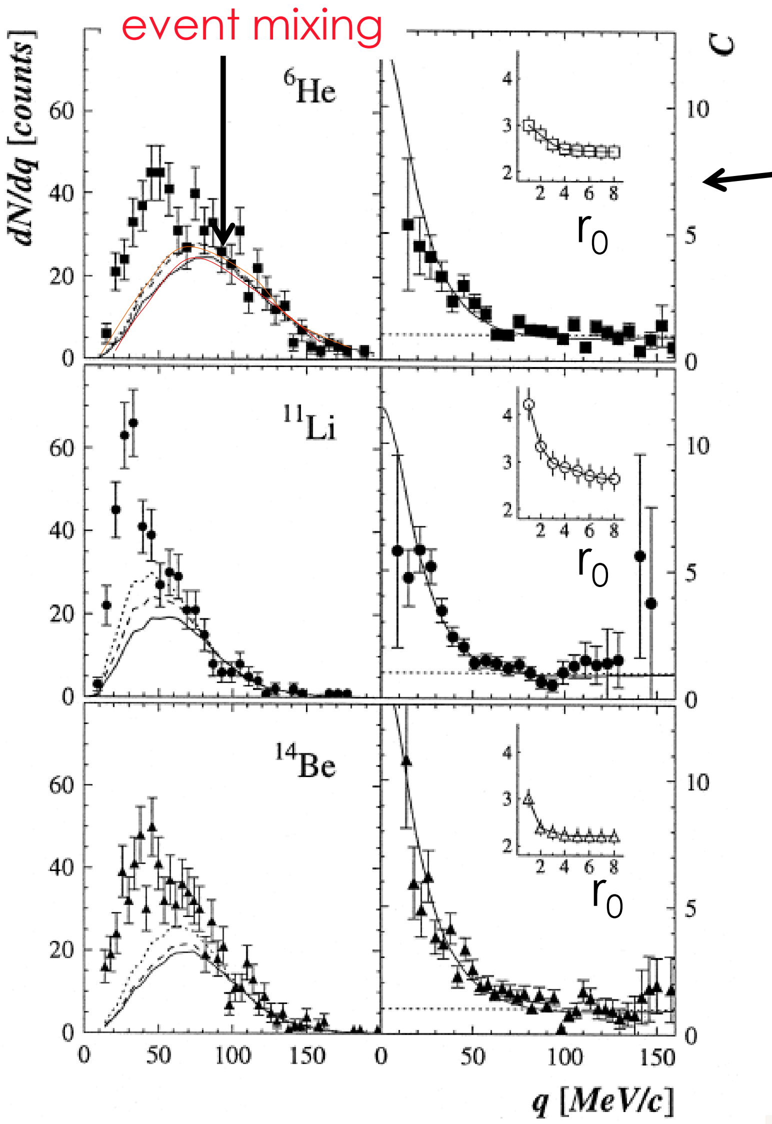
event mixing

C$_{nn}$ governed by **FSI**
(attractive for neutrons)
and **QSS**
(repulsive for fermions)

If the emission is simultaneous :
C$_{nn}$ isolates n-n configurations

➡ ***M. Marquès et al, Phys. Lett. B 476 (2000)***

Coulomb Break-up : Measurements by interferometry



experiment

$$C_{nn}(p_1,p_2) = \frac{d^2n/dp_1dp_2}{(dn/dp_1)(dn/dp_2)}$$

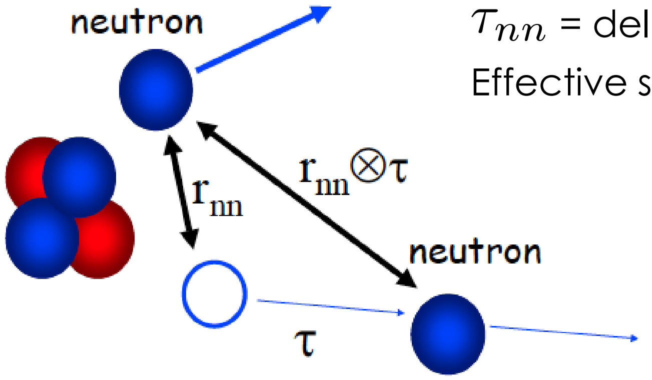
event mixing

	r_0 [fm]	$r_{\mathrm{nn}}^{\mathrm{rms}}$ [fm]
3-body		4.6–5.0
E295	**2.4 ± 0.5**	5.9 ± 1.2
MSU 93	**5.3 ± 0.6**	**13.0 ± 1.5**
3-body		6.7–8.3, 7.1 (8.3), 7.0
E295	**2.7 ± 0.6**	6.6 ± 1.5
3-body		6.1, 4.5–8.4
E295	**2.2 ± 0.4**	5.4 ± 1.0

⋆ Deuteron: $r_{\mathrm{np}}^{\mathrm{rms}} \sim$ **3.8** fm

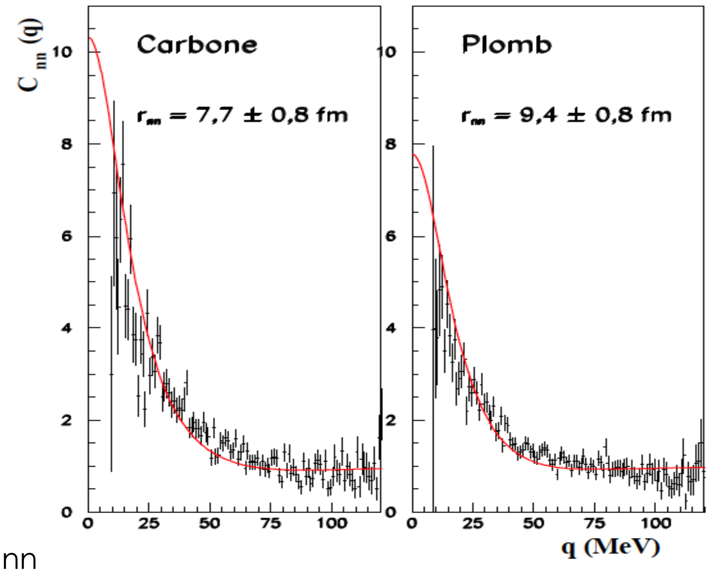
➡ ***M. Marquès et al, Phys. Lett. B 476 (2000)***

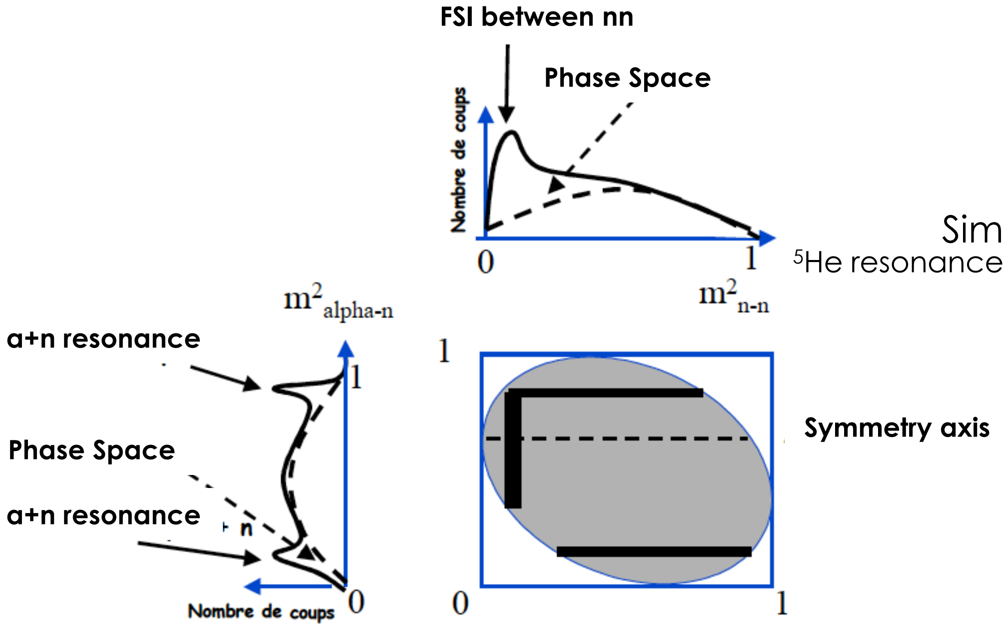
Coulomb Break-up : Measurements by interferometry



τ_{nn} = delay associated to the lifetime of the resonance

Effective source size= $r_{nn} \otimes \tau_{nn}$





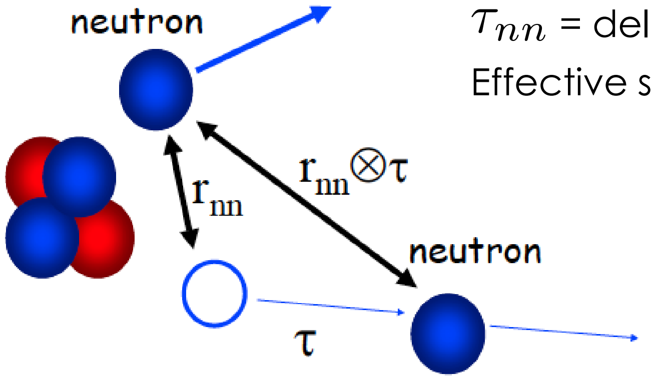
Simulations

^{5}He resonance

FSI nn

➡ ***M. Marquès et al, Phys. Rev. C 64 (2001)***

Coulomb Break-up : Measurements by interferometry



τ_{nn} = delay associated to the lifetime of the resonance

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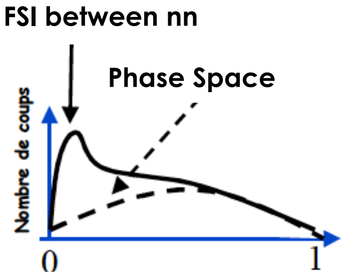
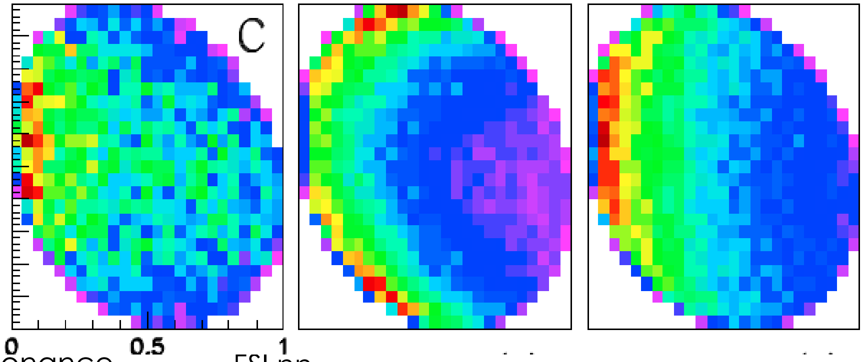
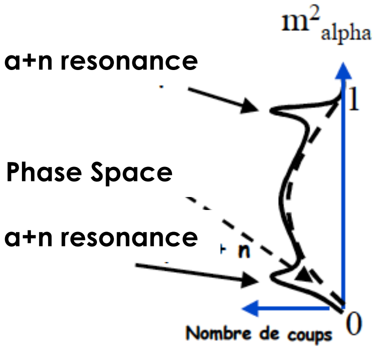
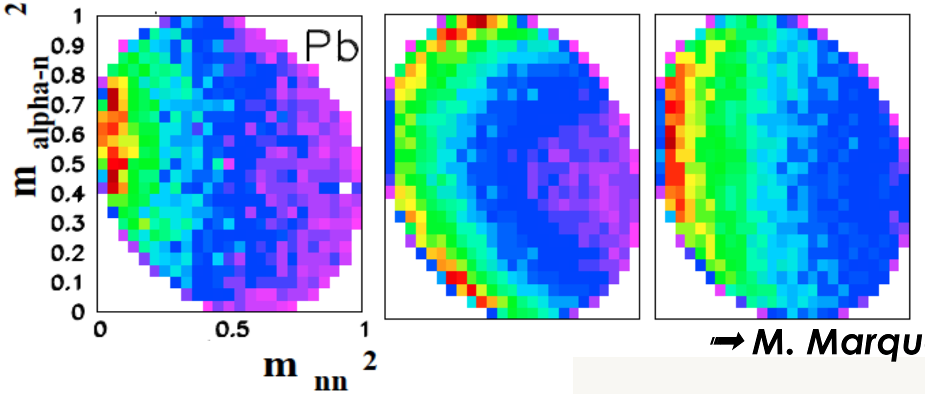




^{5}He resonance

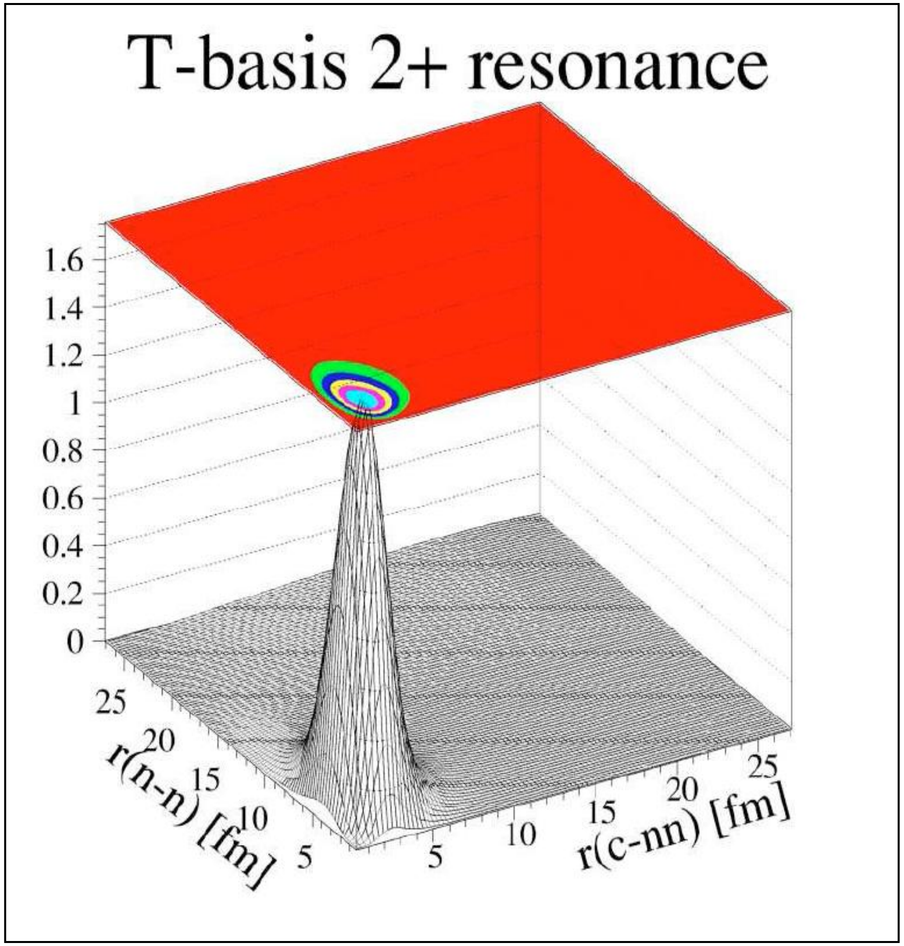
FSI nn

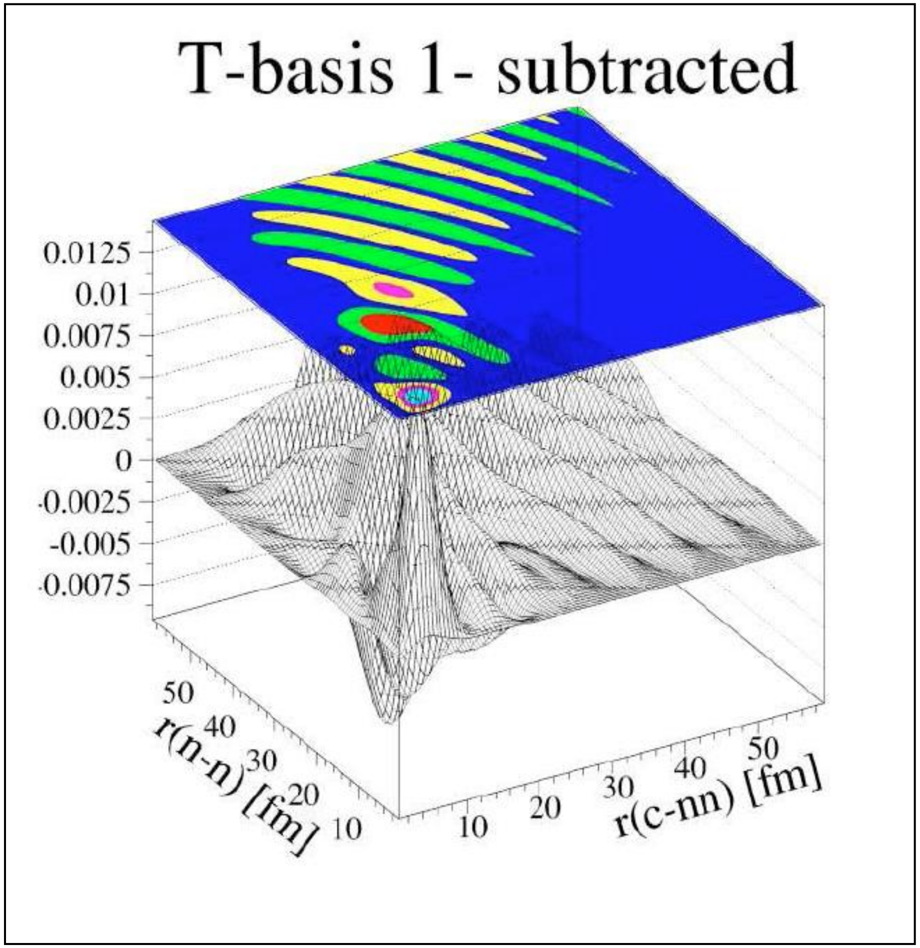




➞ ***M. Marquès et al, Phys. Rev. C 64 (2001)***

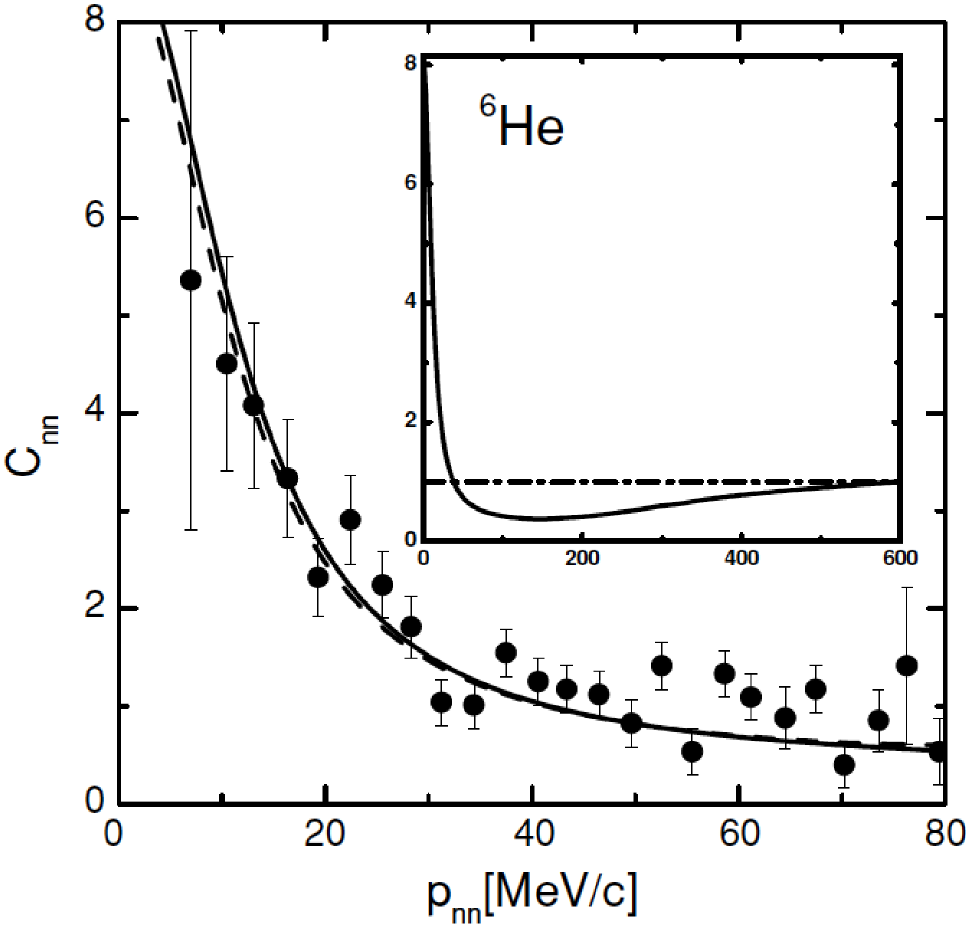
Continuum structure of 6He*: limits of the approach (I)





* B Danilin *et al.*, PRC69 (2004)

Effect of normalization : limits of the approach (I)



2 neutrons =coherent source

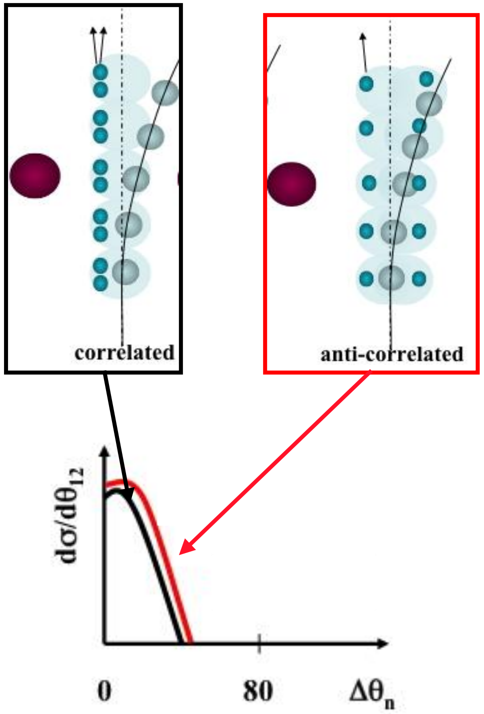
nn FSI + 3 body for the halo nucleus

FSI distort the relative motion of the 2n and creates a minimum in the correlation function

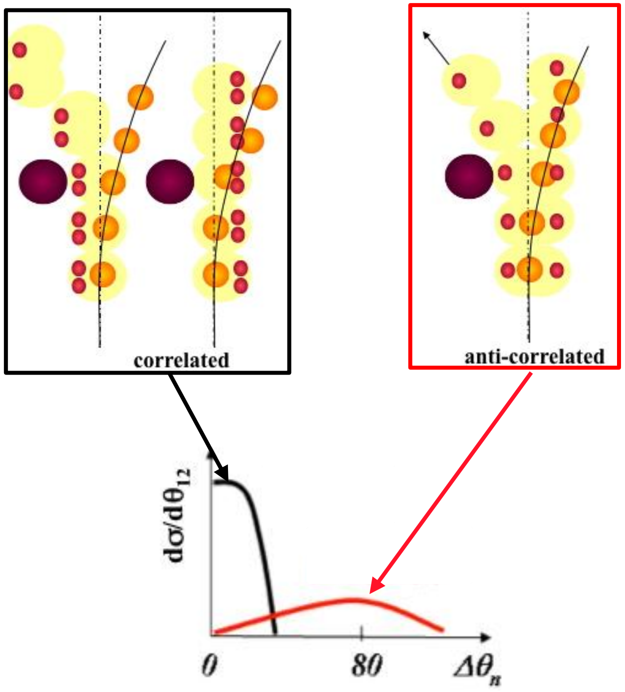
➡ ***Yamashita et al, Phys. Rev. C 72(2004)***
Data : Marquès et al, Phys Lett. B (2000)

Angular correlations : coulomb BU vs. nuclear BU

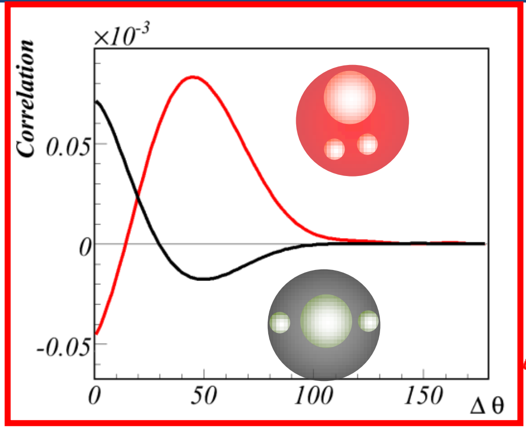
Coulomb break-up



Nuclear break-up



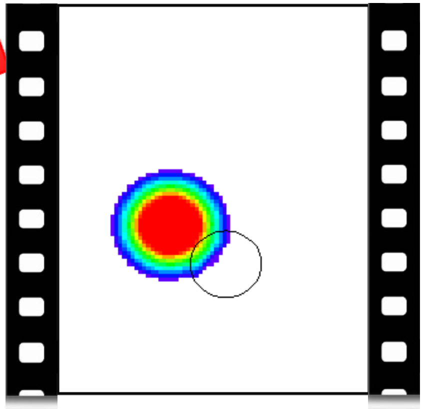
Angular correlations with nuclear break-up



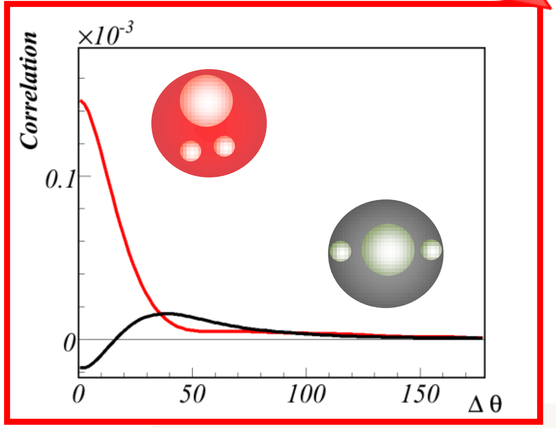
Initial correlations

TDDM^P calculations

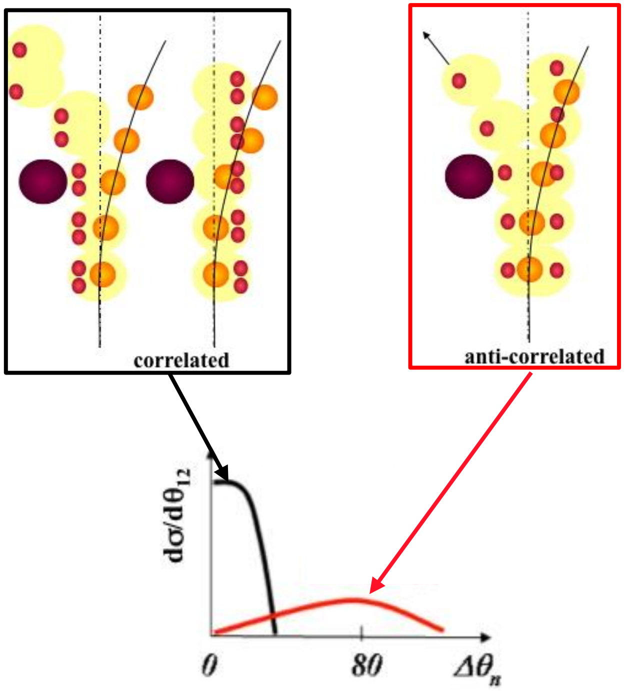
2-body correlations beyond mean-field



Final correlations



Nuclear break-up



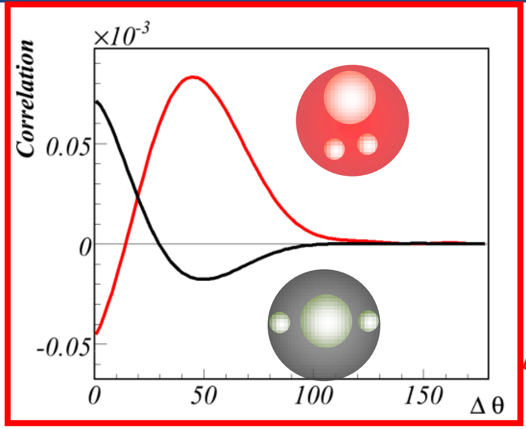
➡ ***MA, D. Lacroix, Phys. Rev. Lett. (2009)***

Angular correlations with nuclear break-up

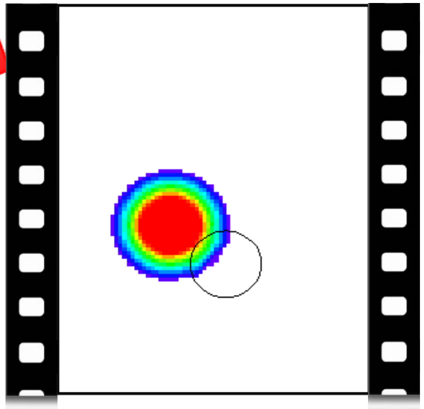
TDDM^P calculations

. TDHF + 2-body correlations (beyond mean-field)

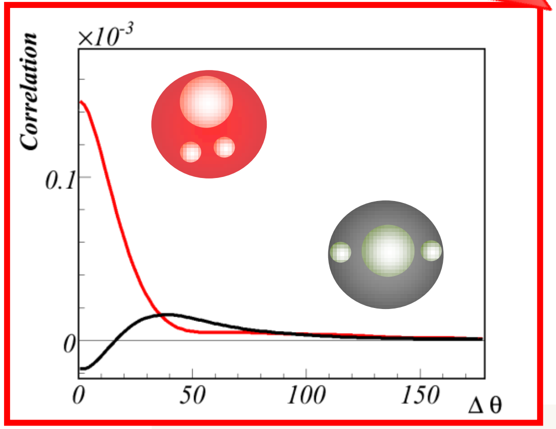
. fully microscopic 3D calculations

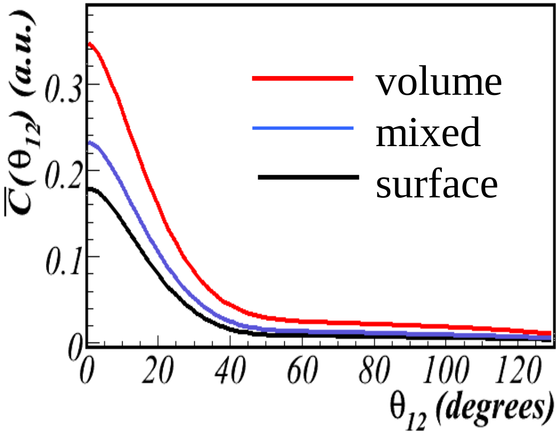


Initial correlations



Final correlations





Nuclear break-up is sensitive to the type of residual interaction

➡ MA, D. Lacroix, Phys. Rev. Lett. (2009)

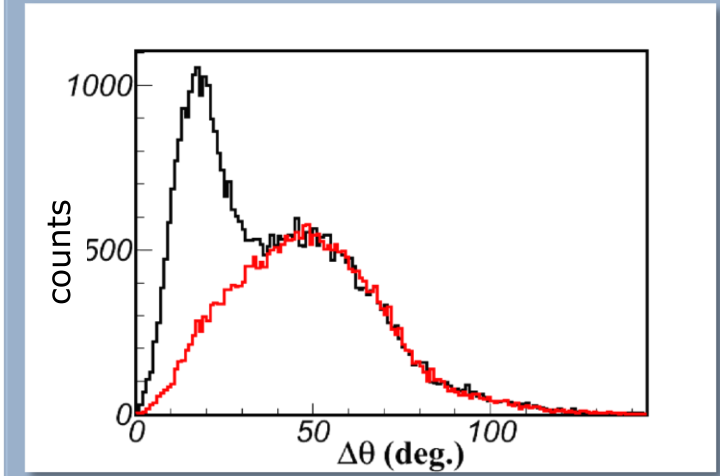
Case of ^{6}He

Correlation function

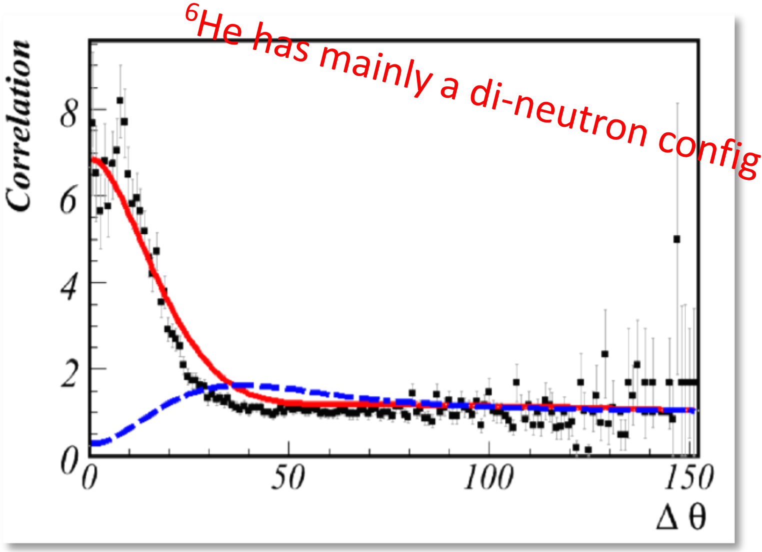
experimental distribution :
emission of correlated neutrons

$$C_{12} = \frac{P(n_1,n_2)}{P(n_1)\,P(n_2)}$$

independent emission



^{208}Pb(^{6}He,^{4}He+n+n) @ 20 MeV


^{6}He has mainly a di-neutron configuratio

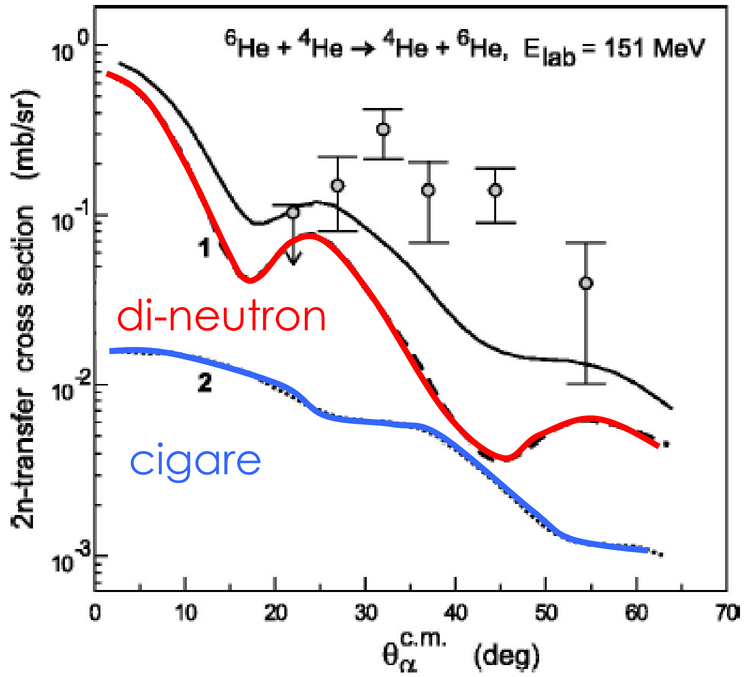
Comparison with theoretical models :

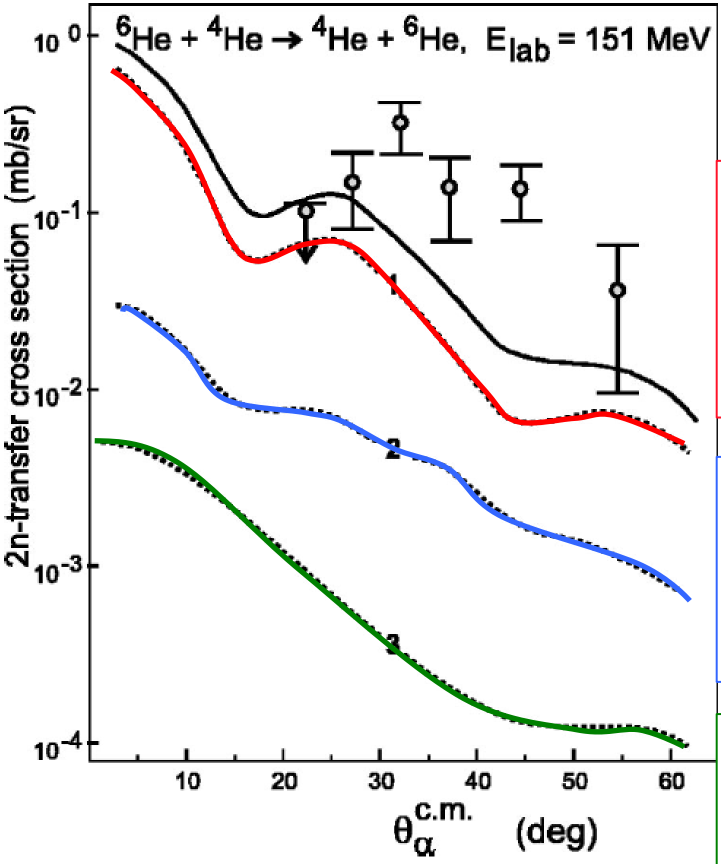
- **4b CDCC** :
  excitation energy up to 30 MeV
- **TDDM^P** :
  few nucleons, very tightly bound

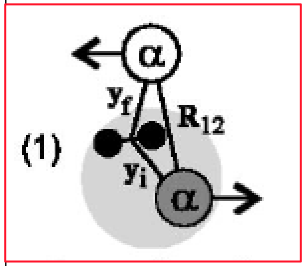
➡ ***MA et al, Eur. Phys. J. A (2009)***

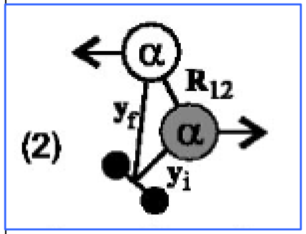
Two-nucleon transfer experiments

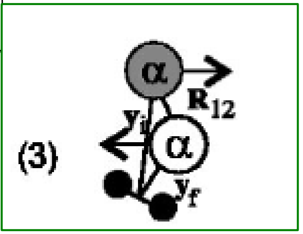
^{4}He(^{6}He, ^{4}He)^{6}He (g.s.), Elab= 151 MeV







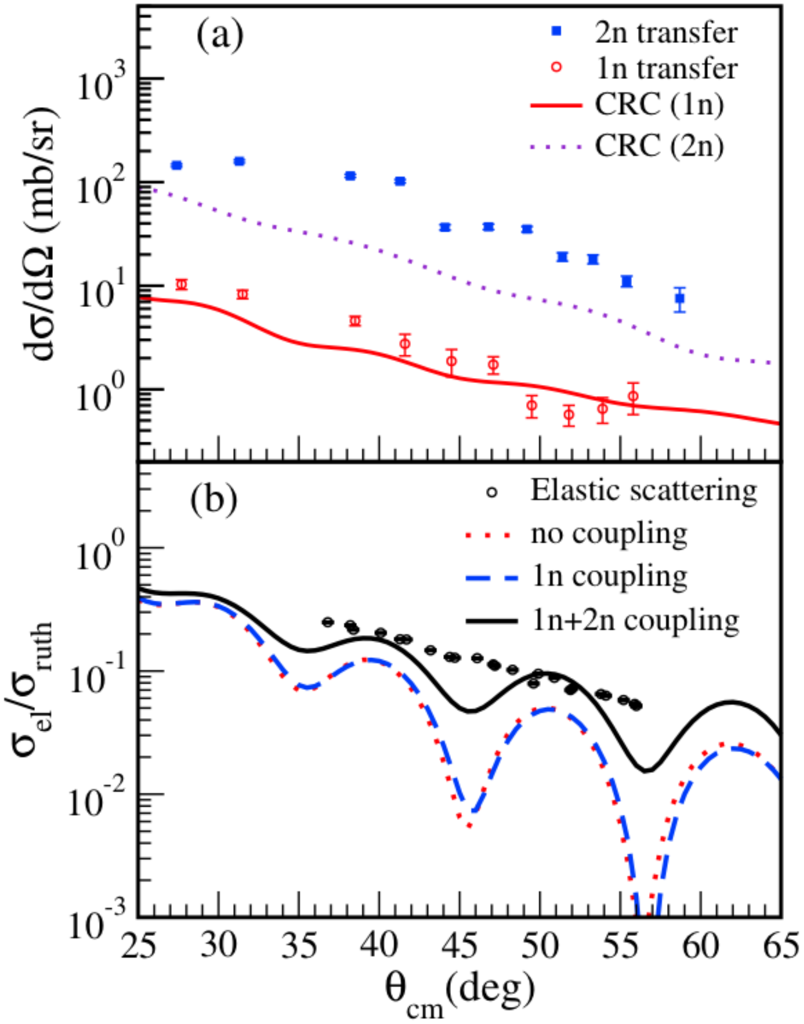


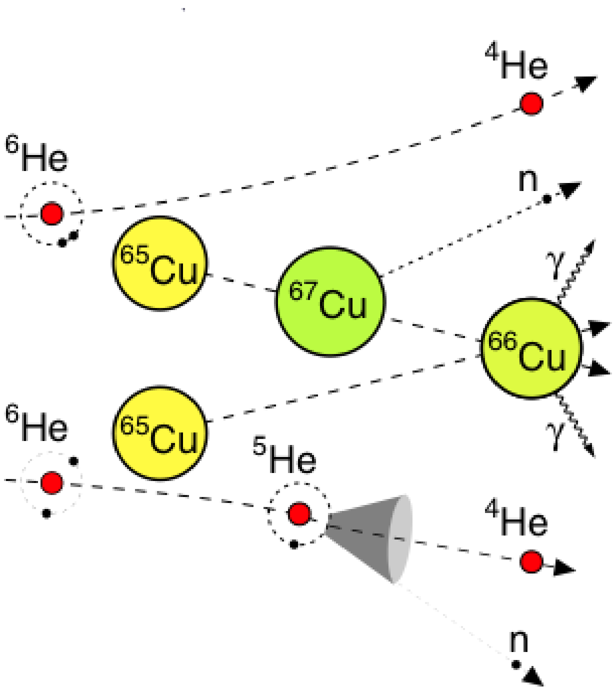


Di-neutron configuration dominant (particularly below 10MeV/A

➡ ***Y. Oganessian, Phys. Rev. Lett. & Phys. Rev. C (1999)***

Two-nucleon transfer experiments





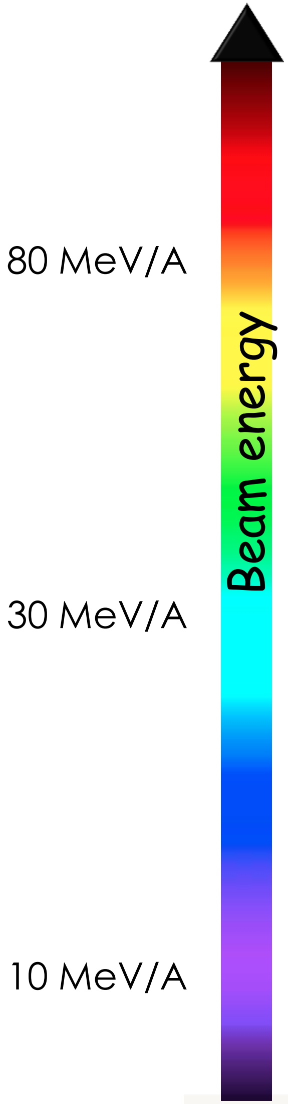
2n-transfer

1n-transfer
(alpha-n correlation)

Di-neutron configuration plays an important role in the reaction mechanisms

➡ ***A. Chatterjee, Phys. Rev. Lett. (2008)***

Experimental studies of pairing



Rotation period of a nucleon on a p-shell = 600 fm/c

sudden approximation ?

Coulomb BU: $T_{reaction}$ = 100 fm/c

Nuclear BU: $T_{reaction}$ = 50 fm/c

Coulomb dissociation : $T_{reaction}$ =120 fm/c

Transfer : @ 151 MeV (Oganessian et al) $T_{reaction}$ = 100 fm/c
@ 22.6 MeV (Chatterjee et al) $T_{reaction}$ = 300 fm/c

Knock-out : parallel momentum

Several phenomena lead to break-up :

- diffraction (nuclear break-up)
- absorption by target
- coulomb dissociation

+ FSI

Transverse momentum distributions:

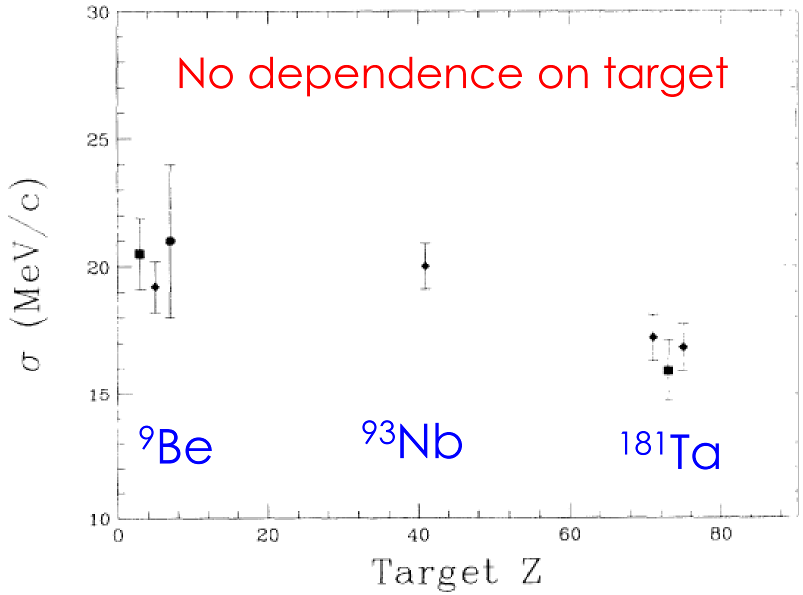
sensitive to the reaction mechanism (deviation of the core by the target)

^{11}Li knock-out @ 66 A. MeV on several targets

$P_{//}$ independent of mechanism

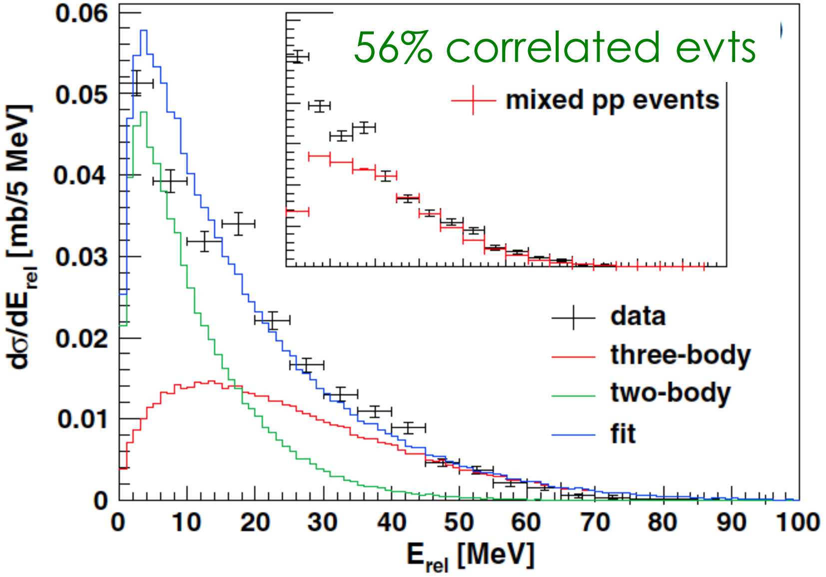
Direct probe of neutrons distribution

$<r^2>^{1/2} = 6$ fm

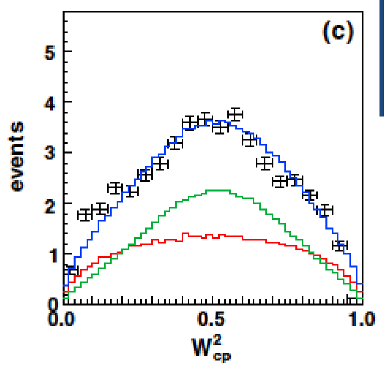


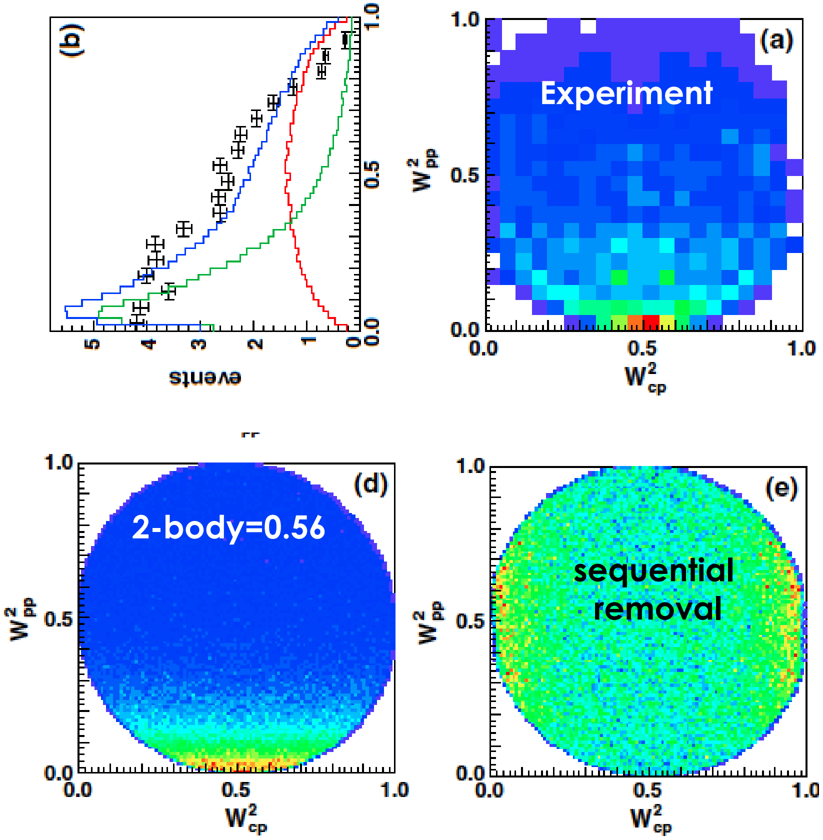
➡ ***N. Orr, Phys. Rev. Lett. 69 (1992), Nucl. Phys. A 616 (1997)***

Two-nucleon knock-out



$^9Be(^{28}Mg,^{26}Ne)$@93A.MeV

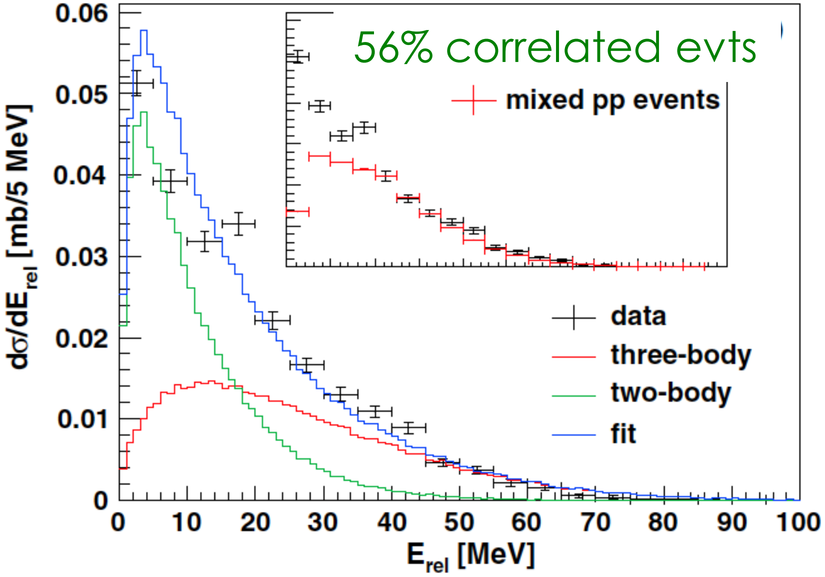




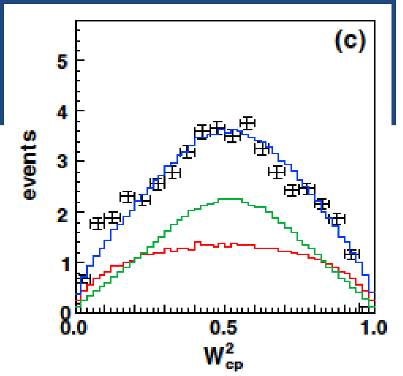
J^π_f	E (MeV)	Overlap ($S = 0$, %)	σ_{th} (mb)	$\sigma_{S=0}$ (mb)	$\sigma_{S=0}$ (%)
0^+	0.0	86	1.190	1.083	90
2^+	2.02	18	0.327	0.071	22
4^+	3.50	38	1.046	0.523	49
2^+_2	3.70	50	0.458	0.250	54
Incl.			3.02	1.93	64

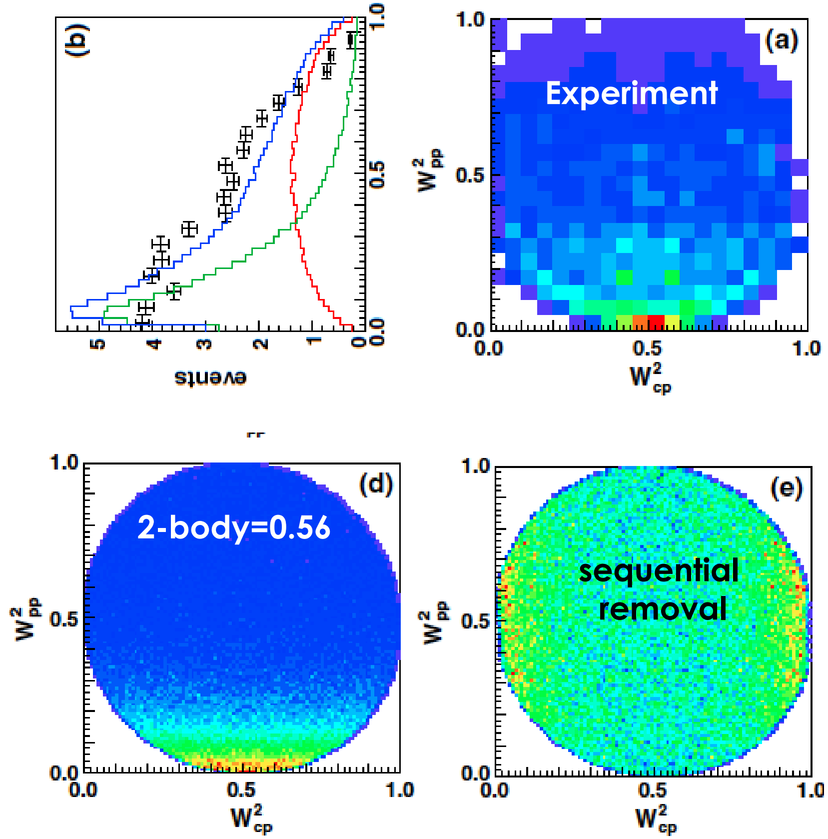
➡ ***K. Wimmer Phys. Rev. Lett. 109(2012)***

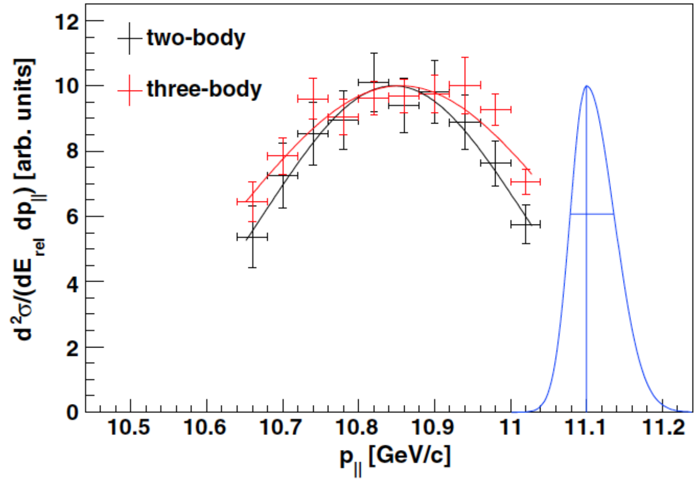
Two-nucleon knock-out



$^{9}Be(^{28}Mg,^{26}Ne)@93A.MeV$





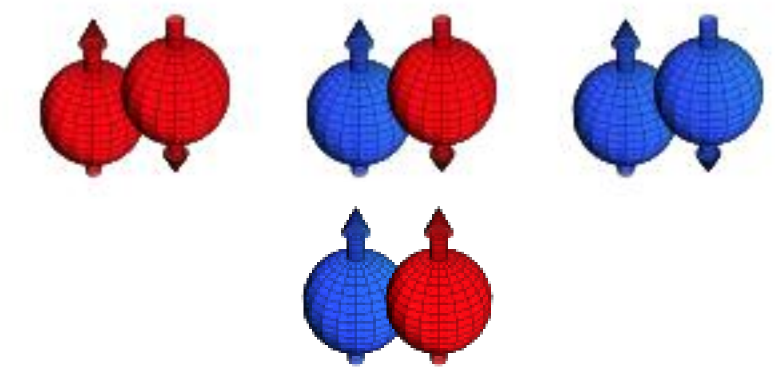


➡ ***K. Wimmer Phys. Rev. Lett. 109(2012)***

n-p pairing in N=Z nuclei

- **Spectrocopy of ^{92}Pd**
- **Deuteron-transfer experiments**

n-p pairing

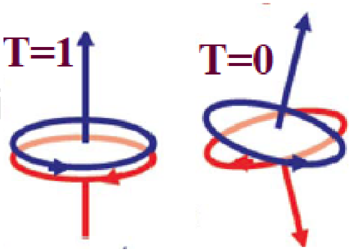


- n-p pairing can occur in 2 different states: **T=0** and T=1. The former is unique to n-p.

- Can be best studied in **N=Z** nuclei through :

  - **spectroscopy**
    ^{92}Pd ➔ B. Cerderwall, Nature 469 (2011) 68

  - **2-nucleon transfer reactions**
    A. Macchiavelli ^{44}T (^{3}He,p), J. Lee (sd-shell nuclei



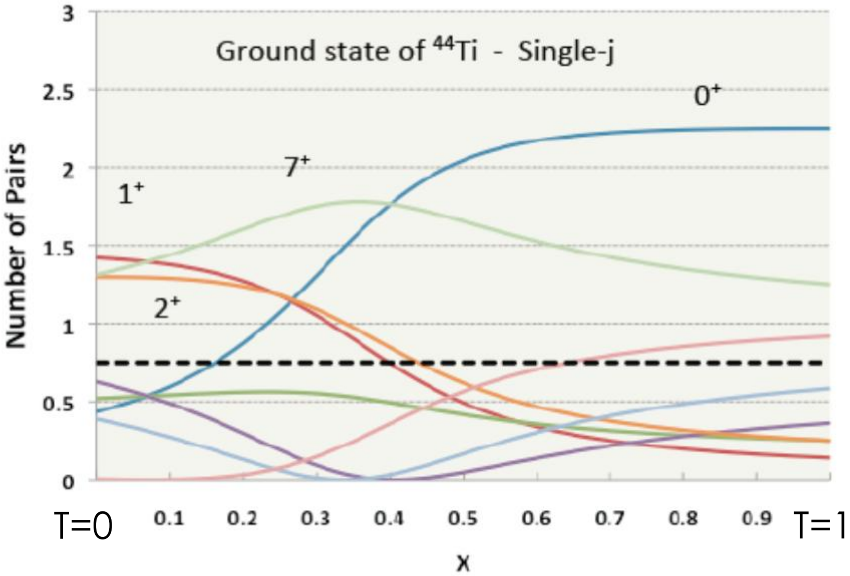
n-p pairing with **transfer reactions**

- If n-p pairing is important, one should see an enhancement of the np transfer probability
- $\sigma(0+)/\sigma(1+)$ reveals pairing
- The transfer can take place in
    - the T=0, S=1 state (**deuteron transfer**)
    - the T=1, S=0 state
- Two reactions can be studied

(p,^{3}He) ΔT = 0,1

(d,α) ΔT = 0 selective

-> study both the T=0 and T=1 pairing



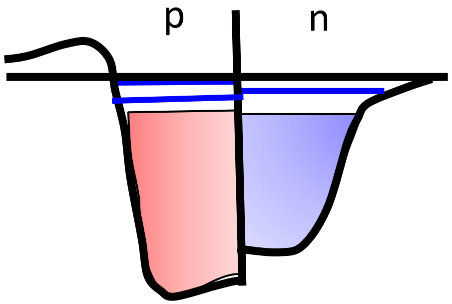
n-p pairing : best candidate for transfer studies

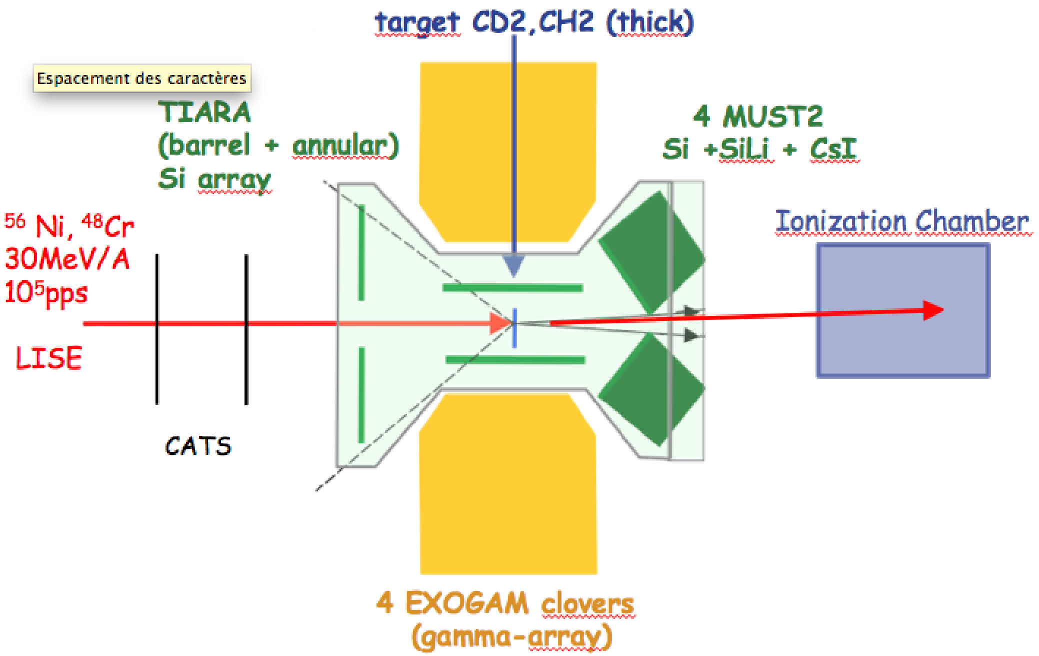
- **middle-shell nucleus + doubly magic nucleus.**
- simultaneously measure other reactions: (p,d), (d,t),(d,p), (d,^{3}He) and (p,t) -> constraints on the **reaction mechanism.**

Which nuclei to study ?

n-p pairing will manifest itself the most in **N=Z nuclei**.
best region: from ^{56}Ni up to mid-shell $g_{9/2}$

^{48}Cr + doubly magic ^{56}Ni

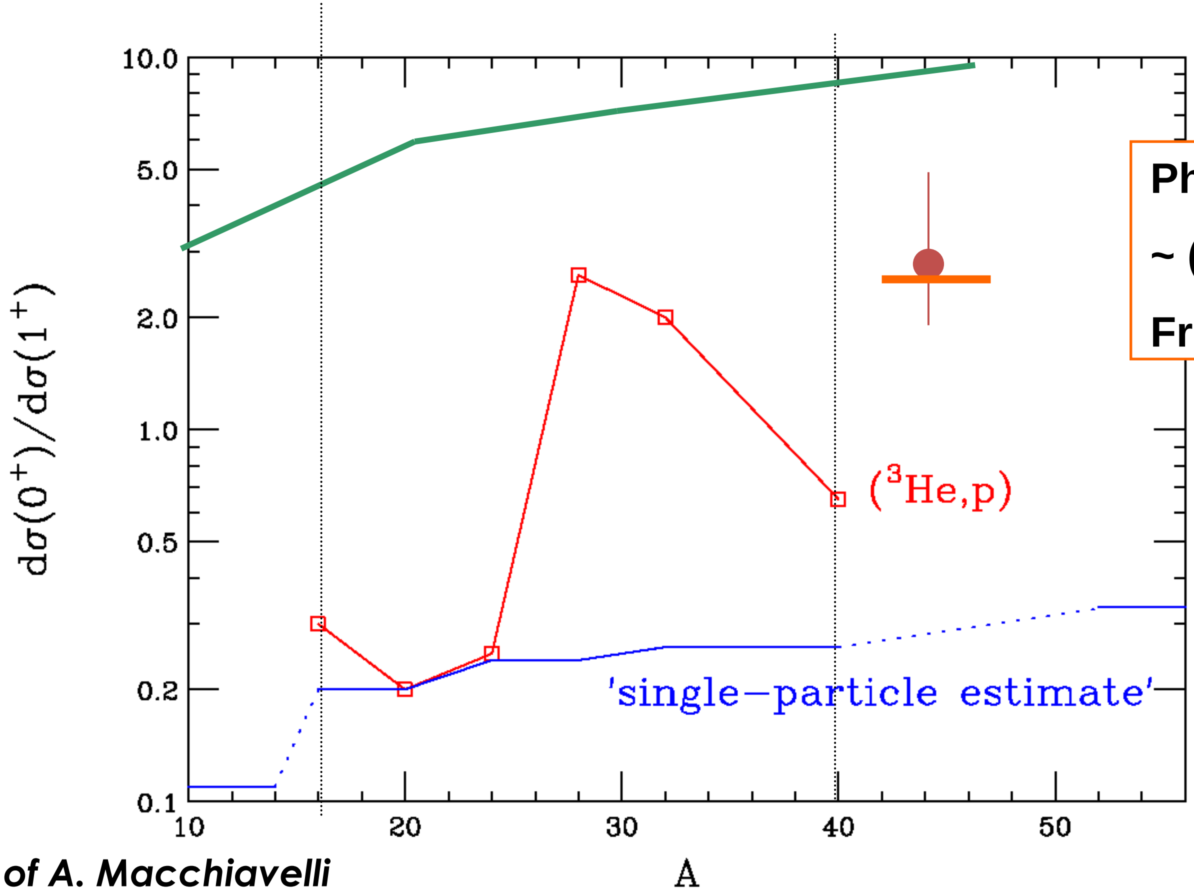




➡ **Experiment to be performed @ GANIL, end of 2013**

Systematic of (^{3}He,p) and (t,p) reactions in stable N=Z nuclei

Superfluid limit ~ $(2\Delta_{T=1}/G)^2$



Phonon Limit

~ (n+1) $\sigma_{0\text{->}1}$

From ^{40}Ca

Courtesy of A. Macchiavelli

Single-particle estimate ~ (spin)x(^{3}He)x(LS -> jj)

Conclusions & Perspectives

- **Experimental study of pairing T=1:**

  several reaction mechanism + formalism
  limits in all methods

  difficult to conclude about nn correlations in light halo nuclei

- **Experimental study of pairing T=0:**

  very beginning of the experimental study.
  Is transfer the best approach ?