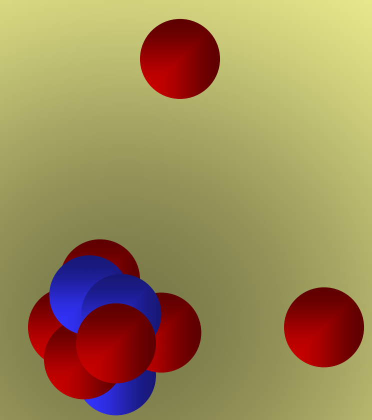
Light Neutron-Rich Systems at and Beyond the Dripline: An Experimental Perspective



Nigel Orr

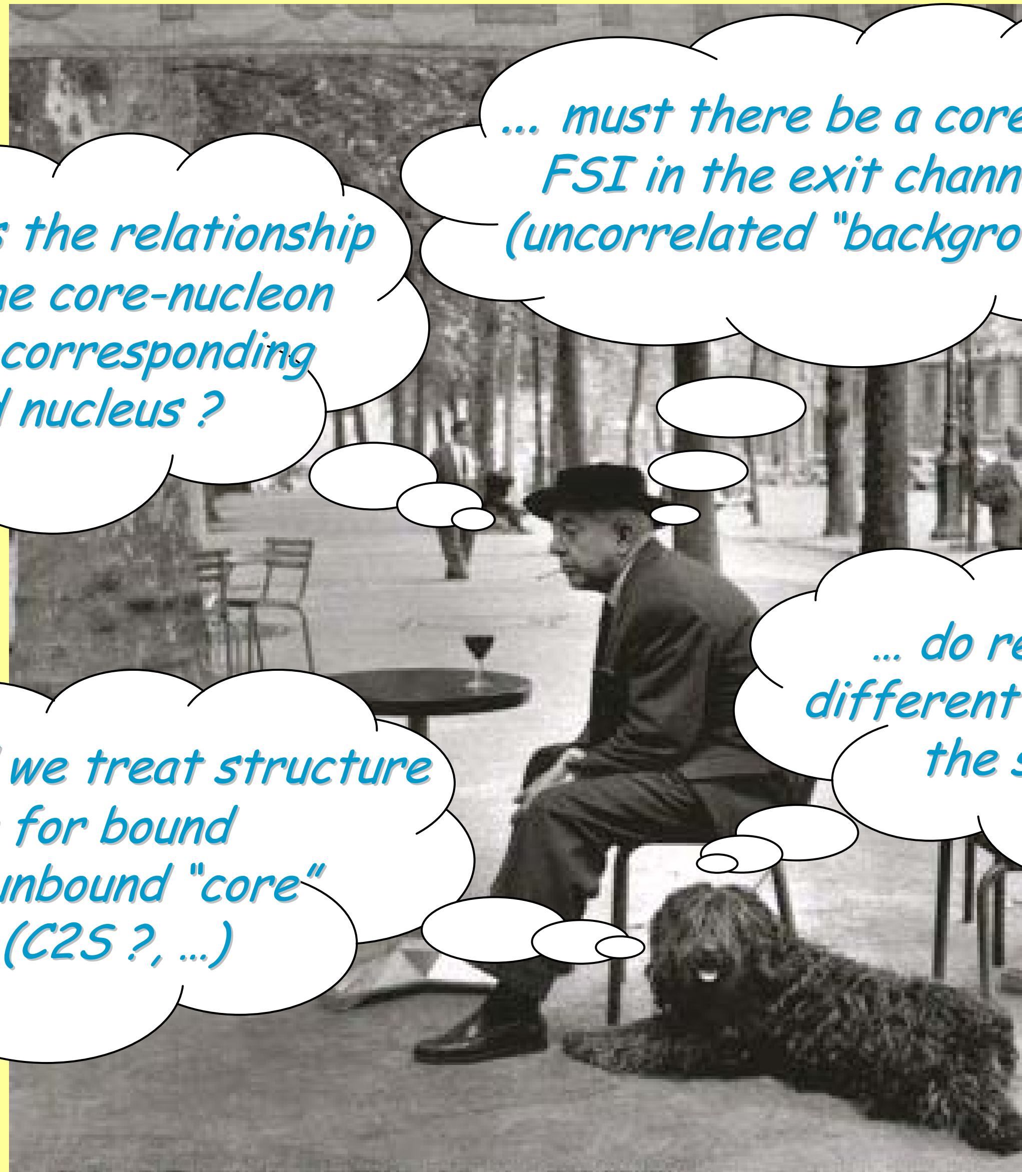
Group "Exotiques" LPC-Caen

LPC-CHARISSA-DEMON Collaboration

… A perspective from the end of the beamline

- Motivation
- High-energy nucleon-removal/“knockout reactions”
- Breakdown in the N=8 shell closure - ^{12}Be
- Structure beyond the driplines
  - Spectroscopy of ^{13}Be
  - Spectroscopy of ^{16}B
- Conclusions & Perspectives

Issues/questions to ponder …



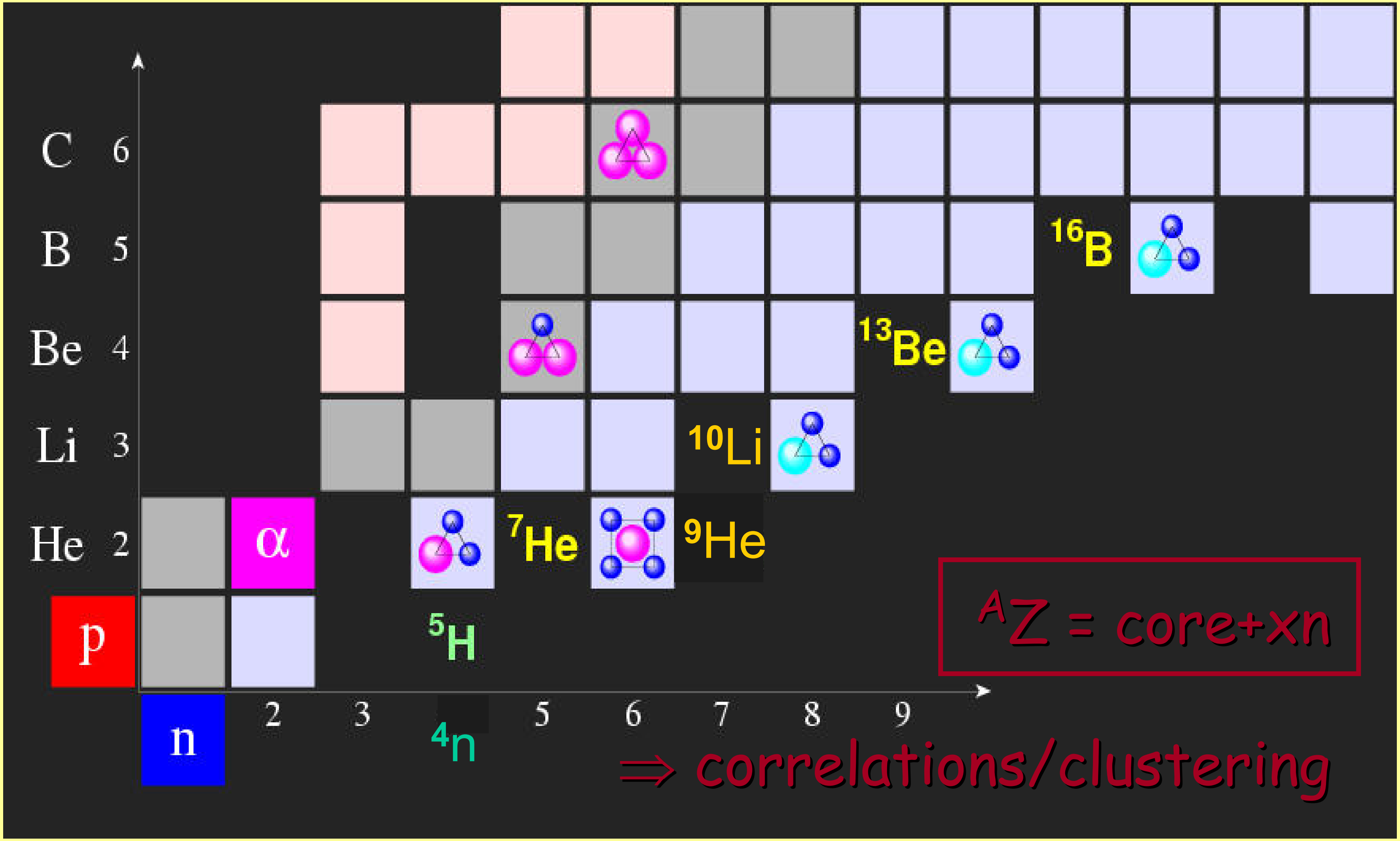
... must there be a core-nucleon FSI in the exit channel ? (uncorrelated "background")

... what is the relationship between the core-nucleon E_{rel} and the corresponding unbound nucleus ?

… do reactions at very different energies populate the same states?

… how **<u>should</u>** we treat structure + reaction for bound projectile → unbound "core" states ? (C2S ?, …)

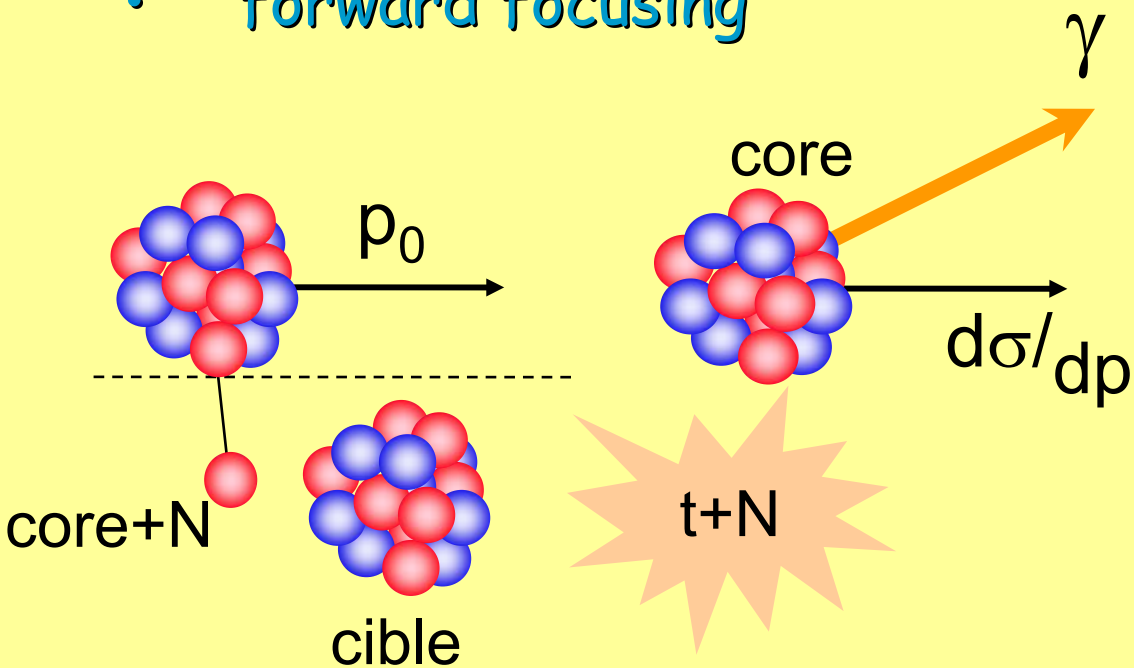
Structure of light, very neutron-rich systems ...

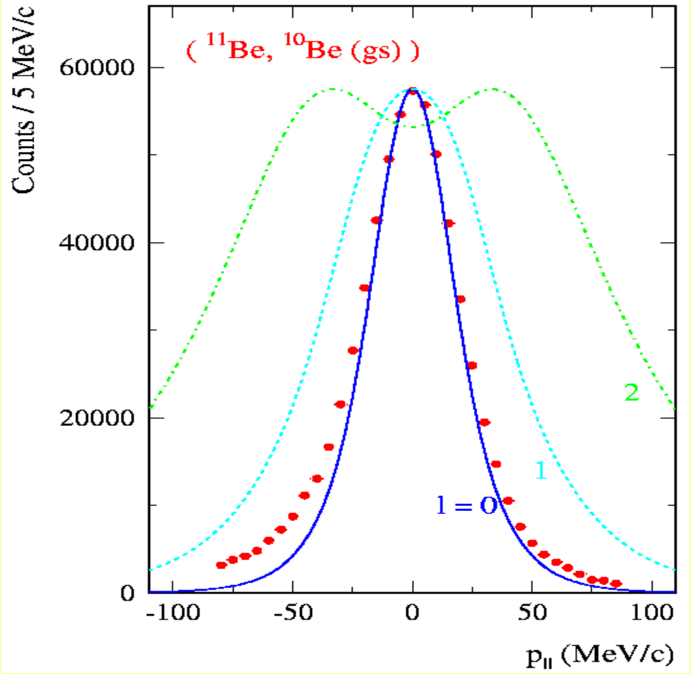


... driplines and beyond experimentally accessible
ab initio calculations tractable, Shell Model in Continuum, ...

High-Energy, Single-Nucleon Removal/"Knockout"

- σ_{-1n} ~ 10-100mb, ρ_s ~ 100 mg/cm2
- forward focusing



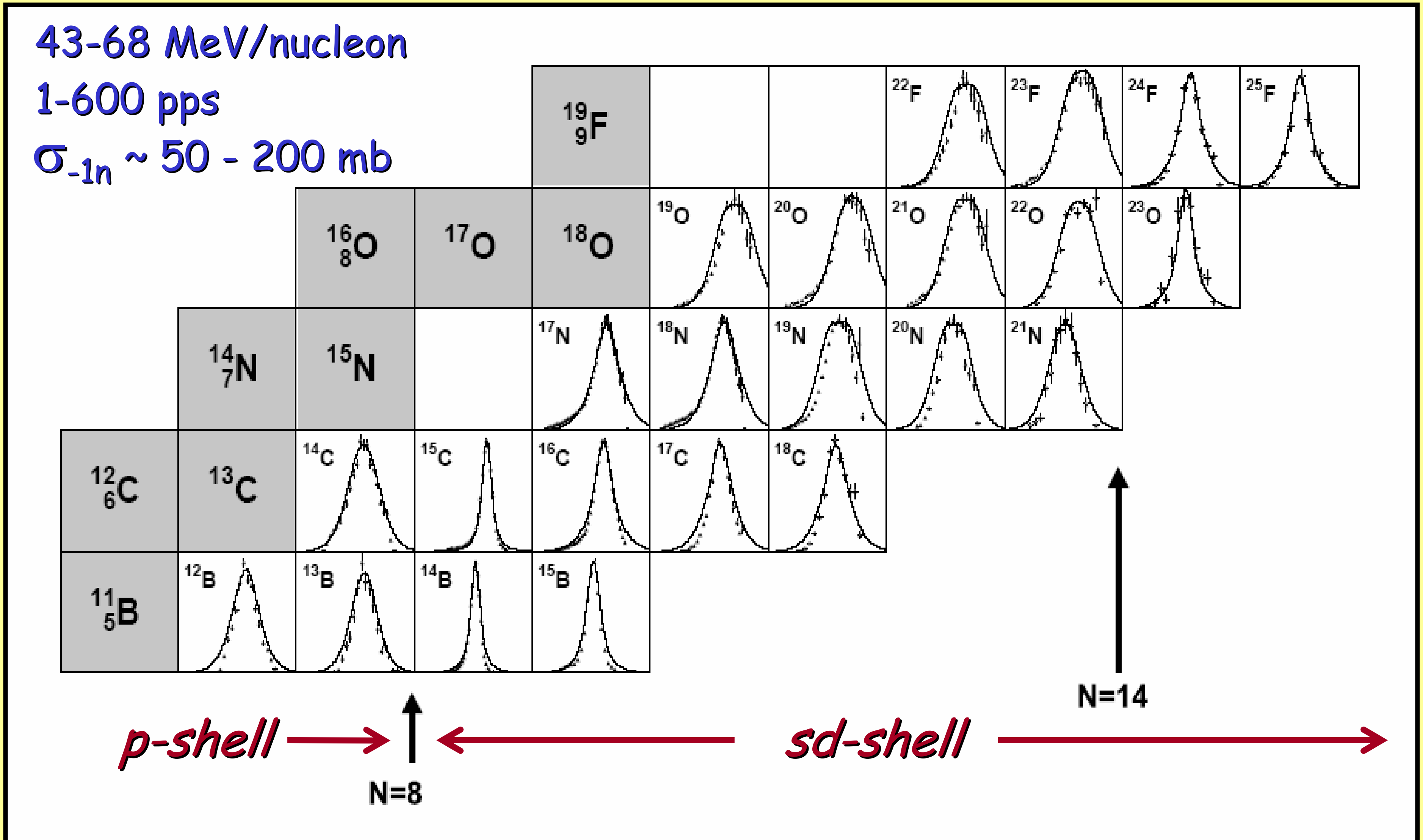


$$\boxed{\gamma \Rightarrow E^x_{core} \qquad d\sigma/dp \Rightarrow \ell_n \qquad \sigma_{-1n}(J^\pi_{core}) \Rightarrow C^2S}$$

Review: Hansen & Tostevin, Ann. Rev. Part. Nucl. Sci. (2003)

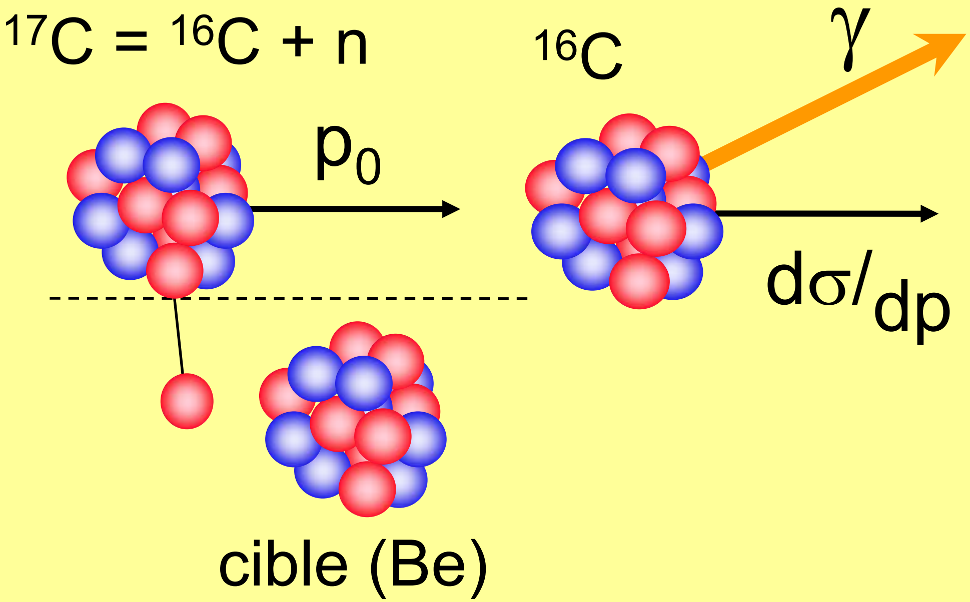
Nucleons c/- Jeff Tostevin

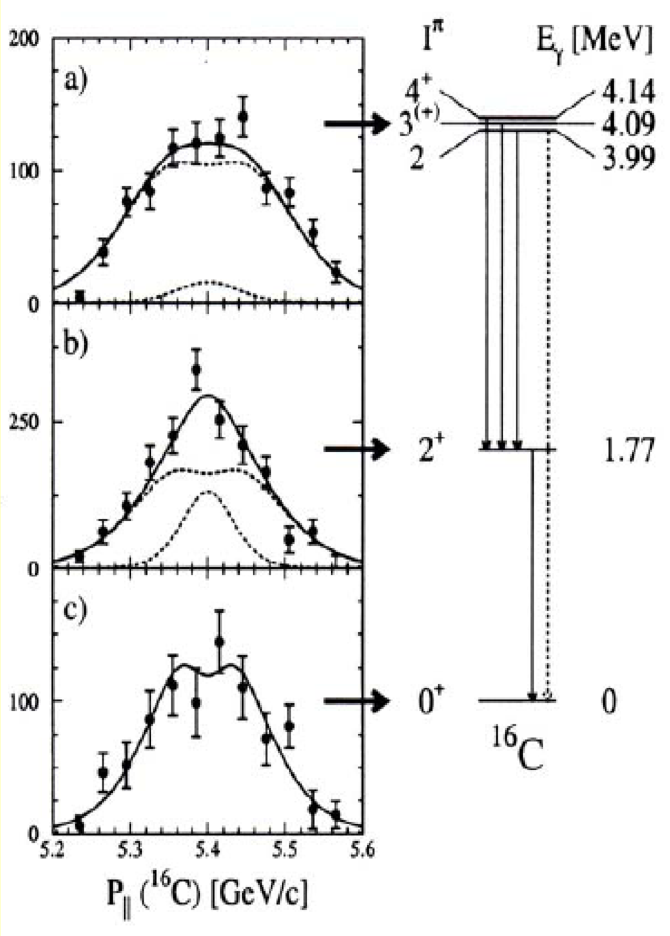
Single-Neutron Removal in the p-sd shell



Inclusive Expt v 's Glauber Theory + Shell Model: Sauvan et al., PRC (2004)

High-Energy, Single-Nucleon Removal as a Spectroscopic Tool





$$\sigma_{sp}(j,B_n) = \overbrace{\sigma_{sp}^{\mathrm{diff}}(j,B_n)}^{\mathrm{T(gs)+n}} + \overbrace{\sigma_{sp}^{\mathrm{strip}}(j,B_n)}^{\mathrm{T^*}}$$

$$\sigma(nI^{\pi}) = \sum C^2 S(j,nI^{\pi})\, \sigma_{sp}(j,B_n)$$

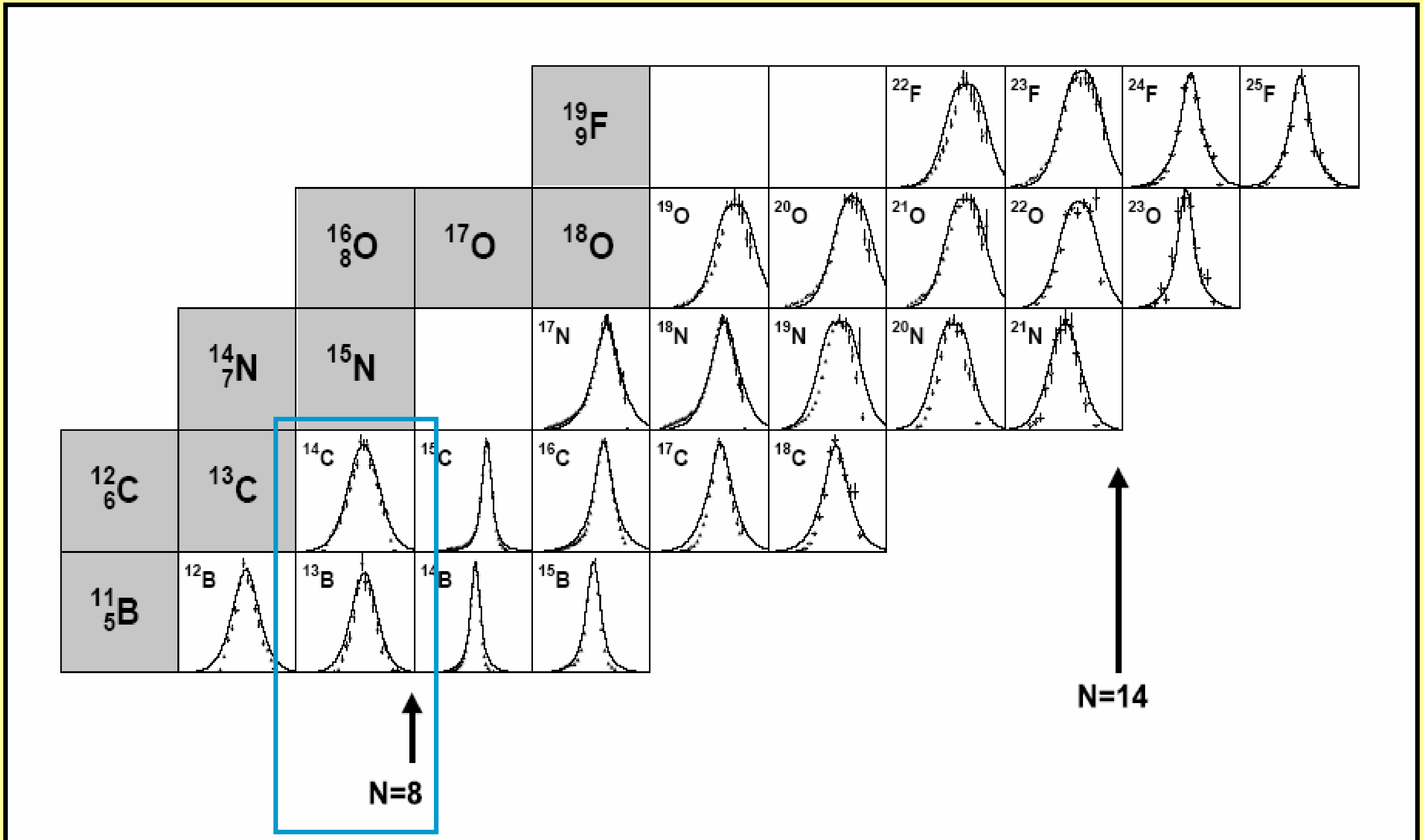
$\mathrm{Be}(^{17}C,^{16}C^*)X$

NSCL/MSU – S800 + NaI

Glauber/eikonal reaction theory

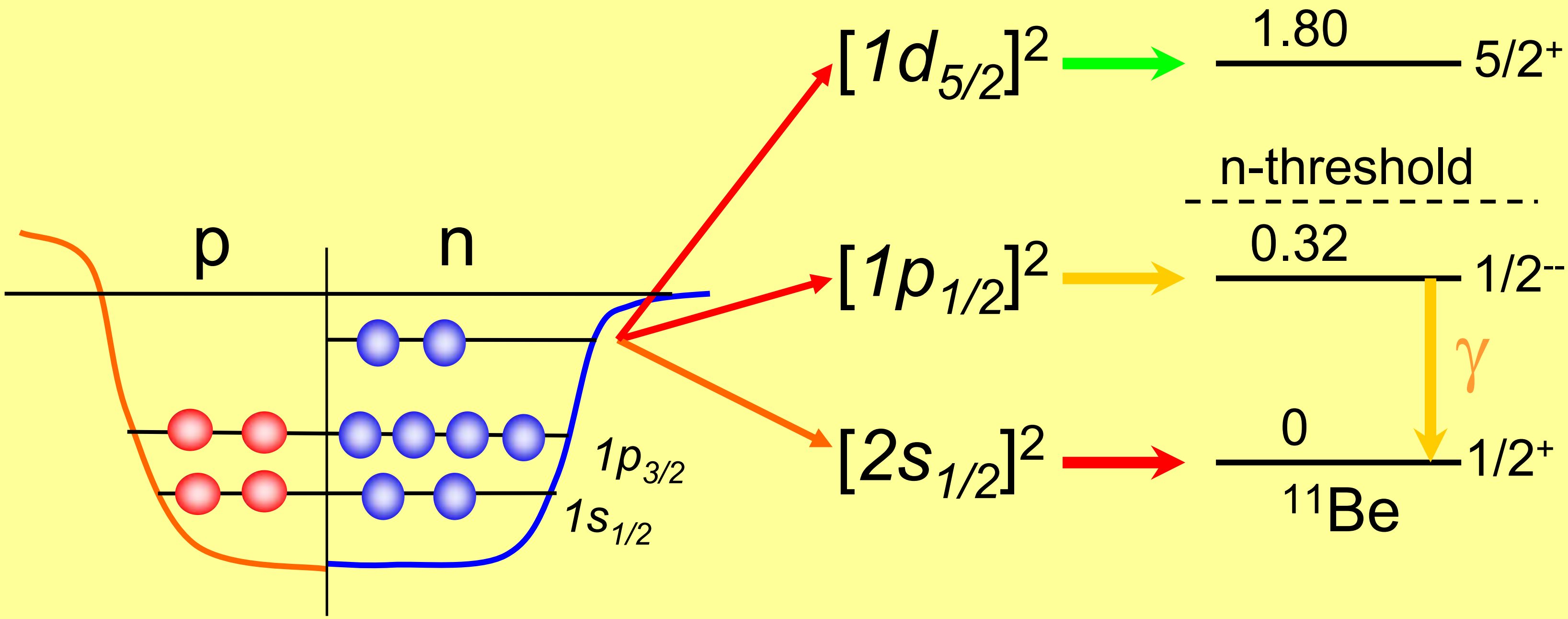
V. Maddalena et al. PRC (2001)

N=8 shell closure : νp^6 ?



^{14}C and ^{13}B ≡ "good" closed p-shell nuclei … ^{12}Be ? (^{11}Li, ^{10}He?)

N=8 shell closure - ^{12}Be ? *



psd-shell ordering in ^{12}Be?

•nb: first proposed by Fred Barker [J. Phys. G (1976)]
indirect measurements - RIKEN (p,p'), …, ^{10}Be(t,p), …

Figure c/- Jeff Tostevin (Surrey/MSU/Tokyo/…)

N=8 shell closure: C(^{12}Be,^{11}Beγ) @ 78 MeV/nucleon *

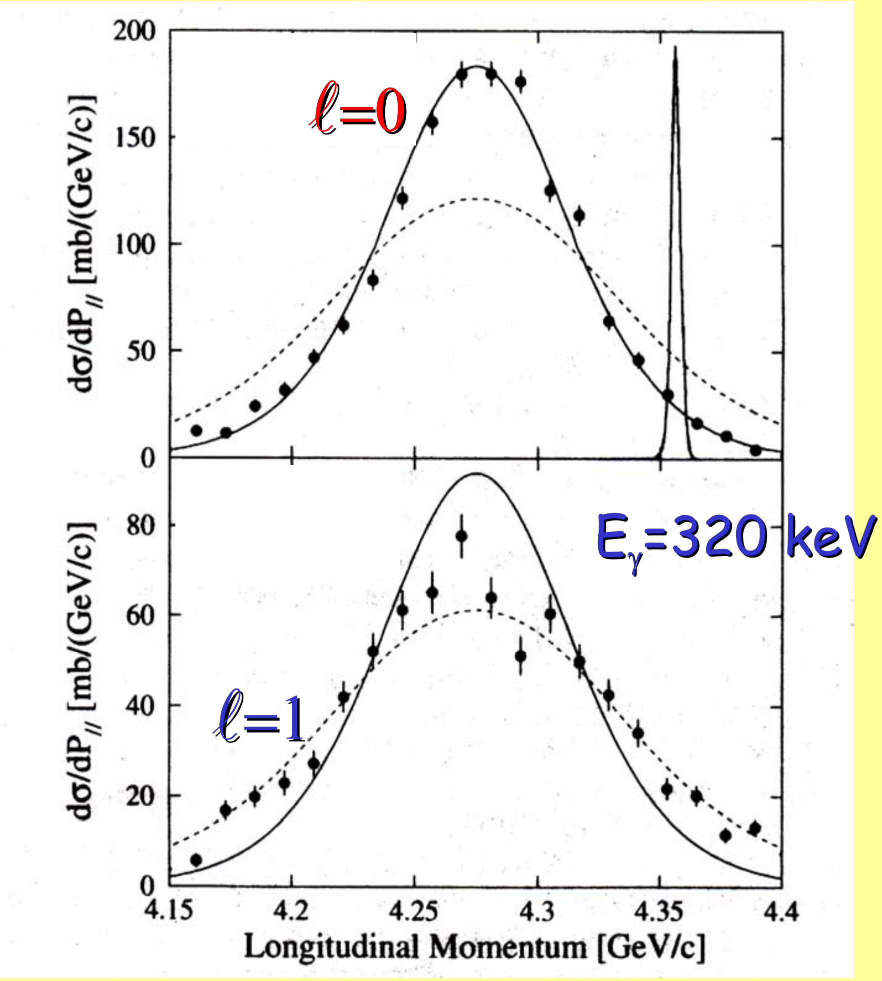
σ_{expt} vs $\sigma_{Glauber}$

$\Downarrow$

$C^2S\ (\nu s_{1/2}) \approx 0.4$

$C^2S\ (\nu p_{1/2}) \approx 0.4$

$C^2S\ (\nu d_{5/2}) =$??

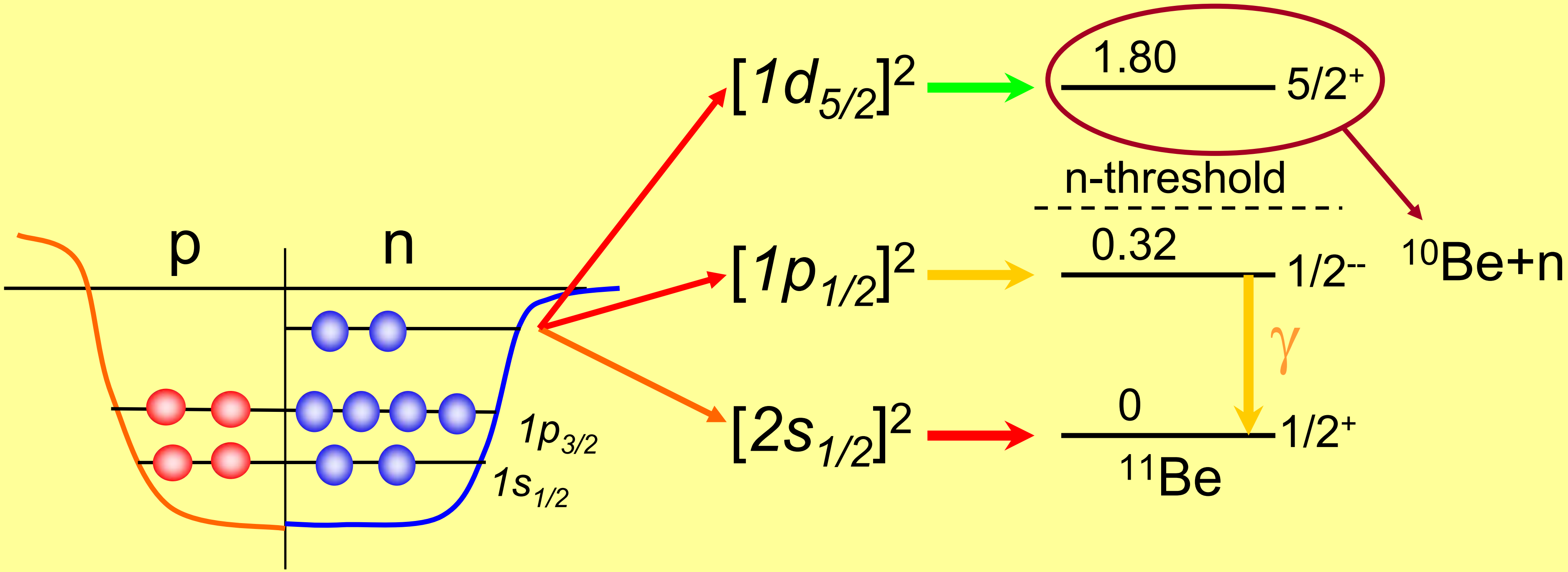


$\nu(p_{1/2})^2, (s_{1/2})^2, (d_{5/2})^2 \approx$ 30%, 20%, 50%

* A. Navin et al., PRL (2000)

eg., G. Gori et al., PRC (2004)

N=8 shell closure - ^{12}Be $\nu(d_{5/2})^2$ admixture

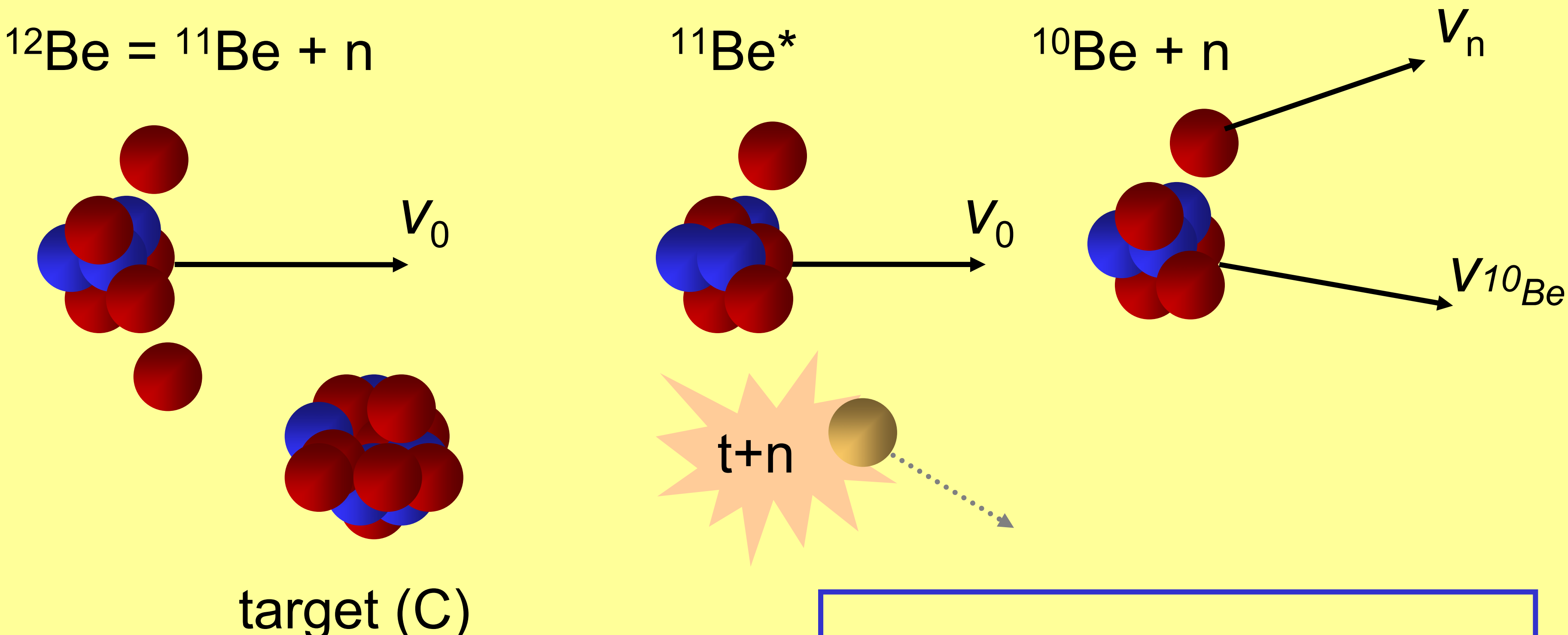


psd-shell ordering in ^{12}Be?

Figure c/- Jeff Tostevin

(Surrey/MSU/Tokyo/Starbucks/....)

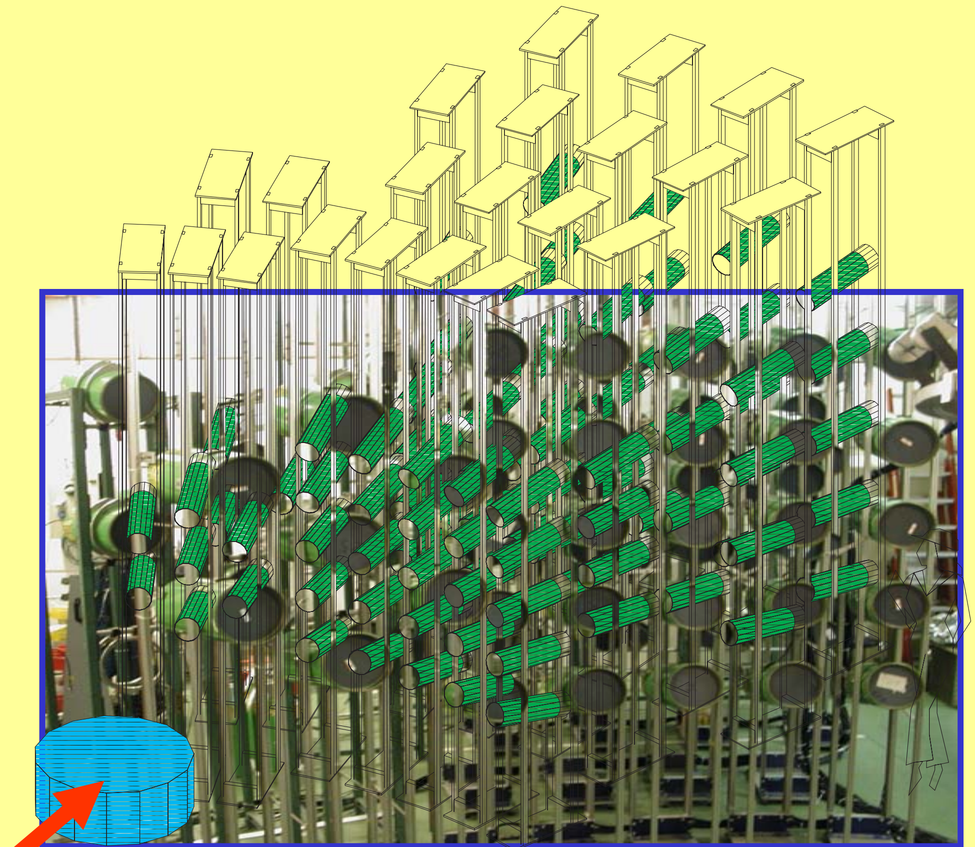
Single-Nucleon Removal to Unbound States:
"Complete Kinematics"



$$p_{core+n} = p_{core} + p_n$$

$$E_{rel} = \mu(v_{core} - v_n)^2/2$$

Experimental Setup "Complete Kinematics"



Fragment → CHARISSA

16 x Si-Si-CsI

Identification (ΔE-E)

➔ Position (~1mm)
➔ Energy (~1%)

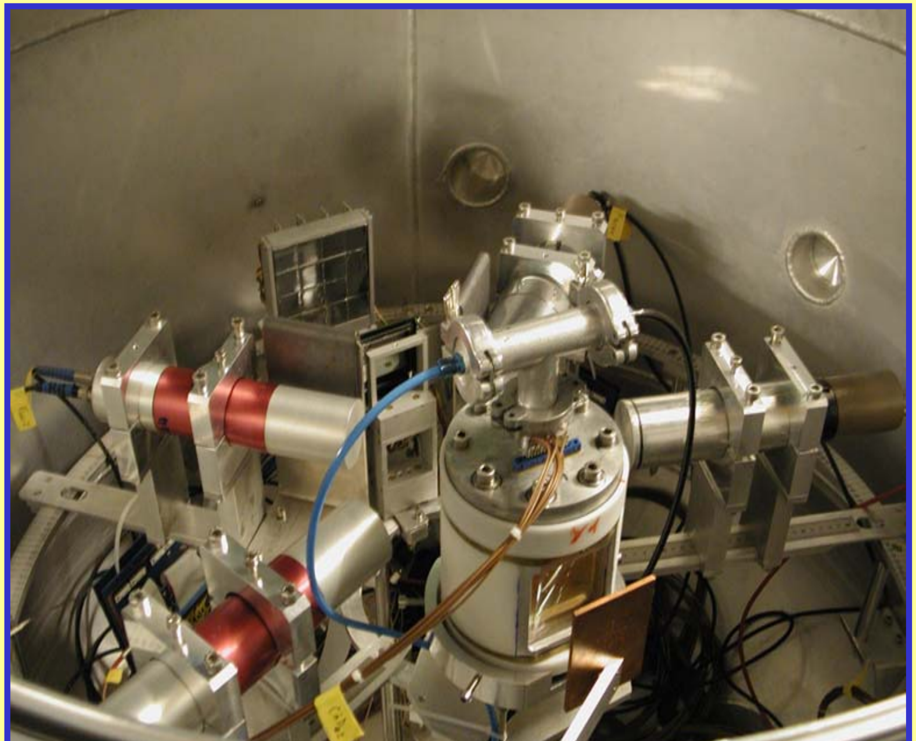
Neutrons → DEMON

90 modules (NE213)

➔ ToF & position

➔ ε_n ~ 10% ε_{nn} ~ 1%

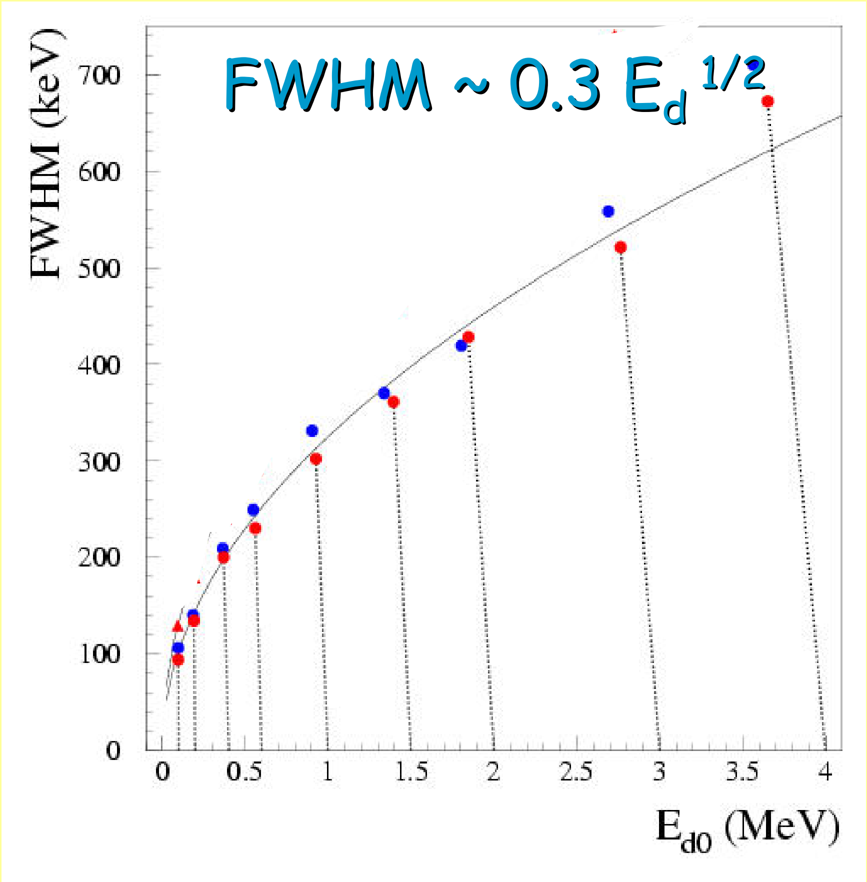
+ *Cross-talk Rejection*



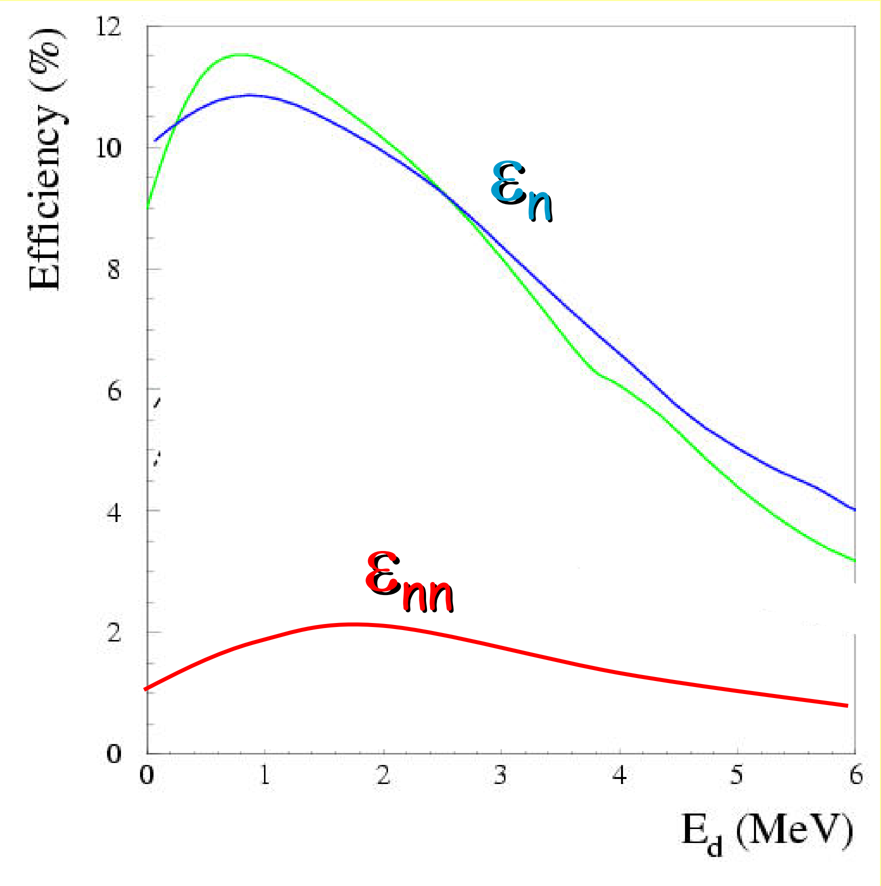
Experimental Response Function *

Complex geometry $\Rightarrow$ simulations

Resolution



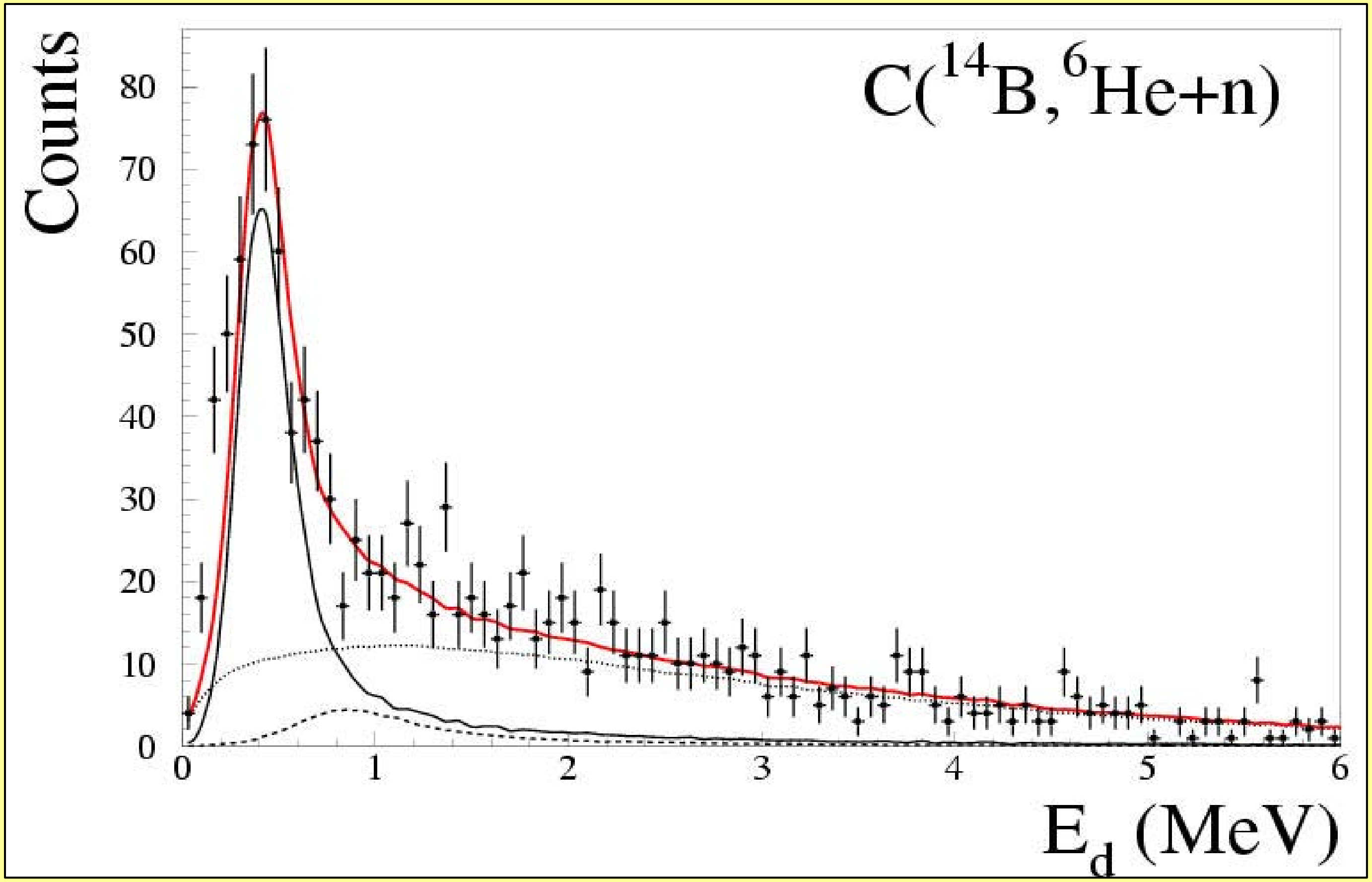
Efficiency



* model distribution <u>must</u> be filtered through the simulations

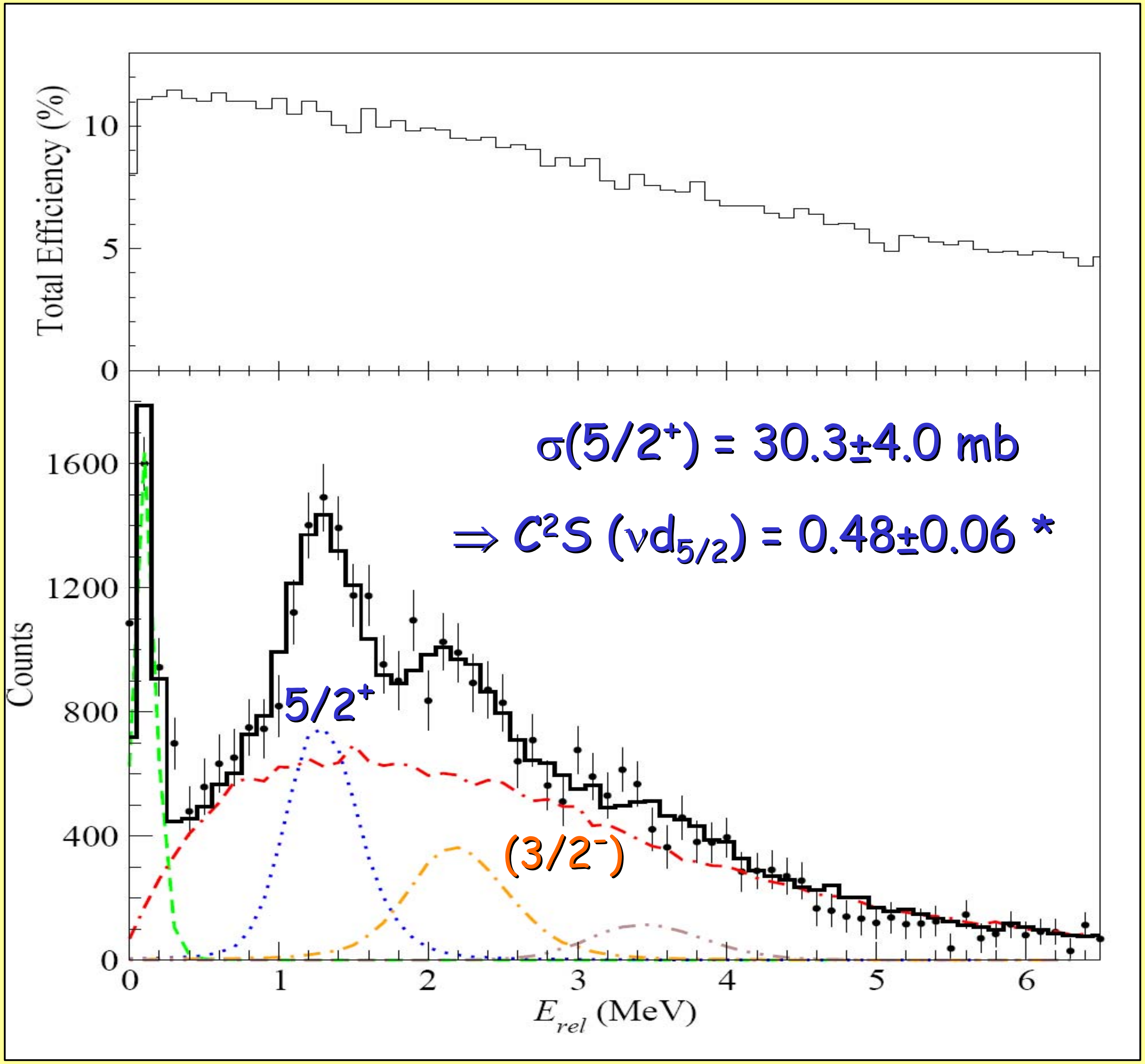
Benchmark System - ^{7}He

Ground state ($3/2^-$) : E_r=0.44, Γ_0=0.16 MeV



[spin-orbit partner E_r ($1/2^-$) = ??? … a "4:00pm question"]

N=8 shell closure: C(^{12}Be,^{10}Be+n) @ 41 MeV/nucleon



* Glauber calculations (Jeff Tostevin)

S. Pain, W.N. Catford, N.A. Orr et al.

N=8 shell closure: C(^{12}Be,^{10}Be+n) @ 41 MeV/nucleon

TABLE I: Cross sections for states in ^{11}Be produced via neutron removal from ^{12}Be on a carbon target at 39.3 MeV/nucleon (present work) compared with reaction calculations and previous work at 78 MeV/nucleon on ^{9}Be. Uncertainties for S_{exp} are experimental only (for comparison, ref. [3] values have been adjusted to remove the assumed 20% theory uncertainty).

J^π	E_x (MeV)	σ_{exp} (mb)	σ_{strip} (mb)	σ_{diff} (mb)	σ_{sp} (mb)	S_{exp} [a] (present work)	S_{exp} [a] Ref. [3]	WBT2 Ref. [3]	WBT2$'$ (see text)	EXC2 Ref. [14]
$1/2^+$	0.00	[b]	61.28	57.69	118.96	$[0.56 \pm 0.18]$[b]	0.42 ± 0.05	0.69	0.55	0.44
$1/2^-$	0.32	32.5 ± 6.1	42.59	30.72	73.31	0.44 ± 0.08	0.37 ± 0.07	0.58	0.47	0.38
$5/2^+$	1.78	30.3 ± 4.0	39.78	22.77	62.55	0.48 ± 0.06	-	0.55	0.44	0.58
$3/2^-$	2.69	22.6 ± 4.1	35.47	20.87	56.35	0.40 ± 0.06	-			

[a] uncertainties do not include contribution from theoretical model of reaction mechanism, estimated to be ±10-20%.
[b] total σ_{exp} not measured, but $\sigma_{diff} = 46 \pm 10$ mb for $1/2^+$ and $1/2^-$ together and S_{exp} deduced from this (see text).

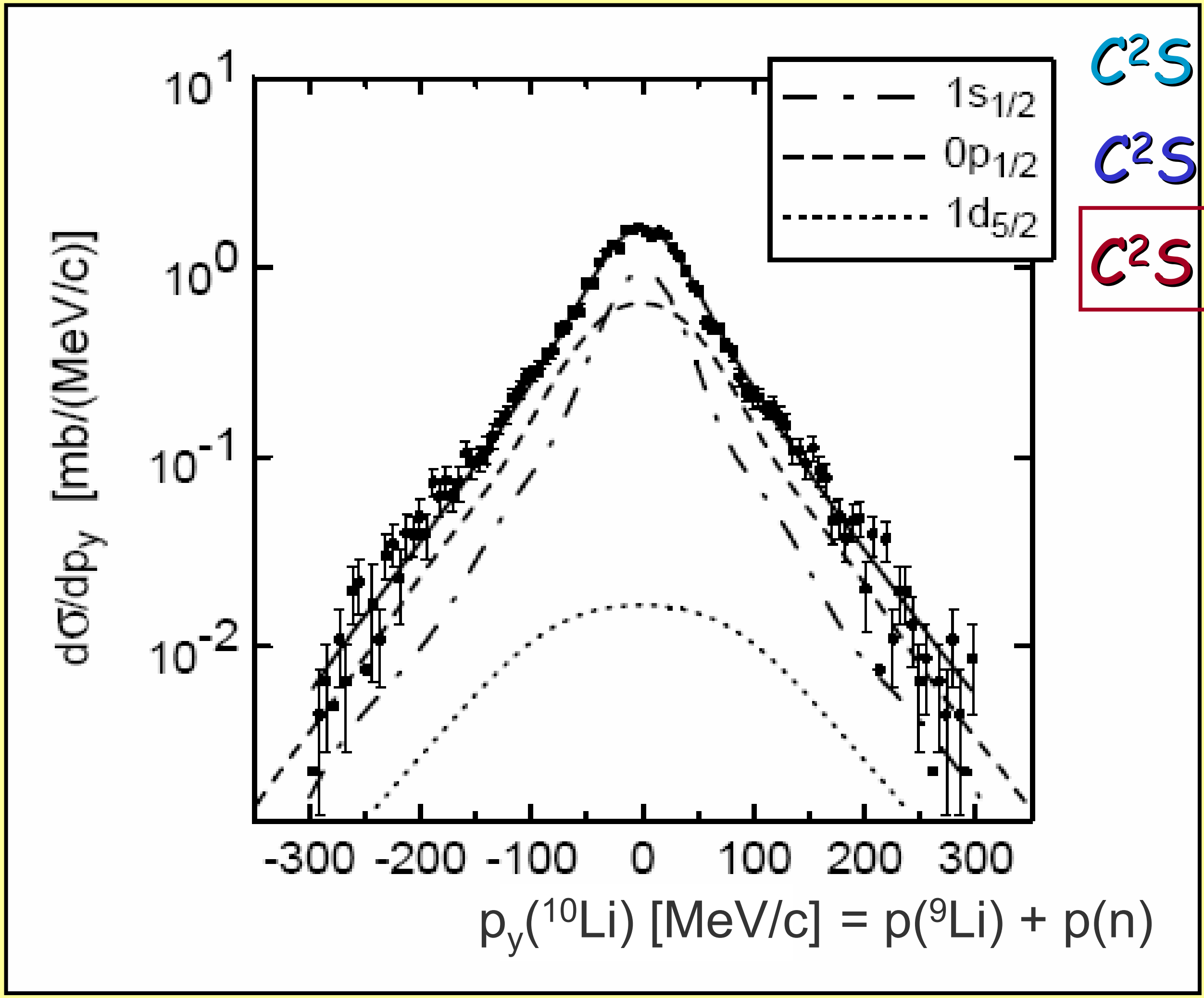
$\Sigma\, C^2S\, (p_{1/2}s_{1/2}d_{5/2}) = 1.48 \pm 0.21$

$\boxed{32\%\ 0\hbar\omega\ (0p^8)\ \text{and}\ 68\%\ 2\hbar\omega}$

nucl-ex/0510048

S. Pain, W.N. Catford, N.A. Orr et al.

N=8 Shell Closure: $C(^{11}Li,^{9}Li+n)$ @ 287 MeV/nucleon *



$C^2S\ (\nu s_{1/2}) \approx 0.65$

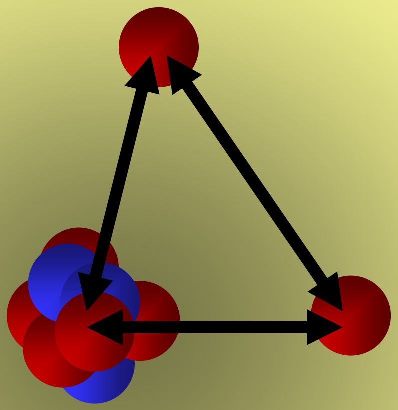
$C^2S\ (\nu p_{1/2}) \approx 1.27$

$\boxed{C^2S\ (\nu d_{5/2}) \approx 0.08}$

* H. Simon et al. [GSI-LAND], PRL (1999)

Glauber Calculations : CA Bertulani, PG Hansen, PRC (2004)

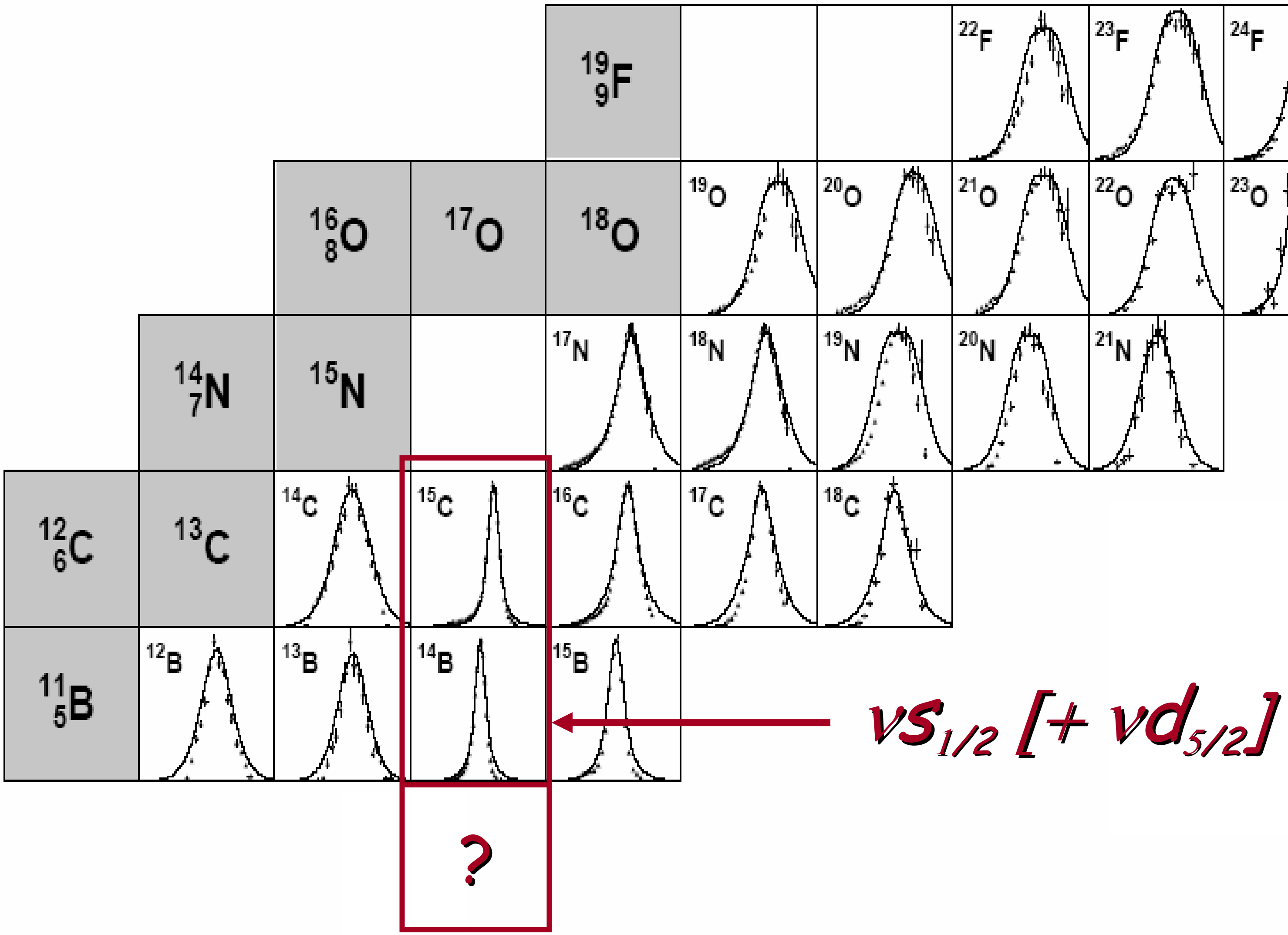
Core-n correlations:
modelling two-neutron halo systems



3-body systems ⇒ n-n and core-n interactions

eg., ^{14}Be ⇒ ^{12}Be-n interaction
⇨ spectroscopy of ^{13}Be

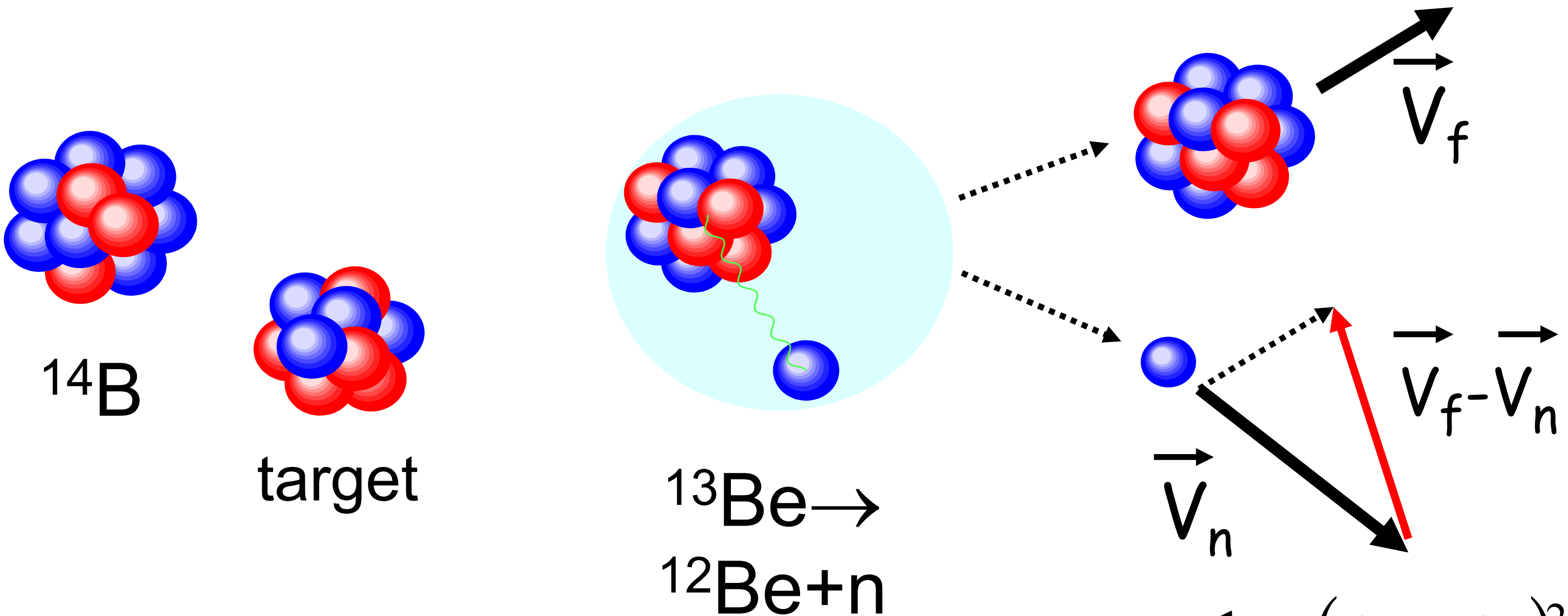
N=9: ^{15}C, ^{14}B, ^{13}<u>*Be*</u>



Expt v 's Glauber Theory + Shell Model: Sauvan, et al., PRC (2004)

Single-Proton Removal at High-Energy

C(^{14}B,^{12}Be+n) @ 41 MeV/nucleon



$$E_d = \frac{1}{2}\mu\left(\vec{V}_f - \vec{V}_n\right)^2$$

"L'espoir" : to first order projectile neutron configuration preserved ($\Delta \ell_n = 0$)

$\Rightarrow$ Selectivity on Final states populated

Interpretation

- sudden approximation

$\Rightarrow$ projectile neutron structure preserved ($\Delta\, \ell_n = 0$)

Bertsch *et al.*, PRC 57 (1998) 1366, Chen *et al.*, PLB 505 (2001) 21

$$a(k) = \int_0^\infty r^2 dr\, \varphi_k^*(r)\, \psi_0(r)$$

Final unbound state

$$|\varphi\rangle = |fragment\rangle \otimes \nu|\ell j\rangle$$

Initial bound state

$$|\psi_0\rangle = |\mathrm{A}-1\rangle \otimes \nu|\ell j\rangle$$

Decay Energy

$$\frac{d\sigma}{dE_d}\, \alpha \sqrt{E_d}\, |a(k)|^2$$

Simulation

Comparison to data

(χ^2)

Projectile Structure

Neutron configuration of projectile preserved

$$|^{14}\mathrm{B}\rangle = |^{13}\mathrm{B}(gs)\rangle \otimes \nu sd$$

Millener & Brown, *priv. comm.*

Sauvan *et al.*, PLB 491 (2000) 1

Guimarães *et al.*, PRC 61 (2000) 064609

$$|^{17}\mathrm{C}\rangle = |^{16}\mathrm{C}(2^+)\rangle \otimes \nu d_{5/2}$$

Brown, *priv. comm.*

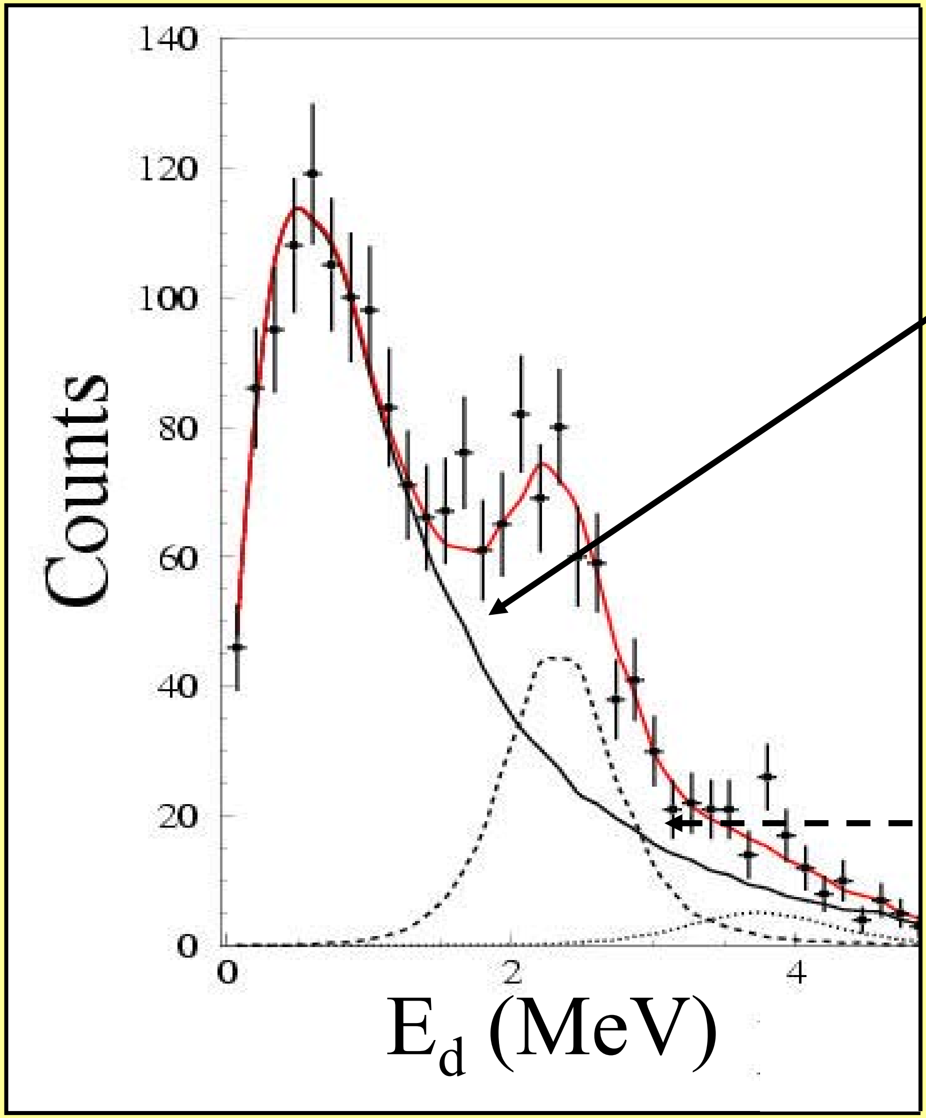
Sauvan *et al.*, PLB 491 (2000) 1

Maddalena *et al.*, PRC 63 (2001) 024613

$\Rightarrow$ Final states populated

- ^{13}Be : $\nu s_{1/2}$ and/or $\nu d_{5/2}$
- ^{16}B : $\nu d_{5/2}$

$C(^{14}B,^{12}Be+n)$ @ 41 MeV/nucleon *



s-wave <u>resonance</u>

$E_r \approx 0.7$ MeV

$\Gamma_0 \approx 2$ MeV

d-wave resonance

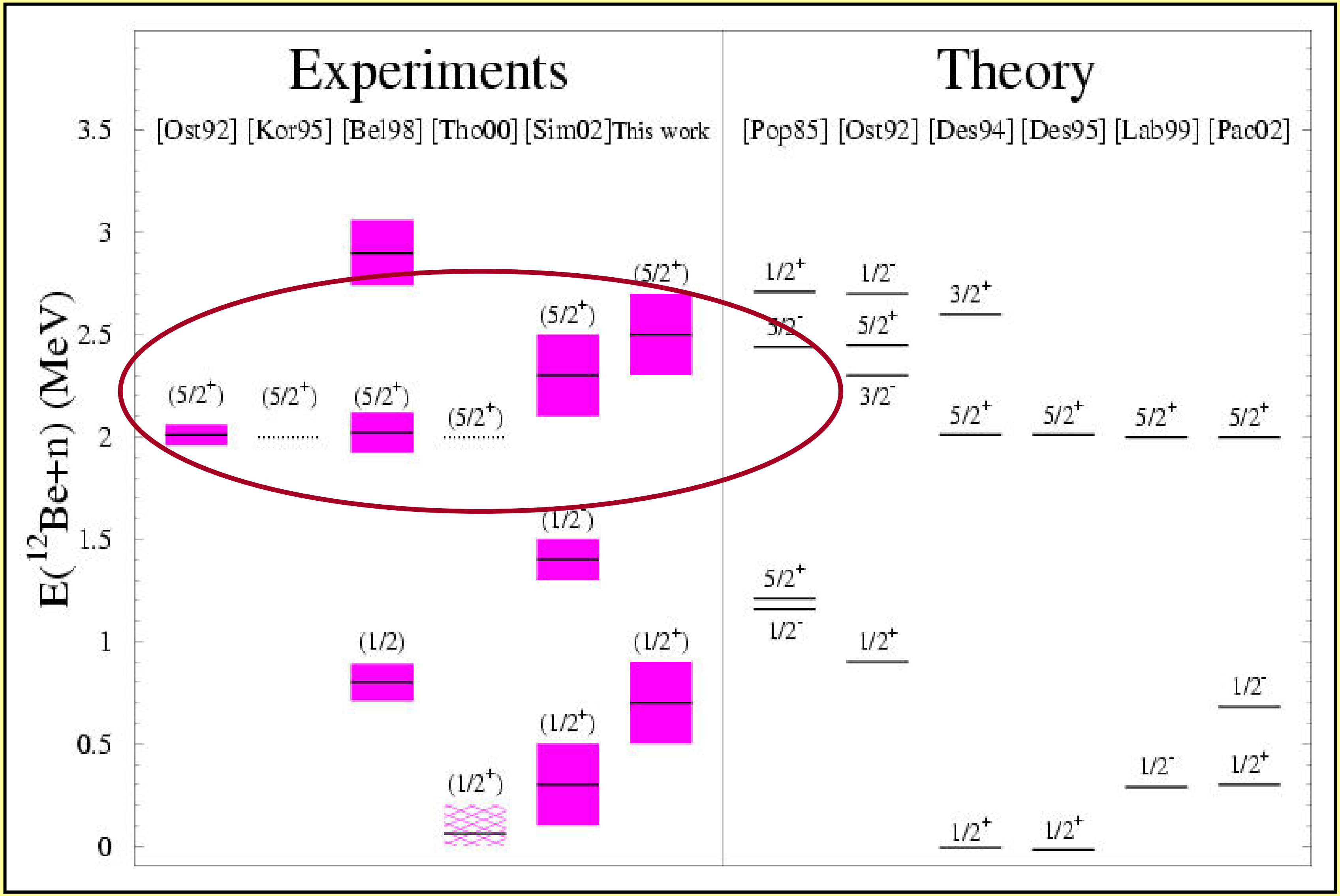
$E_r = 2.5$ MeV

$\Gamma_0 = 0.4$ MeV

* the "sanitized" interpretation

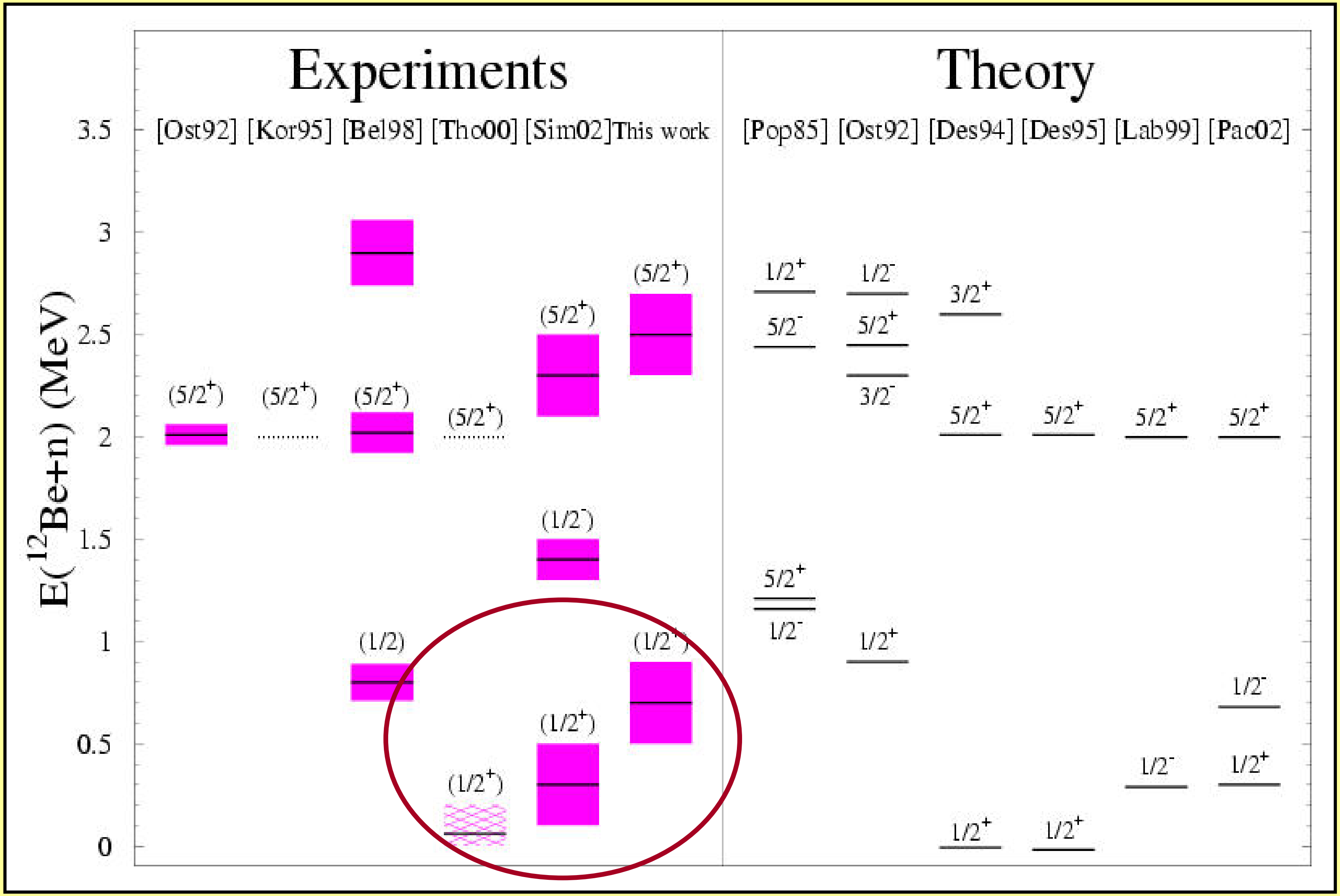
LPC Group "Exotiques" - JL Lecouey et al.

^{13}Be: Experiment-Theory



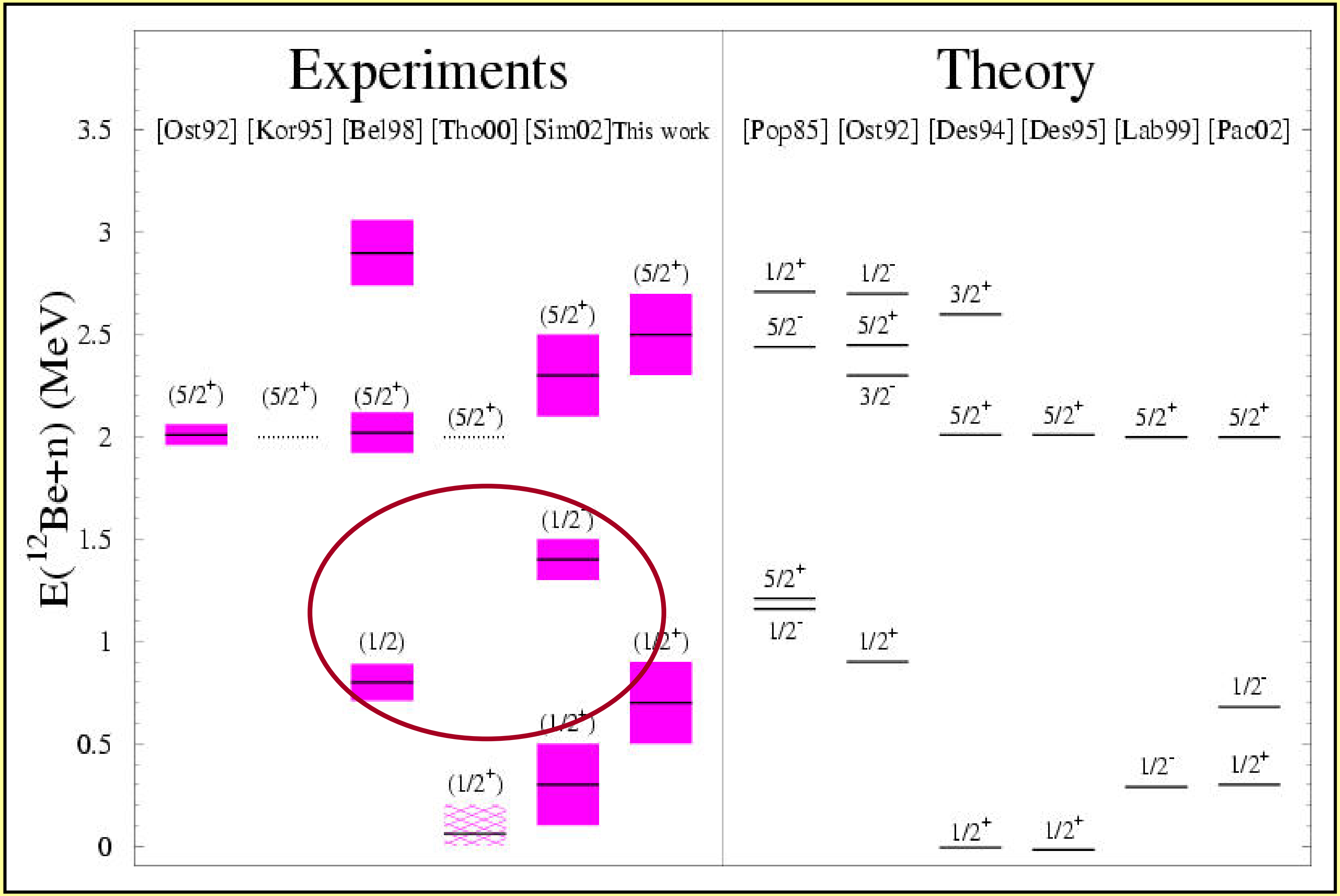
^{13}Be : E_x ~ 2.0-2.5 MeV $\nu d_{5/2}$

^{13}Be: Experiment-Theory



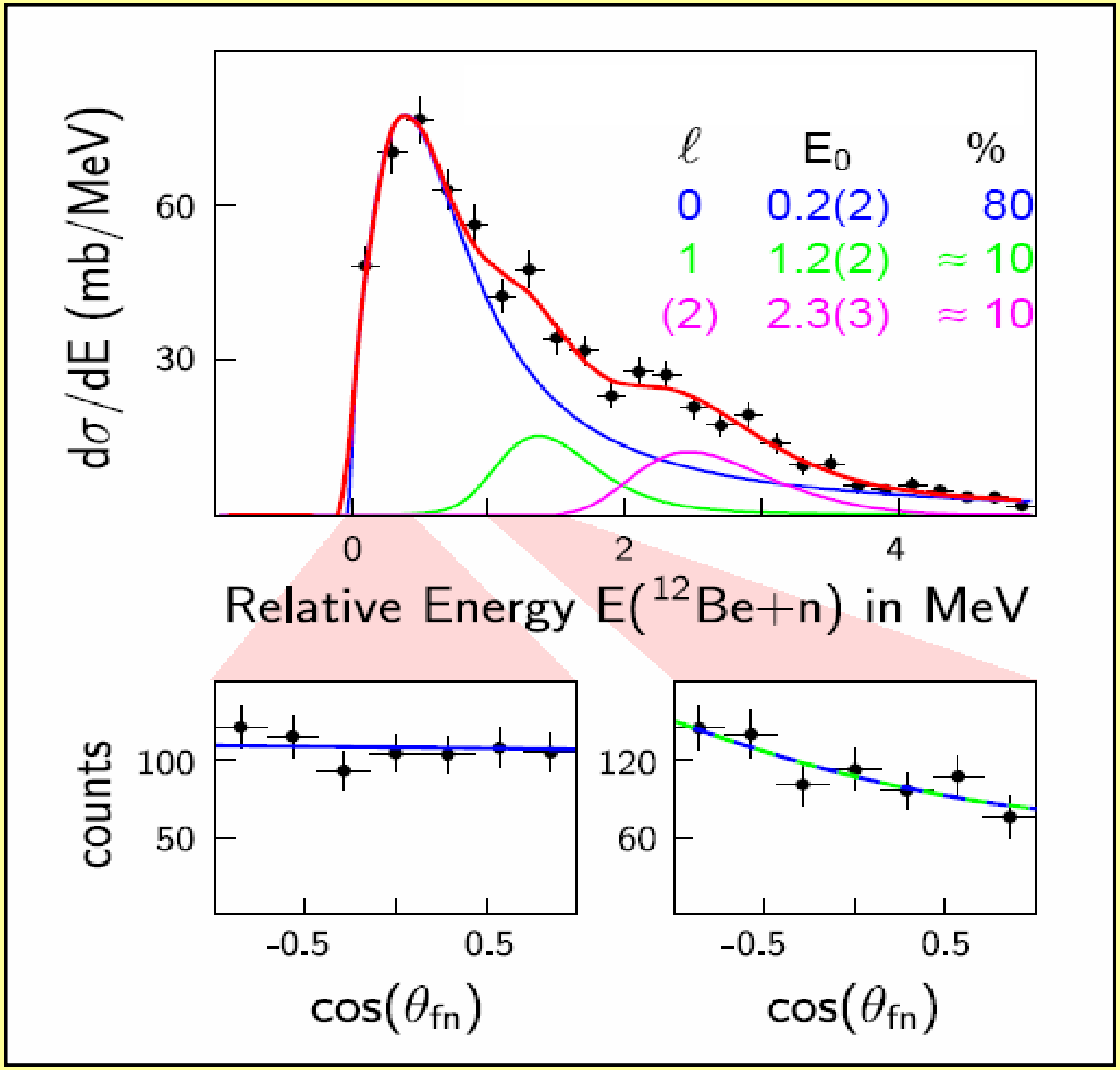
^{13}Be ground state: $\nu s_{1/2}$ (resonance)

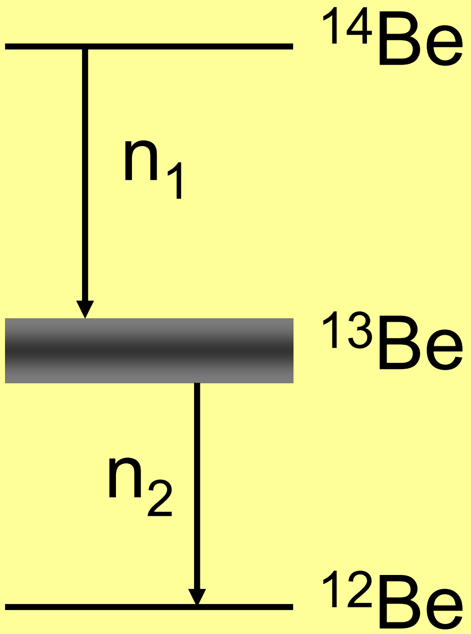
^{13}Be: Experiment-Theory



^{13}Be : $\nu p_{1/2}$ E_x??

Angular Correlations: C(^{14}Be,^{12}Be+n) @ 287 MeV/u *

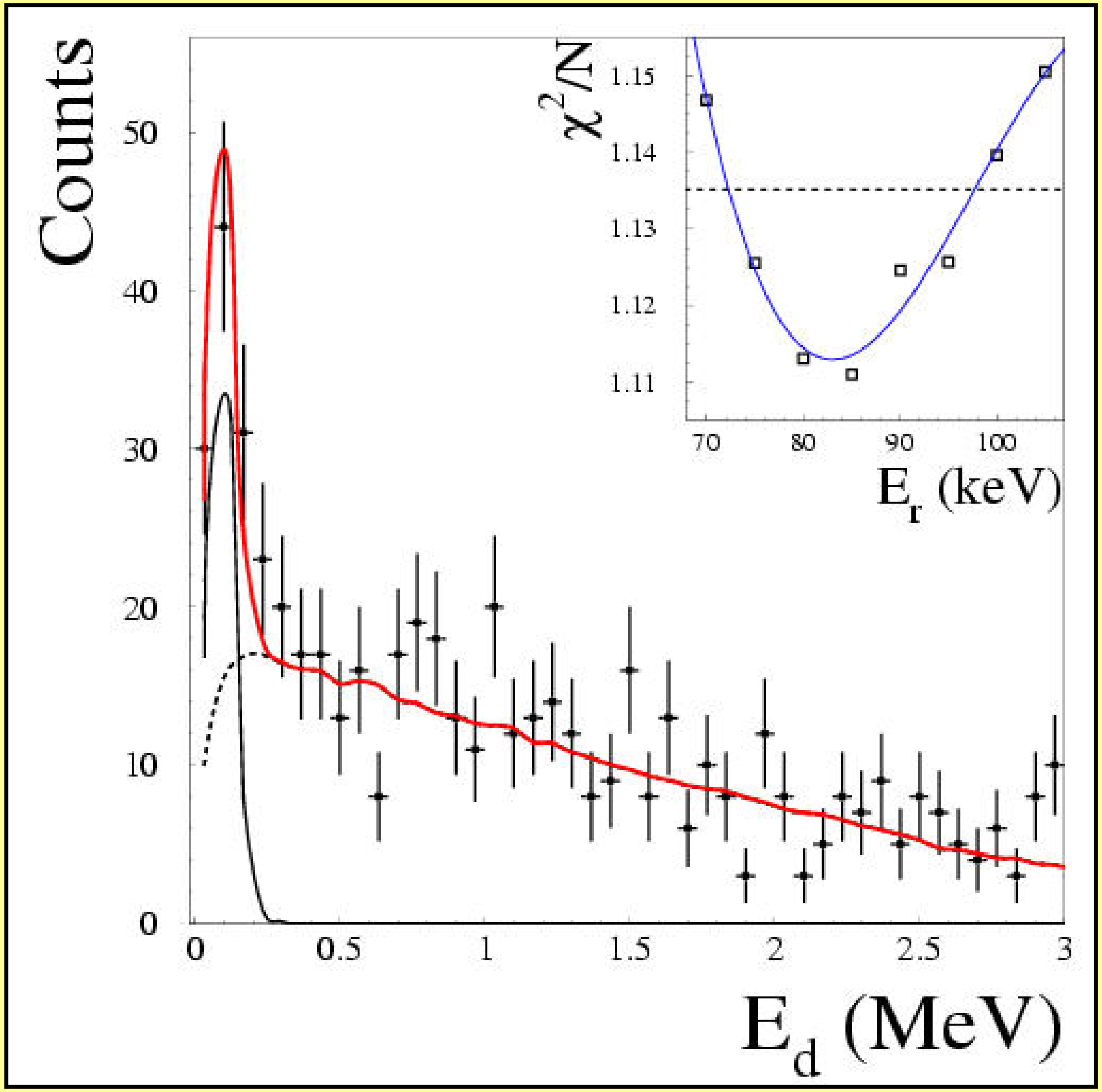




* H. Simon et al. [GSI], priv. comm.

^{15}B+n Coincidences

Structure at low E_d *d-wave* resonance



E_r = 85 ± 15 keV

Γ_{sp} << 100 keV *

+

uncorrelated

^{15}B+n distribution

* $\Gamma_{sp} \approx$ 0.5 keV

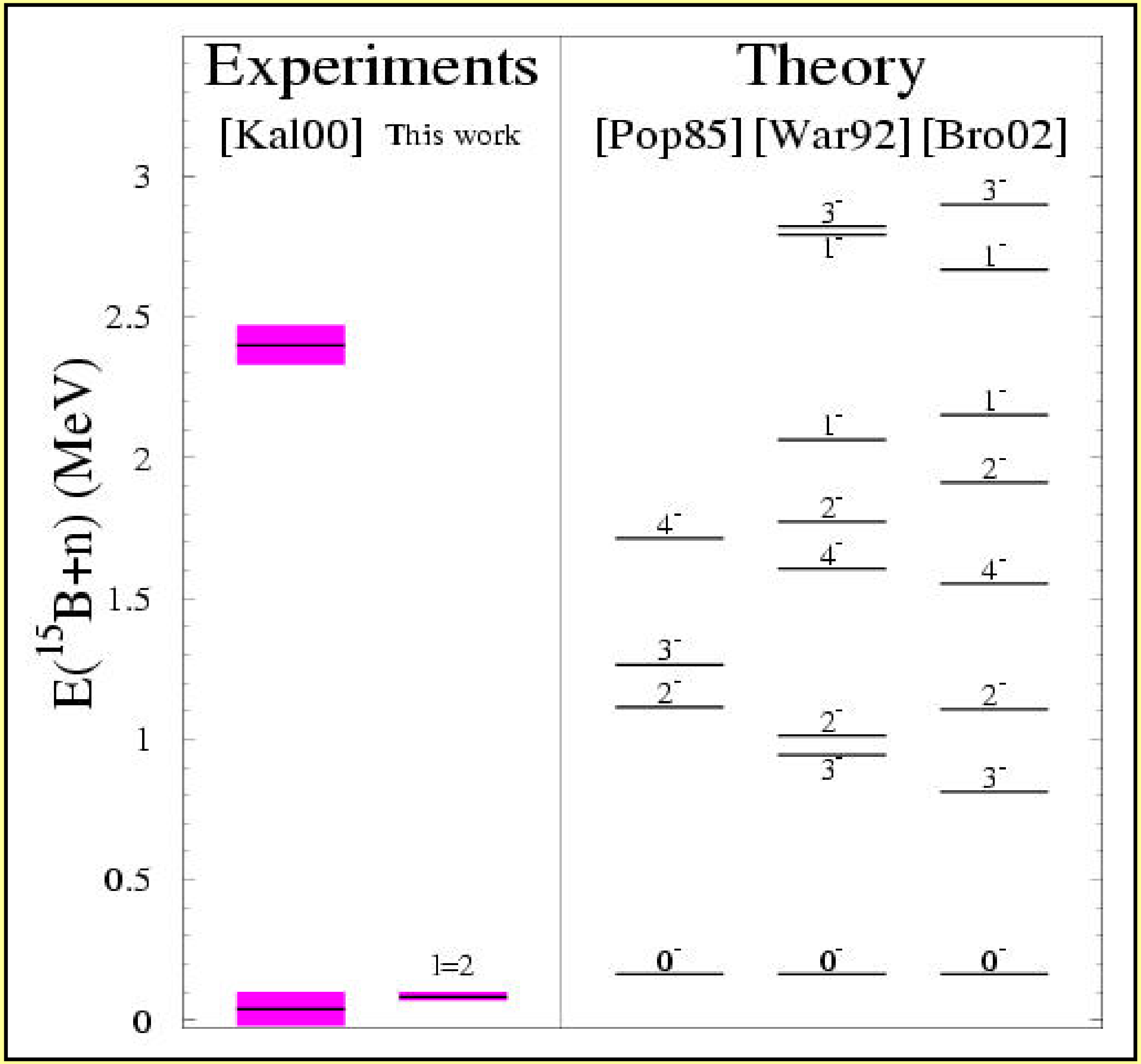
[Brown & Millener, priv. comm.]

^{16}B : Experiment-Theory

Expt ^{15}B+n

[7±1 mb]

σ≈1 mb



"Glauber"

2.2 mb

1.5 mb

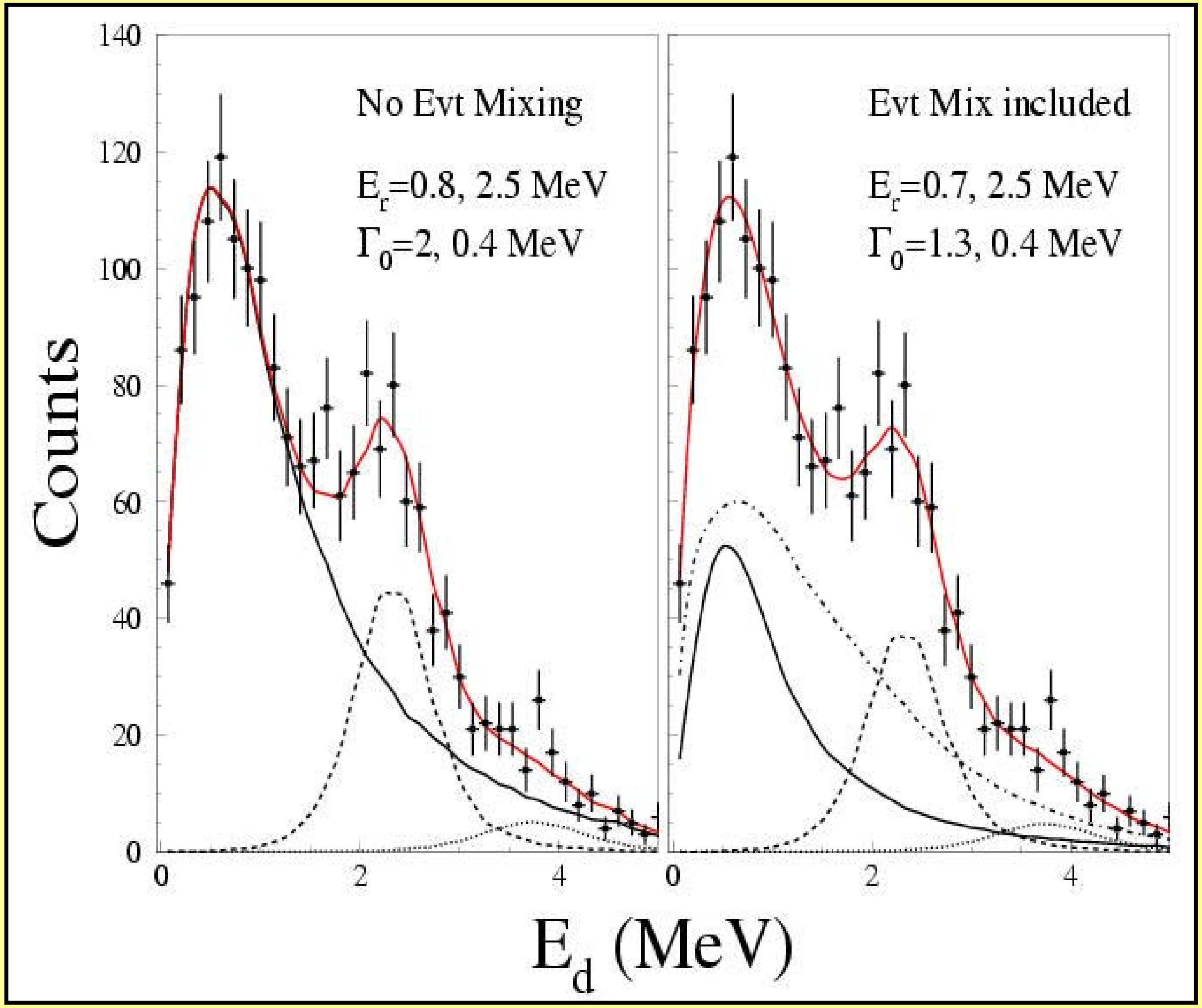
5.2 mb

1.3 mb

$\pi p_{3/2} \otimes \nu(d_{5/2})^3$

C(^{14}B,^{12}Be+n) @ 41 MeV/nucleon *

$s_{1/2}$ resonance + $d_{5/2}$ resonance (E_r=2.5, Γ_0=0.4 MeV)



Good fit with/without uncorrelated frag-n pairs

s-wave resonance

E_r = 0.6-0.8 MeV

Γ_0 = 1-2 MeV

* the "unsanitized" interpretation

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Conclusions

- high-energy nucleon removal used to explore structure and correlations at and beyond the dripline

⇒ N=8 not a closed shell for ^{12}Be, ^{11}Li … ^{10}He ?
significant d-wave strength in ^{12}Be but not ^{11}Li

⇒ N=9 $\nu s_{1/2}$ - $d_{5/2}$ inversion for ^{13}Be (^{14}B, ^{15}C) …
^{14}Be halo

⇒ ^{16}B low-lying narrow ($d_{5/2}$) resonance + clear structureless continuum/uncorrelated ^{15}B+n dist'n

Work in Progress

- Spectroscopy of ^{9}He ($^{11,12}Be$ and ^{14}B beams)

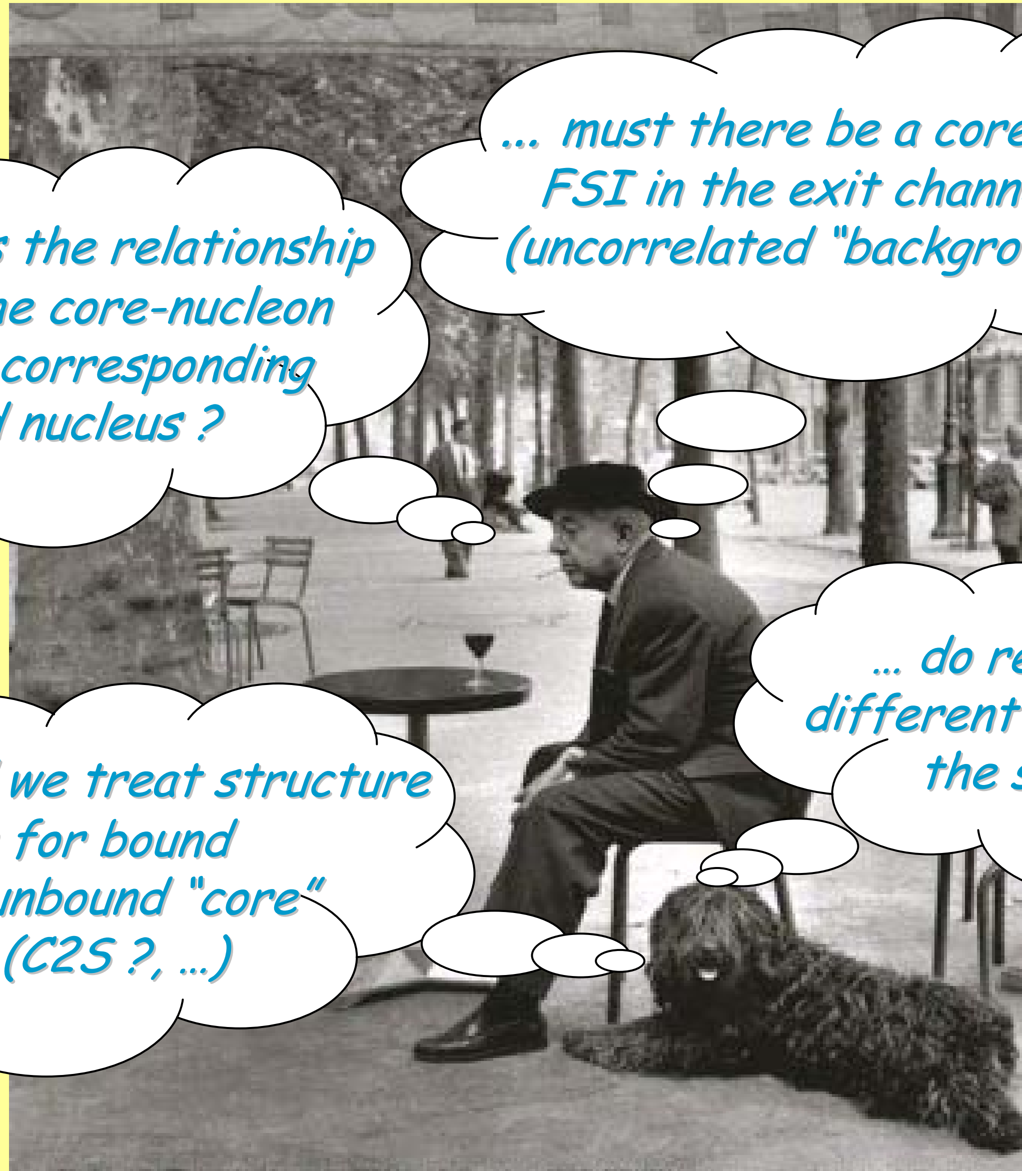
- More complex systems …

  $\rightarrow$ ^{5}H

  $\rightarrow$ probing n-n configuration (^{6}He, …)

  $\rightarrow$ multi-neutron resonances: ^{4}n

Issues/questions to ponder …



… what is the relationship between the core-nucleon E_{rel} and the corresponding unbound nucleus ?

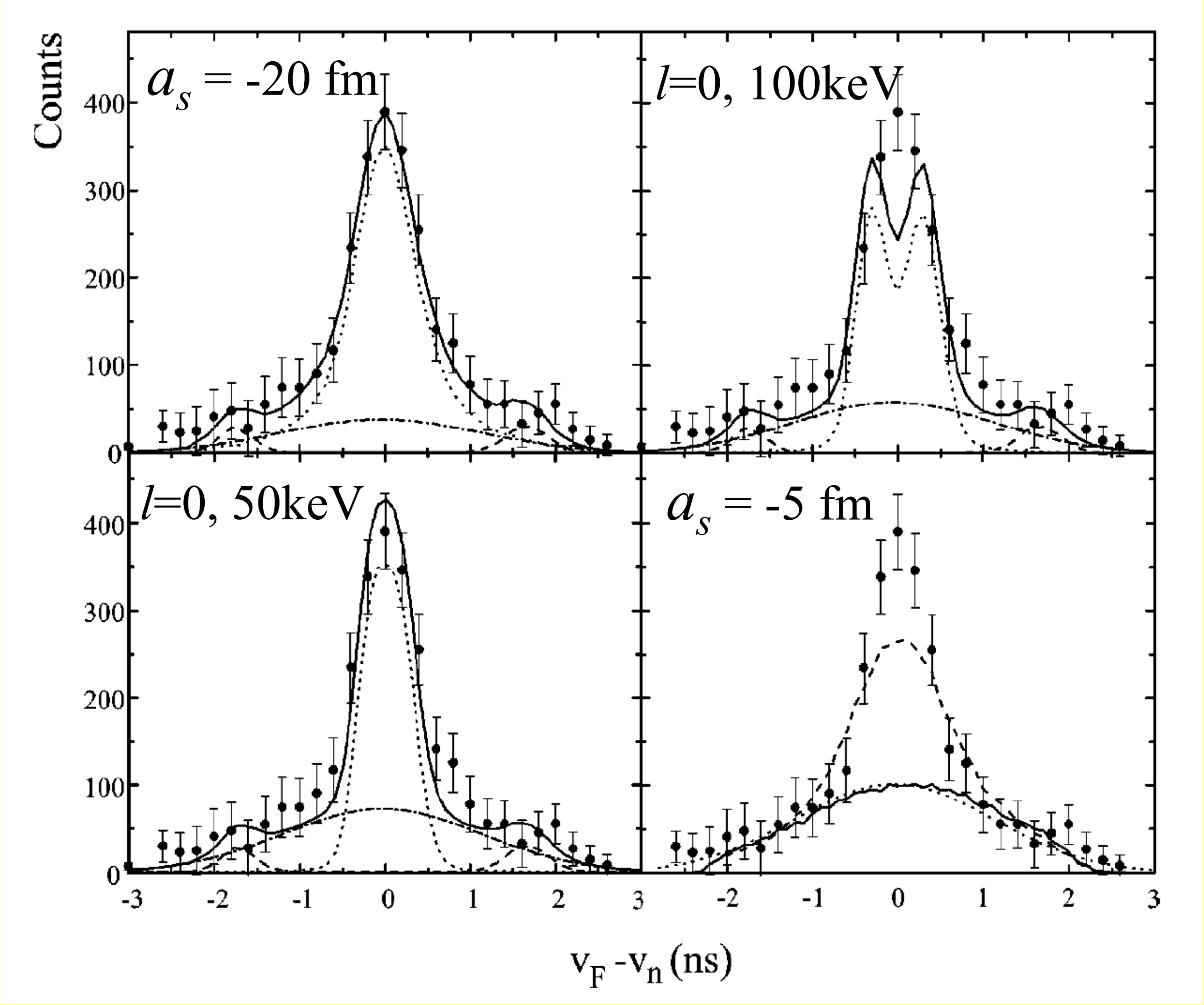
… must there be a core-nucleon FSI in the exit channel ? (uncorrelated "background")

… do reactions at very different energies populate the same states?

… how ***should*** we treat structure + reaction for bound projectile → unbound "core" states ? (C2S ?, …)

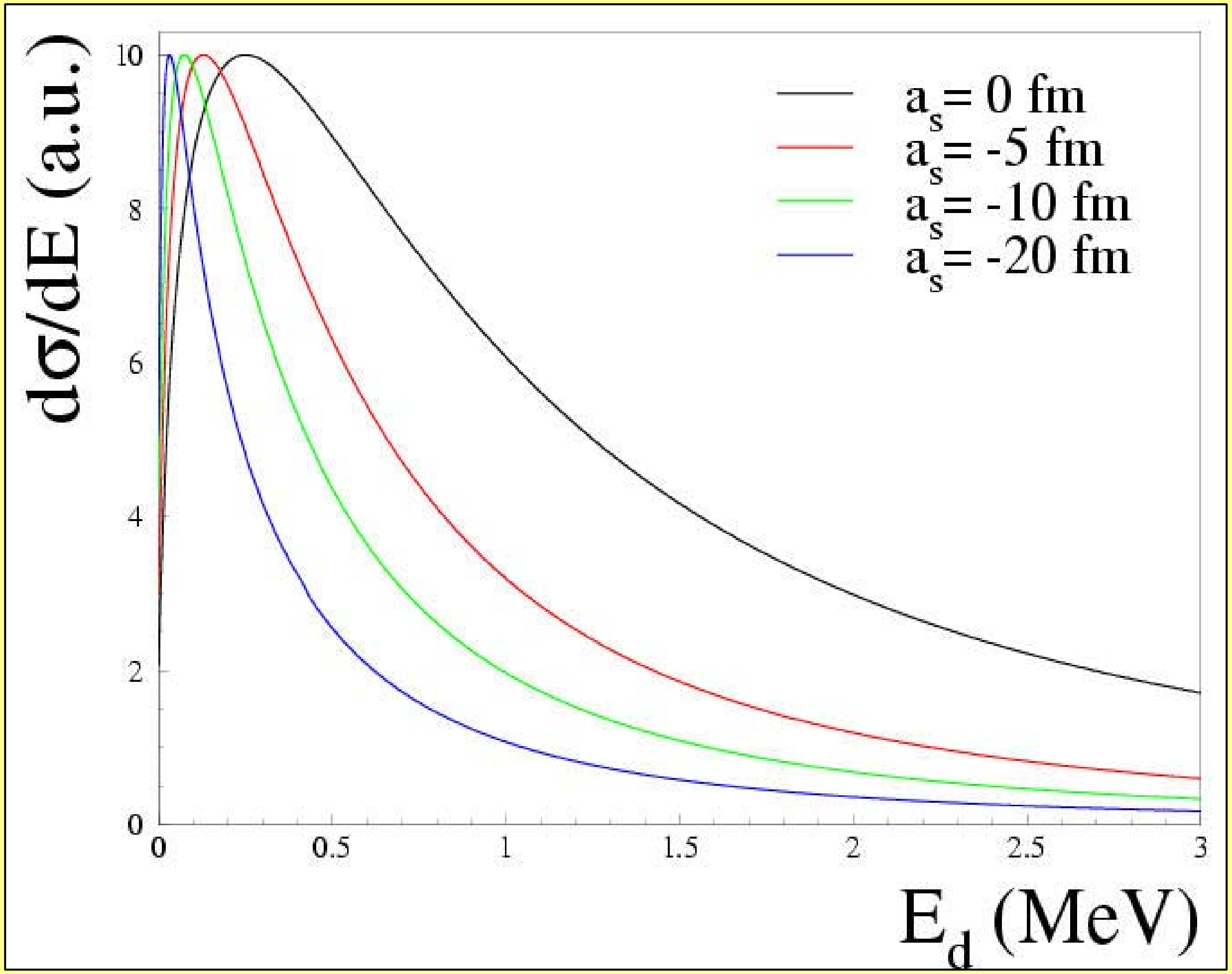
… at 4:00 pm (avec un ballon de rouge)

$^{18}O + Be \rightarrow {}^{12}Be+n+X$



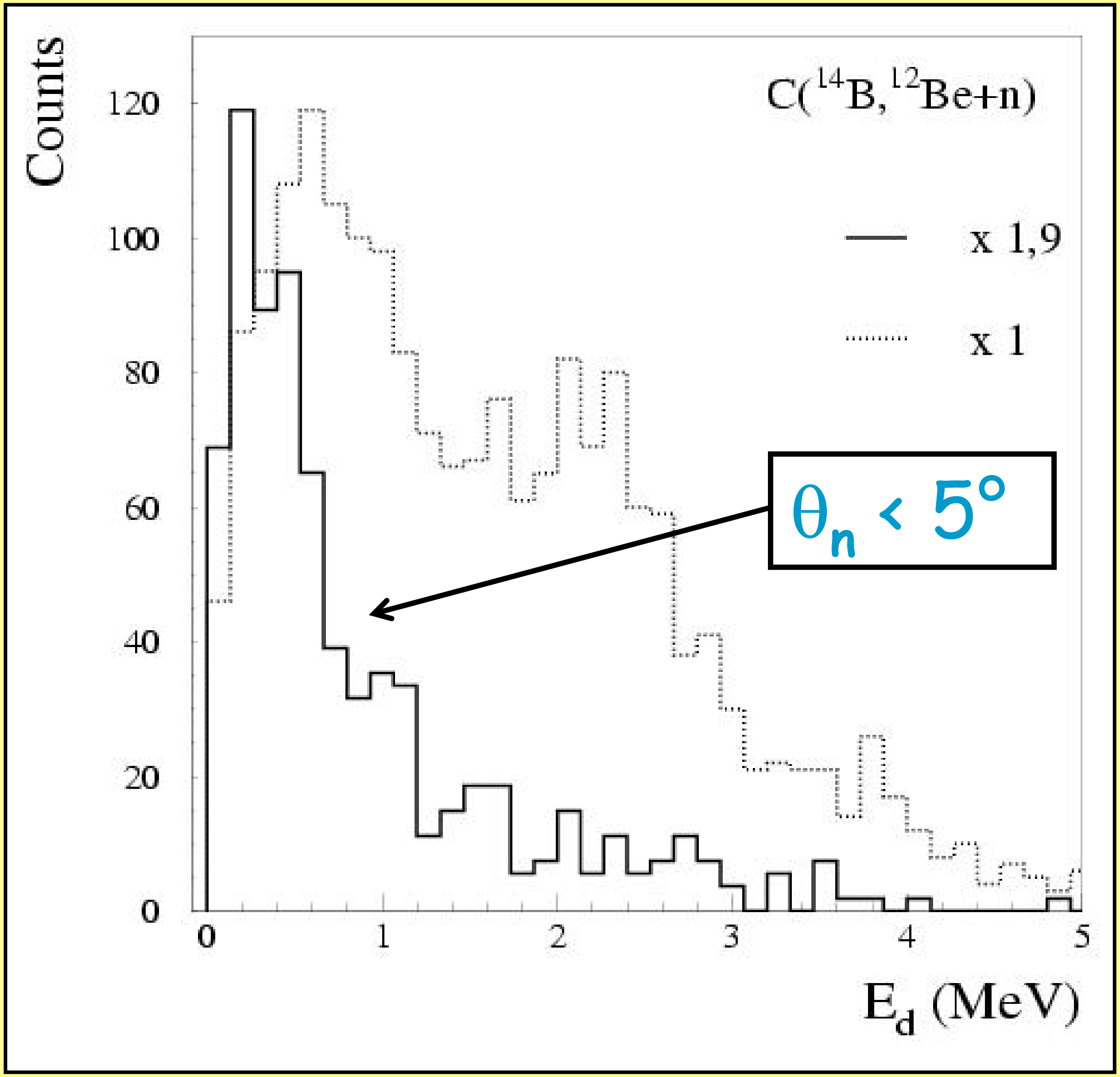
Thoennessen *et al.*, PRC63, 014308 (2000) $\Rightarrow a_s = -20$ fm

^{12}Be+n coincidences:
Behaviour of virtual *s*-states



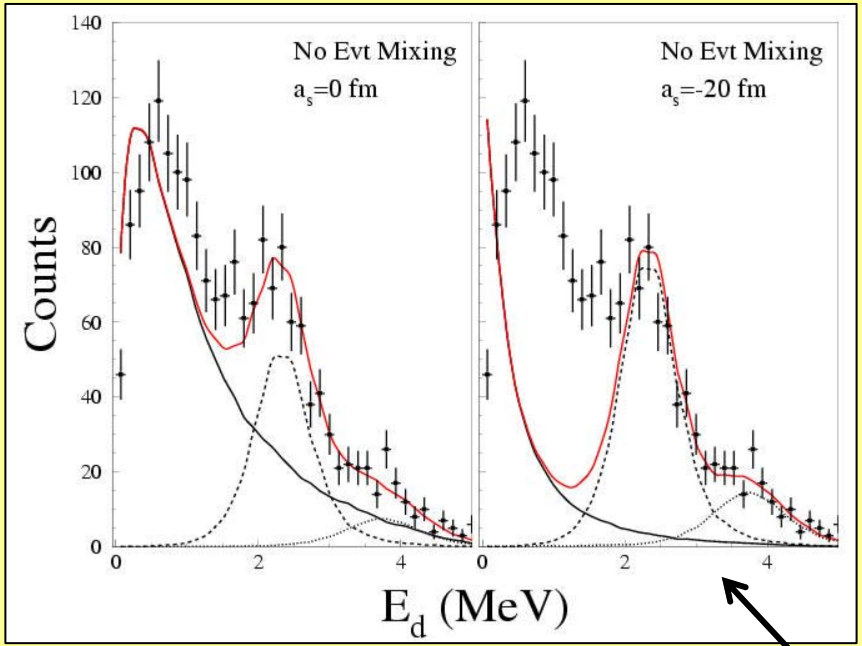
→ a_s = -20 fm : Thoennessen *et al.*, PRC63, 014308

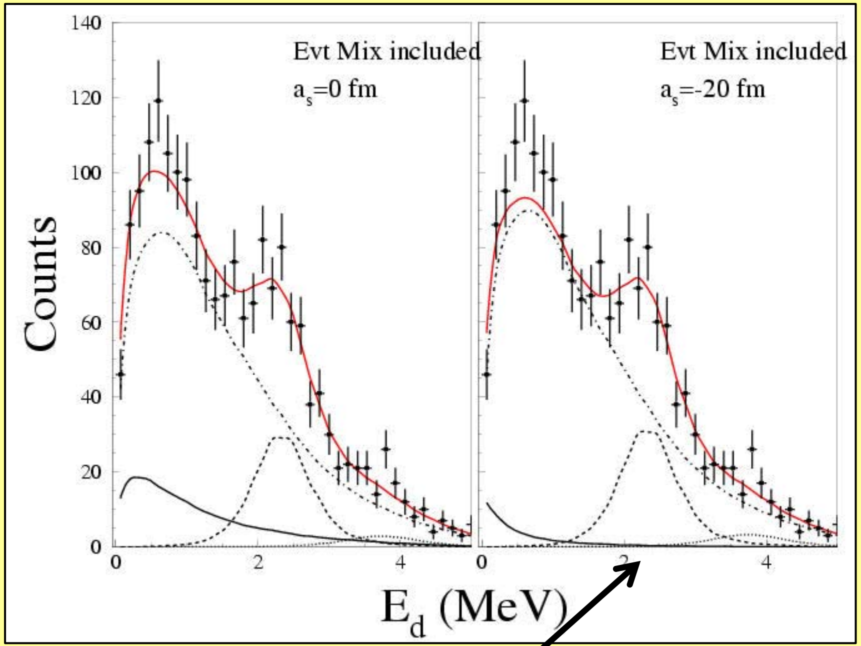
Acceptance Effects



^{12}Be+n coincidences

Virtual *s*-state + *$d_{5/2}$-resonance* (E_r=2.5, Γ_0=0,4 MeV)



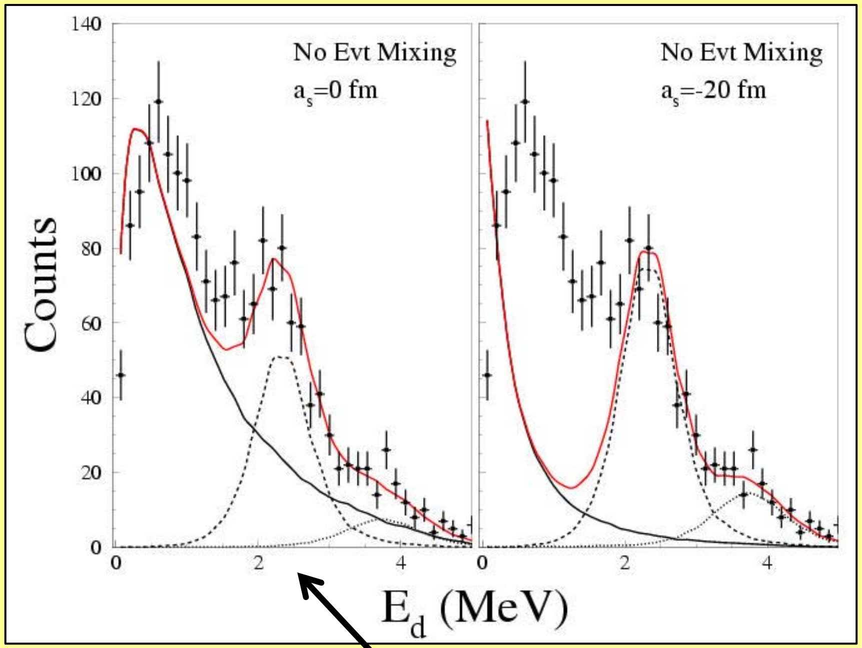


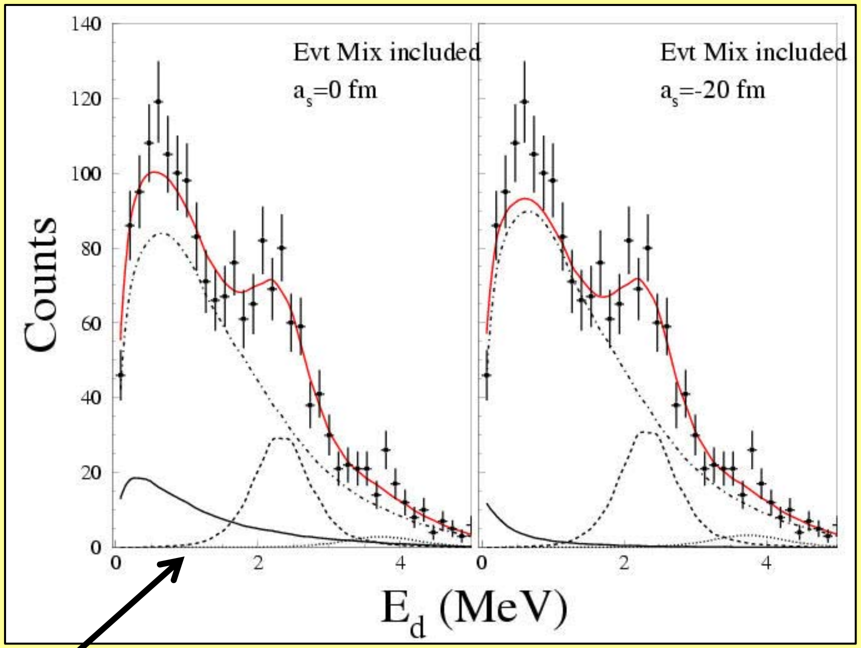
a_s=-20 fm

$\Rightarrow$ poor agreement

^{12}Be+n coincidences

Virtual *s*-state + *$d_{5/2}$-resonance* (E_r=2.5, Γ_0=0,4 MeV)





a_s= 0 fm

(No ^{12}Be-n FSI)

⇒ improved χ^2

⇒ still <u>poor agreement</u>