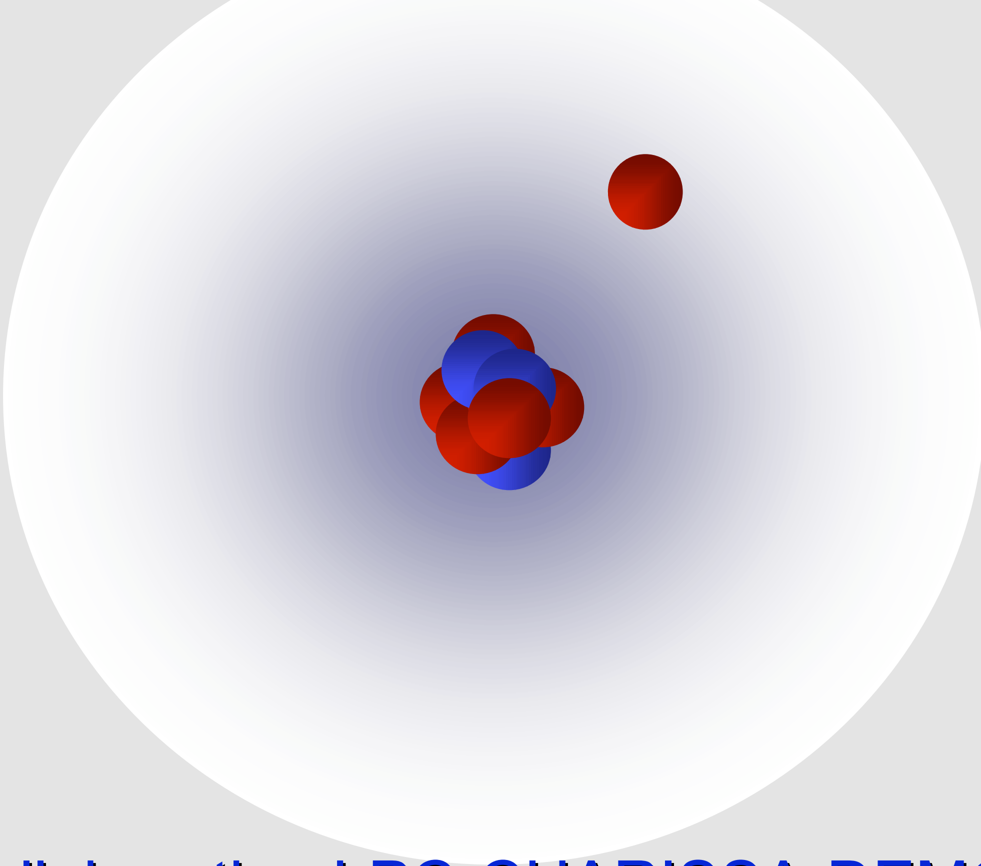
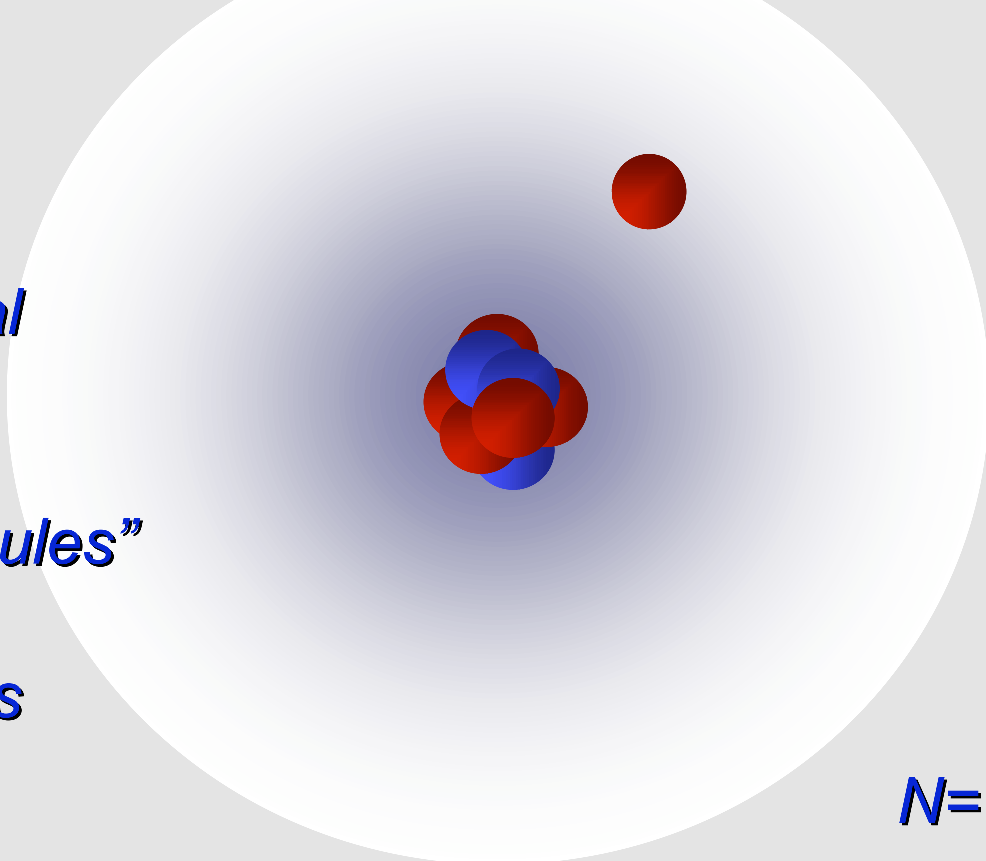
Intermediate Energy Knockout & Breakup to Access Light Systems Beyond the Neutron Dripline



Collaboration LPC-CHARISSA-DEMON

H Al Falou, JL Lecouey, F Carstoiu, FM Marqués, NAO …

Intermediate Energy Knockout & Breakup to Access Light Systems Beyond the Neutron Dripline



Introduction

Experimental Approach

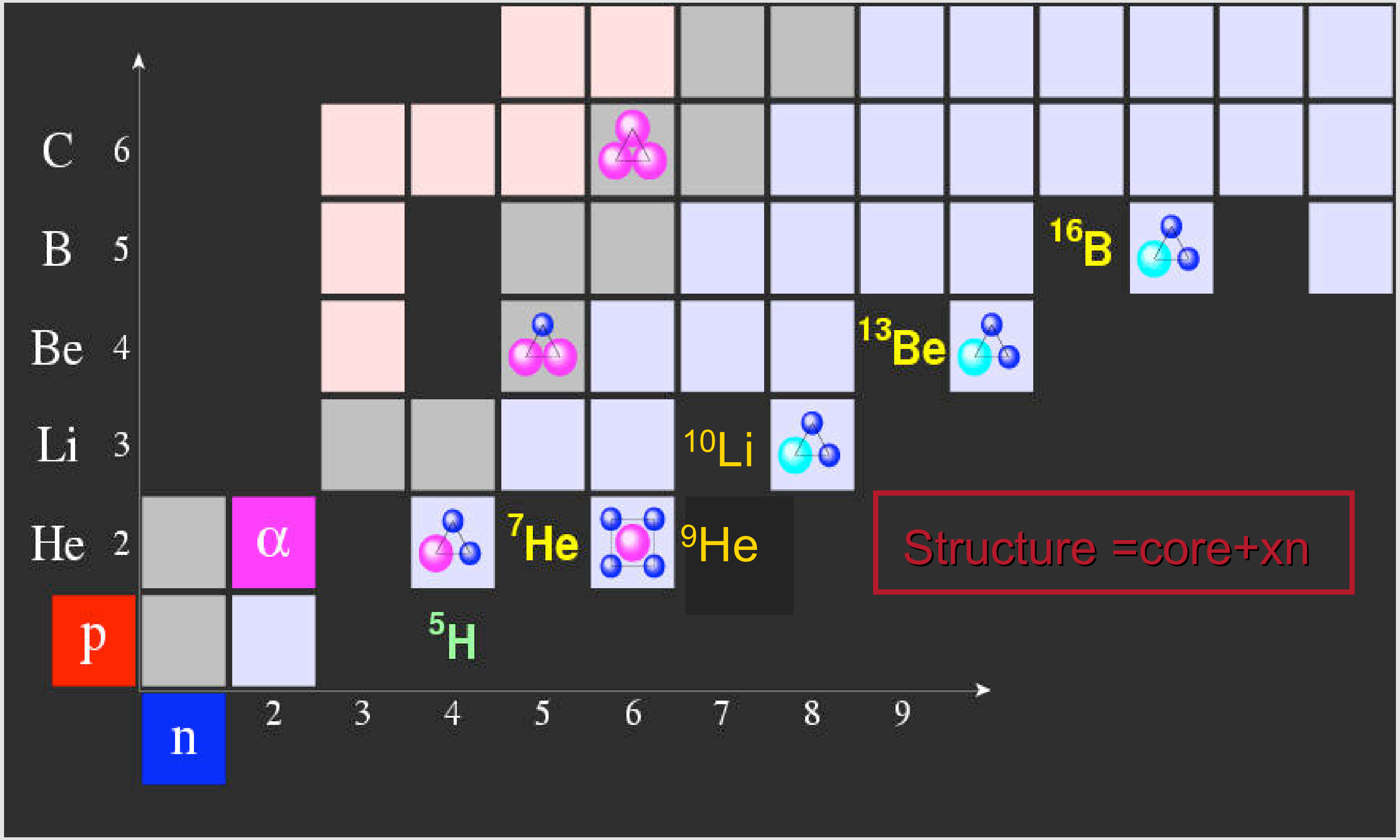
Selection “Rules”

Backgrounds

N=7 : ^{10}Li & ^{9}He

Conclusions & Perspectives

The Light Neutron-Rich Nuclei …



… driplines and beyond experimentally accessible, extreme test of models (shell model, shell model in continuum, "ab initio", cluster, etc)

***LPC Programme** : H Al Falou LPCC 07-03, G Normand LPCC 04-03, JL Lecouey LPCC 02-03*

Strategy …

"Fast" nucleon (proton) removal ⇒ $\Delta_{-(n)} = 0$ *

IFF proj. structure known ⇒ deduce structure of A-1 system
(core^{-1} ⊗ valence nucleon)

→ Proton removal (S_p~15 MeV) from very neutron-rich beams

⇒ systems beyond dripline – observe frag.+ n FSI

* M Zinser et al., PRL **75** (1995) 1719
L Chen et al. PLB **505** (2001) 21

Issues …

Weakly bound valence neutron

⇒ *possible relaxation of $\Delta\_n = 0$*

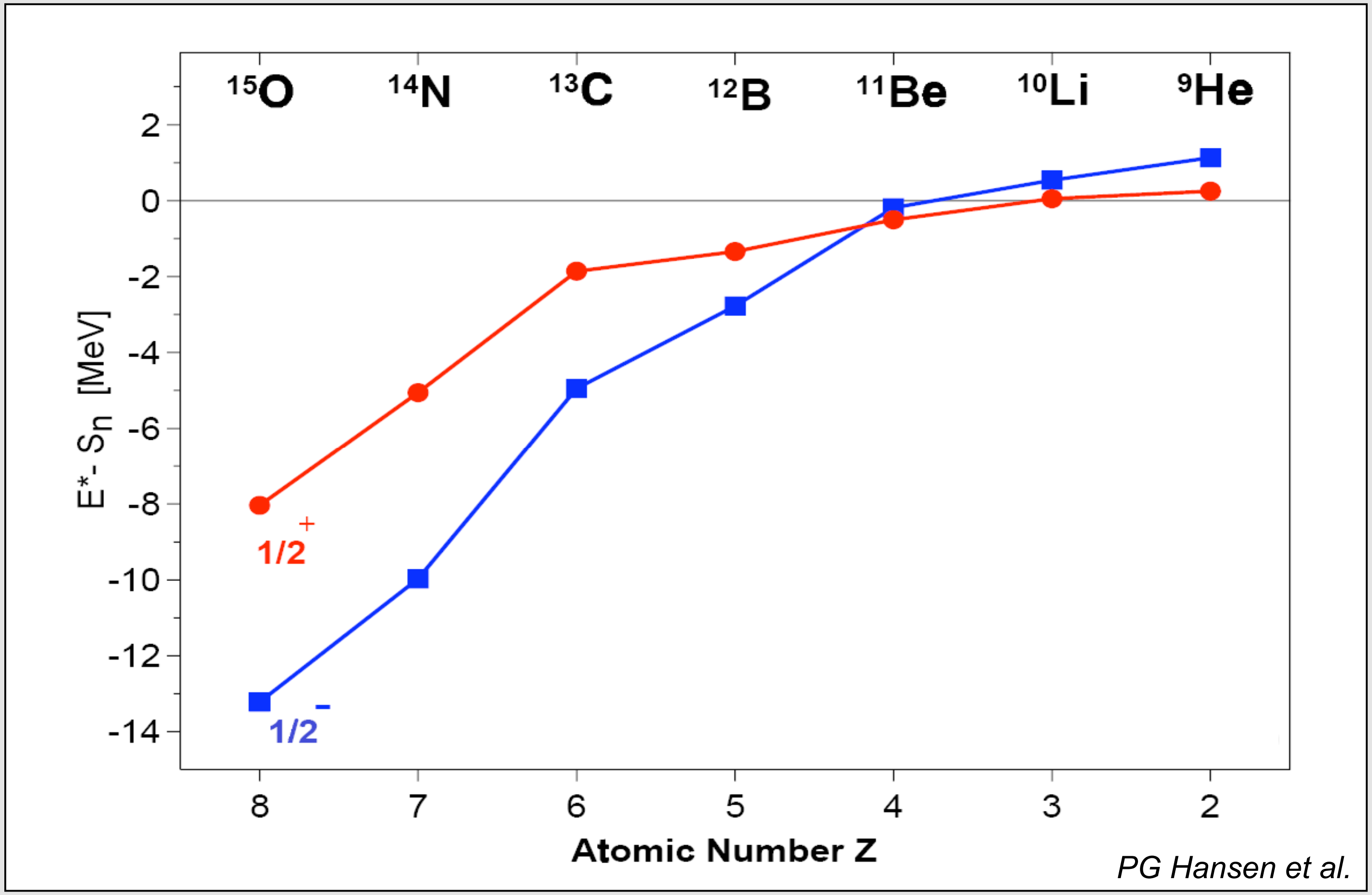
→ *frag. recoil induced by proton removal*

→ *scattering of valence neutron*

TEST approach using ^{11}Be beam (S_n = 0.5 MeV)

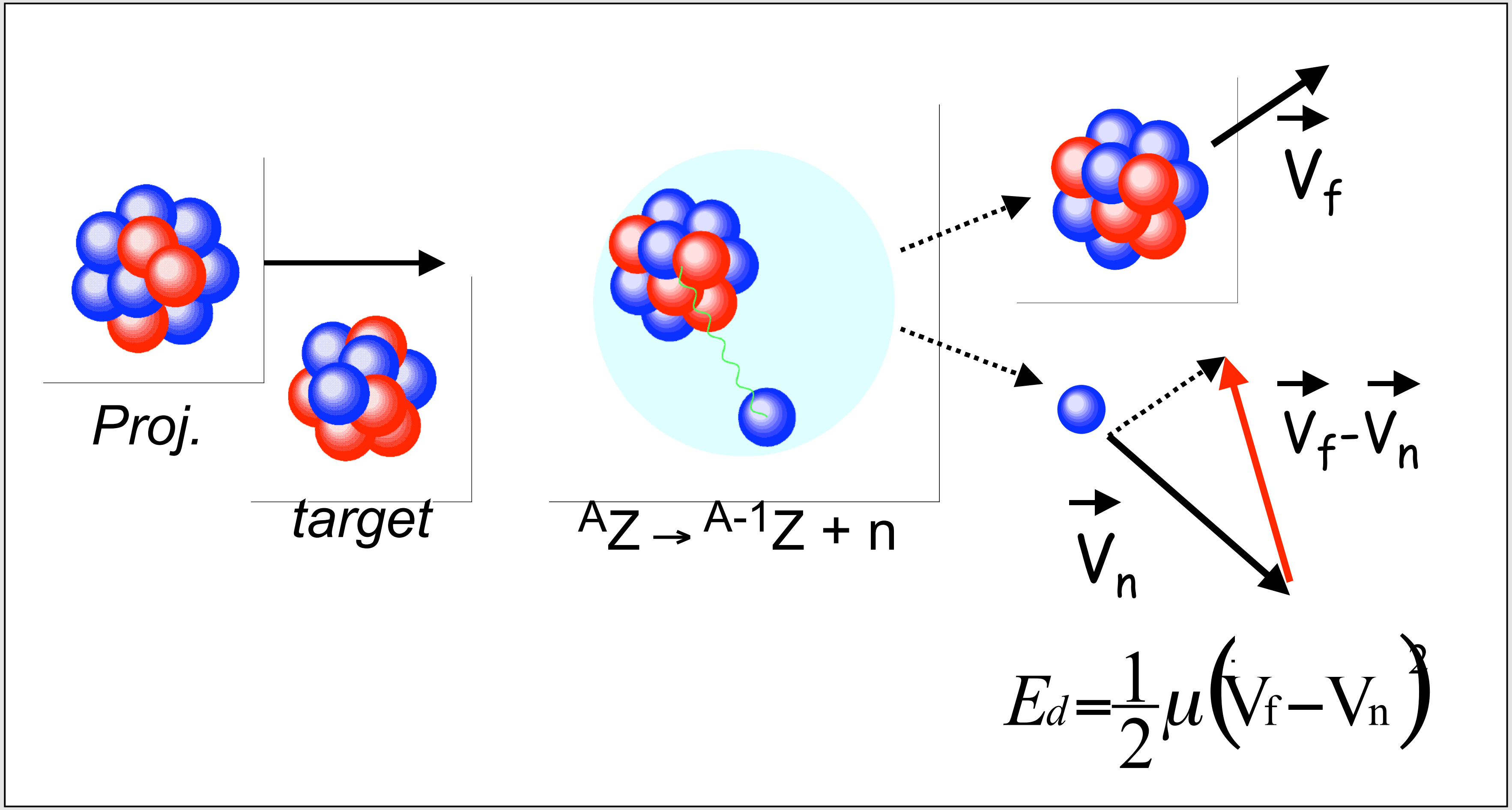
→ *In parallel explore evolution of N=7 g.s. parity inversion*

N=7 $1/2^+$ – $1/2^-$ Level Inversion …



… ^{10}Li & ^{9}He ??

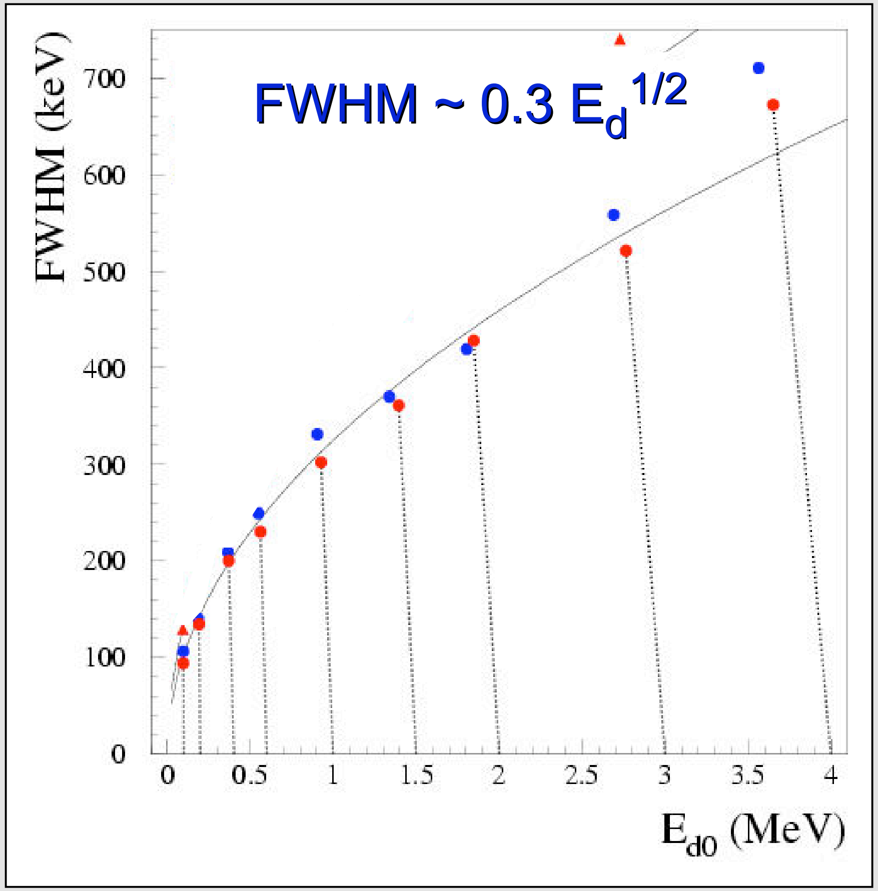
Experimental Approach



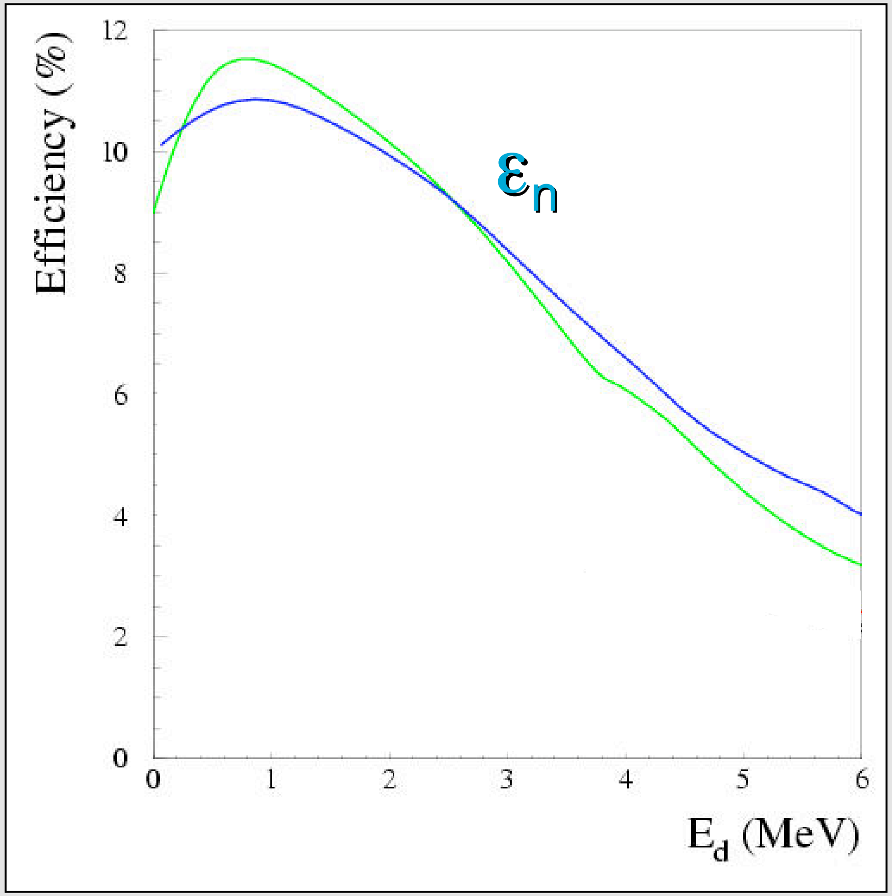
Fast nucleon removal - "knockout" or breakup + inflight decay
projectile structure known

Experimental Response Function

Resolution



Efficiency



model distributions must be "filtered" through the simulation

(Approx.) Selection "Rules" …

(i) 1 & 2-proton knockout ⇒ Δ_n=0 proj. valence neutron config.

$C(^{11}Be,^{10}Li)X$, $C(^{11}Be,^{9}He)X$ → $\nu s_{1/2}$ [^{11}Be $C^2S(\nu s_{1/2}) \approx 0.8$]

→ well adapted to probing low-lying s-wave strength

(ii) fragmentation (-xp,-xn) ⇒ valence neutron config. + others / population via neutron-decay of N+1 system

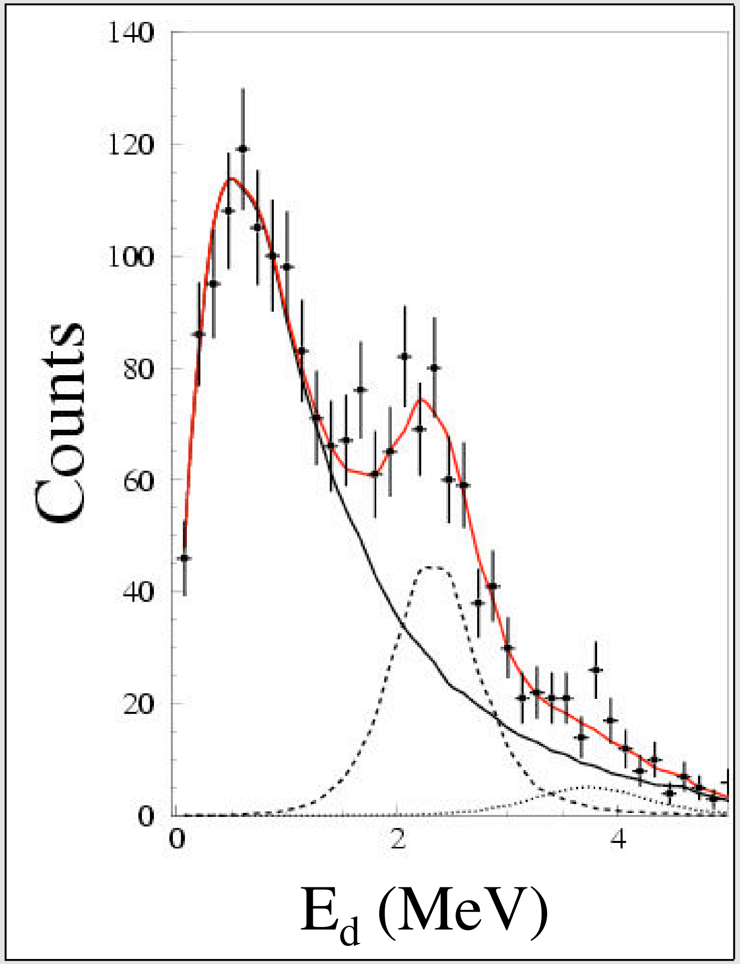
$C(^{14}B,^{10}Li)X$, $C(^{14}B,^{9}He)X$ → $\nu s_{1/2} + \nu p_{1/2} + \ldots$

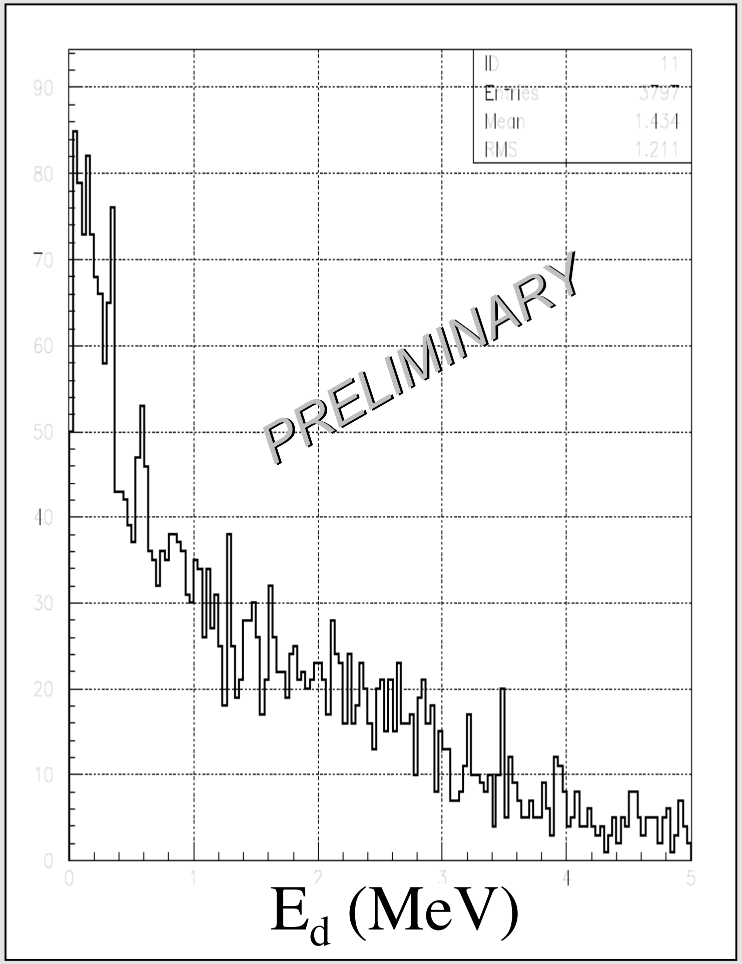
→ CAVEAT*: decay of narrow low-lying resonances in N+1,2,… systems

Note - E_d lineshape dependent on initial state (esp. for broad final states)

* See Kondo-san $^{14}Be^*$ → ^{12}Be+n

$C(^{14}B,^{12}Be+n)X$ | $C(^{15}B,^{12}Be+n)X$

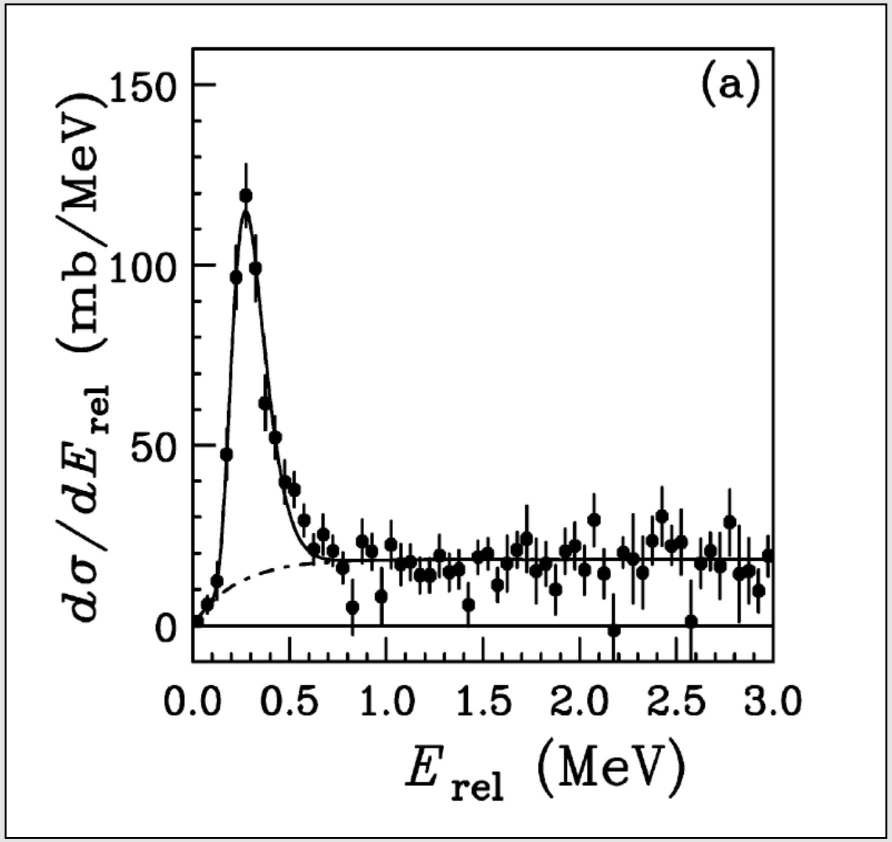




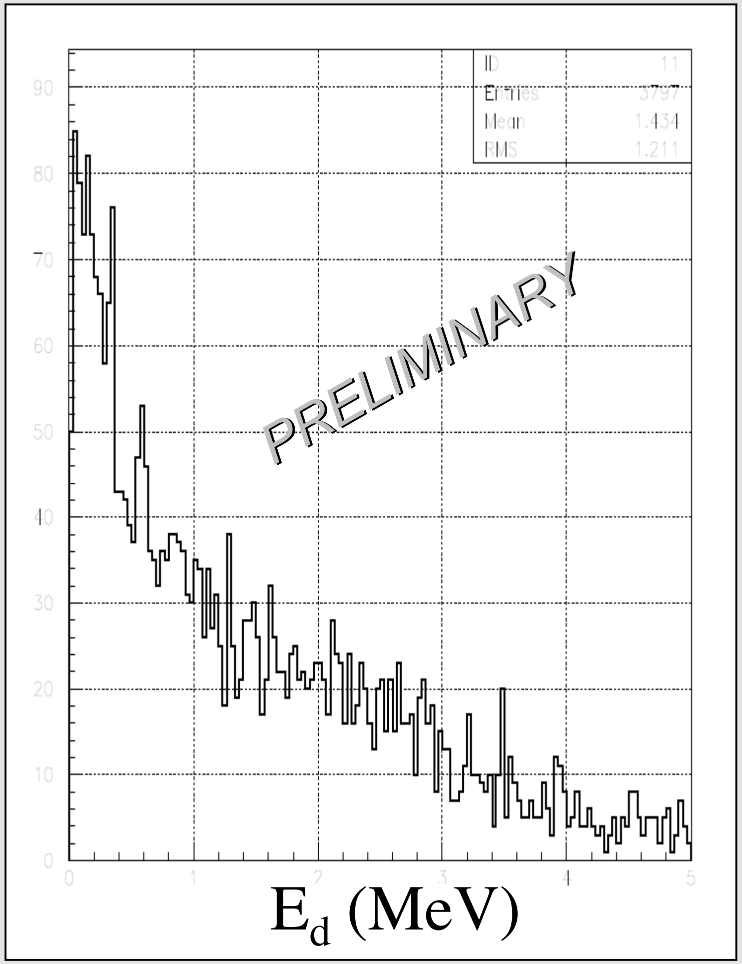
JL Lecouey LPCC 02-03; Few-Body Systems **34** (2004) 21

A Leprince, thèse en cours

C(^{14}Be,^{12}Be+n+n)C | *C(^{15}B,^{12}Be+n)X*



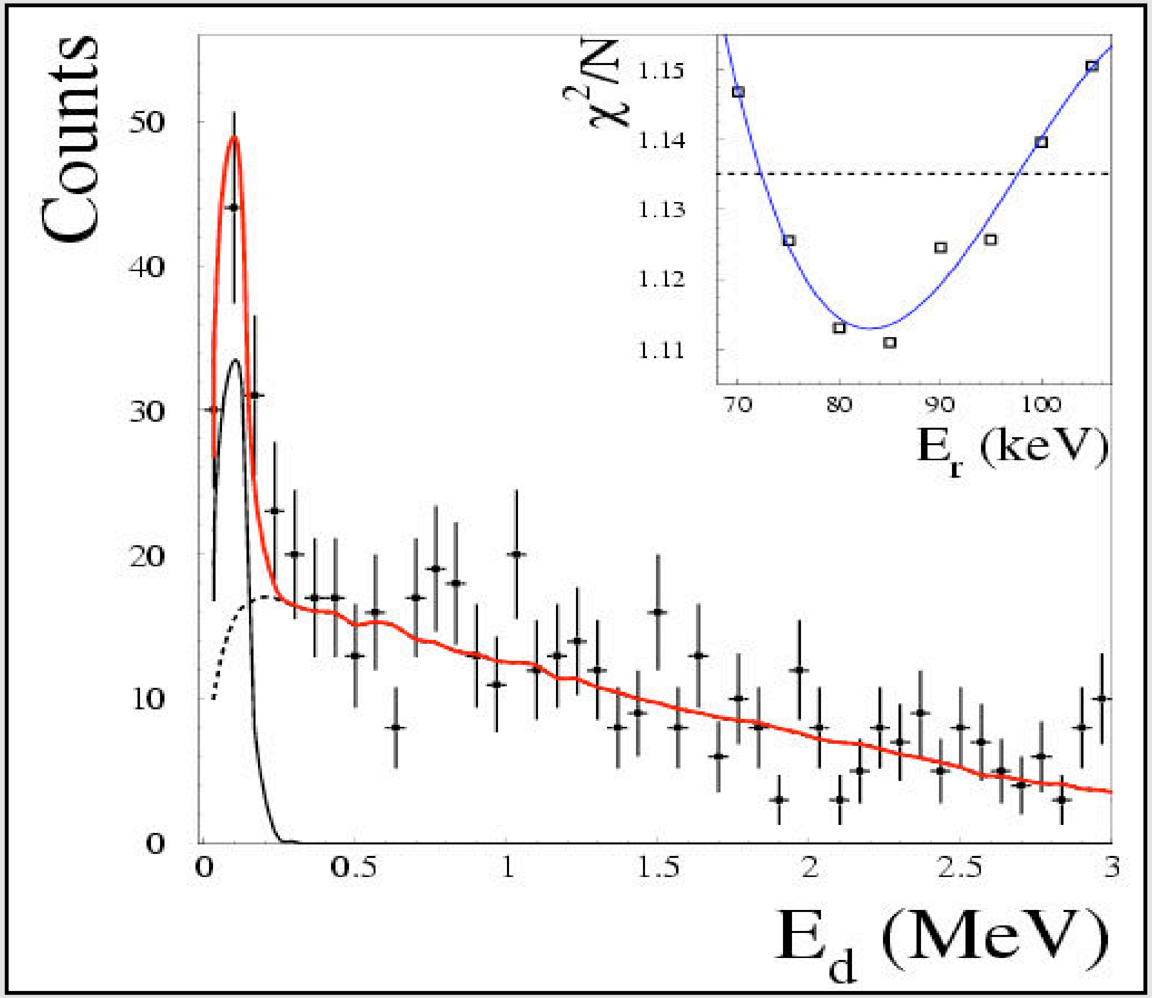
*T Sugimoto et al., PLB **654** (2007) 160*



$^{15}B \rightarrow {}^{14}Be^*(2^+) \rightarrow {}^{13}Be + n \rightarrow {}^{12}Be + [n] + n$

See Kondo-san's talk

BACKGROUND: C(^{17}C,^{15}B+n)X – single-proton knockout



E_r = 85 ± 15 keV

Γ_{sp} << 100 keV

\+

uncorrelated

^{15}B+n distribution

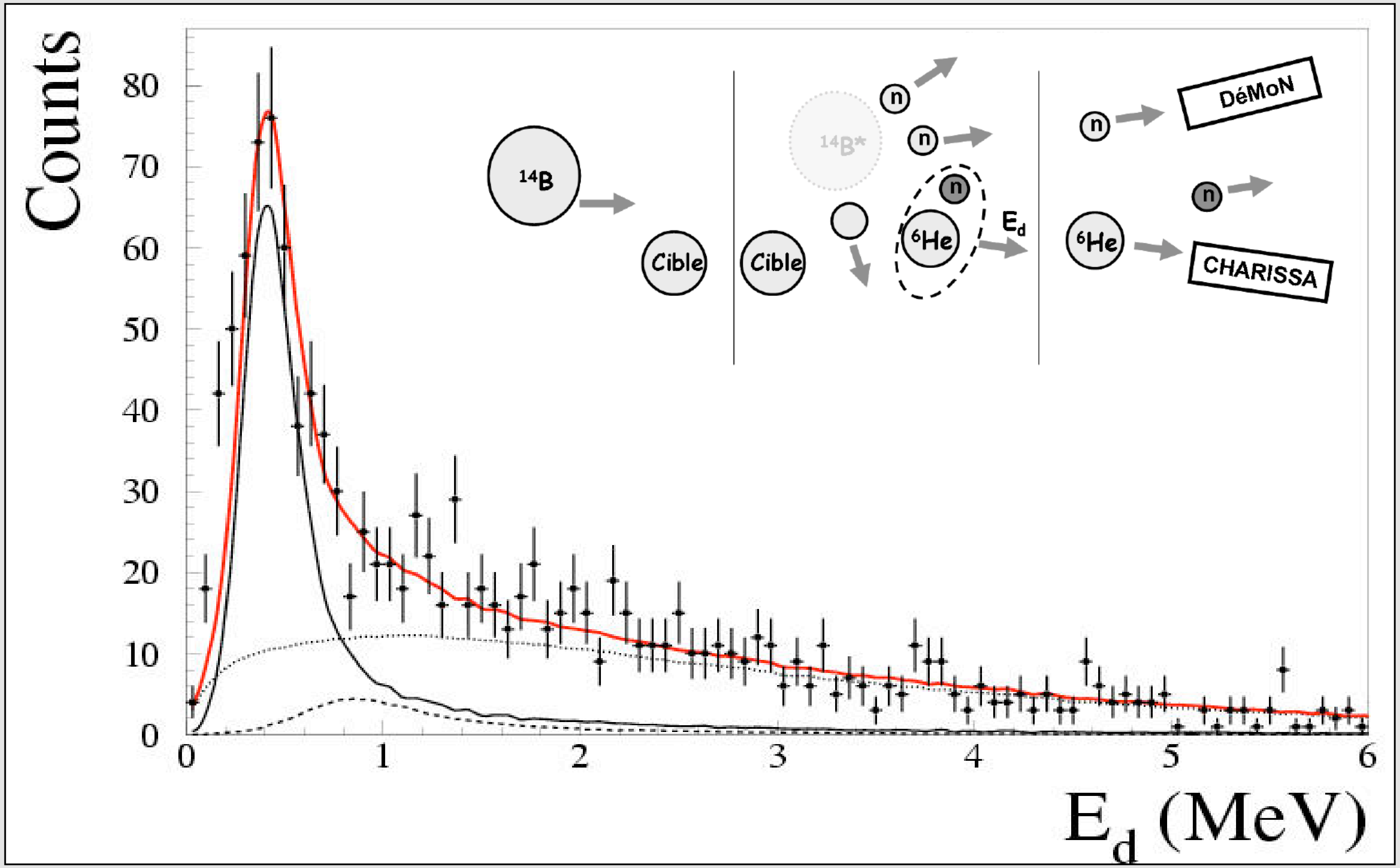
*"background" _ non-resonant continuum ↔ event-mixed distribution **

** ie., <u>uncorrelated</u> fragment-neutron pairs*

JL Lecouey et al, nucl-ex/0802.4225

JL Lecouey, Few-Body Systems 34 (2004) 21

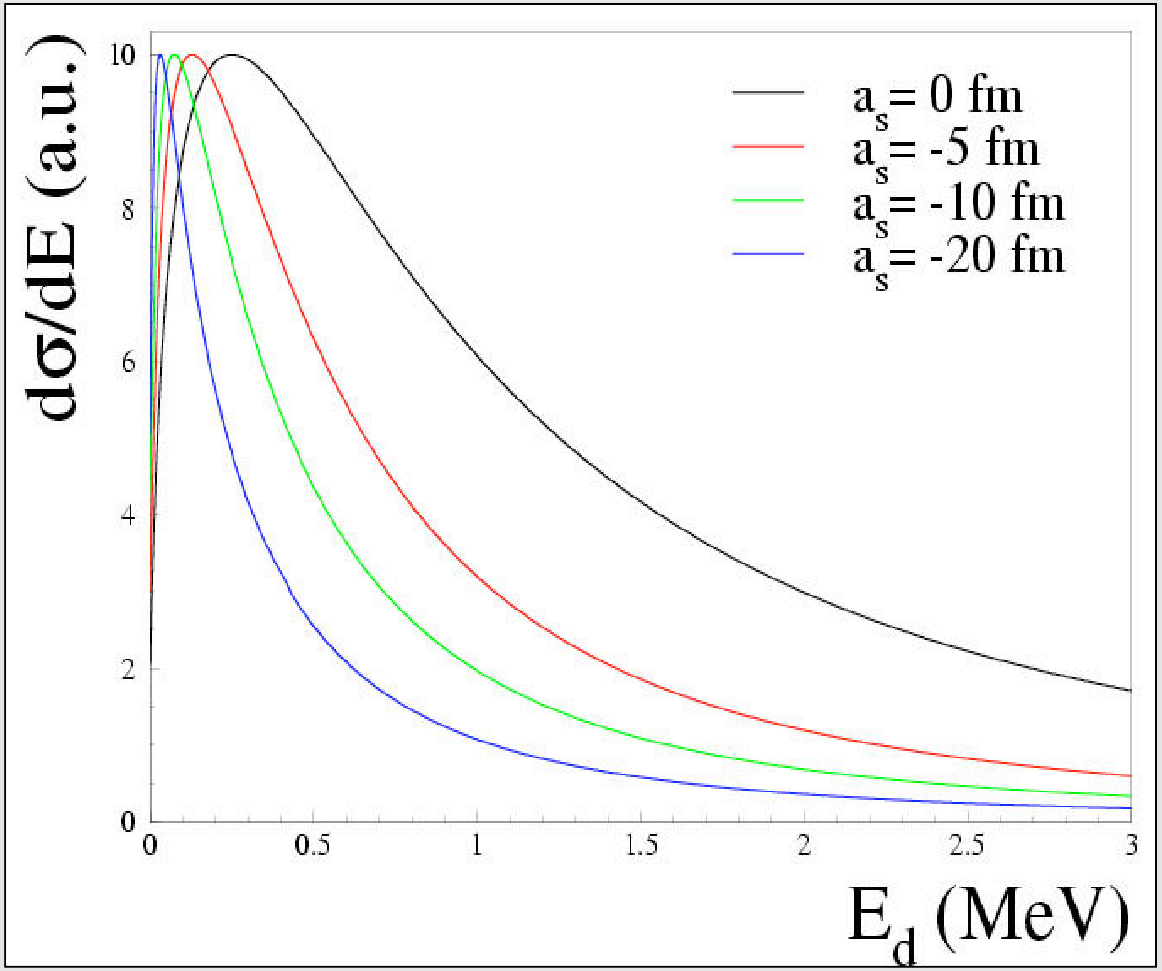
BACKGROUND : $C(^{14}B,^{6}He+n)X$ – fragmentation



"background" _ sequential neutron decay/evaporation from PLF + continuum

JL Lecouey, LPCC T 02-03.

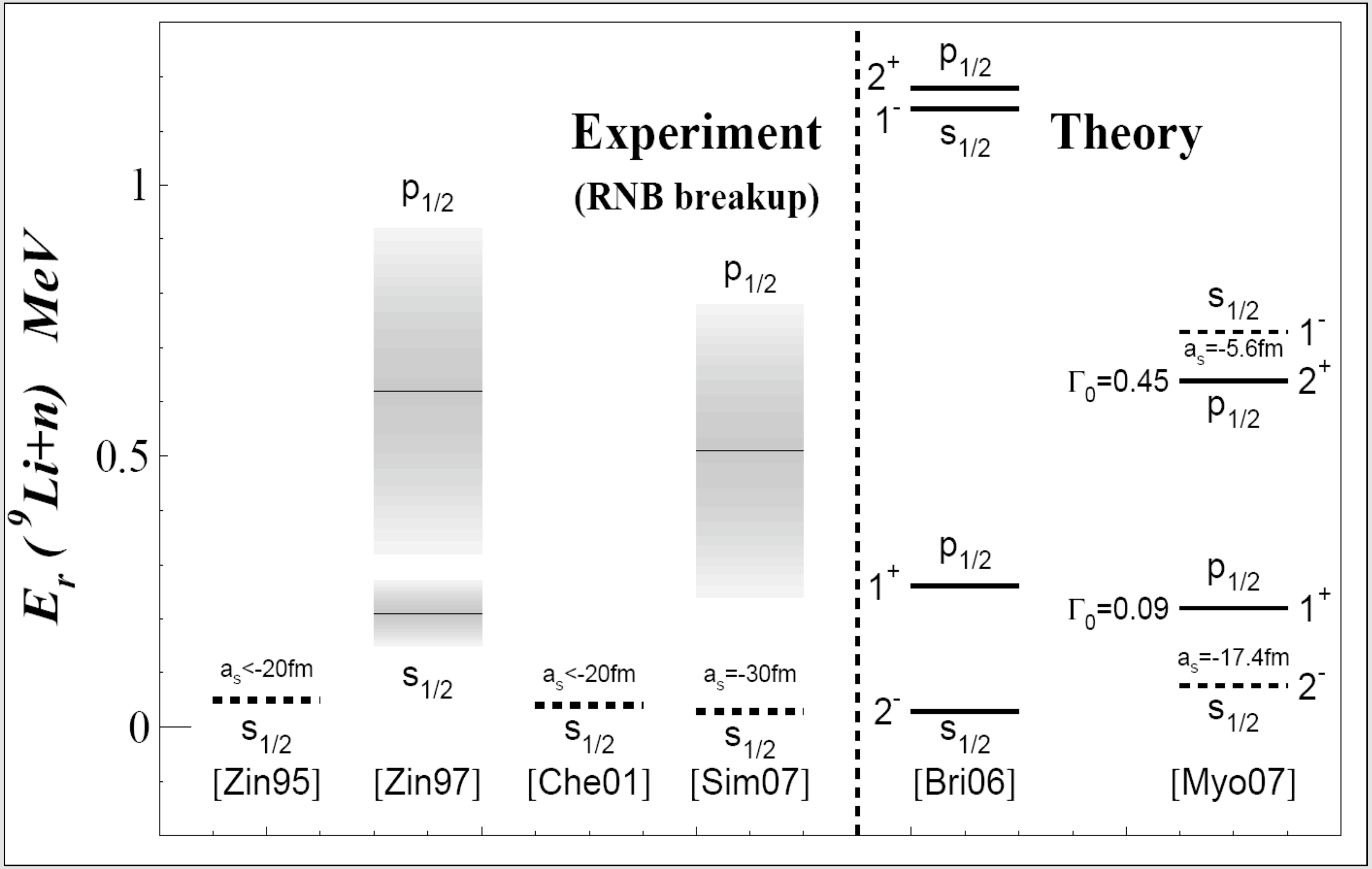
Scattering/Virtual s-wave States



a_s = 0 fm no FSI ; a_s << 0 fm stronger FSI

NB - final lineshape E_d(frag+n) depends on projectile

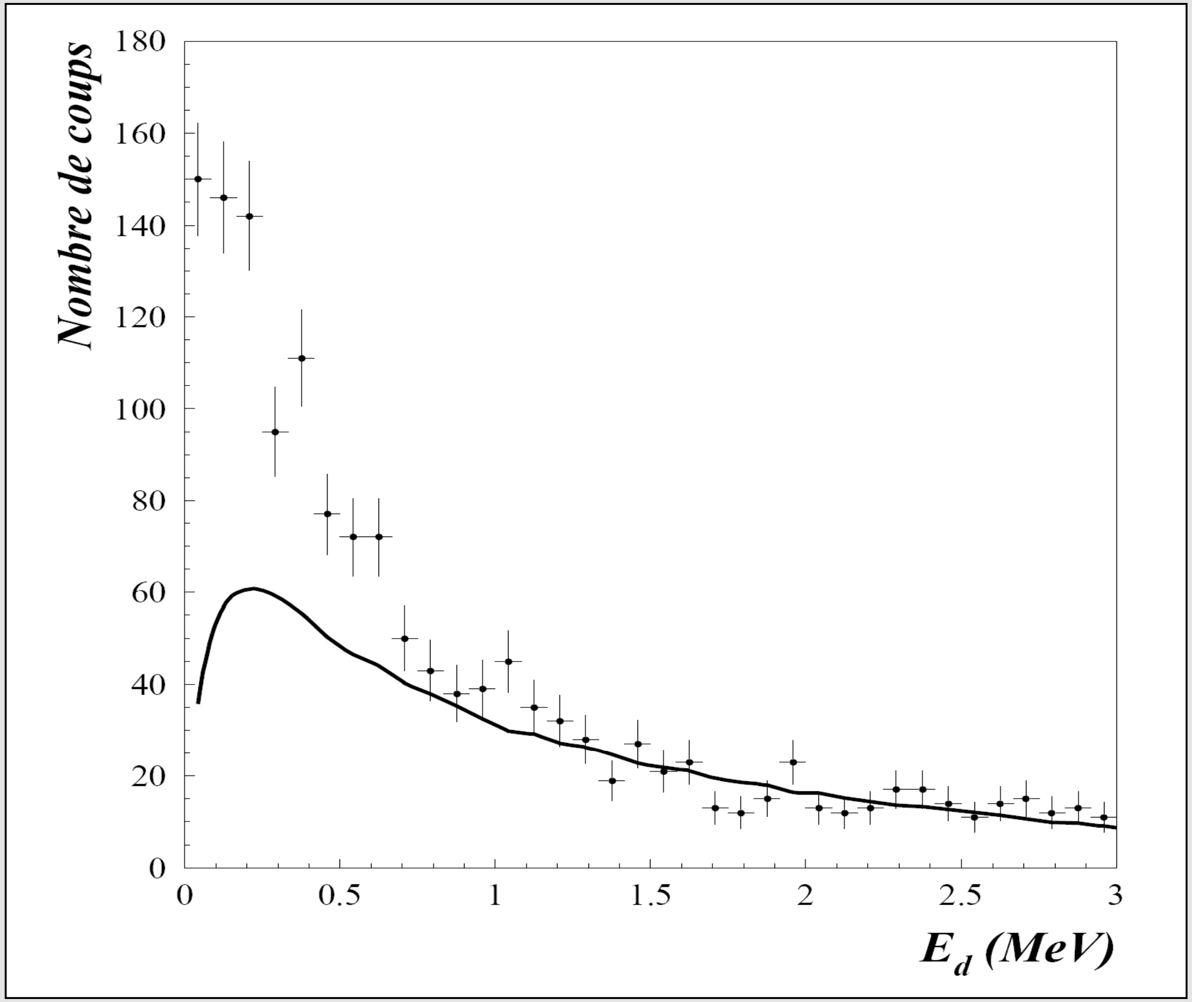
^{10}Li : Low-Lying Level Scheme *



.... s-virtual $E_r \sim \_^2 / 2a_s$

* "Partial" – also d(^{9}Li,p) etc

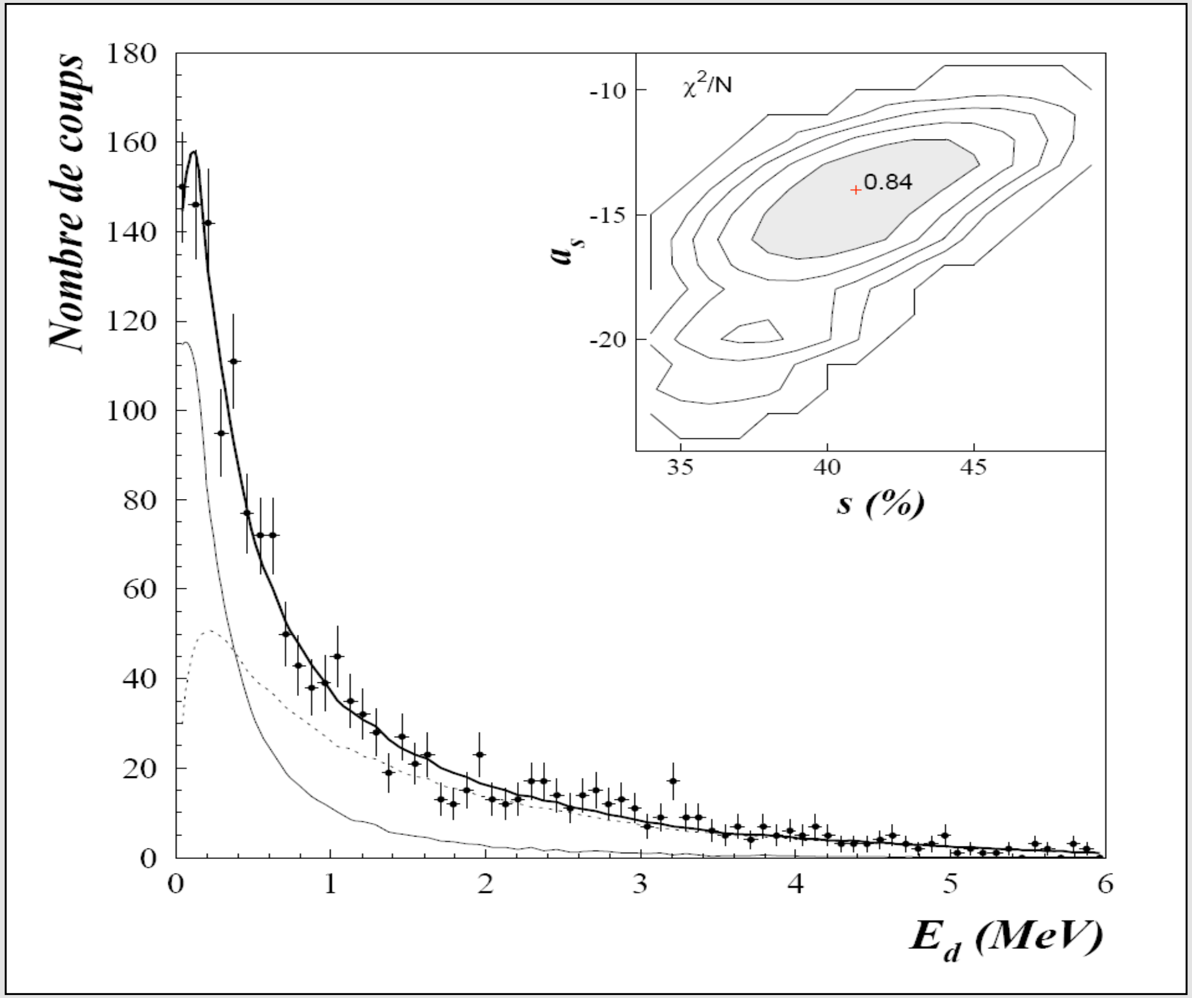
^{10}Li : C(^{11}Be,^{9}Li+n) @ 35 MeV/nucleon [-1p]



uncorrelated / event-mixed distribution *

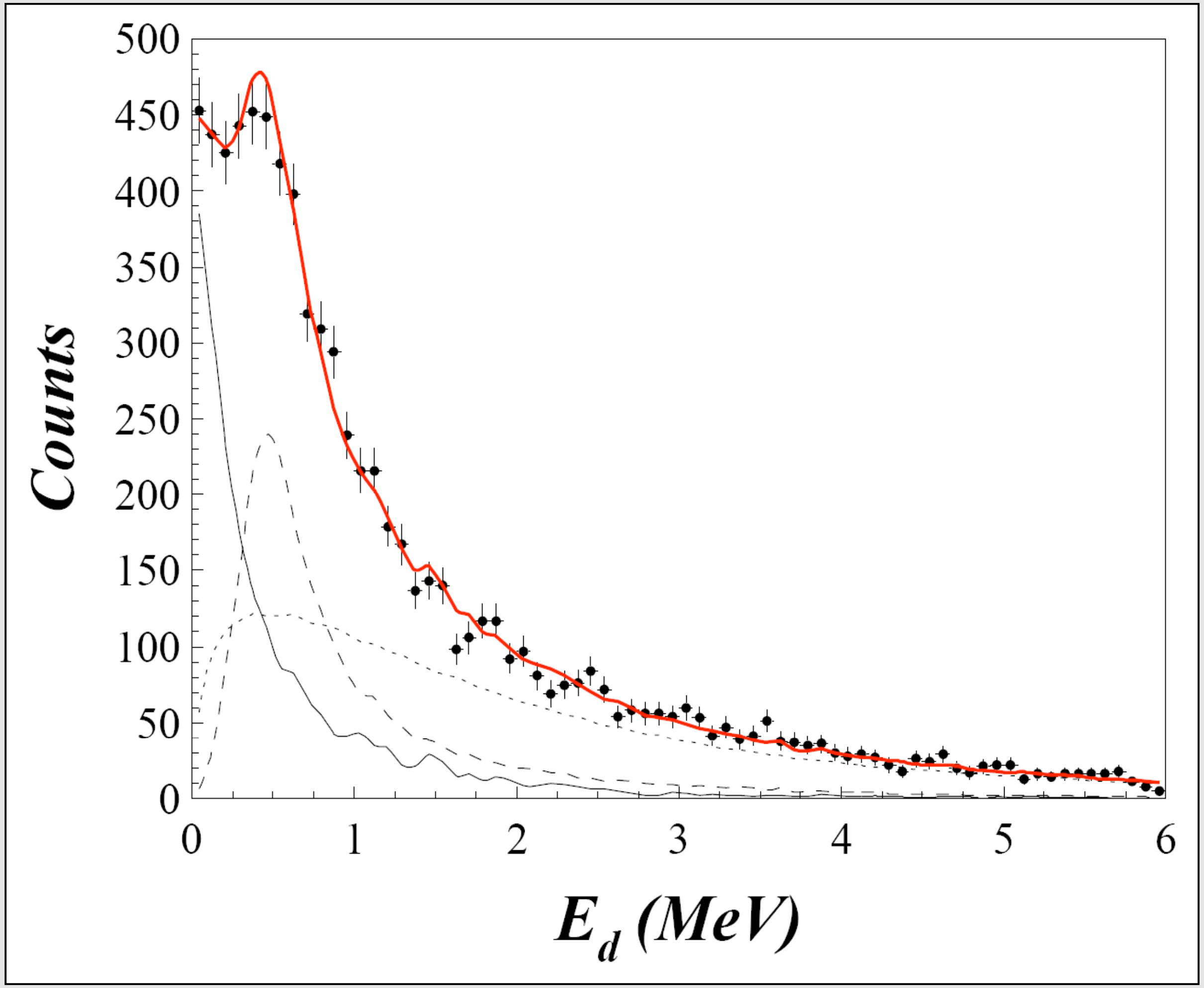
* normalised for comparison at high E_d

^{10}Li : $C(^{11}Be,{}^{9}Li+n)$ @ 35 MeV/nucleon [-1p]



s-wave [a_s = -14±2 fm] + non-resonant continuum

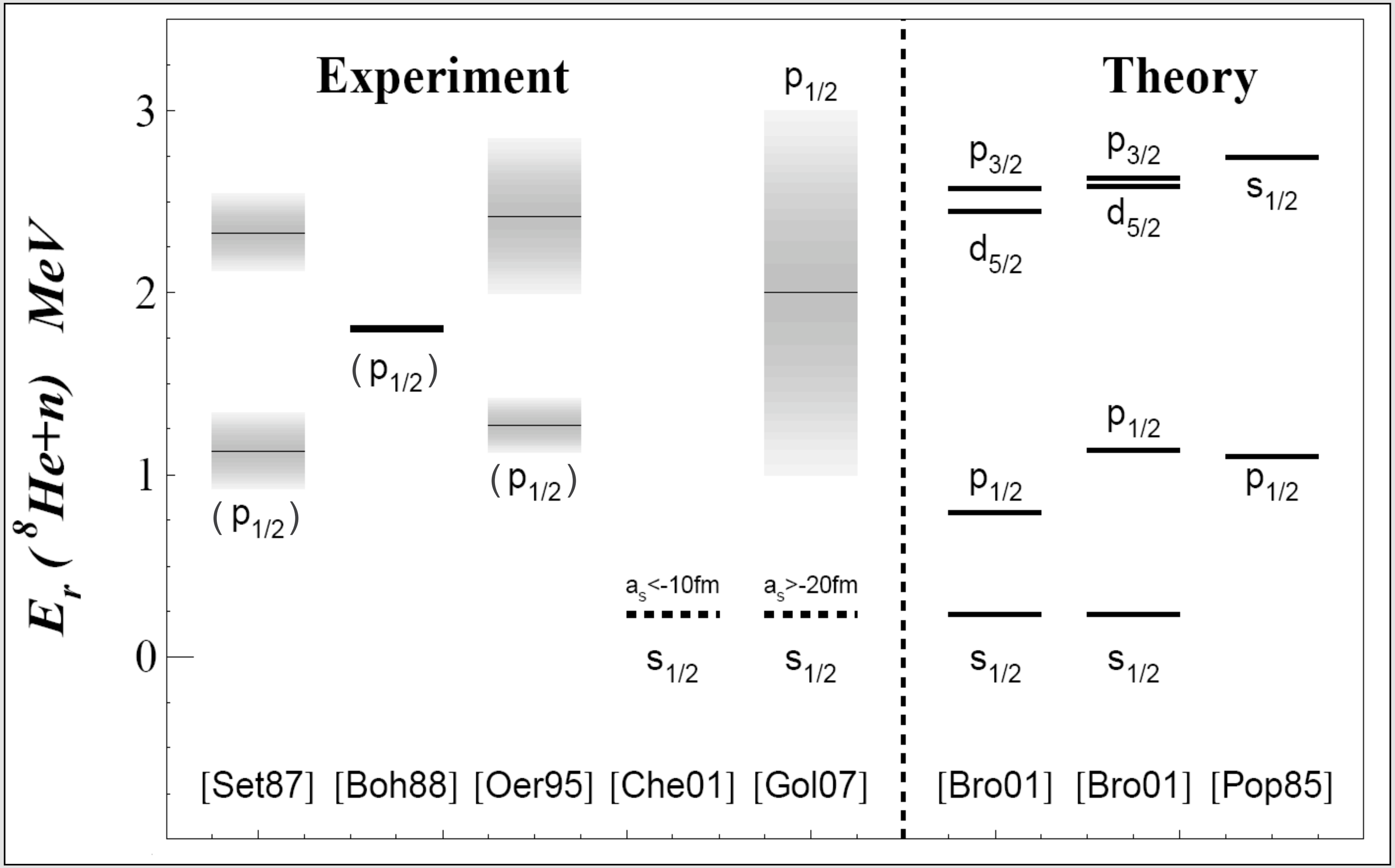
^{10}Li : $C(^{14}B,^{9}Li+n)$ @ 35 MeV/nucleon [-2p,-2n]



s-wave [a_s << -14 fm] + p-wave [E_r = 0.51, Γ_0 = 0.50 MeV] + background

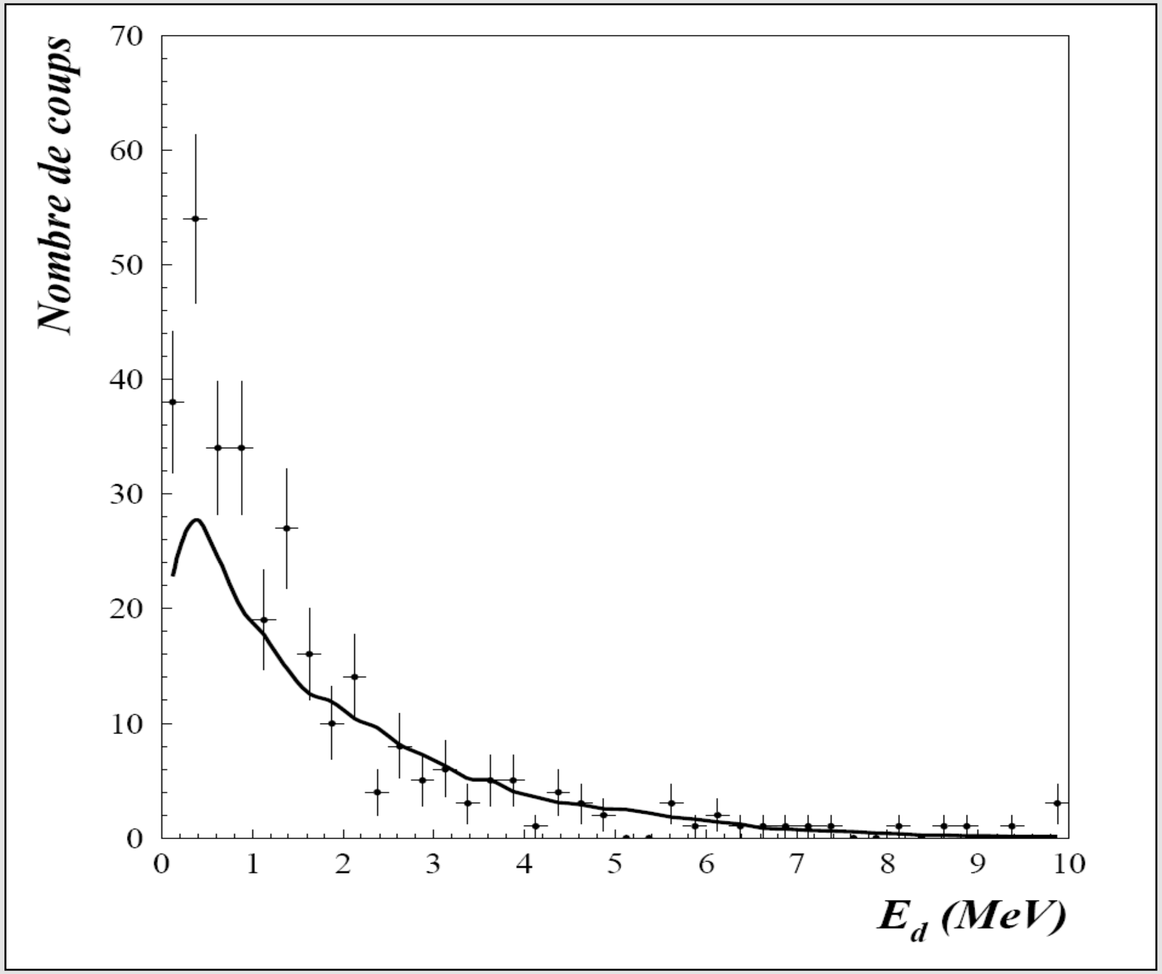
[Decay of $^{11}Li^*$ & ^{12}Li … ?]

^{9}He : *Low-Lying Level Scheme* *



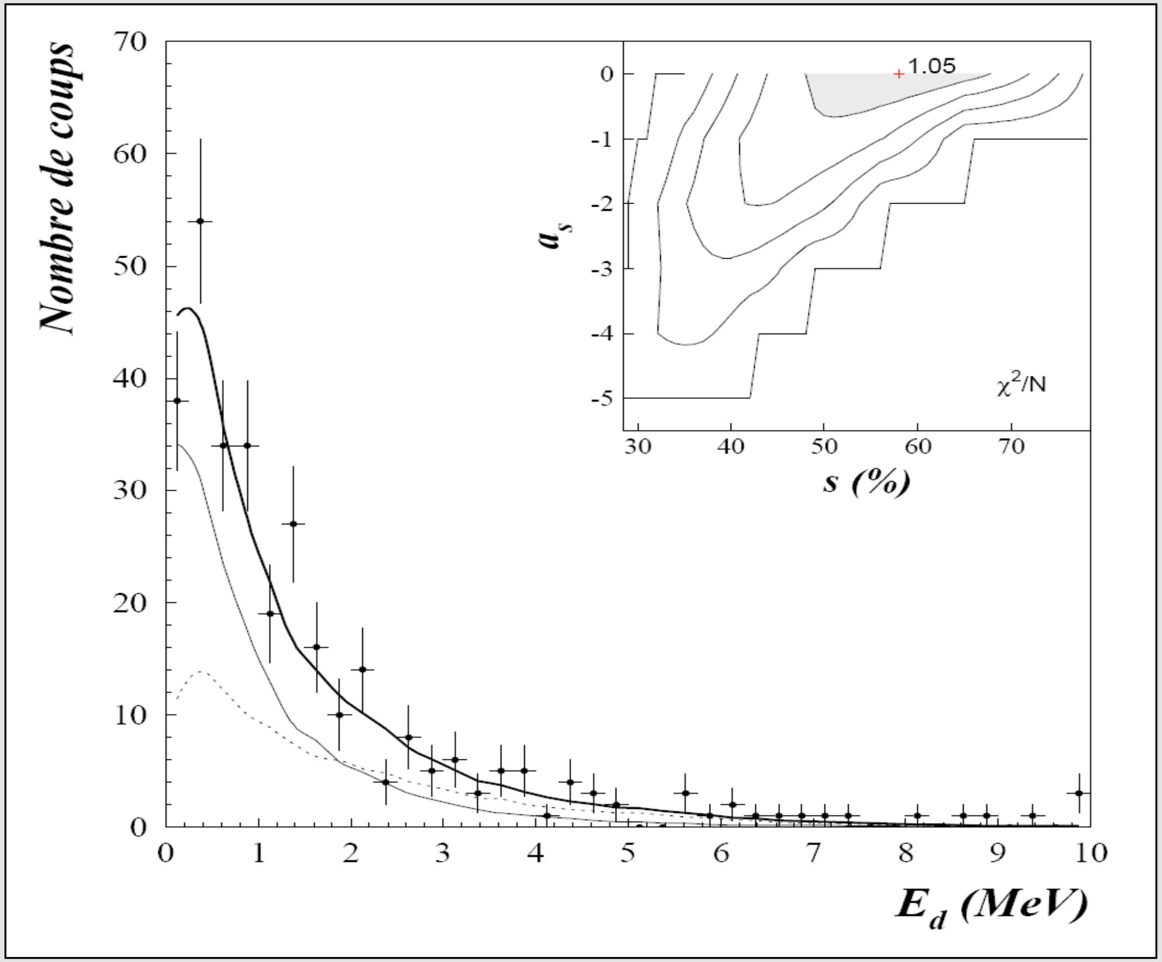
** ^{9}Li IAS expts not shown ; GANIL-MUST (d,p) under analysis*

^{9}He : $C(^{11}Be,^{8}He+n)$ @ 35 MeV/nucleon [-1p]



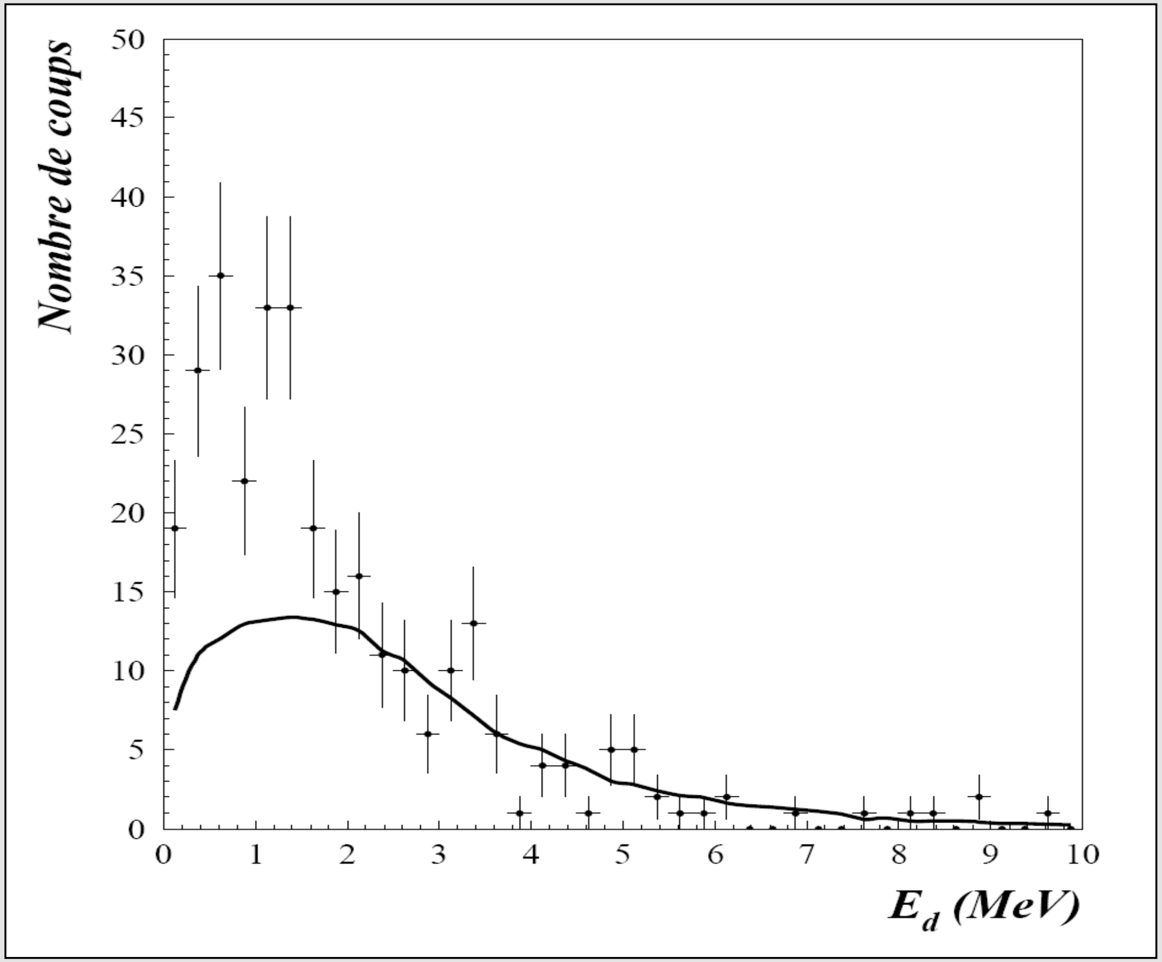
uncorrelated distribution/event mixed distribution

^{9}He : $C(^{11}Be,^{8}He+n)$ @ 35 MeV/nucleon   [-1p]



s-wave [a_s = -3 ~ 0 fm (3σ)] + non-resonant continuum

^{9}He : $C(^{14}B,^{8}He+n)$ @ 35 MeV/nucleon [-3p,-2n]



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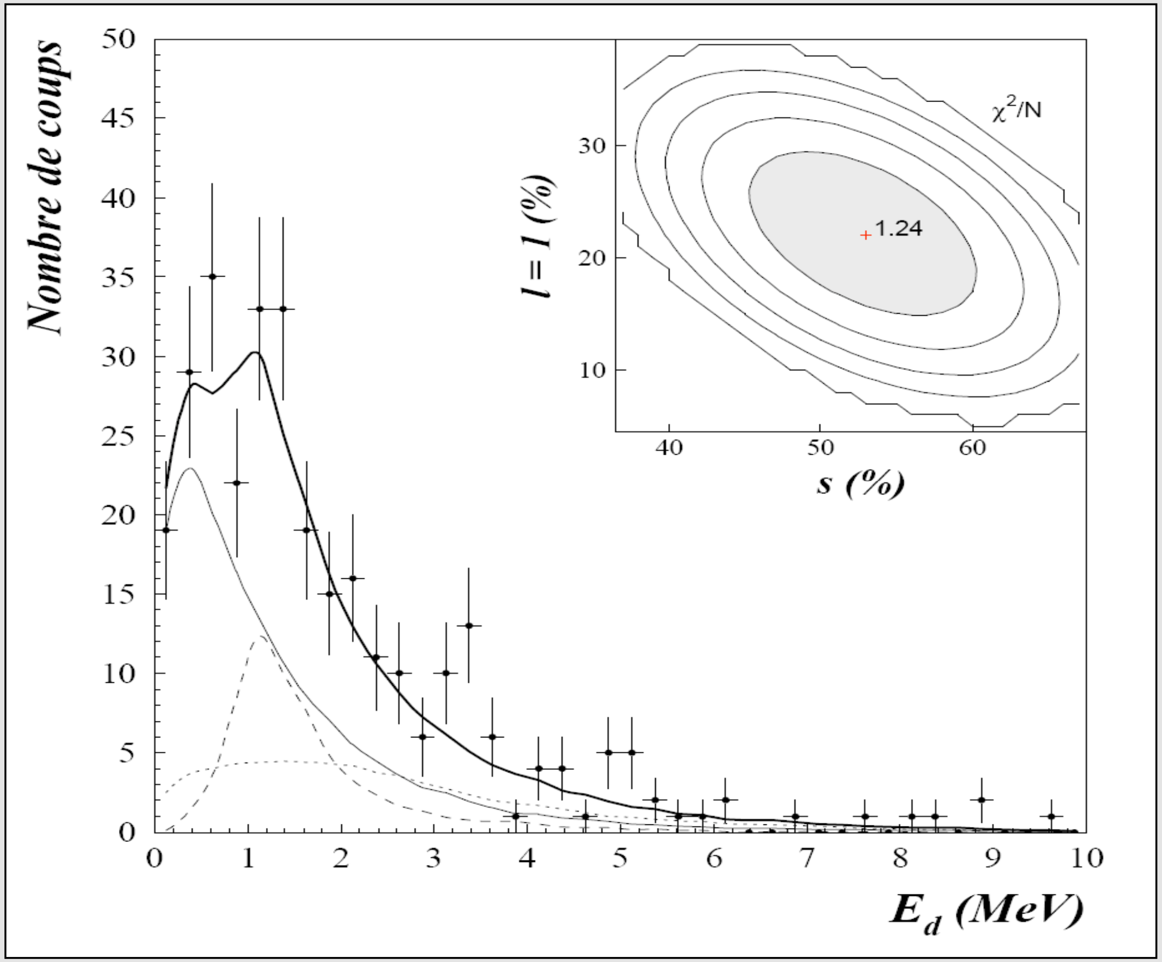
^{9}He : $C(^{14}B,^{8}He+n)$ @ 35 MeV/nucleon [-3p,-2n]



s-wave [a_s = -3 ~ 0 fm] + p-wave [E_r = 1.2, Γ_0 = 1.0 MeV] + background

[Decay of ^{10}He & ^{11}He … ?]

Conclusions & Perspectives

- ^{11}Be proton knockout suggests that selection rule valid

  ⇒ spectroscopy possible beyond the dripline using knockout from RNB …

→ ^{10}Li : low-lying s-wave strength (a_s = -14±2 fm)

low-lying p-wave resonance (E_r = 0.5 MeV)

⇒ N= 7 inversion confirmed

[but … $\pi p_{3/2} \otimes \nu s_{1/2}, \nu p_{1/2}, \nu d_{5/2}$]

→ ^{9}He : low-lying s-wave strength ($a_s \approx$ 0 fm) + $E_x \approx$1.2 & 2.4 MeV (l>0)

⇒ N= 7 inversion … ??

[FSI << ^{9}Li+n ??]

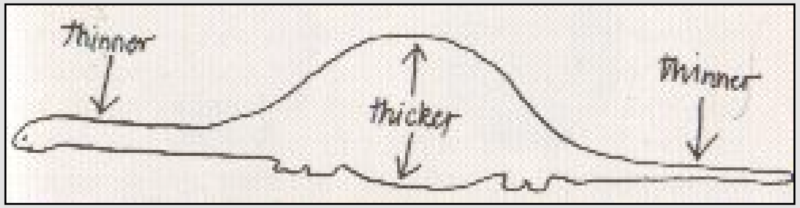
- EXPT: higher resolution & statistics improved neutron detection & I_B

Conclusions & Perspectives

- *validity of s-wave virtual states ??*

  eg., deformed ^{9}Li & ^{12}Be cores

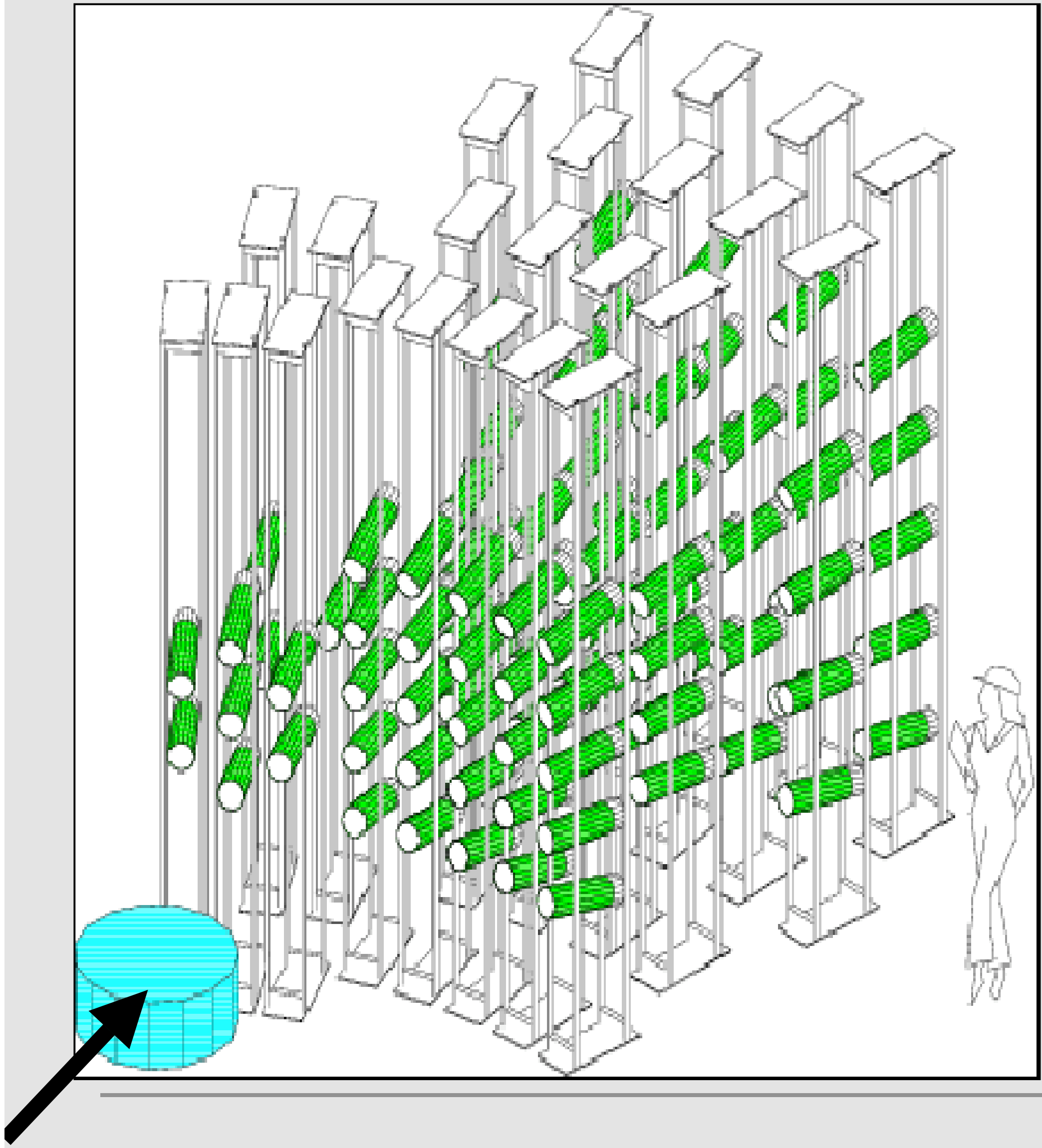
- *realistic <u>structure</u> + <u>reaction modelling</u> needed (lineshape and cross section) including non-resonant continuum + other backgrounds …*



- *first step – estimate frag. recoil effects*
- *valence neutron scattering (approx. free neutron scattering ?)*

“Falling Down” by Tom Waits

Kinematically "Complete" Measurement



DEMON

90 modules (NE213)

⇒ ToF & position

ε_n ~ 10%

Be(^{A}F,$^{A-1}$O) @ 50 MeV/nucleon : Experiment–Theory (Eikonal)

TABLE III. Spectroscopic factors C^2S, single particle σ_{sp}, calculated σ_{calc}, and experimental σ_{exp} single proton knock-out cross sections. The cross sections are given in millibarn.

Reaction	C^2S	σ_{sp}	σ_{calc}	σ_{exp}
(^{24}F, ^{23}O)	0.91	8.3	7.6	6.6±0.9
(^{25}F, ^{24}O)	0.96	8.1	7.8	3.8±0.6
(^{26}F, ^{25}O)	0.98	7.8	7.6	<4.1±1.4

*M Thoennessen et al., PRC **68** (2003) 044318*

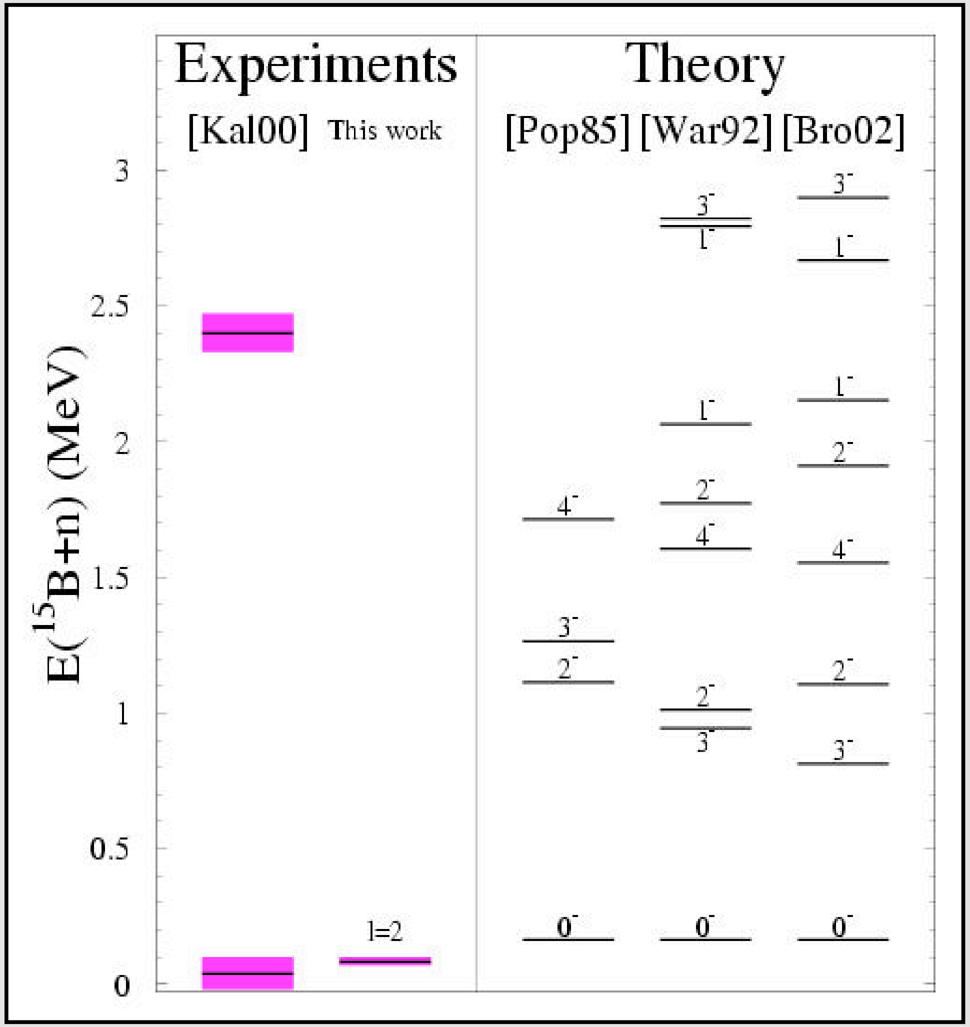
^{16}B : Experiment–Theory (Eikonal)

Expt

$C(^{15}B+n)$

σ_{tot} = 6.5±1.5 mb

$\sigma \approx$ 1 mb



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

"Glauber"

2.6 mb

2.8 mb

2.0 mb

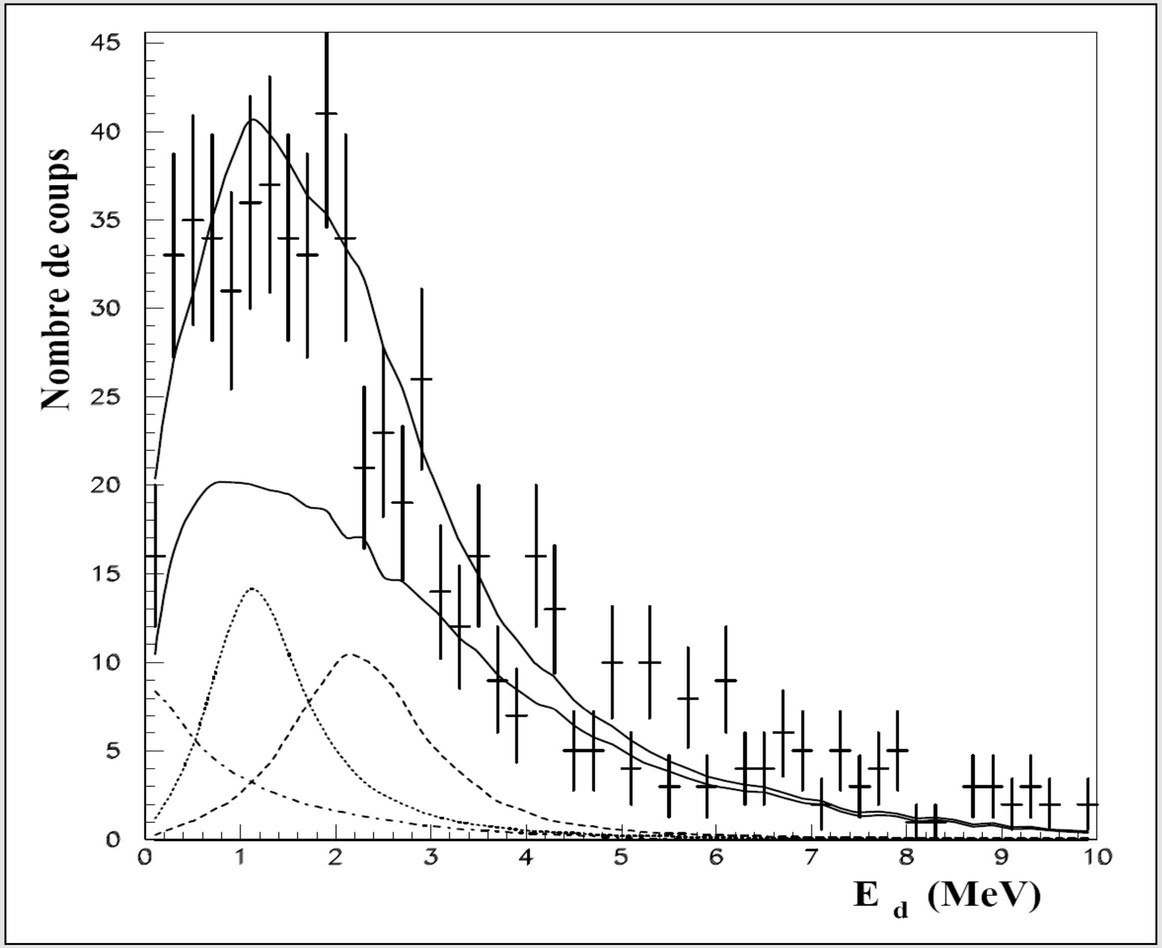
6.8 mb

1.7 mb

σ_{tot} = 16 mb

R_s = 0.5 $\Rightarrow$ 8 mb

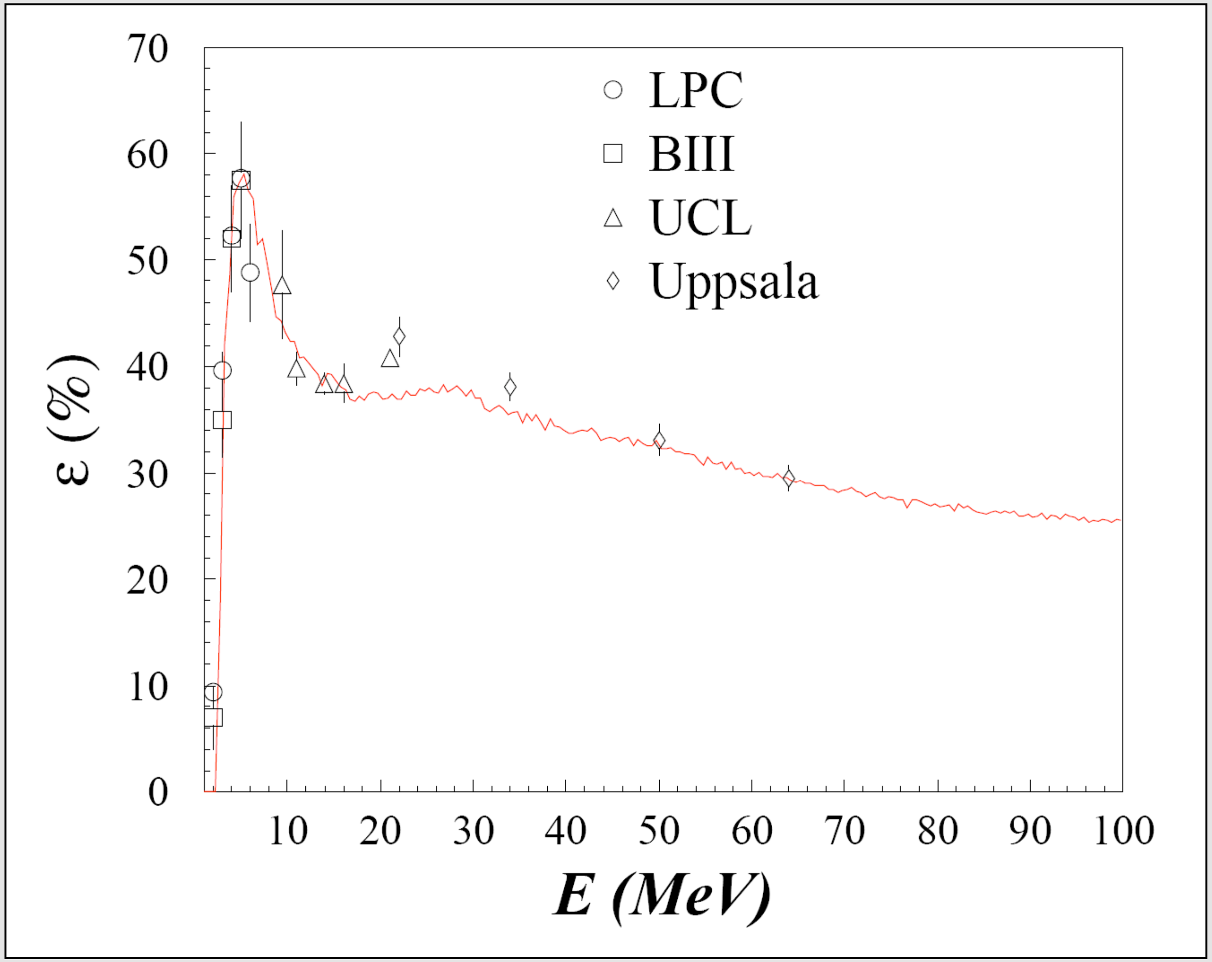
^{9}He : $C(^{12}Be,^{8}He+n)$ @ 41 MeV/nucleon [-2p,-1n]



s-wave [$a_s \approx -10$ fm] + $p_{1/2}$ [E_r = 1.2 MeV] + ($d_{5/2}$) [E_r = 2.4 MeV] + background

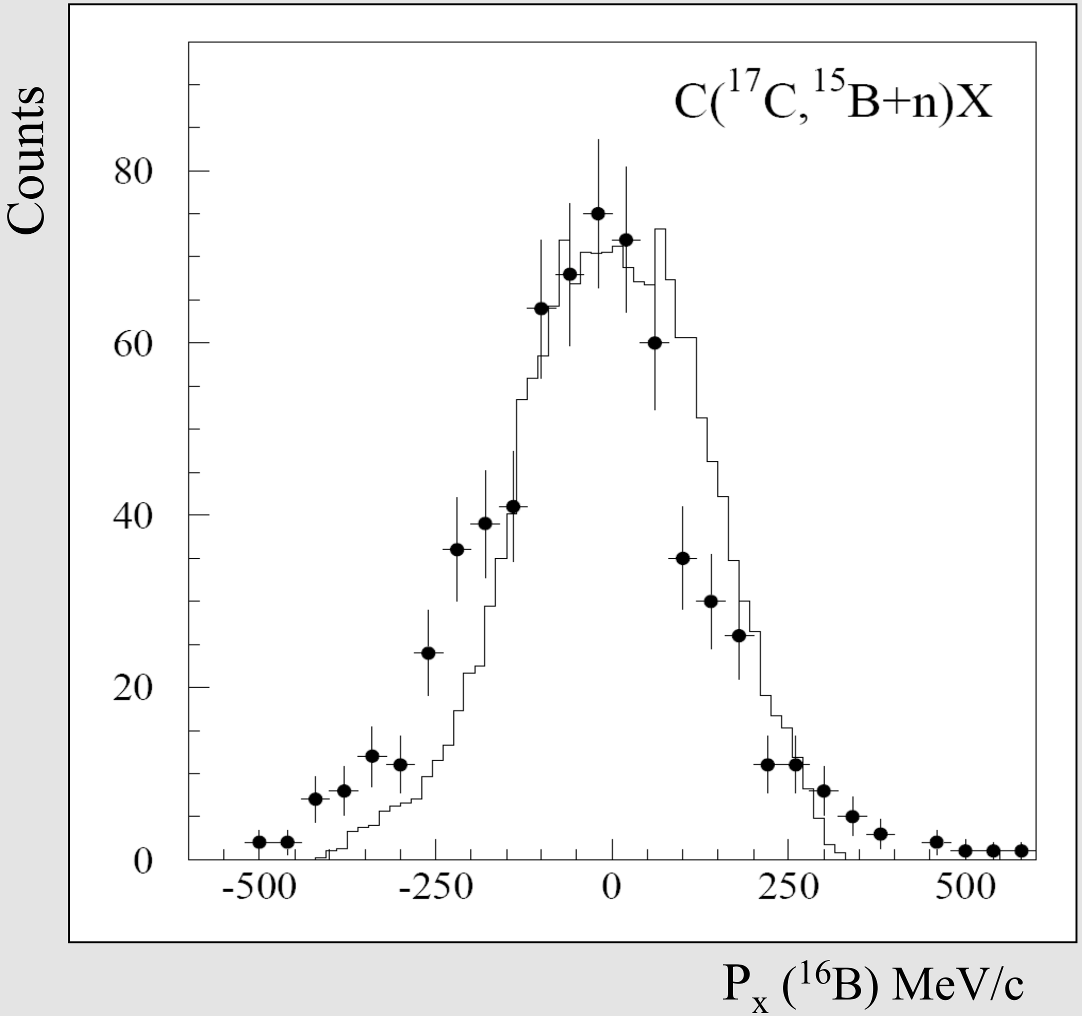
[Decay of ^{10}He … ?]

DEMON: Intrinsic Detection Efficiency



Q_{thresh} = 0.5 MeVee

Sudden Approximation



Sudden-type calculation* for removal of p-wave proton, S_p = -23 MeV

** M Zinser et al., PRL (1995), F Carstoiu et al., PRC (2004)*

Initial State Dependence of Unbound States

- *sudden approximation*

  ⇒ *neutron configuration of projectile preserved (Δ_n = 0)*

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

Final unbound state

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

Initial bound state

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

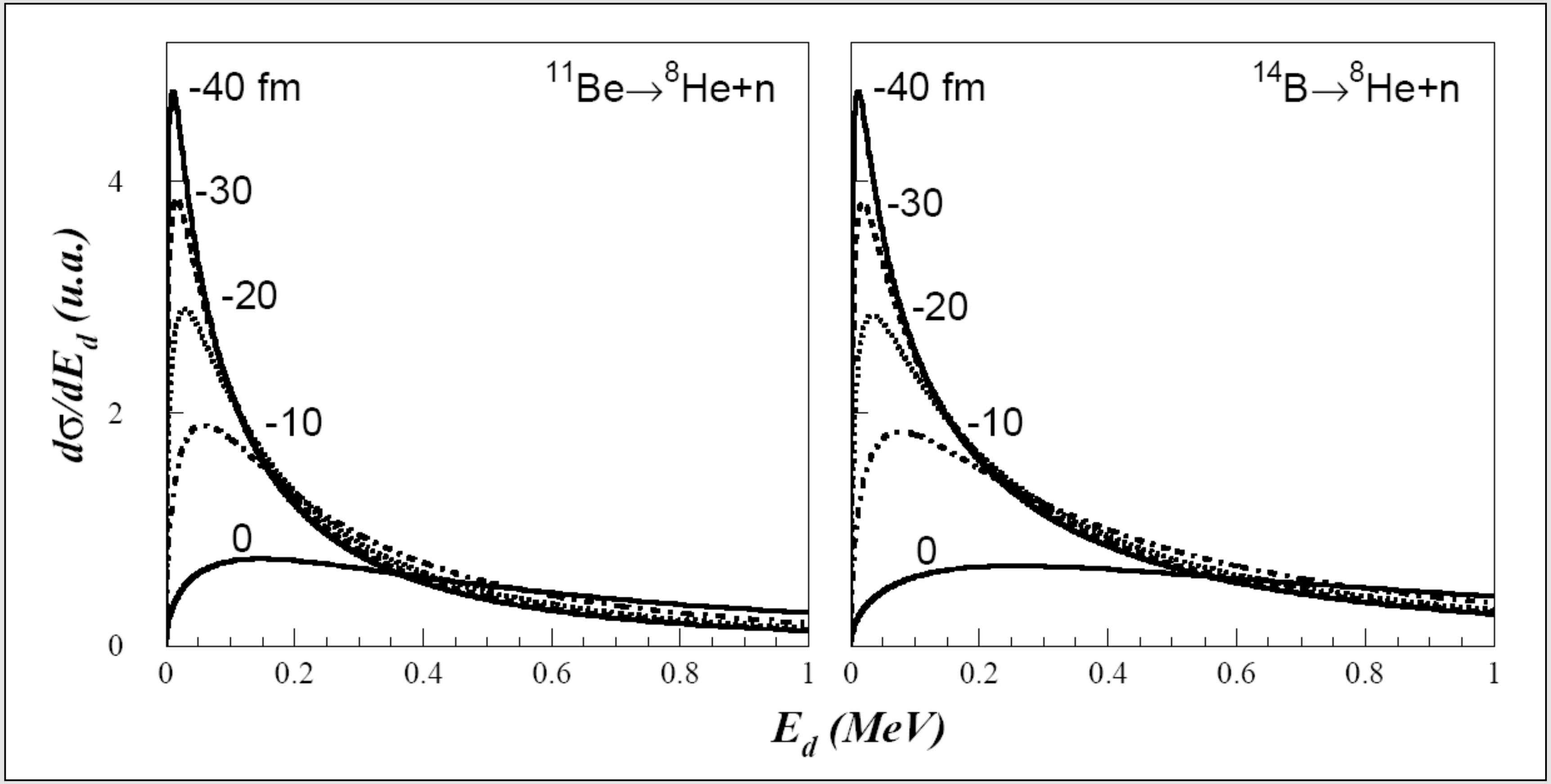
Decay Energy

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

→ Simulation → Comparison to data (χ^2)

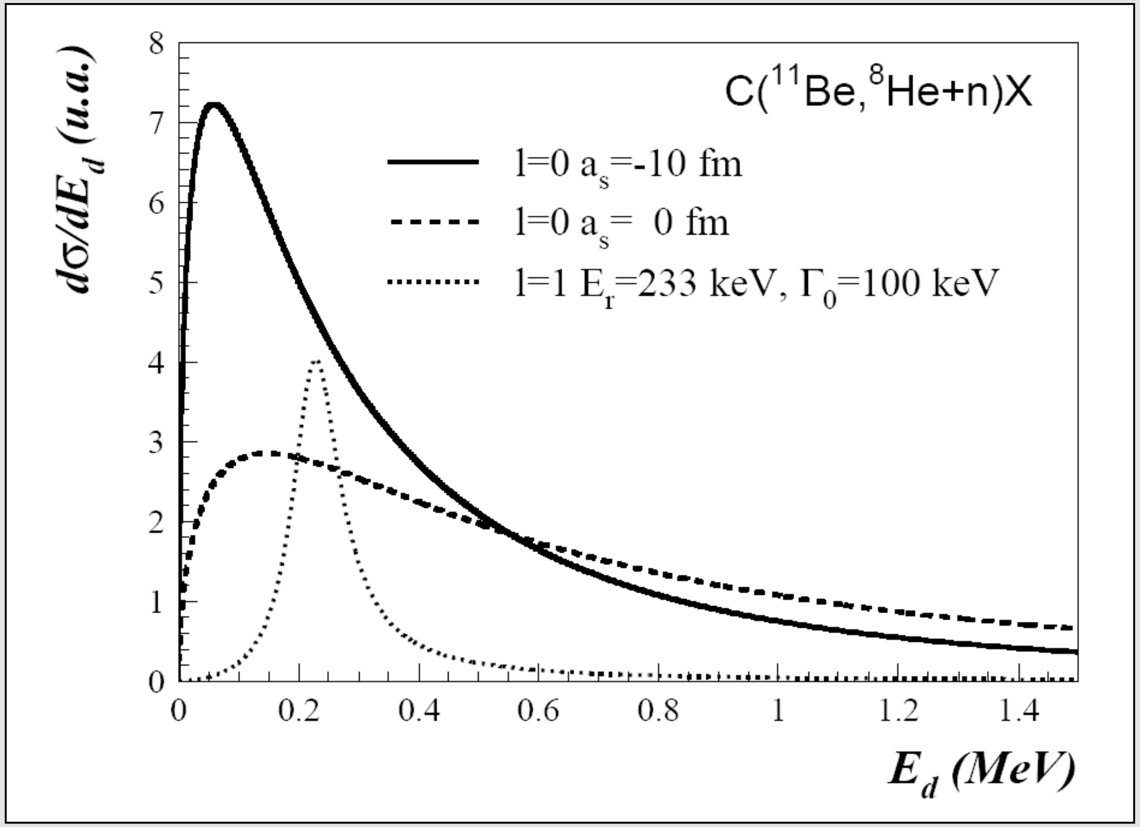
G Bertsch et al., PRC (1998), L Chen et al. PLB (2001)

Initial State Dependence of Virtual s-States



a_s = 0 fm no FSI ; a_s << 0 fm stronger FSI

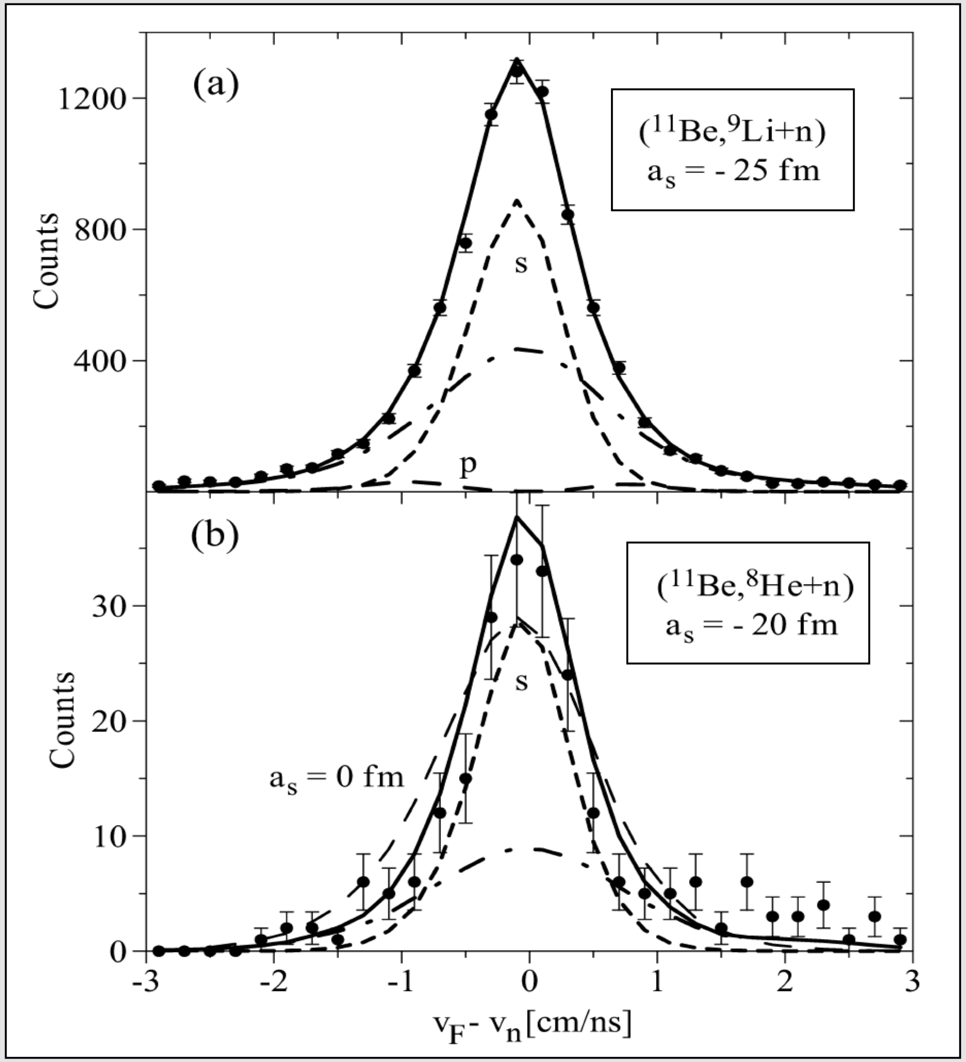
Virtual s-states & resonances



a_s = 0 fm no FSI ; a_s << 0 fm stronger FSI

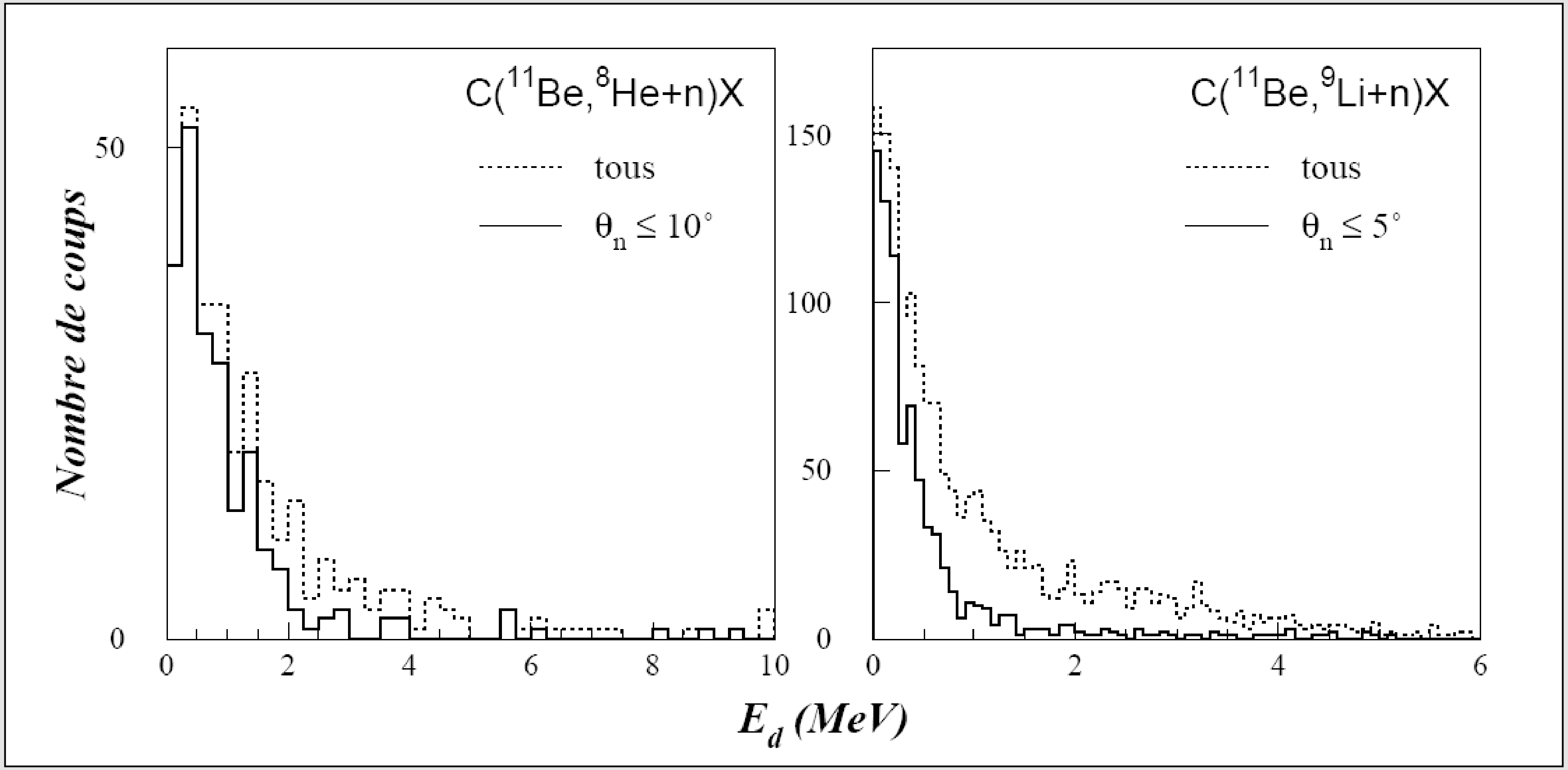
$$E_r \sim \_^2/2\mu a_s^2$$

$^{10}Li, ^{9}He$: $Be(^{11}Be, ^{9}Li+n)$ & $Be(^{11}Be, ^{8}He+n)$

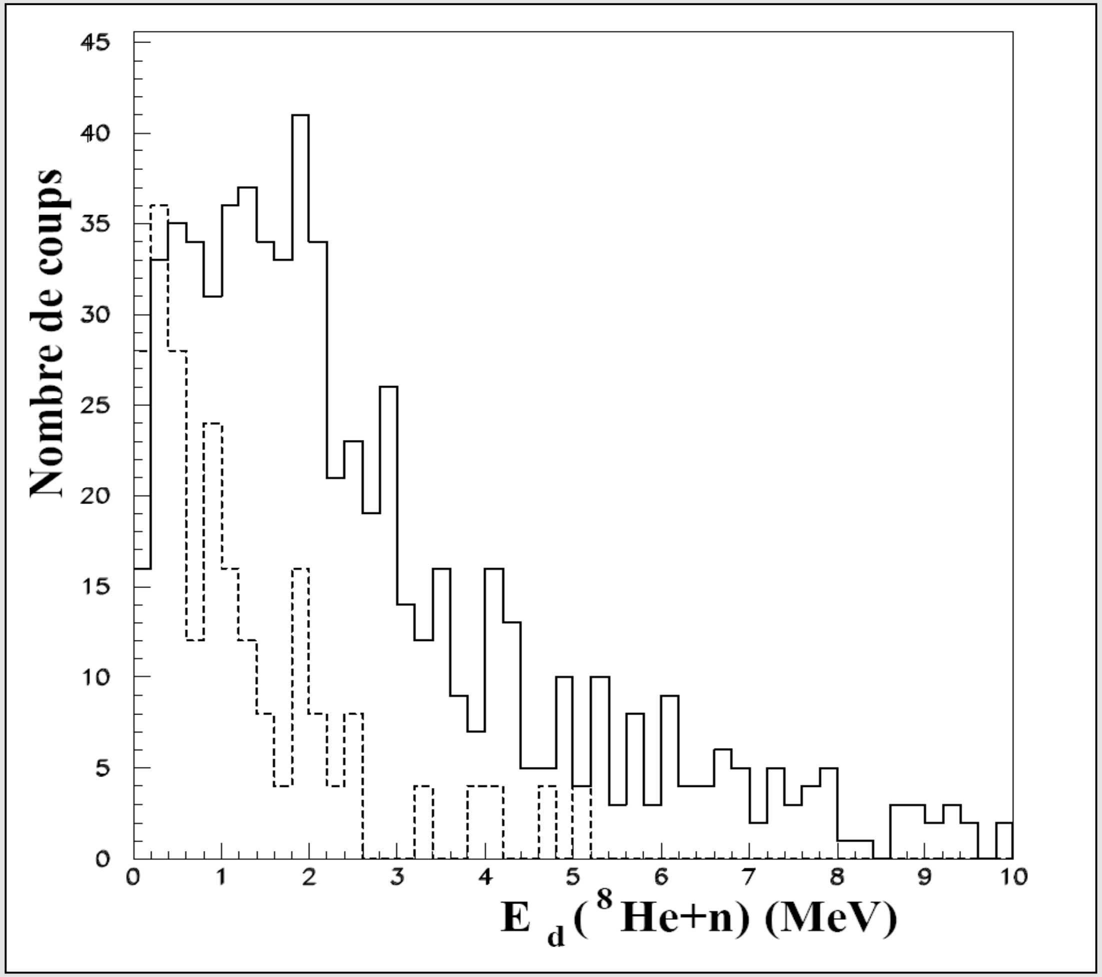


MSU L Chen et al., Phys. Lett. B (2001)

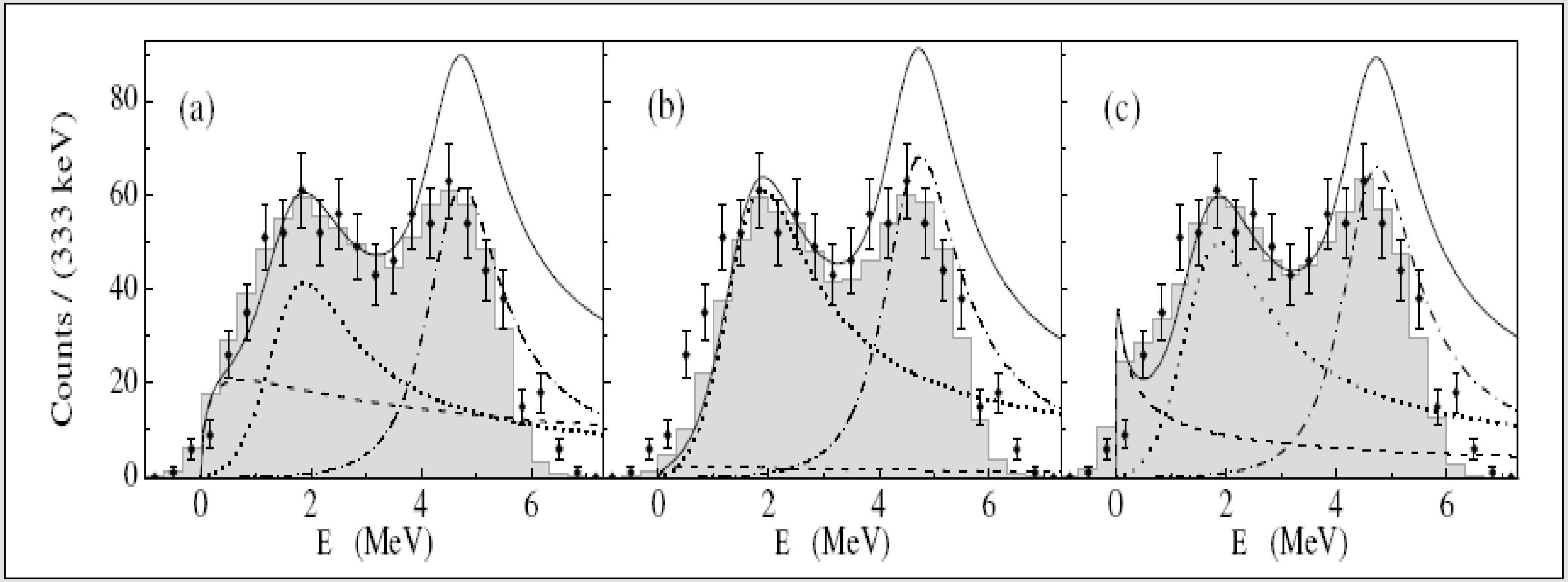
Neutron Angular Acceptance Effects …



^{9}He : $C(^{11,12}Be,{}^{8}He+n)$ @ 41 MeV/nucleon



^{9}He : $d(^{8}He,p)$ @ 25 MeV/nucleon



MS Golovkov et al., PRC76 (2007)