

Structure of the unbound systems

^{10}Li and ^{13}Be

Giacomo Randisi

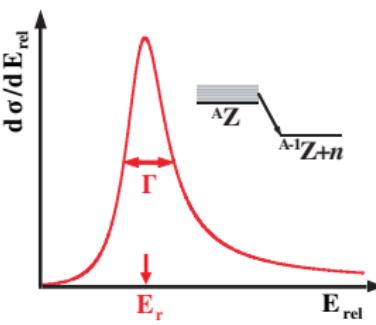
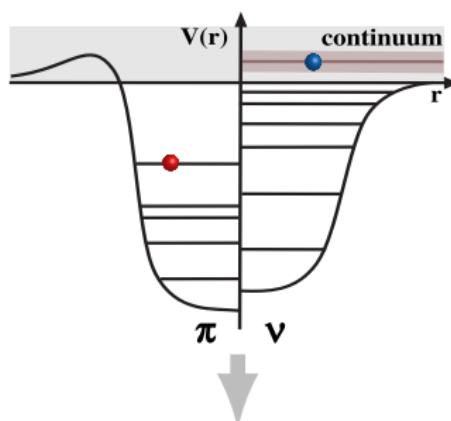
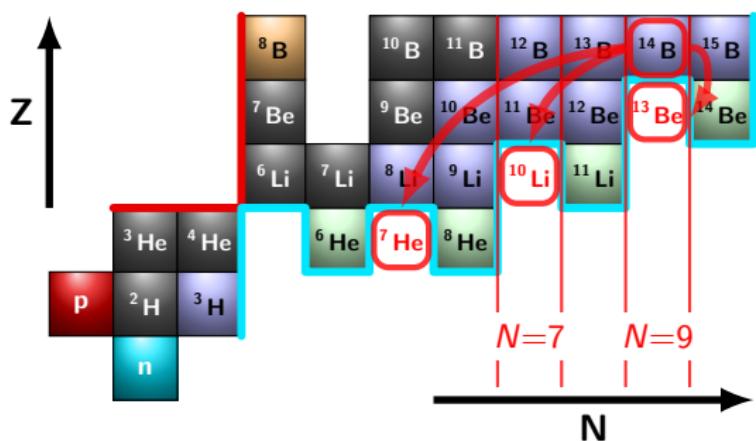
IKS Leuven & LPC Caen

for the LPC-CHARISSA-DEMON Collaboration

DREB 2012
Pisa, March 26th-29th

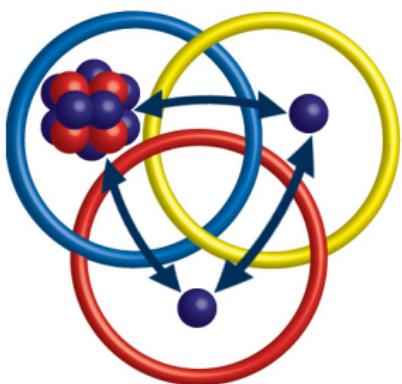


Beyond the neutron drip-line: the unbound systems



- Direct reactions with neutron-rich beams: neutrons toward the continuum
- short-lived resonances ($\tau \sim 10^{-21} \text{s}$)

Motivations: modeling 3-body systems



Borromean nuclei:

3-body systems in which no binary subsystem is bound

core-*n*, *n-n* interactions :
ingredients of 3-body models

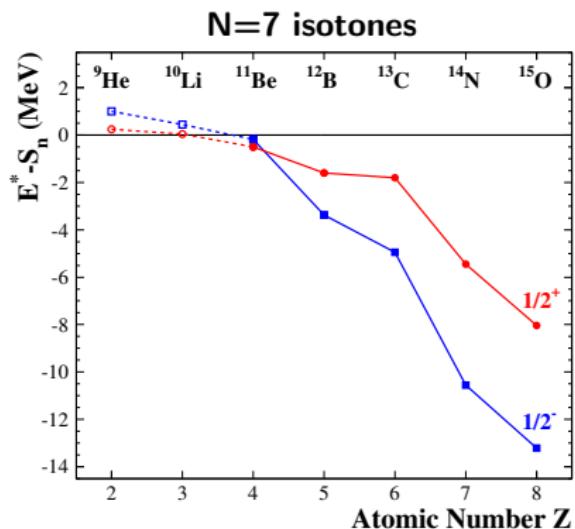
(e.g. I.J. Thompson et al. PRC 49 (1994) 1904)

⇒ study of the **unbound subsystem**
to get information about **core-*n*** interaction

***n* + core as target ⇒ impossible**
⇒ study of **Final State Interaction**

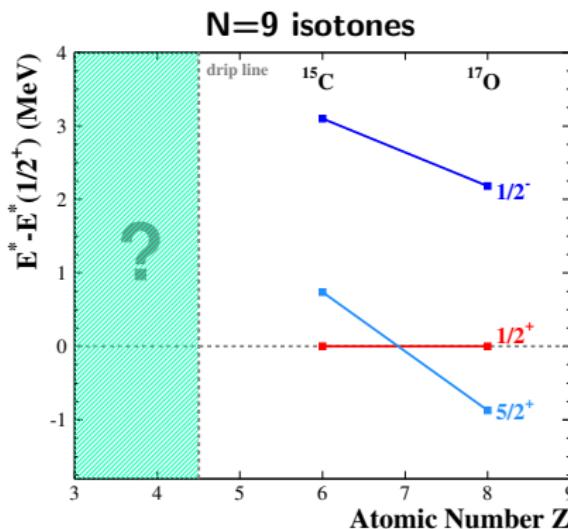
e.g. ^{14}Be
 $^{12}\text{Be}-\text{n}$ interaction ⇒ ^{13}Be spectroscopy

Motivations: Shell structure beyond the neutron drip-line



$1p_{1/2} - 2s_{1/2}$ inversion

L. Chen et al. PLB 510 (2001) 24

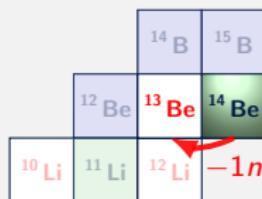


$1d_{5/2} - 2s_{1/2}$ inversion for ^{13}Be ?

Experimental approach: knockout and fragmentation

neutron knockout

e.g. C(^{14}Be , $^{12}\text{Be} + n$)X



$$^{14}\text{Be} (\nu): s^2 + p^2 + d^2$$

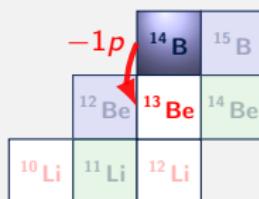
$^{13}\text{Be} (\nu)$: s , p et d can be populated

H. Simon *et al.* NPA 791 (2007) 267

(See L. Chulkov Talk)

proton knockout

e.g. C(^{14}B , $^{12}\text{Be} + n$)X

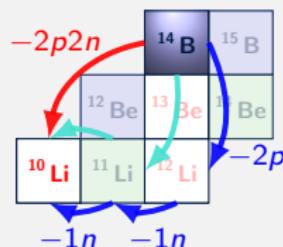


$$^{14}\text{B} (\nu): s + d$$

$^{13}\text{Be} (\nu)$: if $\Delta\ell_n = 0$
(sudden approx.)
 $\Rightarrow s$ and d are favored

fragmentation

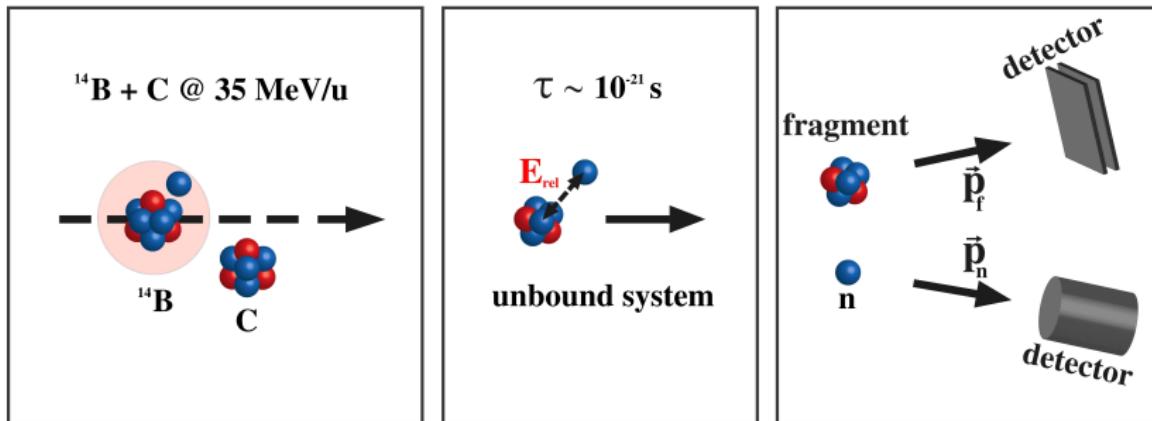
e.g. C(^{14}B , $^{9}\text{Li} + n$)X



—: more complex mechanism

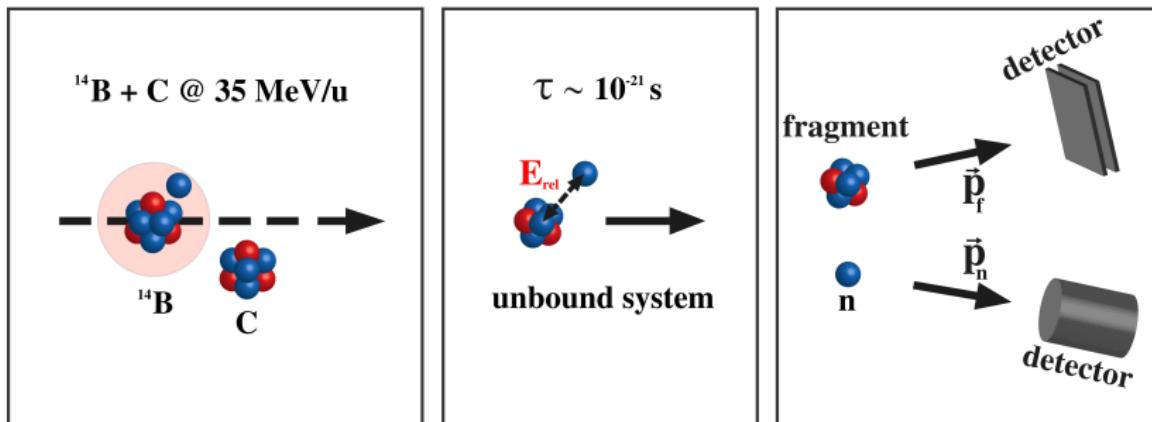
+: many configurations are possible (complementary to knockout)

Experimental approach: the invariant mass method



- ▶ low intensity beams ($\sim 10^4$ pps) can be used
- ▶ relatively high cross sections ($\sim \text{mb}$)
- ▶ thick target (increasing yields)
- ▶ forward focused products

Experimental approach: the invariant mass method



coincidence detection of charged fragment and neutron

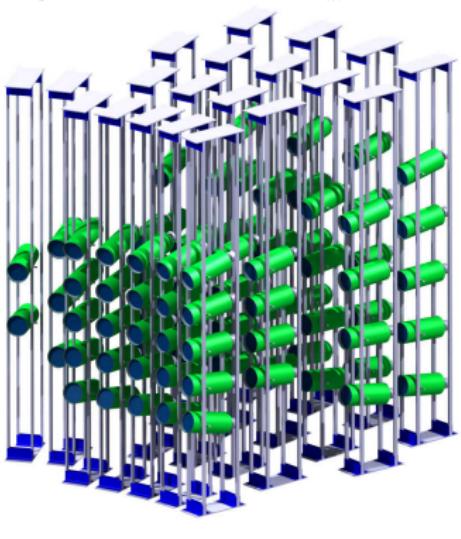
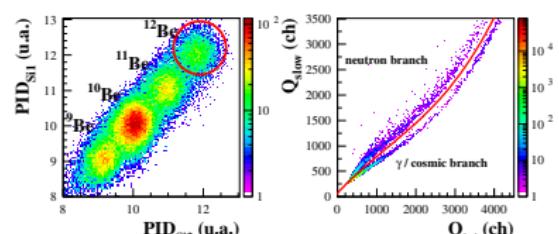
\Rightarrow decay energy E_d

$E_d(^{A+1}_Z X) \Leftrightarrow$ relative energy between fragment and neutron

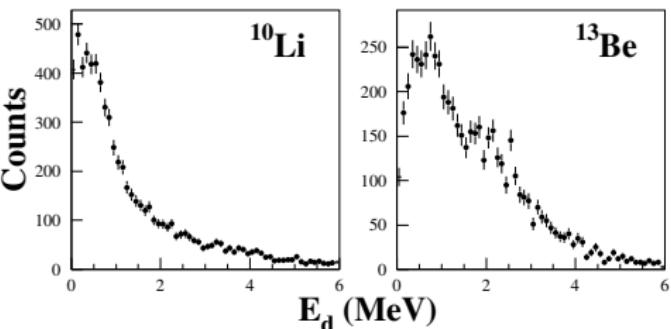
$$E_d(^{A+1}_Z X) = \sqrt{(E_f + E_n)^2 - (\vec{p}_f + \vec{p}_n)^2 c^2} - (M_f + M_n)c^2$$

Experimental setup

fragment (CHARISSA) + neutron (DEMON)



Decay energy spectra



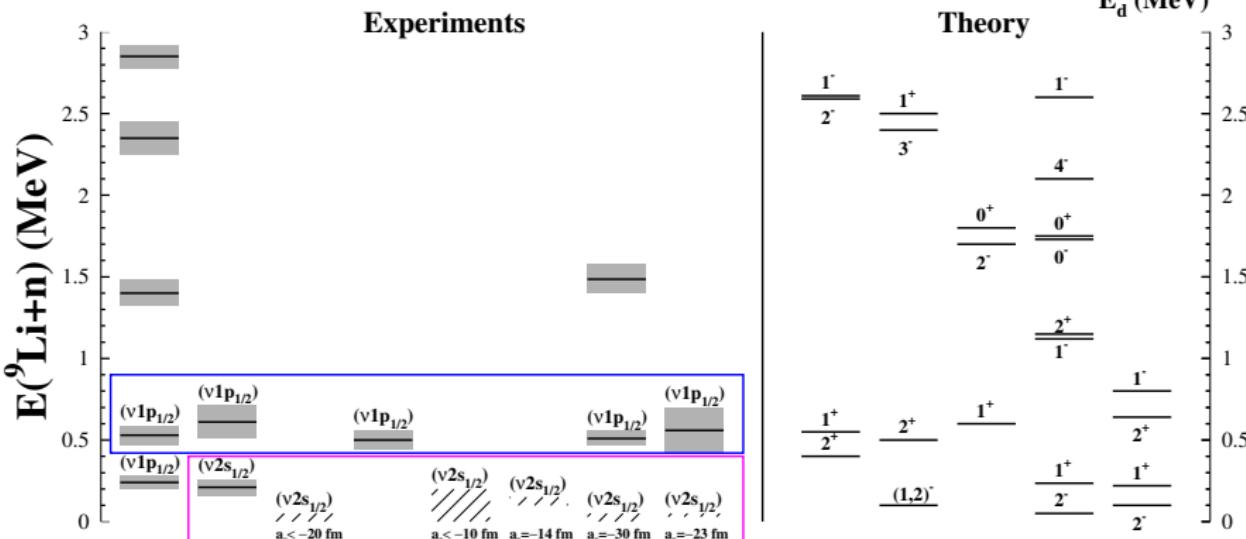
- ▶ fragment in its **g.s.**
- ▶ non-resonant continuum/
uncorrelated distribution (NC) :
event mixing
- ▶ ^7He g.s. : **cross-check**

^{10}Li : level scheme*

^{11}Be p-knockout: $\Delta\ell_n = 0$ approx.

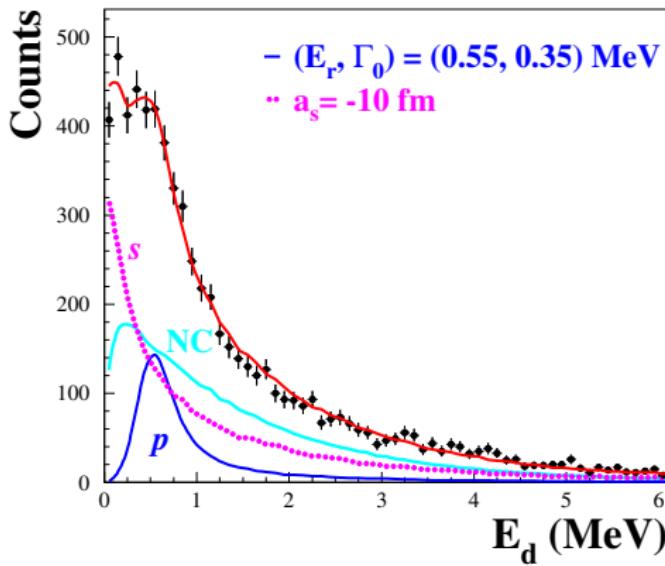
\Rightarrow access to $\nu s_{1/2}$ (Chen '00, Al Falou '07)
 (strong $^{10}\text{Be}_{g.s.} \otimes \nu 2s_{1/2}$ component in ^{11}Be)

^{14}B fragmentation: $\Delta\ell_n \neq 0 \Rightarrow$ access to $\nu s_{1/2}, \nu p_{1/2}$



* Representative selection of results from literature

^{10}Li : virtual s state + p resonance + NC



virtual s state : $a_s = -10_{-3}^{+1}$ [stat] (± 3 [syst]) fm

$\nu 1\text{p}_{1/2} - \nu 2\text{s}_{1/2}$

p resonance : $E_r = 0.55 \pm 0.02 (\pm 0.05)$ MeV
 $\Gamma_0 = 0.35 \pm 0.05 (\pm 0.15)$ MeV

INVERSION :
CONFIRMED

^{13}Be : level scheme

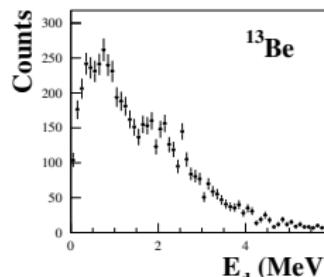
^{14}B p-knockout: $\Delta\ell_n = 0$ approximation

$$^{14}\text{B} = ^{13}\text{B} \otimes \nu 2s_{1/2} + ^{13}\text{B} \otimes \nu 1d_{5/2}$$

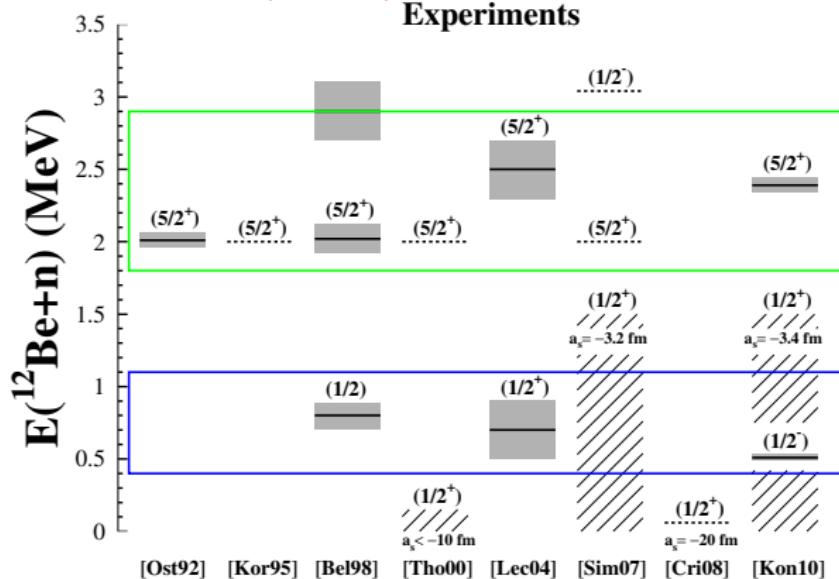
E. Sauvan *et al.* PLB 491 (2000) 1

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

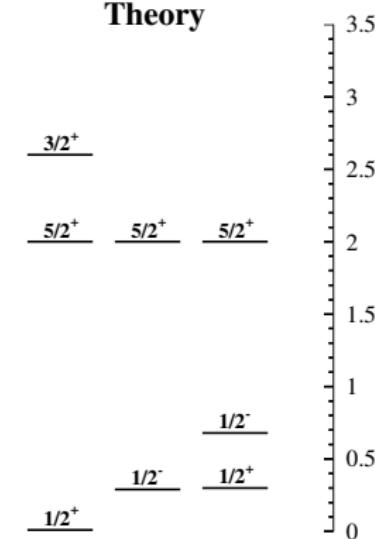
⇒ access to $\nu 2s_{1/2}$, $\nu 1d_{5/2}$



Experiments

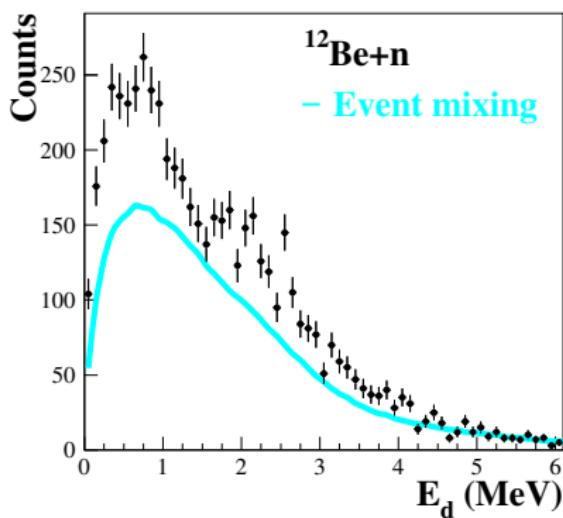


Theory



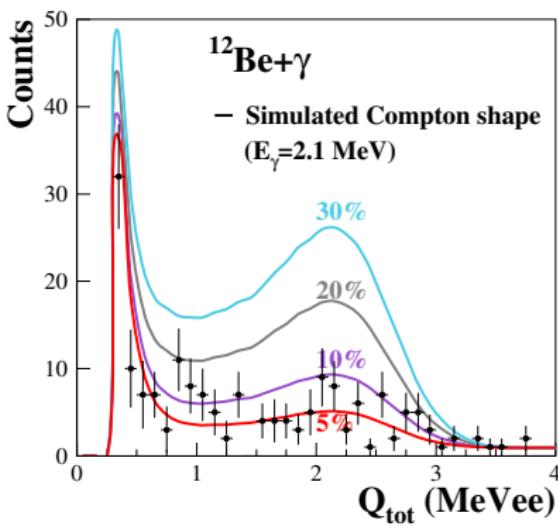
^{13}Be : uncorrelated events, excited fragments

Uncorrelated/non resonant
fragment-neutron distribution



Normalized at high E_d
(where no structures are observed)

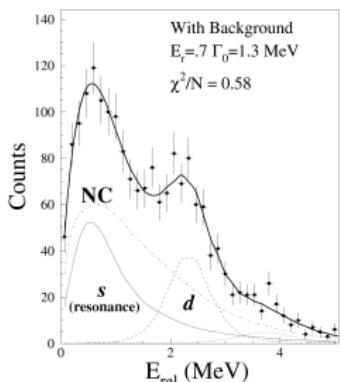
Rate of excited fragments
(DEMON prompt γ)



Resolution, efficiency,
Doppler effect are included

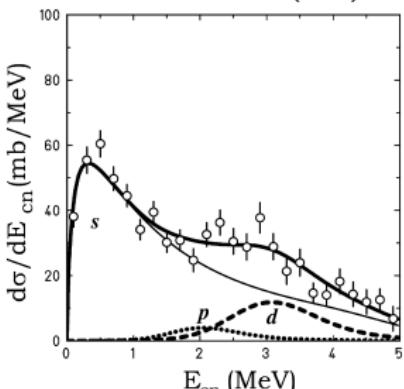
^{13}Be : recent experiments

J. L. Lecouey FBS 34 (2004) 21



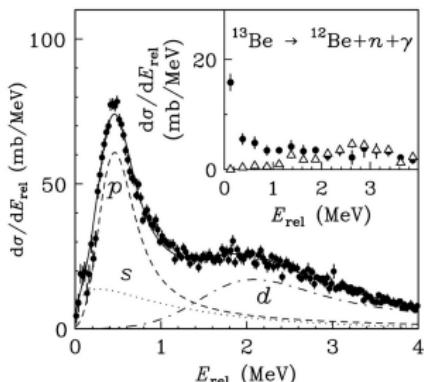
$C(^{14}\text{B}, ^{13}\text{Be} + n)\text{X}$
@ 41 MeV/u

H. Simon et al. NPA 791 (2007) 267



$C(^{14}\text{Be}, ^{13}\text{Be} + n)\text{X}$
@ 287 MeV/u

Y. Kondo et al. PLB 690 (2010) 245



$p(^{14}\text{Be}, ^{13}\text{Be} + n)\text{X}$
@ 69 MeV/u

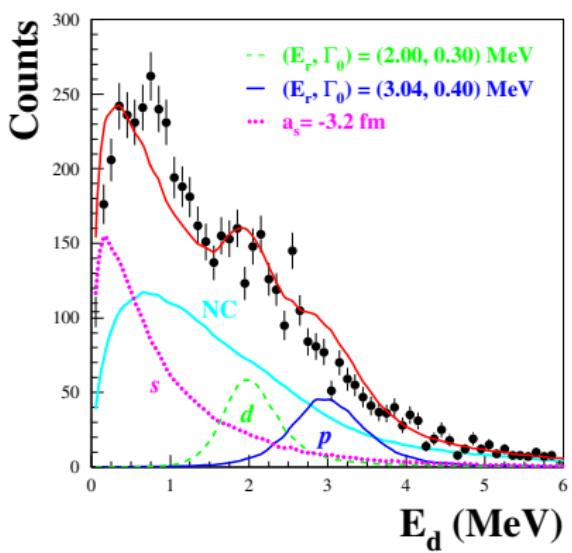
**s resonance,
d resonance, NC**

**s virtual state,
p, d resonances**

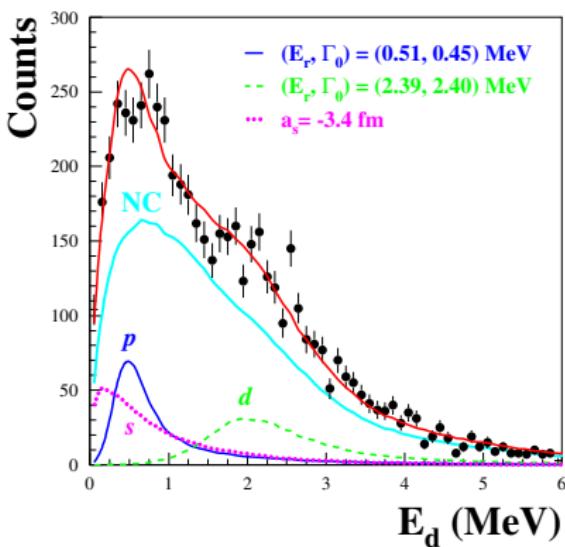
**s virtual state,
p, d resonances**

^{13}Be : previous hypotheses vs our data

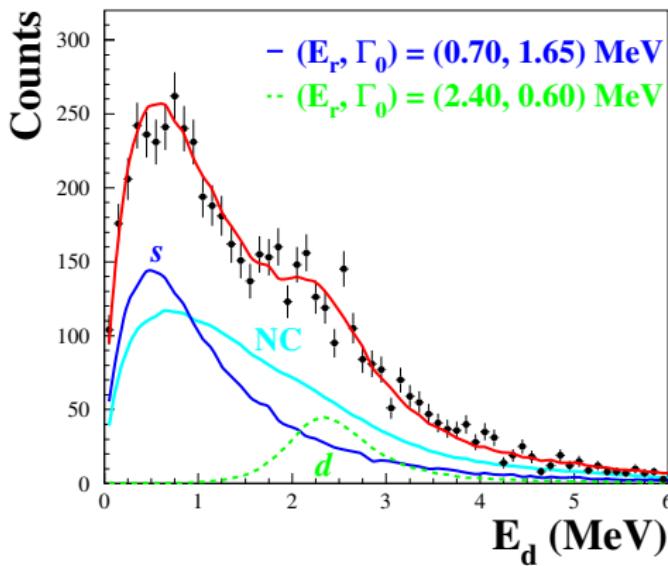
Simon et al.



Kondo et al.



^{13}Be : s resonance + d resonance + NC



s resonance : $E_r = 0.70 \pm 0.05 \text{ [stat]} (\pm 0.07 \text{ [syst]}) \text{ MeV}$
 $\Gamma_0 = 1.7 \pm 0.1 (\pm 0.1) \text{ MeV}$

d resonance : $E_r = 2.4 \pm 0.1 (\pm 0.1) \text{ MeV}$
 $\Gamma_0 = 0.6 \pm 0.2 (\pm 0.1) \text{ MeV}$

$\nu 1d_{5/2} - \nu 2s_{1/2}$
INVERSION

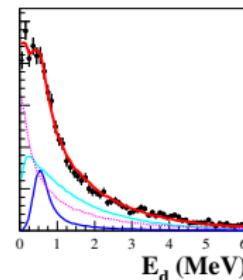
Conclusions

Unbound states populated via proton-knockout and fragmentation of ^{14}B

^{10}Li : $\nu 1\text{p}_{1/2} - \nu 2\text{s}_{1/2}$ inversion confirmed

virtual s state : $a_s = -10_{-3}^{+1} [\text{stat}] (\pm 3 [\text{syst}]) \text{ fm}$

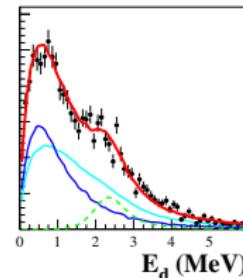
p resonance : $E_r = 0.55 \pm 0.02 (\pm 0.05) \text{ MeV}$
 $\Gamma_0 = 0.35 \pm 0.05 (\pm 0.15) \text{ MeV}$



^{13}Be : indications of a $\nu 1\text{d}_{5/2} - \nu 2\text{s}_{1/2}$ inversion

s resonance : $E_r = 0.70 \pm 0.05 [\text{stat}] (\pm 0.07 [\text{syst}]) \text{ MeV}$
 $\Gamma_0 = 1.7 \pm 0.1 (\pm 0.1) \text{ MeV}$

d resonance : $E_r = 2.4 \pm 0.1 (\pm 0.1) \text{ MeV}$
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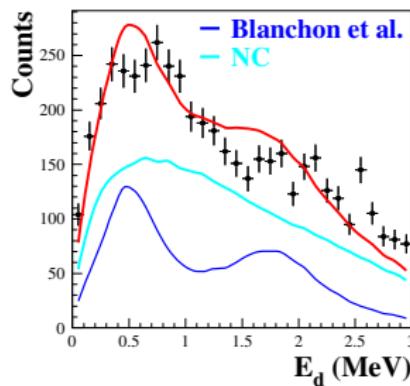


Perspectives

line shapes depend on the projectile structure

⇒ need to use a realistic model, including:

- ▶ reaction process and projectile structure
e.g. Blanchon et al. NPA 784 (2007) 49
 s, p, d admixtures, time-dep approach
- ▶ core structure (deformation, core excitations)



Acknowledgements

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N.A. Orr, F.M. Marques, N.L. Achouri, F. Delaunay, J. Gibelin, M. Parlog,
M. Senoville

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F. Hanappe, A. Ninane, L. Stuttge *et al.*

CHARISSA Collaboration (Birmingham, Surrey, York):

W.N. Catford, M. Freer *et al.*