Invariant mass spectroscopy of light neutron-unbound systems

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IX **W**orkshop on **P**article **C**orrelation and **F**emtoscopy

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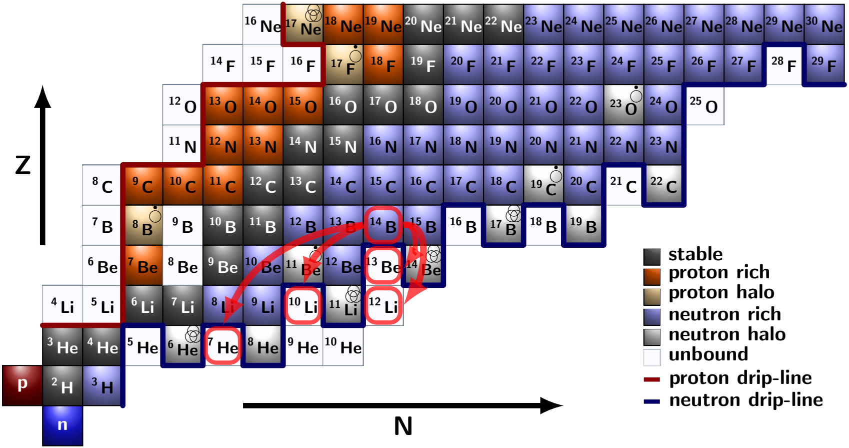
Outline

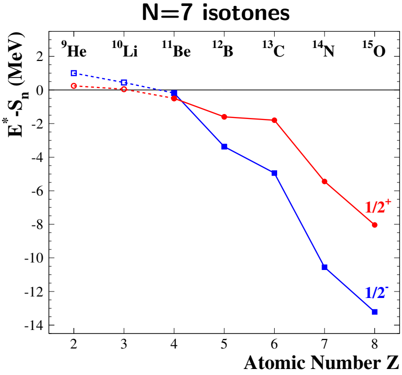
- Motivations: evolution of nuclear structure towards the drip-lines
- Experimental approach: invariant mass method
- Results and interpretation
- Summary and perspectives

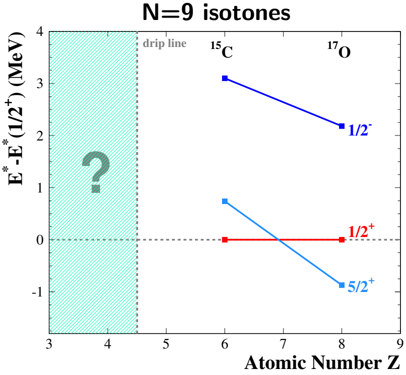
Structure of light drip-line nuclei



Light neutron-rich nuclei: opportunity to access drip-lines and beyond
⇒ **insight on structure evolution for extreme N/Z ratio**

Structure evolution beyond the neutron drip-line





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

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

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

Modeling 3-body systems

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

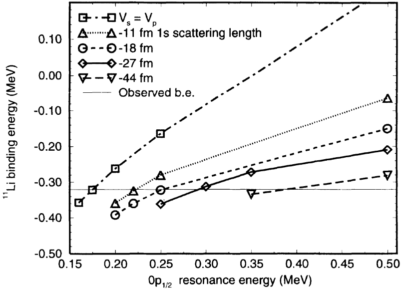
⇒ need input to reproduce radii, S_{2n} of the 3-body system

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

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

⇒ spectroscopy of ^{10}Li, ^{13}Be

Effect of ^{10}Li low-lying states on ^{11}Li structure

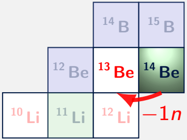


I.J. Thompson *et al.* PRC 49 (1994) 1904

Knockout and fragmentation

neutron knockout

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



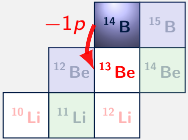
^{14}**Be** (ν): $s^2 + p^2 + d^2$

^{13}**Be** (ν): s, p et d can be populated

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

proton knockout

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

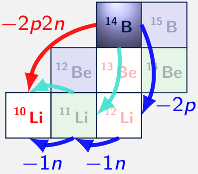


^{14}**B** (ν): $s + d$

^{13}**Be** (ν): if $\Delta\ell_n = 0$
$\Rightarrow$ s and d are favored

fragmentation

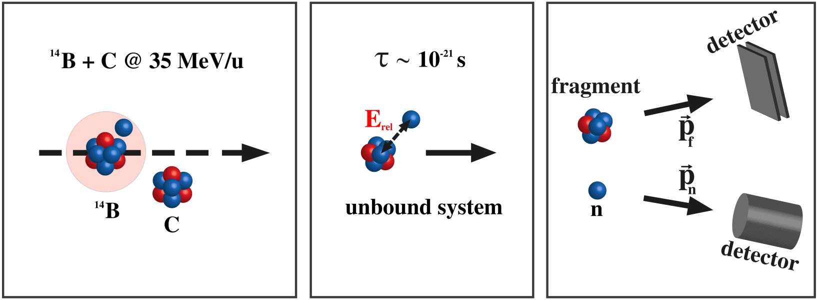
e.g. C(^{14}B,^{9}Li+n)X



—: more complex mechanism

+: many configurations are possible (complementary to knockout)

Experimental approach: the invariant mass method



coincidence detection of charged fragment and neutron

⇒ decay energy E_d

$E_d({}^{A+1}_{Z}X)$ ⇔ relative energy between fragment and neutron

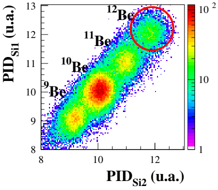
$$E_d({}^{A+1}_{Z}X) = \sqrt{(E_f + E_n)^2 - (\vec{p}_f + \vec{p}_n)^2 c^2} - (M_f + M_n)c^2$$

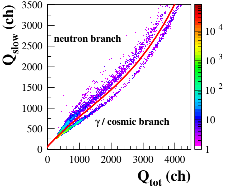
Experimental setup

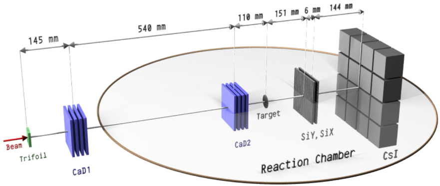
^{14,15}B+C @ GANIL

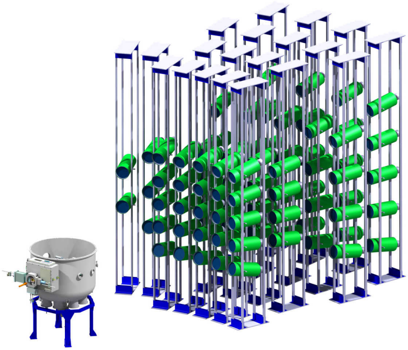
- ^{14,15}B secondary beams from the **LISE3** fragment separator
- ^{14}B: 35 MeV/nucleon, $\sim 1.3 \times 10^4$ pps
- ^{15}B: 35 MeV/nucleon, $\sim 8 \times 10^3$ pps
- thick target (increasing yields)
- forward focused products

fragment (CHARISSA) + neutron (DEMON)







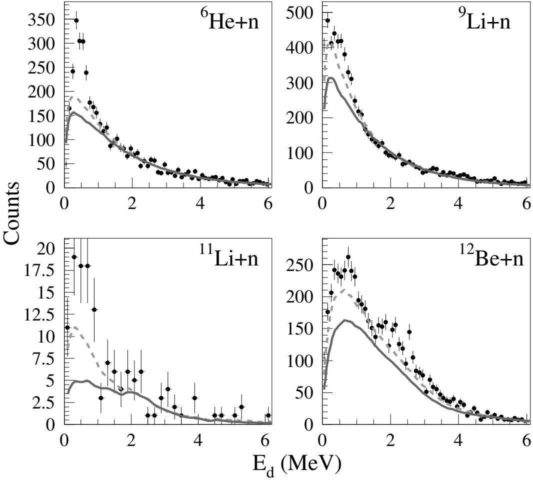


Results

- **Unbound states of ^{7}He, ^{10,12}Li and ^{13}Be populated via one- and multi-nucleon removal**
- Non-resonant continuum/uncorrelated distribution obtained by **event mixing**
- Theoretical description:
  - **Resonances** (E_r,Γ_r)
  - **Virtual states** ($\ell = 0$, scattering length a_s)
- **Simulation**: [Theoretical line shape] $\otimes$ [response function] (resolution, efficiency, phase space, reaction)
- ^{7}He g.s. : **cross-check**

Constructing the uncorrelated distribution: iterative event mixing

- Start from the correlated f-n pairs
- 1^{st} mixing
  ⇒ virtual uncorrelated pairs
- Iterative procedure
  ⇒ suppress residual correlation
  F.M. Marqués *et al.* PLB 476 (2000) 219
  (M. Marques's Talk!)
- Response function is naturally taken into account



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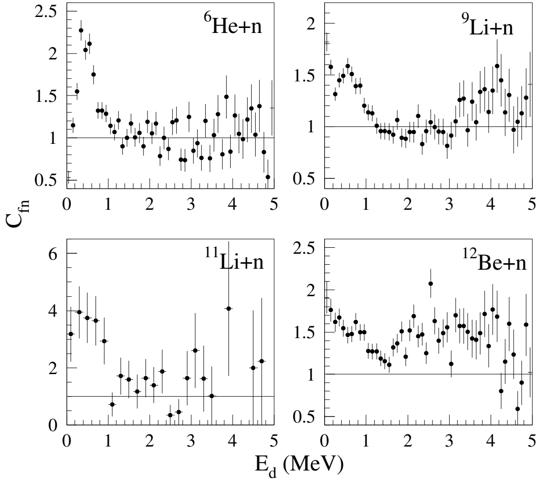
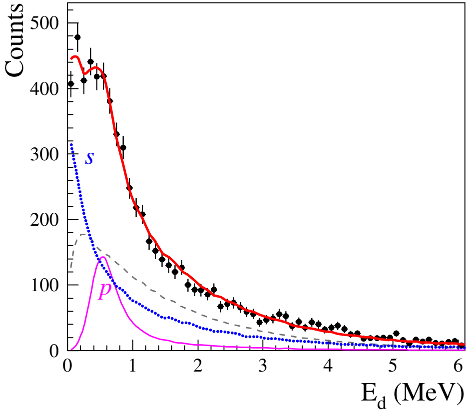


^{10}Li: virtual *s* state + *p* resonance



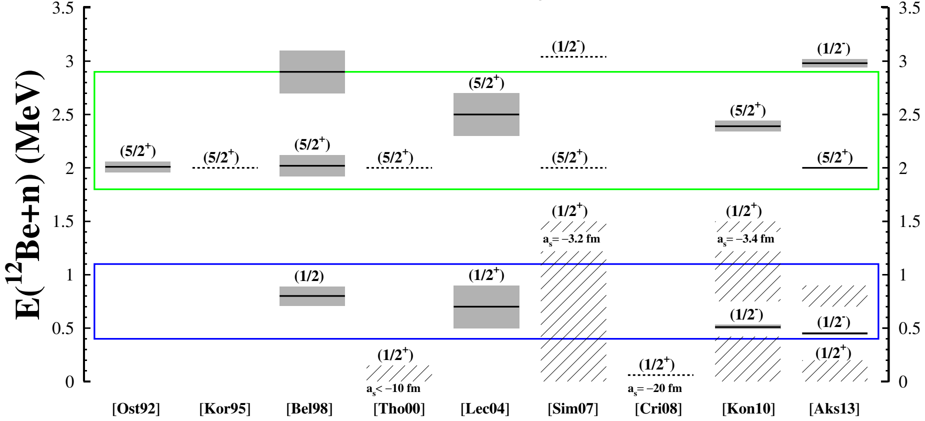
virtual *s* state : $a_s = -10^{+3.1}_{-4.2}$ fm

p resonance : $E_r = 0.55(5)$ MeV
$\Gamma_0 = 0.35(16)$ MeV

$\nu 1p_{1/2} - \nu 2s_{1/2}$ INVERSION : CONFIRMED

^{13}Be: result interpretation

Level scheme: selection of experimental results



^{13}Be: result interpretation

Some important considerations

- Population of ^{13}Be by 1p/1n removal (from ^{14}B/^{14}Be) gives access to different configurations

- $^{14}B_{gs} = \lambda\,[^{13}B_{gs} \otimes \nu 2s_{1/2}] + \mu\,[^{13}B_{gs} \otimes \nu 1d_{5/2}]$

  E. Sauvan *et al.* PLB 491 (2000) 1
  V. Guimarães *et al.* PRC 61 (2000) 064609

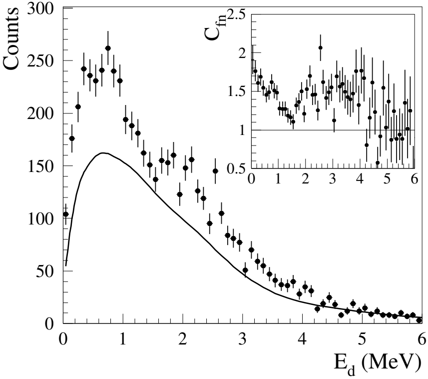
  $\Rightarrow$ **1p-removal from ^{14}B will mainly populate $\nu 2s_{1/2}$ and $\nu 1d_{5/2}$**

- Decay to ^{12}Be bound excited states can affect the decay energy spectrum: no dedicate γ setup $\Rightarrow$ estimate with Demon

- Note: even with dedicated γ detection, not sensitive to decays from ^{12}Be(0_2^+) isomeric state

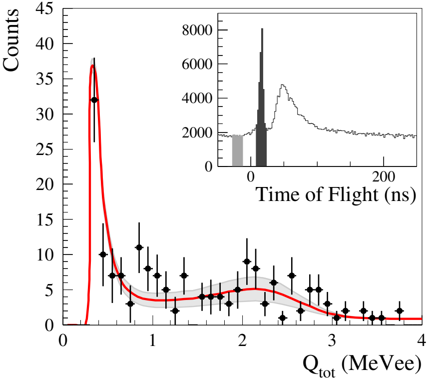
^{13}Be: uncorrelated events, excited fragments

Uncorrelated/non resonant fragment-neutron distribution



Normalized at high E_d
(where no structures are observed)

Rate of ^{12}Be excited fragments (DEMON prompt γ)



Simulated Compton shape: resolution, efficiency, Doppler effect are included
$N(^{12}\text{Be}(2^+))/N_{tot}(^{12}\text{Be}) = 5(2)\%$

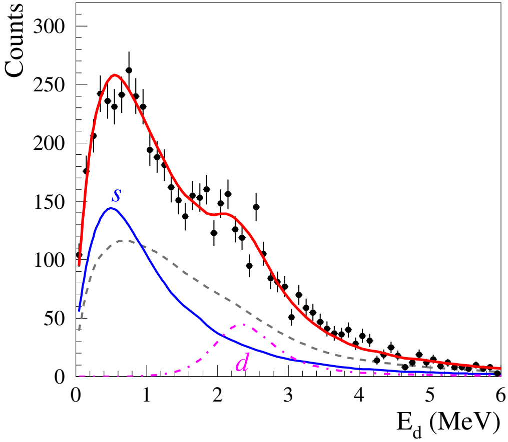
Interpretation: ^{12}Be as N=8 closed-shell core

	E_r (MeV)	Γ_r (MeV)
$s_{1/2}$	0.70±0.11	1.70±0.22
$d_{5/2}$	2.40±0.14	0.70±0.32

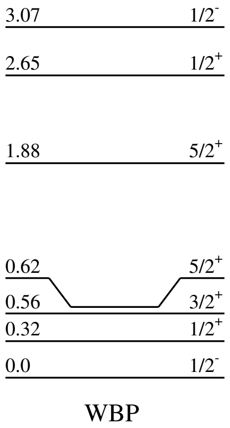
$$\left.\frac{Y(s)}{Y(d)}\right|_{^{13}Be}^{exp} = 3.5\pm0.8$$

$$\left.\frac{C^2S(s)}{C^2S(d)}\right|_{^{14}B}^{Th} = 2.1$$

***s*-resonance + *d*-resonance**



Shell Model Calculations with ^{12}Be $np - nh$ core excitations



- Shell model calculations within the $s - p - sd - pf$ model space with WBP interaction (B.A. Brown)
- $(0-2)\hbar\omega$, $(1-3)\hbar\omega$ excitations possible
- calculations reproduce configuration mixing in ^{12}Be
  R. Kanungo *et al.* PLB 682 (2010) 391
- Spectroscopic Factors for proton removal from ^{14}B

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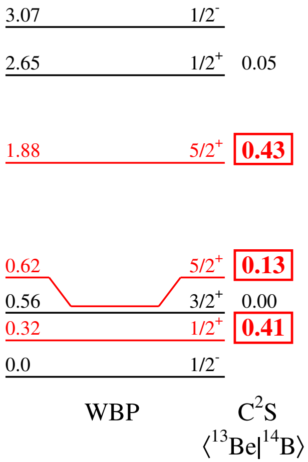

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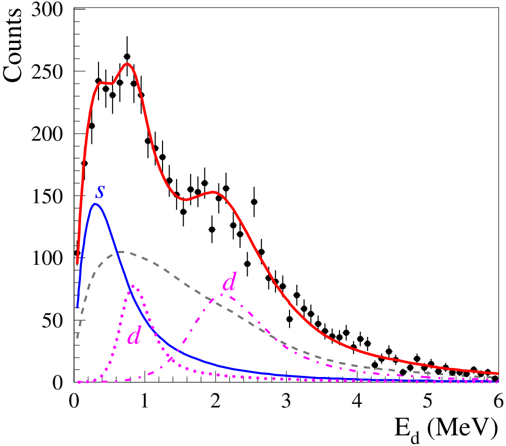
- Spectroscopic Factors for proton removal from ^{14}B
- Calculations suggest the population $0\hbar\omega$ $s_{1/2}$ & $d_{5/2}$ + $2\hbar\omega$ $d_{5/2}$

Interpretation: s + low-lying d + high-lying d

	E_r (MeV)	Γ_r (MeV)
$s_{1/2}$	0.40 ± 0.03	$0.80^{+0.18}_{-0.12}$
$d_{5/2(1)}$	$0.85^{+0.15}_{-0.11}$	$0.30^{+0.34}_{-0.15}$
$d_{5/2(2)}$	2.35 ± 0.14	1.50 ± 0.40

	$\left.\frac{Y}{Y(s_{1/2})}\right\vert_{exp}$	$\left.\frac{C^2S}{C^2S(s_{1/2})}\right\vert_{th}$
$s_{1/2}$	1.00 ± 0.08	1.00
$d_{5/2(1)}$	0.40 ± 0.06	0.32
$d_{5/2(2)}$	0.80 ± 0.06	1.05



Relative energies and strengths in agreement with SM calculations

Summary and perspectives

Neutron-unbound nuclei populated at GANIL using knockout/fragmentation

^{10}Li:

$\nu 1p_{1/2} - \nu 2s_{1/2}$ inversion confirmed

^{13}Be:

- Low-lying *s*-resonant state observed
- Hypothesis of *s* and *d*-wave low-lying states + *d* high-lying state in agreement with SM calculations

Perspectives

Experiments:

- High-resolution Invariant Mass spectroscopy using γ detection (still not sensitive to ^{12}Be(0_2^+))
- Missing Mass spectroscopy not influenced by excited fragment decays, ^{12}Be(d,p) good opportunity to directly populate *s*,*p*,*d* configurations

Theory:

- Coherent treatment of continuum
- Include structure input in a realistic reaction model

Acknowledgements

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

CHARISSA Collaboration (Birmingham, Surrey, York):

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

MSU/NSCL:

B.A. Brown

GANIL/LISE Team