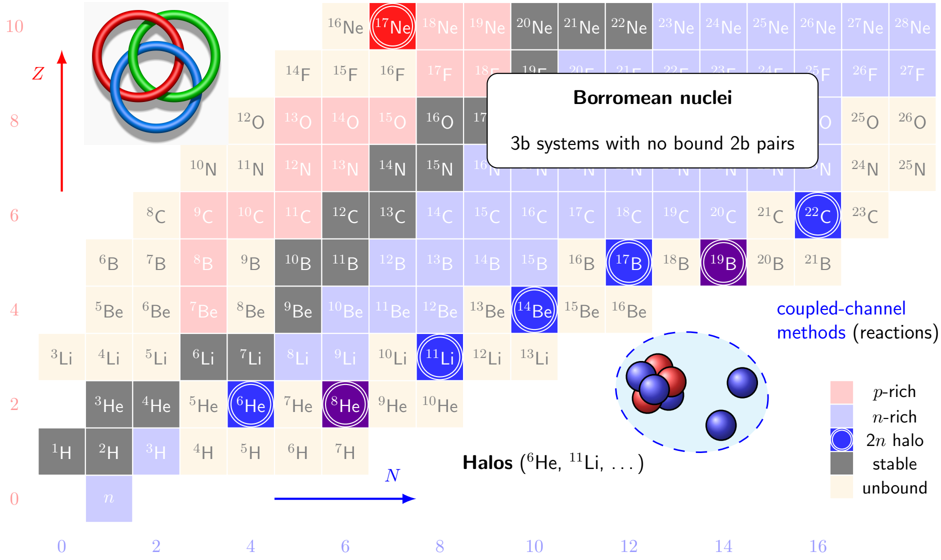
June 28 - July 1, 2021
NPES workshop

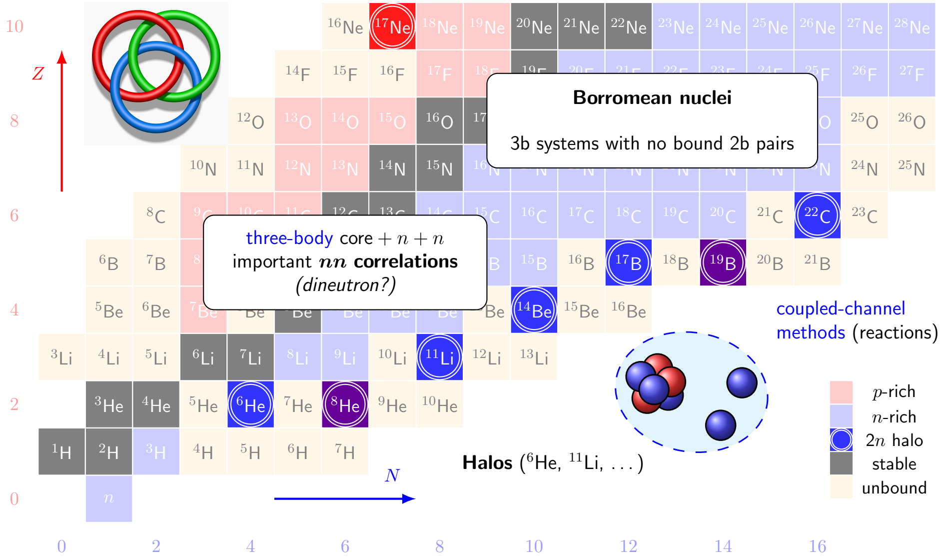
Three-body resonances and two-nucleon correlations

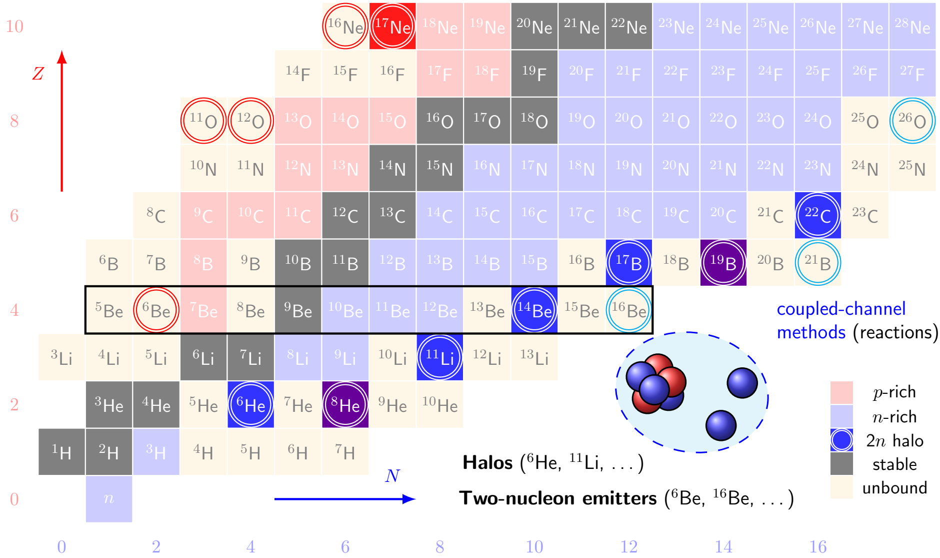
Jesús Casal

MSCA fellow

Universidad de Sevilla, Spain

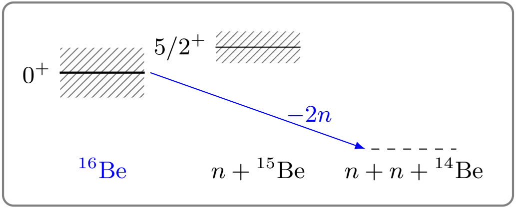

Borromean nuclei
3b systems with no bound 2b pairs
coupled-channel methods (reactions)
Halos (^{6}He, ^{11}Li, . . .)
Z
N
p-rich
n-rich
$2n$ halo
stable
unbound
^{16}Ne ^{17}Ne ^{18}Ne ^{19}Ne ^{20}Ne ^{21}Ne ^{22}Ne ^{23}Ne ^{24}Ne ^{25}Ne ^{26}Ne ^{27}Ne ^{28}Ne
^{14}F ^{15}F ^{16}F ^{17}F ^{25}F ^{26}F ^{27}F
^{12}O ^{13}O ^{14}O ^{15}O ^{16}O ^{25}O ^{26}O
^{10}N ^{11}N ^{12}N ^{13}N ^{14}N ^{15}N ^{24}N ^{25}N
^{8}C ^{9}C ^{10}C ^{11}C ^{12}C ^{13}C ^{14}C ^{15}C ^{16}C ^{17}C ^{18}C ^{19}C ^{20}C ^{21}C ^{22}C ^{23}C
^{6}B ^{7}B ^{8}B ^{9}B ^{10}B ^{11}B ^{12}B ^{13}B ^{14}B ^{15}B ^{16}B ^{17}B ^{18}B ^{19}B ^{20}B ^{21}B
^{5}Be ^{6}Be ^{7}Be ^{8}Be ^{9}Be ^{10}Be ^{11}Be ^{12}Be ^{13}Be ^{14}Be ^{15}Be ^{16}Be
^{3}Li ^{4}Li ^{5}Li ^{6}Li ^{7}Li ^{8}Li ^{9}Li ^{10}Li ^{11}Li ^{12}Li ^{13}Li
^{3}He ^{4}He ^{5}He ^{6}He ^{7}He ^{8}He ^{9}He ^{10}He
^{1}H ^{2}H ^{3}H ^{4}H ^{5}H ^{6}H ^{7}H
n
0 2 4 6 8 10
0 2 4 6 8 10 12 14 16

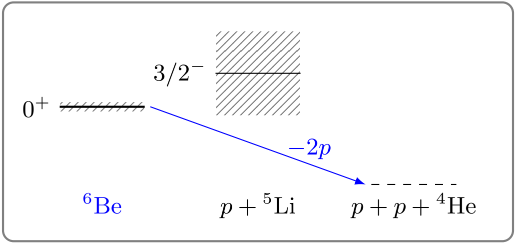

Borromean nuclei
3b systems with no bound 2b pairs
three-body core $+ n + n$
important nn **correlations**
(dineutron?)
coupled-channel methods (reactions)
Halos (^{6}He, ^{11}Li, . . .)
p-rich
n-rich
$2n$ halo
stable
unbound
Z
N



Halos (^{6}He, ^{11}Li, . . .)

Two-nucleon emitters (^{6}Be, ^{16}Be, . . .)





Example: ^{6}**Be**, ^{16}**Be**

$1N$ bound
$2N$ unbound

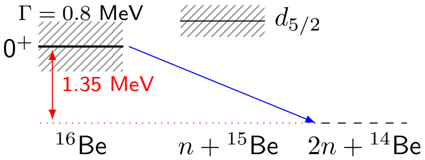
Possible $2N$ decay paths:

- Sequential
- Simultaneous ("Dinucleon"-like ??)

two-nucleon correlations in the ground state?

J.C. [PRC 97 (2018) 034613] arXiv:1801.01280
⇒ using stabilization approach; pseudostates

The link between dineutron or diproton configuration in the initial state and sequential or prompt decay is not clear, especially for excited states

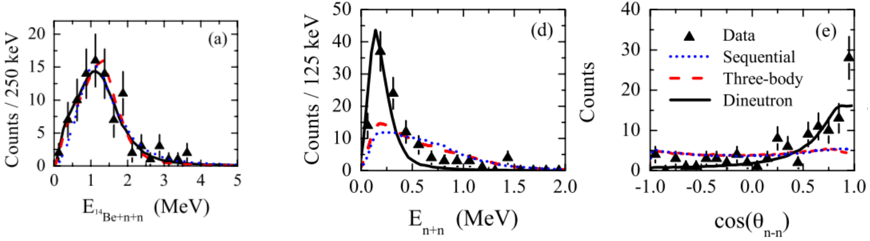


^{16}Be (^{14}Be $+ n + n$)

Known $2n$ emitter

Spyrou [PRL 108 (2012) 102501]

Proton removal from ^{17}B on Be target @ 53 MeV/u (MSU)



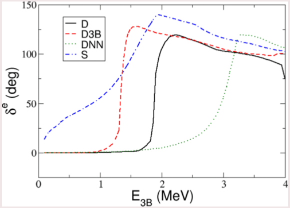
new RIKEN data - B. Monteagudo, F. M. Marqués (LPC Caen)

$\Rightarrow$ previous talk!

A. Lovell *et al.* [PRC 95 (2017) 034605]

Hyperspherical R-matrix method

$\Rightarrow$ "true" continuum (eigenphases) ^{16}Be



0^+ res. $E_{3B} = 1.35$ MeV, $\Gamma = 0.17$ MeV

$\Rightarrow$ clear $2n$ configuration

80% $l_{nn} = 0$ waves

S. Wang and W. Nazarewicz [PRL 126 (2021) 034605]

Time-dependent approach ^{6}Be, ^{6}He'

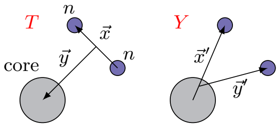
$\Rightarrow$ dynamics of two-nucleon emission at long times and large distances

(talk by S. Wang on 30/06)

Other theoretical works:

- L. V. Grigorenko *et al.*; ^{26}O decay [PRL 111 (2013) 042501]
  ^{6}Be decay [PRC 80 (2009) 034602]
- R. Álvarez-Rodríguez *et al.*; 3body-decays [PRL 100 (2008) 192501]
- ... several different techniques!

Three-body description: Jacobi and hyperspherical coordinates



$$\Psi^{j\mu}(\rho,\Omega) = \rho^{-5/2} \sum_{\beta} \chi_{\beta}^{j}(\rho) \mathcal{Y}_{\beta}^{j\mu}(\Omega)$$

$$\rho = \sqrt{x^2 + y^2},\ \tan\alpha = x/y$$

$\mathcal{Y}_{\beta}^{j\mu}(\Omega)$ expanded in hyperspherical harmonics; $\beta \equiv \{K, l_x, l_y, l, S\}_j$

$$\left[\frac{-\hbar^2}{2m}\left(\frac{d^2}{d\rho^2} - \frac{15/4 + K(K+4)}{\rho^2}\right) - \varepsilon\right] \chi_{\beta}^{j}(\rho) + \sum_{\beta'} V_{\beta'\beta}^{j\mu}(\rho) \chi_{\beta'}^{j}(\rho) = 0$$

- three-body barrier determined by hypermomentum K (even if $K = 0$!!)
- $V_{\beta'\beta}^{j\mu}(\rho)$: binary potentials + three-body force

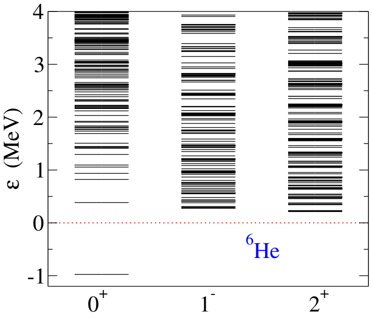
Pseudostate method ⇒ expand $\chi^{j}_{\beta}(\rho)$ in a discrete basis (diagonalize H)

$$\chi^{j}_{\beta n}(\rho) = \sum_{i=0}^{N} C^{j}_{i\beta n} U_{i\beta}(\rho)$$

- $\varepsilon_n < 0$ **bound states**
- $\varepsilon_n > 0$ **discretized continuum**

$U_{i\beta}(\rho)$: Analytical Transformed Harmonic Oscillator (THO) basis
⇒ enables high concentration of discretized states close to threshold

(e.g., J.C. *et al.* [PRC 88 (2013) 014327])

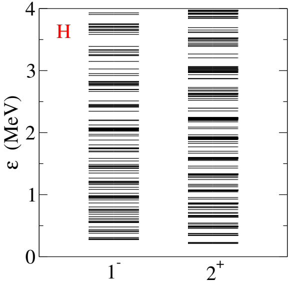


➢ suitable for reactions

➢ excitations into continuum

But no simple characterization of resonant states!

Identifying and characterizing few-body resonances: A new approach



Ex: ^{6}He $(\alpha + n + n)$
non-res. 1^-
2^+ resonance

$\widehat{H}|n\rangle = \varepsilon_n|n\rangle$
mix res. and non-res.

[J.C., J. Gómez-Camacho, PRC **99** (2019) 014604]

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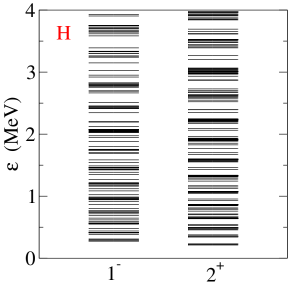

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$\Rightarrow$ Diagonalize a **resonance operator** in a PS basis $\{|n\rangle\}$

$$\widehat{M} = \widehat{H}^{-1/2}\widehat{V}\widehat{H}^{-1/2}, \qquad \widehat{M}|\psi\rangle = m|\psi\rangle; \qquad |\psi\rangle = \sum_n \mathcal{C}_n|n\rangle$$

- It separates resonant states, which are strongly localized, from non-resonant continuum states, which are spatially spread.
- The expansion in terms of $|n\rangle$ allows to build energy distributions.

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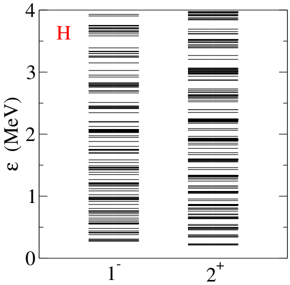

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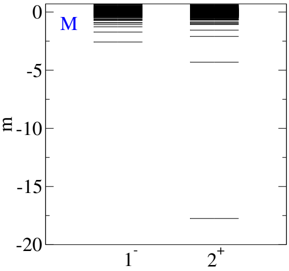

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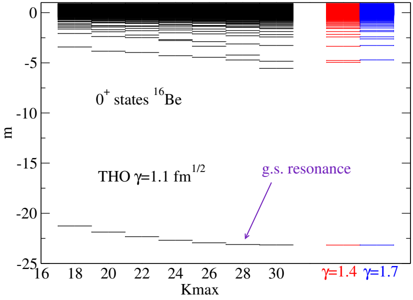
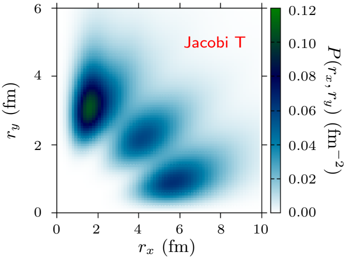


Resonance parameters ^{16}Be

$\varepsilon_r(0^+) = 1.35$ MeV
$\Gamma(0^+) = 0.16$ MeV

width in good agreement with "true" 3b continuum (Lovell et al.)



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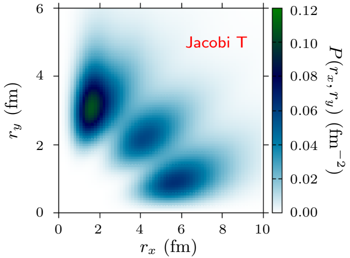

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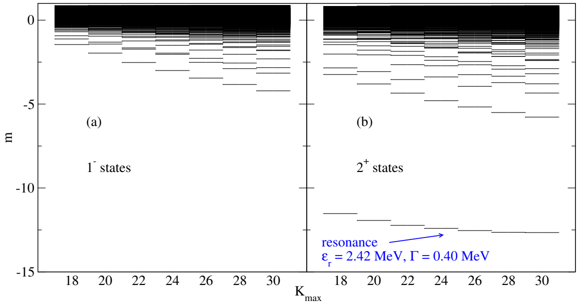
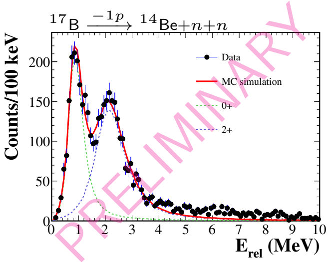
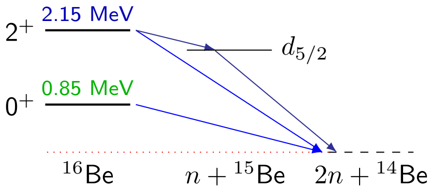
We predicted also a 2^+ resonance



New RIKEN data resolve two peaks! (talk by B. Monteagudo)

1st excited state observed for the first time; likely 2^+





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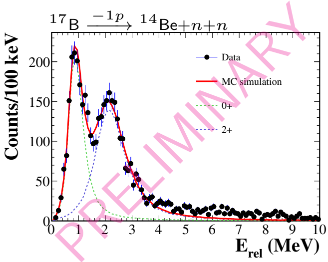

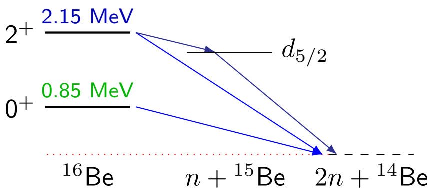

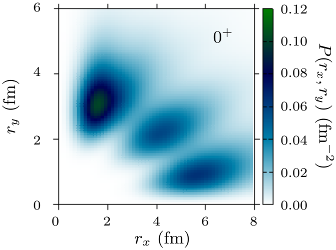

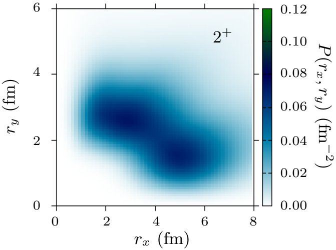

dineutron component is weak for the 2^+

Is there a signature of these dineutron correlations in the decay?

Resonance WF obtained as eigenstate of $\widehat{M}$, evolved in time:

$$\phi_\beta(\rho,t) \longrightarrow \left(\mathcal{A}_\beta^+ H_K^+(k_c\rho) + \mathcal{A}_\beta^- H_K^-(k_c\rho)\right)\exp(-\Gamma t/2 - i\varepsilon_r t)$$

➢ Asymptotically, only outgoing waves $\mathcal{A}_\beta^+ H_K^+(k_c\rho)$ survive
This asymptotic behavior allows to build E_{nn} relative energy distributions

(in progress)

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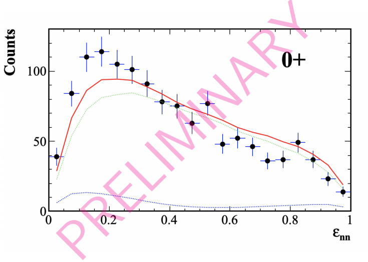
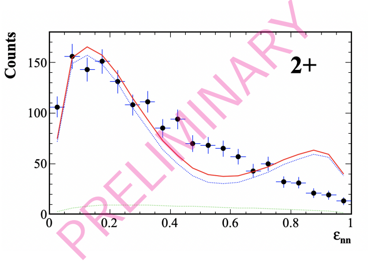




more pronounced low-E_{nn} peak for the 2^+!

$$P(\alpha) = N \sum_{l_x,l_y,l,S} \sum_{K,K'} \mathcal{A}_{\beta}^{+} (\mathcal{A}_{\beta'}^{+})^{*} (-i)^{K-K'} \varphi_K^{l_x,l_y}(\alpha) \varphi_{K'}^{l_x,l_y}(\alpha),$$

- $\varphi_K^{l_x,l_y}(\alpha) \propto$ Jacobi polynomials in $\cos(2\alpha)$ of order $n = \frac{K-l_x-l_y}{2}$
- hyperangle $\alpha \longrightarrow$ relative E_{nn}

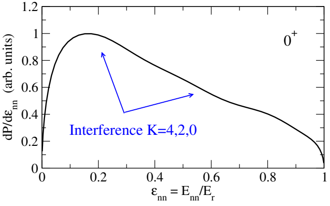
$\mathcal{A}_{\beta}^{+}$ for the lowest possible K values compete with initial w.f. weights

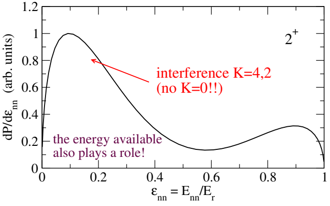
consistent with Wang & Nazarewicz [PRL 126 (2021) 034605]

➢ For ^{16}Be, $K = 4$ mostly. Asymptotically, $K = 2$ and 0 compete

➢ $j^{\pi} = 0^{+} \Rightarrow K_{min} = 0$; $j^{\pi} = 2^{+} \Rightarrow K_{min} = 2$

$\Rightarrow$ $P(\varepsilon_{nn})$ for the 2^{+} state is more asymmetric (no $K = 0$ terms)





Summary and outlook

- The **continuum of three-body systems**, such as $2n$ emitters, can be described using pseudostates within the hyperspherical framework.
- Resonance identification method: Eigenstates of $\widehat{M} = \widehat{H}^{-1/2}\widehat{V}\widehat{H}^{-1/2}$
- ^{16}Be (^{14}Be $+ n + n$): 0^+ g.s. resonance and excited 2^+
  Decay properties from time evolution (resonance amplitudes).
  ⇒ distinct nn configurations
- E_{nn} decay-energy distributions: Matching with asymptotics ($H_K^{\pm}$)
  Preliminary results for ^{16}Be; reasonable agreement with data
  ⇒ shape related to initial wf, $K_{min}(j^\pi)$ and K-interference
- *In progress:*
  - sensitivity to matching conditions; sequential or direct?;
  - sensitivity to nn interaction strength; (see talk by S. Wang)
  - Pauli / core excitation effects on nn correlations;
  - application to other systems (^{6}He, ...); proton decays;

Collaborators:

J. Gómez-Camacho[1,2], B. Monteagudo[3], F. M. Marqués[4], A. M. Moro[1]

[1]: Universidad de Sevilla
[2]: Centro Nacional de Aceleradores (CNA)
[3]: NSCL/FRIB
[4]: LPC Caen

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