Halo-EFT description of one-neutron halo nuclei with core excitation

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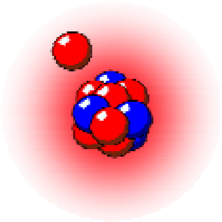
Halo nuclei

- Light, neutron-rich nuclei with large matter radius
- Low $\mathbf{S}_{\mathrm{n}}$ or $\mathbf{S}_{2\mathrm{n}}$: one or two loosely-bound neutrons
- Clusterised structure: neutrons can tunnel far from the core
  $\rightarrow$ halo-nucleus $\equiv$ a compact core + valence neutron(s)



- **Our case study** : ^{11}Be $\equiv$ ^{10}Be + n
- Short-lived $\rightarrow$ studied via reactions (e.g. **breakup**)
  $\rightarrow$ need of a **realistic few-body** model for reaction calculations
  $\rightarrow$ **Halo-EFT**

Halo-EFT description of ^{11}Be

- **Single-particle description**: $H(\mathbf{r}) = \mathrm{T}_{\mathbf{r}} + \mathrm{V}_{\mathrm{cn}}(\mathbf{r})$
  $\rightarrow$ ^{11}Be $=^{10}$Be(0^+)+n [**core has no internal structure**]

- Halo-structure $\rightarrow$ separation of scales
  $\rightarrow$ expansion parameter $\eta = \frac{R_{core}}{R_{halo}} \simeq 0.4 < 1$
  $\rightarrow$ expansion of low-energy behaviour along η
  [Bertulani, Hammer, van Kolck, NP A 712, 37 (2002)]
  [Hammer, Ji, Phillips, JPG 44, 103002 (2017)]

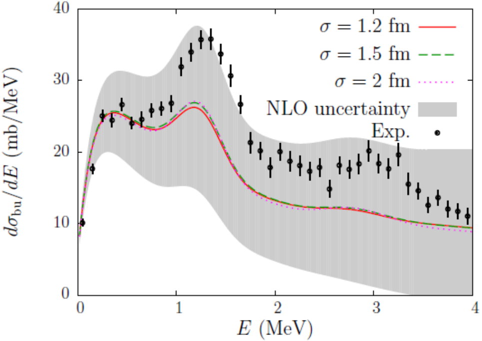
- Effective Gaussian potentials in each partial wave ℓJ @NLO:

$$\mathrm{V}_{\mathrm{cn}}(\mathrm{r}) = \mathrm{V}^{(0)}_{\ell \mathrm{J}} \mathrm{e}^{-\frac{\mathrm{r}^2}{2\sigma^2}} + \mathrm{V}^{(2)}_{\ell \mathrm{J}} \mathrm{r}^2 \mathrm{e}^{-\frac{\mathrm{r}^2}{2\sigma^2}}$$

  $\mathrm{V}^{(0)}_{\ell \mathrm{J}}$ and $\mathrm{V}^{(2)}_{\ell \mathrm{J}}$ fitted to reproduce:
  $\rightarrow$ $\mathbf{S}_{\mathrm{n}}$ & asymptotic normalization coefficient (**ANC**) for bound states
  $\sigma :=$ cutoff [unfitted parameter]
  $\rightarrow$ evaluates sensitivity to short-range physics

What is the problem ?

- Assumption: ^{10}Be remains in its 0^+ ground state still valid ?
  $\rightarrow$ Nuclear breakup: ^{11}Be+C $\rightarrow$ ^{10}Be+n+C



Exp: [Fukuda *et al.* PRC 70, 054606 (2004)]
Th.: [Capel, Phillips & Hammer, PRC 98, 034610 (2018)]

$\Rightarrow$ missing degree of freedom [^{10}Be(2^+)]
$\Rightarrow$ ^{10}Be core can be excited to its first 2^+state
[Moro & Lay, PRL 109, 232502 (2012)]

Core excitation within Halo-EFT

- **Extension of Halo-EFT to include core excitation:**

$$H(\mathbf{r},\xi) = \mathrm{T}_{\mathbf{r}} + \mathrm{V}_{\mathrm{cn}}(\mathbf{r},\xi) + \mathrm{h}_{\mathrm{core}}(\xi)$$

$\mathrm{h}_{\mathrm{core}}(\xi)$:= intrinsic Hamiltonian of the core with eigenstates $\chi^{\mathrm{c}}_{\mathrm{I}}(\xi)$

- **Halo-EFT particle-rotor model** [Bohr and Mottelson (1975)]:

$$\mathrm{V}_{\mathrm{cn}}(\mathbf{r},\xi) = \mathrm{V}_{\mathrm{cn}}(\mathrm{r}) + \beta\sigma \mathrm{Y}^0_2(\hat{\mathrm{r}})\frac{\mathrm{d}}{\mathrm{d}\sigma}\mathrm{V}_{\mathrm{cn}}(\mathrm{r})$$

- Set of radial **coupled-channels** Schrödinger equations:

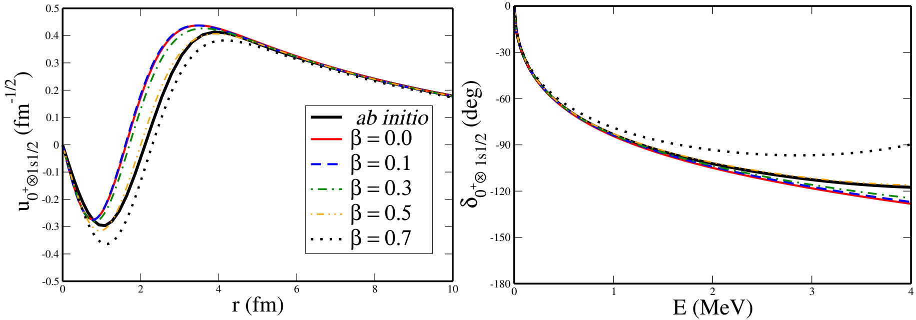
$$\left[\mathrm{T}^{\ell}_{\mathrm{r}} + \mathrm{V}_{\alpha\alpha}(\mathrm{r}) + \epsilon_\alpha - \mathrm{E}\right]\psi_\alpha(\mathrm{r}) = -\sum_{\alpha'\neq\alpha} \mathrm{V}_{\alpha\alpha'}(\mathrm{r})\psi_{\alpha'}(\mathrm{r})$$

with $\mathrm{V}_{\alpha\alpha'}(\mathrm{r}) = \langle \mathcal{Y}_\alpha(\hat{\mathrm{r}})\chi_\alpha(\xi)|\mathrm{V}_{\mathrm{cn}}(\mathrm{r},\xi)|\mathcal{Y}_{\alpha'}(\hat{\mathrm{r}})\chi_{\alpha'}(\xi)\rangle$, α=$\{\ell,\mathrm{s},\mathrm{j},\mathrm{I}\}$

$\rightarrow$ solved within the **R-Matrix method** on a Lagrange mesh
[D. Baye, Physics Reports 565 (2015) 1]
Study impact of core excitation on: ψ_α, δ_α

Compare to *ab initio* predictions [Calci et al., PRL 117, 242501 (2016)]

- $\Psi_{1/2^+} = \psi(\mathrm{r})_{1s1/2} \otimes \chi_{0^+}^{^{10}\mathrm{Be}} + \psi(\mathrm{r})_{0d5/2} \otimes \chi_{2^+}^{^{10}\mathrm{Be}} + \psi(\mathrm{r})_{0d3/2} \otimes \chi_{2^+}^{^{10}\mathrm{Be}}$
- NLO potentials **fitted to** reproduce $\mathbf{S}_\mathrm{n}$ and *ab initio* **ANC**

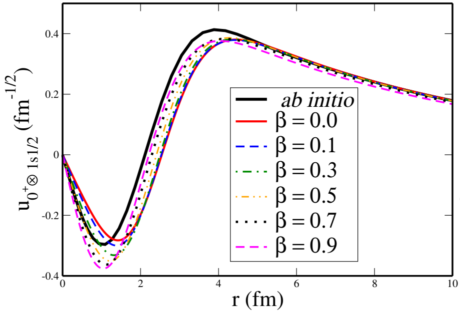


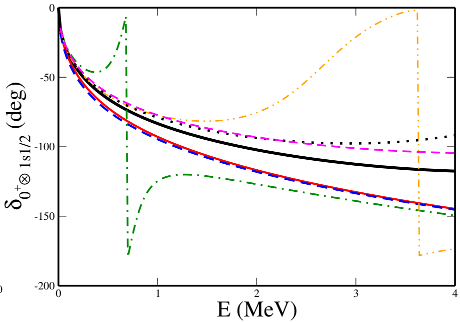
(σ=1.5fm) β=**0.5** in excellent agreement with *ab initio* ψ_α, δ_α

$\frac{1}{2}^+$:=deformed state

Ground state: $1/2^+$ - Type 2 solution

- $\Psi_{1/2^+} = \psi(\mathrm{r})_{1s1/2} \otimes \chi_{0^+}^{^{10}\mathrm{Be}} + \psi(\mathrm{r})_{0d5/2} \otimes \chi_{2^+}^{^{10}\mathrm{Be}} + \psi(\mathrm{r})_{0d3/2} \otimes \chi_{2^+}^{^{10}\mathrm{Be}}$
- Another type of solutions can be found:
  $\rightarrow$ when potential hosts a $0\mathrm{d}5/2$ **bound state at the right energy**



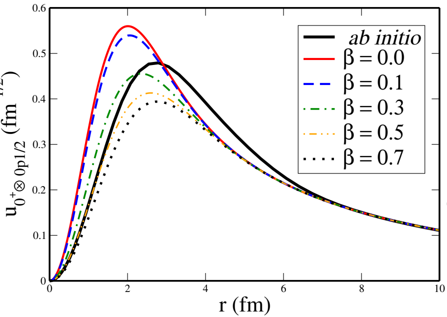


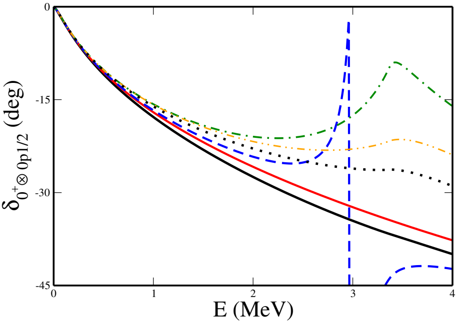
β=**0.9** in **fair** agreement with *ab initio* predictions

Problem: perturbative regime $\rightarrow$ **rejected solution**

First excited state: $1/2^-$

- $\Psi_{1/2^-} = \psi(\mathrm{r})_{0p1/2} \otimes \chi_{0^+}^{^{10}\mathrm{Be}} + \psi(\mathrm{r})_{0p3/2} \otimes \chi_{2^+}^{^{10}\mathrm{Be}} + \psi(\mathrm{r})_{0f5/2} \otimes \chi_{2^+}^{^{10}\mathrm{Be}}$





- $\frac{1}{2}^-$:= **deformation does not improve the model**:
  $\rightarrow$ wfs: no improvement in the **"pre-asymptotic" region (3-6 fm)**
  $\rightarrow$ phaseshifts: less good than without core excitation
- **No "type 2" solution** because $E_{0p3/2}$ not at the right energy

Conclusion

We want to study reactions involving **one-neutron halo nuclei** :

- need of a **realistic few-body** model for reaction calculations
  $\rightarrow$ Halo-EFT

Our model of one-neutron halo nuclei provides:

- perturbative inclusion of **core excitation within Halo-EFT**
- $\frac{1}{2}^+$ **state:** core excitation improves its few-body description
  $\rightarrow$ wavefunction and phaseshift
- $\frac{1}{2}^-$ **state:** few-body model of this state is not improved

Outlook:

- direct access to key observables: rms radius, $\mathrm{B(E1)}$, $\mathrm{dB(E1)/dE}$
- same formalism to study **resonances** [in progress]
- include our model in a reaction code (**breakup**,...)