# Perturbative EFT model of core excitations in one-neutron halo nuclei

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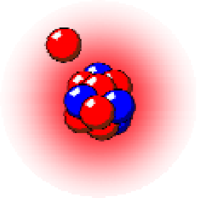
# Overview

1. Halo nuclei
2. Breakup reactions involving halo nuclei
   - Single-particle description of the projectile
   - Halo-EFT & core excitations
3. Coupled-channels calculations of $^{11}$Be's bound states
   - $\frac{1}{2}^{+}$ state
   - $\frac{1}{2}^{-}$ state
4. Conclusion

# Halo nuclei

- **Light, neutron-rich** nuclei
- Low $\mathbf{S}_n$ or $\mathbf{S}_{2n}$: one or two loosely-bound neutrons → large **rms** radius
- Clusterised structure:
  **neutrons can tunnel far from the core** to form a halo
  → halo-nucleus ≡ a compact core + valence neutron(s)
- Halos when low centrifugal barrier (**low** $\ell$)



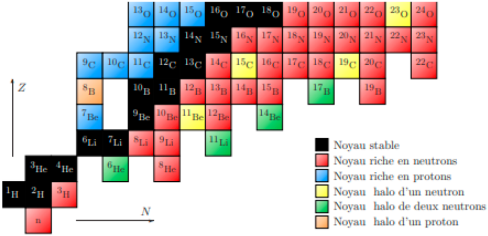
⇒ Halo-nuclei appear to be fascinating nuclear objects to study !

# Where to find them ? How to study them ?

- Exotic nuclear structures found **far from stability**

One-neutron halo
$^{11}$Be ≡ $^{10}$Be + n
$^{15}$C ≡ $^{14}$C + n

Two-neutron halo
$^{6}$He ≡ $^{4}$He + n + n
$^{11}$Li ≡ $^{9}$Li + n + n



→ ∃ one-neutron, two-neutron and proton halos [less probable]

- Short-lived [$\tau_{1/2}(^{11}\text{Be}) = 13$ s] → study via reactions [e.g. **breakup**]
- **Our case study** : $^{11}\text{Be} \equiv {}^{10}\text{Be} + \text{n}$
- **Breakup** of $^{11}$Be ≡ dissociation of halo (**n**) from the core (**$^{10}$Be**) by interaction with target

# Halo-EFT description of $^{11}$Be

- Halo-EFT : separation of scales [in distance/energy]
  → expansion parameter $\eta = \frac{R_{core}}{R_{halo}}$ or $\sqrt{\frac{S_{1n}}{E_{2^+}}} \simeq 0.4$
  → no explicit inclusion of $2^+$ state of $^{10}$Be core [$E_{2^+}$=3.4 MeV]
  → expansion along $\eta$ of low-energy behaviour (long-range physics)
  **[C. Bertulani, et al. NPA 712, 37 (2002)]**
  **[Hammer, Ji, Phillips, JPG 44, 103002 (2017)]**
- Effective potentials in each partial wave **lj** - narrow Gaussians @NLO

$$V_{cn}(r) = V_{lj}^{(0)} e^{-\frac{r^2}{2\sigma^2}} + V_{lj}^{(2)} r^2 e^{-\frac{r^2}{2\sigma^2}}$$

$V_{lj}^{(0)}$ and $V_{lj}^{(2)}$ fitted to reproduce [for bound states]:
→ $\epsilon_{nlj}$ and ANC (@ NLO)
→ $\epsilon_{nlj}$ (@ LO)
$\sigma$:= unfitted parameter → evaluates sensitivity to short-range physics
**[Capel, Phillips, Hammer, PRC 98, 034610 (2018)]**

# $^{11}$Be: resonant breakup reactions & core excitations (1)

- **Assumption**: $^{11}\text{Be} \equiv {}^{10}\text{Be}(0^+) + \text{n} \Rightarrow$ single-particle description
  $\rightarrow$ **one-body** Hamiltonian: $H_0(\mathbf{r}) = T_\mathbf{r} + V_{cn}(\mathbf{r})$
  $\rightarrow$ **single-particle description enough to fully describe breakup ?**
  **e.g.**$^{11}$Be+C $\rightarrow$ $^{10}$Be+n+C

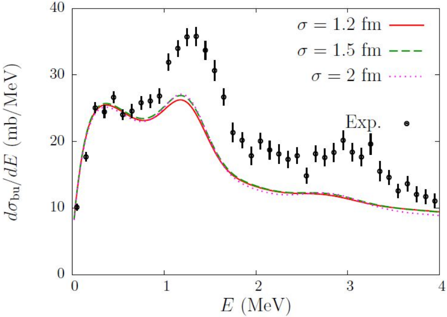
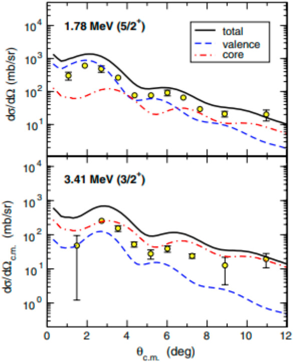


Figure: Capel, Philips & Hammer, PRC 98, 034610 (2018)

- Missing strength at $\frac{5}{2}^+$ and $\frac{3}{2}^+$ resonances
  $\Rightarrow$ significant influence of core excitations $\rightarrow$ **s.p** not enough !

# $^{11}$Be: resonant breakup reactions & core excitations (2)

- Resonant breakup: $^{11}$Be+C $\rightarrow$ $^{10}$Be+n+C
  $\Rightarrow$ $\exists$ missing degrees of freedom [$^{10}$Be($2^+$)] in models
  $\Rightarrow$ **DWBA extension**: Moro & Lay, PRL 109, 232502 (2012)



- To better understand **structure effects on reaction calculations**
  $\rightarrow$ we develop a Halo-EFT that includes **core excitations**

# Extension of halo-EFT to core excitations

- **Aim:= include explicitly** core excitations **in Halo-EFT**
  → allowing $^{10}$Be core to be excited to its $2^+$ state
- **Two-body** Hamiltonian of the projectile:

$$H_0(\mathbf{r},\xi) = T_\mathbf{r} + V_{cn}(\mathbf{r},\xi) + h_c(\xi)$$

- **Particle-rotor model [Bohr and Mottelson (1975)]:**
  → core with a permanent quadrupole deformation
  → multipolar expansion of $V_{cn}$ assuming **small deformation lengths**
  → **perturbative** coupling interaction:

$$V_{cn}(\mathbf{r},\xi) \simeq V_{cn}(r;\sigma_0) + \beta_2\sigma_c Y_2^0(\hat{r})\frac{d}{d\sigma_c}V_{cn}(r;\sigma_c)$$

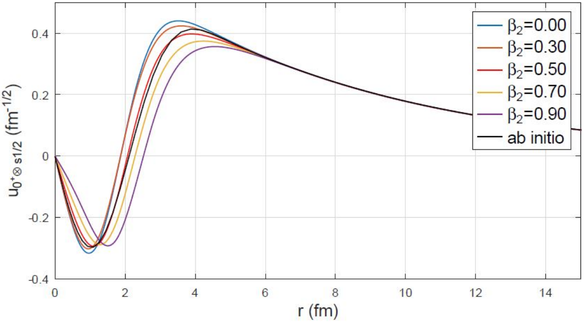
Coupled-channels eqs. with **R-Matrix method on a Lagrange mesh**

$$(\epsilon_{J^\pi}^{^{11}\mathrm{Be}} - \epsilon_\alpha^{^{10}\mathrm{Be}})\psi_\alpha(r) = [T_r^\ell + V_{\alpha\alpha}(r)]\psi_\alpha(r) + \sum_{\alpha'\neq\alpha} V_{\alpha\alpha'}(r)\psi_{\alpha'}(r)$$

$\Rightarrow \epsilon_{J^\pi}^{^{11}\mathrm{Be}}$, ANC, $\delta_\alpha$

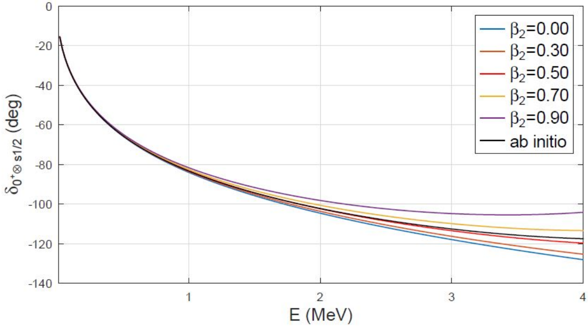
# $\frac{1}{2}^+$: bound state - coupled-channels - $^{11}$Be

- $s_{\frac{1}{2}}$: $\beta_2$, @NLO potentials **fitted to** reproduce *ab initio* predictions:
  → [Calci et al., PRL 117, 242501 (2016)]
  → $\epsilon_{\frac{1}{2}^+}$=-0.503 MeV and ANC = 0.786 fm$^{-1/2}$
- $\forall\ \beta_2$, $\neq$ interiors, **same asymptotics** as *ab initio*
  → $\sigma_c \sim \sigma_0$: no effects
- $\exists\ \beta_2$ **(=0.5)** which gives really good agreement with *ab initio* (SF,...)
  → **e.g.**: $\sigma_0$ = 1.2fm, $\sigma_c$ = 2.2fm ∼ $^{10}$**Be rms radius**



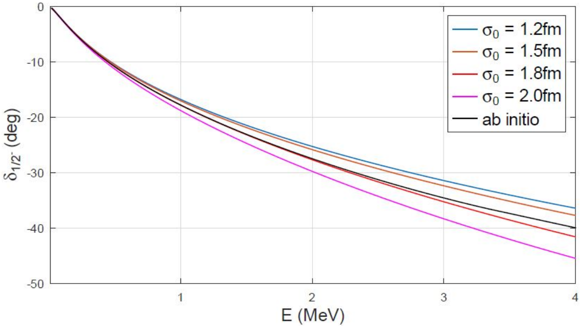
# $\frac{1}{2}^+$: phaseshift - coupled-channels - $^{11}$Be

- $s_{\frac{1}{2}}$: $\beta_2$, @NLO potentials **fitted to** reproduce *ab initio* predictions $\rightarrow$ [Calci et al., PRL 117, 242501 (2016)]
- $\sigma_c \gg \sigma_0$ $\rightarrow$ significative improvement of $\delta_{\frac{1}{2}^+}$ wrt *ab initio* results $\Rightarrow \exists\ \beta_2$**(=0.5)** reproducing *ab initio* **up to 4MeV** & $\beta_{best}$: $\beta_{wf} = \beta_\delta$



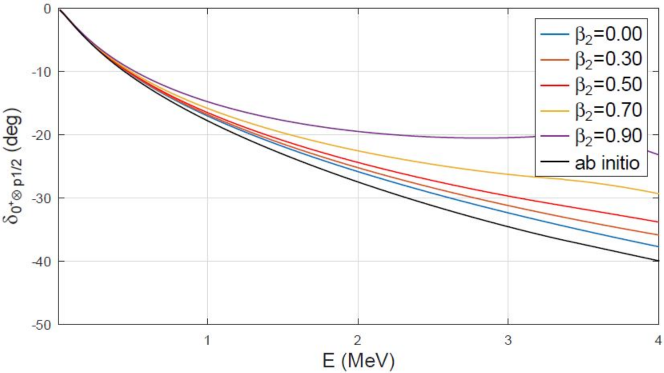
# $\frac{1}{2}^-$: a state with a completely different structure ?

- $p_{\frac{1}{2}}$: @NLO potentials **fitted to** reproduce *ab initio* predictions
  → $\epsilon_{\frac{1}{2}^-}$=-0.184 MeV and ANC = 0.129 fm$^{-1/2}$
- Single-particle description ($\beta_2$=0)**[without deformation]**
- $\sigma_0$ **= 1.8fm**: reproduces *ab initio* predictions up to 3 MeV !
  → $\sigma$**-dependency** → no need of deformation to reproduce *ab initio*
  → **Would core excitations actually improve something here ?**



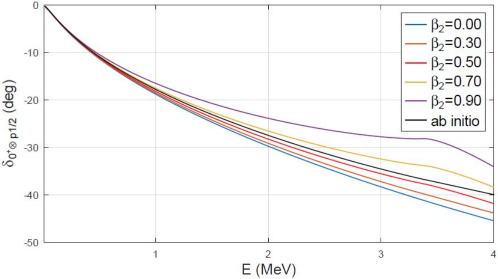
# $\frac{1}{2}^-$ state: core excitations (1)

- $p_{\frac{1}{2}}$: @NLO potentials
- Core excitations do improve phaseshifts if: $1.8\text{fm} \leq \sigma_0 \ll \sigma_c$
  $\Rightarrow \sigma_0 \leq 1.8\text{fm} \rightarrow$ it does not work
  **e.g.**: $\sigma_0 = 1.5\text{fm}$, $\sigma_c = 2.2\text{fm} \sim$ **$^{10}$Be rms radius**



# $\frac{1}{2}^-$ state: core excitations (2)

- $p_{\frac{1}{2}}$: @NLO potentials
- Core excitations do improve phaseshifts if: $1.8\text{fm} \leq \sigma_0 \ll \sigma_c$
  $\Rightarrow$ new structure effect: coupling has to act further wrt to $\frac{1}{2}^+$ state
  $\rightarrow$ **e.g.**: $\sigma_0 = 2.0\text{fm}$, $\sigma_c = 2.7\text{fm}$



- $\sigma_c >{}^{10}$Be radius $\rightarrow$ coupling acts outside of the nucleus [**unphysical**]
  $\Rightarrow$ coupling = artefact $\rightarrow$ not needed $\rightarrow$ $\frac{1}{2}^-$:=shell model state
- **Q: Would working @N2LO in Halo-EFT solve this problem ?**

# Conclusion

→ **Halo nuclei** are fascinating nuclear objects:

- found **far from stability**, low $\mathbf{S}_n$, large **rms** radius,...
- with a short lifetime → study via reactions (e.g.**breakup)**
  → need of a **realistic few-body** model for reaction calculations
  → Halo-EFT

→ **Our model** of one-neutron halo nuclei provides:

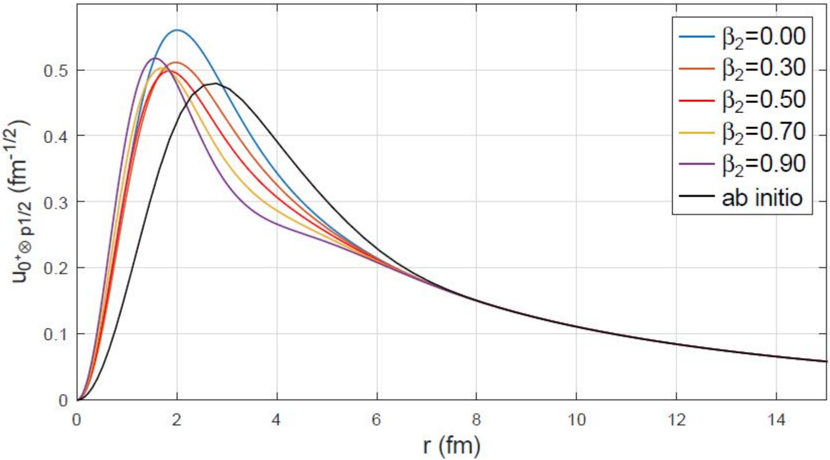
- perturbative inclusion of **core excitations in Halo-EFT**
- $\frac{1}{2}^+$**state:** $\sigma_0 \ll \sigma_c$
  → can improve *ab initio* wave functions and phaseshifts
- $\frac{1}{2}^-$**state:** $1.8\text{fm} \leq \sigma_0 \ll \sigma_c$
  → can improve *ab initio* phaseshifts
  **but** s.p. description seems sufficient for that state with $\sigma_0 = 1.8\text{fm}$
  → **Would working @N2LO in Halo-EFT solve this problem ?**

**End goal:** using our model for breakup calculations

Thank you for your attention !

# Backup (1)

$\frac{1}{2}^-$: wavefunctions with $\sigma_0 = 1.5\text{fm}$, $\sigma_c = 2.2\text{fm} \sim {}^{10}\text{Be}$ rms radius



# Backup (2)

$\frac{1}{2}^-$: wavefunctions with $\sigma_0 = 2.0\text{fm}$, $\sigma_c = 2.7\text{fm}$