# Peripherality of Nuclear-Dominated Breakup Reactions

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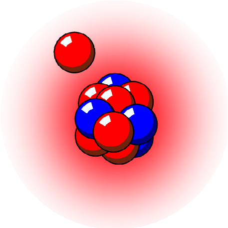
# Halo nuclei

- Light, neutron-rich nuclei
- small $S_{1n}$ or $S_{2n}$
- low-$\ell$ orbital



One-neutron halo

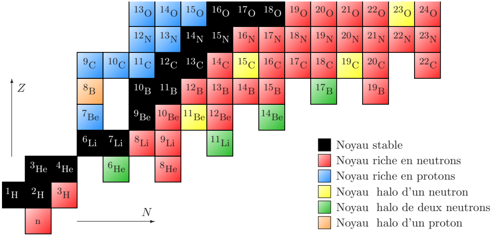
$^{11}$Be ≡ $^{10}$Be + n

$^{15}$C ≡ $^{14}$C + n

Two-neutron halo

$^{6}$He ≡ $^{4}$He + n + n

$^{11}$Li ≡ $^{9}$Li + n + n




However difficult to study experimentally [$\tau_{1/2}(^{11}\text{Be}) = 13$ s]

⇒ require indirect techniques, like reactions : breakup, knockout. . .

Need accurate theoretical description of reaction

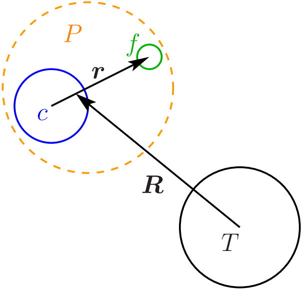
Need to know to what the reaction is sensitive

i.e. which structure information can be inferred from experiments

# Model of Breakup Reactions

Projectile ($P$) modelled as a two-body system :
core ($c$)+loosely bound fragment ($f$) described by

$$H_0 = T_r + V_{cf}(\boldsymbol{r})$$




$V_{cf}$ adjusted to reproduce $P$ spectrum

Target $T$ seen as structureless particle

$P$-$T$ interaction simulated by optical potentials

$\Rightarrow$ breakup reduces to three-body scattering problem :

$$\left[T_R + H_0 + V_{cT} + V_{fT}\right]\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ+\cdots}\,\phi_0(\boldsymbol{r})$

# Study of nuclear spectroscopy ?

Reaction models rely on single-particle model :

$$[T_r + V_{cf}(r)]\, \phi_{nlm}(\boldsymbol{r}) = E_{nl}\, \phi_{nlm}(\boldsymbol{r}) \quad \text{with} \quad \|\phi_{nlm}\| = 1$$

In reality, there is admixture of configurations :

$$^{A}Y(J^{\pi}) = {}^{A-1}X(J_c^{\pi}) \otimes \psi_{lm} + \ldots$$

where $\psi_{lm}$ is the overlap wave function

Spectroscopic Factor : $\mathcal{S}_l = \|\psi_{lm}\|^2$

Single-particle approximation $\equiv \psi_{lm} = \sqrt{\mathcal{S}_l}\, \phi_{nlm}$

$\Rightarrow$ usual idea : $\mathcal{S}_l = \sigma_{\rm bu}^{\rm exp} / \sigma_{\rm bu}^{\rm th}$

But is it correct ?

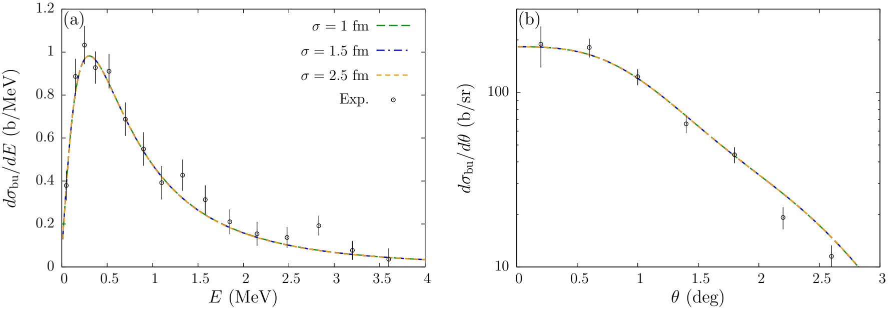
Aren't breakup reaction peripheral ?

$\Leftrightarrow$ probe tail of wave function : $u_l(r) \underset{r\to\infty}{\longrightarrow} C_l\, e^{-\kappa r}$

$\Leftrightarrow$ Asymptotic Normalisation Constant $C_l$

# Analysis of Coulomb breakup $^{19}$C+Pb→$^{18}$C+n+Pb

Once $S_{\rm n}$ and $C_{s1/2}$ fitted, the agreement with data is excellent



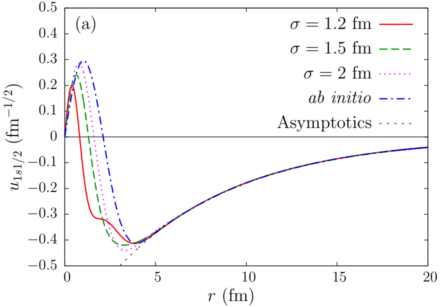

Exp : [Nakamura *et al.* PRL **83**, 1112 (1999)] Th : [P.C., Phillips *et al.* EPJA **53**, 273 (2023)]

No sensitivity to $\sigma$ ⇒ peripheral
⇒ probe ANC $C_{s1/2}$ not SF $\mathcal{S}_{s1/2}$

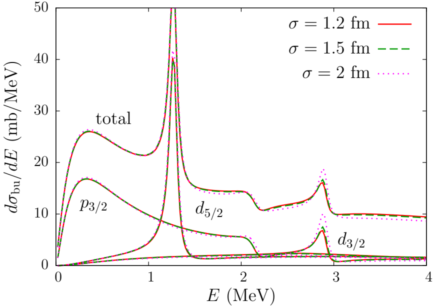
But Coulomb dominated. . .
What about nuclear-dominated reactions ?

# Peripherality of nuclear breakup

Use different $V_{cf}$ to produce wave functions with same ANC obtained by Halo-EFT @ N$^2$LO to include $d$ resonances




$^{11}$Be+$^{12}$C → $^{10}$Be+n+$^{12}$C @ 67$A$MeV



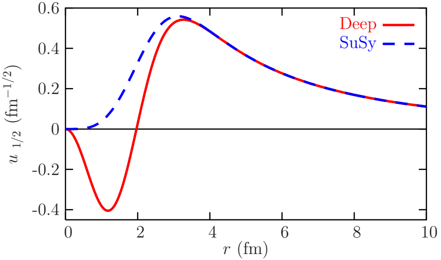

[Kubushishi, P.C., arXiv: 2406.10168 (2024)]

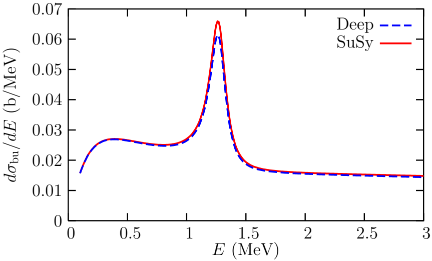
- Different cutoffs $\sigma$ lead to different interiors of wave function
- NO difference in $\sigma_{\rm bu}$ ⇒ insensitive to short range ($r \lesssim 4$ fm)
  but at the resonances
- But all wave functions have same shape. . .

# Peripherality of breakup reactions

Use 2 $V_{cf}$ with different interior but same asymptotics
obtained by SuSy transformations [D. Baye PRL **58**, 2738 (1987)]

$^{11}$Be+$^{12}$C → $^{10}$Be+n+$^{12}$C @ 67$A$MeV



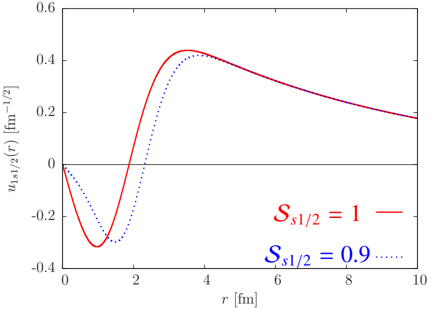

[P.C., Nunes, PRC **75**, 054609 (2007)]

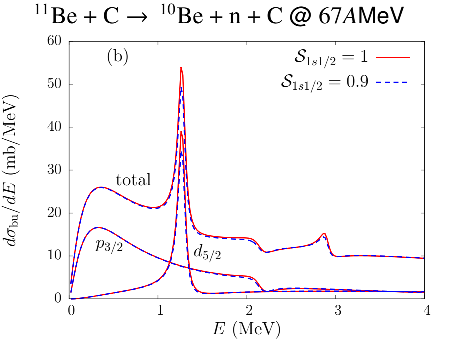
- Deep potential ⇒ deep $0s_{1/2}$ bound state
  ⇒ node in physical bound state
- Remove deep state by SuSy ⇒ remove node
  but keep same asymptotics (ANC and phase shift)
- NO difference in $\sigma_{\rm bu}$ ⇒ insensitive to short range ($r \lesssim 3$ fm)
  but at the resonances
- But both have $\mathcal{S}_{s1/2} = 1$...

# SF *vs* ANC in Nuclear Breakup

Use 2 $V_{cf}$ fitted to reproduce

- $S_{1n}(^{11}\mathrm{Be})$ & *ab initio* ANC $C_{s1/2}$ [Calci *et al.* PRL **117**, 242501 (2016)]
- SF : $\mathcal{S}_{s1/2} = 1$ or $\mathcal{S}_{s1/2} = 0.9$




[P.C., Phillips, Hammer, PRC **98**, 034610 (2018)]

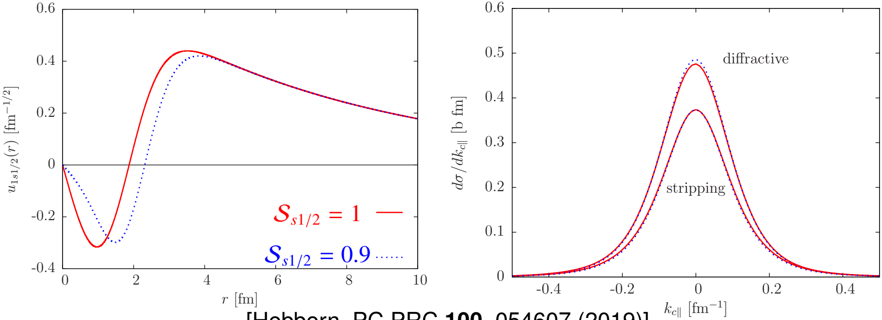
- NO noticeable difference ⇒ confirms breakup is peripheral but at resonances
- Only ANC is probed
- But what about knockout ?

# SF *vs* ANC in Knockout

Use 2 $V_{cf}$ fitted to reproduce

- $S_{1n}(^{11}\mathrm{Be})$ & *ab initio* ANC $C_{1/2^+}$ [Calci *et al.* PRL **117**, 242501 (2016)]
- SF : $\mathcal{S}_{s1/2} = 1$ or $\mathcal{S}_{s1/2} = 0.9$

$^{11}$Be+$^{12}$C → $^{10}$Be+X @ 67$A$MeV

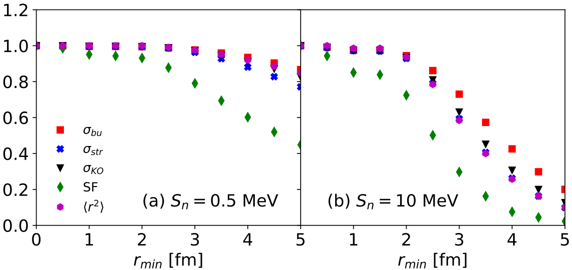



[Hebborn, PC PRC **100**, 054607 (2019)]

- Same results for $\mathcal{S}_{s1/2} = 1$ and $0.9$ ⇒ NO sensitivity to SF
- But excellent probe of the ANC
- But. . . what about more deeply bound nuclei ?

# Sensitivity of KO

Assume $u_{1s1/2}(r) = 0\ \forall r < r_{\rm min}$ and compute
$\sigma_{\rm bu}$ (diffractive breakup), $\sigma_{\rm str}$ (stripping), SF, $\langle r^2 \rangle$
for (a) halo ($S_n = 0.5$ MeV) and (b) deeply bound ($S_n = 10$ MeV)

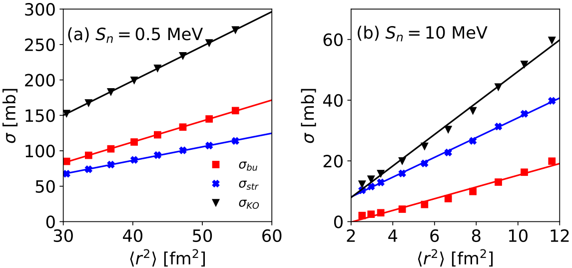



[Hebborn, PC PL**B848**, 138413 (2024)]

- $\sigma_{\rm bu}$ and $\sigma_{\rm str}$ insensitive to cutoff at small $r_{\rm min}$
- SF affected already at $r_{\rm min} = 0.5$ fm
- $\sigma_{\rm bu}$ and $\sigma_{\rm str}$ do not scale with SF
- but $\sigma_{\rm bu}$ and $\sigma_{\rm str} \propto \langle r^2 \rangle$

# $\sigma_{\rm KO} \propto \langle r^2 \rangle$

Using different geometries of $V_{cf}$, different $\langle r^2 \rangle$ can be obtained




[Hebborn, PC PL**B848**, 138413 (2024)]

- $\sigma_{\rm KO} \propto \langle r^2 \rangle$
- True for both components $\sigma_{\rm bu}$ and $\sigma_{\rm str}$
- Explained by a perturbative expansion of eikonal cross section

# Summary and take-home message

- Halo nuclei studied mostly through reactions
- Breakup is purely peripheral, so we probe :
  - ANC of the ground state $C_l$
  - (phase shift in the continuum)
  - Not the SF $\mathcal{S}_l$
- This is true for
  - Coulomb breakup
  - Nuclear breakup
  - Knockout

Be sure to know to what the reaction is sensitive…

# Thanks to my collaborators

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