Halo-EFT analyses of knockout reactions of ^{11}Be and ^{15}C

Chloë Hebborn and Pierre Capel

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In the light neutron-rich sector :

Halo nuclei exhibit a very large matter radius

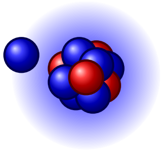
Compact core + one loosely-bound neutrons

Ex : $^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + n$

$S_n = 503$ keV

$^{15}\mathrm{C} \equiv {}^{14}\mathrm{C} + n$

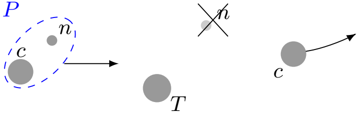
$S_n = 1218$ keV



Short-lived ($\tau_{^{11}\mathrm{Be}} \sim 13$ s) : studied through **reaction processes**

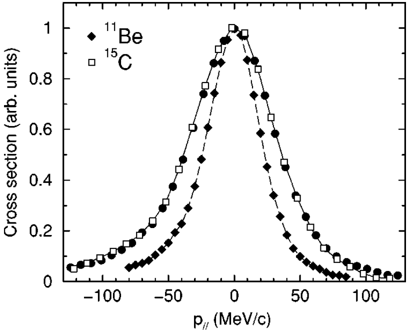
One-neutron knockout :

$P(\equiv c + n) + T \rightarrow c + X$



⇒ high statistics since the neutron is not detected in coincidence !

Knockout reactions a useful probe



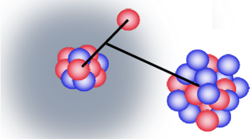
[J. A. Tostevin *et al.*, PRC **66**, 024607 (2002)]

KO Reactions at $> 60A$ MeV

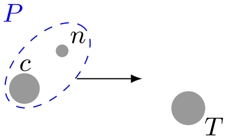
Sudden approximation + Uncertainty principle

→ **width linked to the nucleus size**

Three-body model of reaction



$\Rightarrow$



- c-n interaction : effective interaction V^{cn}
- $P-T$ interactions : optical potentials V_{cT} and V_{nT}

$$\boxed{\sigma_{th} = \sum_i SF_i \times \sigma_{ko}^{sp,i}}$$

$SF_i \rightarrow$ occupancy of a s.p. orbital i

KO cross sections $\sigma_{ko}^{sp,i}$ = Diffractive breakup $\sigma_{bu}^{sp,i}$ + Stripping $\sigma_{str}^{sp,i}$

$\sigma_{bu}^{sp,i} \Rightarrow$ **Dynamical eik. approximation** : ① [Baye, Capel, and Goldstein, PRL **95**, 082502 (2005)]

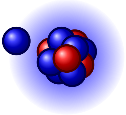
$\sigma_{str}^{sp,i} \Rightarrow$ **Usual eik. approximation** : ① + ② [Glauber, *High energy collision theory*, (1959)]

① Eikonal approximation ② Adiabatic approximation

Halo-EFT model of the projectile

Halo-EFT model of projectile : uses the **separation of scale** to expand low-energy behaviour with $R_{\rm core} \ll R_{\rm halo}$

[H.-W. Hammer *et al.* , JPG **44**, 103002 (2017)]



$\Rightarrow$ c-n **effective potential**

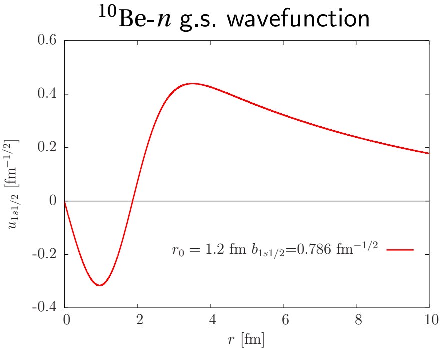
$$\text{At NLO : } V_{lJ}^{cn}(r) = V_{lJ}^{(0)} e^{-\frac{r^2}{2r_0^2}} + V_{lJ}^{(2)} r^2 e^{-\frac{r^2}{2r_0^2}}$$

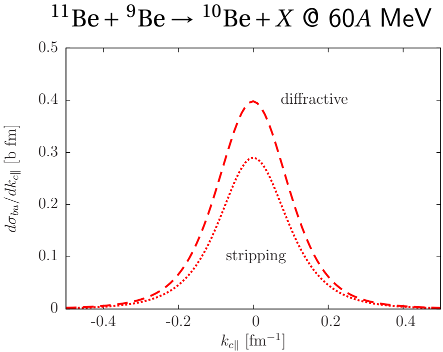
with r_0 the scale of the short-range physics neglected in the model

We constrain $V^{(0)}$ and $V^{(2)}$ in s and p waves

1. Experimental energies of $1/2^+$ ground state and excited state
2. Asymptotic Normalization Constant (ANC) from
   NCSMC calculations (^{11}Be) [Calci *et al.* PRL **117**, 242501 (2016)]
   transfer data (^{15}C) [Moschini, Yang, and Capel PRC **100**, 044615 (2019)]

Sensitivity of knockout of halo nuclei



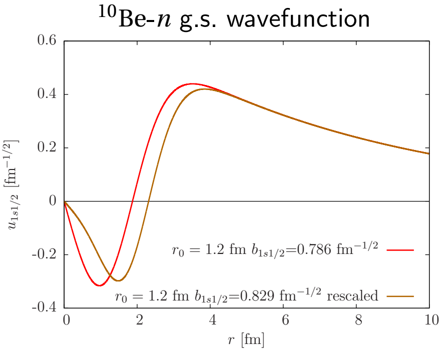


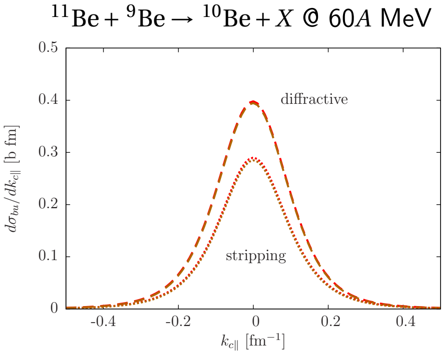
[Hebborn and Capel, Phys. Rev. C **100**, 054607 (2019)]

Reference calculation : ANC=0.786 fm$^{-1/2}$ [Calci *et al.* PRL **117**, 242501 (2016)]

Diffractive breakup > stripping

Sensitivity of knockout of halo nuclei





[Hebborn and Capel, Phys. Rev. C **100**, 054607 (2019)]

Reference calculation : ANC=0.786 fm$^{-1/2}$ [Calci *et al.* PRL **117**, 242501 (2016)]

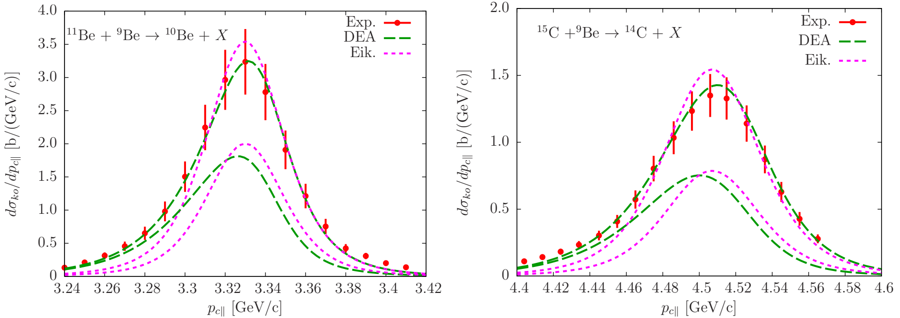
Diffractive breakup > stripping

Same ANC but SF=0.9 : same cross sections → no sensitivity to SF

KO of halo nuclei sensitive only to the asymptotics !

⇒ Possibility to extract an ANC

How does it compare to experimental data ?

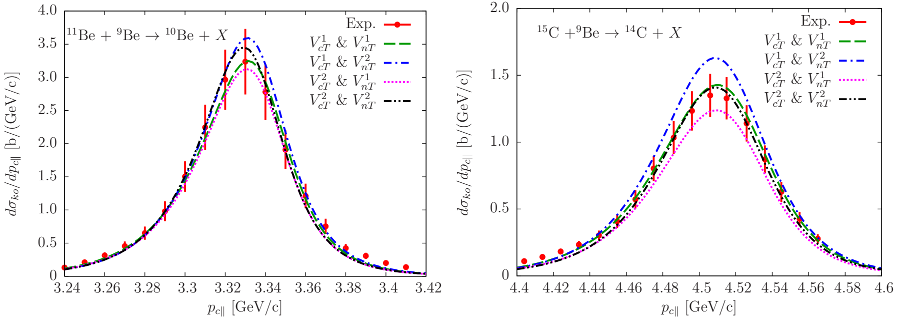


[Exp. : Aumann *et al.* PRL **84**, 35 (2000) ; Tostevin *et al.* PRC **66**, 024607 (2002) ; Th. : Hebborn and Capel, arXiv :2105.04490]

Eikonal **lacks asymmetry** due to the adiabatic approximation

$\sigma_{bu}^{sp,i}$ computed with the DEA → Asymmetry well reproduced

How does it compare to experimental data ?



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Eikonal **lacks asymmetry** due to the adiabatic approximation

$\sigma^{sp,i}_{bu}$ computed with the DEA → Asymmetry well reproduced

Sensitivity to optical potentials : ^{11}Be ANC$^2 = 0.62 \pm 0.06 \pm 0.09$ fm^{-1}
^{15}C ANC$^2 = 1.57 \pm 0.30 \pm 0.18$ fm^{-1}

⇒ Excellent agreement with *ab initio* ANC^2=0.618 fm^{-1} & 1.644 fm^{-1}

ANCs of ^{11}Be and ^{15}C reproduce knockout data,...

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diffractive breakup data

PHYSICAL REVIEW C **98**, 034610 (2018)

Dissecting reaction calculations using halo effective field theory and *ab initio* input

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Reliable extraction of the $dB(\mathrm{E1})/dE$ for ^{11}Be from its breakup at 520 MeV/nucleon

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transfer data,

PHYSICAL REVIEW C **98**, 054602 (2018)

Systematic analysis of the peripherality of the ^{10}Be$(d,p)^{11}$Be transfer reaction and extraction of the asymptotic normalization coefficient of ^{11}Be bound states

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and radiative capture data !

PHYSICAL REVIEW C **100**, 044615 (2019)

^{15}C: From halo effective field theory structure to the study of transfer, breakup, and radiative-capture reactions

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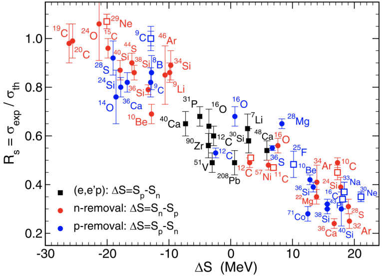
Summary for halo nuclei

Halo nuclei : peripherality of knockout reactions

Halo-EFT bridges *ab initio* and reaction theory



[J.A. Tostevin and A. Gade. PRC **103**, 054610 (2021)]

⇒ One-neutron KO of halo nuclei are not sensitive to SF

⇒ Good agreement probably due to use of a realistic ANC

Sensitivity to the optical potentials → Need for a more systematic study

What happens when the binding energy increases ?

What happens when the binding energy increases ?

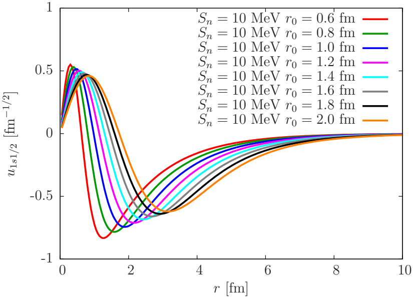
Irrealistic ^{11}Be : $1/2^+$ g.s. $S_n = 10$ MeV

Beyond Halo-EFT : use a Gaussian potential $V_{s1/2}$

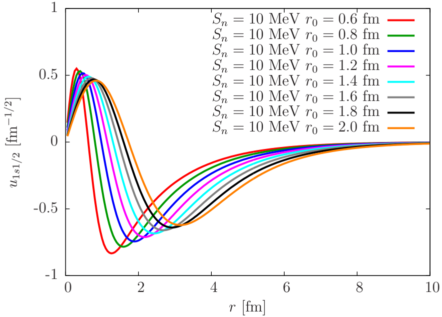
$$V^{cn}_{s1/2}(r) = V^{(0)}_{s1/2} e^{-\frac{r^2}{2r_0^2}}$$

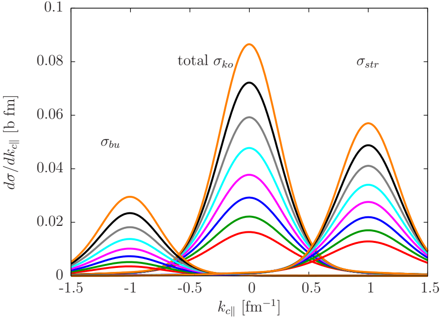
We constrain $V^{(0)}_{s1/2}$ with separation energy S_n

Generation of different g.s. wavefunctions with various r_0

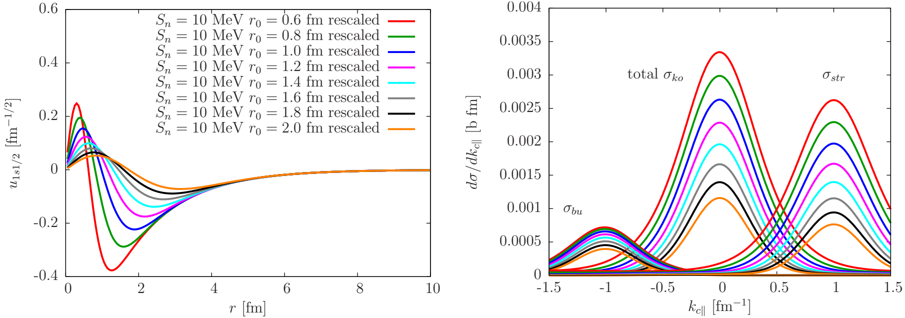


Larger r_0 → larger ANC





- Larger r_0 → larger ANC → larger $\sigma^{sp,i}_{str}$ and $\sigma^{sp,i}_{bu}$ (with $\sigma^{sp,i}_{str} > \sigma^{sp,i}_{bu}$)



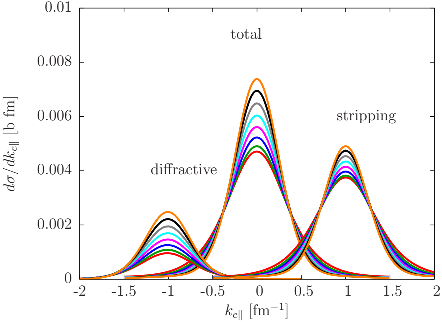
- Larger r_0 → larger ANC → larger $\sigma^{sp,i}_{str}$ and $\sigma^{sp,i}_{bu}$ (with $\sigma^{sp,i}_{str} > \sigma^{sp,i}_{bu}$)
- Rescale with the ANC^2 → same asymptotics but SF=0.2–0.01

Peak does not scale with the ANC^2

$\sigma^{sp,i}_{bu}$ stays mainly peripheral but $\sigma^{sp,i}_{str}$ more sensitive to short distances

⇒ $\sigma^{sp,i}_{ko}$ **depends non-linearly on SF**

Sensitivity for deeply-bound projectile



- Larger r_0 → larger ANC → larger $\sigma^{sp,i}_{str}$ and $\sigma^{sp,i}_{bu}$ (with $\sigma^{sp,i}_{str} > \sigma^{sp,i}_{bu}$)
- Rescale with the ANC^2 → same asymptotics but SF=0.2–0.01
- Rescale with $\langle r^2 \rangle$: peak overestimated and tail underestimated

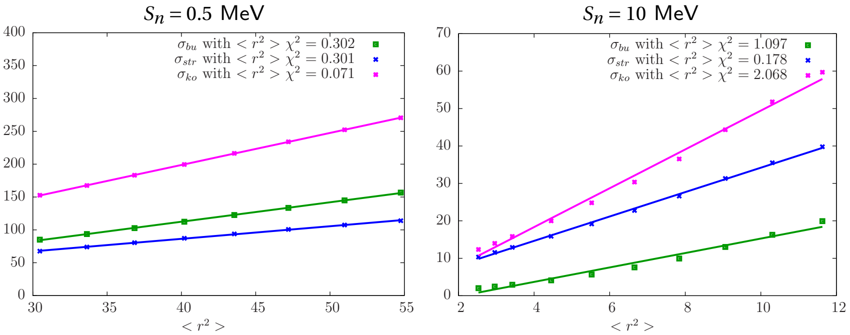
  Peak does not scale with the ANC^2 either with $\langle r^2 \rangle$

  $\sigma^{sp,i}_{bu}$ stays mainly peripheral but $\sigma^{sp,i}_{str}$ more sensitive to short distances

  ⇒ $\sigma^{sp,i}_{ko}$ **depends non-linearly on SF**

What about integrated cross sections ?

Each r_0 generates wave function with various $\langle r^2 \rangle$



Stripping : approximate linear dependence on $\langle r^2 \rangle$

Also for spatially-extended nuclei, e.g., halo nuclei, $\langle r^2 \rangle \propto \text{ANC}^2$

$\Rightarrow$ **Universal behavior of σ_{str} with $\langle r^2 \rangle$**

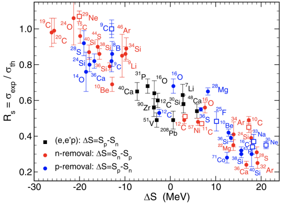
$\rightarrow$ can be also demonstrated with perturbation analysis !

Summary

Halo nuclei : ① peripherality of knockout reactions

⇒ No sensitivity to the SF

⇒ Excellent agreement probably due to use of realistic ANCs



[PRC **103**, 054610 (2021)]

② Halo-EFT bridges structure and reaction theory

⇒ Halo-EFT description at NLO of ^{11}Be and ^{15}C reproduce knockout, diffractive-breakup, transfer and radiative-capture data

Deeply-bound nuclei : σ_{ko} does not depend linearly on SF

σ_{ko} depends approximately on $\langle r^2 \rangle$

⇒ Possibility to extract $\langle r^2 \rangle$ from KO data on various targets

⇒ Need to improve reaction model to understand the asymmetry dependence