Dissecting calculations of breakup and transfer reactions with halo nuclei using Halo EFT

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Preliminary comments

The different references are hyperlinked to the original papers.
When possible, the link to the arXiv page is also provided.

I'd like to thank the organisers for their excellent initiative to set up this series of international seminars : Jin Lei, Mario Gómez Ramos, Kaitlin Cook, and Jesús Casal.

Thanks for joining in for this on-line seminar.

I wish you all to stay healthy and go through this quarantine unscathed.

Pierre Capel

Halo nuclei

Halo nuclei are found far from stability

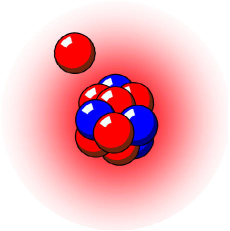
Exhibit peculiar quantal structure :

- Light, n-rich nuclei
- Low S_{n} or $S_{2\mathrm{n}}$

With large matter radius

due to strongly clusterised structure :

neutrons tunnel far from the core and form a diffuse halo



One-neutron halo

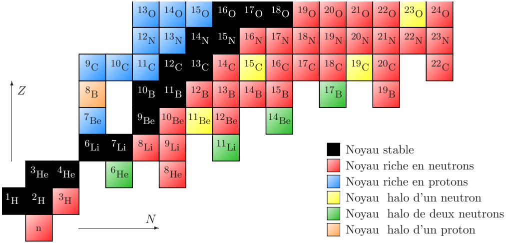
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



Two-neutron halo nuclei are Borromean. . . [see M. Gómez's , A. Corsi's talks]

This exotic structure challenges nuclear-structure models

Reactions with halo nuclei

Halo nuclei are fascinating objects
but difficult to study [$\tau_{1/2}$(^{15}C)= 2.5 s]

How can one probe their structure ?

⇒ require indirect techniques, like reactions :

- transfer : ^{14}C(d,p)^{15}C
- breakup : ^{15}C + Pb → ^{14}C + n + Pb
- knockout : ^{15}C + C → ^{14}C + X
- radiative capture : ^{14}C(n,γ)^{15}C (astrophysical interest)

Need good understanding of the reaction mechanism
(i.e. a good reaction model)
to know what nuclear-structure information is probed

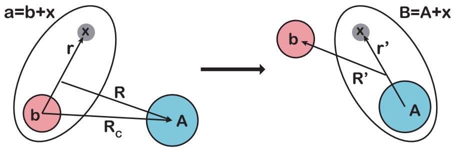
We address this by coupling precise reaction models with Halo EFT

^{11}Be : [P.C., Phillips, Hammer PRC 98, 034610 (2018)] arXiv

^{15}C : [Moschini, Yang, P.C. PRC 100, 044615 (2019)] arXiv

Few-body description of transfer

Transfer : $A + a(\equiv b + x) \to B(\equiv A + x) + b$ aka $A(a, x)B$
described in a few-body model :



Bound states, initial Φ_{bx} and final Φ_{Ax}
obtained from effective interactions : V_{bx} and V_{Ax}

Scattering described by optical potentials U_{aA}, U_{pB},...

For (d, p)

$$T_{\mathrm{post}}(\mathrm{p}\,B, \mathrm{d}\,A) = \left\langle \chi^{(-)}_{\mathrm{p}B} \Phi_{A\mathrm{n}} \middle| V_{\mathrm{pn}} + U_{\mathrm{p}A} - U_{\mathrm{p}B} \middle| \Psi^{(+)}_{\mathrm{d}A} \right\rangle$$

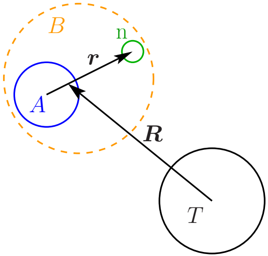
@FR-ADWA $\Psi^{(+)}_{\mathrm{d}A} \approx \chi^{(+)}_{\mathrm{d}A} \Phi_{\mathrm{pn}}$ [Johnson & Tandy NPA 235, 56 (1974)]
[see also M. Gómez Ramos', A. Ratkiewicz's and N. Timofeyuk's talks]

Few-body description of breakup

Breakup : $B(\equiv A + \mathrm{n}) + T \rightarrow A + \mathrm{n} + T$

Projectile (B) ≡ core (A)+loosely bound neutron (n) described by

$H_{A\mathrm{n}} = T_r + V_{A\mathrm{n}}(\boldsymbol{r})$



$V_{A\mathrm{n}}$ effective interaction
describes the A-n system
with ground state $\Phi_{A\mathrm{n}}$

Target T seen as structureless
Interaction with target simulated by optical potentials

⇒ breakup reduces to three-body scattering problem :

$$[T_R + H_{A\mathrm{n}} + U_{AT} + U_{\mathrm{n}T}]\,\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\rightarrow-\infty}{\longrightarrow} e^{iKZ}\Phi_{A\mathrm{n}}(\boldsymbol{r})$

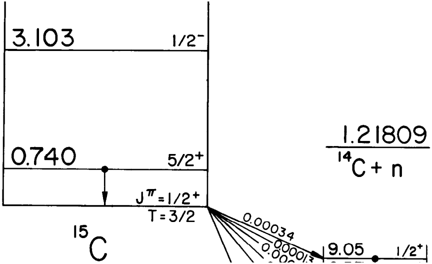
We use the Dynamical Eikonal Approximation (DEA) @ $70A$MeV

[Baye, P. C., Goldstein, PRL 95, 082502 (2005)]

An eikonal approximation with relativistic corrections @ $600A$MeV

[Moschini, P. C. PLB 790, 367 (2019)] arXiv

$^{15}\text{C} \equiv {}^{14}\text{C} \otimes \text{n}$



- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -1.218$ MeV
  Seen as $1s_{1/2}$ neutron bound to $^{14}\text{C}(0^+)$
- $\frac{5}{2}^+$ bound excited state :
  $\epsilon_{\frac{5}{2}^+} = -0.478$ MeV
  Seen as $0d_{5/2}$ neutron bound to $^{14}\text{C}(0^+)$

Single-particle description

In reaction models, one-neutron halo nucleus ≡ two-body system :

$$H_{\rm An} = T_r + V_{\rm An}(\boldsymbol{r}),$$

where V_{An} is a phenomenological Woods-Saxon that reproduces the basic nuclear properties of the projectile (binding energy, J^π,...)

The halo-nucleus structure is described by $H_{\rm An}$ eigenstates

$$\begin{aligned} H_{\rm An}\,\Phi_{nljm}(\boldsymbol{r}) &= \epsilon_{nlj}\,\Phi_{nljm}(\boldsymbol{r}), \\ \Phi_{nljm}(\boldsymbol{r}) &= \frac{1}{r}u_{nlj}(r)\,\mathcal{Y}_{ljm}(\Omega) \end{aligned}$$

Asymptotically, $u_{nlj}(r) \underset{r\to\infty}{\longrightarrow} C_{nlj}\, e^{-\kappa_{nlj}r}$ with $\hbar^2\kappa^2_{nlj}/2\mu_{\rm An} = |\epsilon_{nlj}|$

C_{nlj} is the Asymptotic Normalisation Coefficient (ANC)

In A-n continuum $u_{klj}(r) \underset{r\to\infty}{\longrightarrow} kr\ \sin(kr + \delta_{lj})$ with $\hbar^2k^2/2\mu_{\rm An} = \epsilon$

δ_{lj} is the phaseshift in partial wave lj

Halo-EFT potential

Replace A-n interaction by effective potentials in each partial wave

Use Halo EFT : clear separation of scales (in energy or in distance)
⇒ provides an expansion parameter (small scale / large scale)
along which the low-energy behaviour is expanded

[C. Bertulani, H.-W. Hammer, U. Van Kolck, NPA 712, 37 (2002)] arXiv
[H.-W. Hammer, C. Ji, D. R. Phillips JPG 44, 103002 (2017)] arXiv

Use narrow Gaussian potentials @ LO@ NLO

$$V_{lj}(r) = V_0^{lj}\, e^{-\frac{r^2}{2r_0^2}} + V_2^{lj}\, r^2 e^{-\frac{r^2}{2r_0^2}}$$

r_0 used to evaluate the sensitivity of calculations to short-range physics

@ LO :
Fit V_0^{lj} to reproduce ϵ_{nlj} (known experimentally)

@ NLO :
Fit V_2^{lj} to also reproduce C_{nlj} (obtained by analysing transfer reactions)

[Yang, P.C. PRC 98, 054602 (2018)] arXiv

LO analysis of transfer reaction ^{14}C(d,p)^{15}C

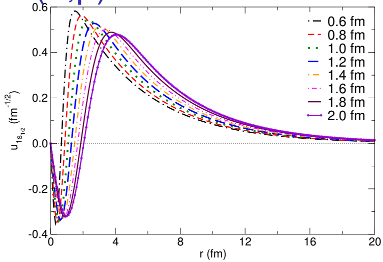
Transfer is purely peripheral
(⇔ probe only ANC) at

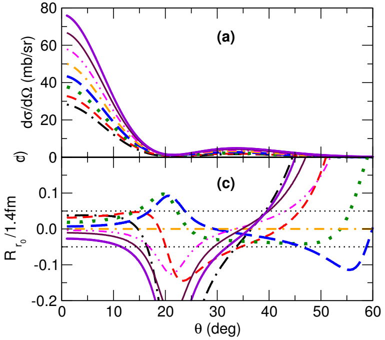
- low E_d
- forward angles

[Yang, P.C. PRC 98, 054602 (2018)] arXiv

1. Generate different wave functions @ LO using different r_0
2. Run transfer calculations (we use FR-ADWA)
3. Determine the zone of peripherality

$$R_{r_0/1.4\text{fm}} = \left(\frac{C^{(1.4\text{fm})}_{1s1/2}}{C^{(r_0)}_{1s1/2}} \right)^2 \frac{d\sigma^{(r_0)}/d\Omega}{d\sigma^{(1.4\text{fm})}/d\Omega} - 1$$





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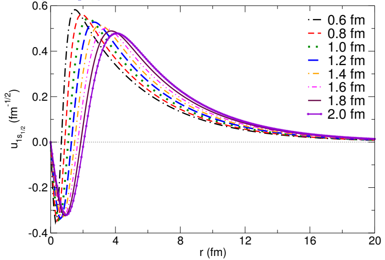
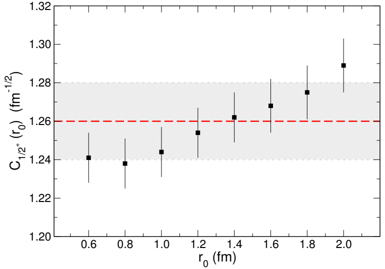
4. Within that zone, fit to data and extract an ANC :
$C_{1s1/2} = 1.26 \pm 0.02$ fm$^{-1/2}$, close to *ab initio* $C_{1s1/2} = 1.28$ fm$^{-1/2}$

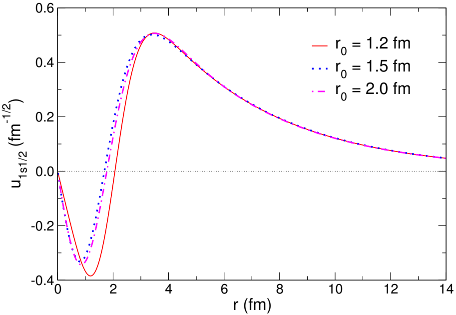




$s\frac{1}{2}$: @ NLO potentials fitted to $\epsilon_{\frac{1}{2}^+}$ and $C_{1s1/2}$

Potentials fitted to $\epsilon_{1s1/2} = -1.218$ MeV and $C_{1s1/2} = 1.26$ fm$^{-1/2}$

Ground-state wave function

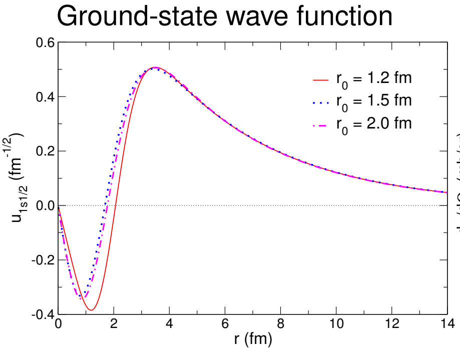


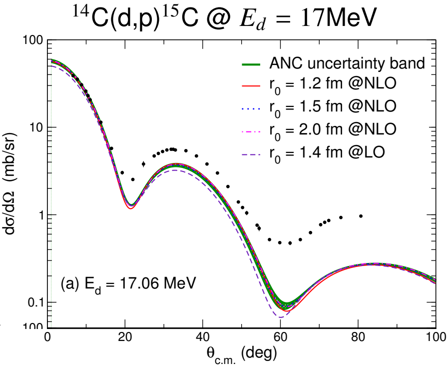
Th : [Moschini, Yang, P.C. PRC 100, 044615 (2019)] arXiv

- Wave functions : same asymptotics but different interior
- In higher partial waves ($l \geq p$) $V_{lj} = 0$

^{14}C(d,p)^{15}C @ E_d = 17MeV

Potentials fitted to $\epsilon_{1s1/2} = -1.218$ MeV and $C_{1s1/2} = 1.26$ fm$^{-1/2}$



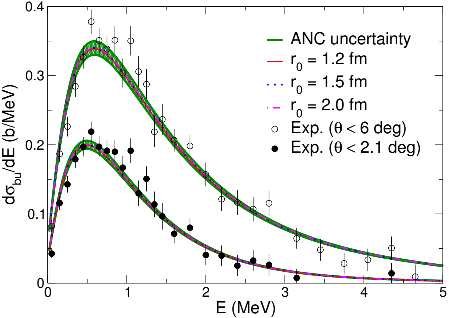


Th : [Moschini *et al.* PRC 100, 044615 ('19)] arXiv Exp : [Mukhamedzhanov PRC 84, 024616 (2011)]

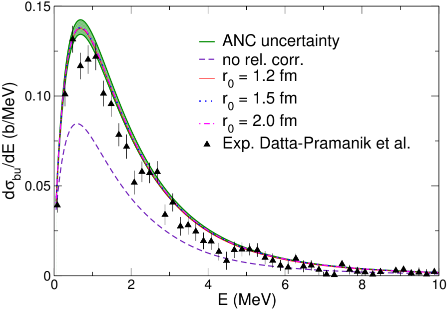
- Wave functions : same asymptotics but different interior
- Excellent agreement with low energy data at forward angle, where little sensitivity to r_0

Coulomb breakup : ^{15}C+Pb→^{14}C+n+Pb

RIKEN : $68A$ MeV



GSI : $605A$ MeV

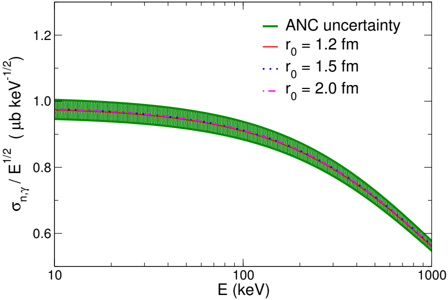


Exp : [Nakamura *et al.* PRC 79, 035805 (2009)]
DEA : [Baye *et al.* PRL 95, 082502 (2005)]

Exp : [Datta Pramanik *et al.* PLB 551, 63 (2003)]
Eikonal : [Moschini, P. C. PLB 790, 367 (2019)]

- All calculations provide very similar results for all r_0 despite the difference in the internal part of the wave function
  ⇒ reaction is peripheral [P.C. & Nunes PRC75, 054609 (2007)] arXiv
- Excellent agreement with data confirms ANC and $\delta_p \approx 0$ [Moschini *et al.* PRC 100, 044615 ('19)] arXiv

Radiative capture ^{14}C(n,γ)^{15}C



E (keV)	$\sigma^{exp}_{n,\gamma}$ (μb)	$\sigma^{th}_{n,\gamma}$ (μb)
23.3	7.1 ± 0.5	5.8 ± 0.2
150	10.7 ± 1.2	10.6 ± 0.3
500	17.0 ± 1.5	15.4 ± 0.4
800	15.8 ± 1.6	16.7 ± 0.5

Exp : [Reifarth *et al.* PRC 77, 015804 (2008)]

Th : [Moschini *et al.* PRC 100, 044615 ('19)] arXiv

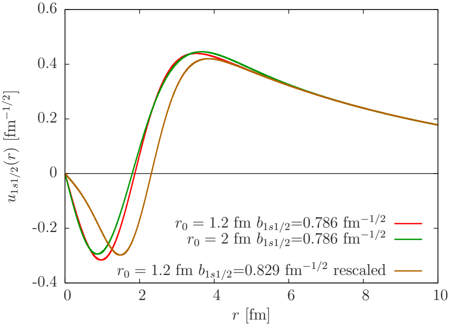
- Insensitive to r_0, because purely peripheral
- $\sigma_{\mathrm{n},\gamma}$ in agreement with *ab initio* prediction
- Good agreement with the data
  but at low energy. . .

Extension of the idea to KO

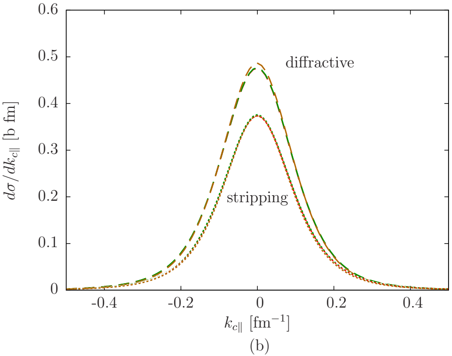
Theoretical analysis of KO : ^{11}Be+C→^{10}Be+X @ $70A$MeV

[Hebborn & P.C. PRC 100, 054607 (2019)] arXiv

Halo-EFT wave functions



KO cross section



- Using NLO Halo-EFT description of ^{11}Be within eikonal model of KO
- Same $d\sigma/dp_{c\|}$ with same ANC ⇒ reaction purely peripheral
- Insensitive to description of continuum ⇒ good probe of ANC

Summary and prospect

- Halo nuclei studied mostly through reactions
- Mechanism of reactions with halo nuclei understood
  How to reliably infer structure information on halos from reactions ?
  Halo EFT : [P.C., Phillips, Hammer PRC 98, 034610 (2018)] arXiv
  Efficient way to include the significant degrees of freedom : ANC, δ_{lj}
- We apply this idea for ^{15}C [Moschini *et al.* PRC 100, 044615 ('19)] arXiv
  Using one Halo-EFT description of ^{15}C, we reproduce
  - transfer ^{14}C(d,p)^{15}C
  - Coulomb breakup (intermediate and high energy)
  - Radiative capture ^{14}C(n,γ)^{15}C
- KO is also purely peripheral [Hebborn, P.C. PRC 100, 054607 ('19)] arXiv
- Future :
  - Analyse existing data on KO
  - Extend to other nuclei (^{31}Ne)
  - Include core excitation in Halo EFT

Thanks to my collaborators

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