Devoping optical potentials from χ_{EFT} NN interactions to describe nuclear reactions involving exotic nuclei

Pierre Capel, Victoria Durant, and Achim Schwenk

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

SFB 1245

TECHNISCHE UNIVERSITÄT DARMSTADT

18 June 2024

Halo Nuclei

Exotic nuclear structures are found far from stability

In particular halo nuclei with peculiar quantal structure :

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

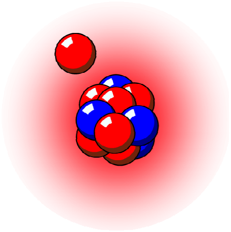


Exhibit large matter radius

due to strongly clusterised structure :

neutrons tunnel far from the core and form a halo

One-neutron halo

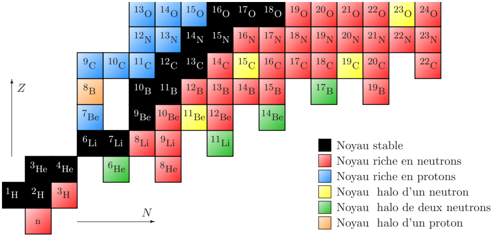
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



Proton halos are possible but less probable : ^{8}B, ^{17}F

Reactions with Halo Nuclei

Halo nuclei are fascinating objects
but difficult to study [$\tau_{1/2}$(^{11}Be)$= 13$ s]
⇒ require indirect techniques, new probes, like reactions :

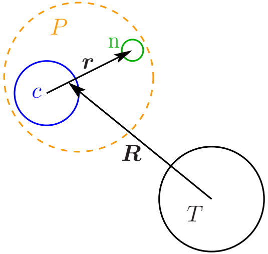
Elastic scattering
Transfer
Knockout
Breakup ≡ dissociation of halo from core
by interaction with target

Need good understanding of the reaction mechanism
(i.e. a good reaction model)
have reliable inputs for the model
(i.e. optical potentials to describe the interactions with target)

Few-Body Model of Reaction

Projectile (P) modelled as a two-body quantum system :
core (c)+loosely bound nucleon (n) described by

$H_0 = T_r + V_{c\mathrm{n}}(\boldsymbol{r})$



$V_{c\mathrm{n}}$ effective interaction
describes the quantum system
with ground state Φ_0

Target T assumed structureless

Interaction with target simulated by optical potentials
$\Rightarrow$ breakup reduces to three-body scattering problem :

$$[T_R + H_0 + V_{cT} + V_{\mathrm{n}T}]\,\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

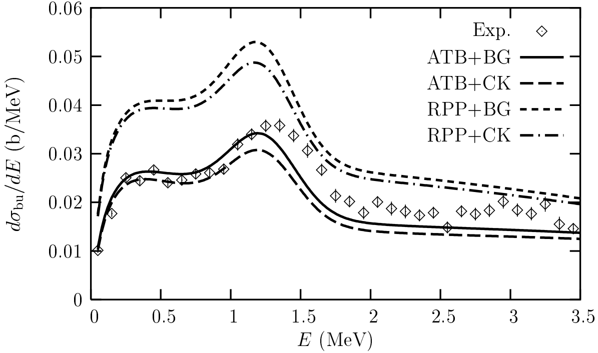
with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0(\boldsymbol{r})$

Significance of Optical Potentials

Breakup of ^{11}Be on C depends on V_{cT} (and slightly on V_{nT})

$$^{11}\mathrm{Be} + {}^{12}\mathrm{C} \rightarrow {}^{10}\mathrm{Be} + \mathrm{n} + {}^{12}\mathrm{C} \text{ @ } 67A\text{MeV}$$

[P.C., Goldstein, Baye, PRC 70, 064605 (2004)]



Exp. : [Fukuda *et al.* PRC 70, 054606 (2004)]

Since the core c is itself exotic, V_{cT} is usually poorly known

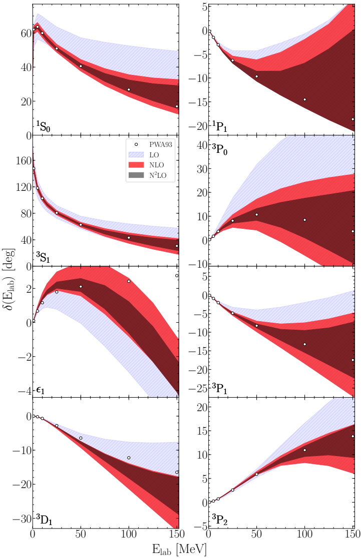
⇒ We build optical potentials by double-folding of χ_{EFT} V_{NN}

Nucleus-Nucleus Interaction

Idea : using a double-folding procedure with accurate NN interactions from χ_{EFT}

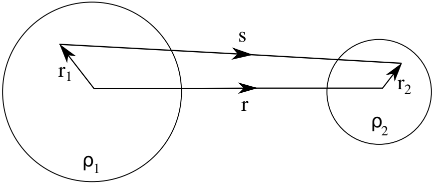
Gezerlis *et al.* have developed local NN interactions up to $\mathrm{N^2LO}$
[PRL 111, 032501 (2013),
PRC 90, 054323 (2014)]

Based on this formalism,
we build a double-folding potential
[Durant *et al.* PLB 782, 668 (2018)]



Double-folding potential : Real Part

We build a double-folding potential at the Hartree-Fock level



$$V_F = V_{\mathrm{D}} + V_{\mathrm{EX}}$$

$$\begin{aligned} V_{\mathrm{D}}(r) &= \int \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)v_{\mathrm{D}}(s)d\boldsymbol{r}_1 d\boldsymbol{r}_2 \\ V_{\mathrm{EX}}(r,E) &= \int \rho_1(\boldsymbol{r}_1,\boldsymbol{r}_2+\boldsymbol{s})\rho_2(\boldsymbol{r}_2,\boldsymbol{r}_1-\boldsymbol{s})v_{\mathrm{EX}}(s)\exp\left[\frac{i\boldsymbol{k}(r)\cdot\boldsymbol{s}}{\mu/m_{\mathrm{N}}}\right]d\boldsymbol{r}_1 d\boldsymbol{r}_2 \\ k^2(r) &= \frac{2\mu}{\hbar^2}\left[E_{\mathrm{c.m.}} - V_{\mathrm{F}}(r,E_{\mathrm{c.m.}}) - V_{\mathrm{Coul}}(r)\right] \end{aligned}$$

⇒ potential built iteratively

[Durant *et al.* PLB 782, 668 (2018)]

Double-folding potential : Imaginary Part

Imaginary part can be taken proportional to real part

$$W(r) = N_W \, V_F(r)$$

with $N_W \simeq 0.5$–1 [Pereira *et al.* PLB 670, 330 (2009)]

or using dispersive relations

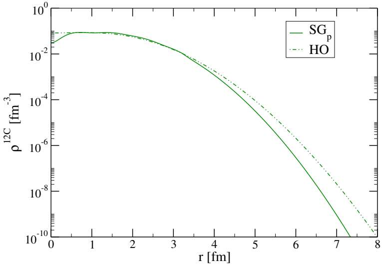
[Durant, PC, Schwenk PRC 102, 014622 (2020)]

$$W(r, E_{\text{c.m.}}) = -\frac{1}{\pi}\mathcal{P}\int_{-\infty}^{+\infty} \frac{V_{\text{Ex}}(r, E)}{E - E_{\text{c.m.}}} dE$$

Nuclear Densities

Use densities from the literature

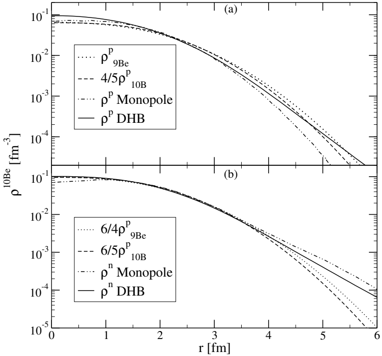
^{12}C



Densities from e scattering

- Sum of Gaussians
- Harmonic Oscillator functions

^{10}Be



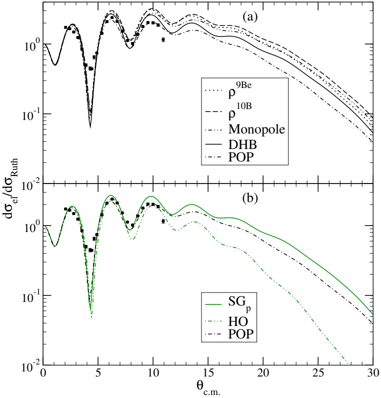
Densities from e scattering on ^{9}Be and ^{10}B

from microscopic calculations

- cluster : [Descouvemont, Itagaki PPTP 2020, 023D02 (2020)]
- DHF : [Chamon *et al.* CPC 267, 108061 (2021)]

^{10}Be Elastic Scattering on ^{12}C @ $E_{\mathrm{Lab}} = 59.4A$MeV

Th : [Durant, PC PRC 106, 044608 (2022)]



Exp : M. Cortina-Gil PhD

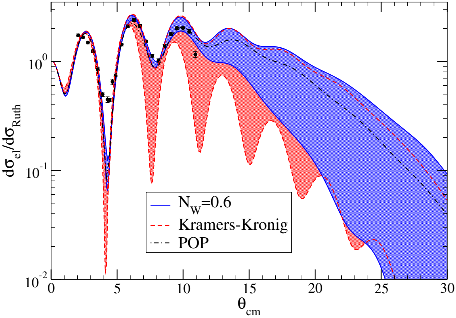
Good agreement with data

Phenomenological Optical Potential works better [Al-Khalili, Tostevin, Brooke PRC 55, R1018 (1997)]

- Little sensitivity to ^{10}Be density
  DHB works best
- Larger sensitivity to C density
  Sum of Gaussian works best

^{10}Be Elastic Scattering on ^{12}C @ $E = 59.4A$MeV

Th : [Durant, PC PRC 106, 044608 (2022)]



Exp : M. Cortina-Gil PhD

Good agreement with data (no fitting parameter)

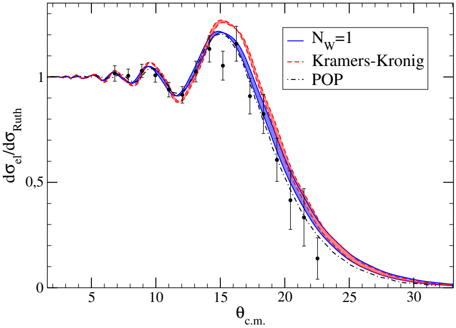
- @ forward angles where Coulomb significant
- @ large angles nuclear dominated

Sensitivity to cutoff R_0 of V_{NN}

- $R_0 = 1.6$ fm is softer ⇒ less absorption
- $R_0 = 1.2$ fm is harder ⇒ more absorptive and more oscillations
- $N_W = 0.6$ is less sensitive to R_0

^{10}Be Elastic Scattering on ^{208}Pb @ $E_{\rm Lab} = 127$ MeV

Th : [Durant, PC PRC 106, 044608 (2022)]



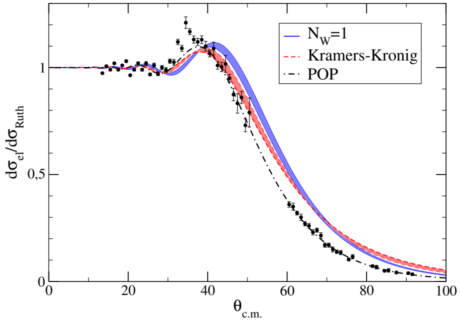
Good agreement with data (no fitting parameter)

- Coulomb dominated
  $\Rightarrow$ less sensitive to nuclear
- $R_0 = 1.6$ and 1.2 fm perform equally well
- $N_W = 1$ slightly better but fitting parameter

Exp : [Duan *et al.* Chin. Phys. C 44, 024001 (2020)]

^{10}Be Elastic Scattering on ^{64}Zn @ $E = 28.3$ MeV

Th : [Durant, PC PRC 106, 044608 (2022)]



Exp : [Di Pietro *et al.* PRC 85, 054607 (2012)]

Fair agreement with data (no fitting parameter)

- Coulomb dominated
  $\Rightarrow$ less sensitive to nuclear
- $R_0 = 1.6$ and 1.2 fm perform equally well
- $N_W = 1$ slightly less good although 1 fitting parameter

Collisions with ^{11}Be

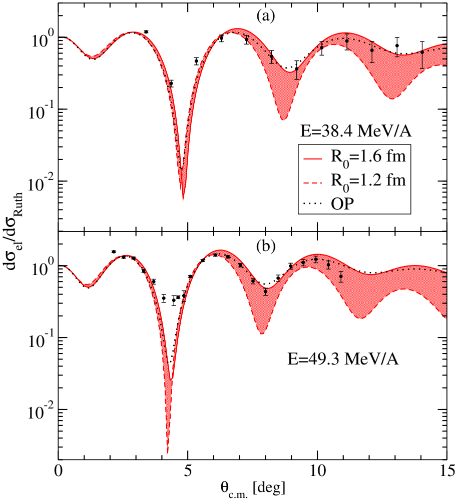
Collision of ^{11}Be on various targets at different energies
analysed in few-body model of reactions
Dynamical Eikonal Approximation (DEA)

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

- ^{11}Be described as ^{10}Be+n
  $V_{c\mathrm{n}}$: Halo-EFT @ NLO
  [PC, Phillips, Hammer PRC 98, 034610 (2018)]
  Parameters fitted on *ab initio* predictions (ANC, δ_s, δ_p...)
  [Calci *et al.* PRL 117, 242501 (2016)]
- $V_{^{10}\mathrm{Be}T}$ built by double folding
- $V_{\mathrm{n}T}$: Koning Delaroche

^{11}Be elastic scattering on C

Th : [Durant, PC in preparation (2024)]



Exp : [Lapoux *et al.* PLB 658, 198 (2008)]

[M. Cortina-Gil PhD]

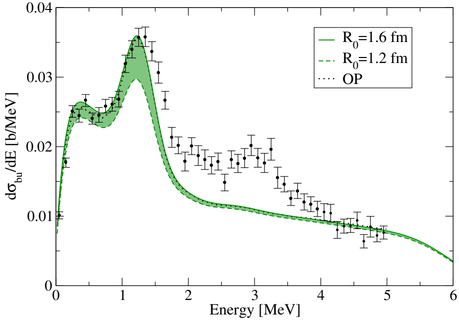
Good agreement with exp.
(no fitting parameter)

- @ forward angles
  where Coulomb significant
- @ large angles
  nuclear dominated
- $R_0 = 1.6$ fm is softer
  $\Rightarrow$ less absorption
  as good as POP
  [Al-Khalili, Tostevin, Brooke
  PRC 55, R1018 (1997)]
- $R_0 = 1.2$ fm is harder
  $\Rightarrow$ more absorptive
  and stronger oscillations

^{11}Be breakup on C @ $67A$MeV

Energy distribution $d\sigma_{\rm bu}/dE$
Excellent agreement with exp. (no fitting parameter in OP)

Th : [Durant, PC in preparation (2024)]

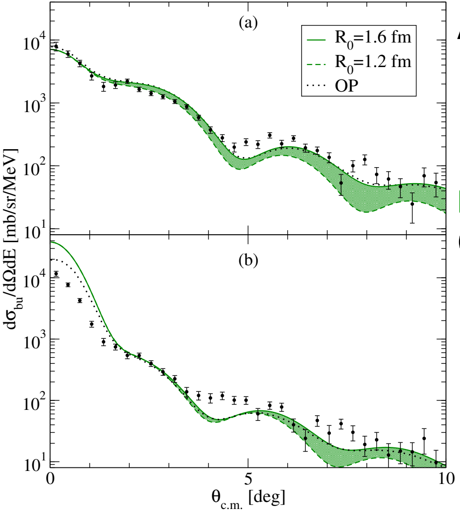


Exp : [Fukuda *et al.* PRC 70, 054606 (2004)]

- reproduces peak @ $E_{5/2^+} = 1.3$ MeV
  V_{3b} simulates ^{10}Be excitation
  [PC, Phillips, Hammer PLB 825, 136847 (2022)]
- missing peak @$E_{3/2^+} = 3$MeV
  $3/2^+$ dominated by ^{10}Be(2^+)
  [Moro, Lay PRL 109, 23250 (2012)]
- $R_0 = 1.6$ fm performs well (less absorption)
- $R_0 = 1.2$ fm too absorptive

^{11}Be breakup on C @ $67A$MeV

Th : [Durant, PC in preparation (2024)]



Angular distributions

- (a) $E_{5/2^+} = 1.3$ MeV
- (b) $E \leq 0.2$ MeV

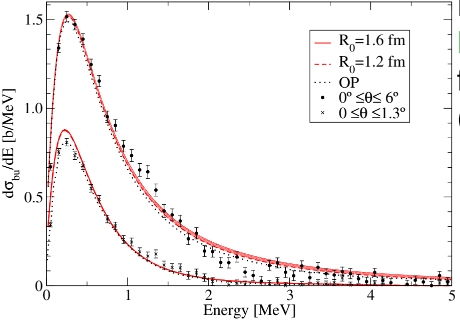
Excellent agreement with exp. (no fitting parameter in OP)

- similar sensitivity as for elastic scattering
- $R_0 = 1.6$ fm performs well (less absorption)
- $R_0 = 1.2$ fm too absorptive

Exp : [Fukuda *et al.* PRC 70, 054606 (2004)]

^{11}Be breakup on Pb @ $69A$MeV

Th : [Durant, PC in preparation (2024)]



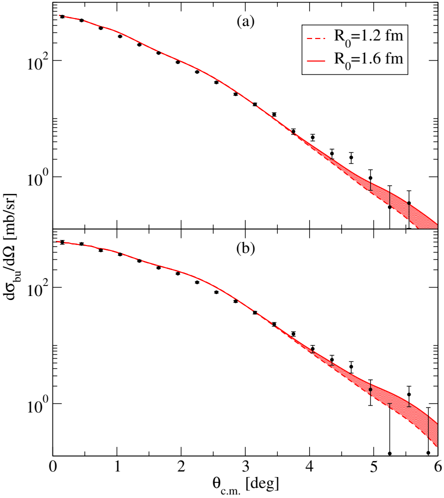
Exp : [Fukuda *et al.* PRC 70, 054606 (2004)]

Energy distributions
Excellent agreement with exp. for both angular cuts
(no fitting parameter in OP)

- Coulomb dominated
  ⇒ less sensitive to nuclear
- $R_0 = 1.6$ and 1.2 fm perform equally well

^{11}Be breakup on Pb @ $69A$MeV

Th : [Durant, PC in preparation (2024)]



Exp : [Fukuda *et al.* PRC 70, 054606 (2004)]

Angular distributions

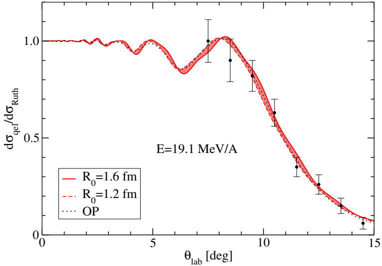
- (a) $E \leq 1$ MeV
- (b) $E \leq 5$ MeV

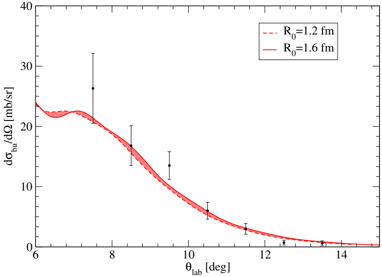
Excellent agreement with exp.
(no fitting parameter in OP)

- Coulomb dominated
  ⇒ less sensitive to nuclear
- $R_0 = 1.6$ and 1.2 fm
  perform equally well

^{11}Be on Pb @ 19*A*MeV

Th : [Durant, PC in preparation (2024)]





Angular distributions for

- Scattering (el. & inel.)
- (inclusive) breakup (n not measured)

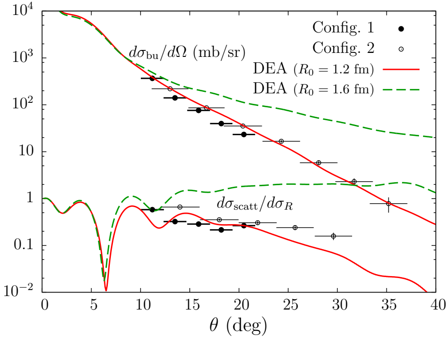
Excellent agreement with exp. (no fitting parameter in OP)

- Coulomb dominated ⇒ less sensitive to nuclear
- $R_0 = 1.6$ and 1.2 fm perform equally well

Exp : [Duan *et al.* PRC 105, 034602 (2022)]

^{11}Be on C @ $22A$MeV

Preliminary data. . .



Exp : [Ota *et al.* in preparation (2024)]

Angular distributions for

- (inclusive) breakup
  (n not measured)
- scattering (el. & inel.)

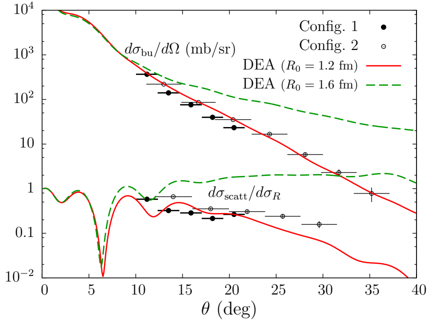
Nuclear dominated
⇒ very sensitive to nuclear int.

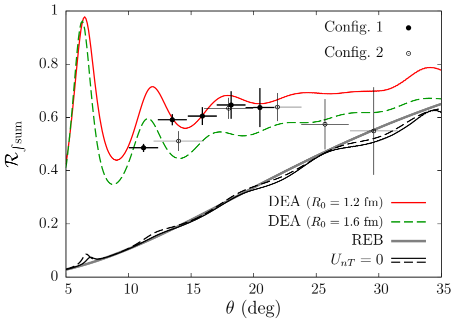
- $R_0 = 1.6$ fm too soft
  ⇒ not absorptive enough
- $R_0 = 1.2$ fm
  performs very well

^{11}Be on C @ 22AMeV

The Ratio Method…

[PC, Johnson, Nunes PLB 705, 112 (2011), PRC 88, 044602 (2013)]





$$\mathcal{R}_{\int \text{sum}} = \frac{\int d\sigma_{\text{bu}}/dEd\Omega \, dE}{d\sigma_{el}/d\Omega + \int d\sigma_{\text{bu}}/dEd\Omega \, dE}$$

- smooth
- independent of V_{cT}

Summary and prospect

- Exotic nuclei studied mostly through reactions
- Optical potentials are necessary inputs
- Optical potentials can be built by double-folding
  - Using $\chi_{\rm EFT}$ $\rm NN$ interactions
  - Densities from literature
  - Good agreement with experiment (no fitting parameter)
    - Scattering of nuclei
    - Reactions of clusterised nuclei (halos)
- Future :
  - include $3\rm N$ forces ?
  - account for non-locality ?

Dream : with the same $\rm NN$ interaction

- Compute densities of core
- Structure of halo nucleus
- Optical potential

Thanks. . .

to you for your attention

and to my collaborators

Victoria Durant

Achim Schwenk
Hans-Werner Hammer

Daniel Phillips

Ron Johnson

Filomena Nunes

Shuya Ota