Uncertainty in nuclear-reaction calculations involving halo nuclei

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1. Introduction
   - Halo nuclei
   - Reaction model
2. Uncertainties in nuclear-reaction modelling
   - in halo-nucleus description
   - solving the problem with Halo-EFT
   - in optical potentials
   - looking for a solution from χEFT N-N interaction
3. Summary

Halo nuclei

Exotic nuclear structures are found far from stability

In particular halo nuclei with
peculiar quantal structure :

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

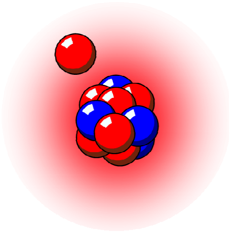


Exhibit large matter radius
due to strongly clusterised structure :
neutrons tunnel far from the core and form a halo

One-neutron halo

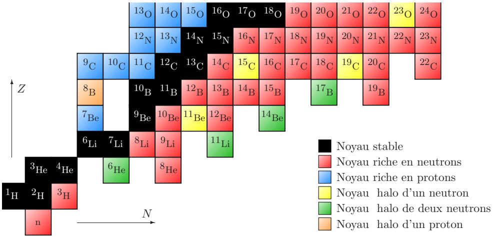
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



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 :

Breakup ≡ dissociation of halo from core
by interaction with target

Need good understanding of the reaction mechanism
(i.e. a good reaction model)
to know to what the probe is sensitive
(i.e. what nuclear-structure information it provides)
have reliable inputs for the model
(i.e. optical potentials to describe the interactions with target)

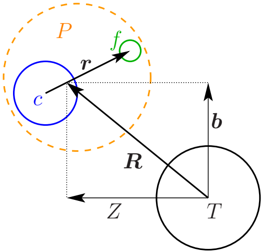
Here I look at the uncertainty related to the last two points
For the former, a precise reaction models is coupled with Halo EFT
For the latter, I do what I can. . .

Reaction model

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

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

V_{cf} effective interaction
describes the projectile structure
with ground state Φ_0



Target T assumed structureless

Interaction with target simulated by optical potentials U_{cT} and U_{fT}
$\Rightarrow$ breakup reduces to three-body scattering problem :

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

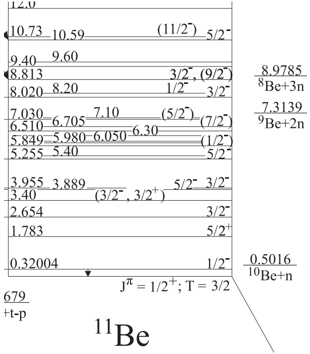
with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0(\boldsymbol{r})$

We use the Dynamical Eikonal Approximation (DEA)
[Baye, P. C., Goldstein, PRL 95, 082502 (2005)]

Sources of uncertainty

- V_{cf}
  - Describes the projectile structure
  - Fitted to external data (binding energy...)
  - Not an observable in the sense of J. Oakley
    but it still has meaning outside the reaction code
- U_{cT} and U_{fT}
  - Optical potentials simulating the c-T and f-T interaction
  - Found in the literature
  - Not observable either
  - Very uncertain
- Numerical parameters
  - Control inputs
  - Value chosen to ensure convergence of numerical scheme

^{11}Be $\equiv$ ^{10}Be $\otimes$ n

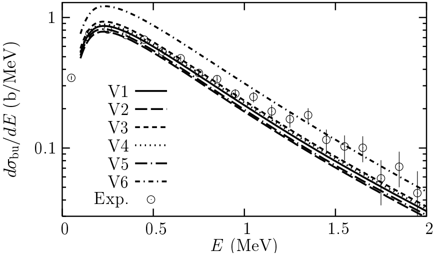


- $\frac{1}{2}^+$ ground state :
  $\epsilon_{\frac{1}{2}^+} = -0.503$ MeV
  In our model, seen as $1s_{\frac{1}{2}}$ neutron bound to ^{10}Be(0^+)
- $\frac{1}{2}^-$ bound excited state :
  $\epsilon_{\frac{1}{2}^-} = -0.184$ MeV
  In our model, seen as $0p_{\frac{1}{2}}$ neutron bound to ^{10}Be(0^+)

Uncertainty in halo-nucleus description

^{11}Be+Pb $\rightarrow$ ^{10}Be+n+Pb @ $69A$MeV

We have used phenomenological V_{cf} with different geometries
Fitted to reproduce ^{11}Be low-energy spectrum



Exp. : [Fukuda *et al.* PRC 70, 054606 (2004)]
Th. : [P.C., Nunes, PRC 73, 014615 (2006)]

$\Rightarrow$ significant variation in $d\sigma_{\rm bu}/dE$

Can we control this uncertainty ?

Halo EFT description of ^{11}Be

Use Halo EFT : clear separation of scales
⇒ provides an expansion parameter (small scale / large scale) upon which the low-energy behaviour is expanded (cf. S. Wesolowski)
[H.-W. Hammer, C. Ji, D. R. Phillips JPG 44, 103002 (2017)]

Use narrow Gaussian potentials : $V_{cf}(r) = V_0\, e^{-\frac{r^2}{2\sigma^2}} + V_2\, r^2 e^{-\frac{r^2}{2\sigma^2}}$

Fit V_0 and V_2 to reproduce known experimental values
(and *ab initio* predictions [A. Calci *et al.* PRL 117, 242501 (2016)])

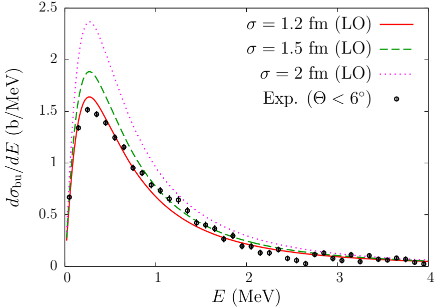
σ = 1.2, 1.5 or 2 fm is a parameter used to evaluate the sensitivity of the calculations to short-range physics

@LO : $V_2 = 0$ & V_0 adjusted to fit $\epsilon_{1/2^+}$ in s wave ($V_{cf} = 0\ \ \forall l > 0$)
@NLO : V_2 & V_0 adjusted in s and p waves to fit $\epsilon_{1/2^+}$ & $\epsilon_{1/2^-}$,
ANCs and $\delta_{p3/2}$ (*ab initio* predictions) ($V_{cf} = 0\ \ \forall l > 1$)

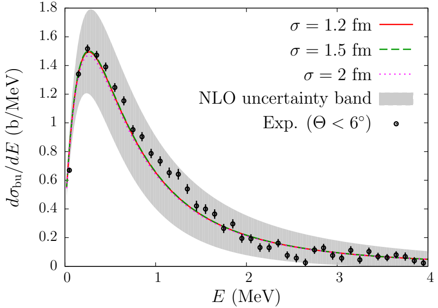
[PC, D. R. Phillips, H.-W. Hammer PRC 98, 034610 (2018)]

LO & NLO analyses of ^{11}Be+Pb→^{10}Be+n+Pb @ 69AMeV

LO breakup cross section



NLO breakup cross section



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

Th. : [PC, D. R. Phillips, H.-W. Hammer PRC 98, 034610 (2018)]

- LO : Large differences due to differences in ANC
- NLO : All calculations identical (ANCs & δ_p fitted)
  Excellent agreement with data

⇒ Halo EFT shows which degrees of freedom matter
i.e. which structure observables are probed in reaction
provides an estimate of the uncertainty due to truncation

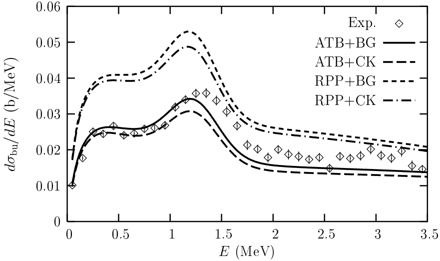
Uncertainty in optical potentials

The reaction model requires optical potentials U_{cT} and U_{fT}

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

How can one estimate the uncertainty related to these interactions ?

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



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

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

⇒ that uncertainty can be huge

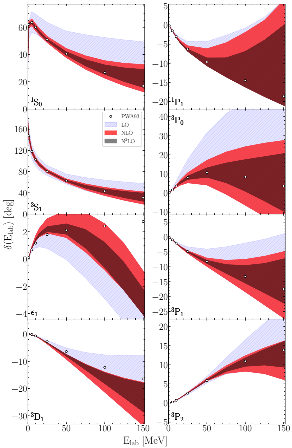
Problem : reaction calculations are expensive ⇒ use emulator ?

Idea : build our own optical potential

Idea : using a double-folding procedure
with accurate NN interactions from χEFT

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

Based on this formalism,
build a double-folding potential V_F

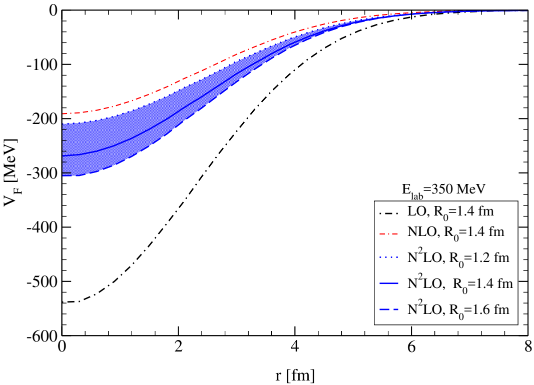


^{16}O-^{16}O potential

Potential built

- at different orders
- for different cutoffs

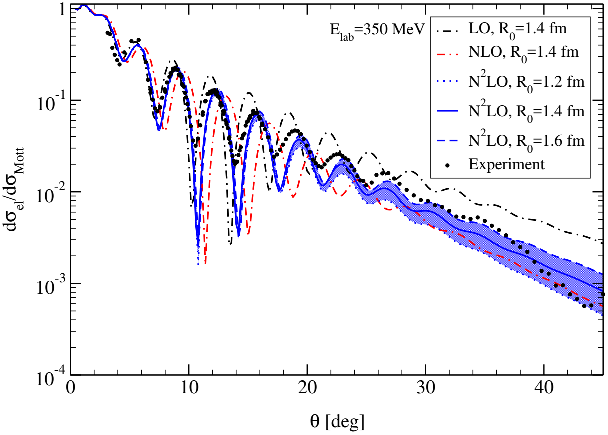
Calculations by V. Durant
PLB 782, 668 (2018)



The imaginary part is assumed proportional to V_F

$$U_F(r) = (1 + N_W\ i)\ \ V_F(r) \qquad \text{with } N_W = 0.6 - 0.8$$

^{16}O-^{16}O elastic scattering @350 MeV



- Fair agreement with experiment (no fitting parameter)
- Systematic order-by-order behaviour
- Small uncertainty related to the cutoff
- Larger uncertainty to N_W

Summary and prospect

- Halo nuclei studied mostly through reactions
- Mechanism of reactions with halo nuclei understood
- Halo EFT
  - emulates *ab initio* structure calculations in reaction codes
  - shows which degrees of freedom matter
  - provides an estimate of the uncertainty
- Optical potentials have huge impacts on reaction calculations
  - Could we estimate this uncertainty using an emulator ?
  - Can be built by double-folding from χEFT NN interactions

Thanks. . .

to you for your attention

and to my collaborators

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