Recent advances in the description of reactions involving exotic nuclei

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2 August 2019
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In Memoriam...
1 Introduction: halo nuclei

2 Few-body description of reaction

3 Developments beyond few-body
   - Microscopic Cluster Model
   - Core excitation

4 Back to the few-body model: Halo EFT

5 Summary
Halo nuclei
Halo nuclei are found far from stability
Exhibit peculiar quantal structure:

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

With large matter radius
due to strongly clusterised structure:
nucleons tunnel far from the core and form a diffuse halo

One-neutron halo
$^{11}\text{Be} \equiv ^{10}\text{Be} + \text{n}$
$^{15}\text{C} \equiv ^{14}\text{C} + \text{n}$

Two-neutron halo
$^{6}\text{He} \equiv ^{4}\text{He} + \text{n} + \text{n}$
$^{11}\text{Li} \equiv ^{9}\text{Li} + \text{n} + \text{n}$

This exotic structure challenges nuclear-structure models

[see talks of P. Navrátil and J. Casal]
Ab initio description of $^{11}$Be

Halo nuclei are now accessible to ab initio models [see talk of P. Navrátil]
Calci et al. have computed $^{11}$Be within NCSMC: [PRL 117, 242501 (2016)]

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**FIG. 2.** NCSMC spectrum of $^{11}$Be with respect to the $n + ^{10}$Be threshold. Dashed black lines indicate the energies of the $^{10}$Be states. Light boxes indicate resonance widths. Experimental energies are taken from Refs. [1,51].

- $\frac{1}{2}^+$ ground state:
  - $\epsilon_{\frac{1}{2}^+} = -0.500$ MeV
  - $C_{\frac{1}{2}^+} = 0.786$ fm$^{-1/2}$
  - $S_{1s_{\frac{1}{2}}} = 0.90$

- $\frac{1}{2}^-$ bound excited state:
  - $\epsilon_{\frac{1}{2}^-} = -0.184$ MeV
  - $C_{\frac{1}{2}^-} = 0.129$ fm$^{-1/2}$
  - $S_{0p_{\frac{1}{2}}} = 0.85$
Reactions with halo nuclei

Halo nuclei are fascinating objects but difficult to study \([\tau_{1/2}(^{11}\text{Be}) = 13 \text{ s}]\)

How can one probe their structure?
⇒ require indirect techniques, 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. an accurate theoretical description of reaction coupled to a realistic model of projectile

(Some) halo nuclei can now be calculated **ab initio**
What has been recently achieved in nuclear-reactions theory?
**Few-body framework**

Usually, projectile \((P)\) modelled as a two-body quantum system: core \((c)\) + loosely bound neutron \((n)\) described by

\[
H_0 = T_r + V_{cn}(r)
\]

\(V_{cn}\) effective interaction describes the quantum system with ground state \(\Phi_0\)

Target \(T\) seen as structureless

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

\[
[T_R + H_0 + V_{cT} + V_{nT}] \Psi(r, R) = E_T \Psi(r, R)
\]

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

Various methods have been developed

Microscopic description of the projectile

Idea: consider an microscopic cluster model of the projectile:

\[ H_0 = \sum_{i=1}^{A} t_i + \sum_{i<j=1}^{A} v_{ij} \]

[Descouvement & Hussein, PRL 111, 082701 (2013)]

- Good agreement with data (no fitting parameter)
- Significant effect of breakup channel especially on heavy targets and for loosely bound projectiles
- Extended to 2-n halo nucleus \(^6\)He [Descouvement PRC 93, 034616]
- So far limited to elastic scattering
Including the core excitation

Idea: consider that the core can be in an excited state:

\[ H_0 = H_c(\xi_c) + T_r + V_{cn}(\xi_c, r) \]

[Summers, Nunes & Thompson PRC 73, 031603 (2006)]
[lay, de Diego, Crespo, Moro, Arias & Johnson PRC 94, 021602 (2016)]

\[ ^{11}\text{Be} \equiv ^{10}\text{Be}(0^+) \otimes n(1s_{1/2}) + ^{10}\text{Be}(2^+) \otimes n(0d_{5/2}) + \ldots \]

Core excitation in structure of the projectile & during reaction process

\[ ^{19}\text{C} + p \rightarrow ^{18}\text{C} + n + p \text{ @ } 70\text{AMeV} \]

\[ ^{11}\text{Be} + p \rightarrow ^{10}\text{Be} + n + p \text{ @ } 63.7\text{AMeV} \]

- Good agreement with data (no fitting parameter)
- Significant influence in resonant breakup [cf. Moro’s talk on Monday]
Halo EFT
Replace core-\( n \) 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


Use narrow Gaussian potentials

\[
V_{lj}(r) = V_{0}^{lj} e^{-\frac{r^2}{2\sigma^2}} + V_{2}^{lj} r^2 e^{-\frac{r^2}{2\sigma^2}}
\]

@ NLO fit \( V_{0}^{lj} \) and \( V_{2}^{lj} \) to reproduce
- \( \epsilon_{nlj} \) (known experimentally)
- \( C_{nlj} \) (from \textit{ab initio} calculation of Calci \textit{et al.} [PRL 117, 242501 (2016)])

\( \sigma = 1.2, 1.5 \) or 2 fm is a parameter used to evaluate the sensitivity of the calculations to the short-range physics
NLO analysis of $^{11}$Be breakup on Pb and C @ 70A\text{MeV}

$^{11}$Be+Pb$\to^{10}$Be+n+Pb

$^{11}$Be+C$\to^{10}$Be+n+C

Exp. (Θ $< 6^\circ$)

NLO uncertainty band

σ = 2 fm

σ = 1.5 fm

σ = 1.2 fm

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

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

- All calculations ($\sigma$) provide identical results ⇒ reaction is peripheral
- Pb : Excellent agreement with data ⇒ confirms ab initio predictions
- C : General shape of experimental cross section well reproduced
  But breakup strength missing at the $5/2^+$ and $3/2^+$ resonances
  ⇒ Need to go beyond NLO and constrain $d$ continuum
- Same results obtained at 520A\text{MeV} [see L. Moschini’s talk 27341]
In nuclear breakup, **resonances** play significant role
⇒ Need to go beyond NLO  [P.C., Phillips & Hammer PRC 98, 034610]

Still need additional breakup strength : missing $^{10}\text{Be}(2^+)$
[de Diego, Crespo & Moro, PRC 95, 044611 (2017)]

Adding an **effective 3-b force** solves the issue
Confirming the role of the excitation of the core in the reaction process
[cf. A. Moro’s talk on Monday]
Summary and prospect

- **Halo nuclei** can now be studied *ab initio*
- They are mostly studied through *reactions*
  - Recently there has been some new developments:
  - Use of a *microscopic cluster model* of the projectile
    - **Good** agreement with data (no fitting parameter)
    - So far limited to *elastic scattering*
  - Include *core excitation*
    - Improve the projectile description and the reaction dynamics
    - Significant in *resonant breakup*
  - Halo EFT description of the projectile
    - Includes nuclear-structure observable *order by order*
    - Effective *3-b forces* can simulate core excitation
- These developments enable us to infer more information from nuclear-reaction data and test *ab initio* predictions
  - Stay tuned...
Thanks to my collaborators

Hans-Werner Hammer
Achim Schwenk

Daniel Phillips

Laura Moschini
Chloë Hebborn
Daniel Baye
Gerald Goldstein