Interfaces between structure and reactions for rare isotopes and nuclear astrophysics

The effect of core excitation if the scattering of two-body halo nuclei

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Outline:

1. Benchmark calculations for CDCC vs Faddeev.
   - $d+^{12}\text{C}$ at 56 MeV: elastic scattering and exclusive breakup.

2. Application to the scattering of two-body halo nuclei.
   - $^{19}\text{C}+p$ at 70 MeV: CDCC vs Faddeev
   - Effect of core excitation.
Part I: The effect of core excitation in the scattering of weakly bound nuclei

(work done with A. Deltuva, E. Cravo, F.M. Nunes and A. Fonseca)
Example: $^{11}\text{Be} + p \rightarrow (^{10}\text{Be} + n) + p$

- Three-body wf expanded in projectile ($^{11}\text{Be}$) internal states
- Breakup treated as single-particle excitations to $n + ^{10}\text{Be}$ continuum
- Continuum is discretized in energy bins and truncated in energy and angular momentum
- Provides elastic and elastic breakup, but not transfer.
The exact solution of a three-body scattering problem is formally given by the Faddeev equations.

The CDCC method can be derived as an approximated solution of the Faddeev equations in a truncated model space (Austern, Yahirō, Kawai, PRL 63 (1989) 2649).

For light systems, Faddeev equations can be now solved, so a comparison with CDCC is possible.
Benchmark Calculations for CDCC vs Faddeev

- **Systems:**
  - $d+^{12}C \ @ \ E_d=56 \ MeV$
  - $d+^{58}Ni \ @ \ E_d=80 \ MeV$

- **Faddeev:** Alt, Grass, Sandas (AGS) formulation
  - Solves Faddeev eqs in momentum space
  - Coulomb included by means of screening procedure
CDCC vs Faddeev: elastic scattering

\[ d^{+12}C \text{ at 56 MeV} \]

\[ d^{+58}\text{Ni at 80 MeV} \]

\[ \frac{d\sigma}{d\Omega}/\frac{d\sigma_R}{d\Omega} \]

Exp. (56 MeV)
Exp. (80.0 MeV)
Exp. (79.0 MeV)
Faddeev
CDCC-BU

CDCC and Faddeev are in perfect agreement!
CDCC vs Faddeev: exclusive breakup x-sections

Observables for exclusive breakup: proton angular distribution

\[ \frac{d^4}{d\Omega_n d\Omega_p} \text{ (mb/sr}^2) \]

\[ ^{12}\text{C}(d,pn)^{12}\text{C} @ E_d=56 \text{ MeV} \]

\[ \theta_n=15^\circ \]

Matsuoka (1982)

Faddeev

CDCC

Application of the CDCC formalism: $d^+^{12}C$

Observables for exclusive breakup: proton energy distribution for fixed $\theta_n$ and $\theta_p$
Part II: The effect of core excitation in the scattering of weakly bound nuclei

(work done with R. Crespo)
**Exclusive breakup measurements of halo nuclei**

Example: $^{19}$C+p at RIKEN (Satou et al., PLB660 (2008) 320)

Excitation energy can be reconstructed from core-neutron coincidences *(invariant mass method)*
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Excitation energy can be reconstructed from core-neutron coincidences (invariant mass method)
Microscopic DWBA calculations, support a $1/2^+ \rightarrow 5/2^+$ mechanism Satou et al., PLB660 (2008) 320.
$^{19}\text{C spectrum}$

$^{18}\text{C+n}$

$\begin{align*}
5/2^+_2 & \quad \text{1.46 MeV} \\
5/2^+_1 & \quad \text{0.59 MeV}
\end{align*}$
\[ 19\text{C} \text{+p within a three-body reaction model} \]

- \(^{19}\text{C}\) states treated as s.p. configurations with the \(^{18}\text{C}\) in the g.s.

\[ ^{19}\text{C}(1/2^+) = |^{18}\text{C}(0^+) \otimes \nu 2s_{1/2}\rangle \]
\[ ^{19}\text{C}(5/2^+) = |^{18}\text{C}(0^+) \otimes \nu 1d_{5/2}\rangle \]

- Reaction mechanism \(\Rightarrow\) CDCC and Faddeev (AGS) methods.

- Interactions:
  - \(n - ^{18}\text{C}\): WS potential
  - \(p - ^{18}\text{C}\): global optical potential (Watson et al, PR182 (1969) 182)
  - \(p - n\): central Gaussian potential reproducing the deuteron gs and \(^3S_1\) phase-shifts
Faddeev and CDCC provide consistent results

The calculations reproduce the magnitude, but not the shape.

- Pair interactions?
- Structure model?
Faddeev calculations with the realistic CD-Bonn interaction shows that the p-n Gaussian potential is too simple
Faddeev calculations with the realistic CD-Bonn interaction shows that the p-n Gaussian potential is too simple.

A simple single-particle excitation mechanism cannot explain the data!
Shell-model spectroscopic factors (WBP) for $^{19}\text{C} = ^{18}\text{C} + n$

<table>
<thead>
<tr>
<th>Core state</th>
<th>$2s_{1/2}$</th>
<th>$1d_{5/2}$</th>
<th>$1d_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_1$</td>
<td>0.58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$2^+_1$</td>
<td>-</td>
<td>0.47</td>
<td>0.0085</td>
</tr>
<tr>
<td>$0^+_2$</td>
<td>0.32</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$2^+_2$</td>
<td>-</td>
<td>0.018</td>
<td>0.086</td>
</tr>
<tr>
<td>$3^+_1$</td>
<td>-</td>
<td>1.52</td>
<td>-</td>
</tr>
<tr>
<td>(… )</td>
<td>(… )</td>
<td>(… )</td>
<td>(… )</td>
</tr>
</tbody>
</table>

$^{19}\text{C}(1/2^+_1)$ g.s.

<table>
<thead>
<tr>
<th>Core state</th>
<th>$1d_{5/2}$</th>
<th>$1d_{3/2}$</th>
<th>$2s_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_1$</td>
<td>0.035</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$2^+_1$</td>
<td>0.29</td>
<td>0.0087</td>
<td>0.61</td>
</tr>
<tr>
<td>$0^+_2$</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$2^+_2$</td>
<td>0.37</td>
<td>0.0053</td>
<td>0.0077</td>
</tr>
<tr>
<td>$3^+_1$</td>
<td>0.094</td>
<td>0.11</td>
<td>0.37</td>
</tr>
<tr>
<td>(… )</td>
<td>(… )</td>
<td>(… )</td>
<td>(… )</td>
</tr>
</tbody>
</table>

$^{19}\text{C}(5/2^+_2)$ resonance
Shell-model calculations predict a significant admixture of core excitation in both states.

These core excited admixtures should be taken into account in the structure model and in the reaction model.
Shell-model calculations predict a significant admixture of core excitation in both states.

These core excited admixtures should be taken into account in the structure model and in the reaction model.

- Faddeev: core-excitation not included in present implementations.
- CDCC: Summers et al, PRC74 (2006) 014606 Extended version of CDCC with core excitation (XCDCC)
DWBA amplitude with core excitation

- DWBA amplitude with core degrees of freedom:

\[
A^{J,M,J',M'} = \langle \chi_f^{(-)}(\vec{R}) \Psi_{J',M'}(\vec{r},\vec{\xi})|\hat{V}_T|\chi_i^{(+)}(\vec{R}) \Psi_{J,M}(\vec{r},\vec{\xi}) \rangle
\]

- Transition operator

\[
\hat{V}_T = V_{vt}(\vec{R}_{vt}) + V_{ct}(\vec{R}_{ct},\vec{\xi}) - U_{aux}(\vec{R})
\]
Rotor model for the $^{19}$C nucleus

- $^{18}$C+n states calculated in a deformed potential:

$$V_{vc}(r, \vec{\xi}) \simeq V^{(0)}_{vc}(r) + \sum_{\lambda>0,\mu} V^{(\lambda)}_{ct}(r) Y_{\lambda\mu}(\hat{r}) Y^*_{\lambda\mu}(\hat{\xi})$$

- Internal (projectile) states:

$$\Psi_{JM}(\vec{r}, \vec{\xi}) = \sum_{\ell,j,I} R^{J}_{\ell,j,I}(r) \left[ [Y_{\ell}(\hat{r}) \otimes \chi_{s}]_{j} \otimes \Phi_{I}(\vec{\xi}) \right]_{JM}$$

| State               | $|0^+ \otimes s_{1/2}\rangle$ | $|0^+ \otimes d_{5/2}\rangle$ | $|2^+ \otimes s_{1/2}\rangle$ | $|2^+ \otimes d_{5/2}\rangle$ |
|---------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Ground state        | 73%                           | -                            | -                             | 24%                           |
| $5/2^+$ resonance    | -                             | 26%                          | 74%                           | $\ll$                         |
Scattering amplitude

- Multipole expansion for the core-target potential

\[ V_{ct}(\vec{R}_{ct}, \vec{\xi}) \simeq V_{ct}^{(0)}(R_{ct}) + V_{ct}^{(\lambda)}(R_{ct})Y_{\lambda \mu}(\hat{r}_{ct})Y_{\lambda \mu}^*(\hat{\xi}) \]

- Scattering amplitude

\[ A_{if} = A_{if}^{(val)} + A_{if}^{(core)} \]

- Valence excitation amplitude:

\[ A_{if}^{(val)} = \langle \chi_f^{-}(\vec{R})\Psi_{J' M'}(\vec{r}, \vec{\xi}) | V_{vc}(\vec{r}) + V_{ct}^{(0)}(R_{ct}) - U_{aux}(\vec{R}) | \chi_i^{(+)}(\vec{R})\Psi_{JM}(\vec{R}, \vec{\xi}) \rangle \]

- Core excitation amplitude:

\[ A_{if}^{(core)} = \langle \chi_f^{-}(\vec{R})\Psi_{J' M'}^f(\vec{r}, \vec{\xi}) | V_{ct}^{(\lambda)}(R_{ct})Y_{\lambda \mu}(\hat{r}_{ct})Y_{\lambda \mu}^*(\hat{\xi}) | \chi_i^{(+)}(\vec{R})\Psi_{JM}^i(\vec{r}, \vec{\xi}) \rangle \]
Evaluation of the core contribution (no-recoil)

- Consider the free scattering amplitude for a core-target inelastic scattering:

\[
A_{ct}(IM_I, IM'_I) = \langle \chi(-)(\vec{R}_{ct})\Phi_{I'M'_I}(\hat{\xi})|V_{ct}(R_{ct})Y_{\lambda\mu}(\hat{R}_{ct})Y^*_{\lambda\mu}(\hat{\xi})|\Phi_{IM_I}(\hat{\xi})\chi(+)\rangle(\vec{R}_{ct})
\]

- In the no-recoil approximation ($\vec{R}_{ct} \approx \vec{R}$):

\[
A^{(\text{core})}_{ij}(JM \rightarrow J'M') = \frac{\langle J'M'|JM\lambda\mu \rangle}{\langle I'M'_c|IM_c\lambda\mu \rangle} \sum_{\alpha,\alpha'} \langle R_{\alpha'}|R_{\alpha} \rangle G^{(\lambda)}_{\alpha,\alpha'} A_{ct}(IM_c \rightarrow I'M'_c)
\]

\[
\alpha \equiv \{\ell, s, j, I\}
\]

\[
G^{(\lambda)}_{\alpha,\alpha'} \equiv \delta_{j,j'}(-1)^{\lambda+j+j'+I}\hat{J}\hat{J}' \left\{ \begin{array}{ccc} J' & J & \lambda \\ I & I' & j \end{array} \right\}
\]
Application to $^{19}\text{C}+\text{p} \rightarrow ^{18}\text{C} + \text{n} + \text{p}$

- $^{18}\text{C}$ treated in a rotor model with $I = 0^+, 2^+$ states
- $^{18}\text{C+n}$ and $^{18}\text{C+p}$ calculated with a deformed potential
- Breakup calculated in first order (Born approximation)
- Recoil effects ignored.
The core-excitation mechanism gives a significant contribution to the cross section.

improved description of the shape.
Conclusions

- For elastic and (exclusive) breakup observables, the CDCC method has proven to be a very accurate approximation to the full Faddeev equations.

- For the scattering of a core+neutron system on a proton target, the breakup is very sensitive to the p-n interaction ⇒ needs to be incorporated in existing implementations of the CDCC method.

- Core excitation plays a very important role in the resonant breakup of halo nuclei with deformed core.
Application to $^{19}\text{C}+p \rightarrow ^{18}\text{C} + n + p$

$p(^{19}\text{C}, ^{19}\text{C}^*)p@70\text{ Mev/nucleon}$

$\frac{d\sigma}{d\Omega}\text{c.m.} (\text{mb/sr})$ vs $\theta_{\text{c.m.}}$ (deg)

Satou et al.
- No-recoil model (1 step)
- XCDCC: 1-step
- XCDCC: all orders
Core excitation in $^{11}$Be+p

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From Elekes et al, PLB 614 (2005) 174

C spectrum from shell-model calculations
Benchmark calculations for $^{11}\text{Be}+p$

- Can we understand the $^{11}\text{Be}+p$ elastic and transfer $(p,d)$ data within a three-body model $(p+n^{10}\text{Be})$?

- DBU vs TC: what approach is more appropriate for inclusive breakup cross sections?
CDCC versus Faddeev: $^{11}\text{Be} + p$ elastic scattering

- Good agreement between Faddeev and DBU (CDCC)
- Significant disagreement with data! ⇒ interactions?
CDCC vs Faddeev: transfer to bound states

$^{11}\text{Be} + p \rightarrow ^{10}\text{Be} + d$

\[
\frac{d\sigma}{d\Omega} \text{ (mb/sr)}
\]

\[\theta_{\text{c.m.}} \text{ (deg)}\]

GANIL data (E=35.3 MeV/u)

Faddeev

CDCC-TR*