Some recent advances in few-body reaction models and their application to reactions with loosely bound nuclei

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Outline

1. Many-body versus few-body models

2. Inclusion of core excitations in reactions
   - Static and dynamic core excitations
   - Implementation in DWBA and XCDCC frameworks
   - Application to breakup and transfer reactions.

3. A 3-body model for inelastic breakup (?)
Why do we use few-body models in reactions?

**Microscopic approach**

- Start from (effective) NN interaction.
- Complicated many-body scattering problem

**Few-body approach**

- Inert clusters (core excitations no explicitly included)
- Projectile described with few-body model
- Phenomenological cluster-target interactions
- More transparent link between reaction and structure
Beyond the strict few-body picture: the effect of core excitation

- Standard few-body models (DWBA, CC, CDCC, Glauber, etc) usually rely on simple single-particle/cluster configurations.
- Dynamical effects arising from cluster excitations are (hopefully) embedded in the effective pairwise interactions.
Beyond the strict few-body picture: the effect of core excitation

Standard few-body models (DWBA, CC, CDCC, Glauber, etc) usually rely on simple single-particle/cluster configurations.

Dynamical effects arising from cluster excitations are (hopefully) embedded in the effective pairwise interactions.

To what extent can we ignore the dynamics of the core?
Core excitation in structure: $^{11}\text{Be}$ case

- **Strict single-particle model:**

\[
|^{11}\text{Be}(1/2^+)\rangle = |^{10}\text{Be}(0^+) \otimes \nu 2s_{1/2}\rangle \\
|^{11}\text{Be}(1/2^-)\rangle = |^{10}\text{Be}(0^+) \otimes \nu 1p_{1/2}\rangle \\
\ldots
\]
Core excitation in structure: $^{11}$Be case

- **Strict single-particle model:**
  
  \[ |^{11}\text{Be}(1/2^+)\rangle = |^{10}\text{Be}(0^+) \otimes \nu \text{2s}_{1/2} \rangle \]
  
  \[ |^{11}\text{Be}(1/2^-)\rangle = |^{10}\text{Be}(0^+) \otimes \nu \text{1p}_{1/2} \rangle \]

- **Core-excited model:** (Shell-Model, PRM, PVM, etc)
  
  \[ |^{11}\text{Be}(1/2^+)\rangle = a |^{10}\text{Be}(0^+) \otimes \nu \text{2s}_{1/2} \rangle + b |^{10}\text{Be}(2^+) \otimes \nu \text{1d}_{5/2} \rangle + \ldots \]

\[ |^{11}\text{Be}(1/2^+)\rangle = a \]

\[ + \]

\[ b \]

\[ \}

\[ \}

\[ a, b = \text{spectroscopic amplitudes} \]
Core excitation in reactions: *frozen-halo* picture

\[ \Psi_{JM}(\vec{r}, \xi) = \left[ \varphi_{J,j}^{(l)}(\vec{r}) \otimes \Phi_I(\xi) \right]_{JM} \]

\[ \varphi_{l,j}^{(l)}(\vec{r}) = \text{valence particle wavefunction} \]

\[ \Phi_I(\xi) = \text{core wavefunction (frozen)} \]

\[ {^{10}\text{Be}(l) \rightarrow ^{11}\text{Be}(J)} \]

\[ \begin{array}{c|c}
3/2^+_1 & 3.41 \text{ MeV} \\
5/2^+_1 & 1.78 \text{ MeV} \\
1/2^-_1 & 0.32 \text{ MeV} \\
1/2^+_1 & 1/2 \text{ Be} \\
\end{array} \]

\[ ^{10}\text{Be}(0^+) \times 1d_{3/2} \]

\[ ^{10}\text{Be}(0^+) \times 1d_{5/2} \]

\[ ^{10}\text{Be}(0^+) \times 1p_{1/2} \]

\[ ^{10}\text{Be}(0^+) \times 2s_{1/2} \]

\[ ^{11}\text{Be} \]

\[ \text{Pb} \]

\[ ^{10}\text{Be} \]
Core excitation in reactions: *frozen-halo* picture

\[ \Psi_{JM}(\vec{r}, \xi) = [\varphi_{\ell,j}(\vec{r}) \otimes \Phi_I(\xi)]_{JM} \]

- \( \varphi_{\ell,j}(\vec{r}) = \) valence particle wavefunction
- \( \Phi_I(\xi) = \) core wavefunction (*frozen*)

\[ 10^\text{Be}(0^+) \times 1d_{3/2} \]

\[ 10^\text{Be}(0^+) \times 1d_{5/2} \]

\[ 10^\text{Be}(0^+) \times 1p_{1/2} \]

\[ 10^\text{Be}(0^+) \times 2s_{1/2} \]

\[ 11^\text{Be}(l) \]

\[ 10^\text{Be}(J) \]

\[ 10^\text{Be} \]

\[ 11^\text{Be} \]

\[ \text{Pb} \]

\[ n \]
Core excitation mechanism in breakup

\[ \Psi_{JM}(\vec{r}, \xi) = \sum_{\ell,j,I} \left[ \varphi_{\ell,j,I}^I(\vec{r}) \otimes \Phi_I(\xi) \right]_{JM} \]

\begin{align*}
9/2^+ & \quad 3.41 \text{ MeV} \\
5/2^+ & \quad 1.78 \text{ MeV} \\
1/2^- & \quad 0.32 \text{ MeV} \\
1/2^+ & \quad 11^Be
\end{align*}

\[ \begin{array}{l}
e^{[\,^{10}Be(0^+) \times 1d_{3/2} \,]} + f^{\left[\,^{10}Be(2^+) \times 2s_{1/2} \,]} \\
c^{[\,^{10}Be(0^+) \times 1d_{5/2} \,]} + d^{\left[\,^{10}Be(2^+) \times 1d_{5/2} \,]} \\
a^{[\,^{10}Be(0^+) \times 2s_{1/2} \,]} + b^{\left[\,^{10}Be(2^+) \times 1d_{5/2} \,]} \\
\end{array} \]
Core excitation mechanism in breakup

\[ \Psi_{JM}(\vec{r}, \xi) = \sum_{\ell,j,I} [\phi_{\ell,j,I}^{J}(\vec{r}) \otimes \Phi_{I}(\xi)]_{JM} \]

**Dynamic core excitation contributes to the inelastic/breakup probabilities**
The Standard DWBA approach for breakup involves the interaction of a projectile-target system described by the wave functions $\Psi_{JM}^i$ and $\Psi_{J'M'}^f$. The transition probability $T_{if}^{JM,J'M'}$ is given by:

$$T_{if}^{JM,J'M'} = \langle \chi_f^(-)(\vec{R})\Psi_{J'M'}^f(\vec{r})|V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct})|\chi_i^+(\vec{R})\Psi_{JM}^i(\vec{r})\rangle$$

- $\chi_f^(-)(\vec{R})$, $\chi_i^+(\vec{R})$ describe the projectile-target relative motion.
- $\Psi_{JM}^i(\vec{r})$, $\Psi_{J'M'}^f(\vec{r})$ are projectile states (inert core).

The wave functions are expressed as:

$$\Psi_{JM}^i(\vec{r},\xi) = [\varphi^J_{\ell,j}(\vec{r}) \otimes \Phi_I(\xi)]_{JM}; \quad \Psi_{J'M'}^f(\vec{r},\xi) = [\varphi^{J'}_{\ell',j'}(\vec{r}) \otimes \Phi_I(\xi)]_{JM}$$
Standard DWBA approach for breakup

\[ T_{if}^{J^M,J'M'} = \langle \chi_f^{(-)}(\vec{R}) \Psi_{J'M'}^f(\vec{r}) | V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct}) | \chi_i^{(+)}(\vec{R}) \Psi_{JM}^i(\vec{r}) \rangle \]

- \( \chi_f^{(-)}(\vec{R}) \), \( \chi_i^{(+)}(\vec{R}) \) describe projectile-target relative motion
- \( \Psi_{JM}^i(\vec{r}) \), \( \Psi_{J'M'}^f(\vec{r}) \) projectile states (inert core):

\[
\Psi_{JM}^i(\vec{r}, \xi) = [\varphi_{\ell,j}^J(\vec{r}) \otimes \Phi_I(\xi)]_{JM} ; \quad \Psi_{J'M'}^f(\vec{r}, \xi) = [\varphi_{\ell',j'}^{J'}(\vec{r}) \otimes \Phi_I(\xi)]_{JM}
\]

Possible excitations of the core or target ignored
Extended DWBA model including core excitation (XDWBA)

\[ T_{if}^{JM,J'M'} = \langle \chi_i^{(+)}(\vec{R}) \Psi_{JM}^f(\vec{r}, \xi) | V_{vt}(\vec{r}_{vt}) + V_{ct}(\vec{r}_{ct}, \xi) | \chi_f^{(-)}(\vec{R}) \Psi_{JM'}^i(\vec{r}, \xi) \rangle \]

Core excitation affects in two ways:

1. \( \Psi_{JM}(\vec{r}, \xi) = \) projectile states \( \Rightarrow \) “static” deformation effect.

\[
\Psi_{JM}(\vec{r}, \xi) = \sum_{\ell,j,I} \left[ \varphi_{\ell,j,I}^J(\vec{r}) \otimes \Phi_I(\xi) \right]_{JM}
\]

2. \( V_{ct}(\vec{r}_{ct}, \xi) \) can modify the core state \( \Rightarrow \) dynamic core excitation.
Reminder of few-body CC (or CDCC)

**Example:** $^7\text{Li}$ scattering in a three-body model

- **Hamiltonian:** $H = T_R + h_r + V_\alpha(r_\alpha) + V_t(r_t)$
- **Model wavefunction:**
  $$\Psi(R, r) = \phi_{gs}(r)\chi_0(R) + \sum_{n>0} \phi_n(r)\chi_n(R)$$
- **Coupled equations:** $[H - E]\Psi(R, r) = 0$

\[
[E - \varepsilon_n - T_R - V_{n,n}(R)]\chi_n(R) = \sum_{n' \neq n} V_{n,n'}(R)\chi_{n'}(R)
\]

- **Transition potentials:**
  $$V_{n,n'}(R) = \int d r \phi_{n'}^*(r) [V_\alpha(r_\alpha) + V_t(r_t)] \phi_n(r)$$
Full CDCC calculations with core excitation

❌ DWBA only valid for intermediate and high energies.
❌ DWBA does not provide elastics (relies on OMP).
Full CDCC calculations with core excitation

- DWBA only valid for intermediate and high energies.
- DWBA does not provide elastics (relies on OMP).

☞ In more general situations, one needs to use a full CC formalism (CDCC)

- **Standard CDCC** ⇒ use coupling potentials:

\[
V_{\alpha;\alpha'}(R) = \langle \Psi_{J'M'}^{\alpha'}(\vec{r}) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}) | \Psi_J^\alpha(\vec{r}) \rangle
\]

- **Extended CDCC (XCDCC)** ⇒ use generalized coupling potentials

\[
V_{\alpha;\alpha'}(R) = \langle \Psi_{J'M'}^{\alpha'}(\vec{r}, \xi) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}, \xi) | \Psi_J^\alpha(\vec{r}, \xi) \rangle
\]

☞ \(\Psi_J^\alpha(\vec{r}, \xi)\): multi-channel bound & unbound wfs.

- *R. de Diego et al, PRC 89, 064609 (2014)* (THO pseudo-states)
Valence-core and core-target interactions in a simple collective model

- **Valence-core**: reproduces projectile properties (separation energy, resonances, etc).

\[ V_{vc}(\vec{r}, \xi) \approx V_{vc}^{(0)}(r) - \delta_2 \frac{dV_{vc}^{(0)}}{dr} Y_{20}(\hat{r}) \quad (\delta_2 = \beta_2 R_0) \]

- **Core-target**: reproduces elastic and inelastic core+target scattering.

\[ V_{ct}(\vec{r}_{ct}, \xi) \approx V_{ct}^{(0)}(r_{ct}) - \delta_2 \frac{dV_{ct}^{(0)}}{dr} Y_{20}(\hat{r}_{ct}) \]

...but more sophisticated models might be used!
Application to Coulomb breakup: $^{11}\text{Be}+^{208}\text{Pb}$ at 69 MeV/u

Exclusive measurement: $^{11}\text{Be}+^{208}\text{Pb} \rightarrow ^{10}\text{Be} + \text{n} + ^{208}\text{Pb}$

**Common assumptions:**
- Pure E1 excitation mechanism for small $\theta$.
- One-step breakup mechanism.
- Nuclear effects (e.g. absorption) simulated with cutoff in impact parameter.
- Exp. $B(E1)$ compared with a single-particle model $\Rightarrow$ SF / ANC
XCDCC calculations for $^{11}\text{Be} + ^{208}\text{Pb}$ at 69 MeV/u

XCDCC calculations with THO pseudo-states and PRM model of $^{11}\text{Be}$.

- XCDCC ⇒ breakup treated to all orders.
- Absorption and nuclear effects accounted for by $n + ^{208}\text{Pb}$ and $^{10}\text{Be} + ^{208}\text{Pb}$ OMP
- Confirm dominance of $E1 \ (1/2^-, 3/2^-)$ for $\theta \ll 1$
- Dynamic core excitation small, but mixing of core states important.
Coulomb barrier breakup at low energies: $^{11}\text{Be}+^{197}\text{Au}$ at 31.9 MeV ($\sim0.8V_b$)

**Experiment:** TRIUMF (Aarhus - LNS/INFN - Colorado - GANIL - Gothenburg -Huelva - Louisiana - Madrid - St. Mary - Sevilla - TRIUMF - York collaboration)

**Breakup probability:**

$$P_{bu}(\theta) = \frac{\sigma_{bu}(\theta)}{\sigma_{bu}(\theta) + \sigma_{qel}(\theta)} = \frac{N_{bu}(\theta)}{N_{bu}(\theta) + N_{qel}(\theta)}$$

**Inelastic probability (requires $\gamma$-rays coincidences):**

$$P_{inel}(\theta) = \frac{\sigma_{inel}(\theta)}{\sigma_{el}(\theta) + \sigma_{inel}(\theta) + \sigma_{bu}(\theta)} = \frac{N_{inel}(\theta)}{N_{el}(\theta) + N_{inel}(\theta) + N_{bu}(\theta)}$$
The single-particle model reproduces the continuum $B(E1)$ with $S = 1$, but overestimates the $B(E1)$ for the bound state by a factor of $\sim 2$.

The PRM model reproduces the bound and unbound $B(E1)$ strengths.
Application to $^{11}$Be+$^{197}$Au at 31.9 MeV (∼0.8 $V_b$)

EPM calculations (with experimental B(E1)'s):
- Reproduce forward-angle inelastic probability (large angles affected by nuclear effects)
- Underestimate breakup probability (not a simple 1-step E1 mechanism!)
Application to $^{11}\text{Be}+^{197}\text{Au}$ at 31.9 MeV ($\sim 0.8 \text{ } V_b$)

**Standard CDCC calculations:**

- Reproduces well breakup but...
- underestimate elastics and overestimate inelastic probabilities.
XCDCC calculations:

- XCDCC accounts well for elastics, inelastic and breakup.
- Dynamic core excitation ($^{10}$Be excitation) small (dominance of E1 couplings).
- Multistep breakup important (eg.: $^{11}$Be(g.s.) → $3/2^-$ → $1/2^+$).
- Some underestimation remains for breakup (convergence?, non-elastic breakup?)
Application to $^{11}\text{Be}+^{197}\text{Au}$ at 31.9 MeV ($\sim 0.8$ $V_b$)

XCDCC calculations:

- XCDCC accounts well for elastics, inelastic and breakup.
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- Some underestimation remains for breakup (convergence?, non-elastic breakup?)
Application of CDCC to nuclear breakup

1\over2^+_1, 5\over2^+_1, 1\over2^-_1, 1\over2^+_1

11\text{Be}

3.41 \text{MeV} \n
1.78 \text{MeV} \n
0.50 \text{MeV} \n
0.32 \text{MeV}
Application to $^{11}\text{Be}$: spectroscopic factors

| State                  | Model       | $|0^+ \otimes (\ell s)j\rangle|$ | $|2^+ \otimes s_{1/2}\rangle|$ | $|2^+ \otimes d_{5/2}\rangle|$ |
|------------------------|-------------|---------------------------------|---------------------------------|---------------------------------|
| $1/2^+$ (g.s.)         | PRM         | 0.857                           | –                               | 0.121                           |
|                        | SM (WBT)    | 0.76                            | –                               | 0.184                           |
| $5/2^+$ (1.78 MeV)     | PRM         | 0.702                           | 0.177                           | 0.112                           |
|                        | SM (WBT)    | 0.682                           | 0.177                           | 0.095                           |
| $3/2^+$ (3.41 MeV)     | PRM         | 0.165                           | 0.737                           | 0.081                           |
|                        | SM (WBT)    | 0.068                           | 0.534                           | 0.167                           |

- $1/2^+_1$, $5/2^+_1 \Rightarrow$ dominant $^{10}\text{Be}(\text{gs}) \otimes nlj$ configuration
- $3/2^+_1 \Rightarrow$ dominant $^{10}\text{Be}(2^+) \otimes 2s_{1/2}$ configuration
## Application to $^{11}$Be: spectroscopic factors

| State                  | Model    | $|0^+ \otimes (\ell s)j\rangle|$ | $|2^+ \otimes s_{1/2}\rangle|$ | $|2^+ \otimes d_{5/2}\rangle|$ |
|------------------------|----------|---------------------------------|---------------------------------|---------------------------------|
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| $5/2^+$ (1.78 MeV)     | PRM      | 0.702                           | 0.177                           | 0.112                           |
|                        | SM(WBT)  | 0.682                           | 0.177                           | 0.095                           |
| $3/2^+$ (3.41 MeV)     | PRM      | 0.165                           | 0.737                           | 0.081                           |
|                        | SM(WBT)  | 0.068                           | 0.534                           | 0.167                           |

- $1/2_1^+, 5/2_1^+ \Rightarrow$ dominant $^{10}$Be(gs) $\otimes nlj$ configuration
- $3/2_1^+ \Rightarrow$ dominant $^{10}$Be($2^+$) $\otimes 2s_{1/2}$ configuration

$\text{\textit{Dynamic core excitation effects expected for the excitation of the 3/2}^+ \text{ resonance.}}$
Application to $p(^{11}\text{Be},p')$ at 64 MeV/u

Data: *Shrivastava et al, PLB596 (2004) 54* (MSU)

- $E_{\text{rel}}=0–2.5$ MeV contains $5/2^+$ resonance (expected single-particle mechanism)
- $E_{\text{rel}}=2.5–5$ MeV contains $3/2^+$ resonance (expected core excitation mechanism)
Application to p($^{11}\text{Be}, p'$) at 64 MeV/u

Data: Shrivastava et al, PLB596 (2004) 54 (MSU)

Core-excitation gives a large contribution to nuclear breakup!
(A.M.M. and R. Crespo, PRC 85, 054613 (2012); R.de Diego et al, PRC 89, 064609 (2014))
Application to $^{11}\text{Be} + ^{12}\text{C}$ resonant breakup

RIKEN: *Fukuda et al, PRC70 (2004), 054606*
Application to $^{11}\text{Be} + ^{12}\text{C}$ resonant breakup

RIKEN: *Fukuda et al, PRC70 (2004), 054606*

☞ Angular distribution of $5/2^+$ and $3/2^+$ resonances extracted by background subtraction.
Neither the valence nor core excitation alone describe the shape of the data

- 5/2\(^+\) x-section dominated by s.p. excitation
- 3/2\(^+\) x-section dominated by core excitation mechanism

*A.M.M. and J.A. Lay, PRL109, 232502 (2012)*
Neither the valence nor core excitation alone describe the shape of the data

- $5/2^+$ x-section dominated by s.p. excitation
- $3/2^+$ x-section dominated by core excitation mechanism

Absolute magnitude overestimated by $\sim 40\%$ (?)

_A.M.M. and J.A. Lay, PRL109, 232502 (2012)_
Dynamic core excitation effects in transfer reactions
Core excitations in transfer; the \((d, p)\) case

DWBA transfer amplitude with core excitations for \(d + t \rightarrow p + (t + n)\):

\[
T_{d,p}^{\text{post}} = \langle \chi_p^{(-)}(\vec{R}')\psi_B(\vec{r}', \xi) | V_{pn}(\vec{r}) + U_{pt}(\vec{r}_p, \xi) - U_{pB}(R') | \chi_d^{(+)}(\vec{R})\psi_d(\vec{r})\psi_t(\xi) \rangle
\]

Three kinds of core excitations may be present:

1. Mixing of configurations in the composite B (structure effects)
2. Excitations occurring previous/after transfer (coupled-channels dynamical effects)
3. Core transitions \(U_{pt}(\vec{r}_p, \xi)\) (prompt dynamical effects)
Core excitations in transfer; the \((d, p)\) case

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\]

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☞ Effects 1, 2 are well-known and studied, but 3 has been historically ignored.
Core excitation in transfer: $^1\text{H}(^{11}\text{Be},^{10}\text{Be})^2\text{H}$ example

Fortier et al, PLB461, 22 (1999)

Transfer experiments provide information on the amount of core excitation

$$|^{11}\text{Be}\rangle = a |^{10}\text{Be}(0^+) \otimes v2s_{1/2}\rangle + b |^{10}\text{Be}(2^+) \otimes v1d_{5/2}\rangle + \ldots$$

In DWBA:

$$\sigma(0^+) \propto |a|^2; \quad \sigma(2^+) \propto |b|^2$$
Core excitations effects are negligible for $^{11}$Be ($\sim$3\%) and modest for $^{31}$Ne ($\sim$10\%).

The transfer processes imposes more restrictive conditions due to the required overlap between the initial and final functions in different mass partitions and the transition potential.

Non-local transfer form-factors associated to the $Q = 2$ part of $U_{ab}$ are smaller and concentrate at shorter distances, as compared to those of $Q = 0$. 
Application of CDCC to inelastic breakup
Non-elastic breakup:

- Breakup accompanied by target or fragment excitation.
- Breakup followed by absorption (transfer, fusion) of any of the fragments.

(by J.A. Tostevin)
Formal expression for non-elastic breakup (NEBU)

- Inclusive breakup:
  \[ a(= b + x) + A \rightarrow b + \text{anything} \]

- Inclusive differential cross section:
  \[ \sigma_{inc}^b = \sigma_{EBU}^b + \sigma_{NEBU}^b \]

- Elastic + non-elastic breakup contribution to inclusive breakup:
  \[ a(= b + x) + A \rightarrow b + c (= x + A*) \]

\[
\frac{d^2\sigma}{d\Omega_b E_b} = \frac{2\pi}{\hbar v_a} \rho(E_b) \sum_c |\langle \chi_{b}^{(-)} \psi_{xA}^{c,(-)} | V_{bx} + V_{bA} - U_{bA} | \psi^{(+)} \rangle|^2 \delta(E - E_b - E_c)
\]

- \( \psi_{xA}^{c,(-)} \) wavefunctions for \( c = x + A \) states
- \( \psi^{(+)} \) exact many-body wavefunction
Non-elastic breakup:

\[
\frac{d\sigma_{\text{NEBU}}}{d\Omega_b dE_b} = -\frac{2}{v_a} \langle \varphi_x | W_{xA} | \varphi_x \rangle
\]

\[\text{☞ } \varphi_x(r_{xA}) \text{ is the } x\text{-particle WF following breakup:}\]

\[
[K_x + U_{xA} - E_x] \varphi_x(r_x) = \langle \chi_b^{(-)} | V_{bx} | \Psi_{xb}^{3b(+)} \rangle \approx \langle \chi_b^{(-)} | V_{bx} | \chi_a^{(+)} \phi_a(r_{bx}) \rangle
\]

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**J. Lei (PhD thesis)**

(also Pampus et al, NPA311 (1978)141)
$^6\text{Li} + ^{209}\text{Bi} \rightarrow \alpha + \text{anything}$

Interplay of Structure and Dynamics in Heavy Ion Collisions, Trento May 2015  
A. M. Moro  
Universidad de Sevilla
Conclusions

- Current few-body reaction frameworks rely on *inert* cluster approximations.

- We have studied the effect of core excitation in the scattering of halo nuclei (core+n), within DWBA and full CC frameworks and found that:
  - For **nuclear breakup** both the core-excited admixtures in projectile wfs and the dynamic core excitation are essential for an accurate interpretation of the data.
  - For **Coulomb dissociation** (heavy targets, small angles) dynamic core excitation is small but the core-excited admixtures important for describing absolute normalization (spectroscopic factors, B(E1), etc)
  - For **transfer** reactions, the effects are in general small but increase as the core excitation energy decreases.

- These effects should be studied in other processes: knockout, QFS, etc
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  - For transfer reactions, the effects are in general small but increase as the core excitation energy decreases.

- These effects should be studied in other processes: knockout, QFS, etc.

☞ “Everything should be made as simple as possible, but not simpler”
List of collaborators

- Raquel Crespo, Raúl de Diego, Arnoldas Deltuva (Lisbon, Portugal)

- Mario Gómez-Ramos, José Miguel Arias, Joaquín Gómez-Camacho (Univ. of Sevilla, Spain).

- José Antonio Lay (INFN / Univ. di Padova)

- Ron Johnson (Univ. of Surrey, UK).