Core excitations and non-elastic breakup in reactions induced by weakly bound nuclei

Antonio M. Moro

University of Seville (Spain)

Three-body systems in reactions with rare isotopes, ECT*, Trento, Oct 2016
1. Few-body reduction of the many-body problem
2. Core excitation effects
3. Inclusive breakup
4. Conclusions
Few-body reduction of the many-body problem

**Microscopic approach**
- Start from (effective) NN interaction
- Complicated many-body scattering problem
- Fragments degrees of freedom included microscopically

**Few-body approach**
- Projectile described with few-body model
- Inert clusters (cluster excitations not explicitly included)
- Phenomenological cluster-target interactions
Inclusion of **target excitations**, eg. $d + A \rightarrow p + n + A^*$


2. Inclusion of **core excitations** in the projectile (eg. $^{11}\text{Be}=^{10}\text{Be} + n$).

- **Michigan/Surrey (bins)**: Summers *et al*, PRC74, 014606 (2006)
- **Seville (pseudo-states)**: R. de Diego *et al*, PRC 89, 064609 (2014)

3. Use of **microscopic projectile** WFs (microscopic CDCC):

- **Brussels**: Descouvemont and Hussein, PRL 111, 082701 (2013)
How do core excitations affect the breakup of weakly-bound nuclei?

Core excitations will affect:

1. the **structure** of the projectile ⇒ core-excited admixtures

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

2. the **dynamics** ⇒ collective excitations of the \(^{10}\text{Be}\) during the collision compete with halo (single-particle) excitations.

⇒ Both effects have been recently implemented in an extended version of of the CDCC formalism (CDCC): Summers et al, PRC74 (2006) 014606, R. de Diego et al, PRC 89, 064609 (2014)
How do core excitations affect the breakup of weakly-bound nuclei?

Core excitations will affect:

1. **the structure** of the projectile $\Rightarrow$ core-excited admixtures

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

2. **the dynamics** $\Rightarrow$ collective excitations of the $^{10}\text{Be}$ during the collision compete with halo (single-particle) excitations.

$\Rightarrow$ Both effects have been recently implemented in an extended version of the CDCC formalism (CDCC): Summers et al, PRC74 (2006) 014606, R. de Diego et al, PRC 89, 064609 (2014)
Extending CDCC to include core excitations

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

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

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

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

- \(\psi_{JM}(\vec{r}, \xi)\): projectile WFs involving core-excited admixtures (structure).

- \(V_{ct}(r_{ct}, \xi)\): non-central potential allowing for core excitations/de-excitations (dynamic core excitation).

- **Summers et al, PRC74 (2006) 014606** (bins)

- **R. de Diego et al, PRC 89, 064609 (2014)** (THO pseudo-states)
Evidence of *dynamical* core excitations in p$^{(11}\text{Be},p')$ at 64 MeV/u (MSU)

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)

⇒ Dynamic core excitations gives additional (and significant!) contributions to breakup
Dominance of dynamical core excitations in $p^{(19}C,^{18}C+n)p$ resonant breakup

Satou et al, PLB660 (2008) 320 (RIKEN)
Dominance of *dynamical* core excitations in \( p(^{19}C, ^{18}C+n)p \) resonant breakup

Satou et al, PLB660 (2008) 320 (RIKEN)

The core-excitation mechanism gives the dominant contribution to the cross section
Effective model 3-body Hamiltonian with target excitation:

\[ H = H_{pn}(r) + H_{\text{tar}}(\xi_t) + \hat{T}_R + U_{nA}(r_{nA}, \xi_t) + U_{pA}(r_{pA}, \xi_t), \]
Three-body observables from XCDCC calculations

\[
T^{ls;J_0}_{\mu\sigma;M_0}(\vec{k}_l, \vec{K}) = \langle \phi^{(-)}_{k_l;\mu\sigma} e^{iK \cdot R} | U | \psi_{J_0,M_0} \rangle 
\approx \sum_{i,J',M'} \langle \phi^{(-)}_{k_l;\mu\sigma} | \psi_{i,J',M'} \rangle \langle \psi_{i,J',M'} e^{iK \cdot R} | U | \psi^{CDCC}_{J_0,M_0} \rangle
\]
Three-body observables from XCDCC calculations

\[
T_{\mu;J_0;M_0}(\vec{k}_I, \vec{K}) = \langle \phi_{k_I I; \mu \sigma; s \sigma} \rangle \mathcal{N} \mid U \mid \Psi_{J_0, M_0} \rangle \\
\approx \sum_{i, J', M'} \langle \phi_{k_I I; \mu \sigma; s \sigma} \mid \Psi_{i, J', M'} \rangle \langle \Psi_{i, J', M'} \mathcal{N} \mid U \mid \Psi^{\text{CDCC}}_{J_0, M_0} \rangle
\]

Two-body (n-core relative energy) observable

![Graph showing the distribution of energy and reaction cross-sections for \(^{11}\text{Be} + p\) at 63.7 MeV/nucleon. The graph includes data from XCDCC calculations for \(^{10}\text{Be} (0^+ + 2^+)\) and \(^{10}\text{Be} (2^+)\), as well as a comparison with no DCE.]
Three-body observables from XCDCC calculations

\[ T_{I\mu;J_0;M_0}(\vec{k}_I, \vec{K}) = \langle \phi_{-}^{(-)}_{k_I;I\mu;S\sigma} e^{i\vec{K}\cdot\vec{R}} | U | \Psi_{J_0, M_0} \rangle \]

\[ \approx \sum_{i, J', M'} \langle \phi_{k_I;I\mu;S\sigma}^{(-)} | \Psi_{i;J', M'} \rangle \langle \Psi_{i;J', M'} e^{i\vec{K}\cdot\vec{R}} | U | \Psi_{CDCC}^{J_0, M_0} \rangle \]
Core excitations in $^{11}$Be+$^{64}$Zn at 28 MeV

The problem of inclusive breakup
For a reaction of the form \((b + x) + A \rightarrow b + \text{anything}\)

\[
\sigma_b = \sigma_{EBU} + \sigma_{NEB} + \sigma_{CN}
\]
Evaluation of the inclusive breakup

For a reaction of the form \((b + x) + A \rightarrow b + \text{anything}\)

\[ \sigma_b = \sigma_{EBU} + \sigma_{NEB} + \sigma_{CN} \]
Why studying inclusive breakup?

- **Surrogate reactions** at low energies to extract neutron-induced cross sections.
  
  E.g.: $d + A \rightarrow p + B^*$ surrogate for $A(n, f)$

- Understanding of large “singles” yields in inclusive breakup of weakly-bound nuclei.
  
  E.g.: $^6,^7\text{Li} + A \rightarrow \alpha + X$, $^6\text{He} + A \rightarrow \alpha + X$

- Evaluation of **Incomplete fusion**, which is part of the NEB cross section.

- **Knockout reactions** at intermediate energies (dominated by NEB)
Evidence of NEB contributions in inclusive \((^6\text{Li}, \alpha X)\)

Santra et al, PRC85,014612(2008)
Evidence of NEB contributions in inclusive \((^6\text{Li},\alpha X)\)

Santra et al, PRC85,014612(2008)
Evidence of NEB contributions in inclusive $^{209}$Bi($^6$Li,$\alpha$)X

Elastic scattering

(3b-CDCC requires reduced d+$^{209}$Bi absorption → Ogata’s talk)
Evidence of NEB contributions in inclusive $^{209}$Bi($^{6}$Li,$\alpha$)X

Elastic scattering

Inclusive $\alpha$'s

(3b-CDCC requires reduced d+$^{209}$Bi absorption → Ogata’s talk)
Explicit evaluation of inclusive breakup

- Inclusive breakup:
  \[(b + x) + A \rightarrow b + (x + A)^*\]

- Inclusive differential cross section: \(\sigma_{b}^{BU} = \sigma_{b}^{EBU} + \sigma_{b}^{NEB}\)

- Post-form expression for inclusive breakup:
  \[
  \frac{d^2\sigma}{d\Omega_b dE_b} = \frac{2\pi}{\hbar v_a} \rho(E_b) \sum_c |\langle \chi_b(-) \psi_{xA}^{c,(-)} | V_{bx} | \psi^{(+)} \rangle|^2 \delta(E - E_b - E^c)
  \]

  - \(\psi_{xA}^{c,(-)}\) wavefunctions for \(c \equiv x + A\) states
  - \(\psi^{(+)}\) exact scattering wavefunction

*Inclusion of all relevant \(c = x + A\) channels is not feasible in general ⇒ use closed-form models*
Searching in the eighties for inclusive breakup models

- **Baur & co**: DWBA sum-rule with surface approximation.

- **Hussein & McVoy**: extraction of singles cross section combining the spectator model with sum rule over final states.

- **Ichimura, Austern, Vincent (IAV)**: Post-form DWBA.

- **Udagawa, Tamura (UT)**: prior-form DWBA.

> Most of these theories have fallen into disuse and should be revisited.
Searching in the eighties for inclusive breakup models

- **Baur & co**: DWBA sum-rule with surface approximation.

- **Hussein & McVoy**: extraction of singles cross section combining the spectator model with sum rule over final states.

- **Ichimura, Austern, Vincent (IAV)**: Post-form DWBA.

- **Udagawa, Tamura (UT)**: prior-form DWBA.

⚠️ *Most of these theories have fallen into disuse and should be revisited*
Treat $b$ particle as spectator $\Rightarrow \chi_b^{(-)}(\vec{k}_b, \vec{r}_b)$

Model Hamiltonian (still many-body for $x + A$):

$$H = K_b + V_{bx} + U_{bA}(\vec{r}_{bA}) + K_x + H_A(\xi) + V_{xA}(\xi, \vec{r}_x),$$

$x - A$ wave function projected on given final $b$ state:

$$Z_x^{(b)}(\xi, \vec{r}_x) \equiv \langle \chi_b^{(-)}(\vec{k}_b) | \psi \rangle = \left[ E^+ - E_b - H_B \right]^{-1} \langle \chi_b^{(-)} | V_{\text{post}} | \psi \rangle$$

$V_{\text{post}} \approx V_{bx}$
Define projector onto target g.s. \((A_{g.s.})\): \(P = |\phi_A^{(0)}\rangle\langle \phi_A^{(0)}|\)

3-body reduction: \(PZ_x^{(b)}(\xi, r_x) = \varphi_x^{(0)}(r_x)\phi_A^{(0)}(\xi)\)

\[
[K_x + U_{xA} - E_x] \varphi_x^{(0)}(r_x) = (\chi_b^{(-)}| V_{bx} | \psi_{3b}^{(+)}\rangle
\]

\(\psi_{3b}^{(+)}\) = three-body scattering wave function (DWBA, CDCC, Faddeev...)

\(U_{xA}\) = optical model potential operator.

The asymptotics of \(\varphi_x^{(0)}(r_x)\) gives ONLY the EBU part.

\(\sigma_b^{\text{NEB}}\) is the flux loss ("absorption") in the \(x + A_{gs}\) channel:

\[
\frac{d\sigma_b^{\text{NEB}}}{d\Omega_b dE_b} = -\frac{2}{\hbar v_a} \rho_b(E_b) \varphi_x^{(0)}| W_{xA} | \varphi_x^{(0)}\rangle
\]

(optical theorem)
Ignore internal spins $\Rightarrow \vec{l}_a + \vec{l}_{bx} = \vec{l}_b + \vec{l}_x$

DWBA: $\psi_{3b}^{(+)} \approx \chi_d^{(+)}(R) \phi_d(r_{bx})$

$\chi_b^{(-)}(\vec{k}_b, \vec{r}_b)$ distorted waves averaged in energy bins.

Details in:
J. Lei and A.M.M., PRC 92, 044616 (2015); PRC 92, 061602 (2015)
J. Lei, PhD thesis. University of Seville (available online)
Application of IAV model to deuteron inclusive breakup

- EBU → CDCC (Fresco).
- NBU → post-form IAV model.

Data: Pampus et al, NPA311 (1978)141
Application of IAV model to deuteron inclusive breakup

- **EBU** → CDCC (Fresco).
- **NBU** → post-form IAV model.

![Graph](image)

**Data:** Pampus et al, NPA311 (1978)141
Elastic scattering

Application to $^{209}$Bi ($^6$Li+, $\alpha$ + X)
Application to $^{209}\text{Bi} (^6\text{Li}+, \alpha + X)$

**Elastic scattering**

- Data points and curves for elastic scattering are shown for various energies: 24 MeV, 26 MeV, 28 MeV, 30 MeV, 32 MeV, 34 MeV, 36 MeV, 38 MeV, 40 MeV, 50 MeV.

**Inclusive $\alpha$’s**

- Data points and curves for inclusive $\alpha$’s are shown for various energies: 24 MeV, 26 MeV, 28 MeV, 30 MeV, 32 MeV, 34 MeV, 36 MeV, 38 MeV, 40 MeV, 50 MeV.

- The figure includes comparisons with different models and models combinations (EBU, NEB, IAV model, EBU+NEB).
$^6\text{Li} + ^{209}\text{Bi}$: incident energy dependence of cross sections

![Graph showing incident energy dependence of cross sections for $^6\text{Li} + ^{209}\text{Bi}$ reaction.](image-url)
$^6\text{Li} + ^{209}\text{Bi}: \text{incident energy dependence of cross sections}$

$^6\text{Li} + ^{209}\text{Bi}$

![Graph showing the incident energy dependence of cross sections for $^6\text{Li} + ^{209}\text{Bi}$](graph.png)

- $\sigma_{\text{R}}$ (CDCC)
- $\alpha + d$ EBU (CDCC)

$V_b$
$^6$Li$^{209}$Bi: incident energy dependence of cross sections

![Graph showing the incident energy dependence of cross sections for $^6$Li$^{209}$Bi. The graph plots $\sigma$ (mb) against $E_{\text{lab}}$ (MeV). The data points are represented by different markers for $\sigma_R$ (CDCC), $\alpha + d$ EBU (CDCC), and NEB-$\alpha$ (d "absorbed").]
$^{6}\text{Li}^{209}\text{Bi}$: incident energy dependence of cross sections

\begin{align*}
\sigma_{R} \text{ (CDCC)} & \\
\alpha + d \text{ EBU (CDCC)} & \\
\text{NEB-}\alpha \text{ (d "absorbed")} & \\
\text{NEB-d (}\alpha \text{ "absorbed")} & \\
\end{align*}

$V_{b}$
$^6\text{Li}+^{209}\text{Bi}$: incident energy dependence of cross sections

![Graph showing the incident energy dependence of cross sections for $^6\text{Li}+^{209}\text{Bi}$.]
$^6\text{Li} + ^{209}\text{Bi}$: incident energy dependence of cross sections

\[ \sigma_{\text{reac}} \approx \sigma_{\alpha + d}(\text{EBU}) + \sigma_{\alpha}(\text{NBU}) + \sigma_d(\text{NBU}) + \sigma(\text{CF}) \]
$^{208}\text{Pb}(^{7}\text{Li}, \alpha + X)$

Data:
- Kelly et al, PRC63, 024601 (2000)
- Signorini et al, PRC67, 044607 ('03)

Other sources of $\alpha$'s?

$^{7}\text{Li} + ^{208}\text{Pb} \rightarrow \alpha + t + ^{208}\text{Pb} \rightarrow \alpha + \alpha + ^{207}\text{Tl}$

$^{7}\text{Li} + ^{208}\text{Pb} \rightarrow ^{8}\text{Be} + ^{207}\text{Tl} \rightarrow \alpha + \alpha + ^{207}\text{Tl}$
Application to the $^7$Be case

Data: Mazzocco et al: $\sigma_\alpha \approx 5\sigma_{^3\text{He}}$

(a) $^{58}\text{Ni}(^7\text{Be},\alpha X)@21.5\text{ MeV}$

(b) $^{58}\text{Ni}(^7\text{Be},^3\text{HeX})@21.5\text{ MeV}$
Effect of binding energy and incident energy: $^{209}\text{Bi}(^6\text{Li}+,\alpha)X$

- $S_\alpha^d = 0.47 \text{ MeV}$
- $S_\alpha^d = 1.47 \text{ MeV}$
- $S_\alpha^d = 2.47 \text{ MeV}$

![Graphs showing the effect of binding energy and incident energy on the reaction $^{209}\text{Bi}(^6\text{Li}+,\alpha)X$.](image-url)
Application to halo nuclei: $^{11}\text{Be} + ^{64}\text{Zn} \rightarrow ^{10}\text{Be} + X @ E=28\text{ MeV}$

(a) Standard CDCC + NEB
(b) Extended CDCC + NEB

$\theta_{\text{lab}}$ (deg)

$\frac{d\sigma}{d\Omega}$ (mb/sr)

Both core deformation/excitations and NEB essential to explain the BU data
Possible applications and extensions

- Assuming, \( W_{xA} = W_{xA}^{\text{dir}} + W_{xA}^{\text{fus}} \), ICF might be computed as

\[
\frac{d\sigma_{\text{NEB}}}{d\Omega_b dE_b} = -\frac{2}{\hbar v_a} \rho_b(E_b) \langle \varphi_x | W_{xA}^{\text{fus}} | \varphi_x \rangle
\]

- Calculations for “stripping” part in one-nucleon removal cross sections (knockout) at intermediate energies may provide a benchmark for standard semiclassical approaches.

- Application to more weakly bound (e.g. halo) nuclei should be possible, but might require going beyond (DWBA) in the calculation of \( \varphi_x \) (eg. CDCC):

\[
[K_x + U_{xA} - E_x] \varphi_x(r_x) = (\chi_b^{(-)} | V_{bx} | \psi_{3b}^{(+)})
\]
Summary and conclusions

CDCC and its extensions

- The CDCC method, and its extensions (core/target excitations, 3-body projectiles) provide a powerful and accurate method to calculate elastic breakup observables.
- These extensions should be made available in standard reaction codes.

Evaluation of inclusive cross sections

- Old theories (1980s) are being revisited and implemented 😊.
- So far, they use DWBA, but may need to go beyond for halo nuclei. 😊
List of collaborators

- Inclusion of core excitation effects with:
  - José Miguel Arias (Univ. of Sevilla).
  - Raquel Crespo, Raúl de Diego (Lisbon, Portugal)

- Extension of CDCC for target excitations:
  - Mario Gómez-Ramos (Univ. of Sevilla)

- Inclusive breakup calculations done with Jin Lei (PhD at Univ. of Sevilla; now at Ohio University).
The effect of binding energy

$^6$Li ($S_{\alpha d} = 1.47$ MeV)

$^{11}$Li ($S_{2n} = 0.370$ MeV)

Distant breakup triggered by long-range Coulomb E1 couplings favors EBU mode in $^{11}$Li (NEB expected to be small in this case)

J. Lei, PhD thesis

CDCC vs post-DWBA for EBU

$^{93}\text{Nb}(d,pX) @ E_d=25.5\text{ MeV}$

$(E_p=14\text{ MeV})$

$\frac{d\sigma}{d\Omega_p dE_p} (\text{mb/sr/MeV})$

- EBU (CDCC)
- EBU (FR-DWBA)

$\Rightarrow$ Good agreement in this case, but needs to be tested for other cases.
Zero-range accurate for deuterons, but not for other projectiles like $^6$Li
Remnant term also important for $^6$Li
Post-prior equivalence

\[
\frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{NEB}} = -\frac{2}{\hbar v_a} \rho_b(E_b) \langle \psi_x \| W_x \| \psi_x \rangle,
\]

\[
(E_x^+ - K_x - U_x) \psi_{x}^{\text{post}}(r_x) = (\chi_b^{(-)} \| V_{\text{post}} \| \chi_a^{(+)} \phi_a) ; \quad V_{\text{post}} \equiv V_{bx} + U_{bA} - U_{bB}
\]

\[
(E_x^+ - K_x - U_x) \psi_{x}^{\text{prior}}(r_x) = (\chi_b^{(-)} \| V_{\text{prior}} \| \chi_a^{(+)} \phi_a) ; \quad V_{\text{prior}} \equiv U_{xA} + U_{bA} - U_{aA}
\]

\[
\psi_{x}^{\text{post}} = \psi_{x}^{\text{prior}} + \psi_{x}^{\text{NO}}
\]

\[
\psi_{x}^{\text{NO}}(\vec{r}_x) \equiv \langle \chi_b^{(-)} \| \chi_a^{(+)} \phi_a \rangle
\]

\[
\frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{IAV}} = \frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{NEB}} + \frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{UT}} + \frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{NO}} + \frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{IN}}
\]
Numerical assessment of post-prior equivalence

$^{62}\text{Ni}(d,pX) \ @ \ E_d=25.5 \text{ MeV}$

(a) $d\sigma/dE_p$ (mb/MeV)

(b) $d^2dE_p/d\Omega_p$ (mb/sr MeV)

J. Lei, A.M.M., PRC 92, 061602(R) (2015)
Numerical assessment of post-prior equivalence

$^{209}\text{Bi}({}^6\text{Li},\alpha X) @ E=36 \text{ MeV}$

Graphs showing the $d\sigma/dE_\alpha$ (mb/MeV) as a function of $E_\alpha^{c.m.}$ (MeV) and $\theta_{lab}$ (deg) for various models: IAV, UT, NO, IN, UT+NO+IN.

Graphs also show comparisons with experimental data from Santra et al. EBU, EBU+NEB (IAV), EBU+NEB (UT).
Evidence of NEB contributions in inclusive $^{208}\text{Pb}(^{6}\text{He},\alpha)X$
Incomplete fusion in $^6$Li+$^{209}$Bi

(a) $\alpha^{209}$Bi

(b) d+$^{209}$Bi

- Barnett & Lilley: $(\alpha,n)$
- Hassan: $(\alpha,n)+(\alpha,2n)$
- $\sigma_{\text{fus}}$ \(W^{\text{CN}}\)
- $\sigma_{\text{fus}}$ \(W^{\text{CN}}\)

E$_{\alpha}$ (MeV) vs. $\sigma$ (mb)

E$_{d}$ (MeV) vs. $\sigma$ (mb)
Incomplete fusion in $^6\text{Li} + ^{209}\text{Bi}$

\begin{align*}
\sigma_R \text{ (CDCC)} \\
\text{NEB} \left( ^6\text{Li}, \alpha \right) X \\
\text{ICF} \left( ^6\text{Li}, \alpha \right) \text{CN}
\end{align*}

\begin{align*}
\sigma_R \text{ (CDCC)} \\
\text{NEB} \left( ^6\text{Li}, d \right) X \\
\text{ICF} \left( ^6\text{Li}, d \right) \text{CN}
\end{align*}

\begin{align*}
\sigma_R \text{ (CDCC)} \\
d + \alpha \text{ ICF} \\
\text{Exp. ICF (Dasgupta )}
\end{align*}

---

\begin{align*}
\sigma &\left( \text{mb} \right) \\
30 &\text{E}_{\text{lab}} \left( \text{MeV} \right) \\
40 &\text{E}_{\text{lab}} \left( \text{MeV} \right) \\
50 &\text{E}_{\text{lab}} \left( \text{MeV} \right)
\end{align*}
Application to $^{118}\text{Sn}(^6\text{Li},\alpha)X$
The effect of binding energy

$^6$Li ($S_{\alpha d} = 1.47$ MeV)

$^1$Li ($S_{2n} = 0.370$ MeV)

Distant breakup triggered by long-range Coulomb E1 couplings favors EBU mode in $^{11}$Li (NEB expected to be small in this case)
$^{208}$Pb($^7$Li, $\alpha + X$)

Data:
- Kelly et al, PRC63, 024601 (2000)
- Signorini et al, PRC67, 044607 ('03)

Other sources of $\alpha$'s?

$^7$Li + $^{208}$Pb → $\alpha + t + ^{208}$Pb → $\alpha + \alpha + ^{207}$Tl

$^7$Li + $^{208}$Pb → $^8$Be + $^{207}$Tl → $\alpha + \alpha + ^{207}$Tl