Unravelling the mechanisms for suppression of complete fusion in reactions of weakly bound nuclei

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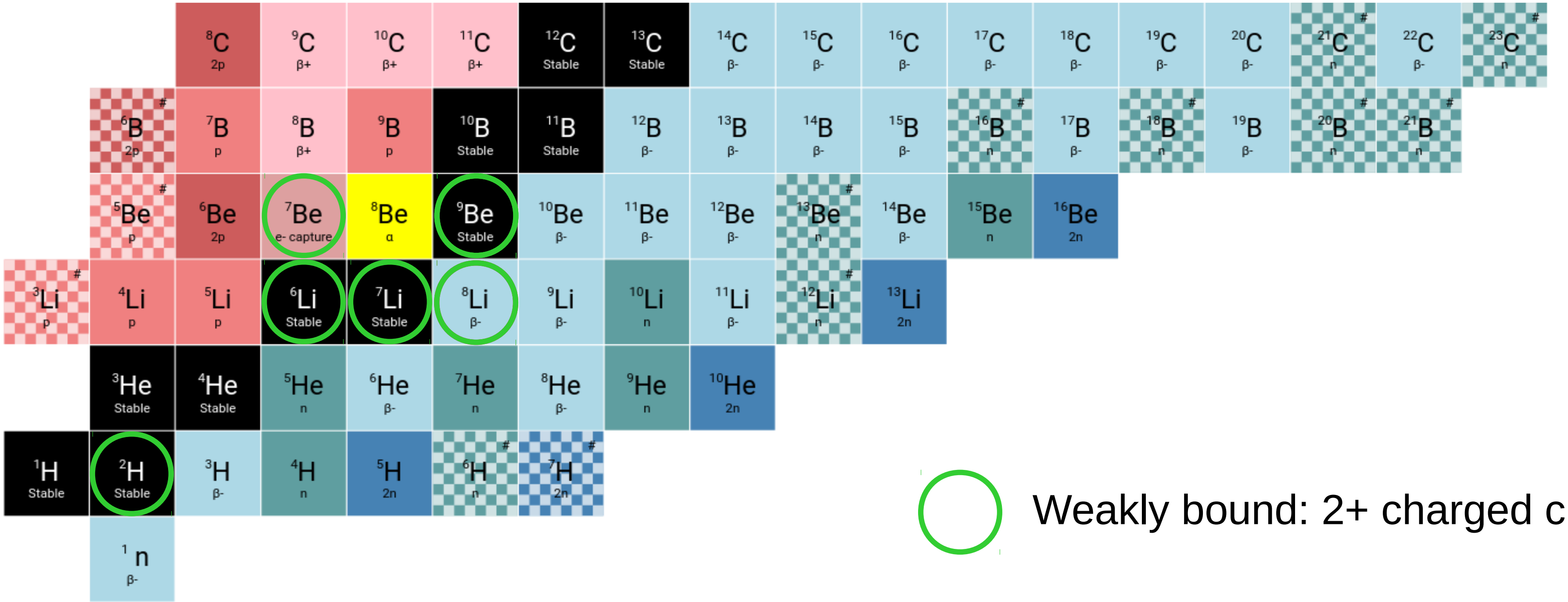
FRIB

Weakly bound nuclei



		^{8}C 2p	^{9}C β+	^{10}C β+	^{11}C β+	^{12}C Stable	^{13}C Stable	^{14}C β-	^{15}C β-	^{16}C β-	^{17}C β-	^{18}C β-	^{19}C β-	^{20}C β-	# ^{21}C n	^{22}C β-	# ^{23}C n
	# ^{6}B 2p	^{7}B p	^{8}B β+	^{9}B p	^{10}B Stable	^{11}B Stable	^{12}B β-	^{13}B β-	^{14}B β-	^{15}B β-	# ^{16}B n	^{17}B β-	# ^{18}B n	^{19}B β-	# ^{20}B n	# ^{21}B n	
	# ^{5}Be p	^{6}Be 2p	○ ^{7}Be e- capture	^{8}Be α	○ ^{9}Be Stable	^{10}Be β-	^{11}Be β-	^{12}Be β-	# ^{13}Be n	^{14}Be β-	^{15}Be n	^{16}Be 2n					
# ^{3}Li p	^{4}Li p	^{5}Li p	○ ^{6}Li Stable	○ ^{7}Li Stable	○ ^{8}Li β-	^{9}Li β-	^{10}Li n	^{11}Li β-	# ^{12}Li n	^{13}Li 2n							
	^{3}He Stable	^{4}He Stable	^{5}He n	^{6}He β-	^{7}He n	^{8}He β-	^{9}He n	^{10}He 2n									
^{1}H Stable	○ ^{2}H Stable	^{3}H β-	^{4}H n	^{5}H 2n	# ^{6}H n	# ^{7}H 2n											
	^{1}n β-																

○ Weakly bound: 2+ charged clusters

(“weakly” is ~<4 MeV)

https://people.physics.anu.edu.au/~ecs103/chart/

Weakly bound nuclei

○ Weakly bound: 2+ charged clusters

○ Weakly bound: core + nucleon/s

○ Weakly bound: core + nucleon/s & halo

(“weakly” is ~<4 MeV)

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Weakly bound nuclei

🟢 Weakly bound: 2+ charged clusters

🔴 Weakly bound: core + nucleon/s

🟠 Weakly bound: core + nucleon/s & halo

What are the reaction dynamics of weakly bound nuclei?

(“weakly” is ~<4 MeV)

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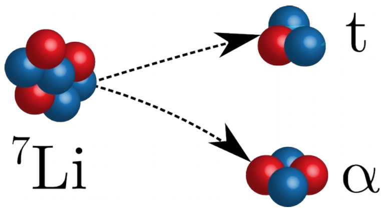
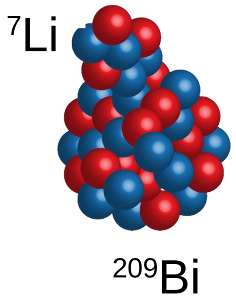
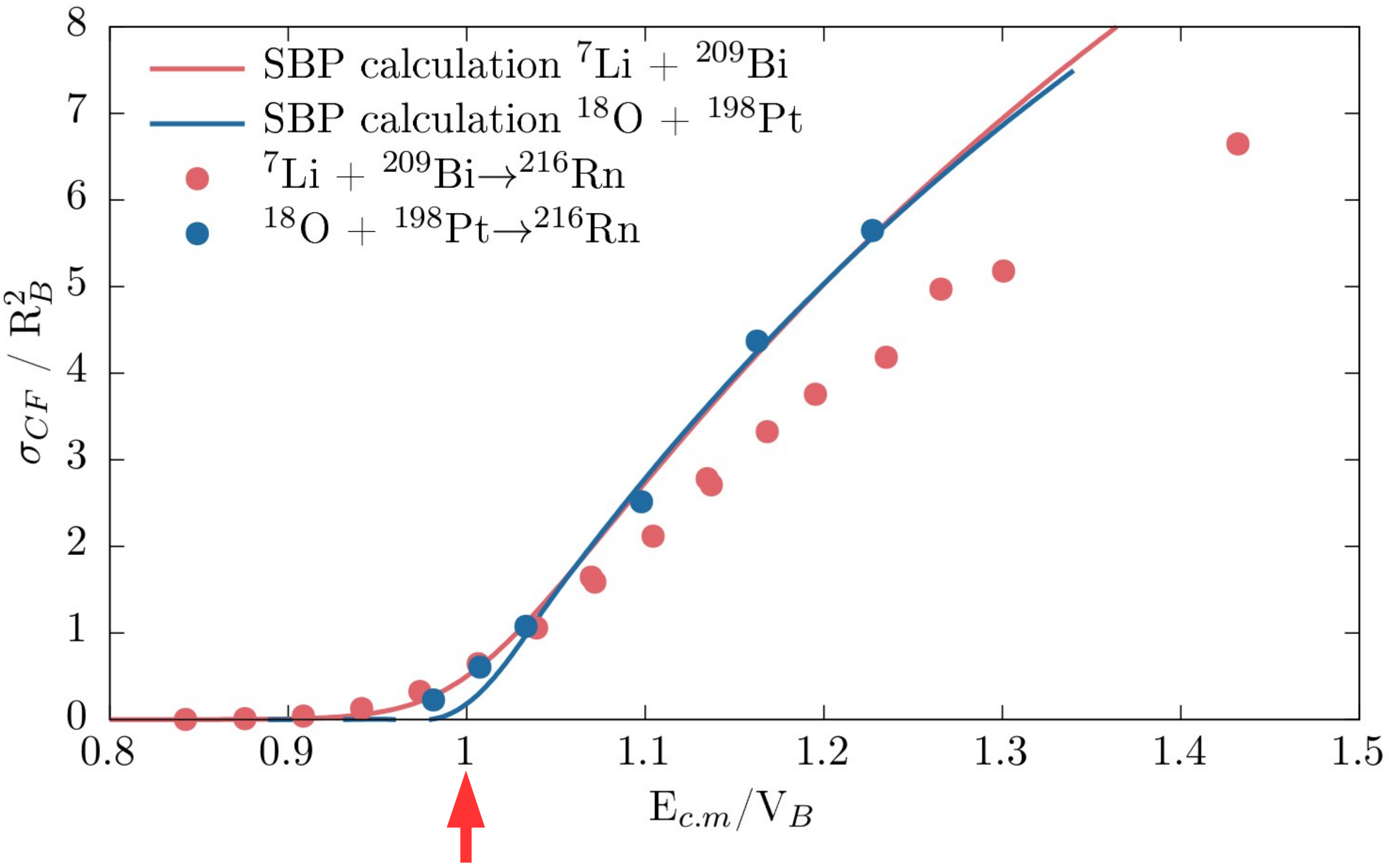
Above-barrier suppression of complete fusion





Single Barrier Penetration model calculation vs Experiment



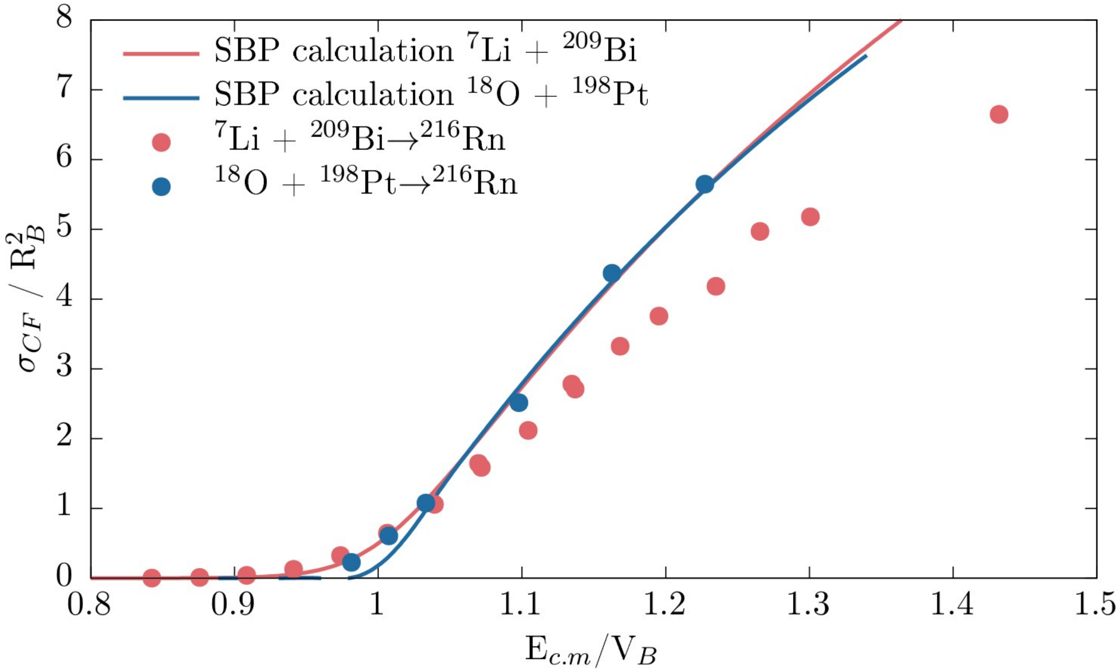
Precision measurements → Unambiguous determination of suppression

Dasgupta, PRC 70, 024606 (2004)

Above-barrier suppression of complete fusion

Well established phenomenon across stable weakly bound nuclei (^{6,7}Li, ^{9}Be …)
e.g:

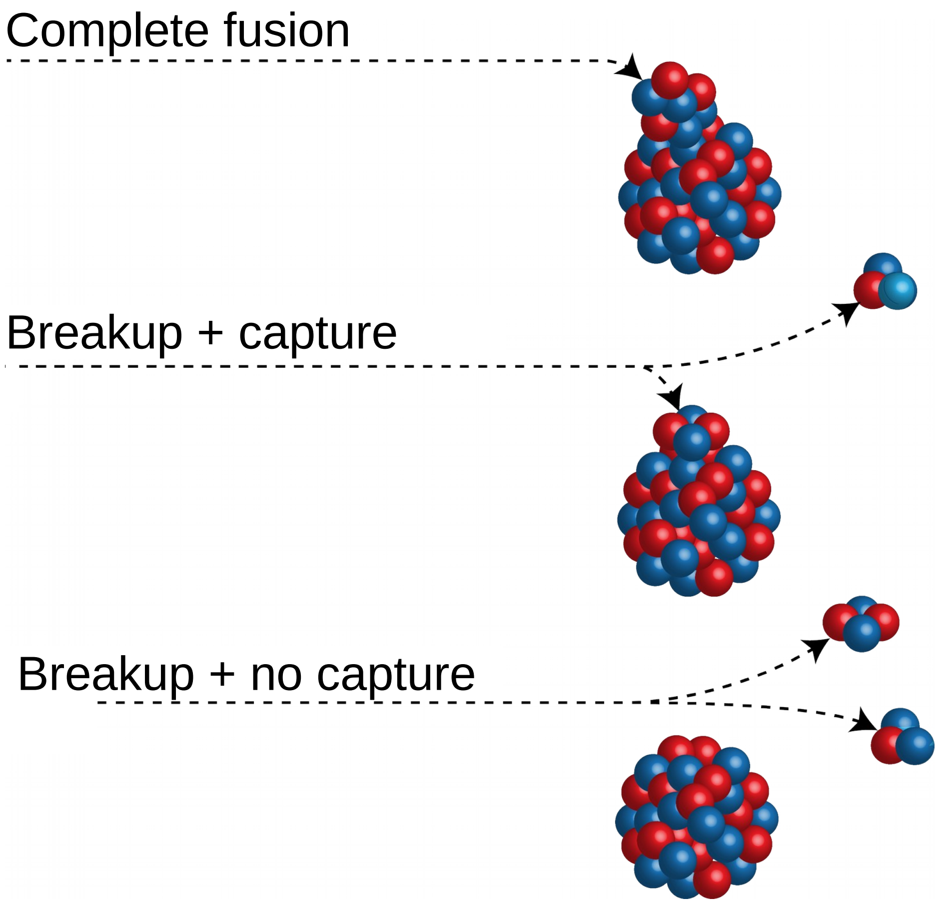
Dasgupta, PRL **82** 1395 (1999)
Signorini, EPJ A **5** 7 (1999)
Tripathi, PRL **88** 172701 (2002)
Dasgupta, PRC **70** 024606 (2004)
Signorini PTPS **154** 024606 (2004)
Wu, PRC **68** 044605 (2004)
Gomes, PRC **73** 064606 (2006)
Mukherjee, PLB **636** 91 (2006)
Aguilera PRC **80** 044605 (2009)
Rath, PRC **79** 051601 (2009)
Gasques, PRC **79** 034605 (2009)
Palshetkar, PRC **82** 044608 (2010)
Parkar, PRC **82** 054601 (2010)
Fang, PRC **87** 024604 (2013)
Shaikh, PRC **90** 024615 (2014)
Zhang, PRC **90** 024621 (2014) …



Dasgupta, PRC 70, 024606 (2004)

Recent review: Canto, Physics Reports 596 (2015)

Hypothesis: breakup



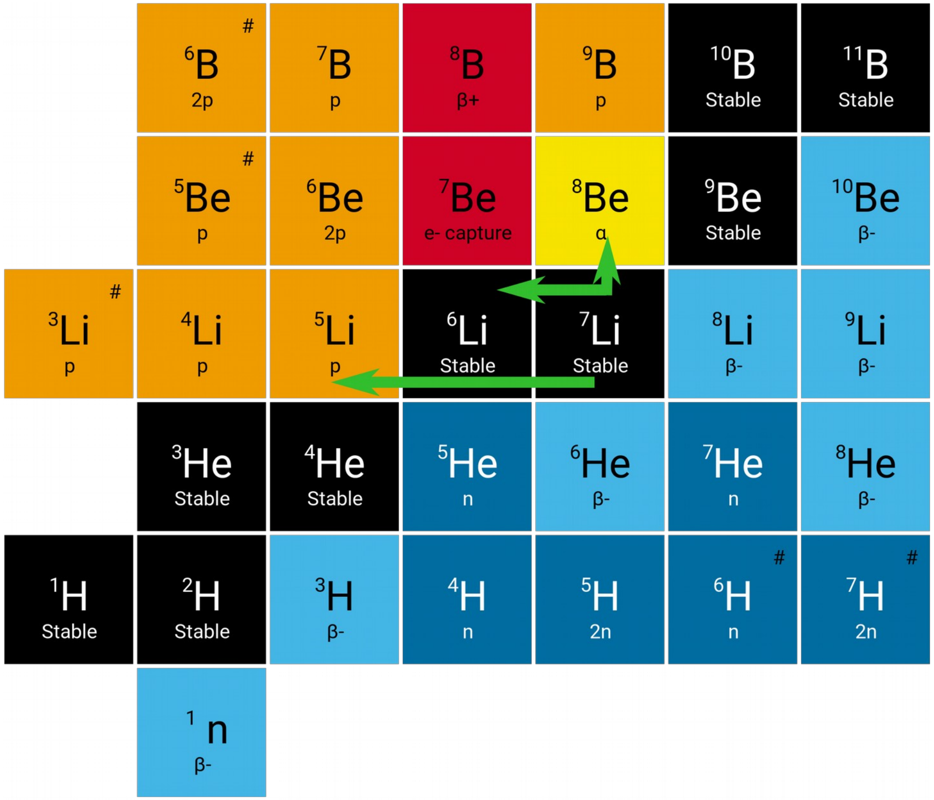
- Breakup into charged clusters (e.g ^{7}Li → α+t) **reduces** complete charge capture (**complete fusion, CF**) and **increases** incomplete charge capture (**incomplete fusion, ICF**)
  - CF suppression ∝ σ(ICF)
- On less central trajectories, we observe breakup where no fragment is captured (**no capture breakup**)

Complications: breakup mechanisms

Not just direct breakup: Must consider the substantial amount of transfer to unbound states of neighbouring nuclei.

$$\begin{array}{ll} {}^{7}\mathrm{Li} \rightarrow \alpha+t & \longleftarrow \text{Direct} \end{array}$$

$$\left.\begin{array}{l} {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} \rightarrow \alpha+\alpha \\ {}^{7}\mathrm{Li} \rightarrow {}^{6}\mathrm{Li} \rightarrow \alpha+d \\ {}^{7}\mathrm{Li} \rightarrow {}^{5}\mathrm{Li} \rightarrow \alpha+p \end{array}\right\} \text{Transfer-triggered}$$



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	^{5}Be p #	^{6}Be 2p	^{7}Be e- capture	^{8}Be α	^{9}Be Stable	^{10}Be β-
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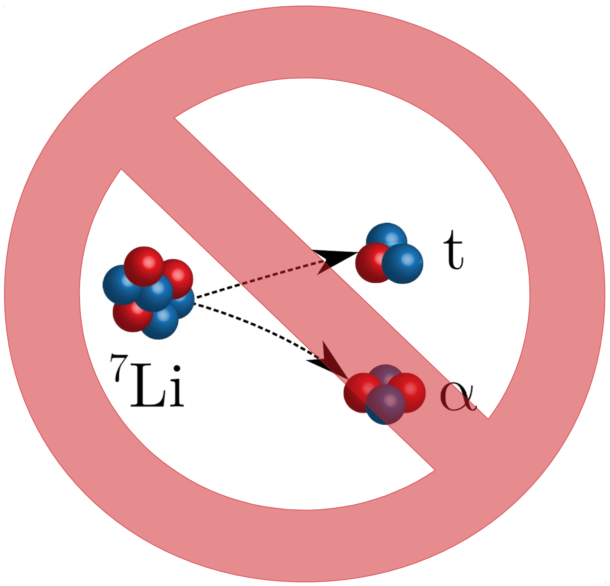

Shrivastava PLB 633 463 (2006)
Rafiei PRC 81 024601 (2010)

Luong PLB 695 105 (2011)
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Cook PRC 97 021601(R) (2018)

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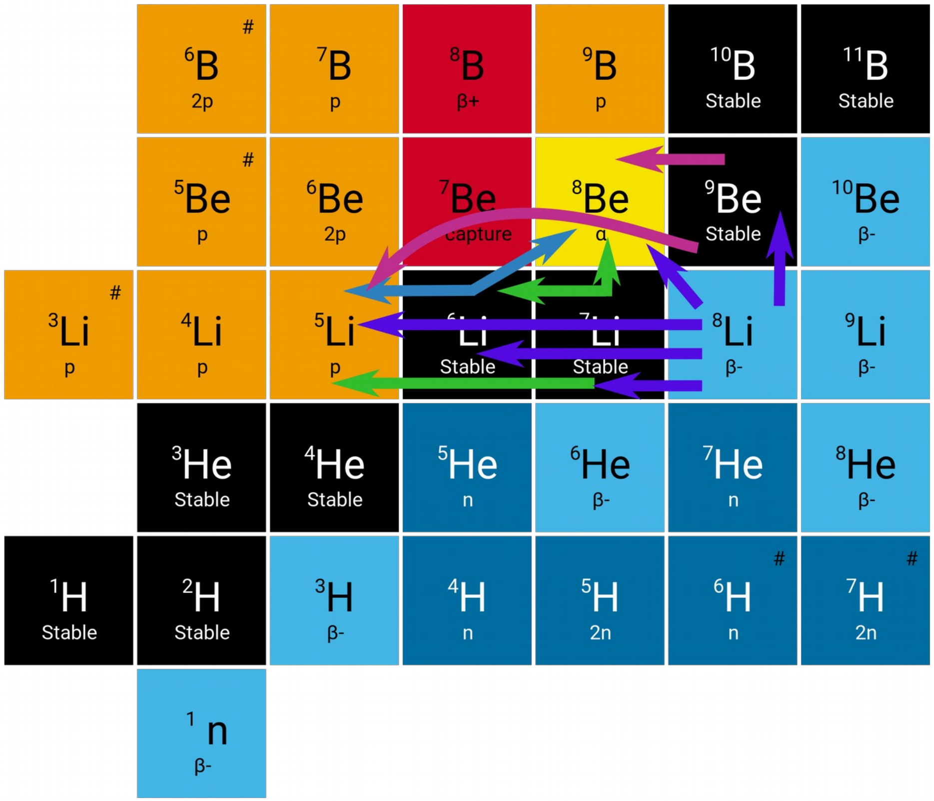

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^{9}Be → α + α + n ← Direct
^{9}Be → ^{8}Be → α + α } Transfer-triggered

^{8}Li → ^{7}Li + n ← Direct
^{8}Li → ^{7}Li → α+t
^{8}Li → ^{6}Li → α+d
^{8}Li → ^{5}Li → α+p
^{8}Li → ^{8}Be → α+α
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… Challenging theoretically!

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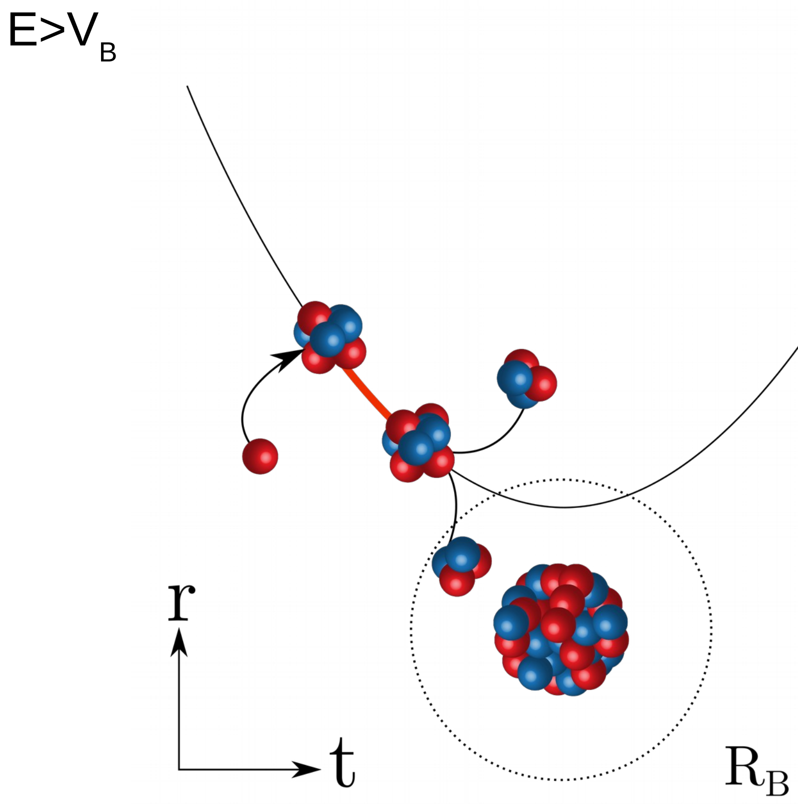
Complications: breakup timescales

Intermediate nucleus after transfer or direct excitation has a lifetime. → Nuclei propagate for some time prior to breakup!



Simpson, Cook *et al.*
EPJ WoC 163 2017

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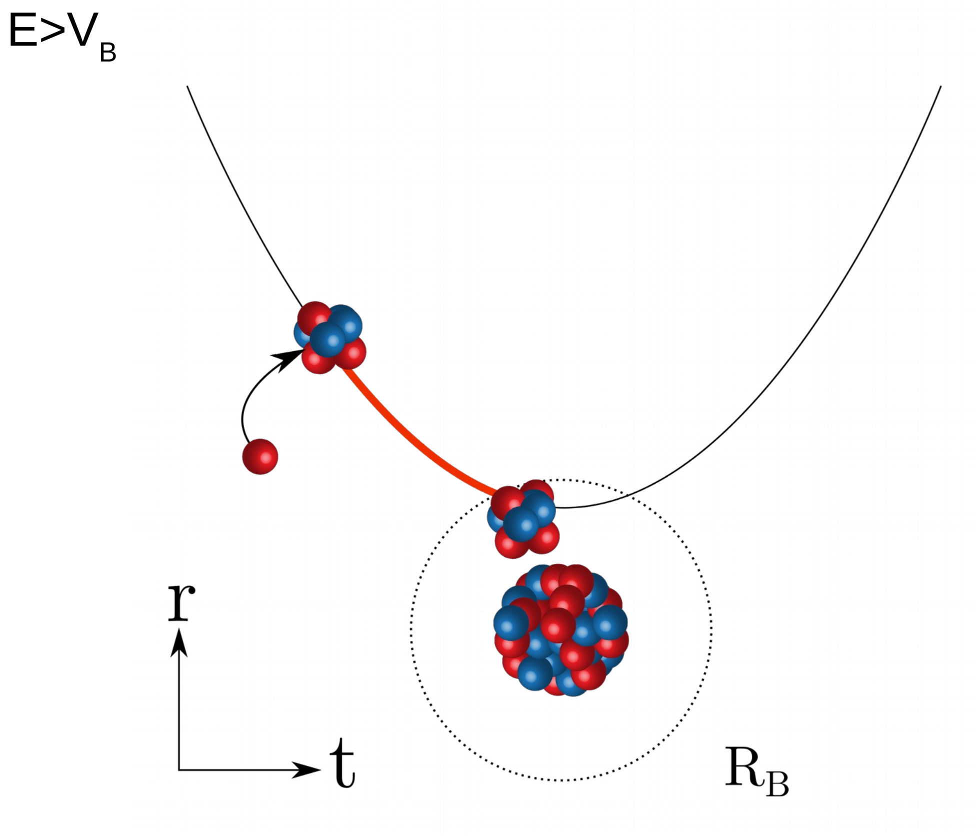

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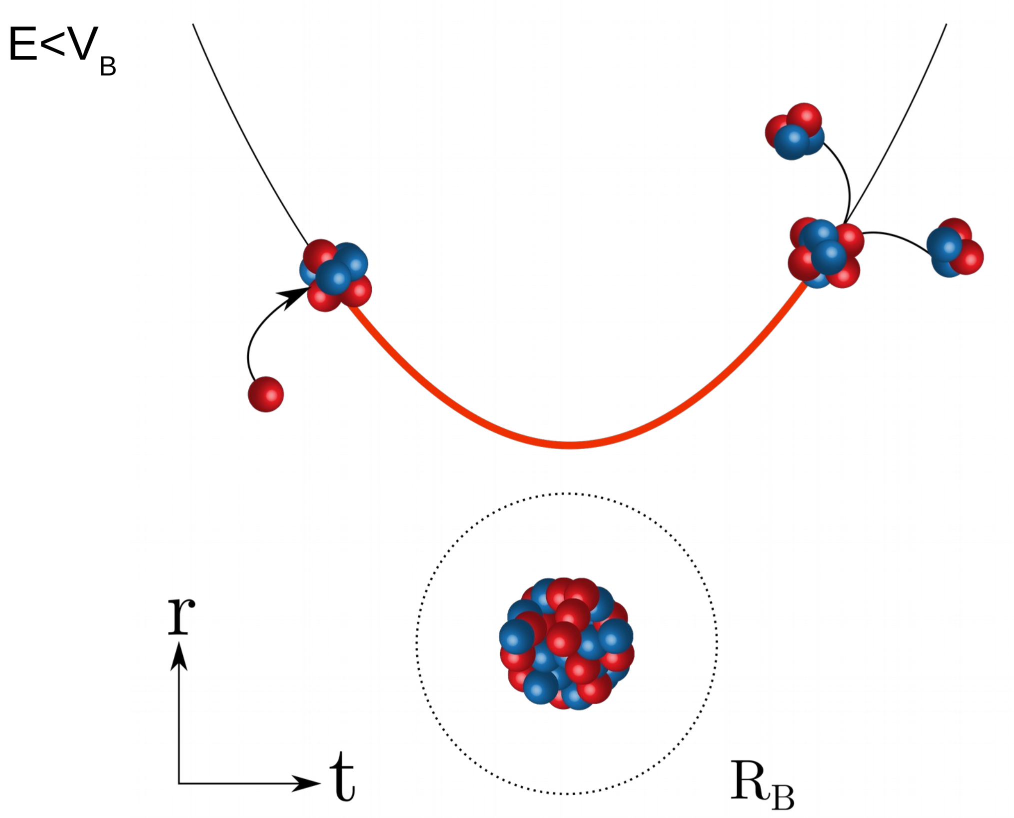

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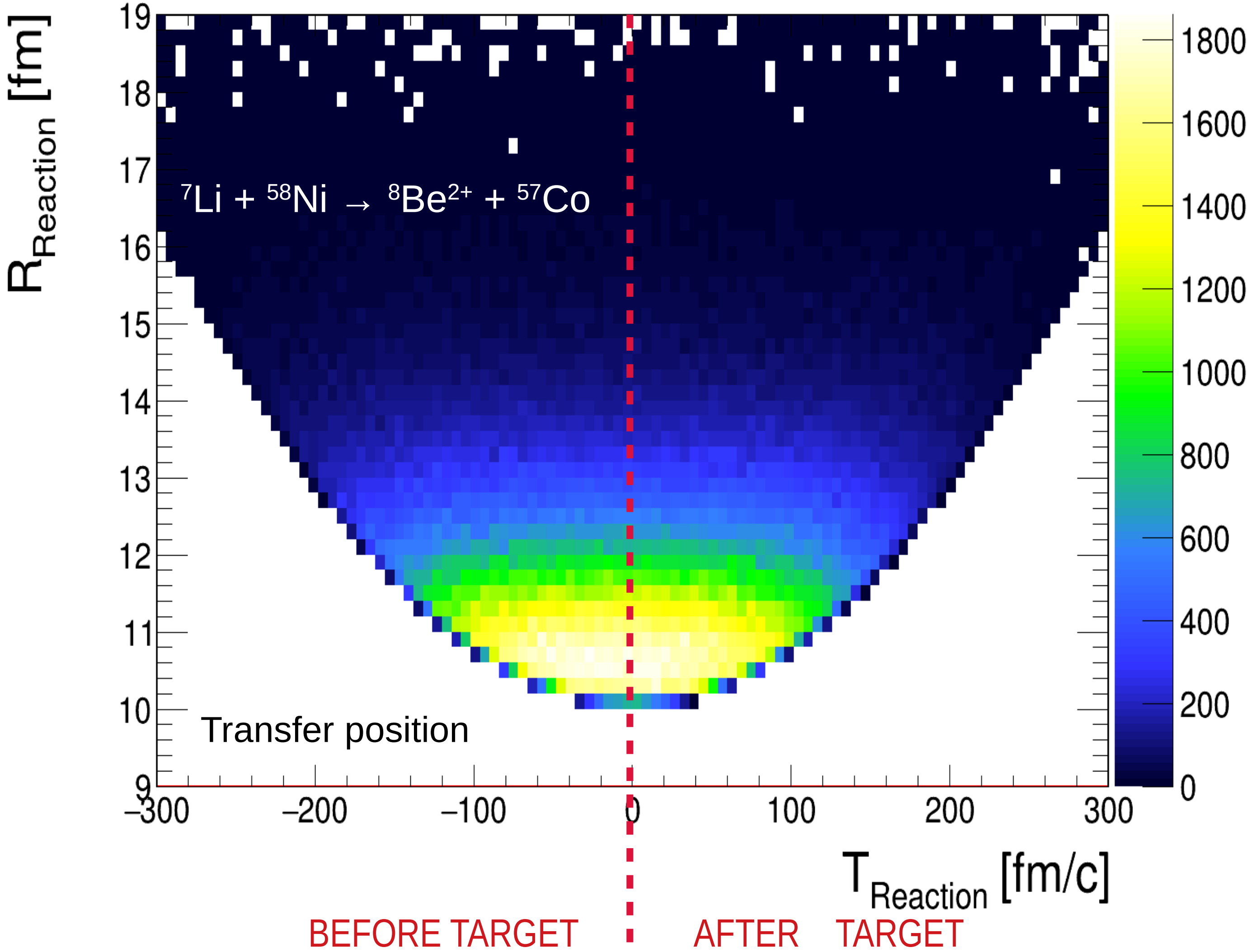
If transfer probabilities look like this:



Simpson, Cook *et al.*
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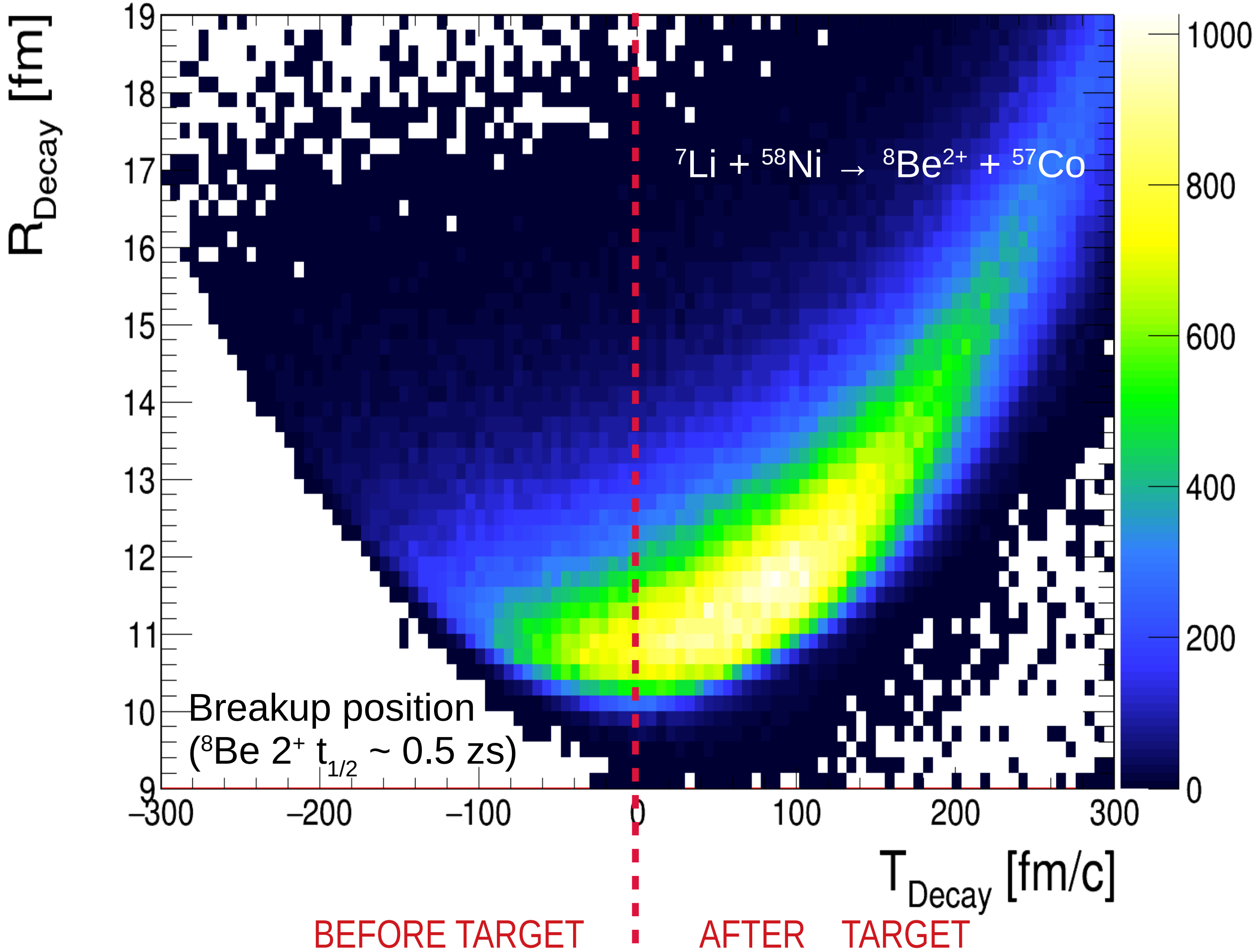


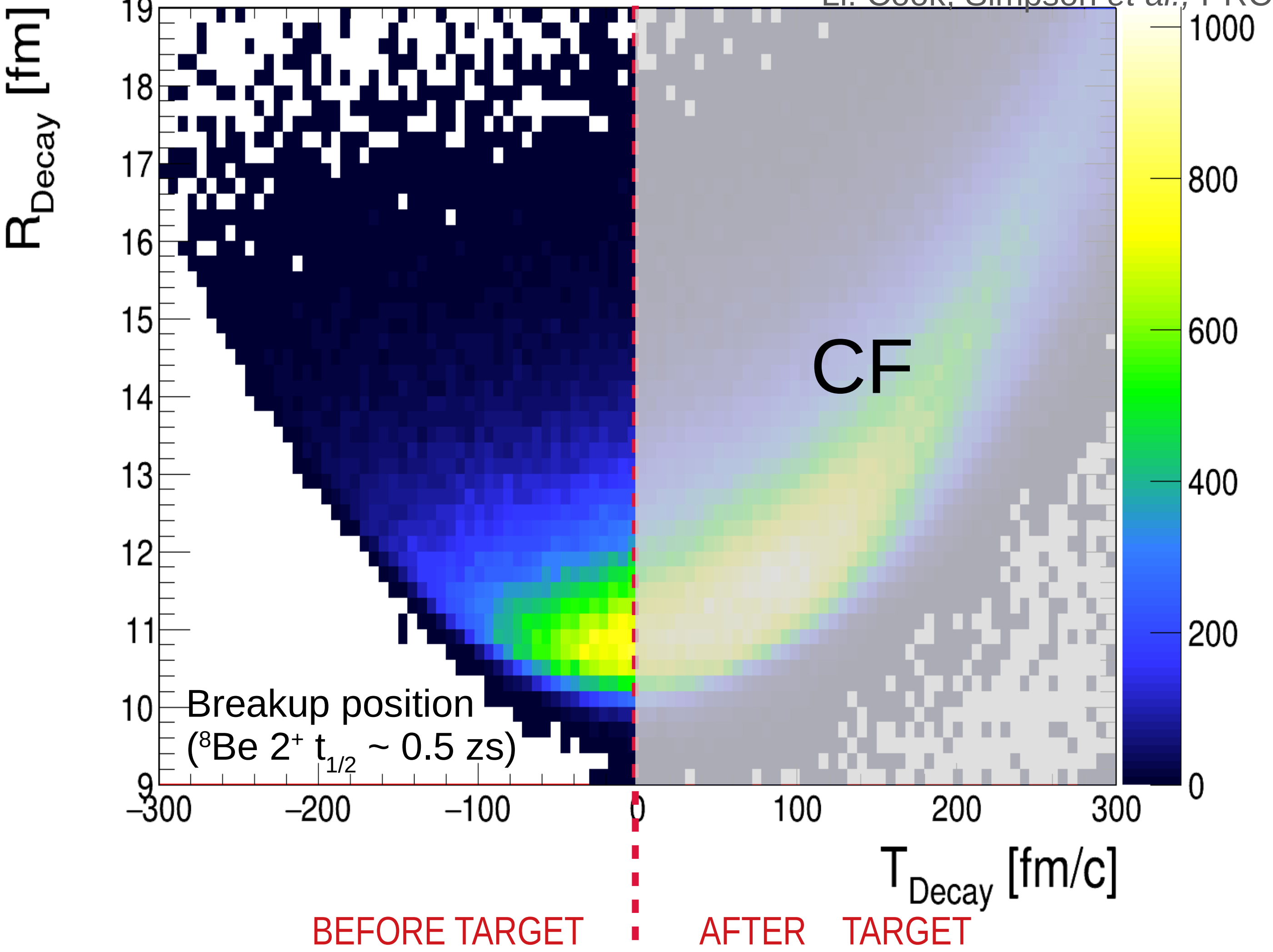
Simpson, Cook *et al.*
EPJ WoC 163 2017

Complications: breakup timescales

When lifetimes are included realistically in model calculations, breakup-capture cannot explain observed complete fusion suppression. Lifetimes must be included to explain the observed correlations in energy and angle between the breakup fragments.

^{9}Be: Cook, Simpson *et al.*, PRC 93 064604 (2016)

^{8}Li: Cook, Simpson *et al.*, PRC 97 021601(R) (2018)



^{9}Be + ^{144}Sm...^{209}Bi

- Measure no-capture breakup at below barrier energies.
- Infer breakup-capture above barrier with a model that includes lifetimes
- Compare to incomplete fusion cross-sections.

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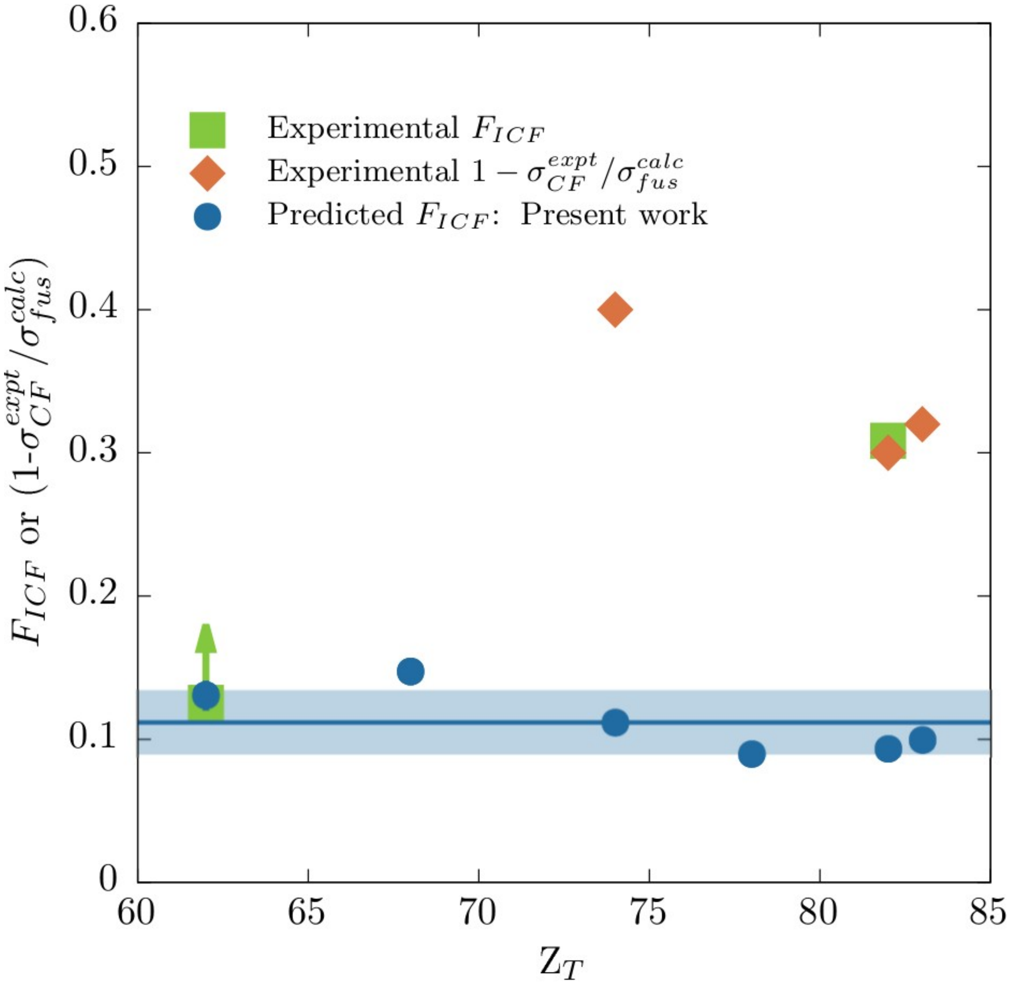

Cook, Simpson *et al.*, PRC 93 064604 (2016)

Experiments:
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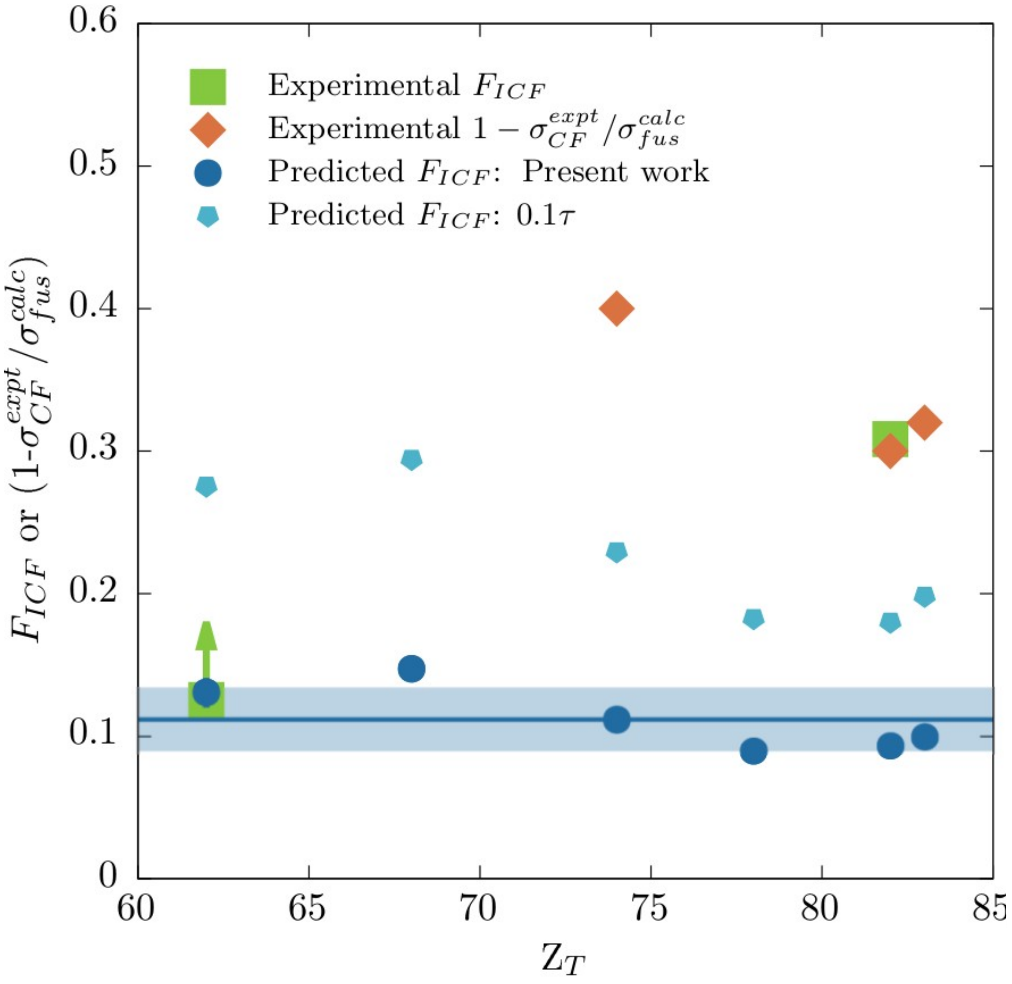

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Cook, Simpson *et al.*, PRC 93 064604 (2016)

Where do we go from here?

So, how can we understand the mechanism for complete fusion suppression?

Old strategy:

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So, how can we understand the mechanism for complete fusion suppression?

Old strategy:

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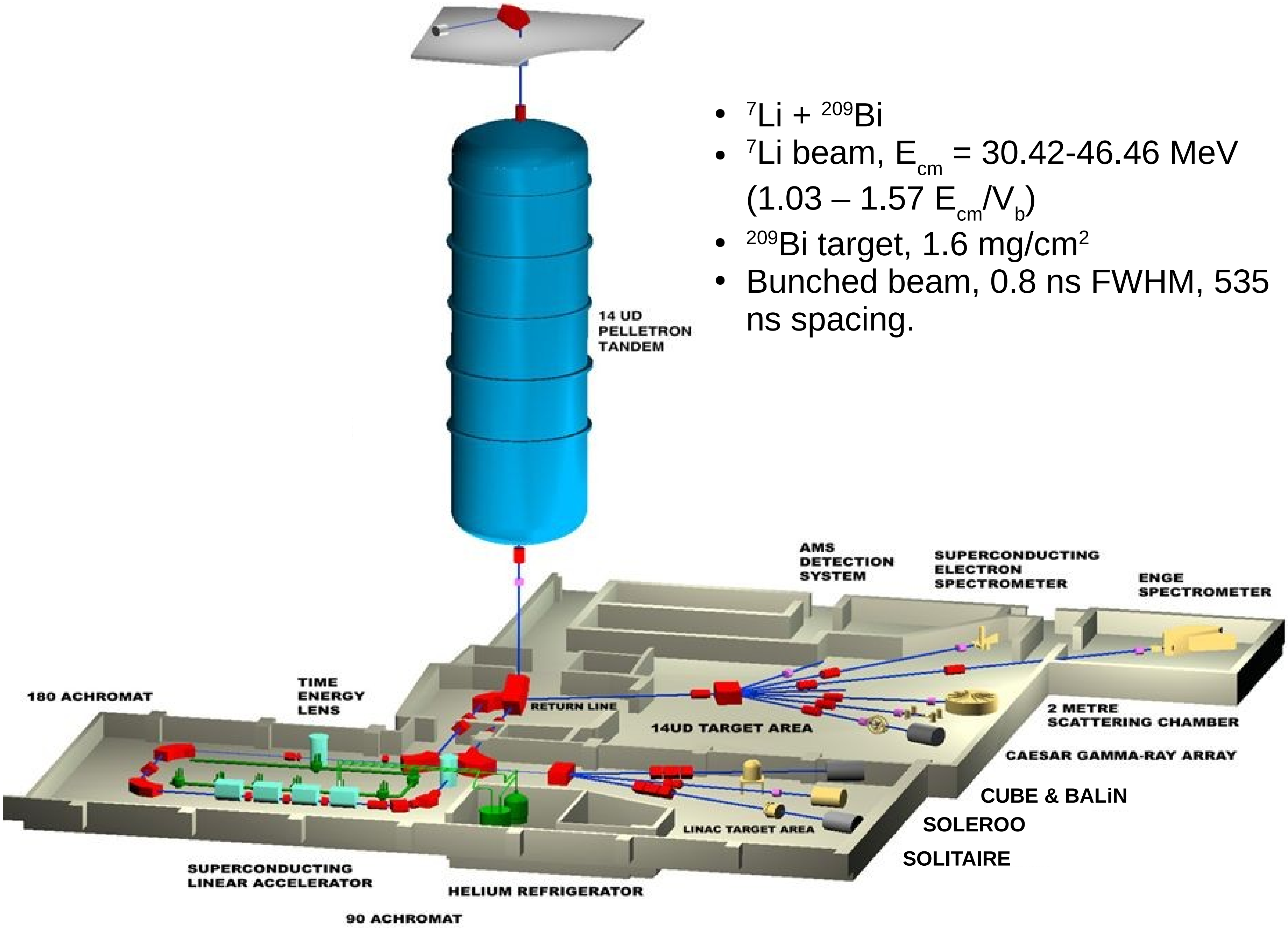
An innovative experimental approach:

- Measure projectile-like particles left over after incomplete fusion (“unaccompanied particles”), and compare *directly* to no-capture breakup.

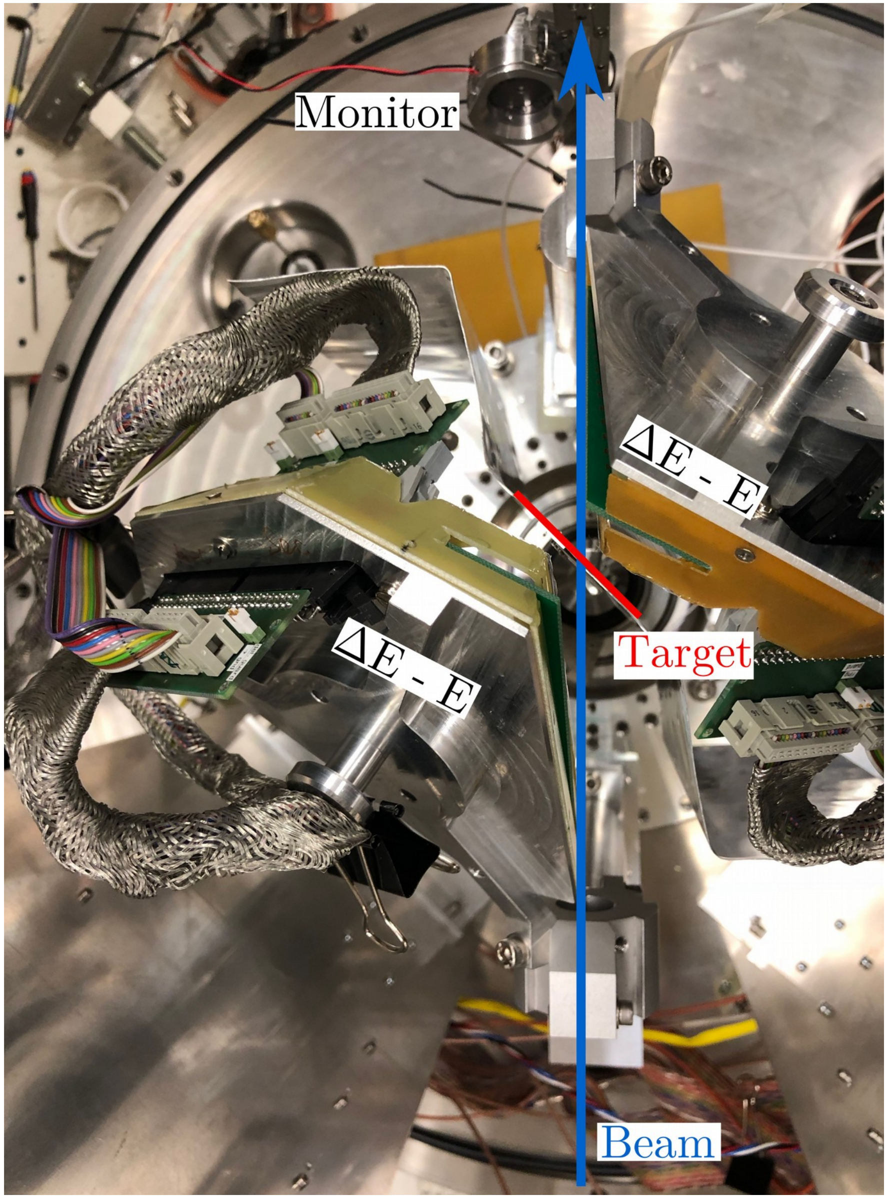
The experiment: ANU Heavy Ion Accelerator Facility

- ^{7}Li + ^{209}Bi
- ^{7}Li beam, E_{cm} = 30.42-46.46 MeV (1.03 – 1.57 E_{cm}/V_{b})
- ^{209}Bi target, 1.6 mg/cm^{2}
- Bunched beam, 0.8 ns FWHM, 535 ns spacing.



The experiment: BALiN

- Two DSSD ΔE-E telescopes
  - Particle ID via ΔE-E & ToF
  - θ ($29° < \theta_{lab} < 89°$ and $94° < \theta_{lab} < 157°$)
  - $107° < \varphi < 176°$ and $185° < \varphi < 254°$



Cook, Simpson *et al.* PRL 122 102501 (2019)

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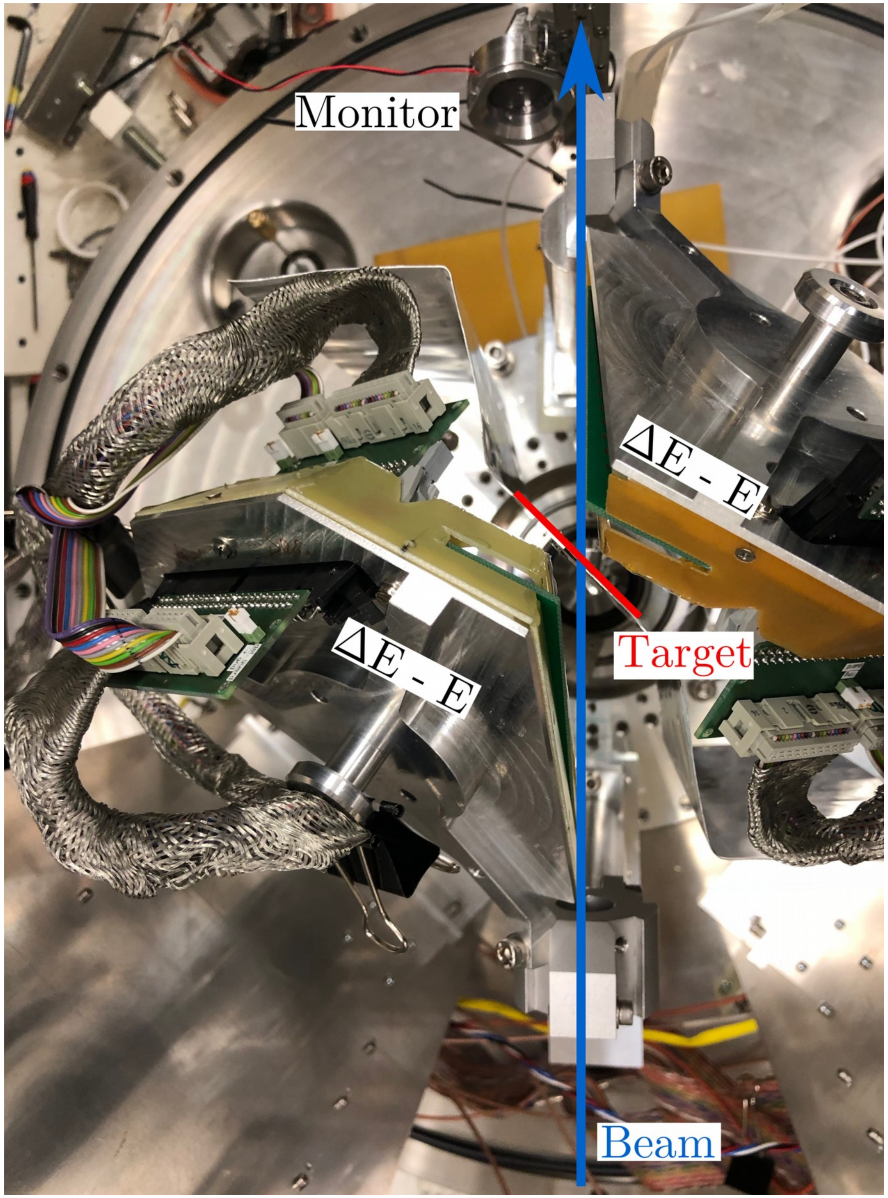
- Extracted:
  - Elastic scattering
  - Inclusive α
  - Coincidences between beam-associated charged particles (no-capture breakup)
  - Coincidences between decay α and beam-associated α for short-lived ^{212}Po



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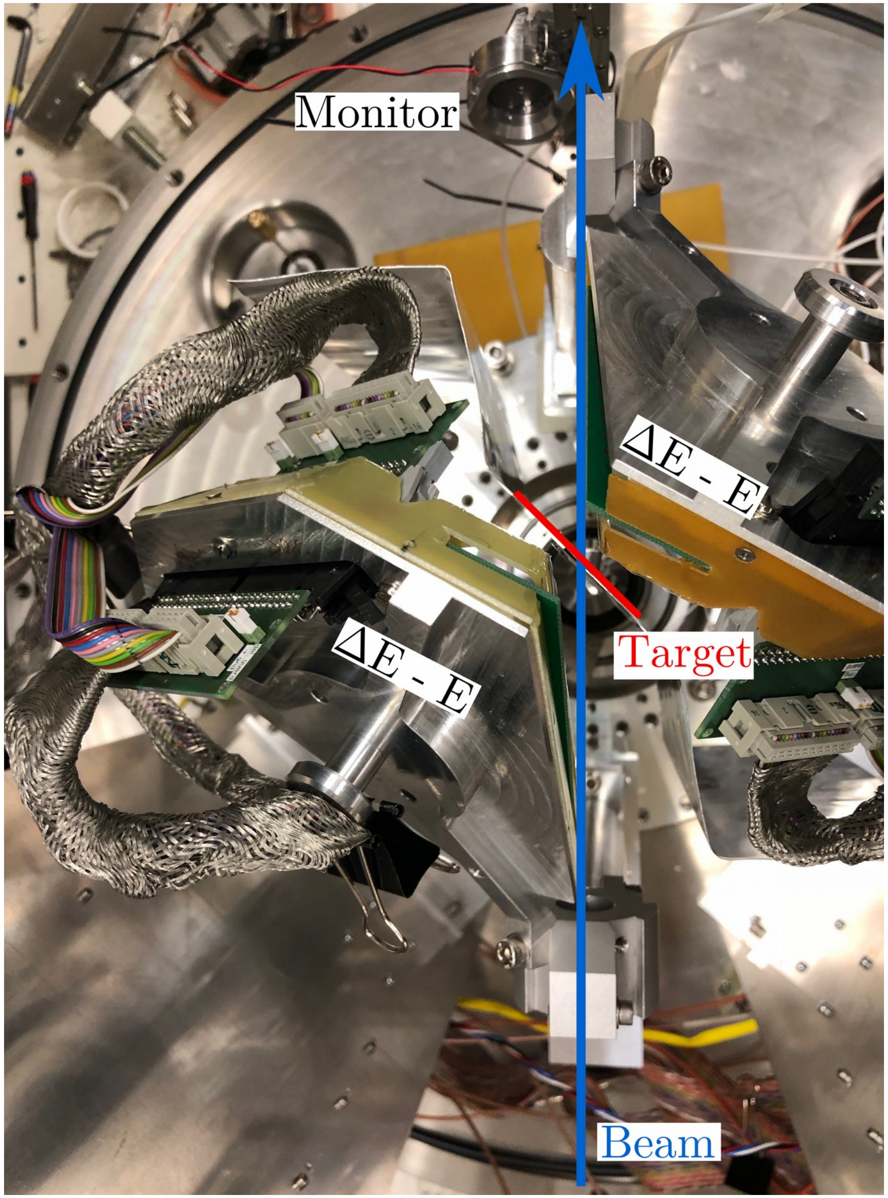
- Detector efficiency for no-capture breakup determined using classical dynamical model simulation (Cook PRC 2016, Simpson EPJ Web. Conf. 2017)



Cook, Simpson *et al.* PRL 122 102501 (2019)

No Capture Breakup

At E_{cm} = 38.72 MeV, σ_{NCBU} = 36 ± 1 mb

Modes:

Direct breakup: $\sigma_{\alpha t}$ = 9.6 ± 0.6 mb

1p pickup: $\sigma_{\alpha\alpha}$ = 7.3 ± 0.4 mb

1n stripping: $\sigma_{\alpha d}$ = 10.8 ± 0.5 mb

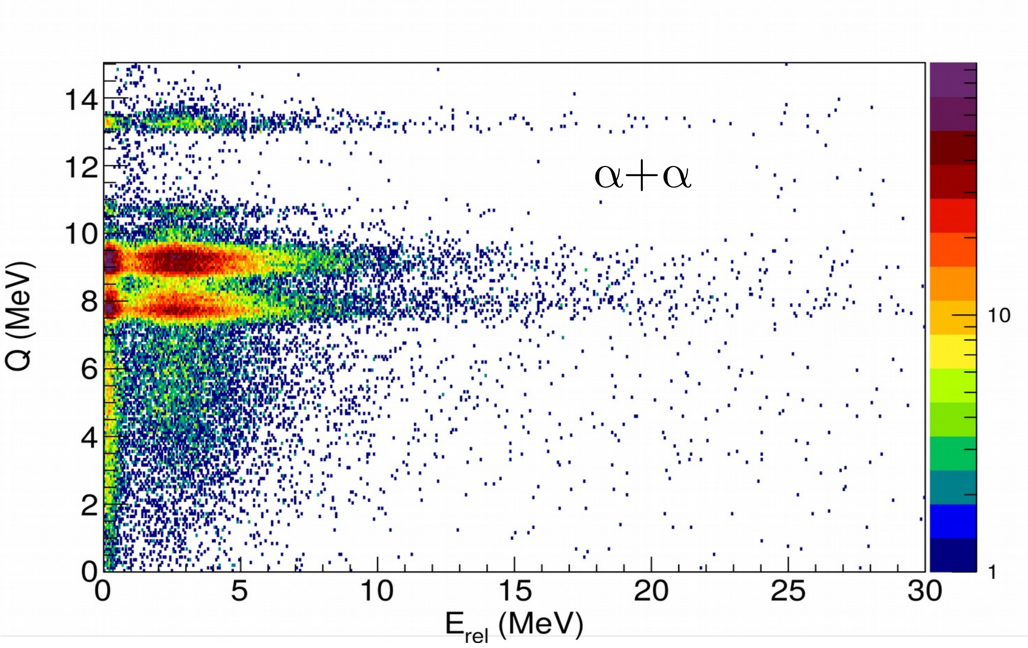
2n stripping: $\sigma_{\alpha p}$ = 8.6 ± 0.5 mb

Lifetimes (determined from E_{rel}):

~16 mb of the breakup occurs via long-lived resonant states ($\gtrsim 10^{-20}$ s)

Of the remaining 20mb, only a small fraction occurs fast enough to suppress CF ($\lesssim 10^{-21}$ s)

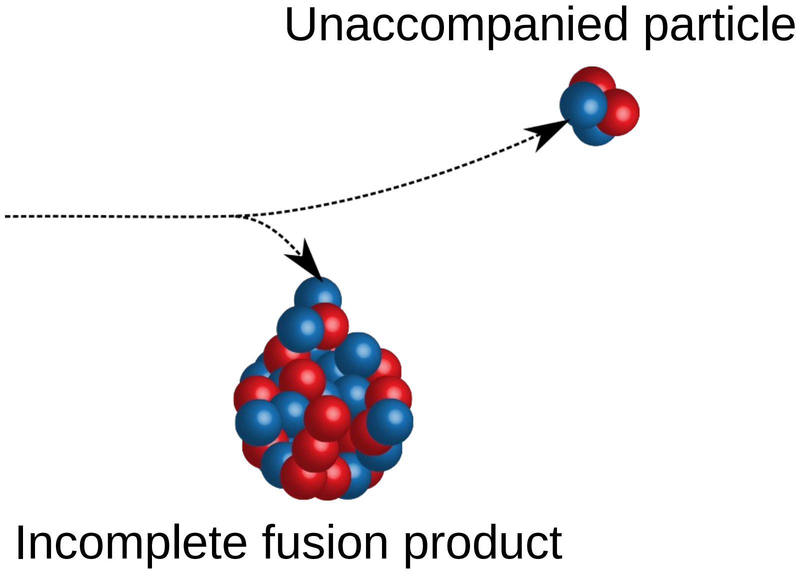
Consistent with previous studies: no-capture breakup shows that breakup-capture cannot significantly contribute to incomplete fusion.



New insight: unaccompanied α

$^{7}Li + {}^{209}Bi \rightarrow \alpha + {}^{212-x}Po + xn$

(negligible charged particle evaporation!)



- Polonium incomplete fusion products must be associated with a Z=2 particle that is unaccompanied by any other charged fragment: “unaccompanied α”

Cook, Carter *et al.* PRC 97 021601(R) (2018)
Cook, Simpson *et al.* PRL 122 102501 (2019)

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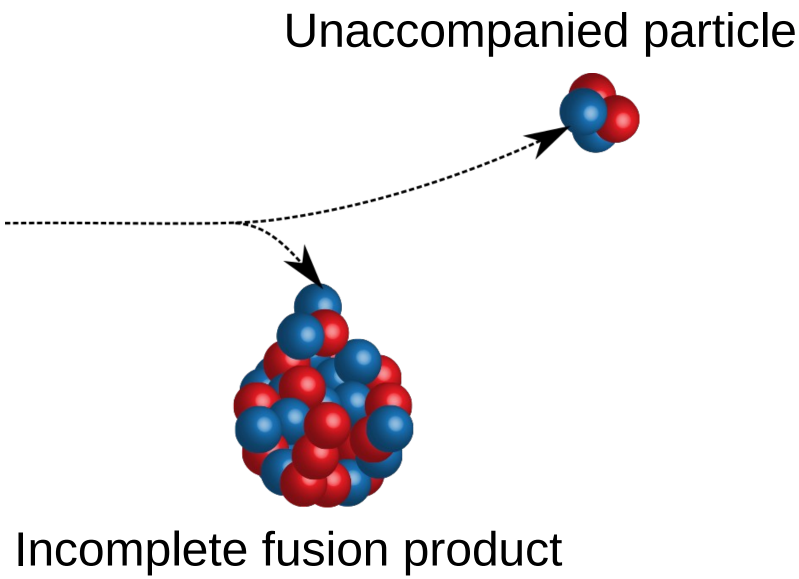

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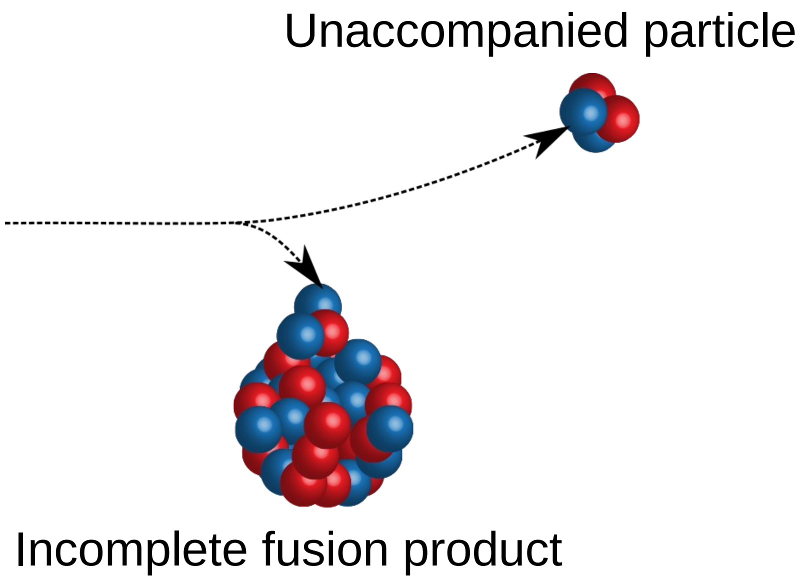

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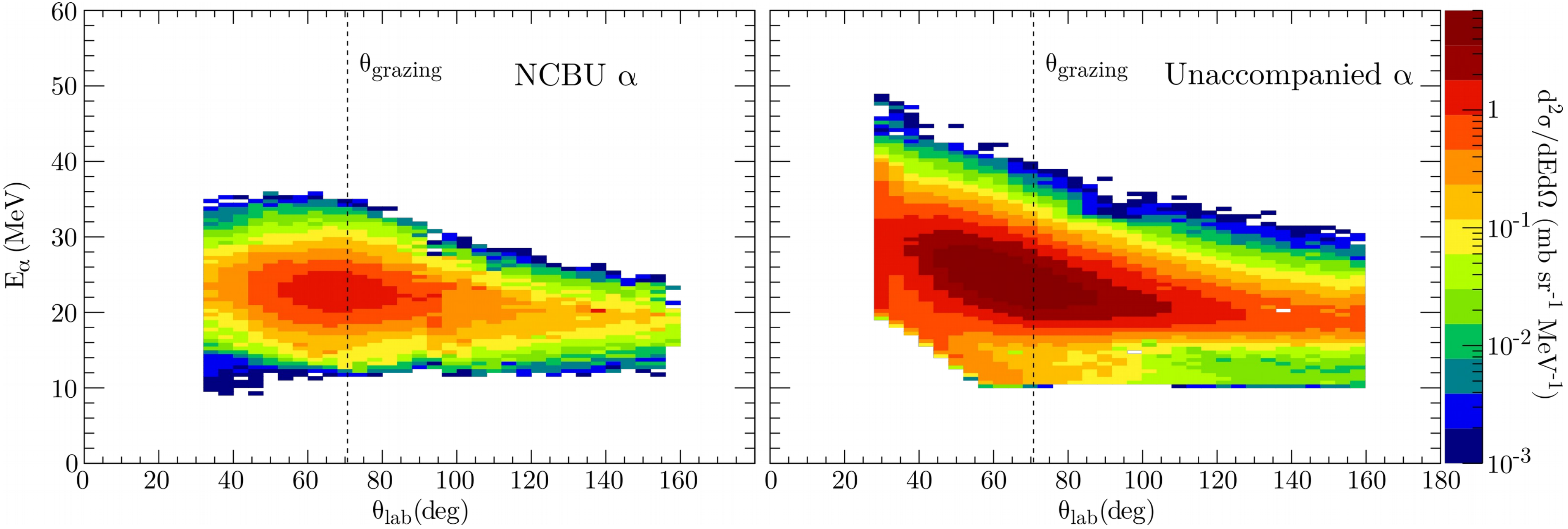
- The same reaction mechanism that produces incomplete fusion products (and CF supp) produces unaccompanied particles!
- Experimentally: σ(Unaccompanied α) = σ(Inclusive α) – σ(NCBU α)

Easy-ish

Hard!

Cook, Carter *et al.* PRC 97 021601(R) (2018)
Cook, Simpson *et al.* PRL 122 102501 (2019)

Unaccompanied α vs BU

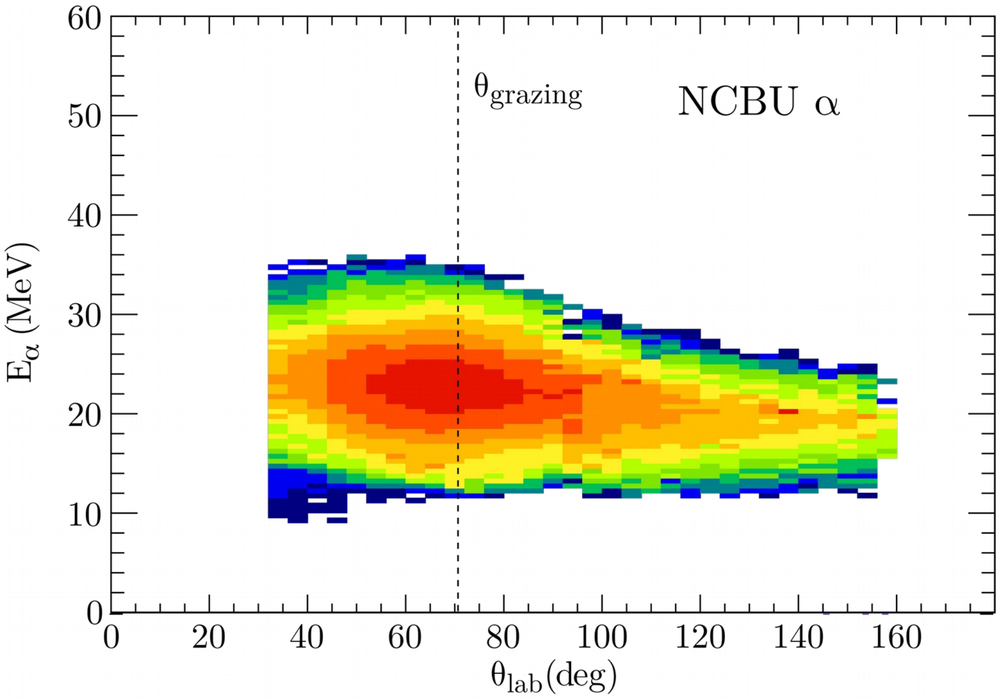


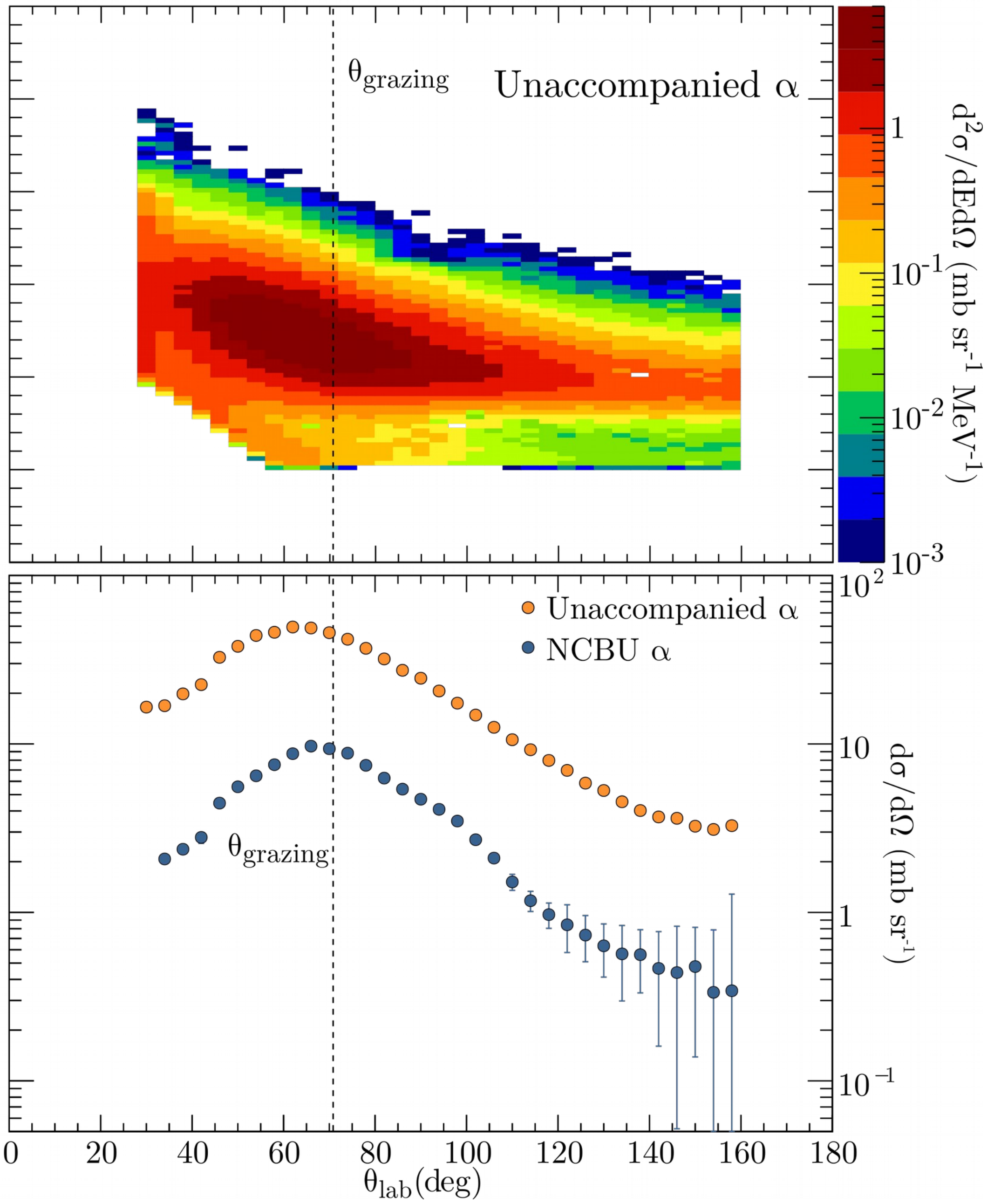
The unaccompanied α particles:

- Extend to much higher energies
- Exhibit a very different correlation in E_α and θ
- Have a much higher cross section at all angles
- Peak at a more forward angle

Cook, Simpson *et al.* PRL 122 102501 (2019)

Unaccompanied α vs BU





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Cook, Simpson *et al.* PRL 122 102501 (2019)

Classical dynamical model calculations

Can the unaccompanied α and the no-capture breakup be explained by the same reaction mechanism?

- Classical dynamical simulation of breakup
- Constrained to individual no-capture breakup cross-sections & relative energy distributions

Model information:
Simpson, Cook *et al EPJ WoC 163 2017*

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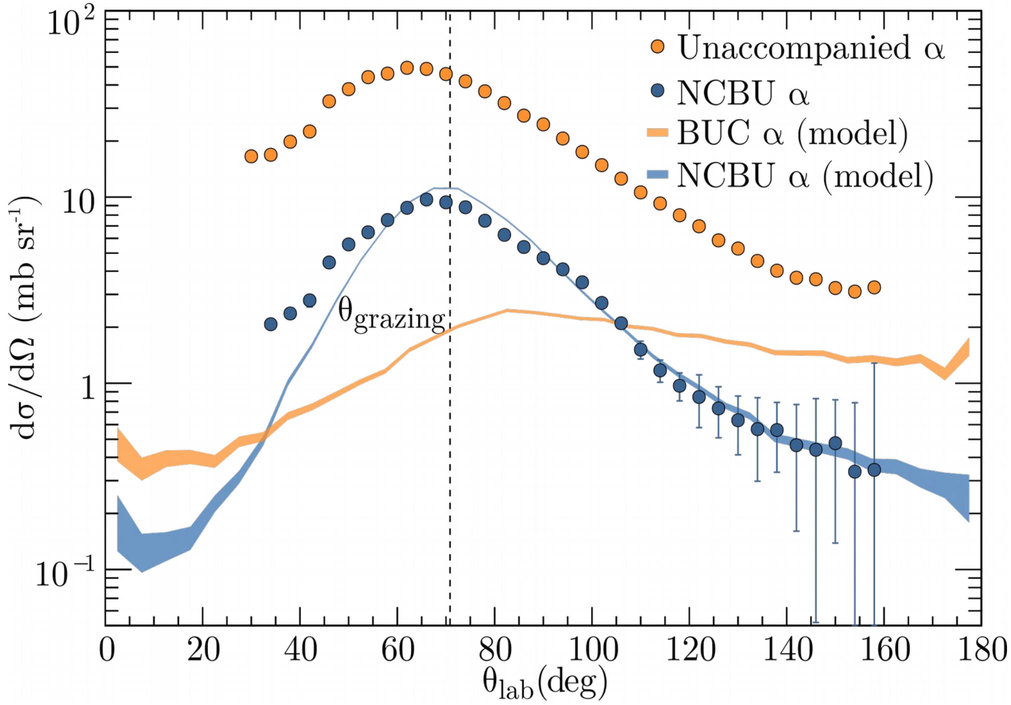

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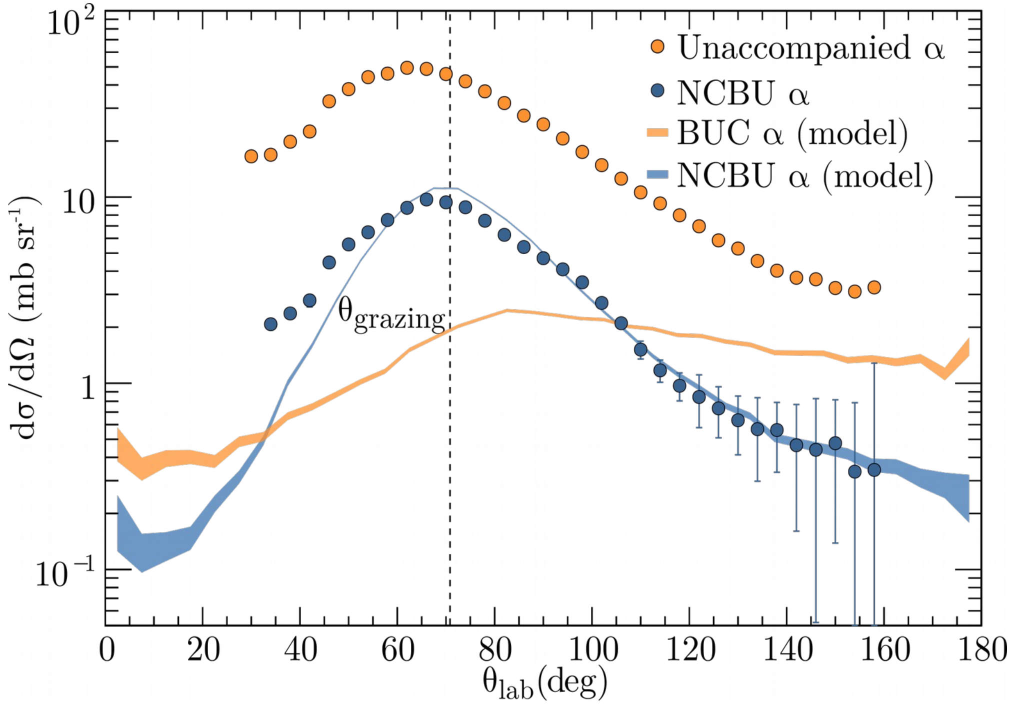
- Constrained to individual no-capture breakup cross-sections & relative energy distributions
- Simulation reproduces no-capture breakup but not the unaccompanied α
- Breakup-capture peaks backward of no-capture breakup.
- Breakup-capture does not explain unaccompanied α yields.

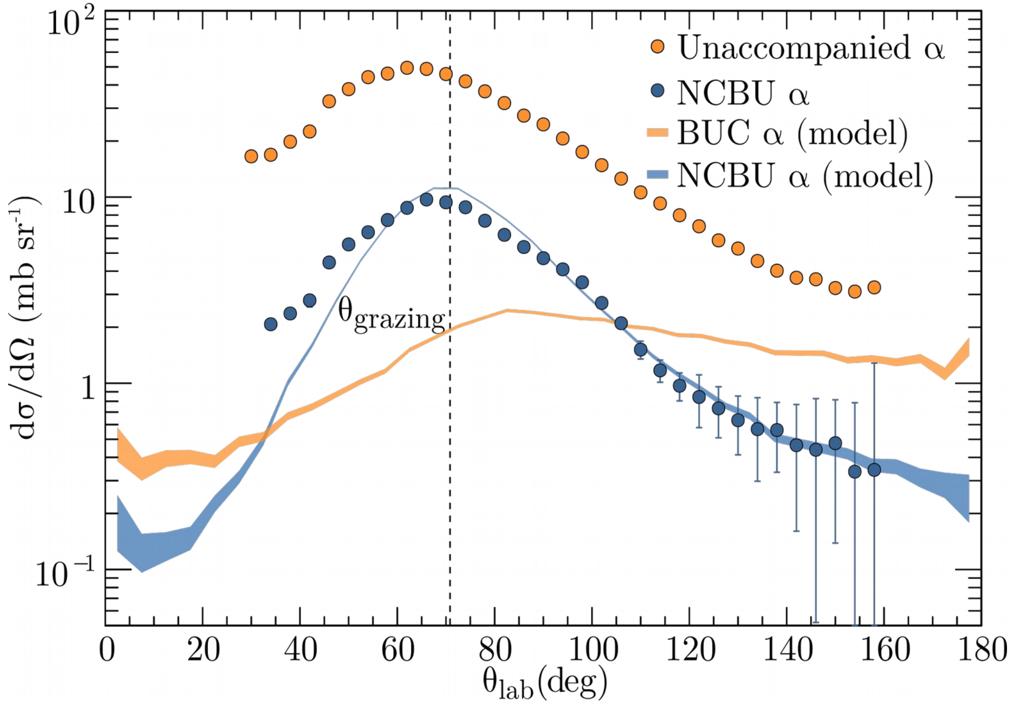


Model information:
Simpson, Cook *et al EPJ WoC 163 2017*

Classical dynamical model calculations

Can the unaccompanied α and the no-capture breakup be explained by the same reaction mechanism?

- Classical dynamical simulation of breakup
- Constrained to individual no-capture breakup cross-sections & relative energy distributions
- Simulation reproduces no-capture breakup but not the unaccompanied α
- Breakup-capture peaks backward of no-capture breakup.
- Breakup-capture does not explain unaccompanied α yields.

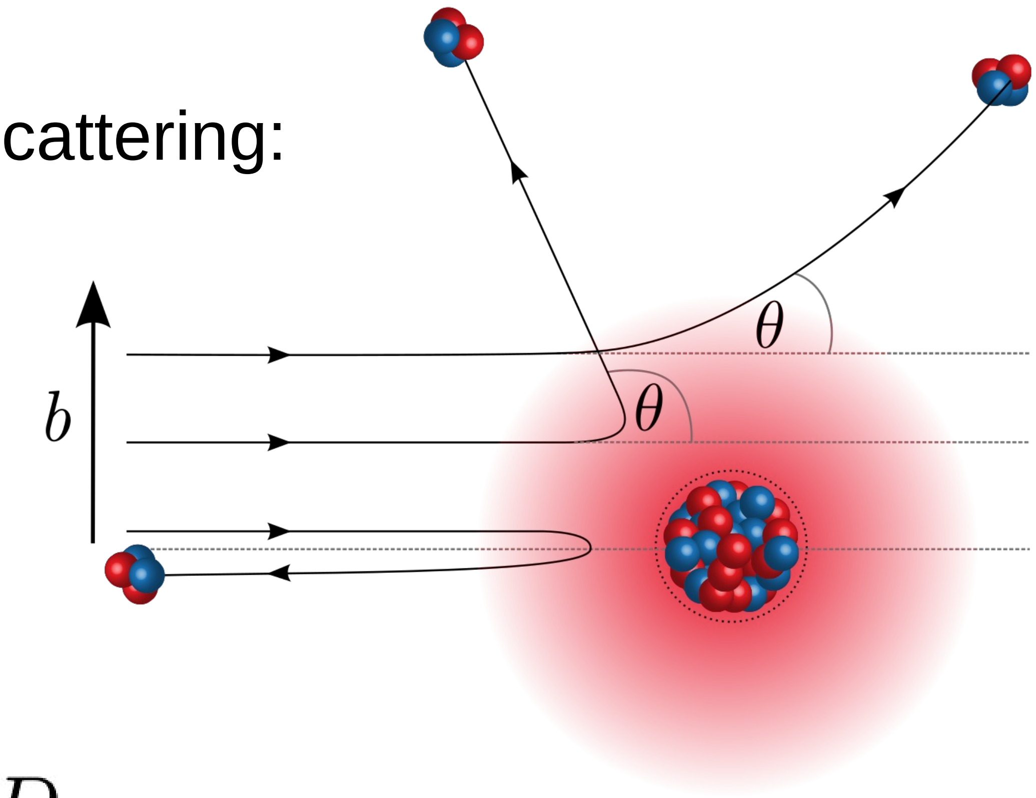


But maybe we don’t need a model…

Model information:
Simpson, Cook *et al EPJ WoC 163 2017*

Can the unaccompanied α be explained by BU?

Rutherford scattering:



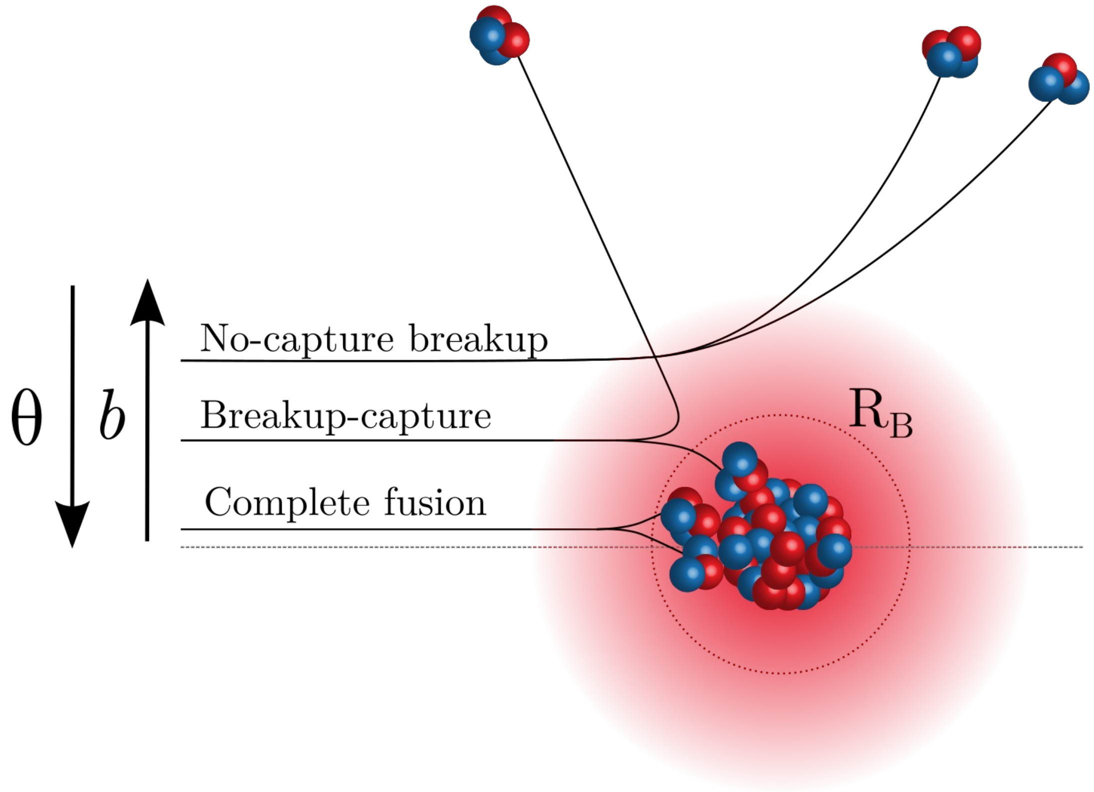
$$\tan\frac{\theta}{2} = \frac{D}{2b}$$

$$D = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 E}$$

b↑ θ↓

More central trajectories → scattering to more backward angles

Can the unaccompanied α be explained by BU?



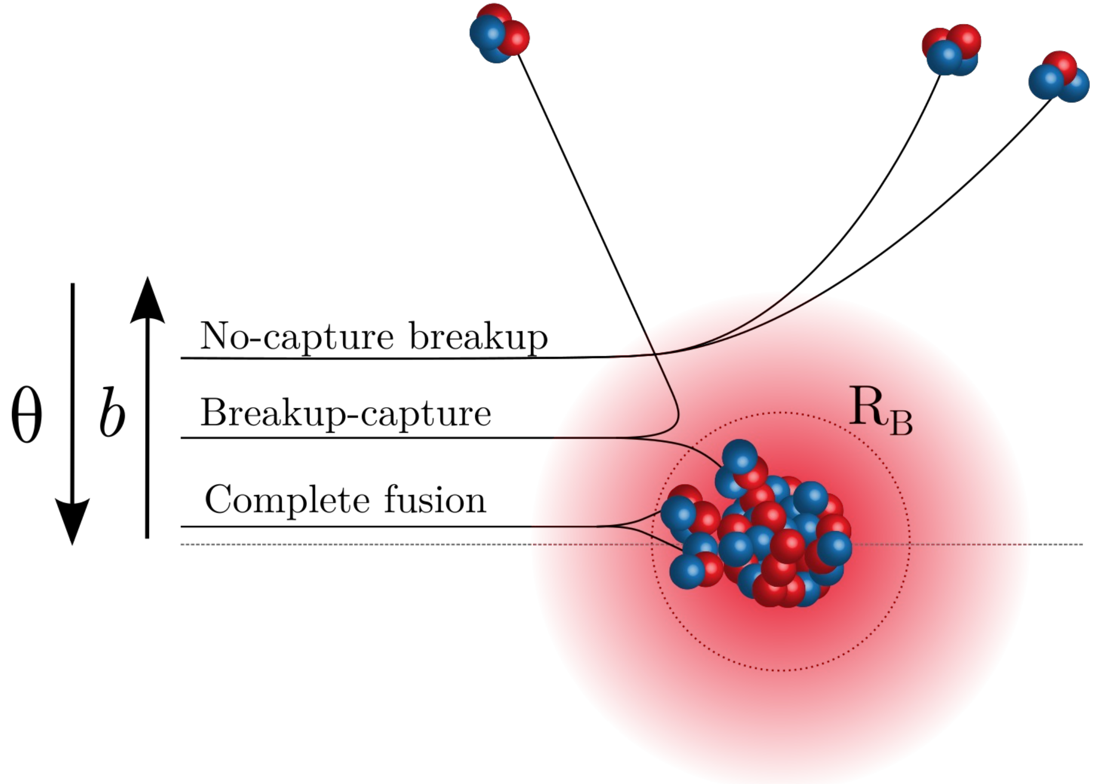
Breakup followed by capture of one fragment (breakup-capture) leading to incomplete fusion products will occur on more central trajectories than no-capture breakup:

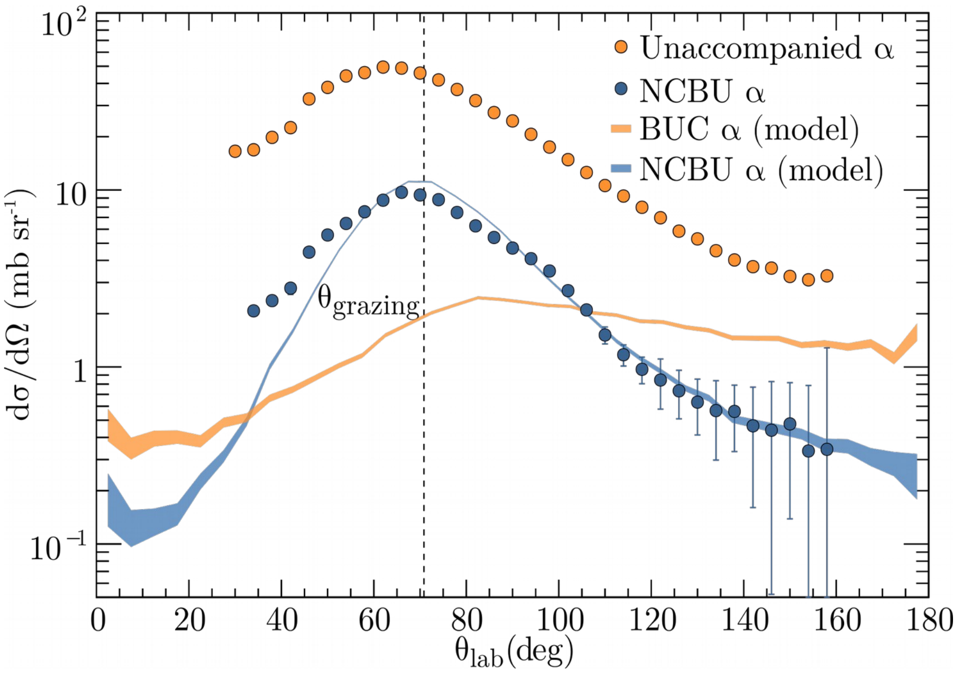
b(breakup-capture) < b(no-capture breakup)

↓

θ(breakup-capture) > θ(no-capture breakup)

Can the unaccompanied α be explained by BU?





Breakup followed by capture of one fragment (breakup-capture) leading to incomplete fusion products will occur on more central trajectories than no-capture breakup:

b(breakup-capture) < b(no-capture breakup)

θ(breakup-capture) > θ(no-capture breakup)

… But the unaccompanied α peak *forward* of the no-capture breakup.
So, what is the mechanism? Cluster transfer is the only mechanism left!

Clues: Coincidences with decay alphas

$$^{7}\mathrm{Li} + {}^{209}\mathrm{Bi} \rightarrow \alpha + {}^{212}\mathrm{Po}$$

$$\alpha + {}^{208}\mathrm{Pb}\ (t_{1/2} = 295\ \mathrm{ns})$$

Tag the prompt α with the decay α

Cook, Simpson *et al.* PRL 122 102501 (2019)

Clues: Coincidences with decay alphas

$$^{7}\mathrm{Li} + {}^{209}\mathrm{Bi} \rightarrow \alpha + {}^{212}\mathrm{Po}$$

$$\downarrow$$

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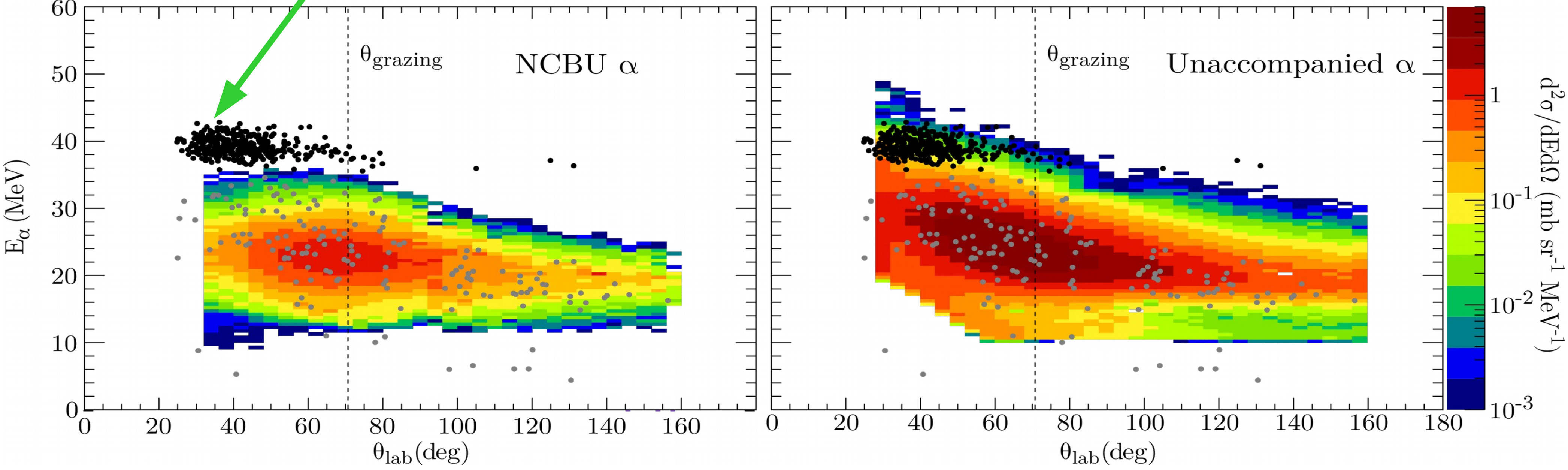
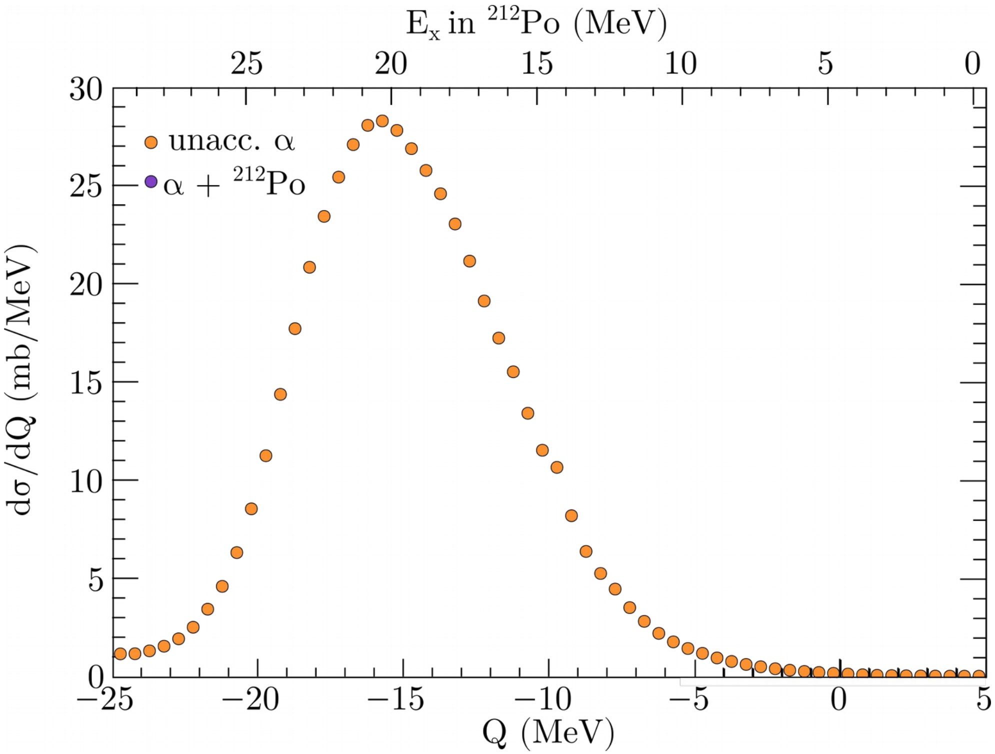


These α fall totally outside range of NCBU α and are in the high energy, forward angle tail of unaccompanied α

Cook, Simpson *et al.* PRL 122 102501 (2019)

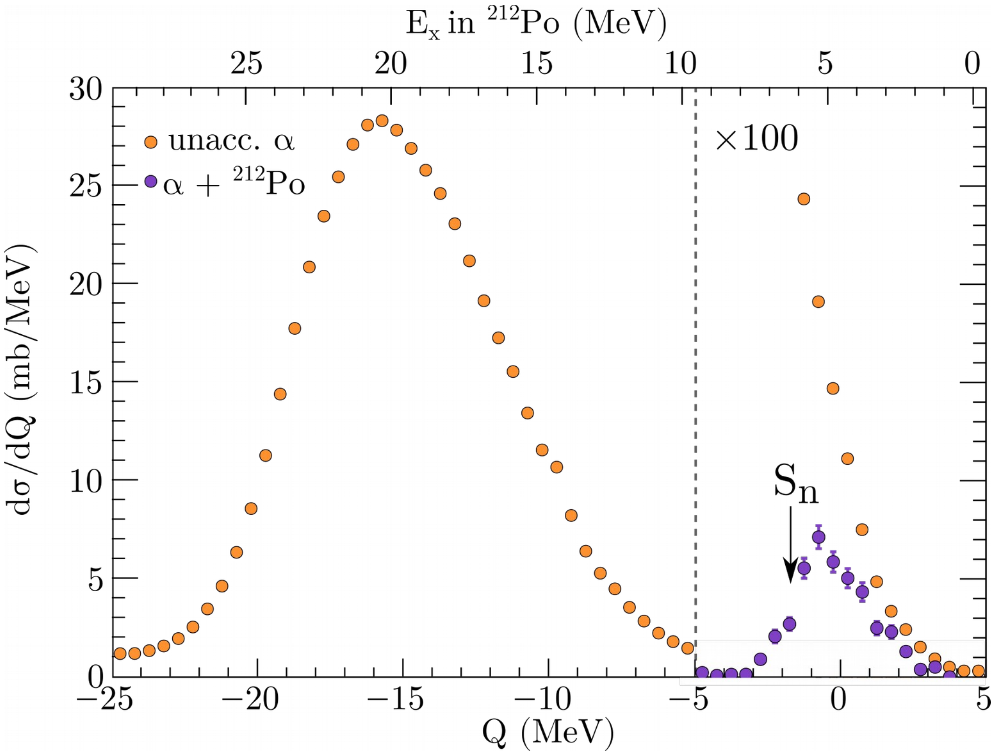
Evidence for cluster transfer



Q-value spectrum reconstructed from dσ/dEdθ

Cook, Simpson *et al.* PRL 122 102501 (2019)

Evidence for cluster transfer



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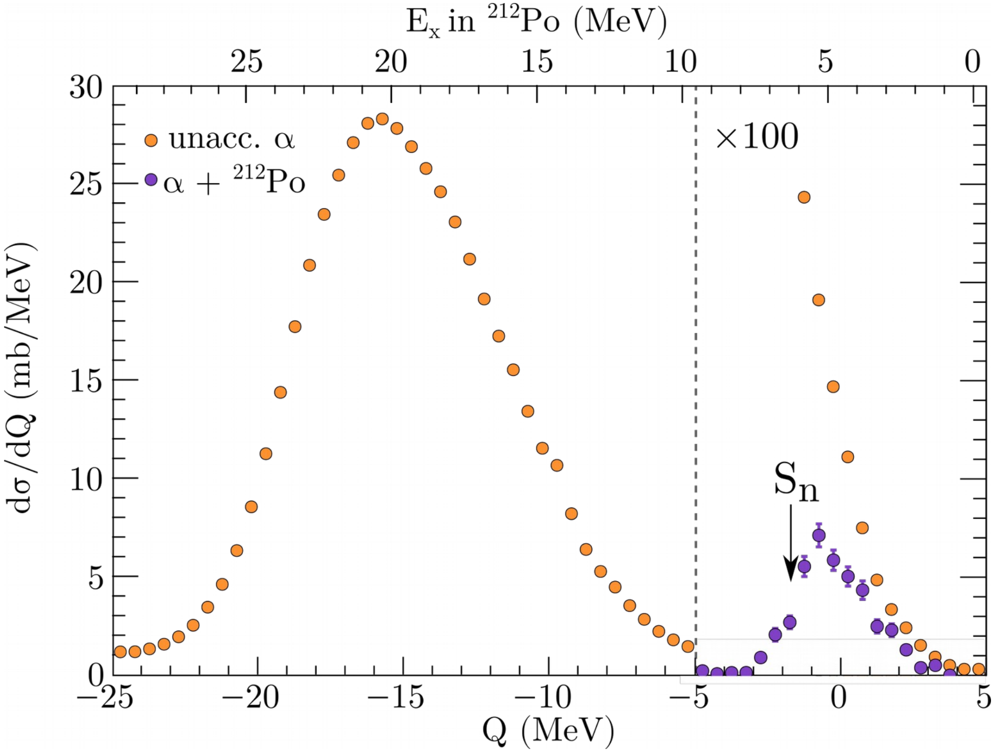
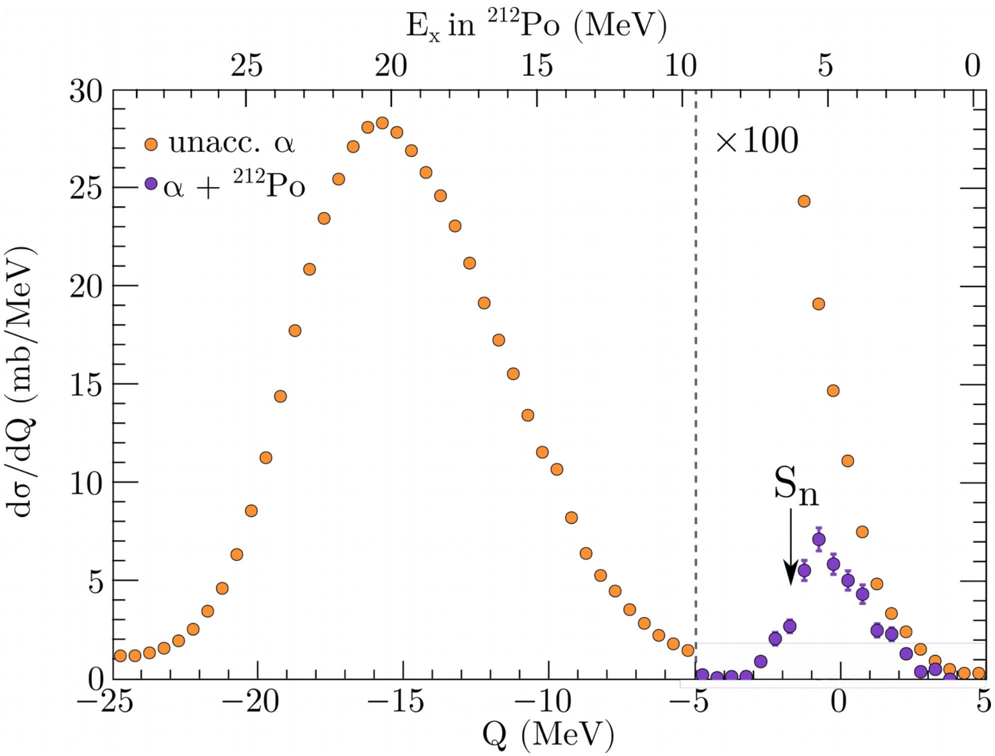


Q-value spectrum reconstructed from dσ/dEdθ

- Coincidence α associated with production of ^{212}Po at low excitation energy, E_x, below S_n = 6.01 MeV.

Cook, Simpson *et al.* PRL 122 102501 (2019)

Evidence for cluster transfer



Q-value spectrum reconstructed from dσ/dEdθ

- Coincidence α associated with production of ^{212}Po at low excitation energy, E_x, below S_n = 6.01 MeV.
- E_x from triton capture after breakup > 7.061 MeV (Q-value for triton capture).

Cook, Simpson *et al.* PRL 122 102501 (2019)

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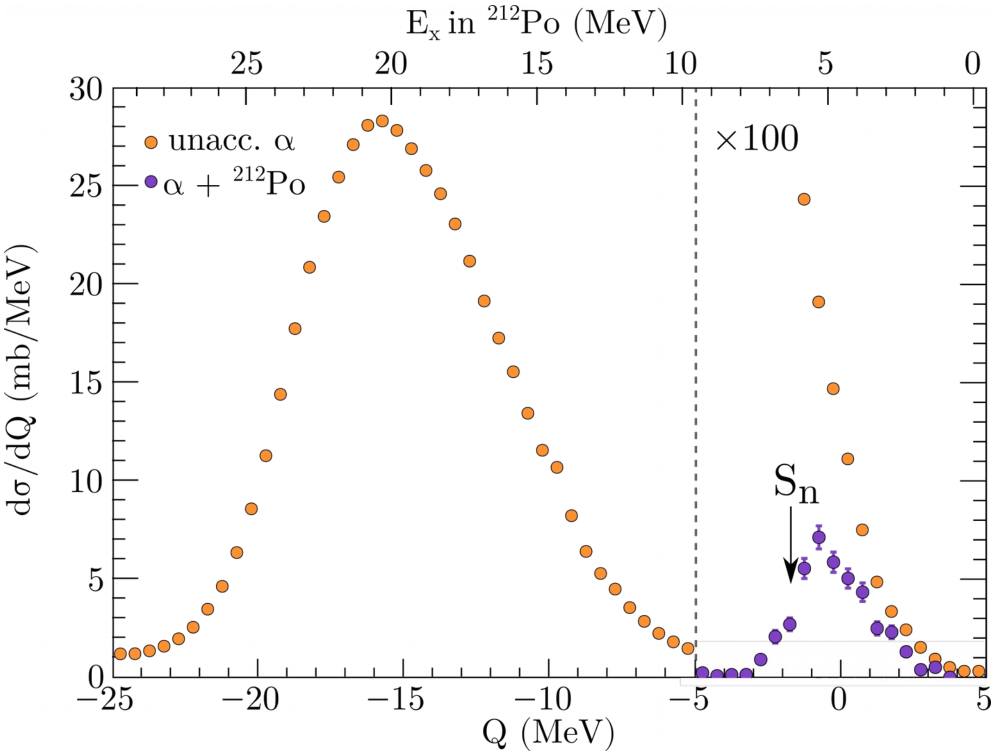

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- E_x from triton capture after breakup > 7.061 MeV (Q-value for triton capture).
- The ^{212}Po yield *must* arise from direct triton cluster transfer from ^{7}Li.

Cook, Simpson *et al.* PRL 122 102501 (2019)

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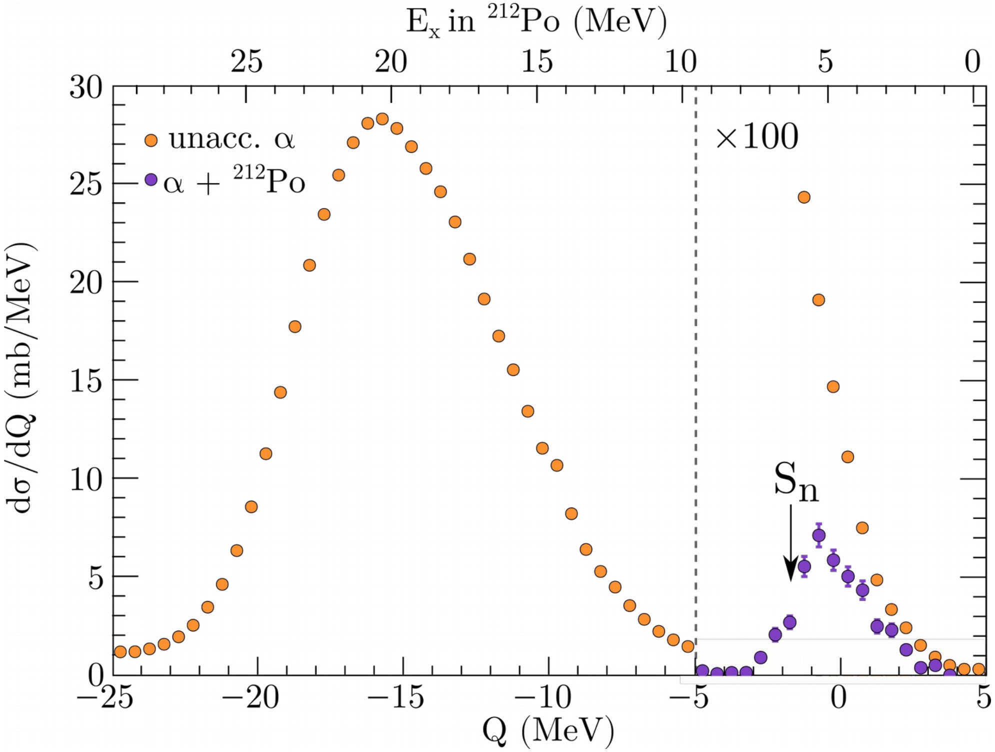
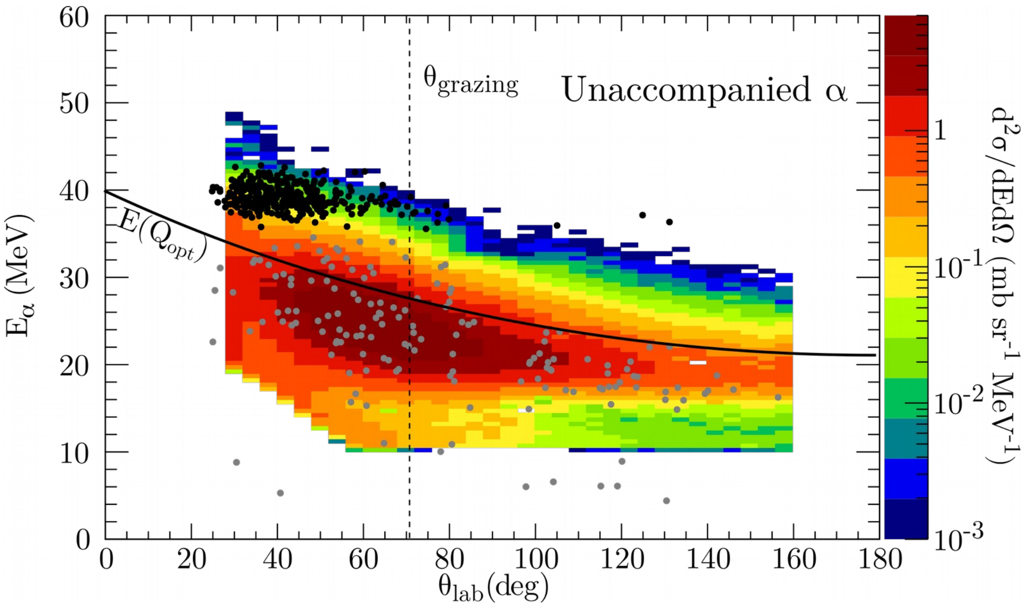


Q-value spectrum reconstructed from dσ/dEdθ

- Coincidence α associated with production of ^{212}Po at low excitation energy, E$_x$, below S$_n$ = 6.01 MeV.
- E$_x$ from triton capture after breakup > 7.061 MeV (Q-value for triton capture).
- The ^{212}Po yield *must* arise from direct triton cluster transfer from ^{7}Li.
- The ^{212}Po events form the tail of the much broader unaccompanied α Q-value distribution.

Cook, Simpson *et al.* PRL 122 102501 (2019)

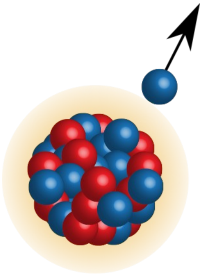
Evidence for cluster transfer

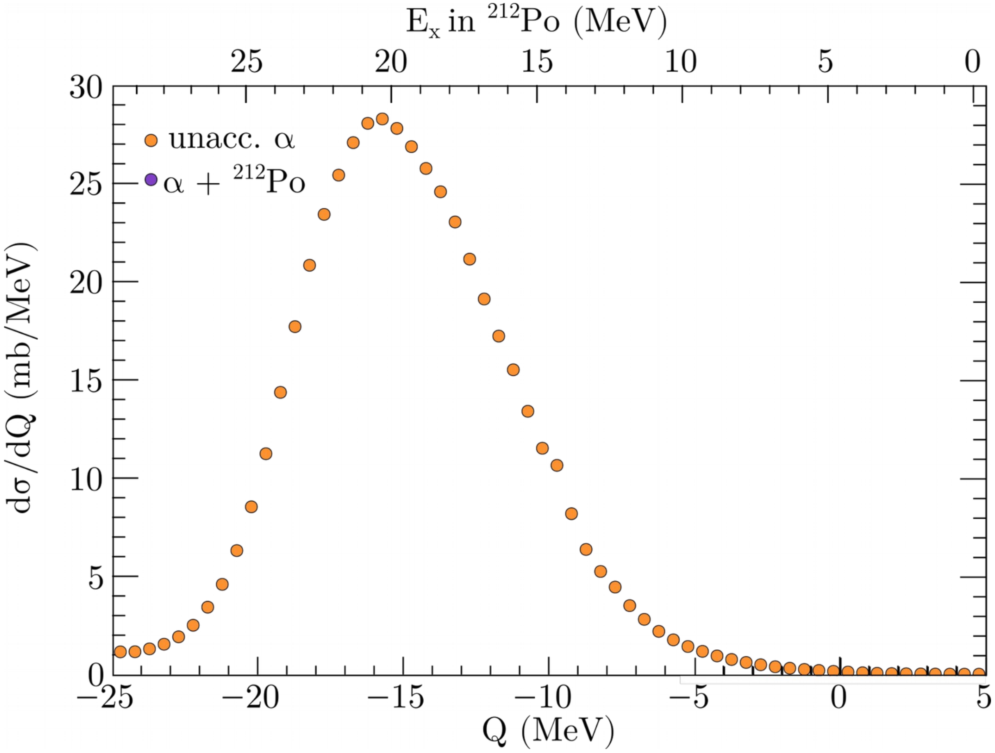


- Unaccompanied α E vs θ → consistent α produced at the Optimum Q-value (Q_{opt}) [Schiffer PLB 44 (1973)]. (Excitation energy with highest cross-section, expected from a transfer reaction)
- The total unaccompanied α distribution is therefore broadly consistent with production of ^{212}Po up to E_x ~ 28 MeV via triton cluster transfer.

Cook, Simpson *et al.* PRL 122 102501 (2019)

Excitation energy + n evaporation

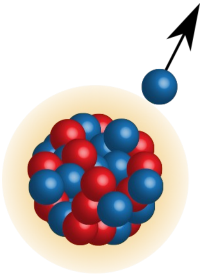


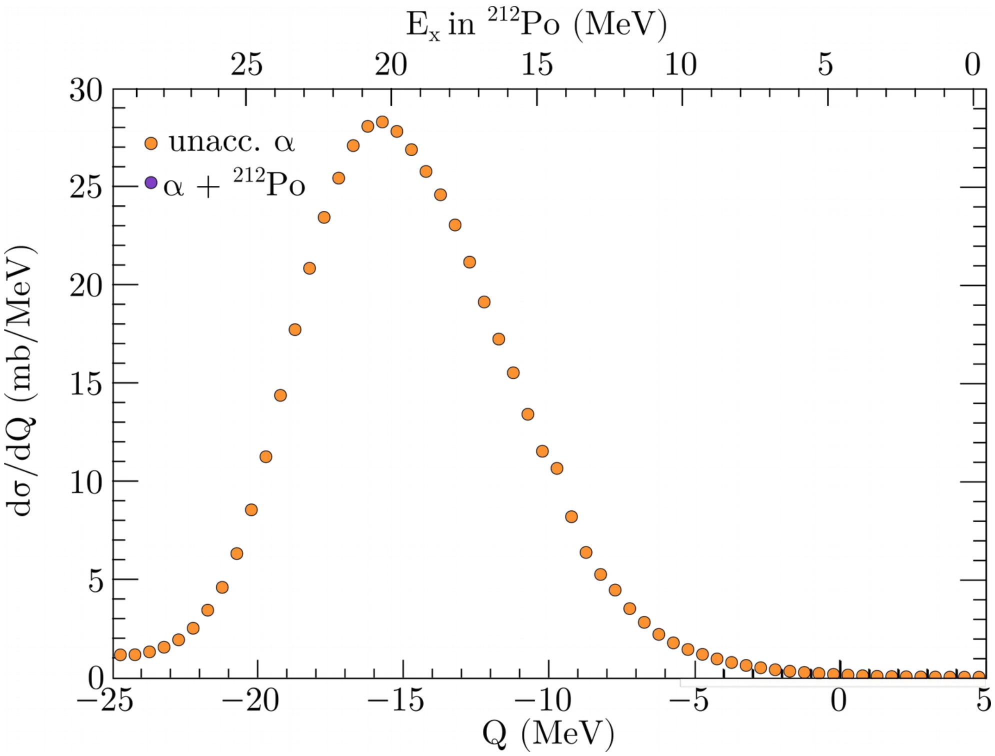


- ^{212}Po produced at high E_x → neutron evaporation. This is the mechanism producing lighter Po.

Cook, Simpson *et al.* PRL 122 102501 (2019)

Excitation energy + n evaporation

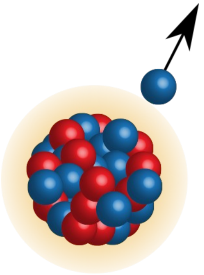


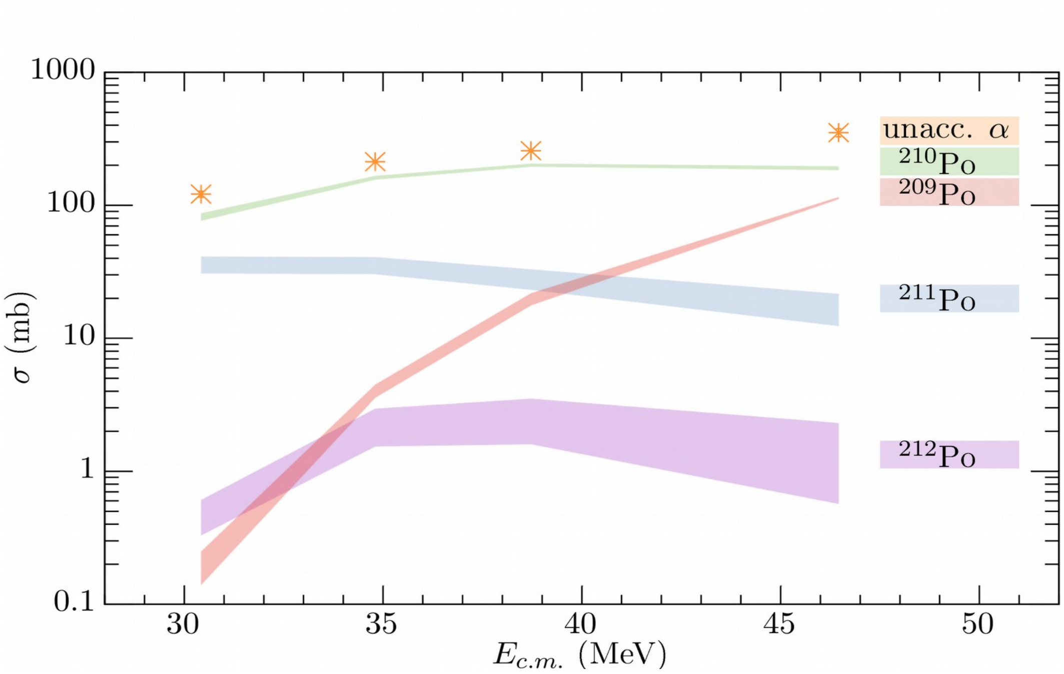


- ^{212}Po produced at high E_x → neutron evaporation. This is the mechanism producing lighter Po.
- How to test? Use statistical model calculations (PACE4) to give probability of neutron evaporation as a function of E_x, and fold with experimental E_x distributions.

Cook, Simpson *et al.* PRL 122 102501 (2019)

Excitation energy + n evaporation





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Cook, Simpson *et al.* PRL 122 102501 (2019)

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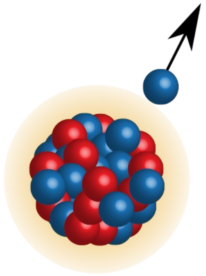

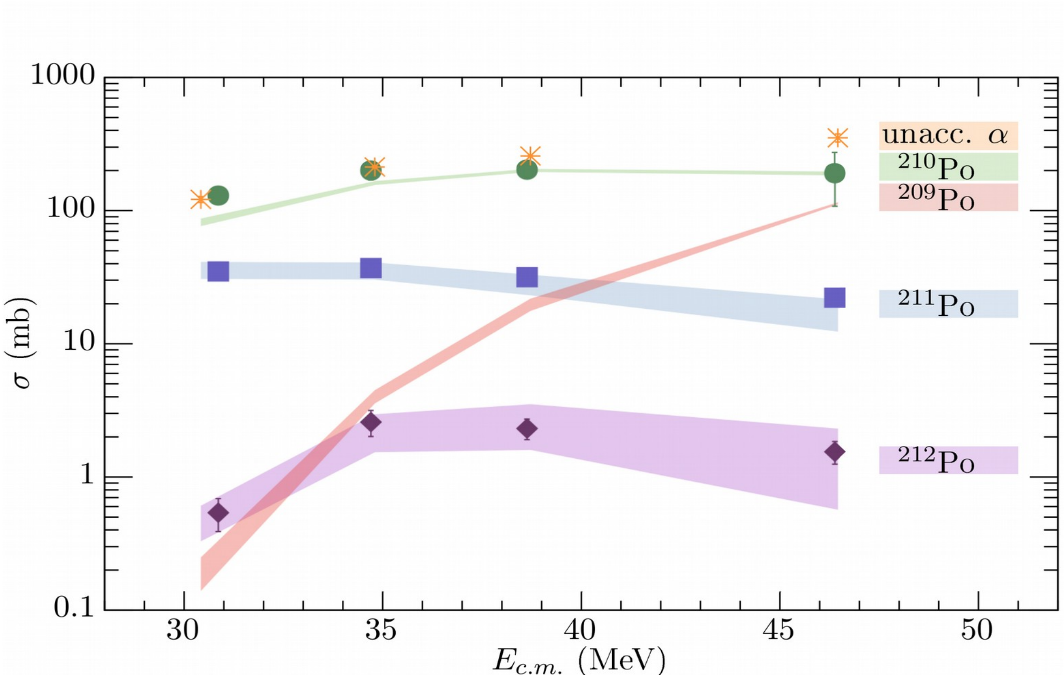

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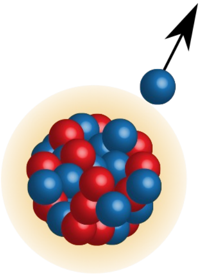
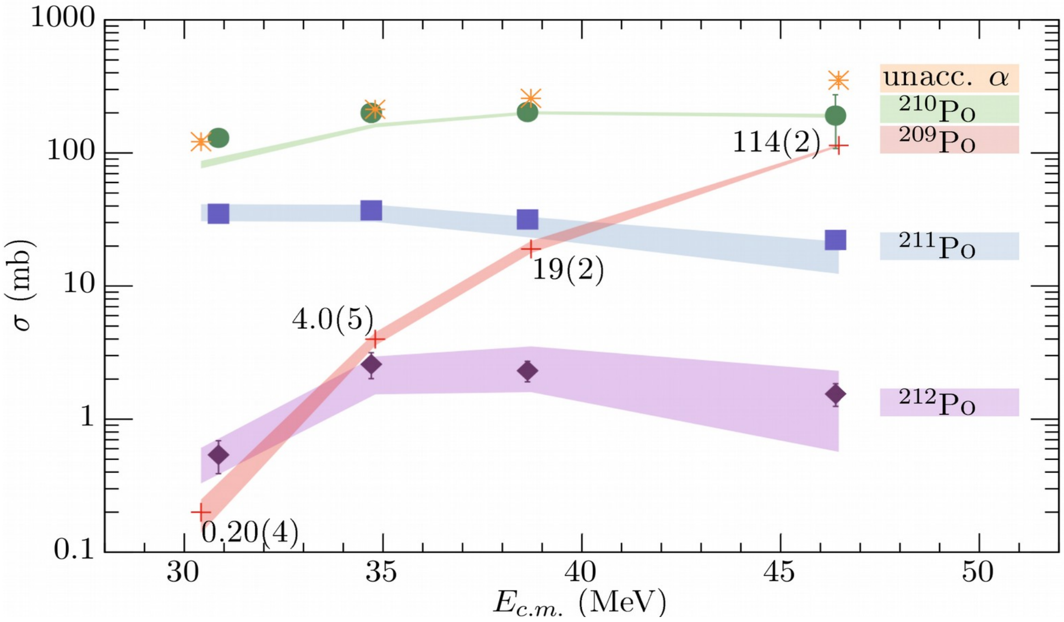
- The Po cross-sections from this procedure compare very favorably with existing measurement from α decay (Dasgupta PRC 2004) → The Po isotopic distribution is consistent with production of ^{212}Po via *t* transfer followed by evaporation.

Cook, Simpson *et al.* PRL 122 102501 (2019)

Excitation energy + n evaporation





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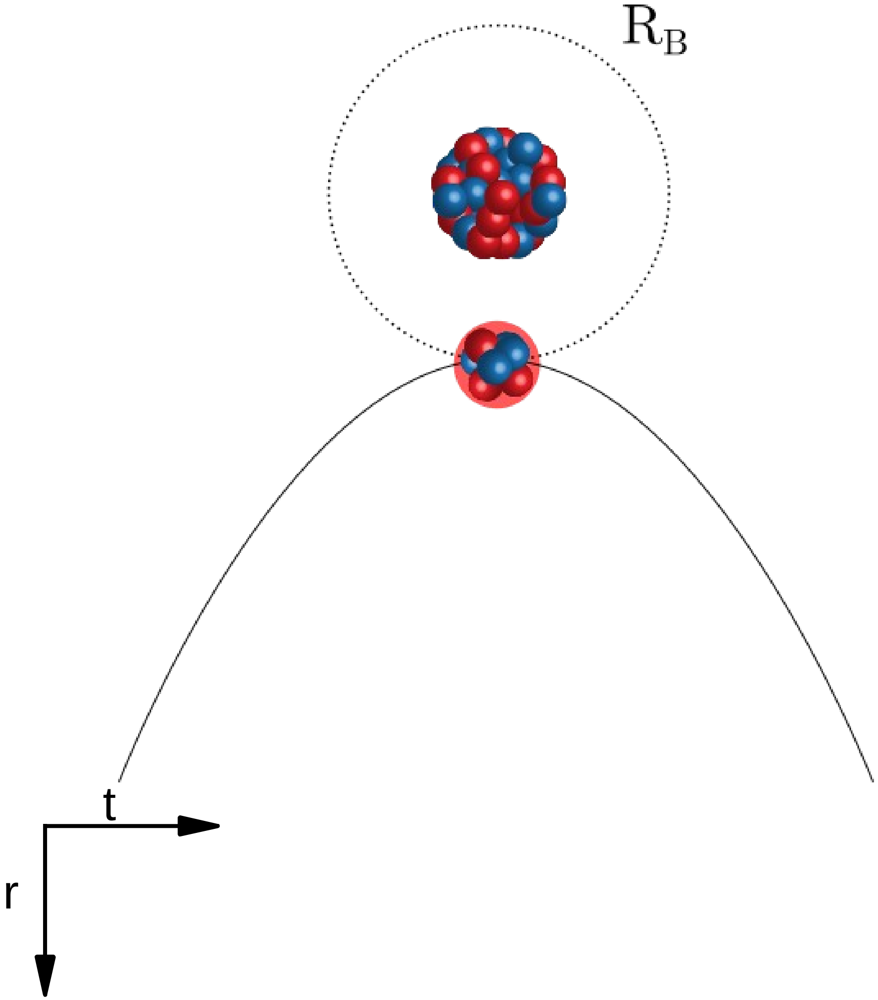
- Prediction for ^{209}Po ($t_{1/2}$ = 124 years)

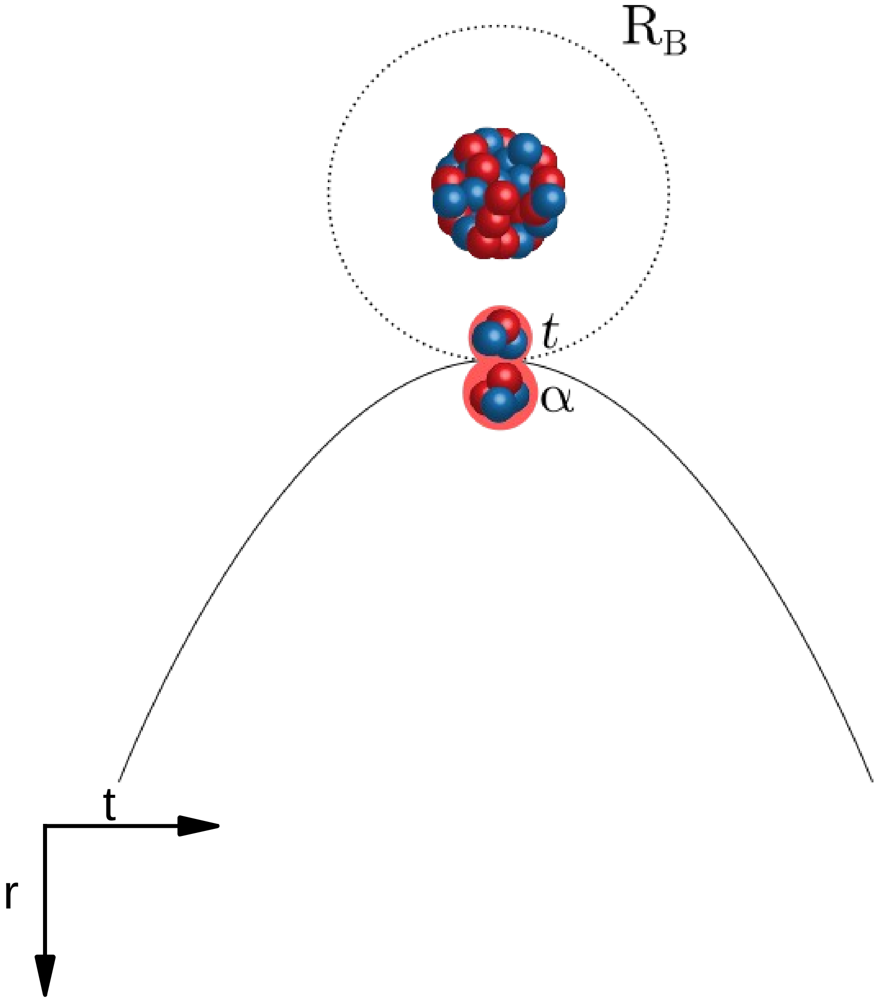
Cook, Simpson *et al.* PRL 122 102501 (2019)

What is the mechanism for suppression of complete fusion?



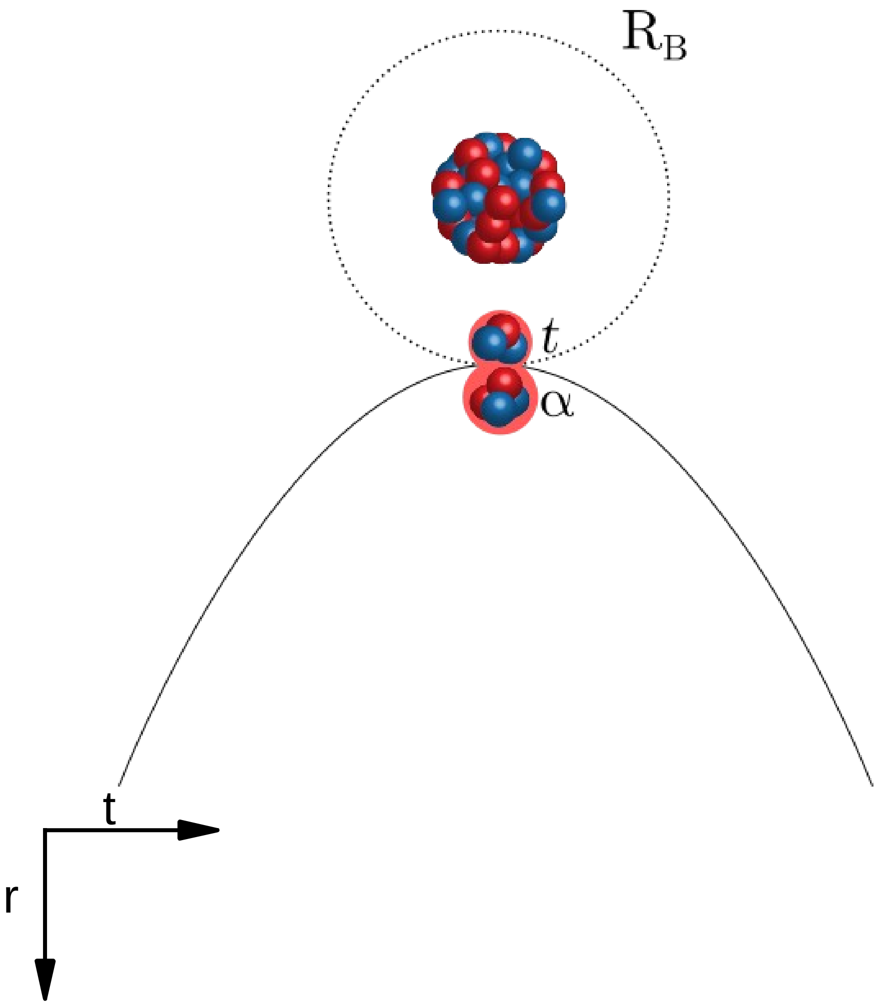
What is the mechanism for suppression of complete fusion?

- Weak binding leads to strong clustering → Displacement of clusters from the center of mass.



What is the mechanism for suppression of complete fusion?

- Weak binding leads to strong clustering → Displacement of clusters from the center of mass.
- This makes the triton amenable to transfer → **ICF**



What is the mechanism for suppression of complete fusion?

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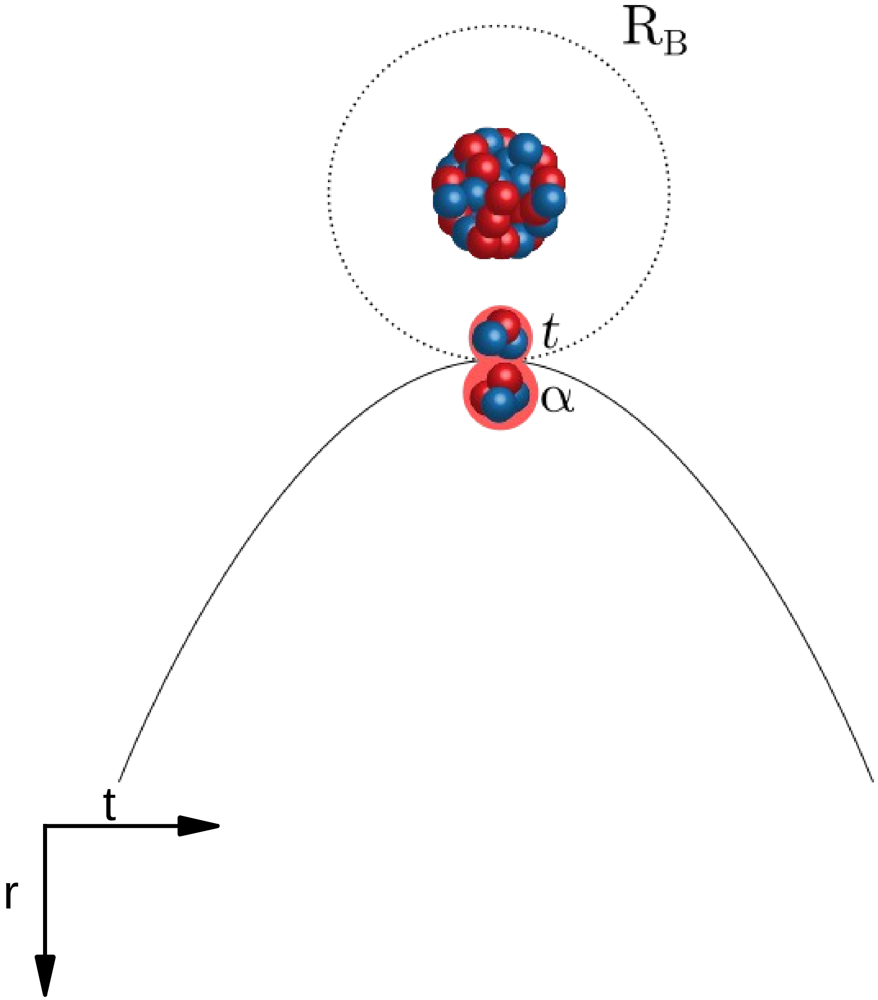
- Requires the center of mass of the ^{7}Li projectile to get closer to the target so that the entire projectile fuses. → **CF suppression**



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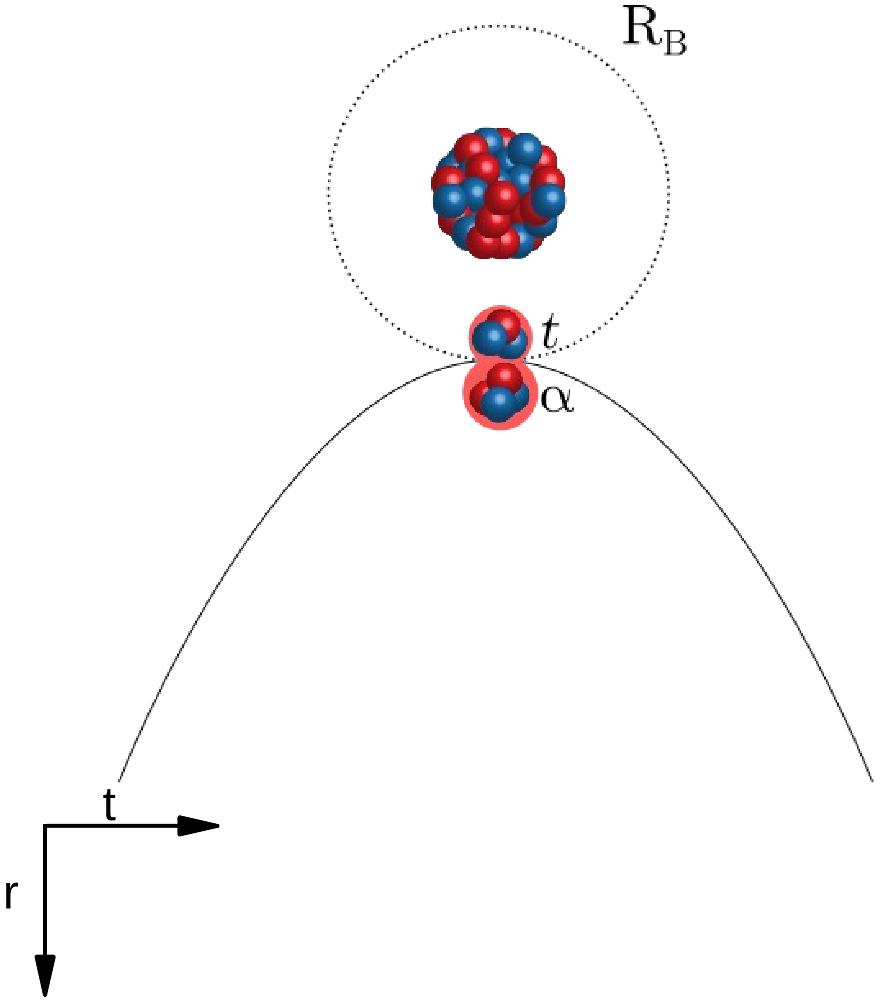
- Numerical support from Lei & Moro PRL 122 042503 (2019) using the Ichimura, Austern, and Vincent (IAV) spectator-participant inclusive breakup model. They associate it with a “Trojan Horse” mechanism.



This should be true wherever nuclei are strongly clustered!

Summary

- Breakup followed by capture cannot produce most of the incomplete fusion products in ^{7}Li + ^{209}Bi reactions.
- ^{212}Po is produced by direct triton cluster transfer.
- Unaccompanied α particles (all Po isotopes) are consistent with production via triton transfer.
- Clustering of the projectile nucleus → explains both incomplete fusion products and the suppression of complete fusion.

Outlook

- **New technique:** Measurements of unaccompanied particle spectra offer a new and widely applicable approach to understand near-barrier fusion dynamics of weakly bound nuclei.
- **New interpretation:** The idea that cluster transfer rather than breakup is responsible for complete fusion suppression should be valid for any nuclides that exhibit strong clustering.
- **Need new measurements:**
  - How does this picture evolve at the limits of weak binding? The cross sections for complete and incomplete fusion products in reactions of exotic nuclei, such as ^{6}He, ^{8}Li, and ^{7,10,11}Be, ^{8}B, will provide very interesting insights into near-barrier reaction dynamics.

Physics is a team sport

Ed Simpson
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Sunil Kalkal
Nanda Dasgupta
David Hinde

Lauren Bezzina
Chandrima Sengupta
Cedric Simenel
Kaushik Banerjee

Ben Swinton-Bland
Kirsten Vo-Phouc
Elizabeth Williams
Yun Jeung
Annette Berrimann

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