Colliding heavy nuclei have multiple identities on the path to fusion

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Kaitlin J. Cook, Dominic C. Rafferty, David J. Hinde, Edward C. Simpson, Mahananda Dasgupta, Lorenzo Corradi, Maurits Evers, Enrico Fioretto, Dongyun Jeung, Nikolai Lobanov, Duc Huy Luong, Tea Mijatović, Giovanna Montagnoli, Alberto M. Stefanini & Suzana Szilner

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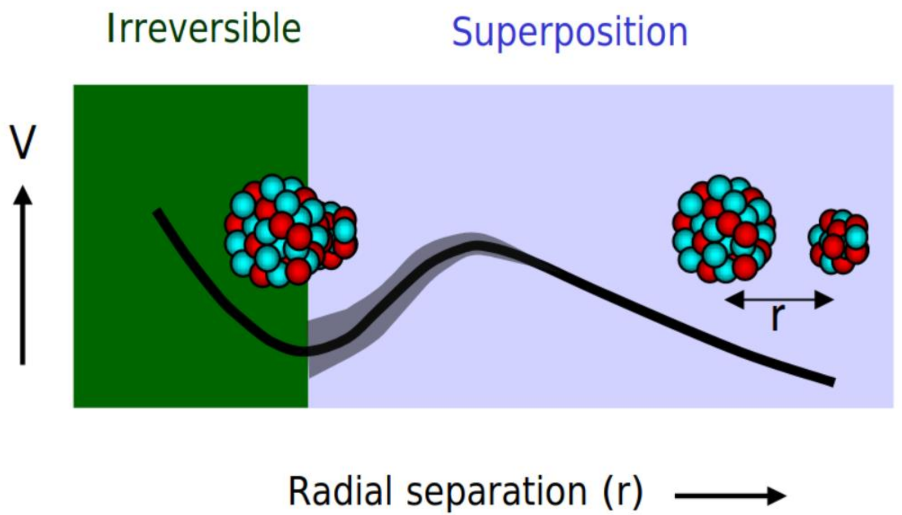
Barrier passing models of fusion



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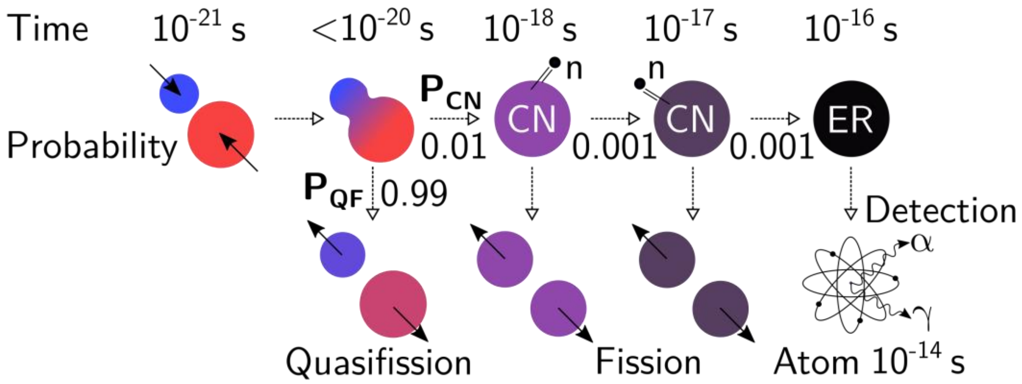
Barrier passing models of fusion

$$\sigma_{EVR} = \sum_{l=0}^{l_{max}} \sigma_{cap}(E_{cm}, l) P_{CN}(E^*, l) W_{surv}(E^*, l)$$



Capture (barrier passing) and subsequent evolution are explicitly decoupled from each other.

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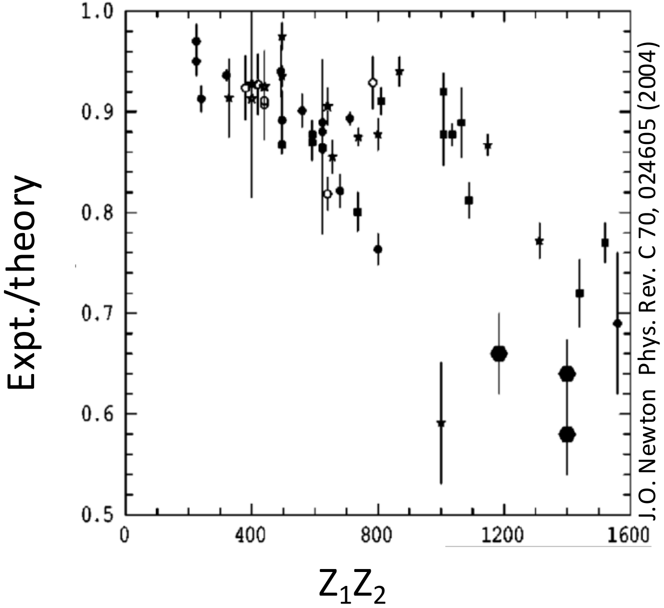
Above barrier σ_{cap} are systematically reduced cf cc

Or: "No one (woods-saxon) potential can reproduce below and above-barrier capture cross-sections"



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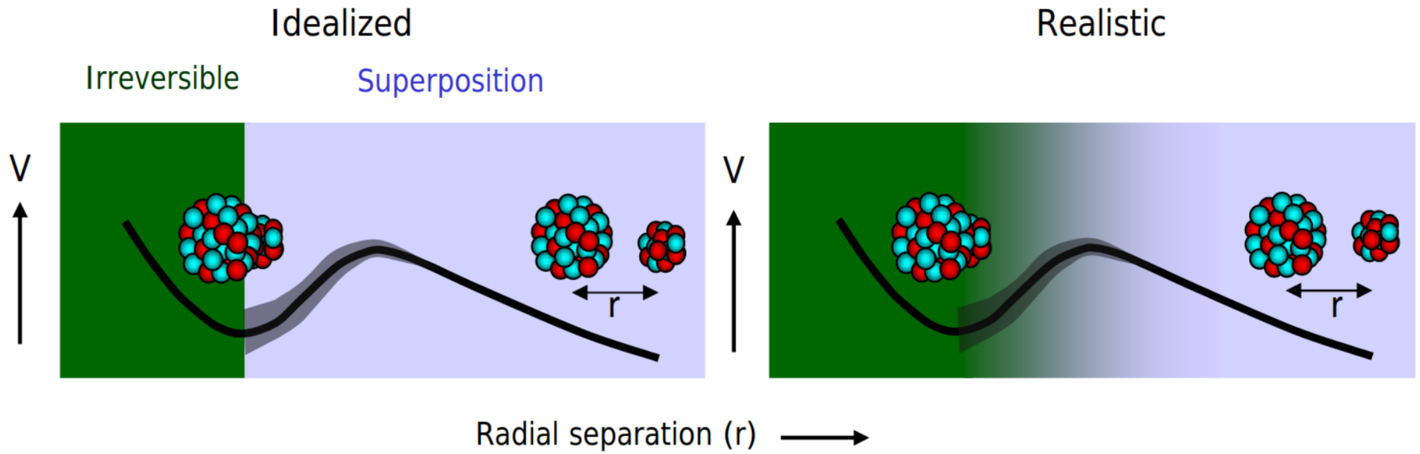
A gradual onset of energy dissipation?



- Proposed to be important at above-barrier and deep sub-barrier energies [Dasgupta 2007]
- Models include Diaz-Torrez (PRC 2010), Yusa, Hagino & Rowley (PRC 2013)
- How do we test this idea, link what we observe to fusion, and provide input for theory?

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MEASUREMENTS OF REFLECTED FLUX

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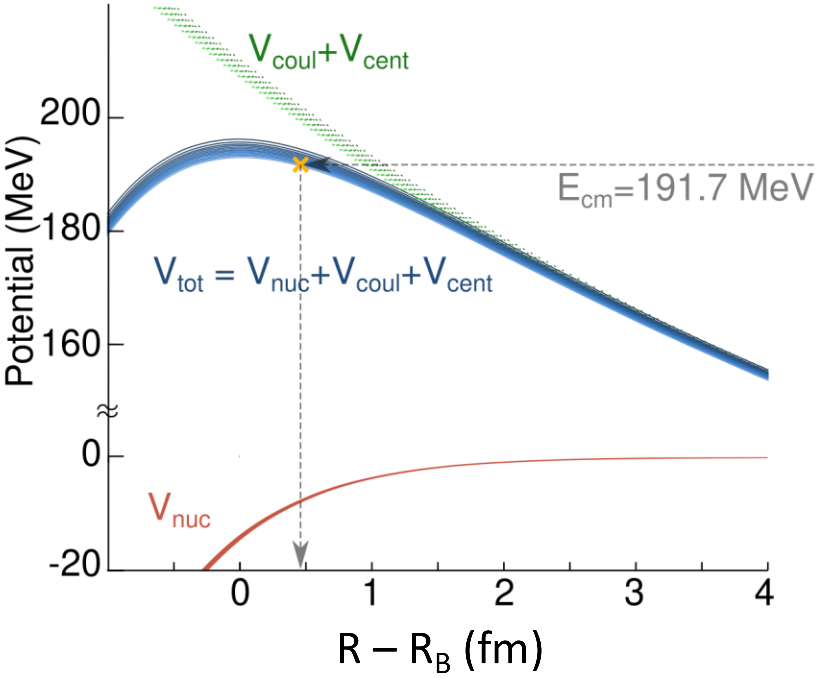
The principle

Measurements at below-barrier energies at a fixed angle (maps to l) represent the integral of all reactions along a trajectory defined by R_{min}



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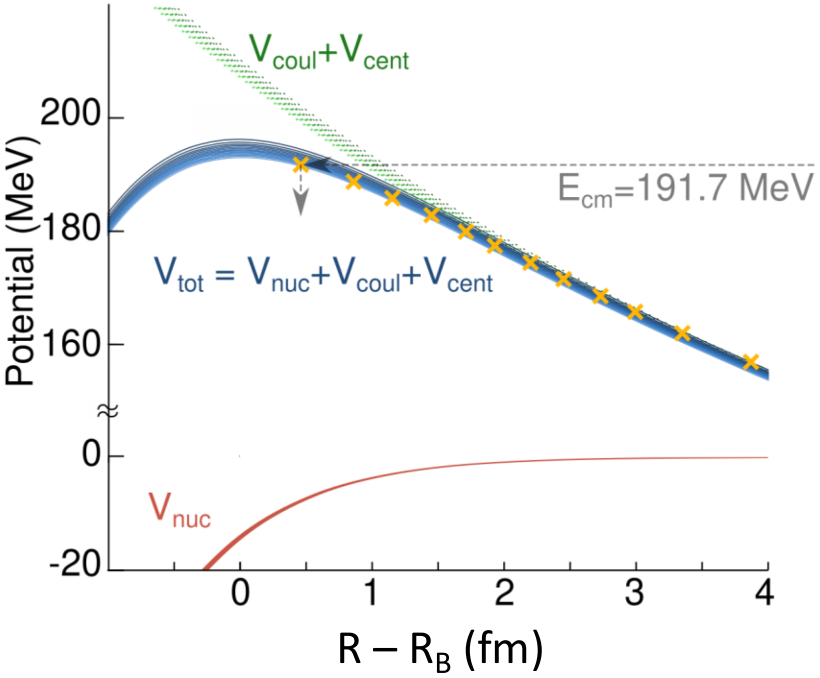
The principle

Measurements at below-barrier energies at a fixed angle (maps to *l*) represent the integral of all reactions along a trajectory defined by R_{min}

→ So, measure the *reflected flux* at different R_{min} (small energy steps) and interrogate how outcomes change as matter overlap increases



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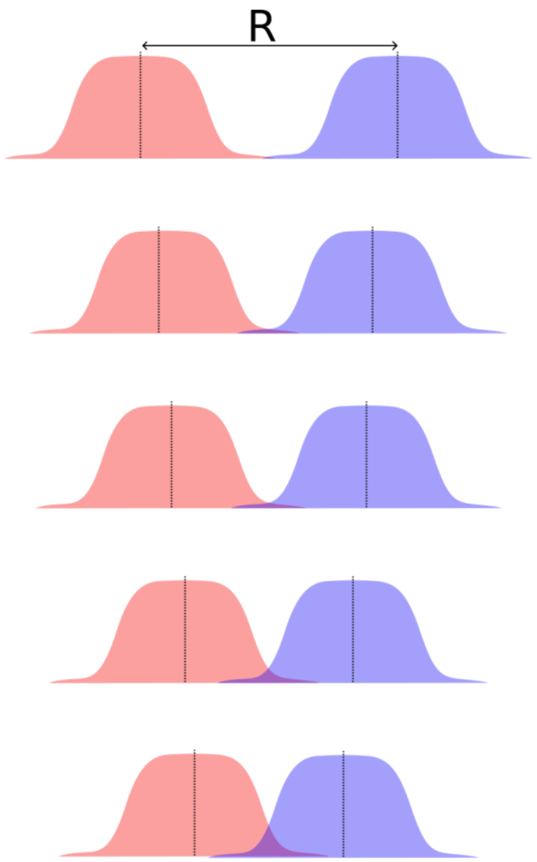
The principle



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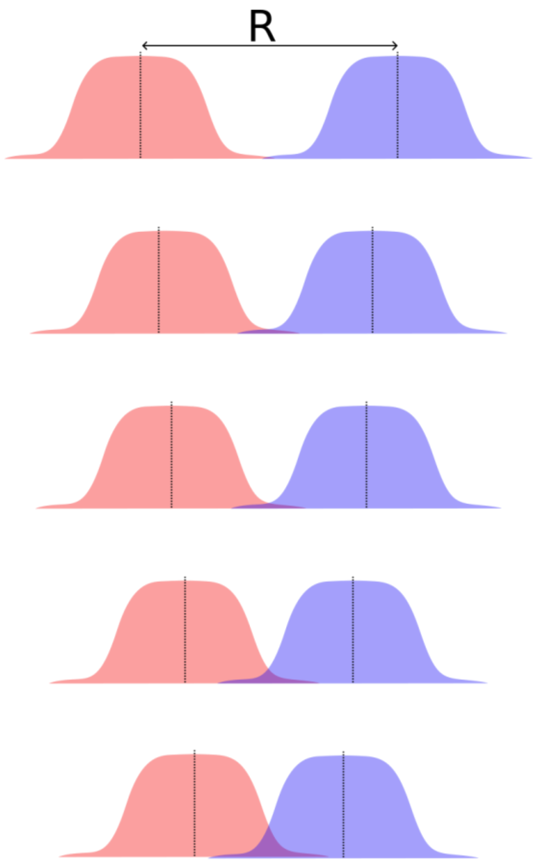
The principle



Measurements at below-barrier energies at a fixed angle (maps to *l*) represent the integral of all reactions along a trajectory defined by R_{min}

→ So, measure the *reflected flux* at different R_{min} (small energy steps) and interrogate how outcomes change as matter overlap increases

→ Reactions that *do* lead to fusion require passage through the same sequences of matter overlap

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$^{40}Ca + ^{208}Pb$ @ PRISMA

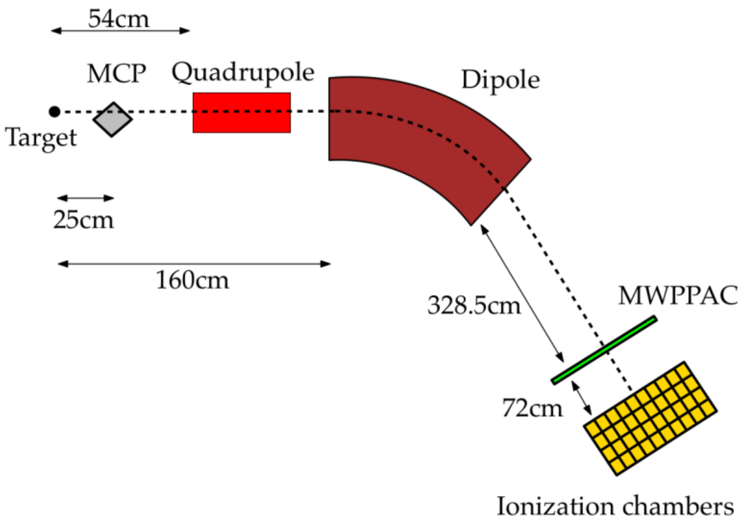
- Expect ~40% fusion suppression ($Z_1Z_2 = 1640$)
- Substantial signatures of transfer and energy loss above the barrier already seen [Szilner PRC 044610 2005]
- Is a rough analogy for superheavy synthesis reactions (while avoiding many experimental & interpretation issues)

Measurement:

ANU NRD group + PRISMA collaboration

Kinematically complete: reflected flux at 115° measured with PRISMA -> A, Z, KE

12 energy steps, 0.8 - 0.99 $E/V_B(l)$



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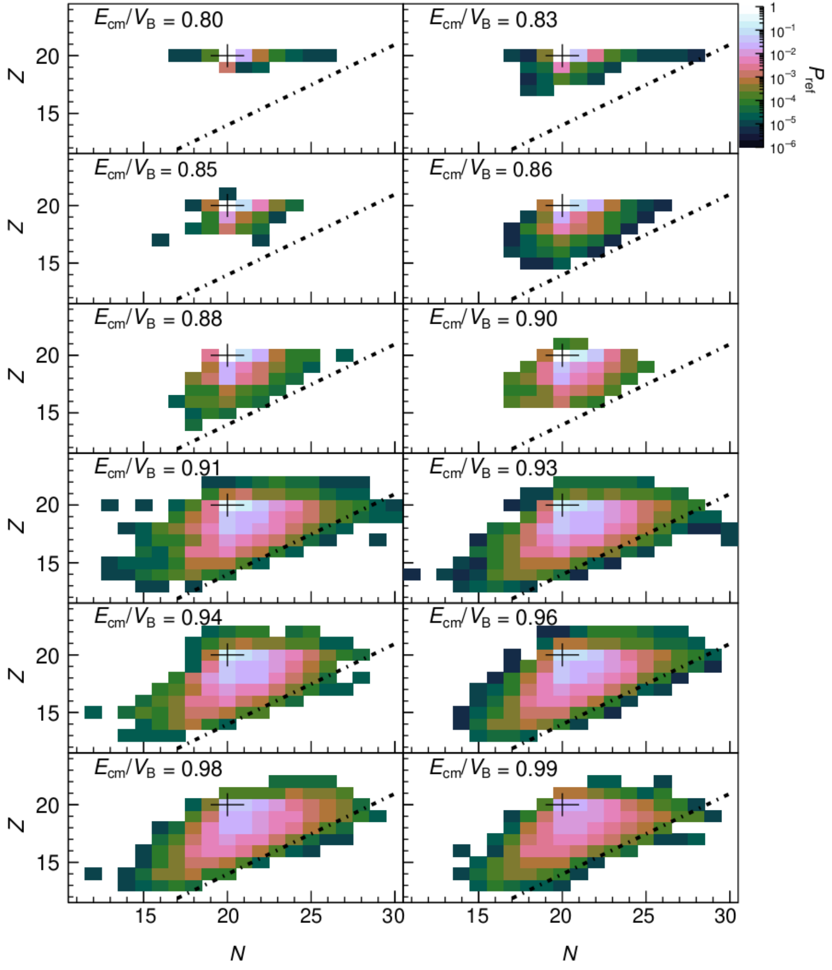
N,Z distributions



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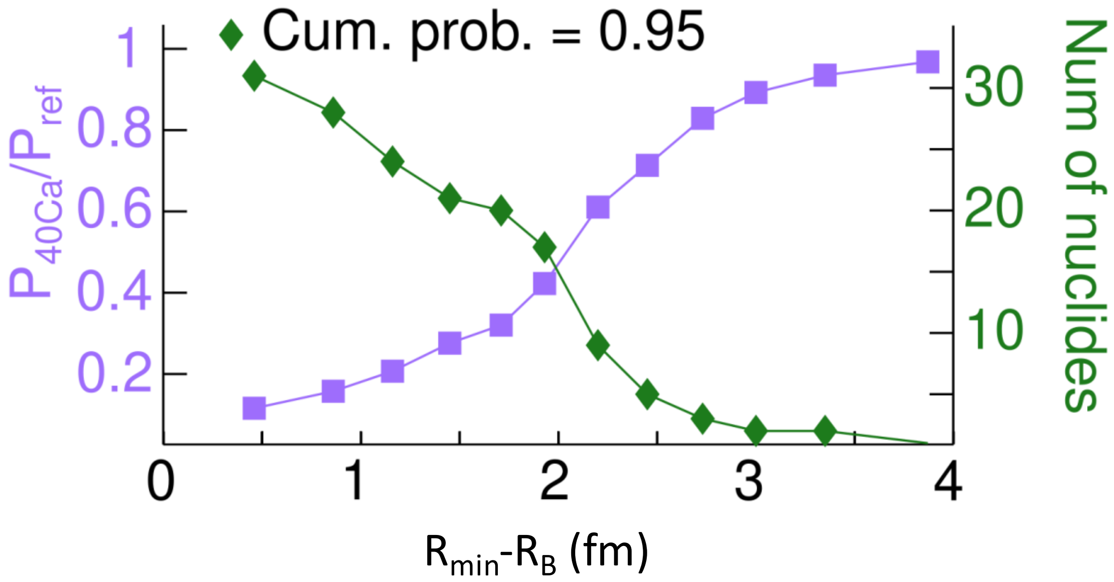
Rapidly increasing complexity



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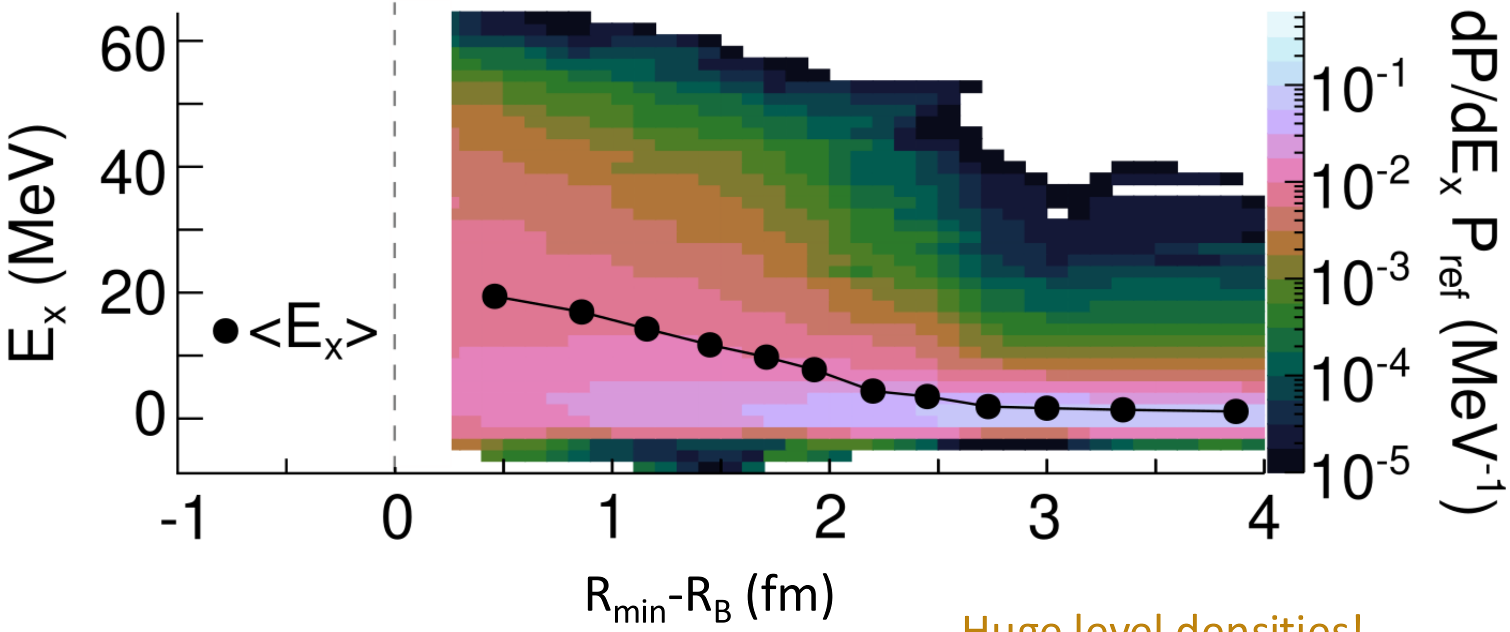
Excitation energy distributions



Huge level densities!

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Summary so far

Substantial amounts of multinucleon transfer begins outside the barrier.

The transfers lead to high excitation energies.

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"This looks awfully like deep inelastic scattering"!

A general feature of heavy-ion collisions [Corradi 2009], and we've shown here that it begins *outside* the barrier*

Long identified as the "energy loss mode" in heavy-ion collisions [Bjørnholm & Swiatecki 1982]

Modelled classically but it evolves smoothly from few-nucleon transfer + inelastic scattering which *must* be treated coherently

*Also seen by

Wolfs PRC 36 1987
Gehrig PRC 55 1997

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HOW DO BARRIER PASSING MODELS WORK AS WELL AS THEY DO?

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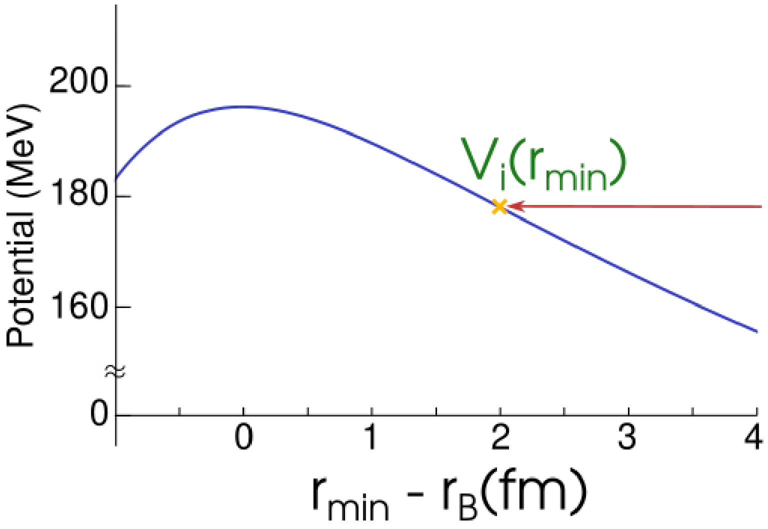
Change in available energy



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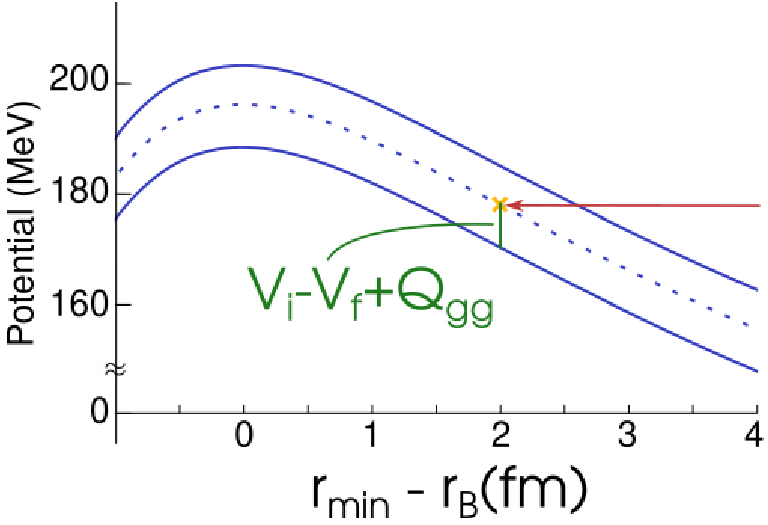
Change in available energy

Transfer of nucleons results in a change in the **available** energy:



$$\Delta E_{gg} = Q_{gg} + (V_i(R_{min}) - V_f(R_{min}))$$

This energy can go into **kinetic energy** or **excitation energy**

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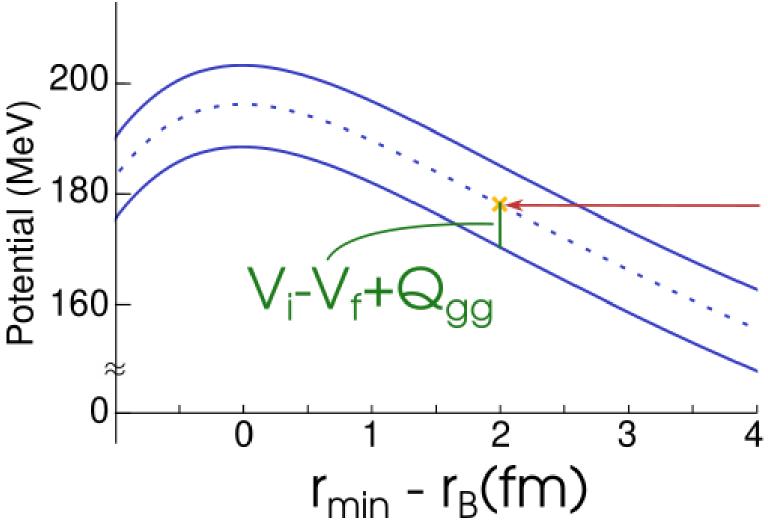

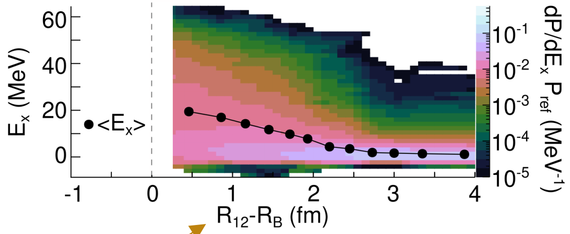

$$\Delta E_{gg} = Q_{gg} + (V_i(R_{min}) - V_f(R_{min}))$$

This energy can go into **kinetic energy** or **excitation energy**

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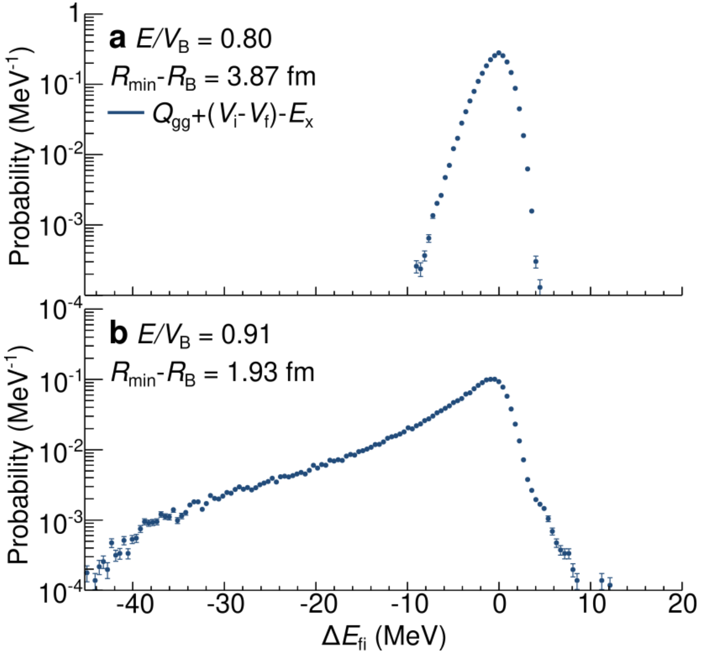
Change in **kinetic** energy (relative to the new barrier)



$$\Delta E_{\mathrm{fi}} = (K_{\mathrm{f}} - V_{\mathrm{f}}(R_{\mathrm{min}})) - (K_{\mathrm{i}} - V_{\mathrm{i}}(R_{\mathrm{min}}))$$

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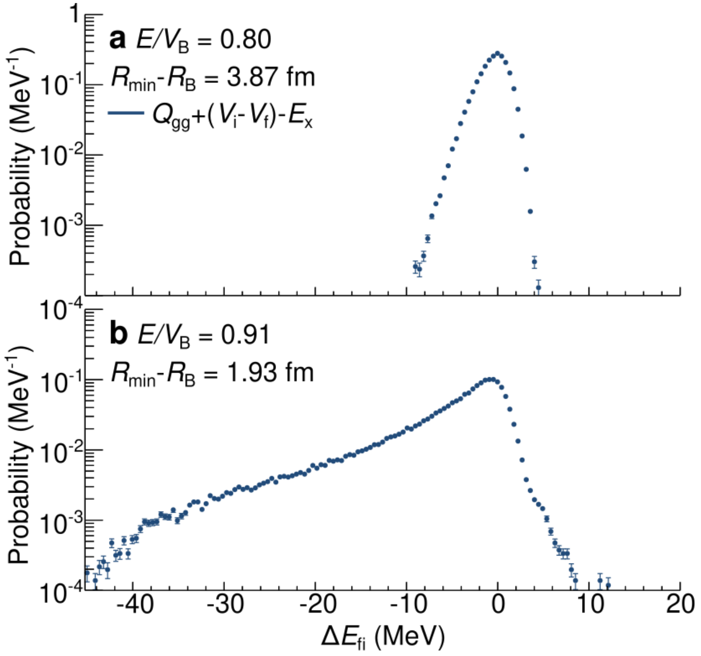
Why barrier passing models work and why they fail



Work: Barrier passing models approximately work as most of the flux still has the same kinetic energy relative to the barrier. This is just optimum Q-value considerations.

Fail: The significant tail of very low kinetic energies relative to the new barrier explains above-barrier fusion suppression.

New quantitative measure of impact of multinucleon transfer on fusion.

$$\Delta E_{\mathrm{fi}} = (K_{\mathrm{f}} - V_{\mathrm{f}}(R_{\mathrm{min}})) - (K_{\mathrm{i}} - V_{\mathrm{i}}(R_{\mathrm{min}}))$$

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Speculations: superheavy element synthesis

$$\sigma_{EVR} = \sum_{l=0}^{l_{max}} \sigma_{cap}(E_{cm}, l) P_{CN}(E^*, l) W_{surv}(E^*, l)$$

- Capture (barrier passing) and subsequent evolution are explicitly decoupled from each other.
  - Only once the nuclei stick can irreversible energy dissipation begin, and the nuclei equilibrate, eventually reaching their ground-state deformation.
- How does multinucleon transfer enroute to capture influence capture and the **subsequent evolution of the system**?
  - Superheavy element synthesis is by far the least likely outcome → fluctuations are likely critical

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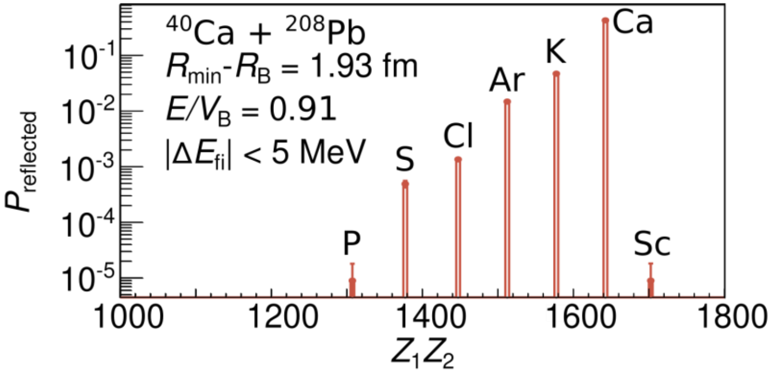
Post capture: Lower Z_1Z_2



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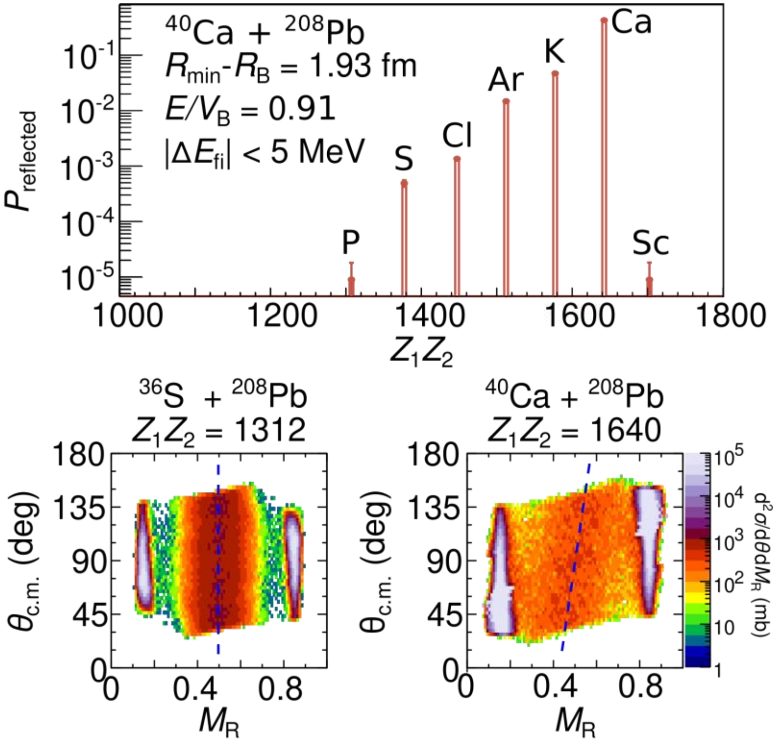

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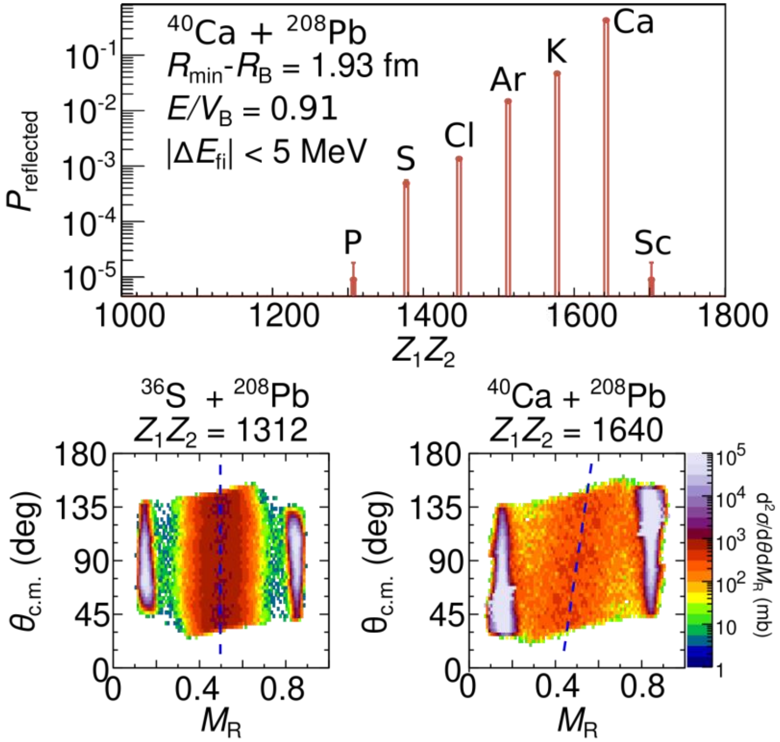

Likely more important for Superheavy element production reactions: much larger Z_1Z_2, and much lower P_{CN}: much stronger dependence of P_{CN} on Z_1Z_2

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Summary

- Nuclei do not (on average) capture in the same state they started with
  - They change their mass and charge substantially, giving broad distributions in N,Z and high (average) excitation energies.

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Summary

- Nuclei do not (on average) capture in the same state they started with
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- The most popular phenomenological models of fusion do not describe the full complexity of the colliding nuclei at contact.
  - Next gen. models need to describe the transition from coherent superposition to (effective) energy dissipation.

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    - Next gen. models need to describe the transition from coherent superposition to (effective) energy dissipation.
- Barrier passing models approximately work as most of the flux has the same kinetic energy relative to the barrier. The significant tail of very low kinetic energies relative to the new barrier explains above-barrier fusion suppression.

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Summary

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- The most popular phenomenological models of fusion do not describe the full complexity of the colliding nuclei at contact.
  - Next gen. models need to describe the transition from coherent superposition to (effective) energy dissipation.
- Barrier passing models approximately work as most of the flux has the same kinetic energy relative to the barrier. The significant tail of very low kinetic energies relative to the new barrier explains above-barrier fusion suppression.
- Next:
  - Multinucleon transfer yields and N,Z distributions depend strongly on the colliding system. Further quantitative measurements required, particularly for deformed actinide nuclei. Also, angular distributions.
  - How does (effective) energy dissipation outside the barrier imprint on fusion barrier distributions?
  - Fundamentally, we need to understand how the apparent **energy dissipation** relates to ideas of **irreversibility** and effective **removal of flux** from a coherent superposition.

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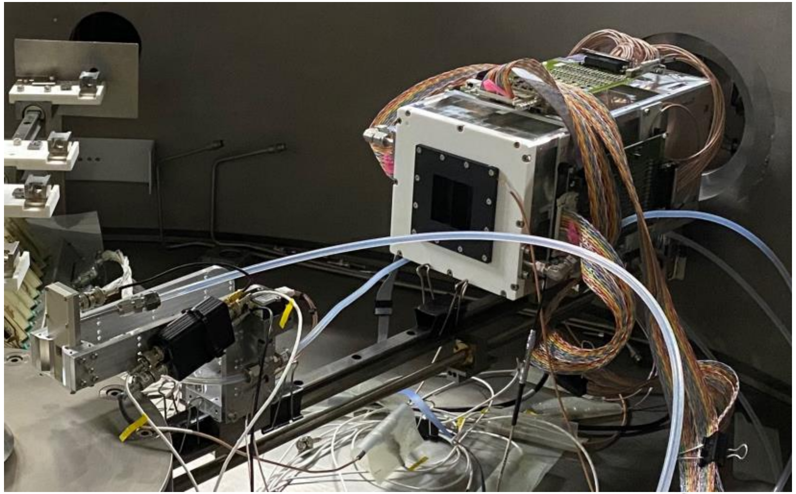
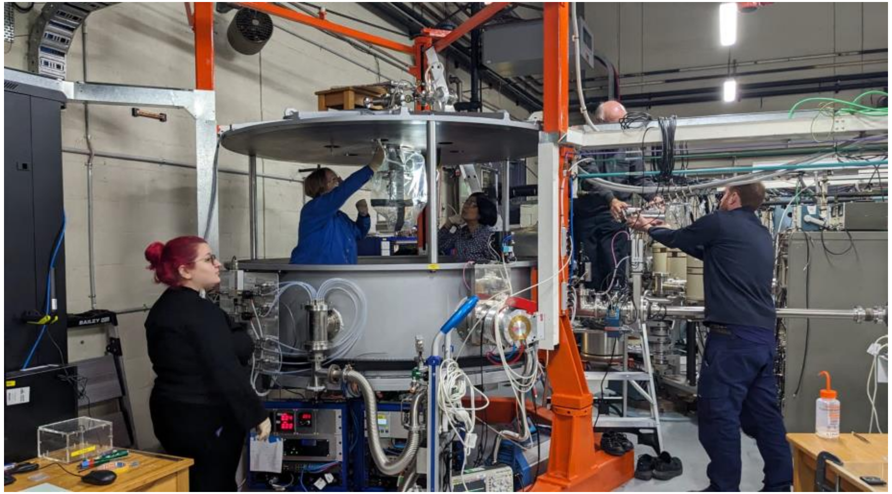
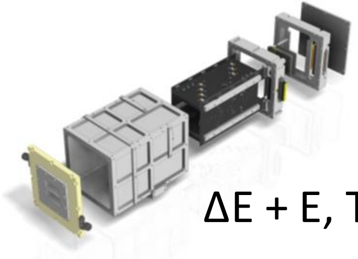
The MANTEIS Array







$\Delta E + E$, ToF, θ

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Physics is a team sport

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D.J. Hinde
E.C. Simpson
M. Dasgupta
M. Evers
D.Y. Jeung
D.H. Luong

L. Corradi
E. Fioretto
T. Mijatovic
G. Montagnoli
A.M. Stefanini
S. Szilner







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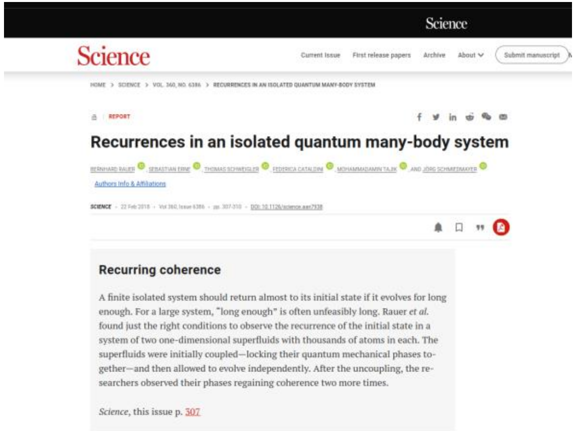
Dissipation? Irreversibility? Decoherence?



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REPORT

Recurrences in an isolated quantum many-body system

BERNHARD RAUER, SEBASTIAN ERNE, THOMAS SCHWEIGLER, FEDERICA CATALDINI, MOHAMMADAMIN TAJIK AND JÖRG SCHMIEDMAYER

Authors Info & Affiliations

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Recurring coherence

A finite isolated system should return almost to its initial state if it evolves for long enough. For a large system, "long enough" is often unfeasibly long. Rauer *et al.* found just the right conditions to observe the recurrence of the initial state in a system of two one-dimensional superfluids with thousands of atoms in each. The superfluids were initially coupled—locking their quantum mechanical phases together—and then allowed to evolve independently. After the uncoupling, the researchers observed their phases regaining coherence two more times.

Science, this issue p. 307

For fully reversible processes, coupled channels calculations should reproduce experiments if every single coupling can be included.

↓

However, the density of states is very high (here it's ~$10^{5\text{-}6}$/MeV).

↓

The very many states will couple to each other in a complex scheme that results in a coupling that is *effectively* irreversible on the time scale of the nuclear collision (10^{-21} s)

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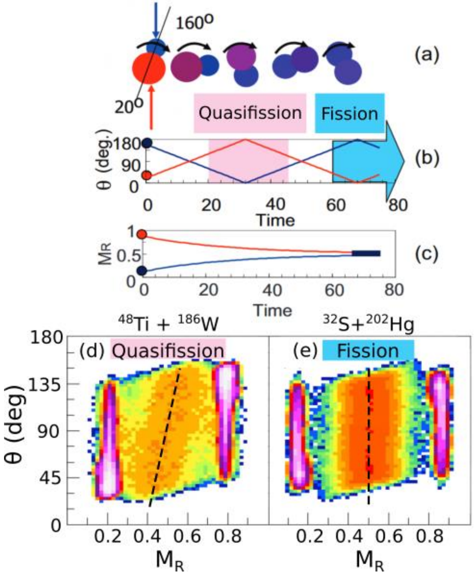
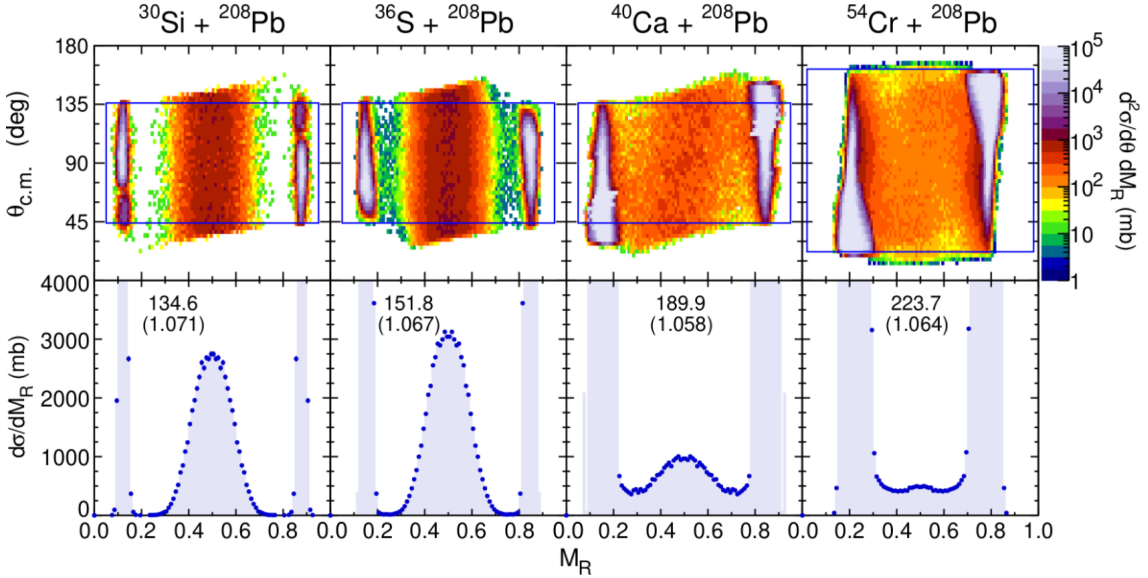
Lower Z_1Z_2 = longer sticking times





Z_1Z_2 = 1148 1312 1640 1968

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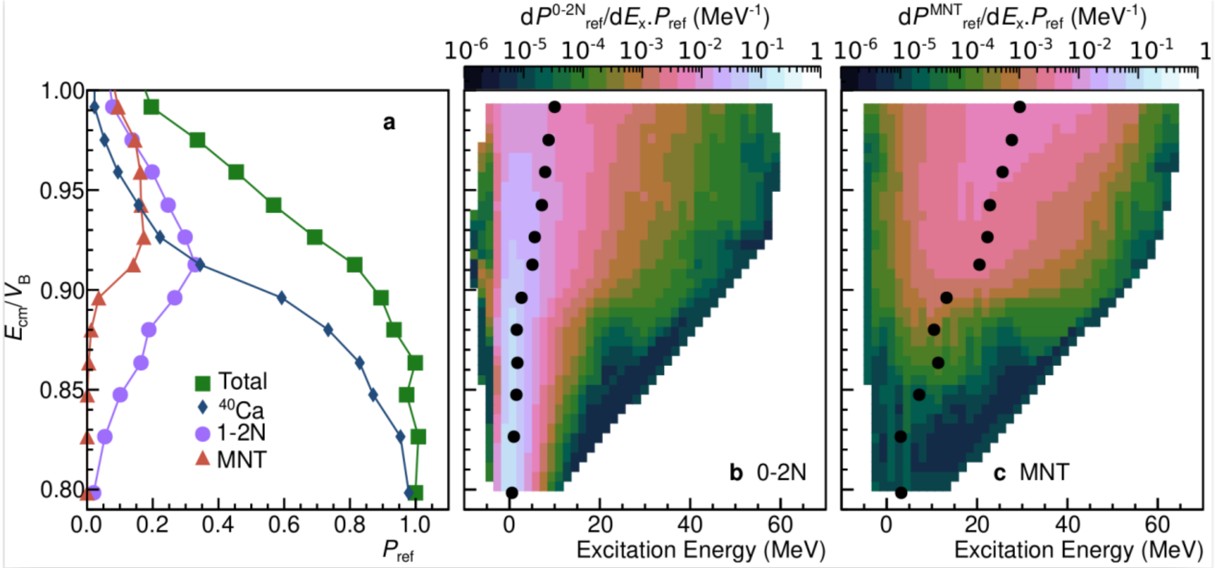
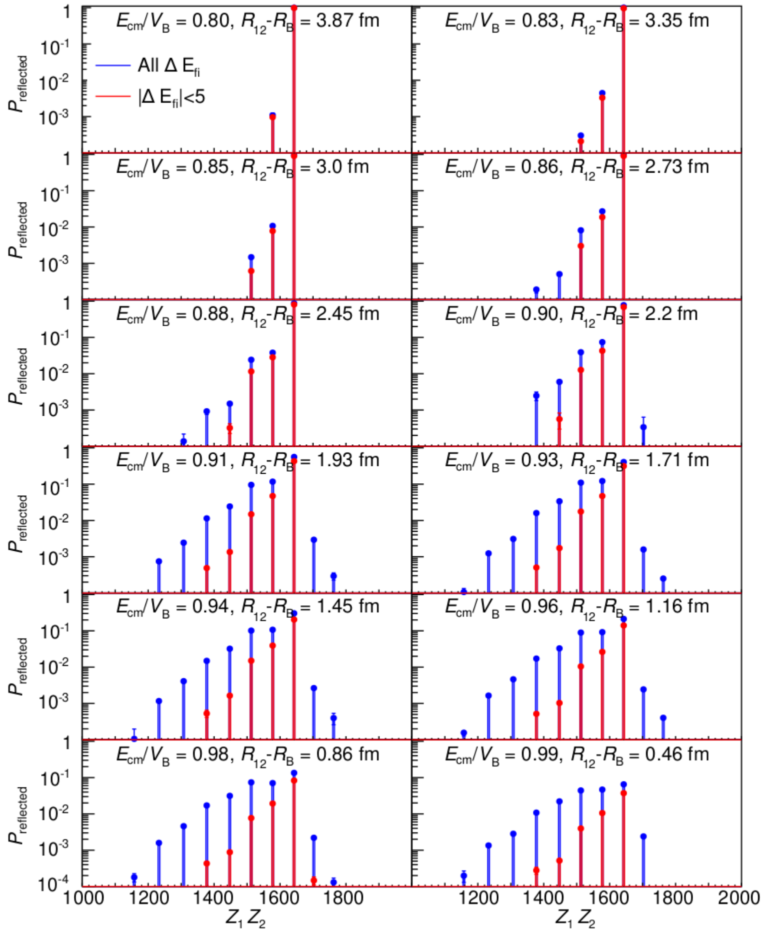


a
E_{cm}/V_B
1.00
0.95
0.90
0.85
0.80
0.0 0.2 0.4 0.6 0.8 1.0
P_{ref}
Total
^{40}Ca
1-2N
MNT
$dP^{0-2N}_{ref}/dE_x.P_{ref}$ (MeV^{-1})
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
b 0-2N
0 20 40 60
Excitation Energy (MeV)
$dP^{MNT}_{ref}/dE_x.P_{ref}$ (MeV^{-1})
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
c MNT
0 20 40 60
Excitation Energy (MeV)



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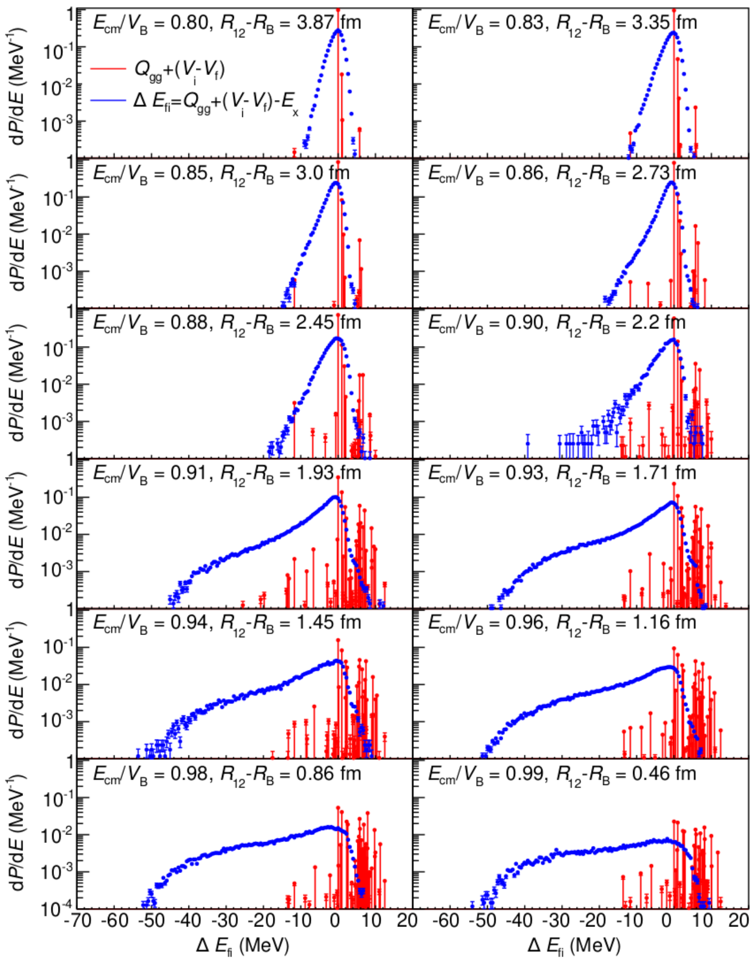


E_{cm}/V_B = 0.80, R_{12}-R_B = 3.87 fm
E_{cm}/V_B = 0.83, R_{12}-R_B = 3.35 fm
E_{cm}/V_B = 0.85, R_{12}-R_B = 3.0 fm
E_{cm}/V_B = 0.86, R_{12}-R_B = 2.73 fm
E_{cm}/V_B = 0.88, R_{12}-R_B = 2.45 fm
E_{cm}/V_B = 0.90, R_{12}-R_B = 2.2 fm
E_{cm}/V_B = 0.91, R_{12}-R_B = 1.93 fm
E_{cm}/V_B = 0.93, R_{12}-R_B = 1.71 fm
E_{cm}/V_B = 0.94, R_{12}-R_B = 1.45 fm
E_{cm}/V_B = 0.96, R_{12}-R_B = 1.16 fm
E_{cm}/V_B = 0.98, R_{12}-R_B = 0.86 fm
E_{cm}/V_B = 0.99, R_{12}-R_B = 0.46 fm
$Q_{gg}+(V_i-V_f)$
$\Delta E_{fi}=Q_{gg}+(V_i-V_f)-E_x$
dP/dE (MeV^{-1})
ΔE_{fi} (MeV)

Energy (MeV)	V_B (θ_{lab} = 115°) (MeV)	$R_{min} - R_B$	E_{cm}/V_B
156.7	196.3	3.87	0.80
161.8	195.8	3.35	0.83
165.6	195.4	3.00	0.85
168.5	195.1	2.73	0.86
171.5	194.9	2.45	0.88
174.4	194.6	2.20	0.90
177.4	194.4	1.93	0.91
179.9	194.0	1.71	0.93
182.8	193.7	1.45	0.94
185.8	193.5	1.16	0.96
188.7	193.3	0.86	0.98
191.7	193.1	0.46	0.99

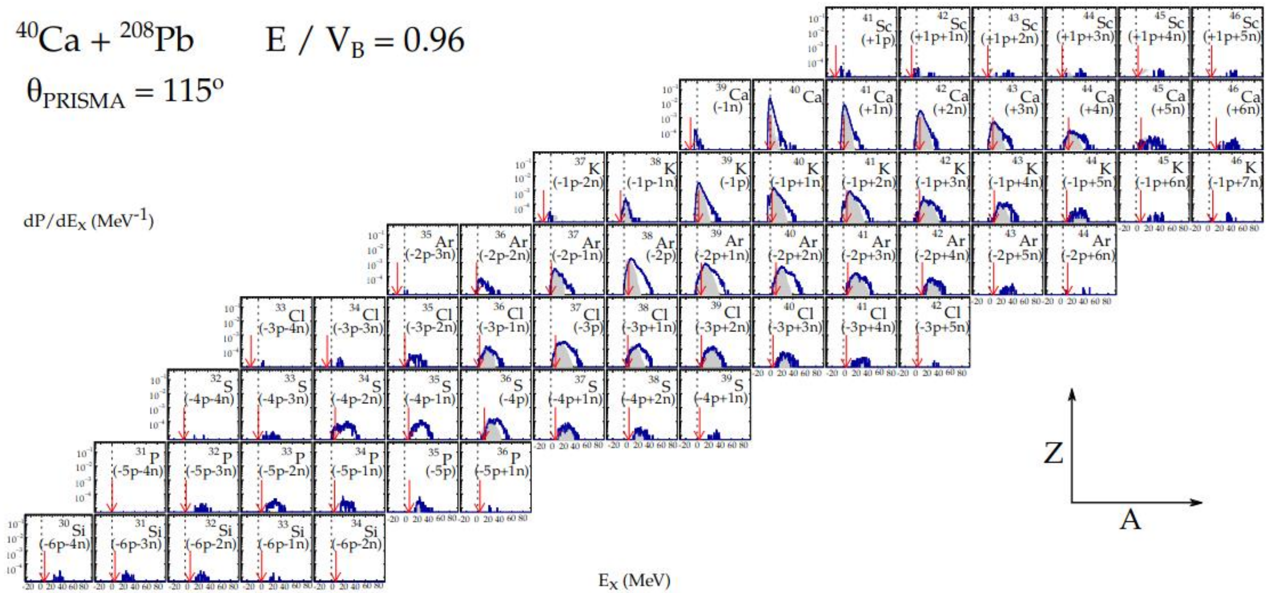
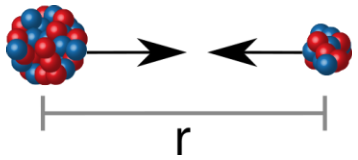
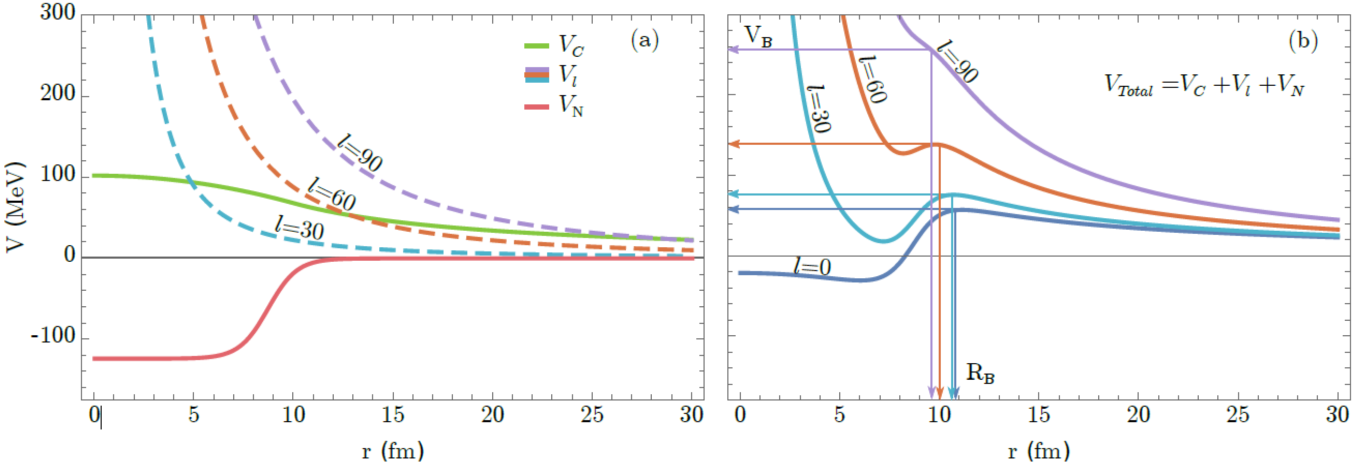


FIGURE 5.22: Excitation energies for the various observed transfer modes in the measurement of ^{40}Ca + ^{208}Pb at $0.95V_B$ (adjusted from the s-wave barrier according to the mean scattering angle), for the $\theta_{\text{PRISMA}} = 115°$ setting. $E_x = 0$ is indicated by the vertical dashed line in each panel. The red arrows indicate the optimum E_x values. Modes with a very low number of counts have been excluded from this figure. The grey shaded region indicates the distribution of excitation energy calculated with GRAZING (see text for details).

How do we model fusion?



- Barrier passing models: two colliding nuclei approach each other, pass over (or through) their potential barrier, hit a boundary condition/short-range imaginary potential, and stick.



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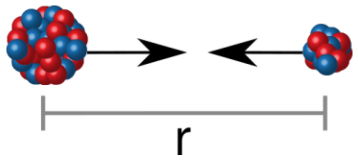
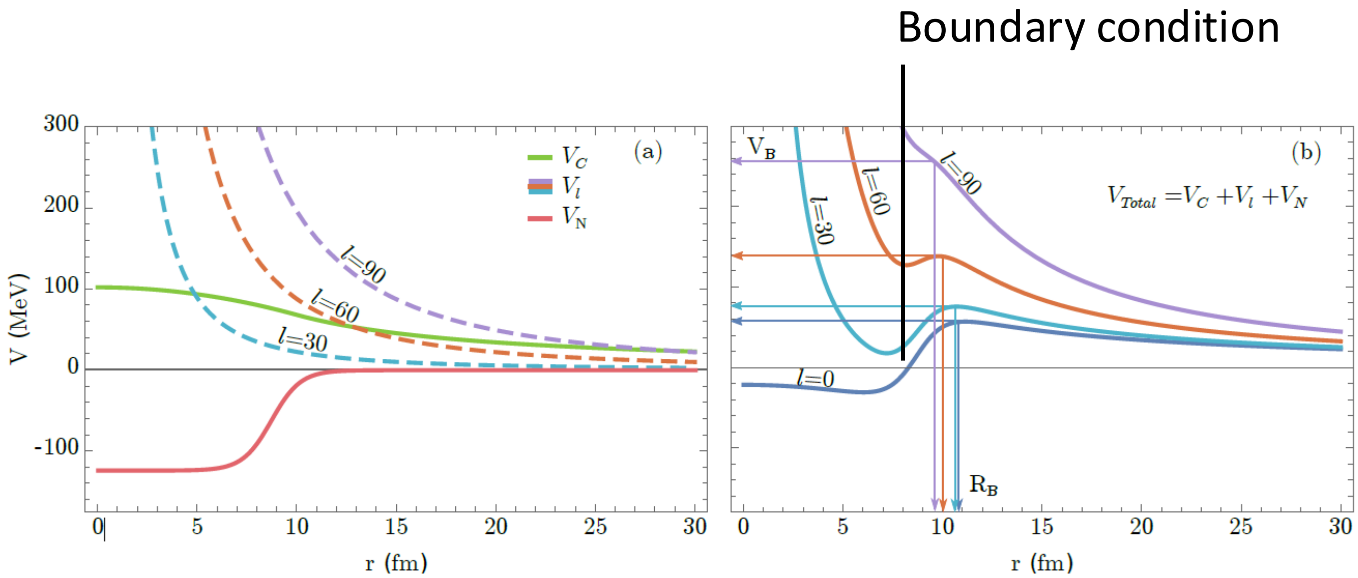
4 APRIL 2023

How do we model fusion?



- Barrier passing models: two colliding nuclei approach each other, pass over (or through) their potential barrier, hit a boundary condition/short-range imaginary potential, and stick.



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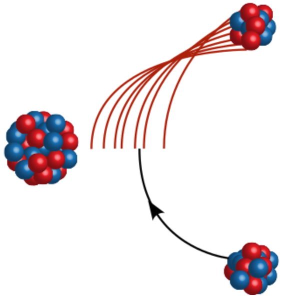
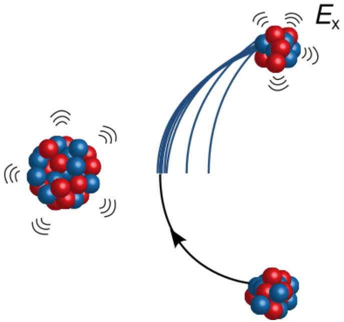
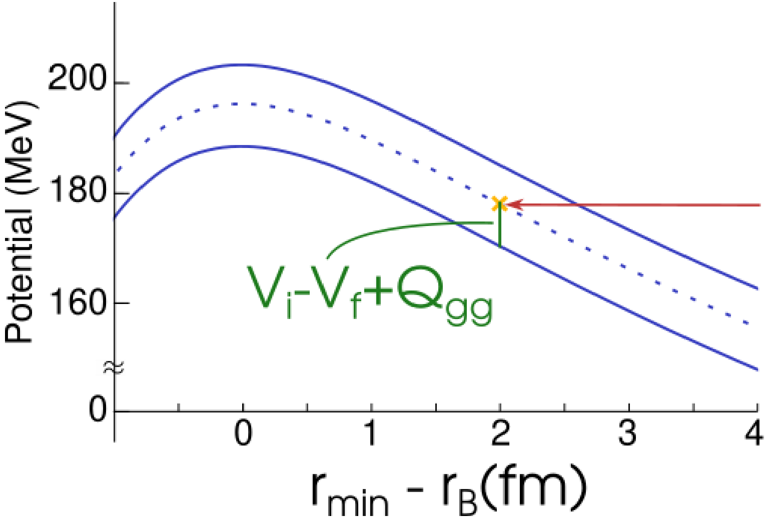
Trajectory matching

Ground-state to ground-state transfer



Trajectory matching transfer leading to excitation





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