

# Heavy-ion subbarrier fusion reactions and multi-nucleon transfer process

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N. Rowley (IPN Orsay)



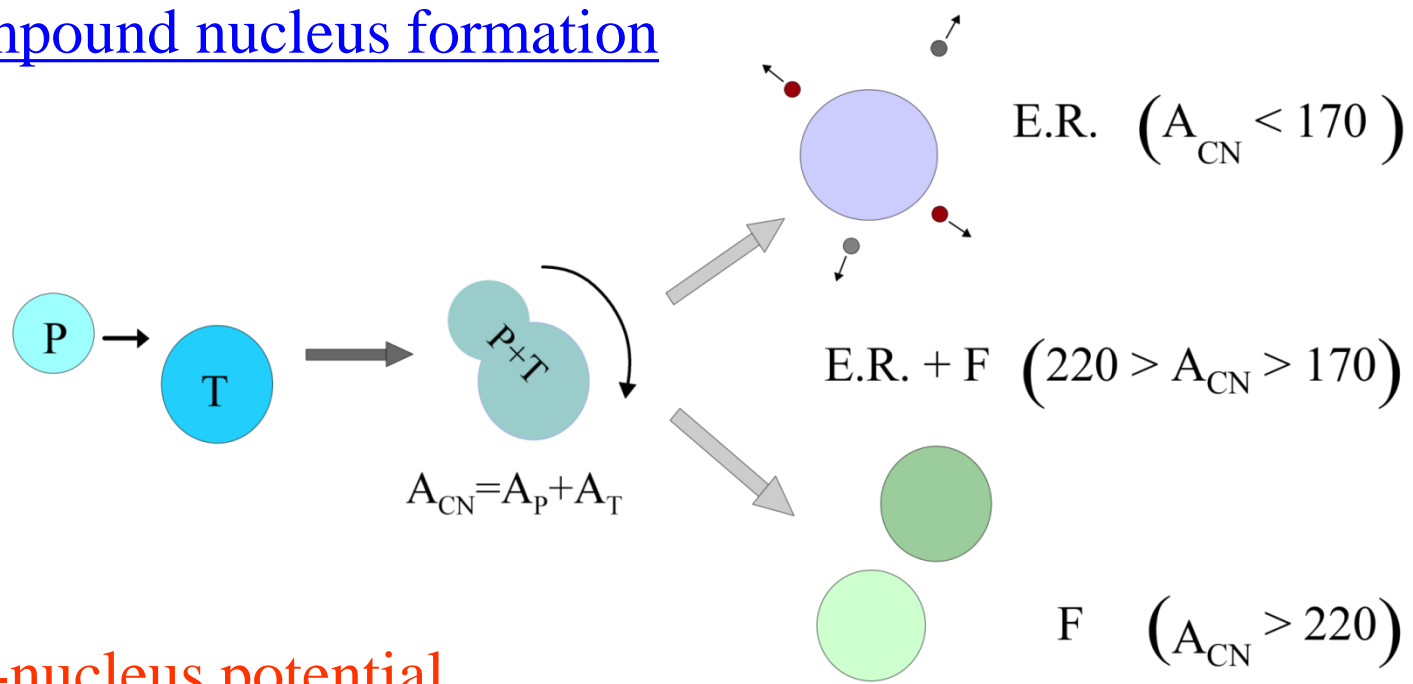
TOHOKU  
UNIVERSITY

- 1. Subbarrier fusion reactions: overview*
- 2. Multi-neutron transfer reactions*
- 3. New simple approach*
- 4. Summary*

Recent review on subbarrier fusion:

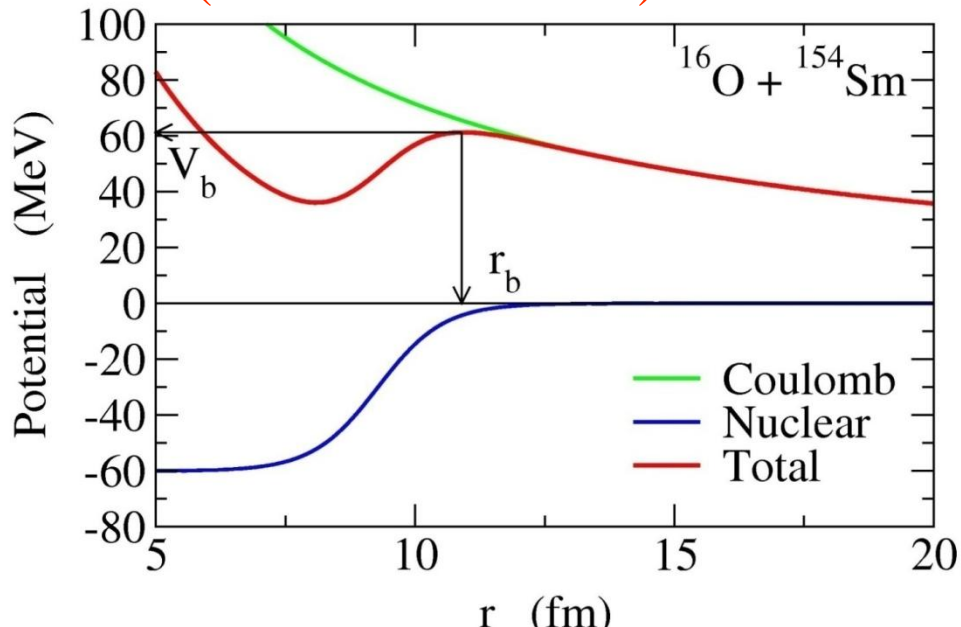
K. Hagino and N. Takigawa, Prog. Theo. Phys., in press.  
arXiv:1209.6435 [nucl-th].

# Fusion: compound nucleus formation



courtesy: Felipe Canto

## Inter-nucleus potential (Coulomb barrier)

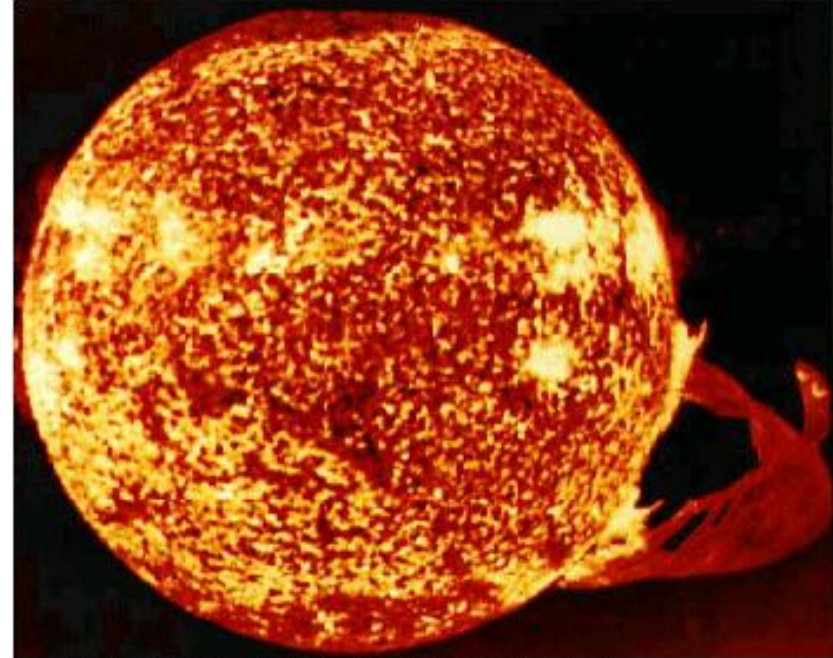
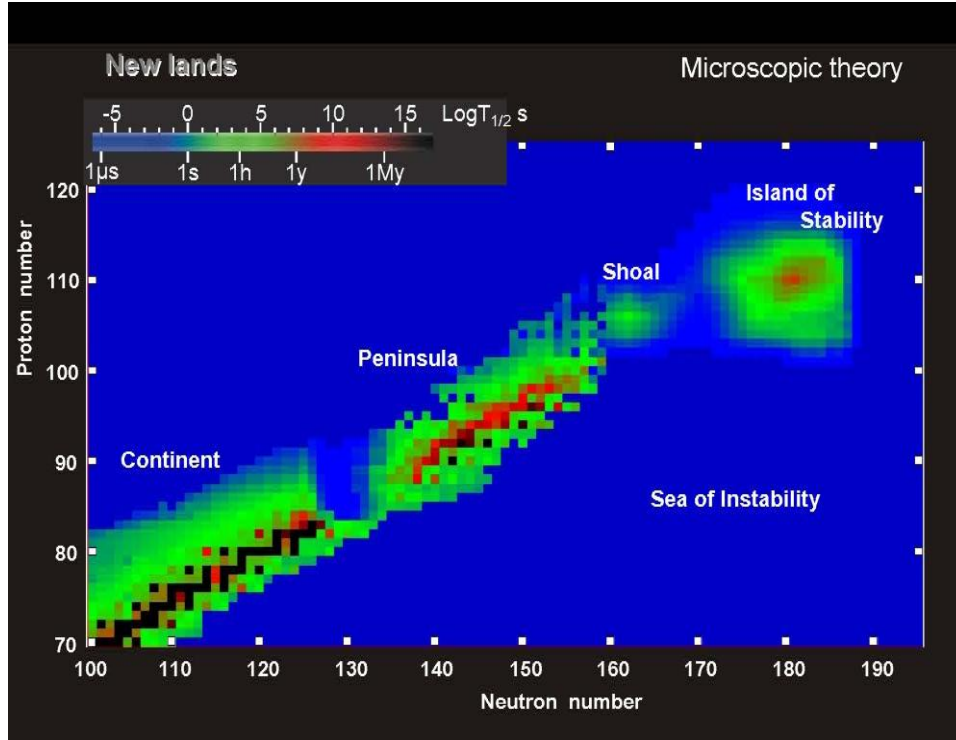


- above barrier energies
- sub-barrier energies ←
- deep subbarrier energies

subbarrier fusion reactions

# Why subbarrier fusion?

Two obvious reasons:



NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

discovering new elements  
(SHE by cold fusion reactions)

cf. K. Morita's talk

nuclear astrophysics  
(fusion in stars)

cf. S. Cherubini's talk  
A. Guglielmetti's talk

## Why subbarrier fusion?

Two obvious reasons:

- ✓ discovering new elements (SHE)
- ✓ nuclear astrophysics (fusion in stars)

Other reasons:

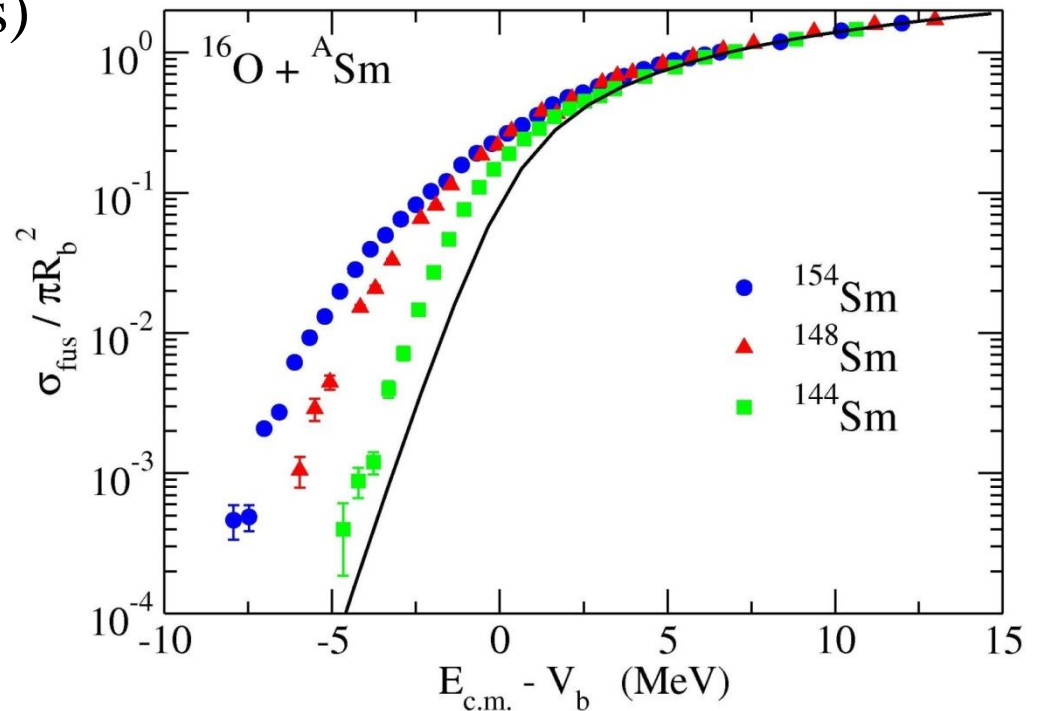
- ✓ reaction mechanism

**strong interplay between reaction and structure**

(channel coupling effects)

- ✓ many-particle tunneling

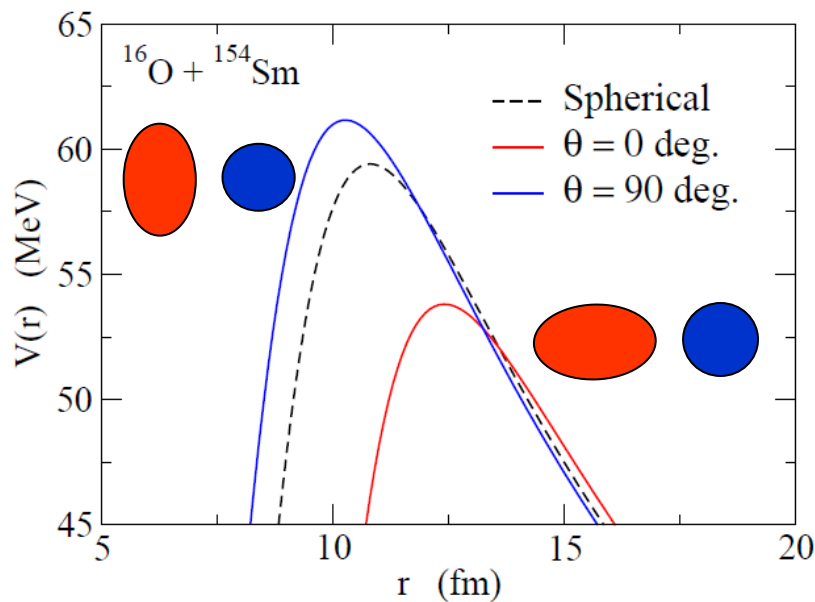
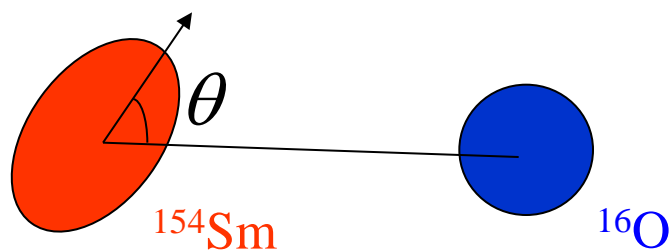
cf. alpha decay  
: fixed energy



Strong target dependence at  $E < V_b$

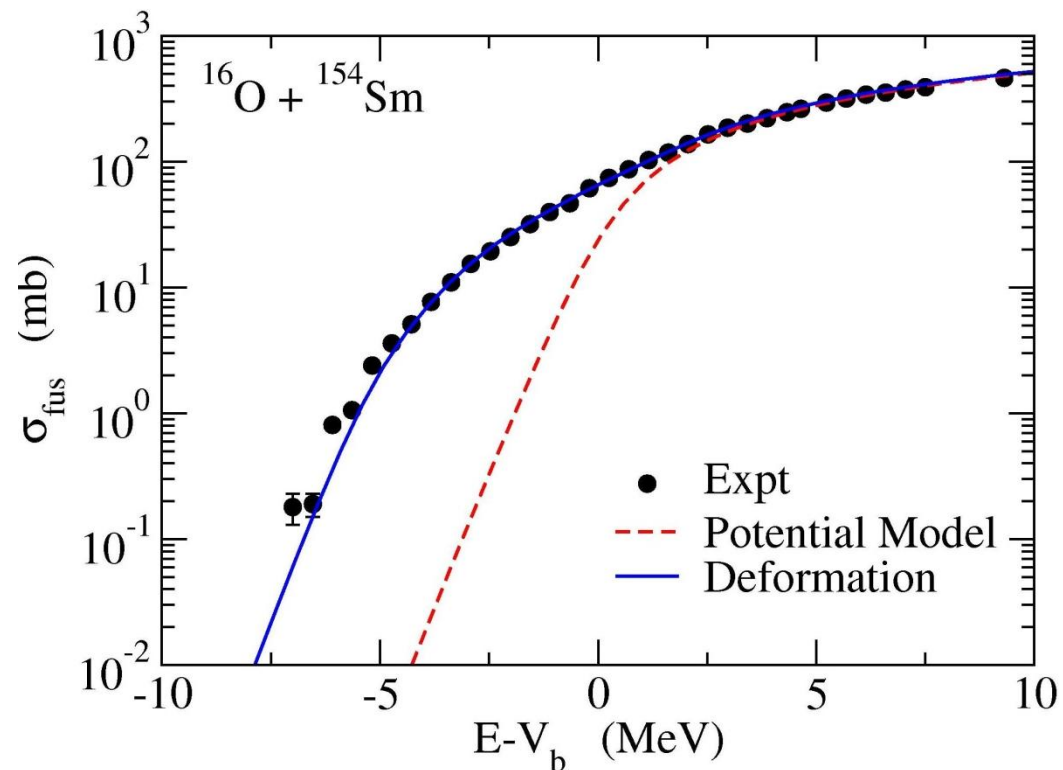
## Subbarrier fusion:

strong interplay between  
reaction and structure

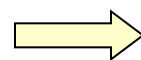


coupled-channels equations

→ 
$$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos \theta) \sigma_{\text{fus}}(E; \theta)$$



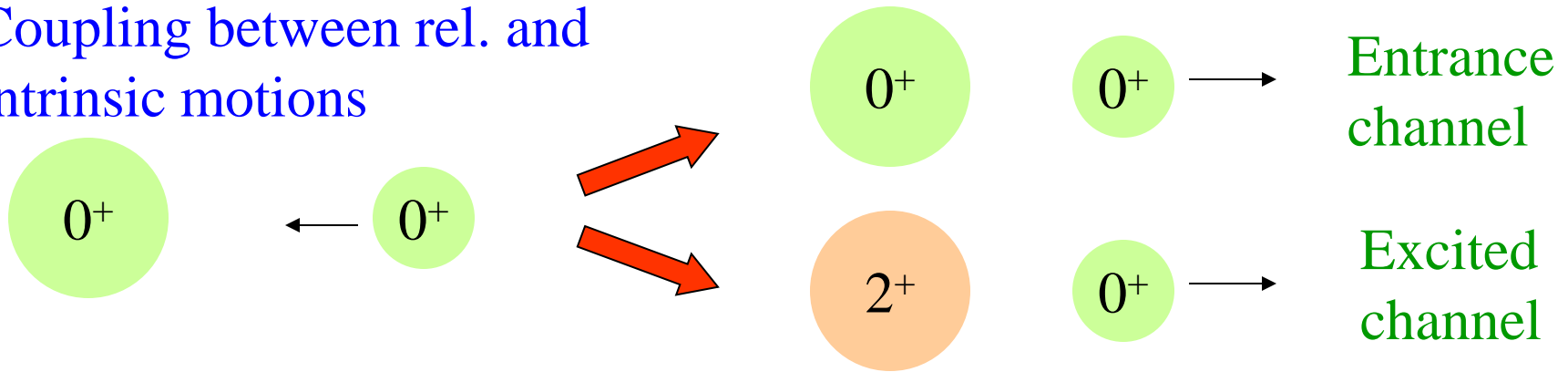
**Def. Effect:** enhances  $\sigma_{\text{fus}}$  by a factor  
of 10 ~ 100



**Fusion:** interesting probe for  
nuclear structure

## Coupled-channels calculations: scatt. + **collective excitations**

Coupling between rel. and intrinsic motions



$$\left[ -\frac{\hbar^2}{2\mu} \nabla^2 + V_0(r) + \epsilon_k - E \right] \psi_k(\mathbf{r}) + \sum_{k'} \langle \phi_k | V_{\text{coup}} | \phi_{k'} \rangle \psi_{k'}(\mathbf{r}) = 0$$

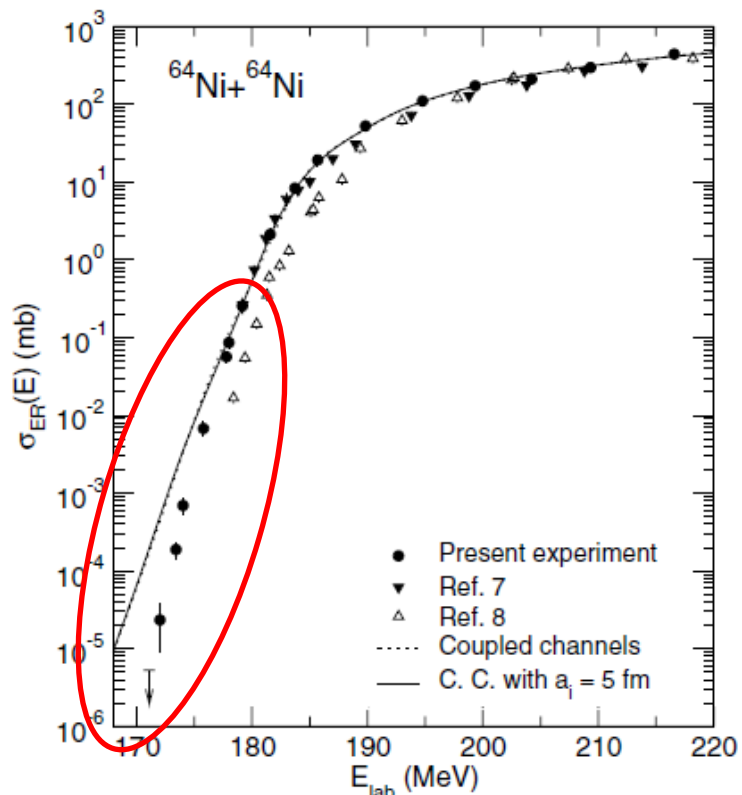
A standard tool to analyze heavy-ion subbarrier fusion reactions

e.g. CCFULL, K.H., N. Rowley, A.T. Kruppa, CPC123 ('99) 143

## Open current issues

- ✓ deep subbarrier fusion hindrance?
  - role of dissipation?
- ✓ fusion of unstable nuclei? cf. D. Pierroutsakou's talk
  - breakup, (pair) transfer
- ✓ **how to treat (multi-nucleon) transfer?**

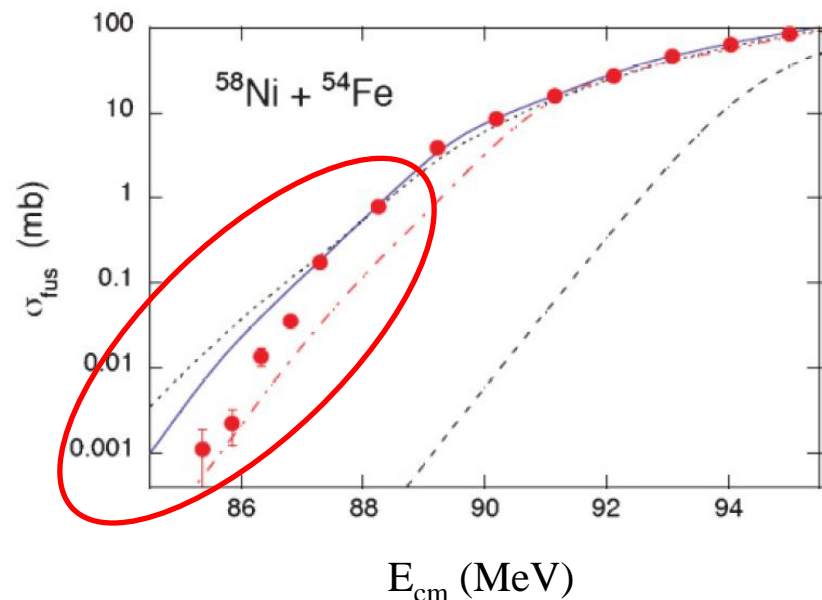
# deep subbarrier hindrance of fusion cross sections



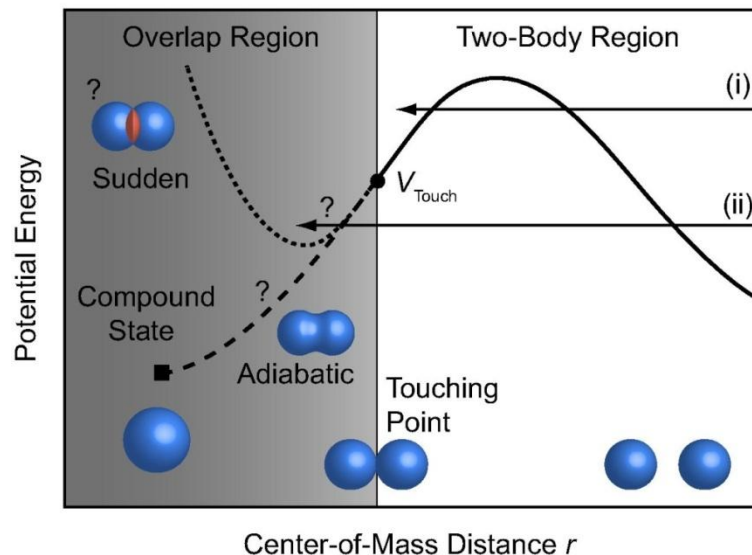
C.L. Jiang et al., PRL89('02)052701;  
PRL93('04)012701

## Theory:

- ✓ S. Misicu and H. Esbensen, PRL96('06)112701
- ✓ T. Ichikawa, K.H., and A. Iwamoto, PRL103('09)202701



A.M. Stefanini et al., PRC82('10)014614



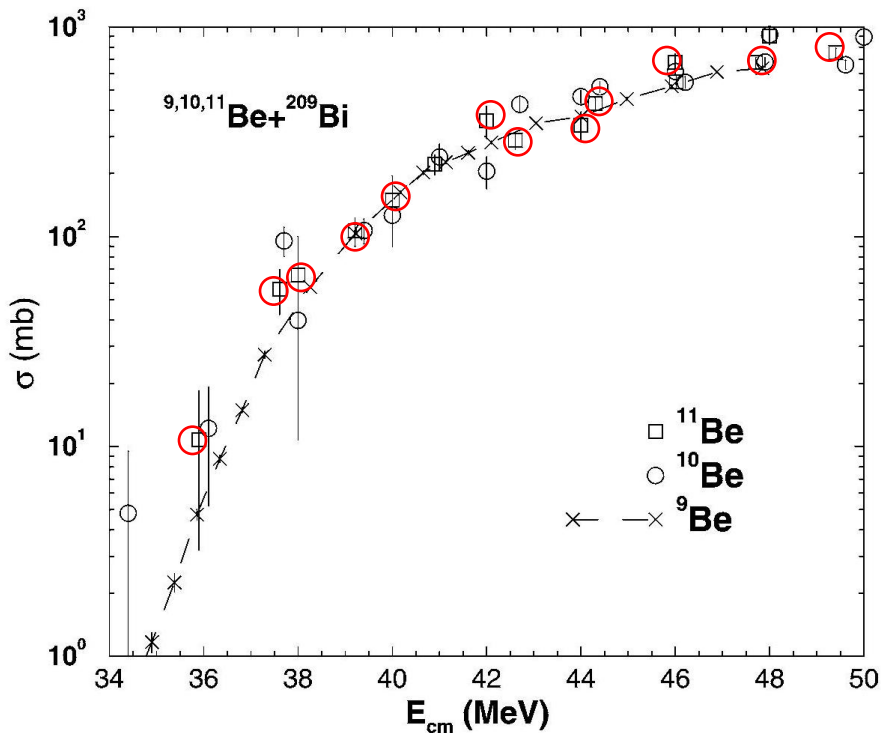
# Fusion of unstable nuclei

Fusion of stable nuclei: large enhancement of fusion cross sections

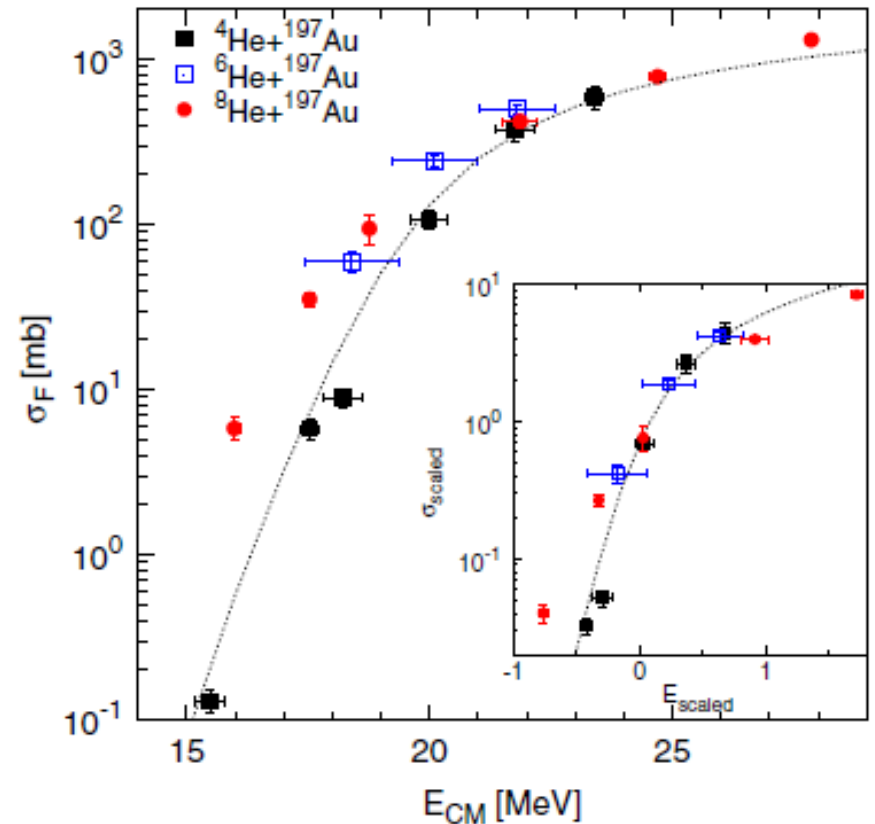
→ Fusion of unstable (weakly bound) nuclei?

fusion cross section: enhanced? hindered? no change?

*still not known completely*



C. Signorini et al., NPA735 ('04) 329



A. Lemasson et al., PRL103('09)232701

cf. Recent data for <sup>12,13,14,15</sup>C + <sup>232</sup>Th

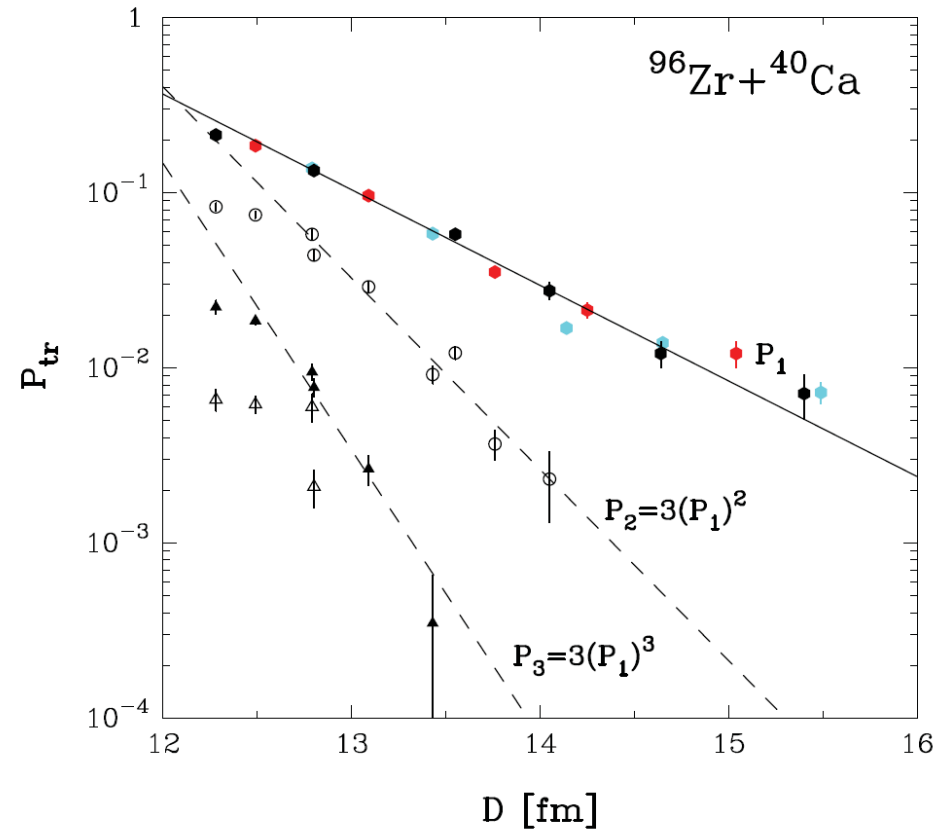
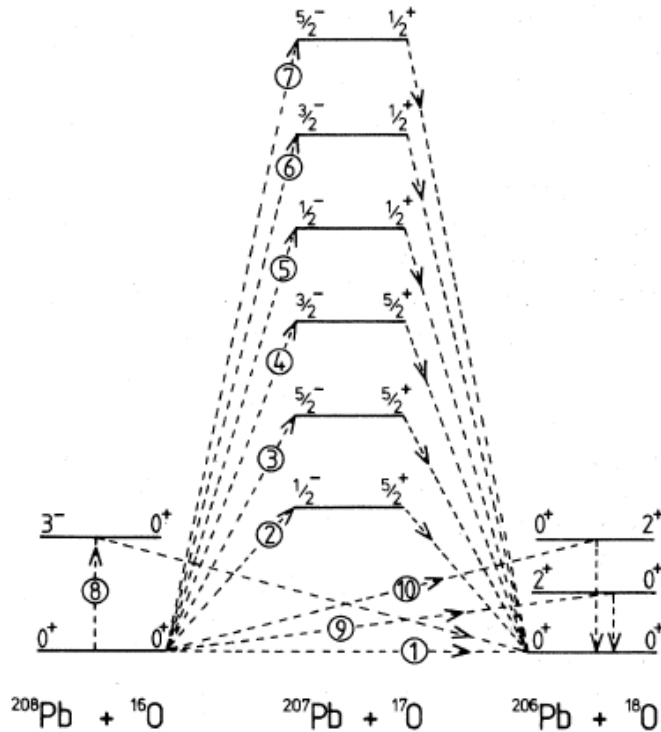
M. Alcorta et al., PRL106('11)172701

## Pair transfer:

### ✓ Reaction mechanism?

- sequential vs simultaneous

cf. Modern calculations for  ${}^A\text{Sn}(p,t)$ :  
G. Potel et al., PRL107('11)092501

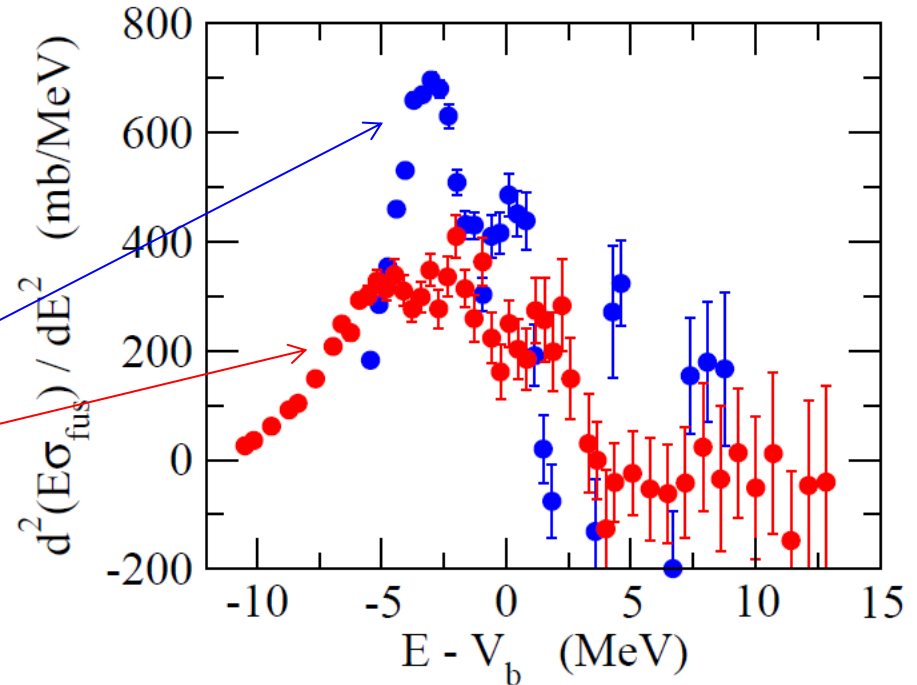
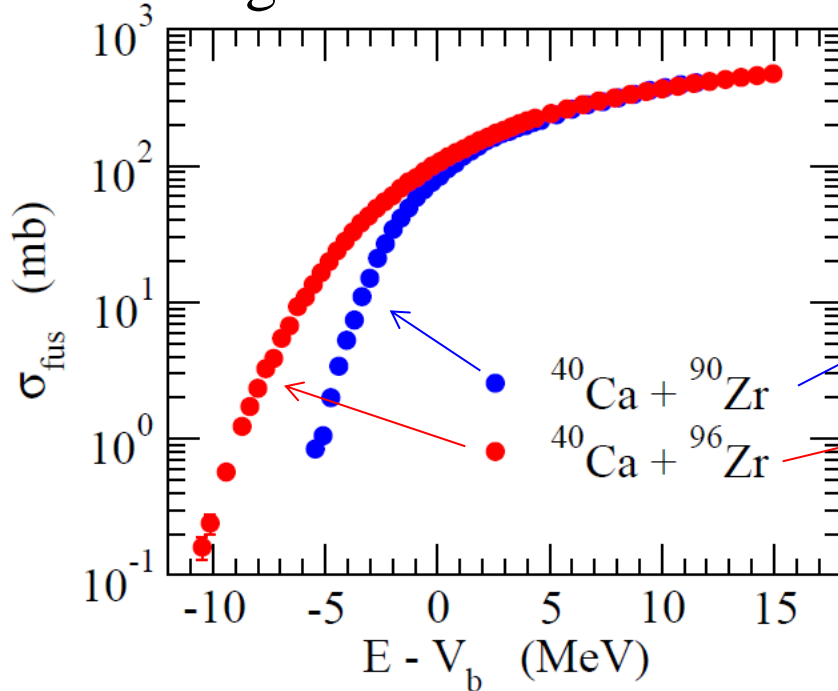


L. Corradi et al., PRC84('11)034603

*how is the reaction mechanism modified  
when most of intermediate states are unbound?*

# Role of multi-neutron transfer process in subbarrier fusion

Legnaro data for  $^{40}\text{Ca} + ^{90,96}\text{Zr}$



H. Timmers et al., NPA633('98)421

$^{40}\text{Ca} + ^{96}\text{Zr}$

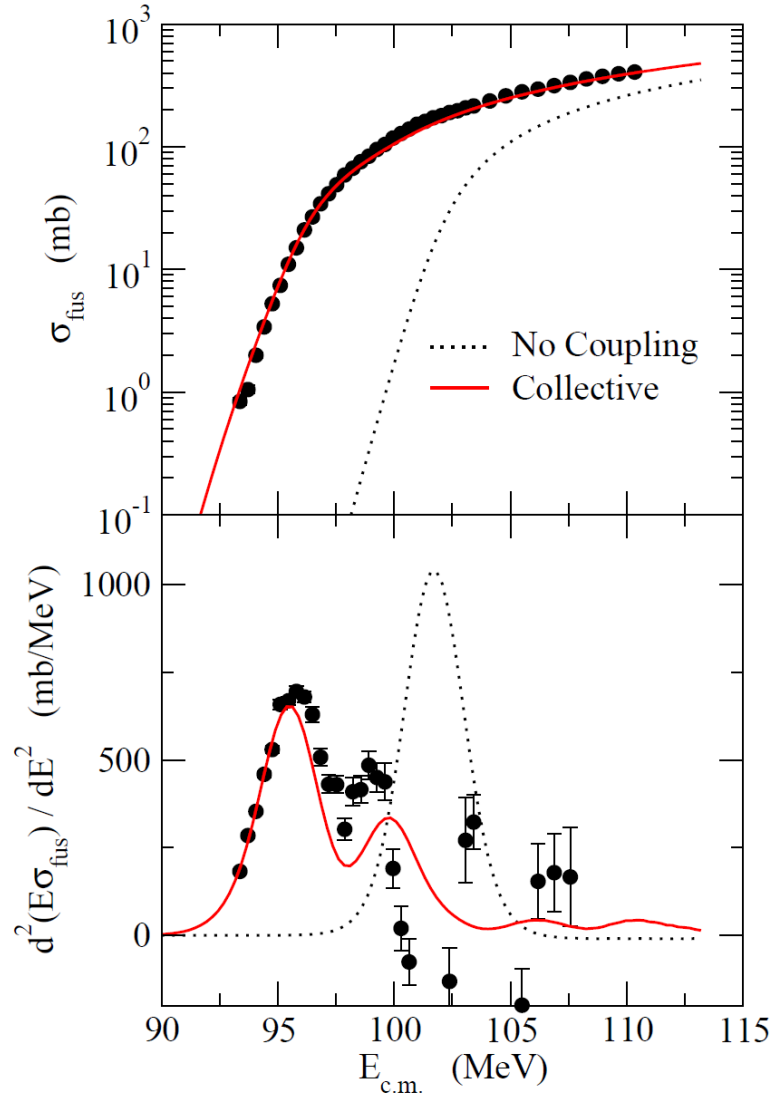
- more enhancement of fusion cross sections
- flatter barrier distribution
  - ✓ stronger octupole collectivity
  - ✓ multi-neutron transfer process

# stronger octupole collectivity in $^{96}\text{Zr}$

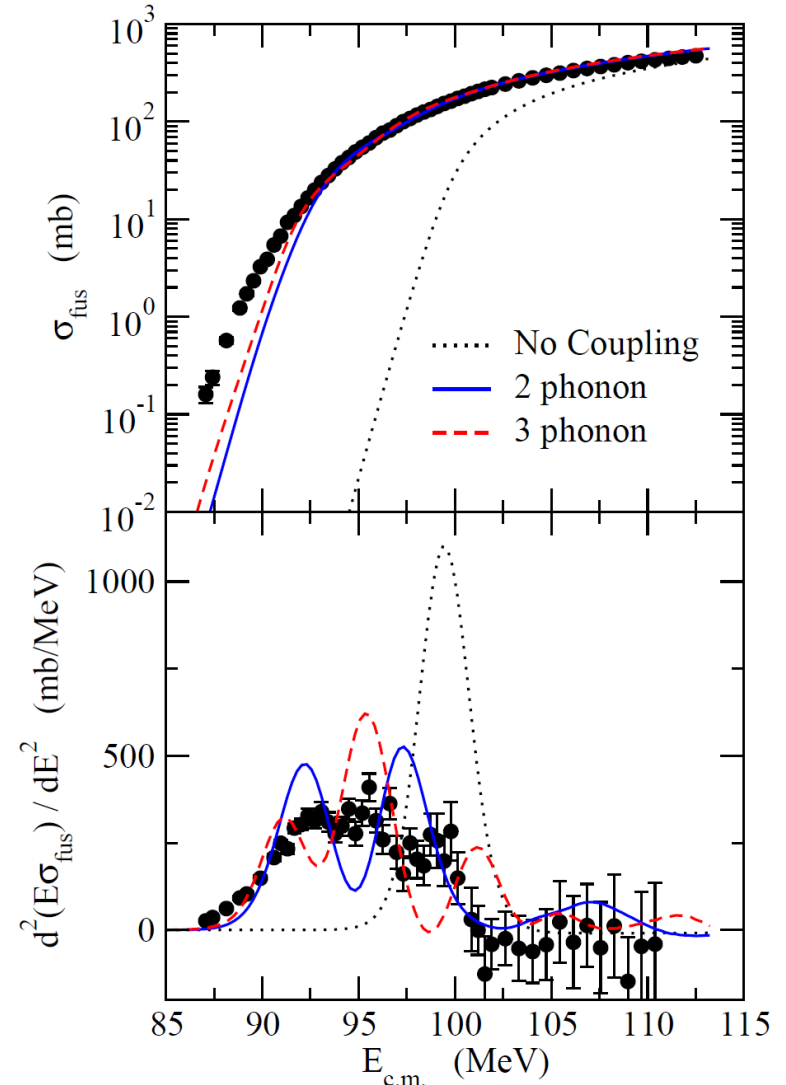
$$^{90}\text{Zr}: B(E3: 3^-_1 \rightarrow 0^+) = 29.1 \text{ W.u.}, E_{3^-} = 2.748 \text{ MeV}$$

$$^{96}\text{Zr}: B(E3: 3^-_1 \rightarrow 0^+) = 52.7 \text{ W.u.}, E_{3^-} = 1.897 \text{ MeV}$$

$^{40}\text{Ca} (3^-) + ^{90}\text{Zr} (2^+ : 2 \text{ phonon}, 3^- : 2 \text{ phonon})$



$^{40}\text{Ca} (3^-) + ^{96}\text{Zr} (2^+ : 2 \text{ phonon}, 3^- : 2 \text{ phonon})$



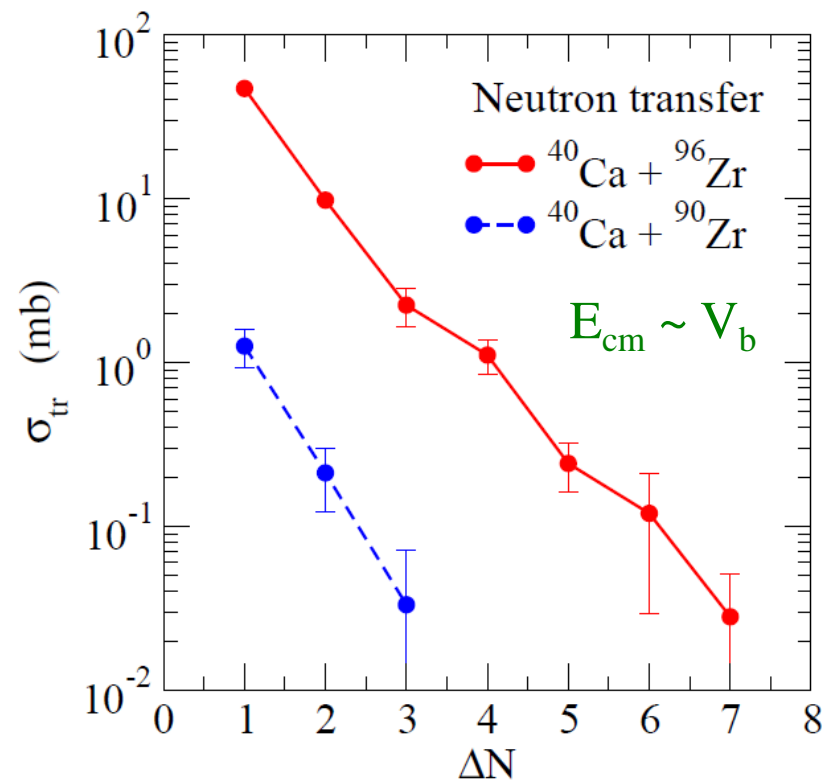
# Q-values for multi-neutron transfer channels

$Q_{gg}$  (MeV)

	$^{40}\text{Ca} + ^{90}\text{Zr}$	$^{40}\text{Ca} + ^{96}\text{Zr}$
+1n	-3.61	+0.51
+2n	-1.44	+5.53
+3n	-5.86	+5.24
+4n	-4.17	+9.64
+5n	-9.65	+8.42
+6n	-9.05	+11.62

cf.  $Q_{gg}(-1n) = -8.45$  MeV for  $^{40}\text{Ca} + ^{90}\text{Zr}$

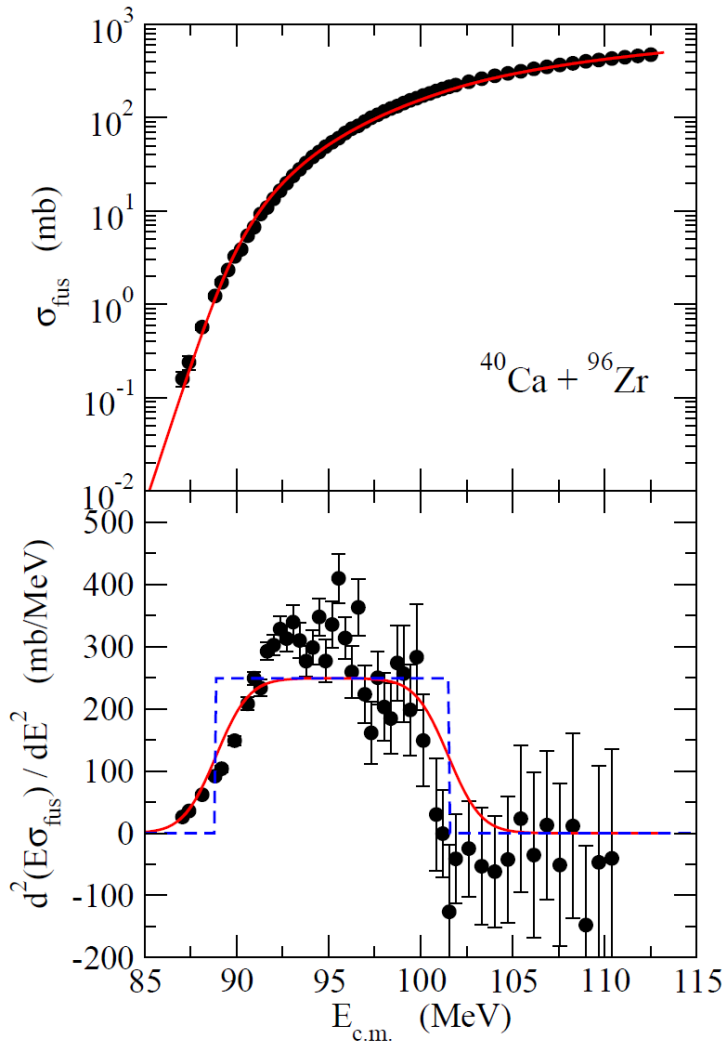
Experimental data for  
total transfer cross sections



G. Montagnoli et al.,  
J. of Phys. G23('97)1431

# How to treat multi-neutron transfer?

## 1. Stelson model: P.H. Stelson, PLB205('88)190



- Flat barrier distribution  
( $B_{min}$ ,  $B_{max}$ : parameters)
- Simple, and easy to implement
- Purely phenomenological
- No connection to transfer cross sections

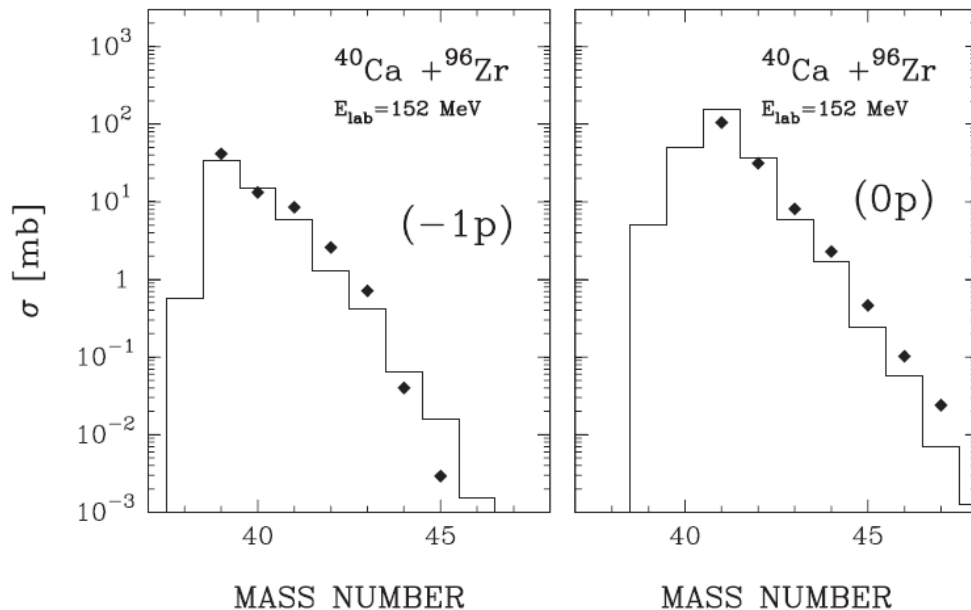
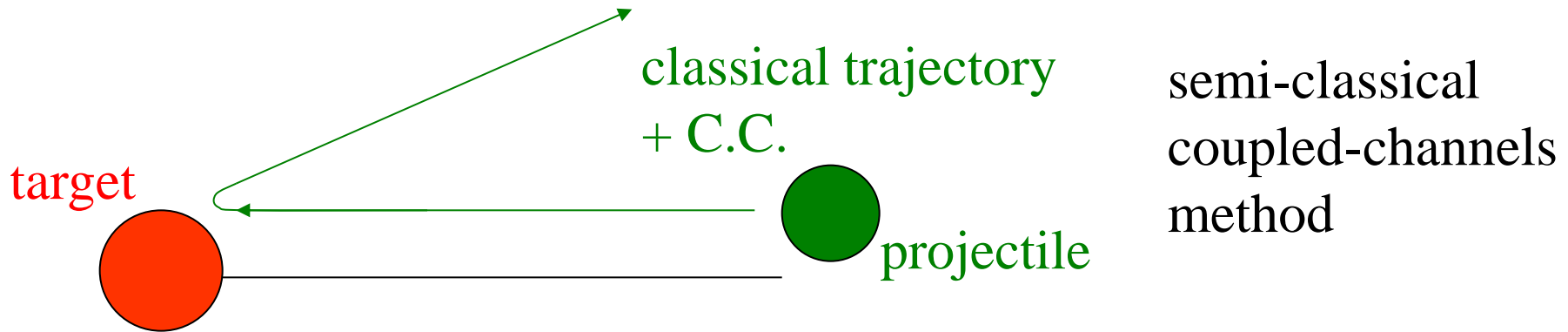
## 2. GRAZING: G. Pollarolo and A. Winther, PRC62('00)054611

## 3. Zagrebaev's model: V.I. Zagrebaev, PRC67('03)061601(R)

# How to treat multi-neutron transfer?

1. Stelson model: P.H. Stelson, PLB205('88)190

2. GRAZING: G. Pollarolo and A. Winther, PRC62('00)054611



➤ Good for transfer reactions

➤ No dynamics for tunneling in fusion reactions (classical trajectory up to the turning point)

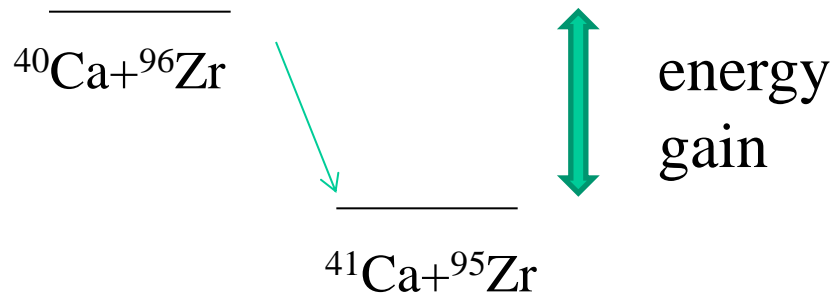
S. Szilner et al., PRC76('07)024604

3. Zagrebaev's model: V.I. Zagrebaev, PRC67('03)061601(R)

# How to treat multi-neutron transfer?

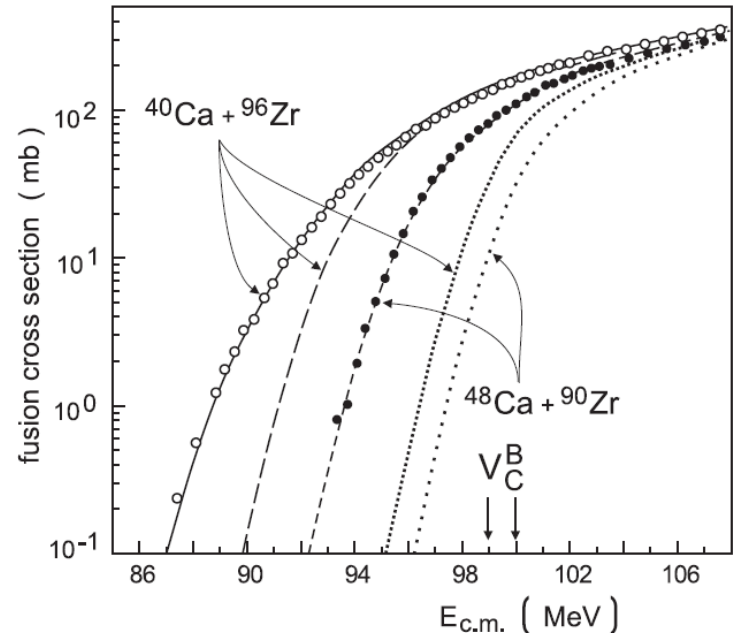
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$$\sigma(E) \sim \sum_k \int_{-E}^{Q_{gg}(k)} dQ \underbrace{\alpha_k(Q)}_{\text{Q-value distribution}} \underbrace{\sigma_{CC}(E+Q)}_{\text{fusion at } E+Q}$$



→ too naive

cf. 3<sup>-</sup> excitation: energy loss  
 but still large enhancement of  $\sigma_{\text{fus}}$



# New simple model

K.H., N. Sekine, and N. Rowley, in preparation

- ✓ Stelson model: purely phenomenological, no connection to  $\sigma_{\text{transfer}}$
- ✓ GRAZING: not for fusion
- ✓ Zagrebaev's model: basically wrong
- ✓ Time-Dependent Hartree-Fock (TDHF): no tunneling

—————→ **New simple model for multi-nucleon transfer**

c.f. a preliminary version:

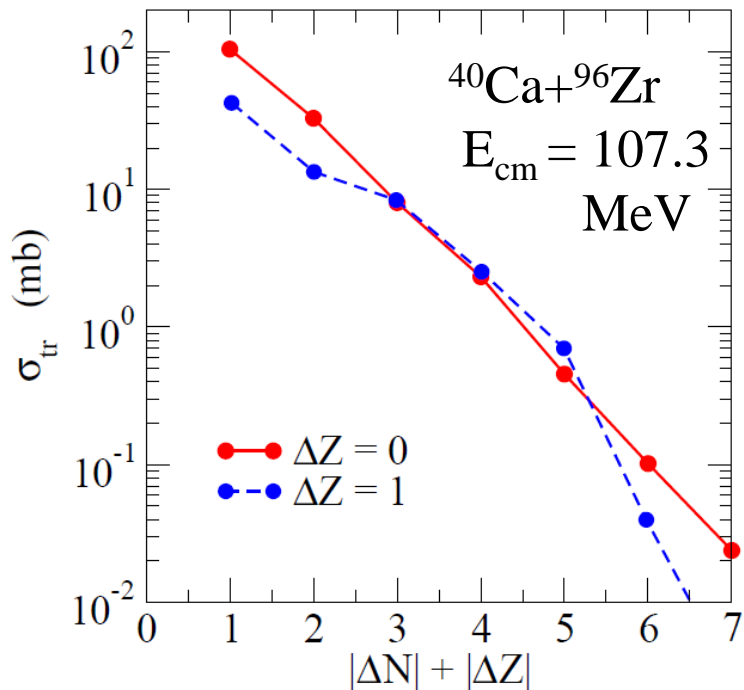
N. Rowley, in Proc. of fusion workshop at Dubna ('01)

See also:

H. Esbensen, C.L. Jiang, and K.E. Rehm,  
PRC57('98)2401

# New simple model

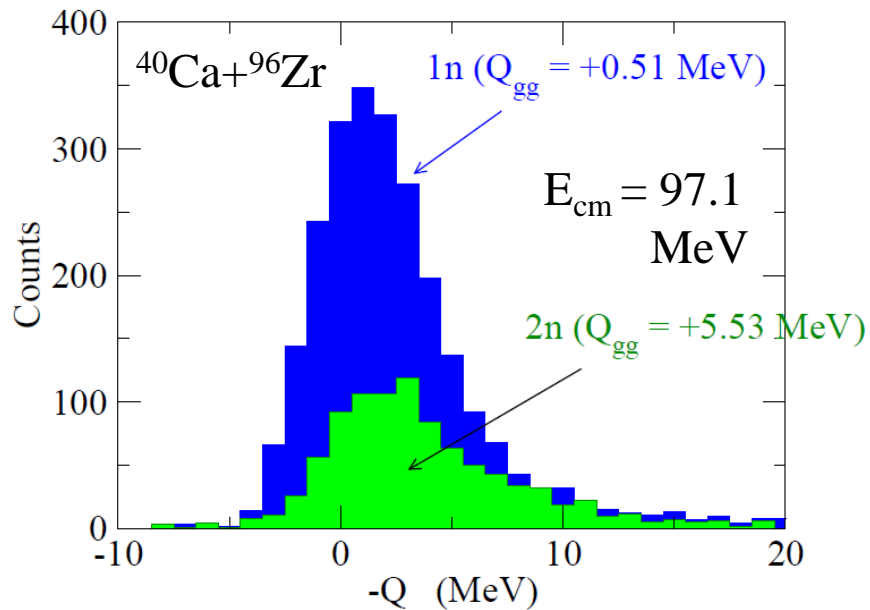
## 1. Neutron transfer chain only



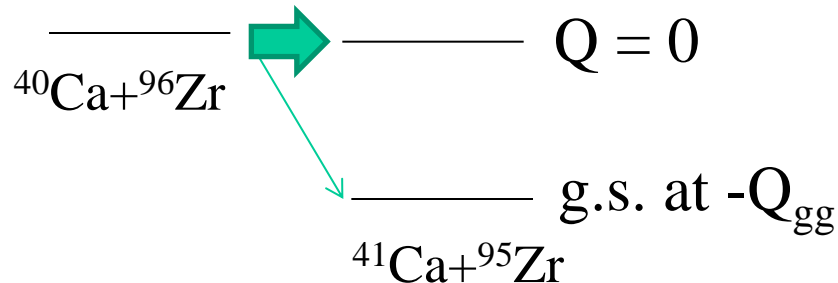
S. Szilner et al., PRC76('07)024604

proton transfer: less strongly coupled to the entrance channel

## 2. Approximate Q-value distribution



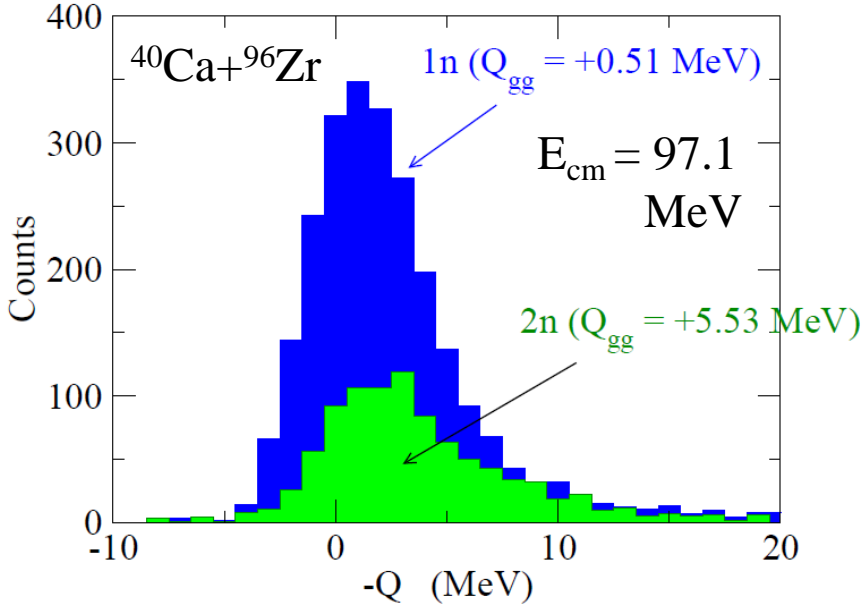
L. Corradi et al., PRC84('11)034603  
(Recent data with PRISMA)



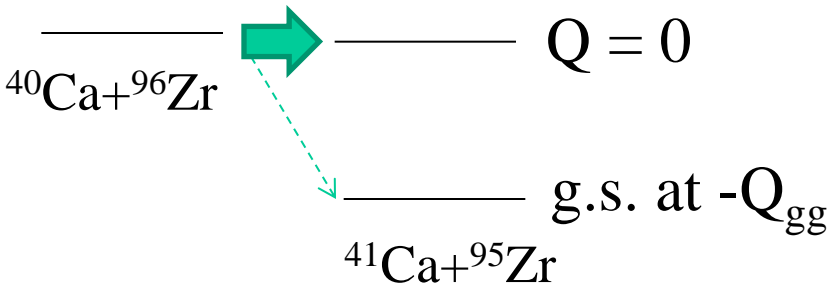
Q-value matching

→ put all the strength to a single state at  $Q=0$

## 2. Approximate Q-value distribution



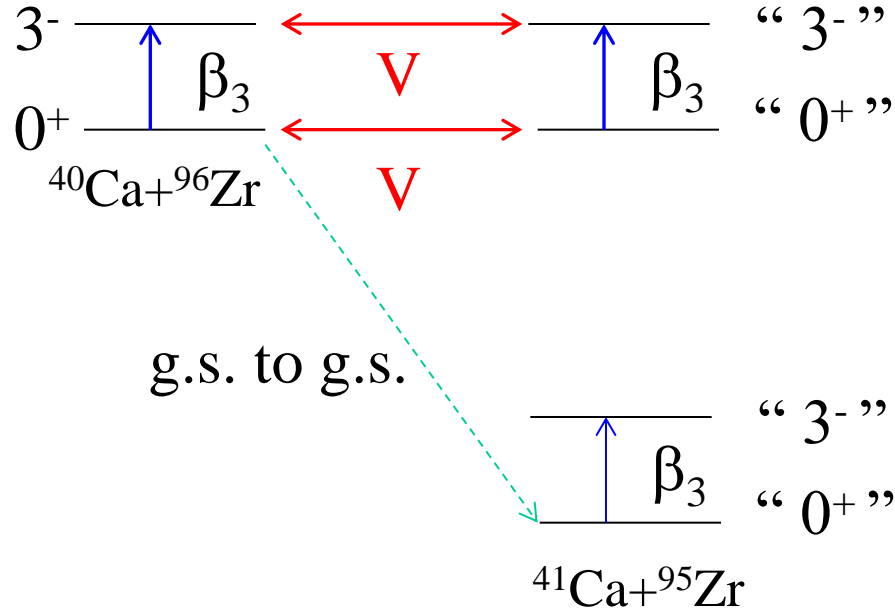
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Q-value matching

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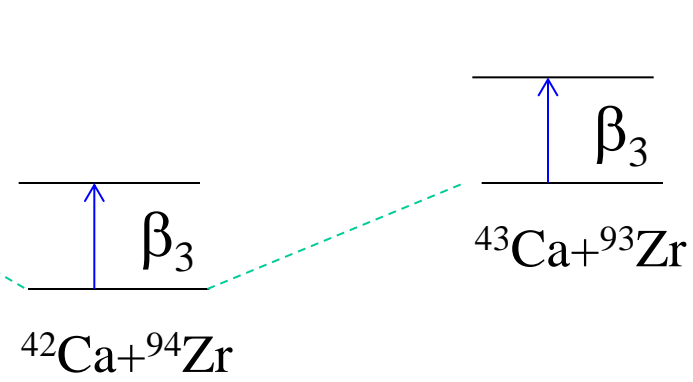
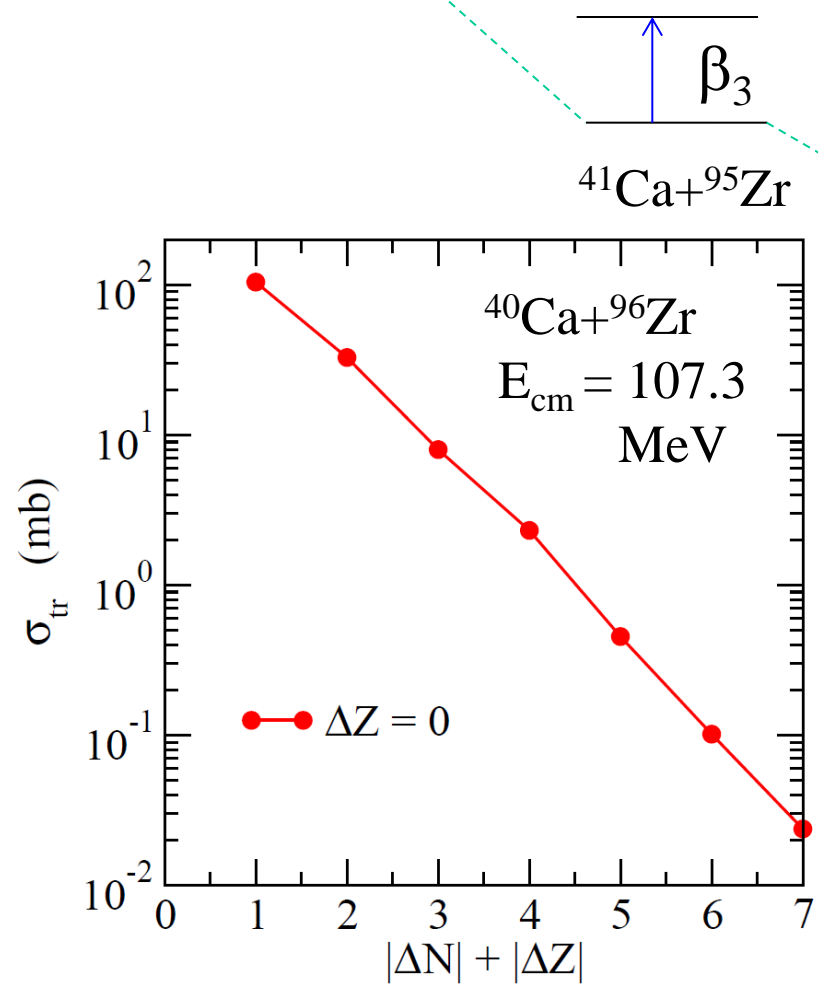
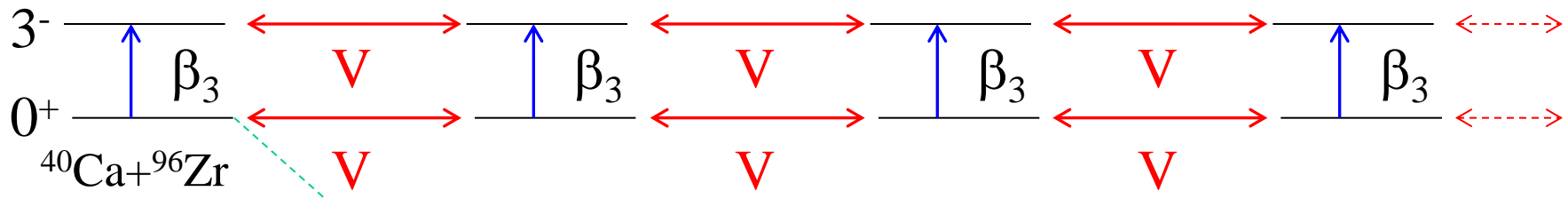
## 3. Same coupling scheme for inelastic excitations



Brink-Axel hypothesis

constant coupling approximation for transfer

# 4. Sequential coupling to each transfer partition with the same strength

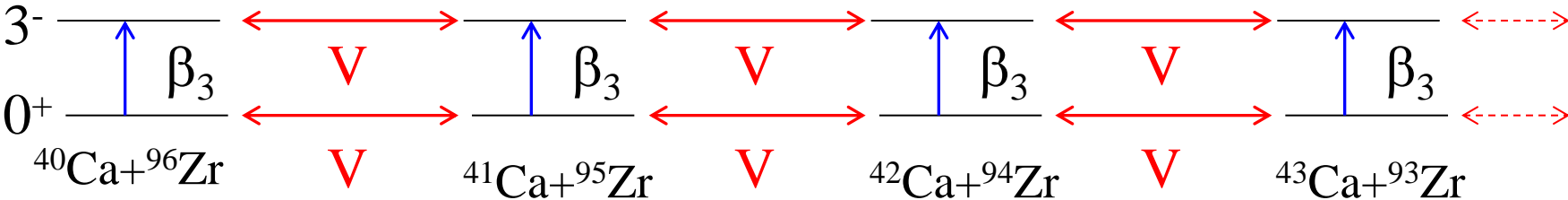


Brink-Axel hypothesis

experimental data:

$$\frac{\sigma_{\Delta N}}{\sigma_{\Delta N-1}} \sim const.$$

# 4. Sequential coupling to each transfer partition with the same strength



## Eigen-channel approach

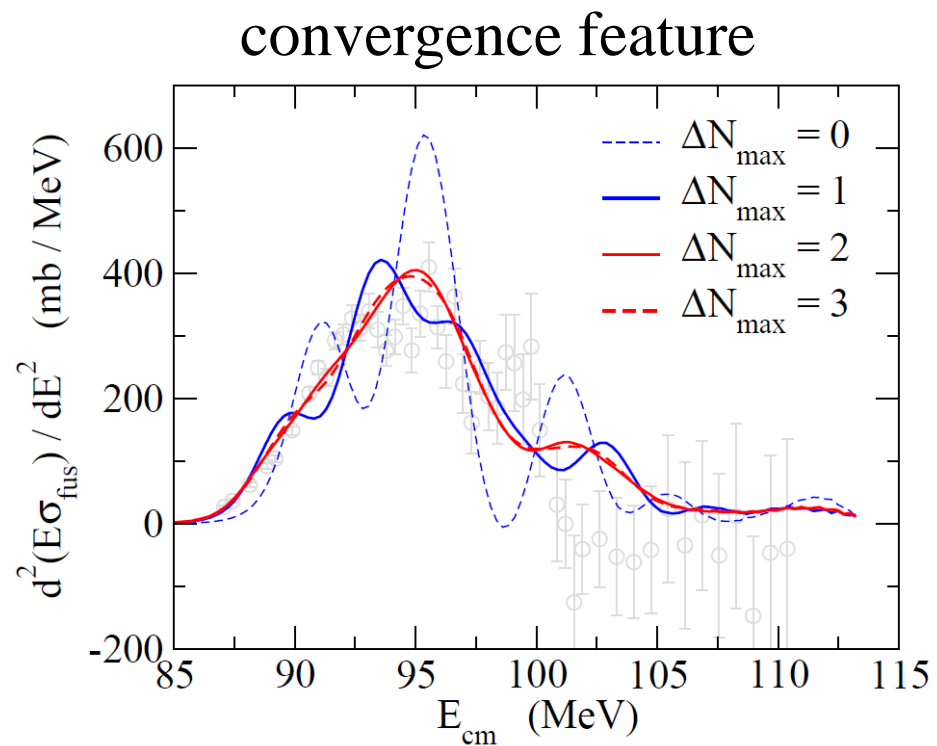
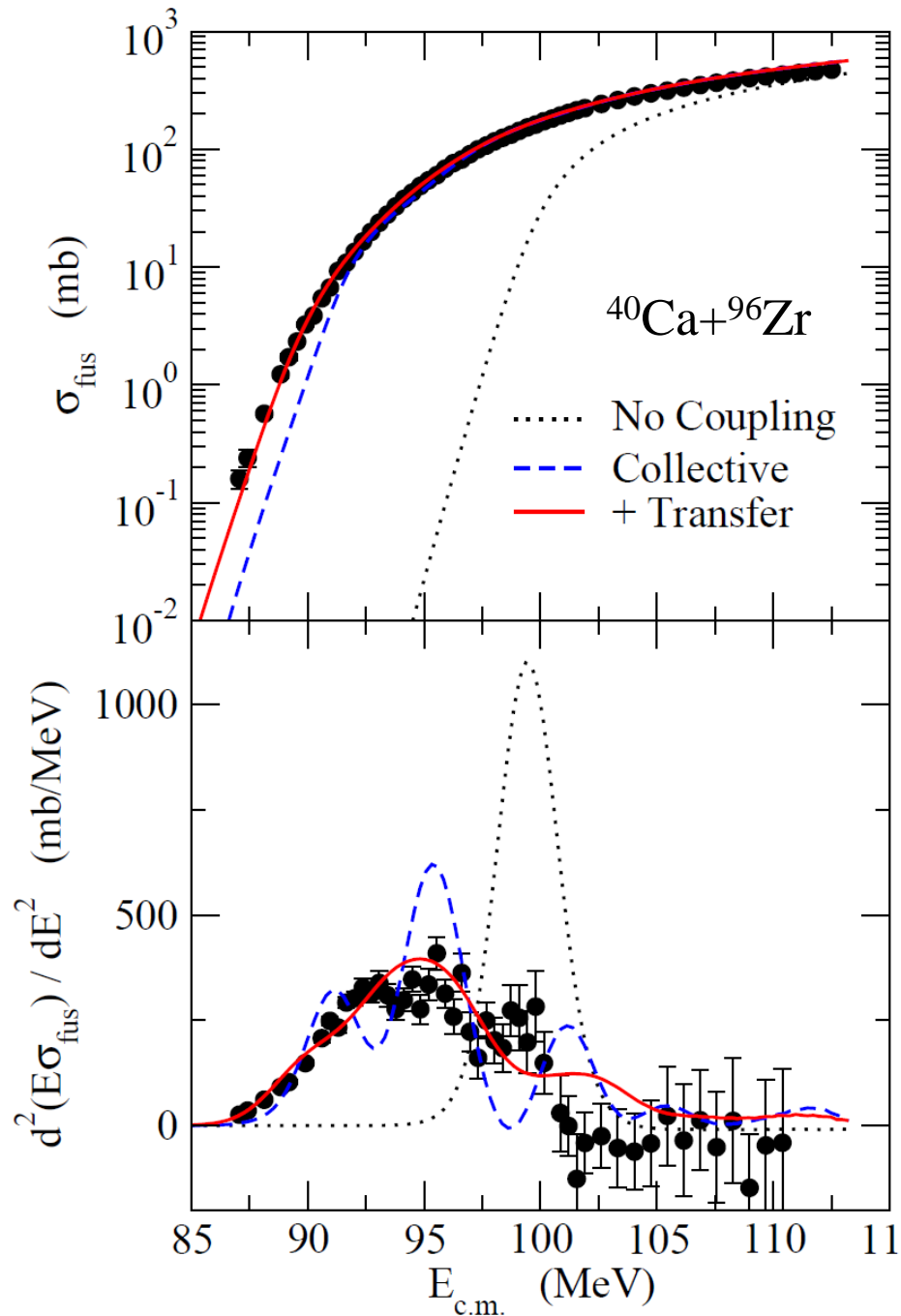
$$\sigma_{\text{fus}}(E) = \sum_i w_i \sigma_{\text{CC}}(E + \lambda_i)$$

$$V \begin{pmatrix} 0 & 1 & 0 & \dots \\ 1 & 0 & 1 & \dots \\ 0 & 1 & 0 & \dots \\ \dots & & & \end{pmatrix}$$

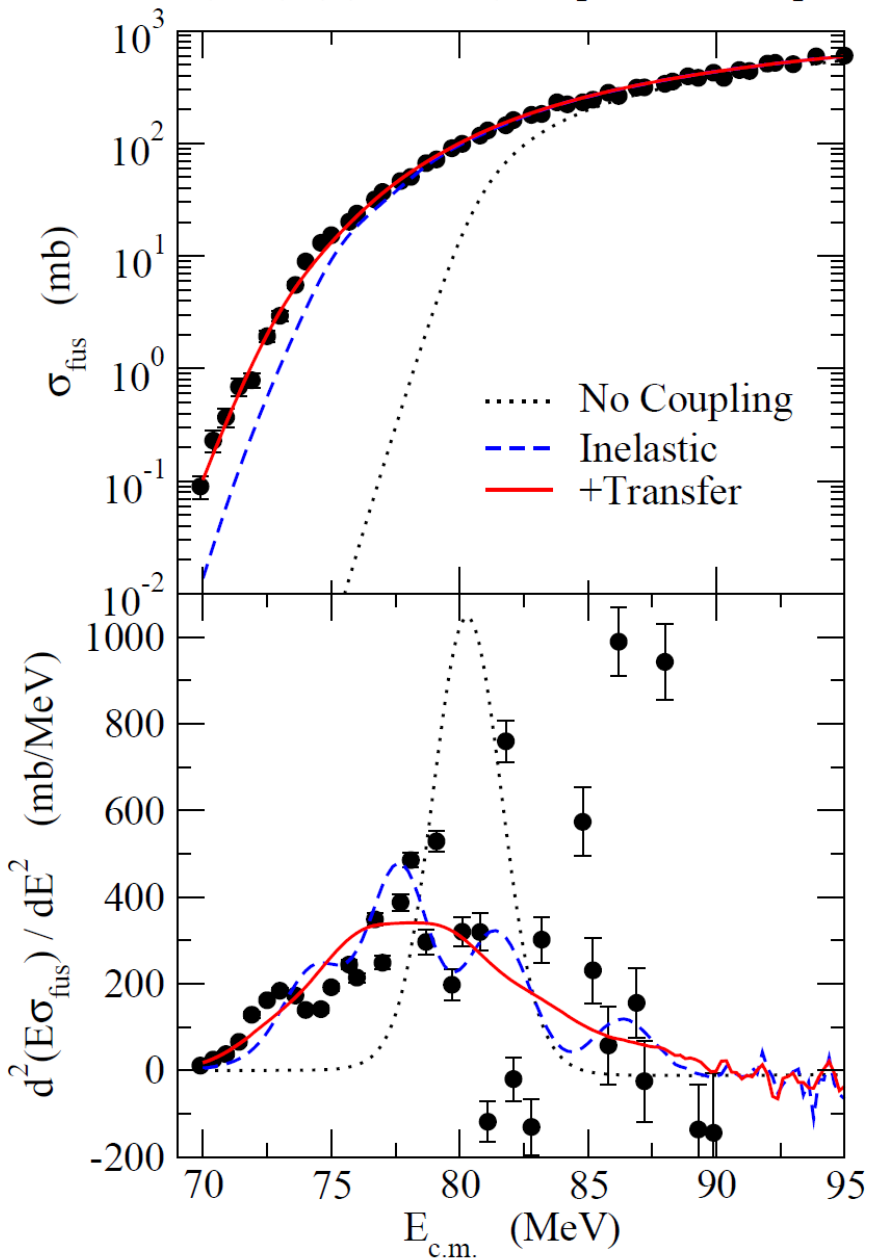
diagonalization

eigen-values  $\lambda_\alpha$   
 eigen-vectors  $|\lambda_\alpha\rangle$   
 $w_\alpha = |\langle 1 | \lambda_\alpha \rangle|^2$

Model: One adjustable parameter:  $V$



$^{32}\text{S} (2^+, (2^+)^2) + ^{96}\text{Zr} (2^+ : 2\text{phonon}, 3^- : 3\text{phonon})$



Experimental data:  
H.Q. Zhang, C. Beck et al.,  
PRC82('10)054609

	$^{32}\text{S} + ^{90}\text{Zr}$	$^{32}\text{S} + ^{96}\text{Zr}$
+1n	-3.33	+0.79
+2n	-1.23	+5.74
+3n	-6.59	+4.51
+4n	-6.32	+7.66

# Summary

## Multi-neutron transfer process in heavy-ion subbarrier fusion reactions

### New simple model

- ✓ Constant coupling approximation for transfer
- ✓ barrier distribution for transfer couplings
- ✓ inelastic excitations with full C.C.
- ✓ tunneling dynamics
- ✓ easy to extend existing C.C. codes
- ✓ application to  $^{40}\text{Ca} + ^{96}\text{Zr}$

### Things to do

- ✓ application to other fusion systems
- ✓ radial dependence of transfer form factor
- ✓ analyses of experimental data for transfer reactions (PRISMA, KISS)

