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

Kouichi Hagino
Tohoku University, Sendai, Japan

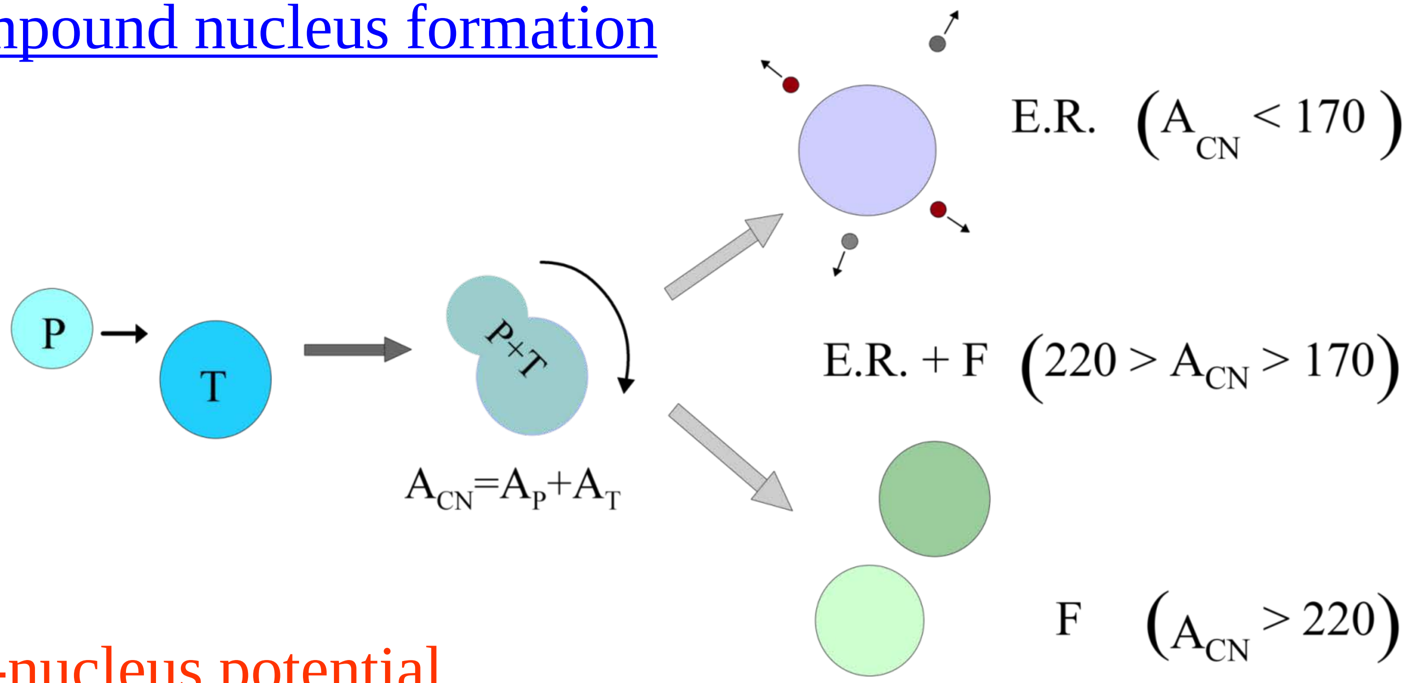
N. Sekine (Tohoku University)
N. Rowley (IPN Orsay)

TOHOKU UNIVERSITY

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

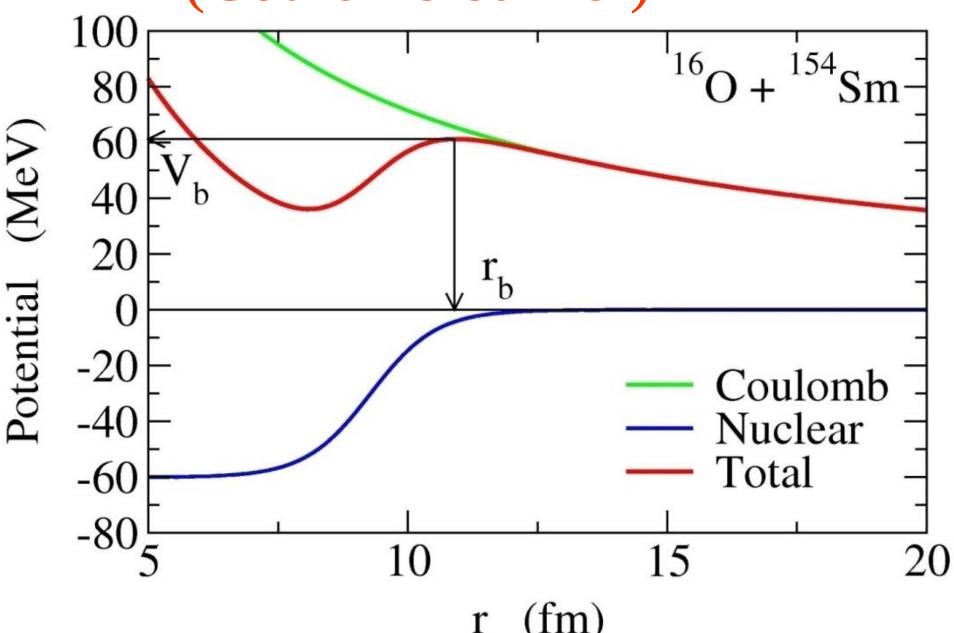
Recent review on subbarrier fusion:
K. Hagino and N. Takigawa, Prog. Theo. Phys., in press.
arXiv:1209.6435 [nucl-th].

Fusion: compound nucleus formation



courtesy: Felipe Canto

Inter-nucleus potential
(Coulomb barrier)

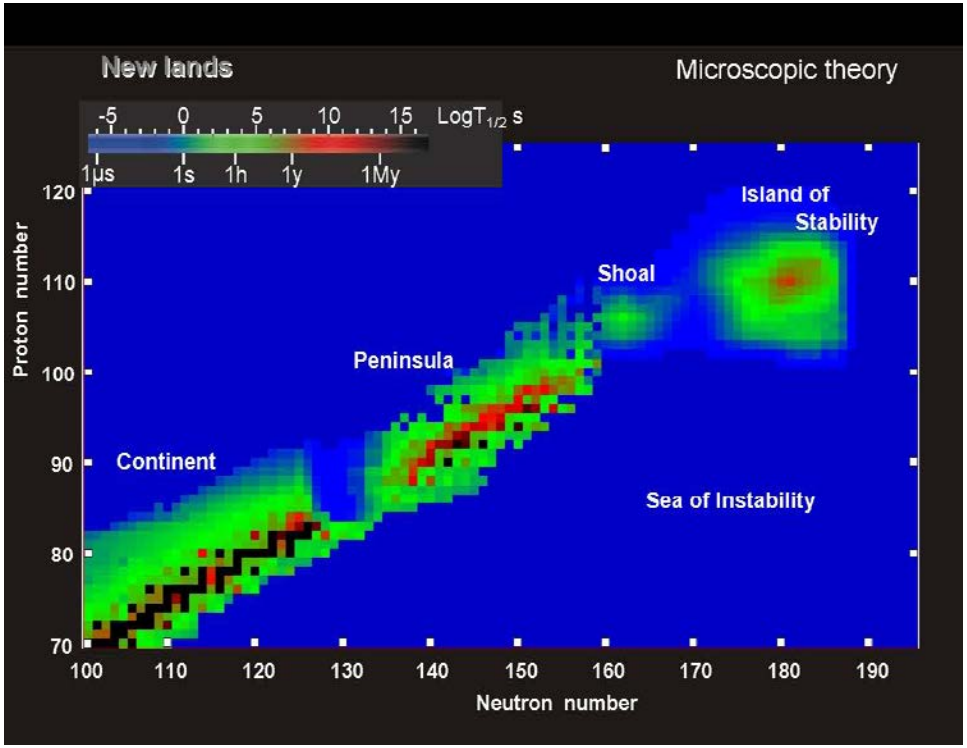


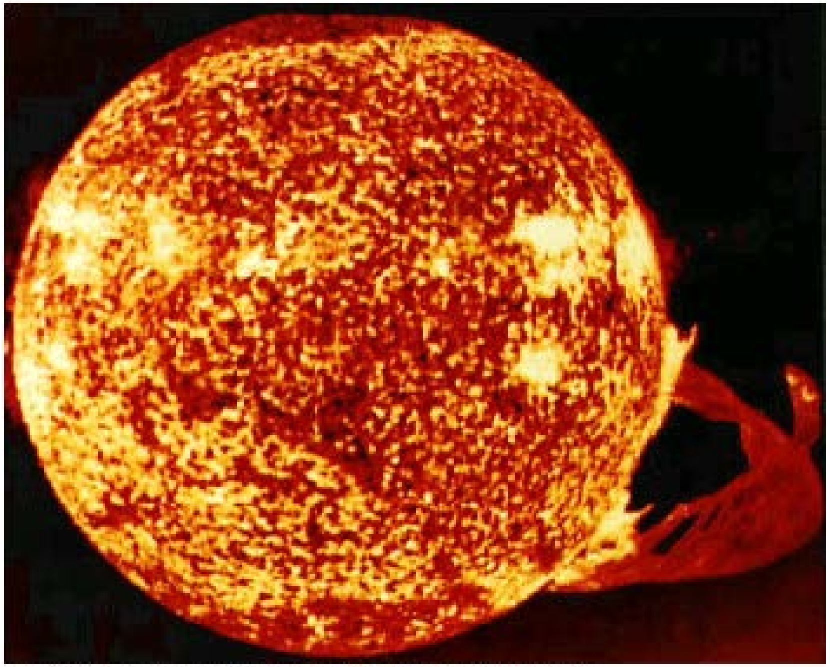
- above barrier energies
- sub-barrier energies ⬅
- deep subbarrier energies

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

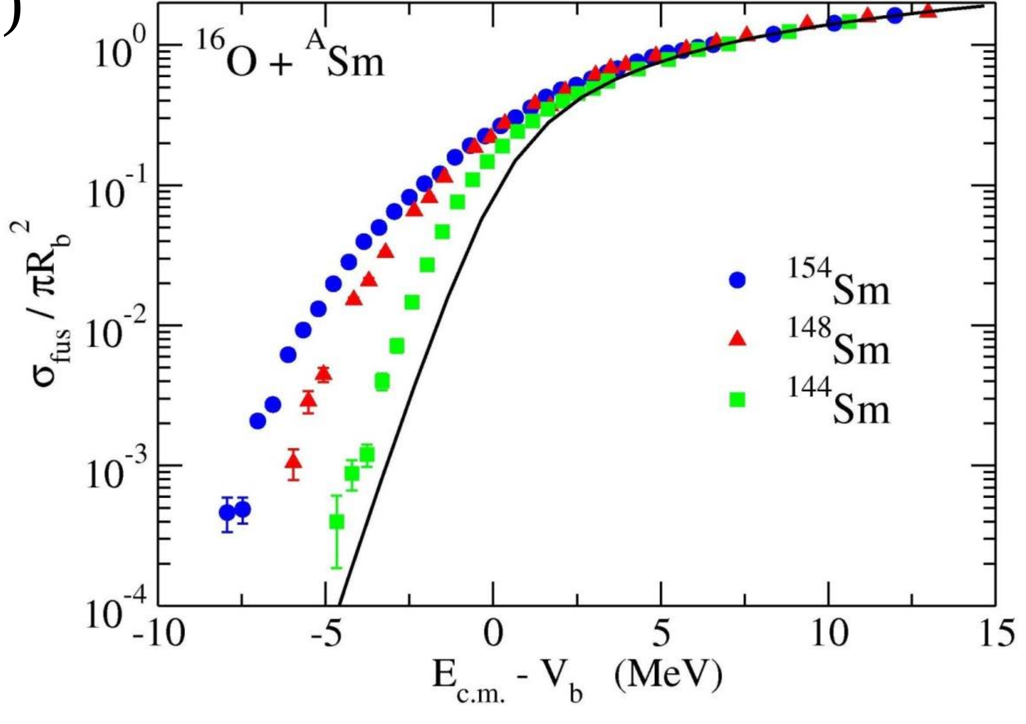
strong interplay between reaction and structure

(channel coupling effects)

✓many-particle tunneling

cf. alpha decay

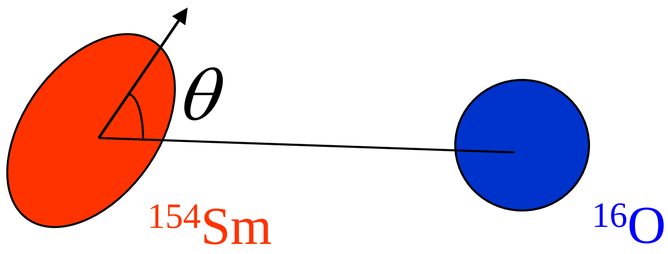
: fixed energy



Strong target dependence at $E < V_b$

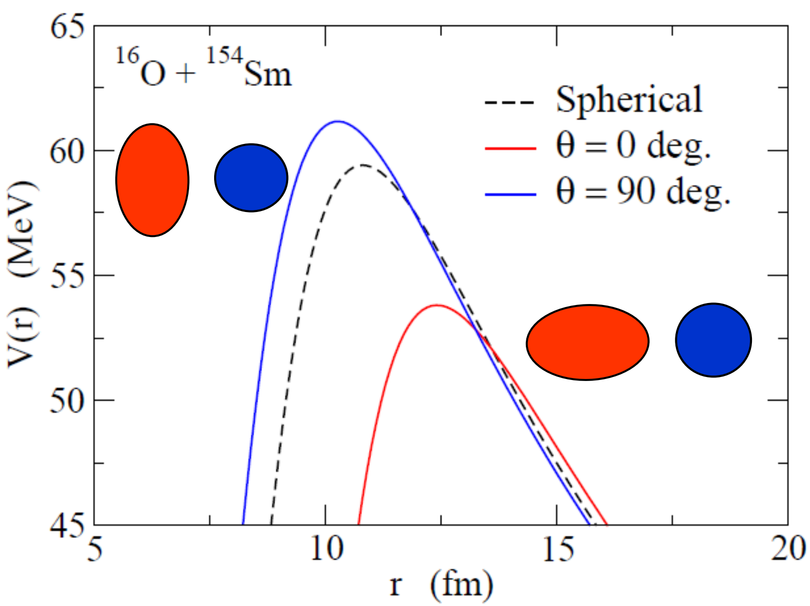
Subarrier fusion:

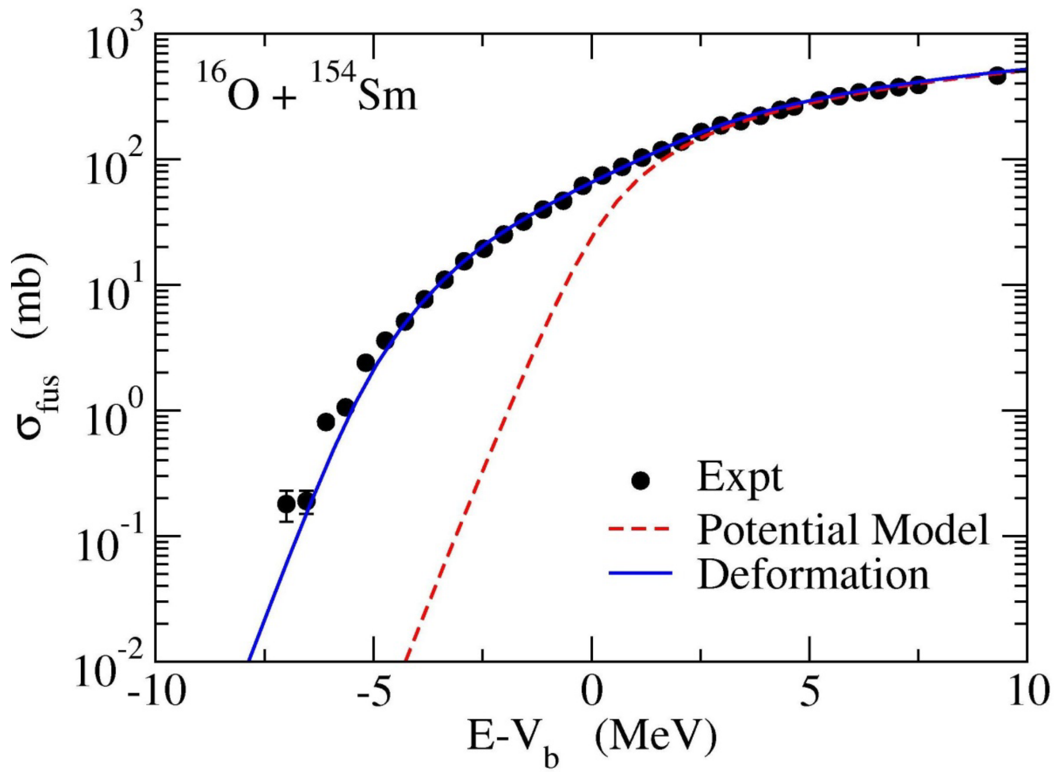
strong interplay between reaction and structure



coupled-channels equations

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



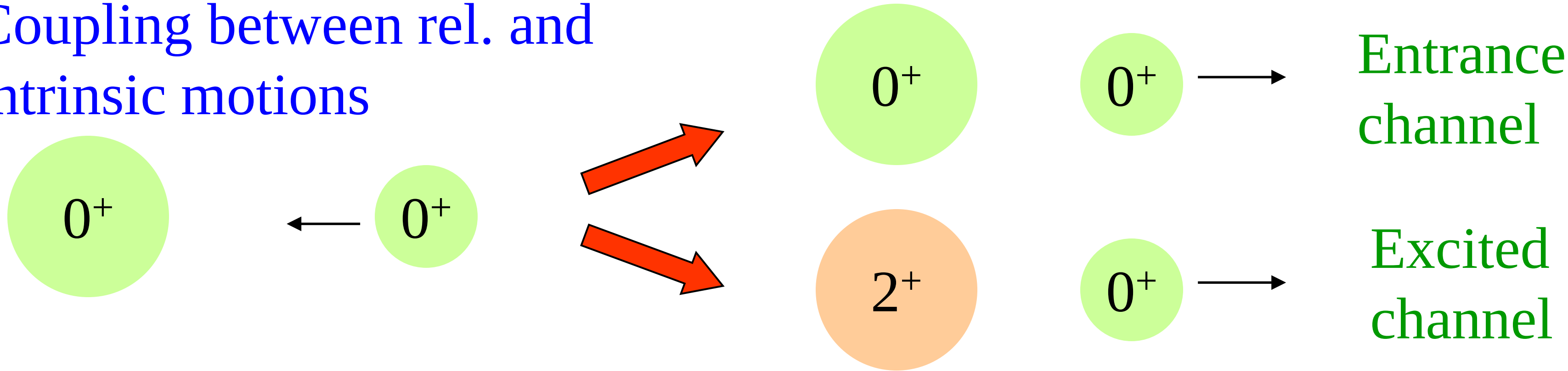


Def. Effect: enhances $\sigma_{\rm fus}$ by a factor of 10 ~ 100

Fusion: interesting probe for nuclear structure

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

Coupling between rel. and intrinsic motions



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

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?

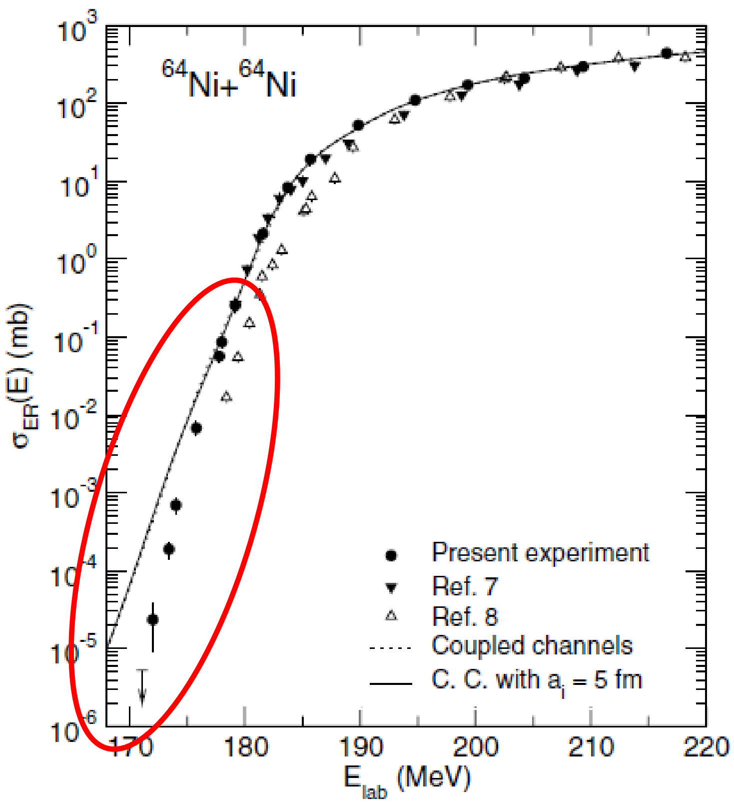
- role of dissipation?

✓fusion of unstable nuclei? cf. D. Pierroutsakou's talk

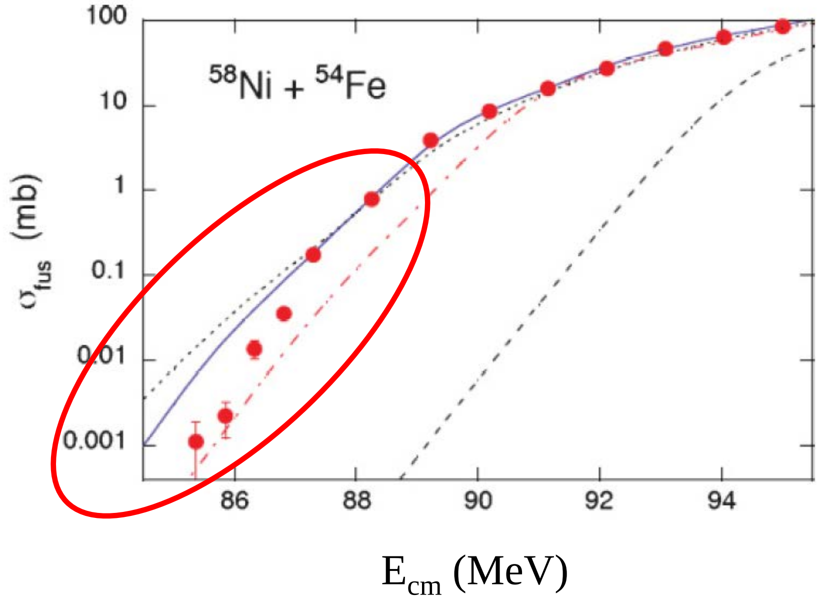
- breakup, (pair) transfer

✓**how to treat (multi-nucleon) transfer?**

deep subbarrier hindrance of fusion cross sections



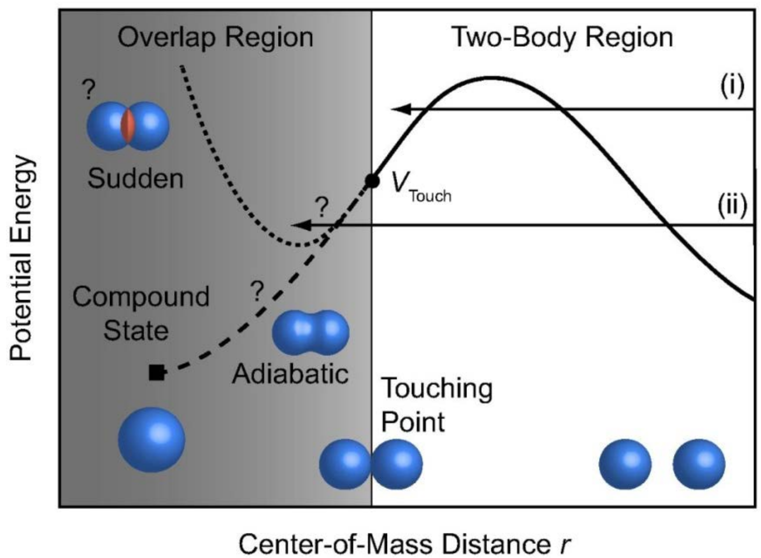
C.L. Jiang et al., PRL89('02)052701;
PRL93('04)012701



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

Theory:

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



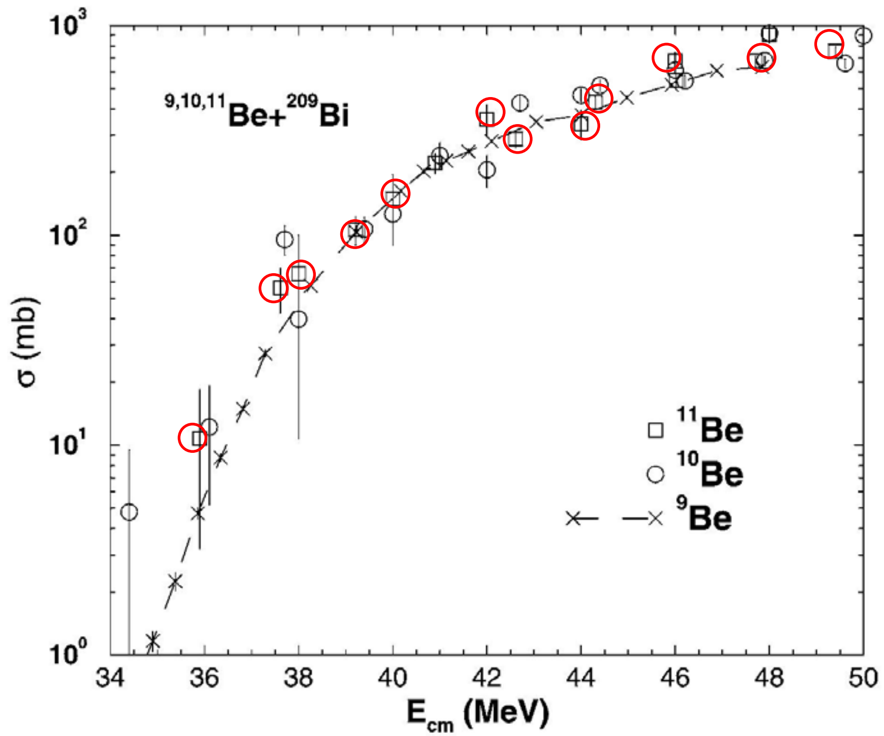
Fusion of unstable nuclei

Fusion of stable nuclei: large enhancement of fusion cross sections

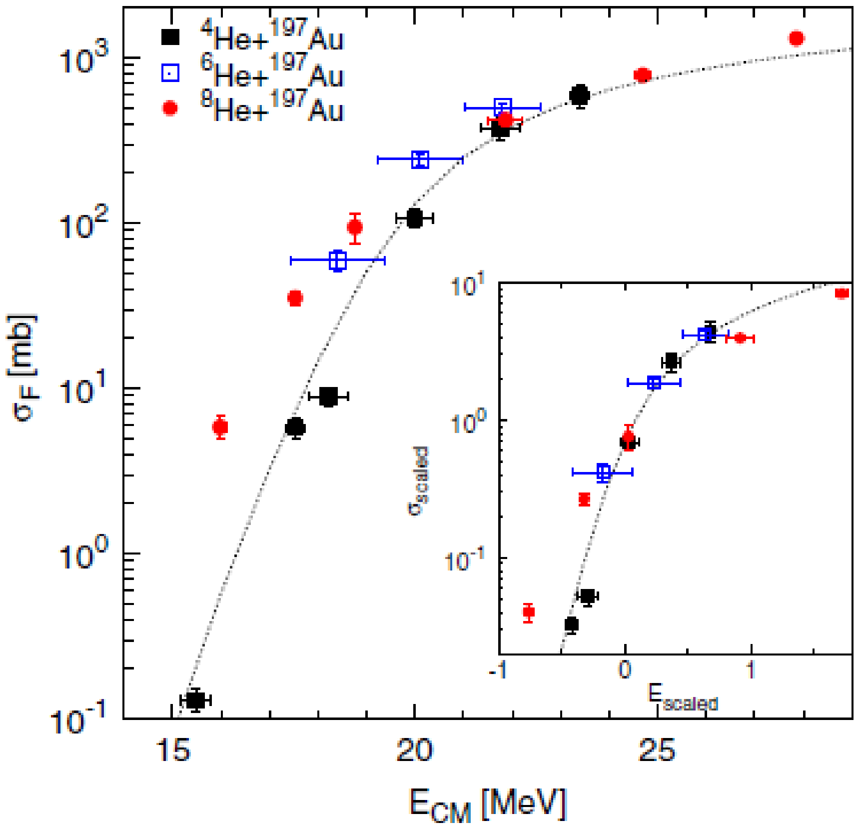
⟶ Fusion of unstable (weakly bound) nuclei?

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 $^{12,13,14,15}C + ^{232}Th$

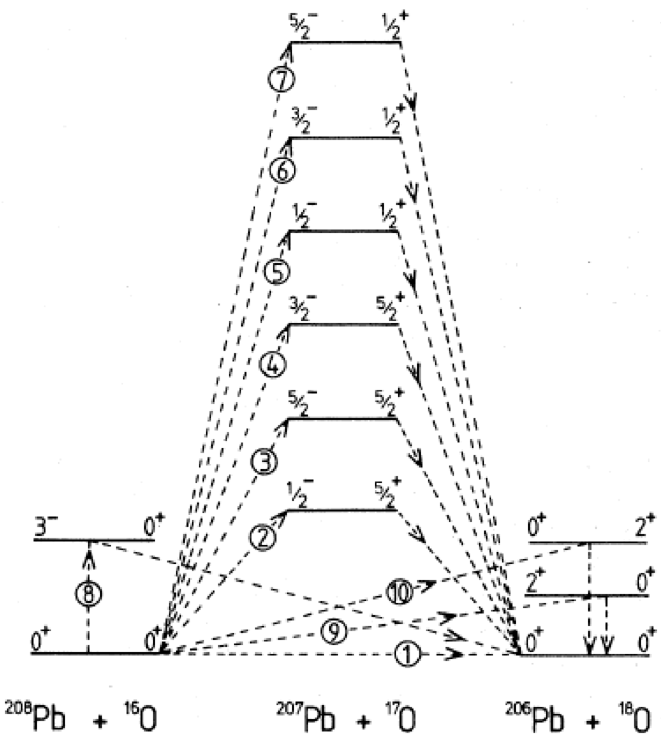
M. Alcorta et al., PRL106('11)172701

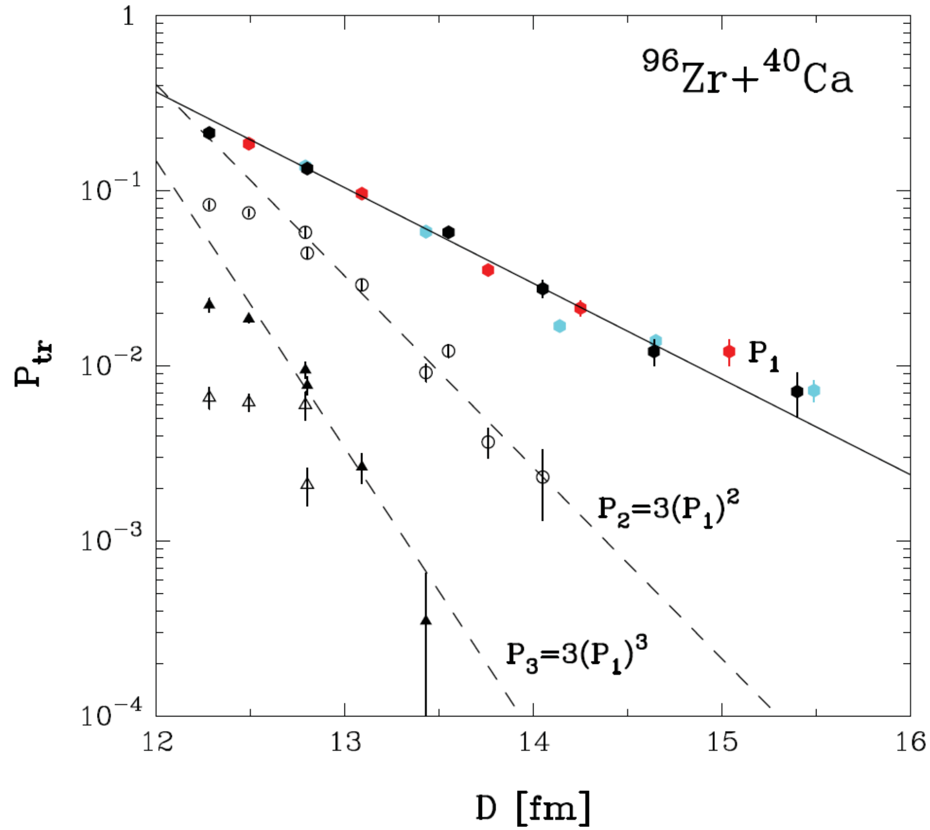
Pair transfer:

✓**Reaction mechanism?**

- sequential vs simultaneous

cf. Modern calculations for ^{A}Sn(p,t):
G. Potel et al., PRL107(‘11)092501



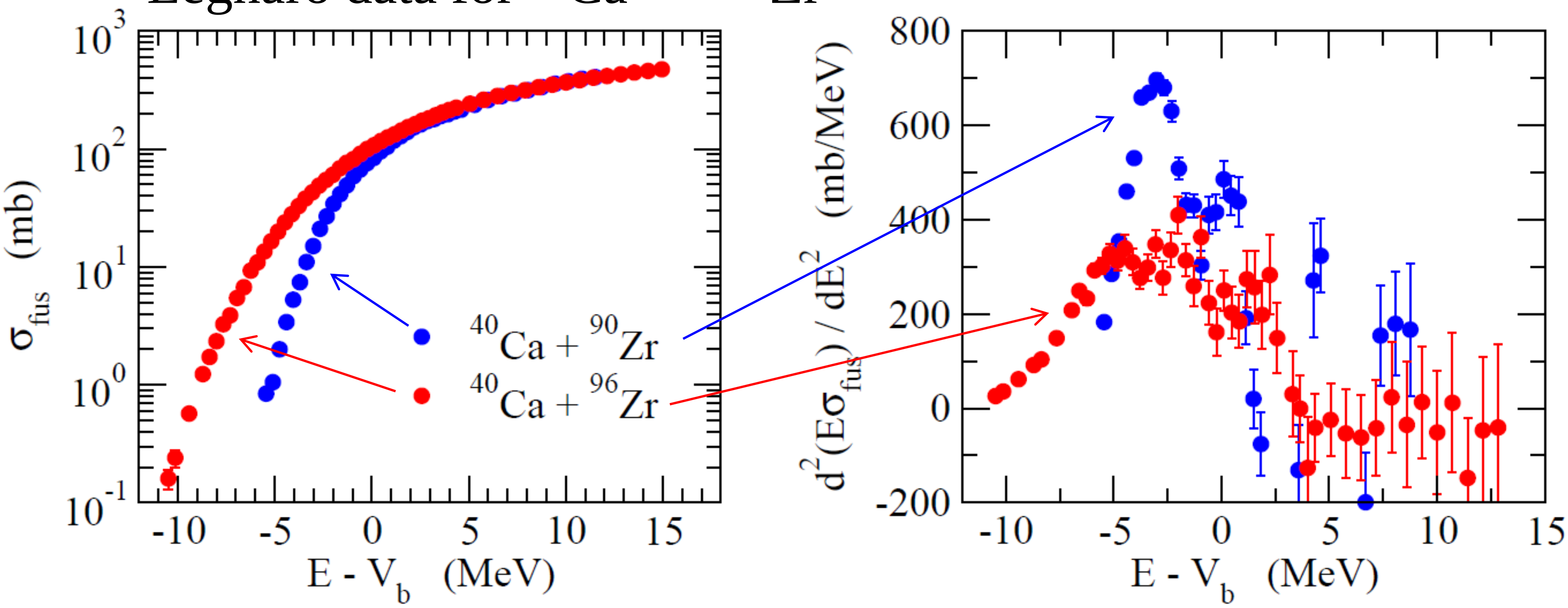


L. Corradi et al., PRC84(‘11)034603

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}Ca + $^{90,96}Zr$



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

^{40}Ca + ^{96}Zr

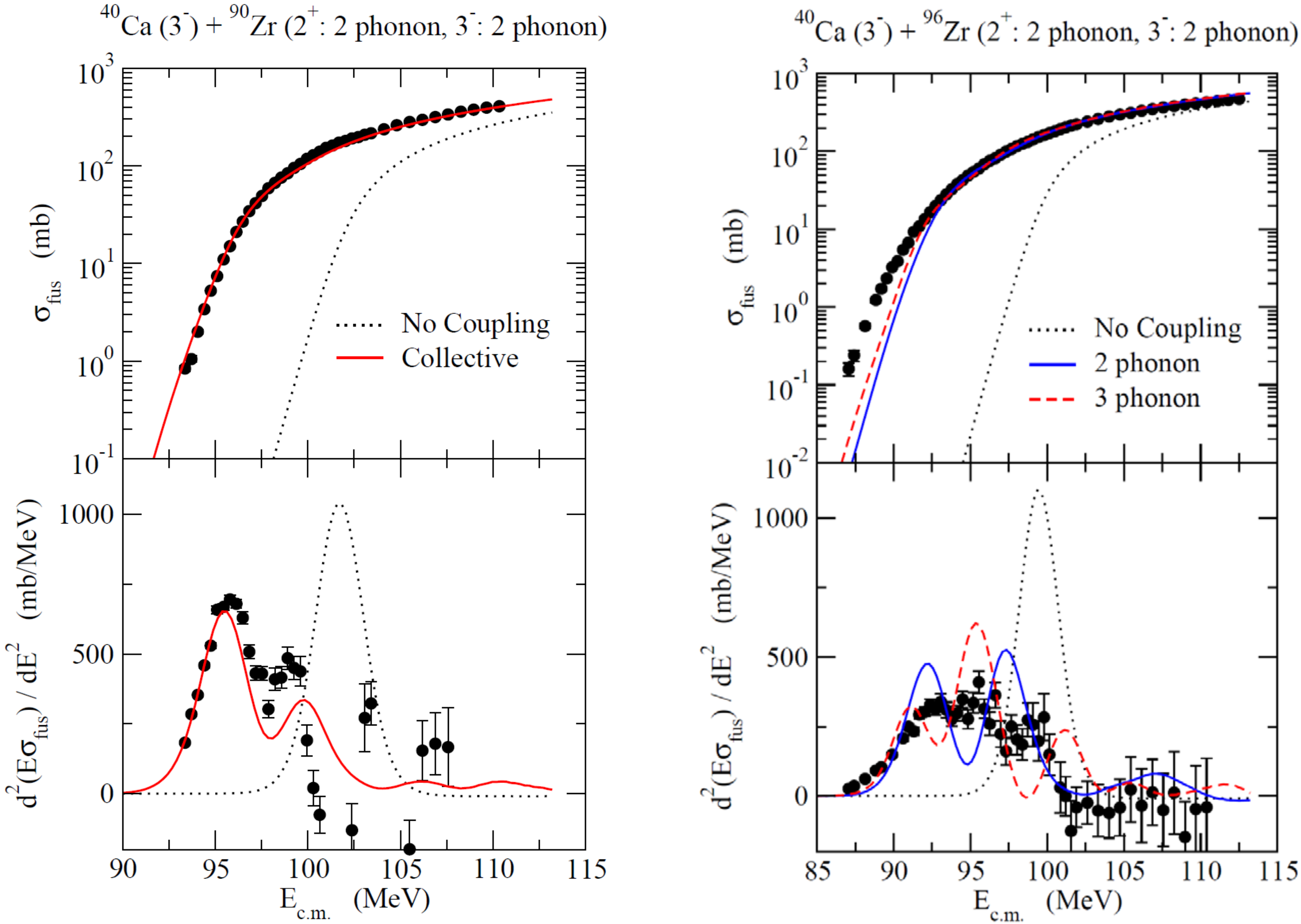
- more enhancement of fusion cross sections
- flatter barrier distribution

✓stronger octupole collectivity
✓multi-neutron transfer process

stronger octupole collectivity in ^{96}Zr

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

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



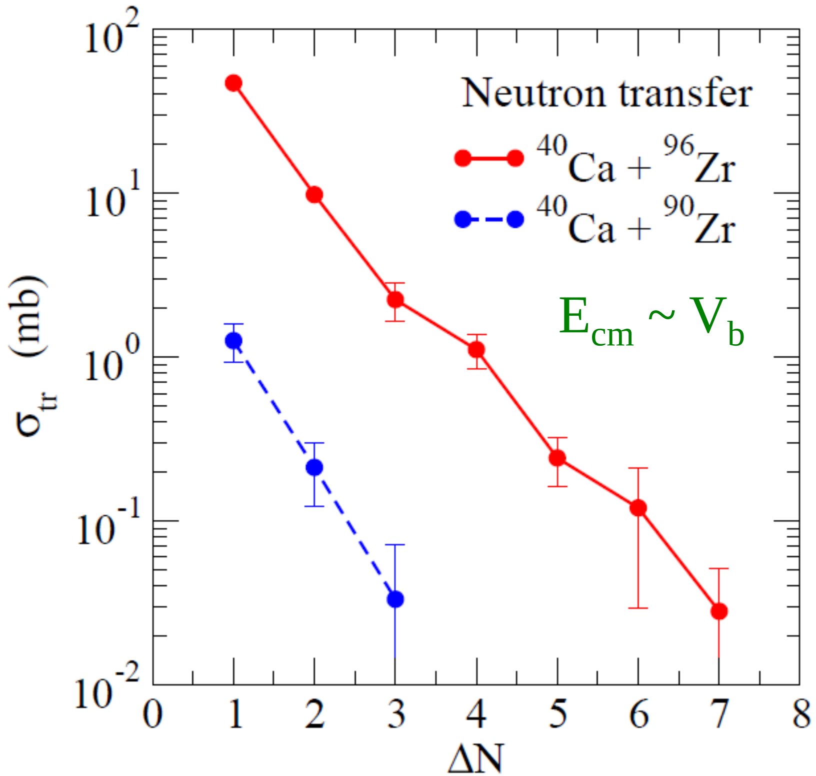
Q-values for multi-neutron transfer channels

Q_{gg} (MeV)

	^{40}Ca + ^{90}Zr	^{40}Ca + ^{96}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}Ca+^{90}Zr

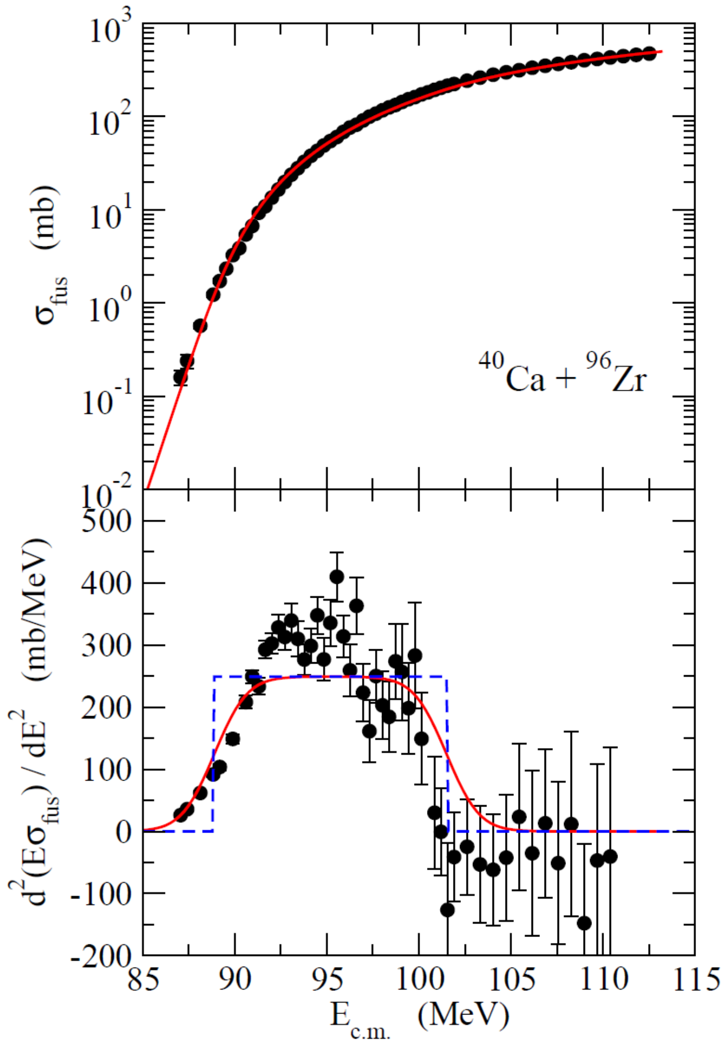
Experimental data for
total transfer cross sections



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

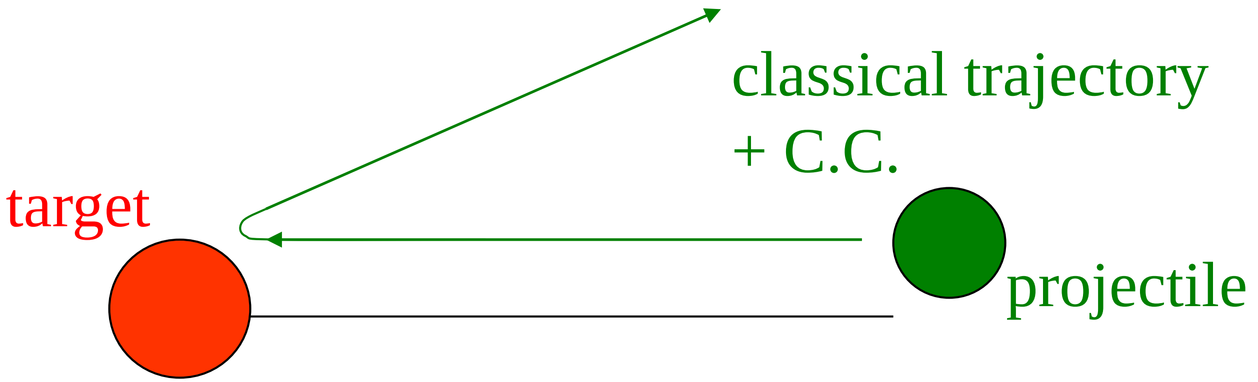


- ➢Flat barrier distribution
  (B_{min}, B_{max}: parameters)
- ➢Simple, and easy to implement
- ➢Purely phenomenological
- ➢No connection to transfer cross sections

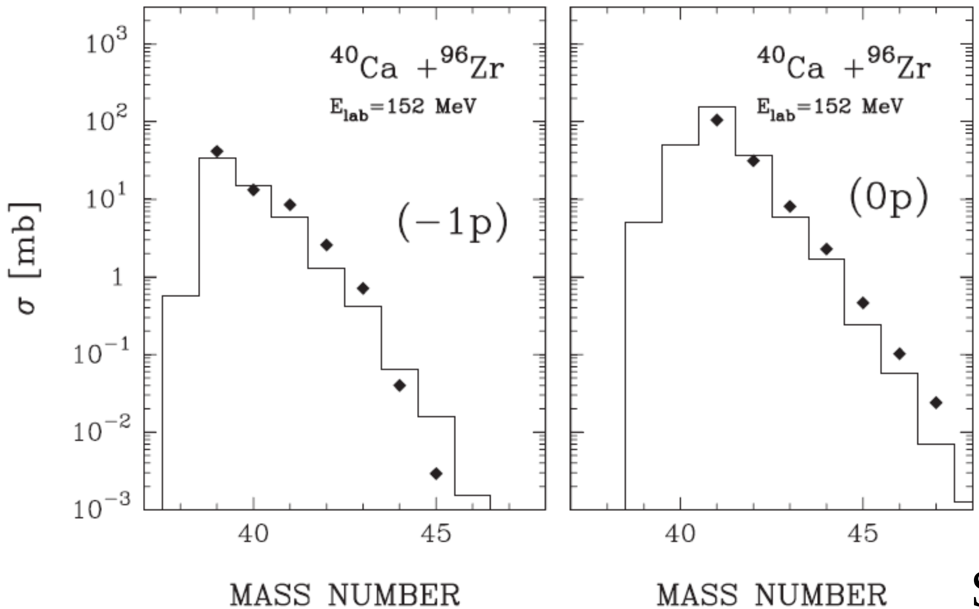
2. GRAZING: G. Pollarolo and A. Winther, PRC62('00)054611
3. Zagrebaev's model: V.I. Zagrebaev, PRC67('03)061601(R)

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



semi-classical
coupled-channels
method



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

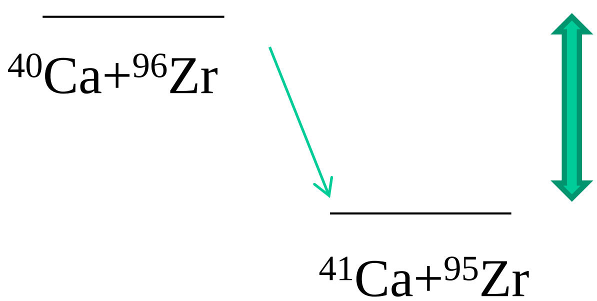
S. Szilner et al., PRC76('07)024604

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

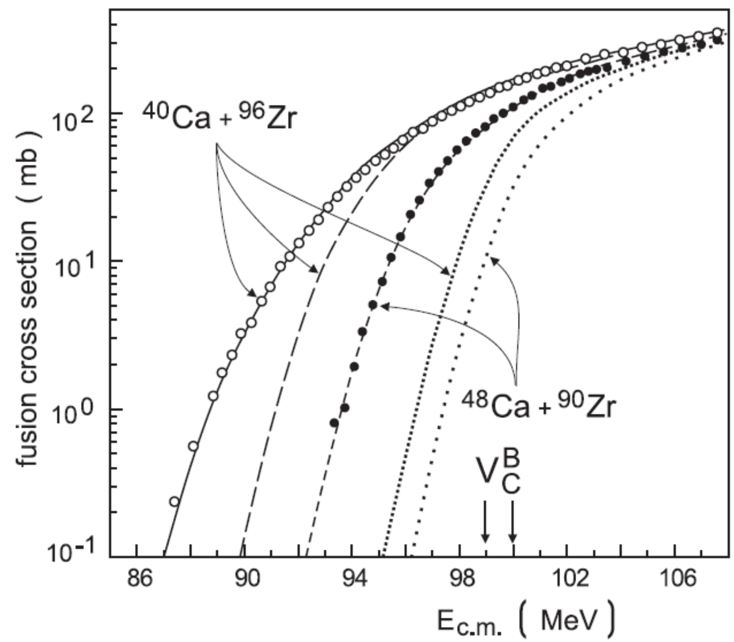
How to treat multi-neutron transfer?

1. Stelson model: P.H. Stelson, PLB205(‘88)190
2. GRAZING: G. Pollarolo and A. Winther, PRC62(‘00)054611
3. Zagrebaev’s model: V.I. Zagrebaev, PRC67(‘03)061601(R)

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



energy gain



→ too naive

cf. 3^- excitation: energy loss

but still large enhancement of σ_{fus}

New simple model

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

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

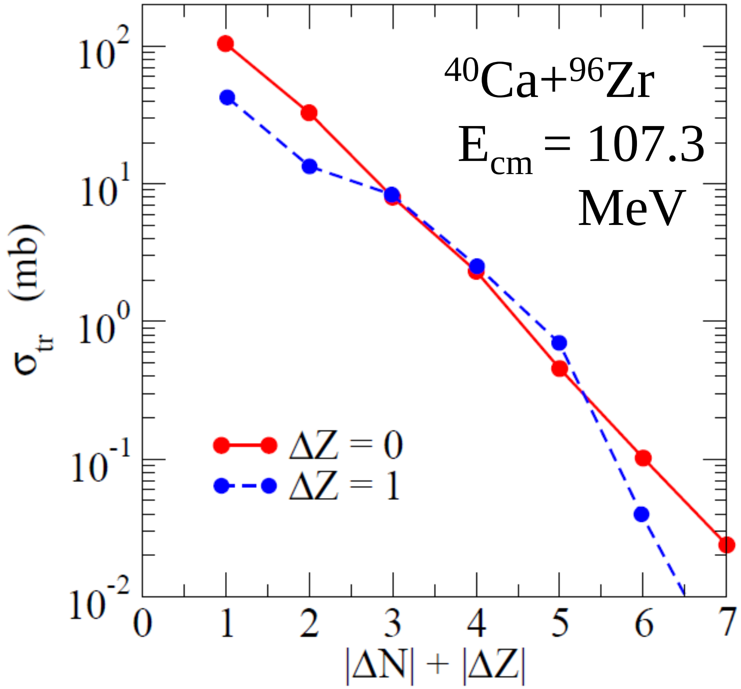
$\longrightarrow$ New simple model for multi-nucleon transfer

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

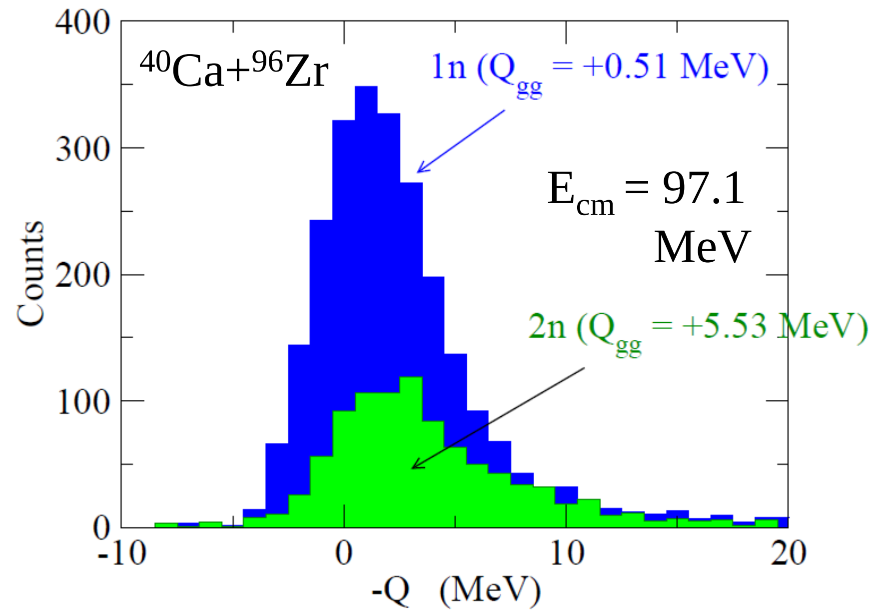
1. Neutron transfer chain only



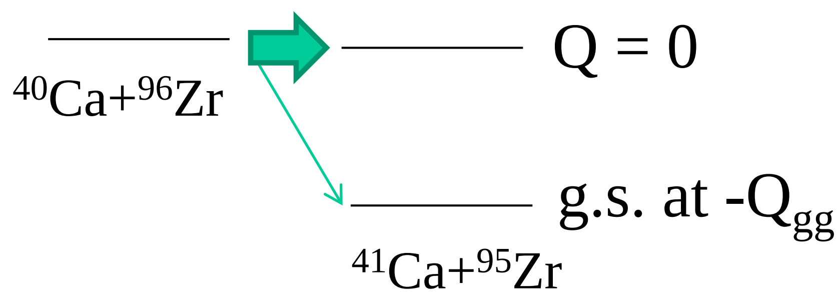
S. Szilner et al., PRC76('07)024604

proton transfer: less strongly coupled to the entrance channel

2. Approximate Q-value distribution



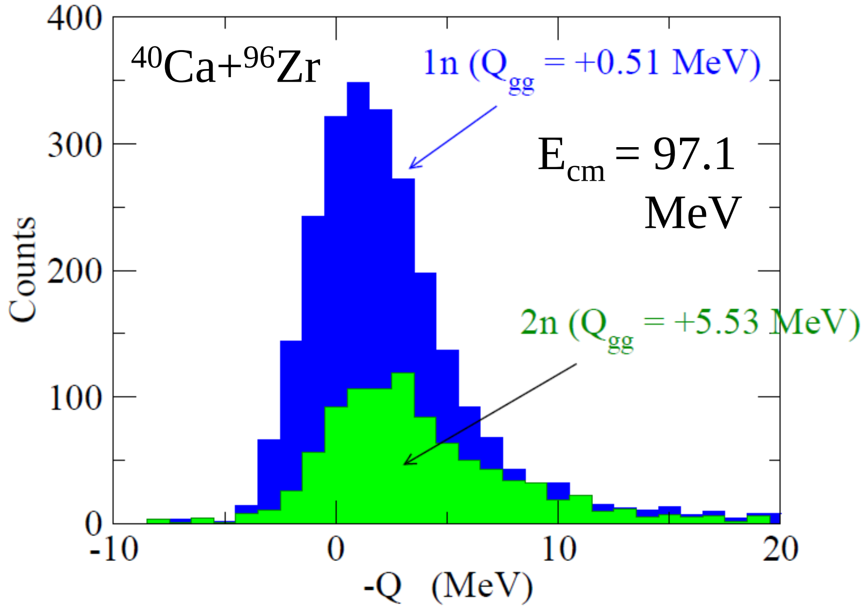
L. Corradi et al., PRC84('11)034603
(Recent data with PRISMA)



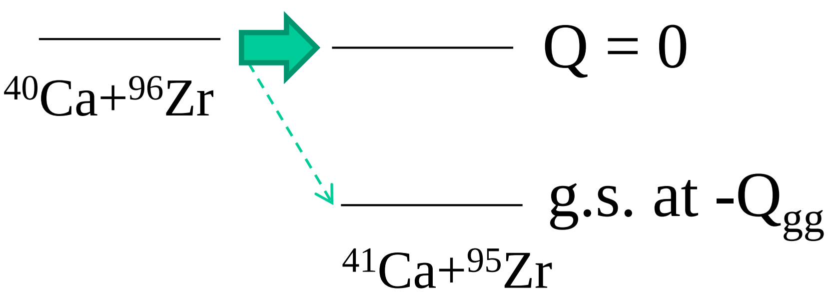
Q-value matching

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

2. Approximate Q-value distribution



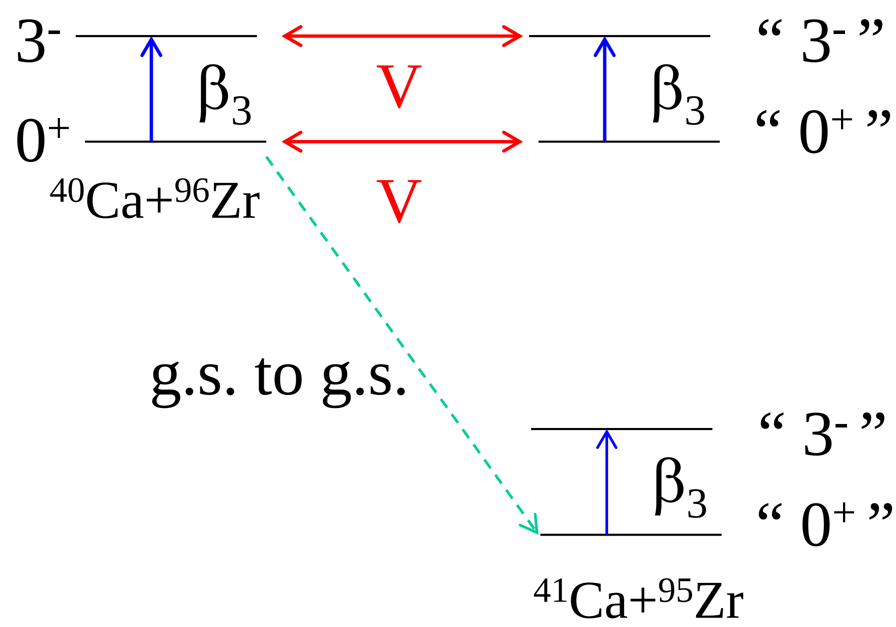
L. Corradi et al., PRC84(‘11)034603
(Recent data with PRISMA)



Q-value matching

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

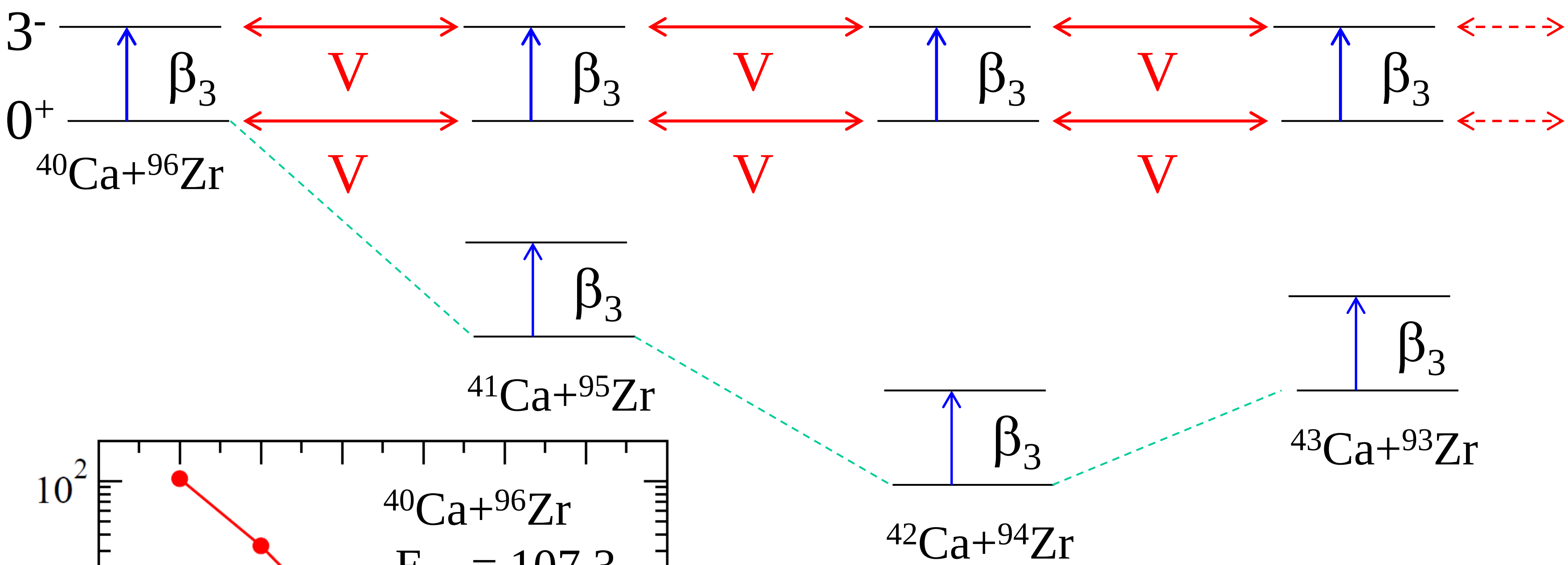
3. Same coupling scheme for inelastic excitations

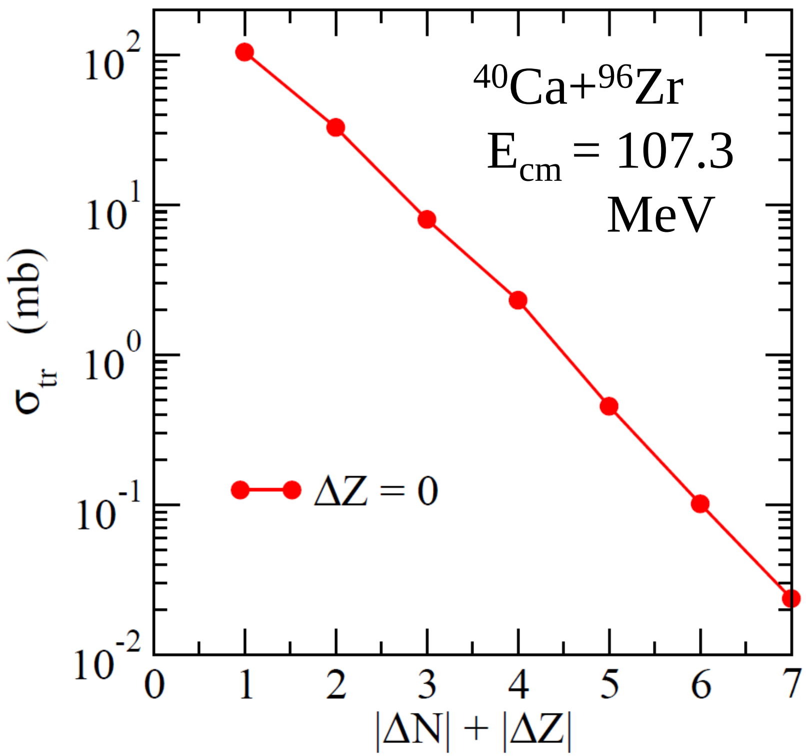


Brink-Axel hypothesis

constant coupling approximation for transfer

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





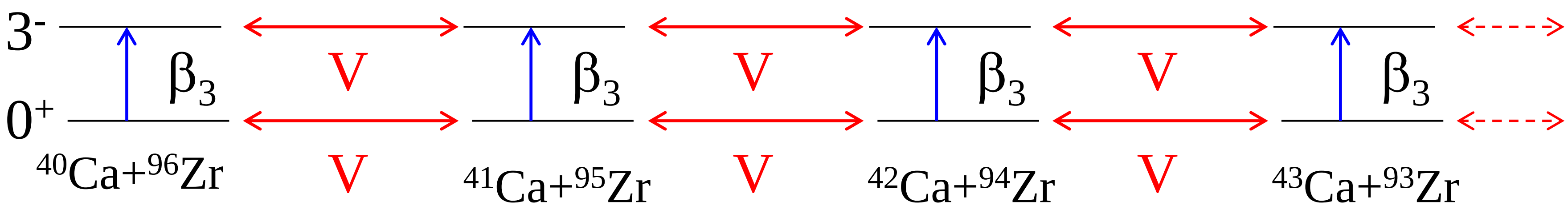
Brink-Axel hypothesis

experimental data:

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

S. Szilner et al., PRC76(‘07)024604

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



Eigen-channel approach

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

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

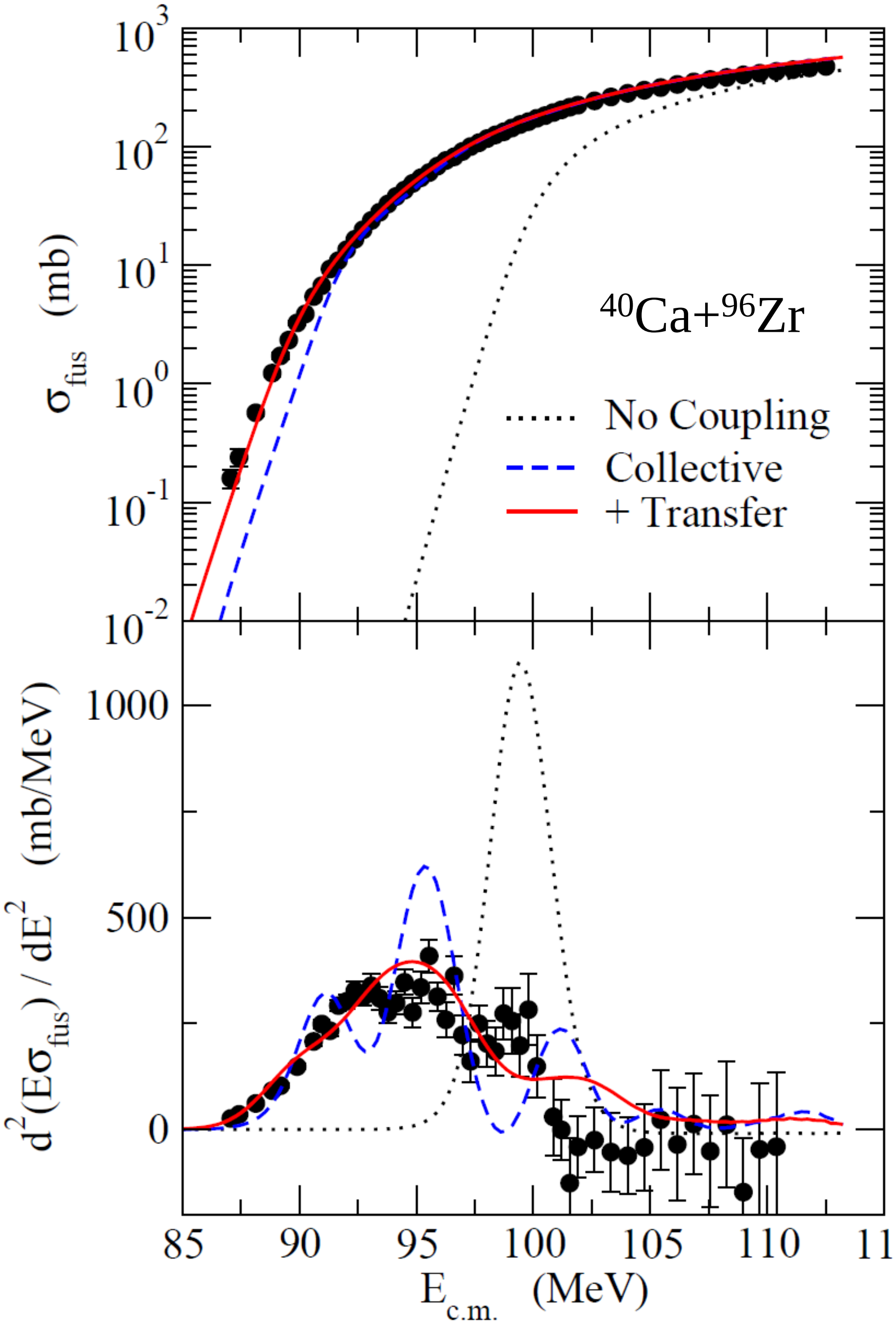
→ diagonalization

eigen-values λ_α

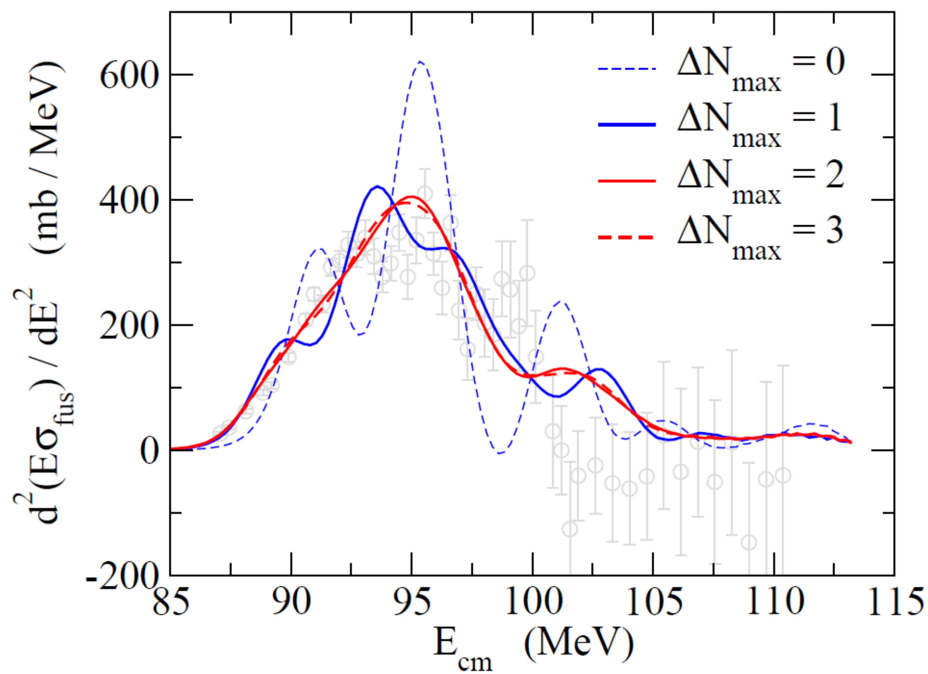
eigen-vectors $|\lambda_\alpha>$

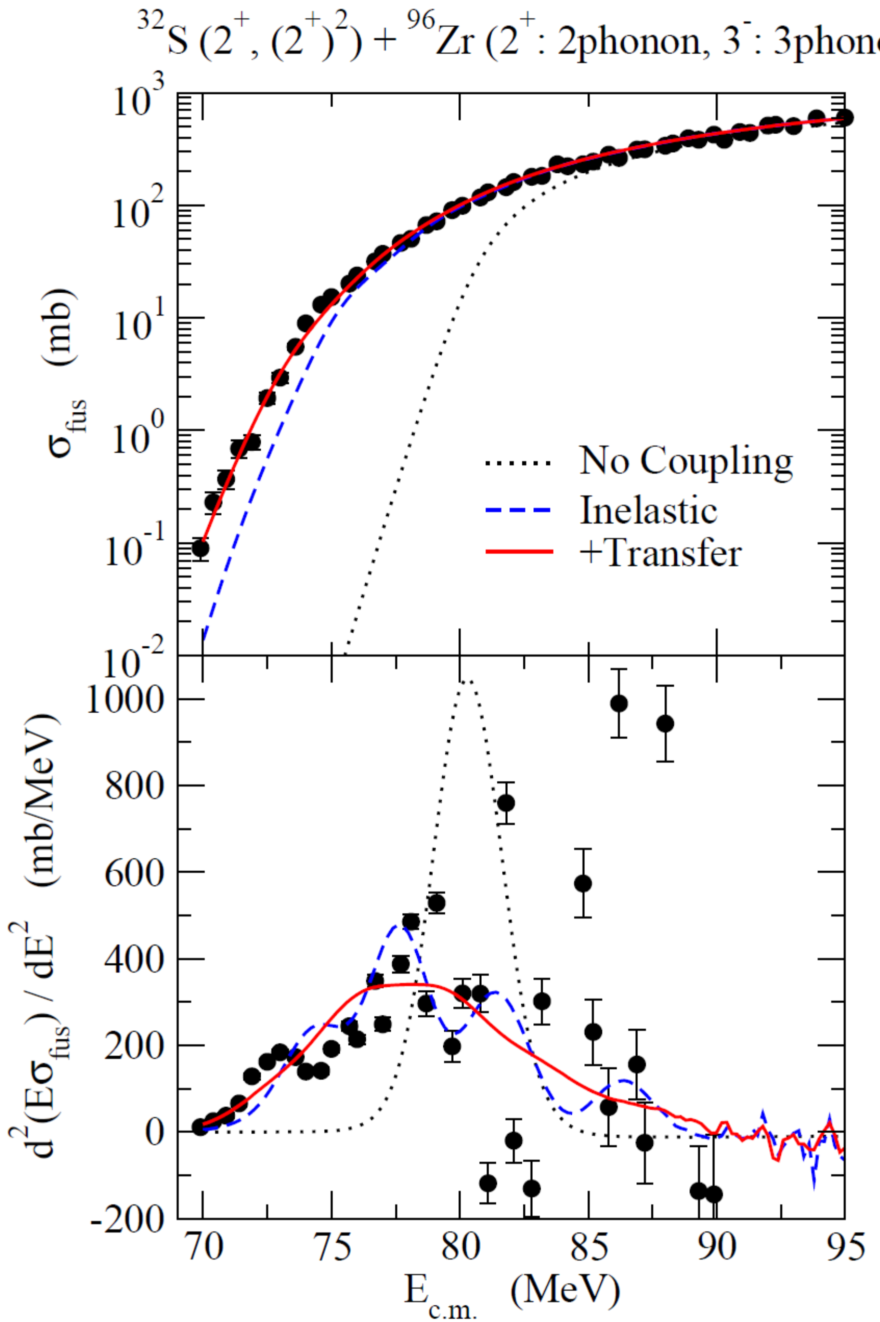
$$w_\alpha = |< 1 \,|\, \lambda_\alpha >|^2$$

Model: One adjustable parameter: *V*



convergence feature





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

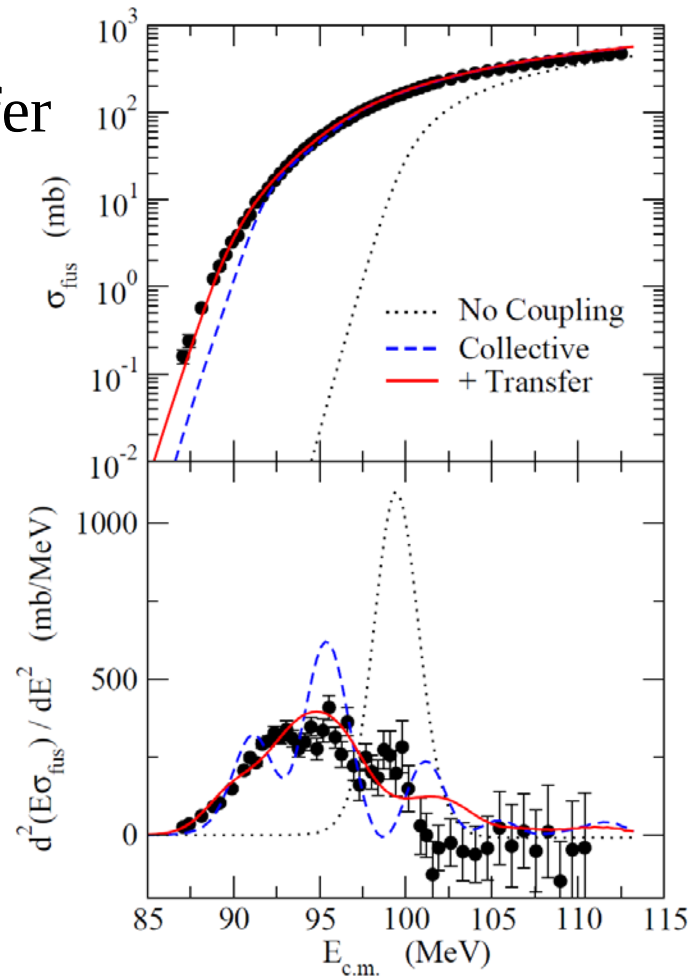
	^{32}S+ ^{90}Zr	^{32}S + ^{96}Zr
+1n	-3.33	+0.79
+2n	-1.23	+5.74
+3n	-6.59	+4.51
+4n	-6.32	+7.66

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

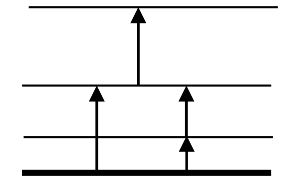


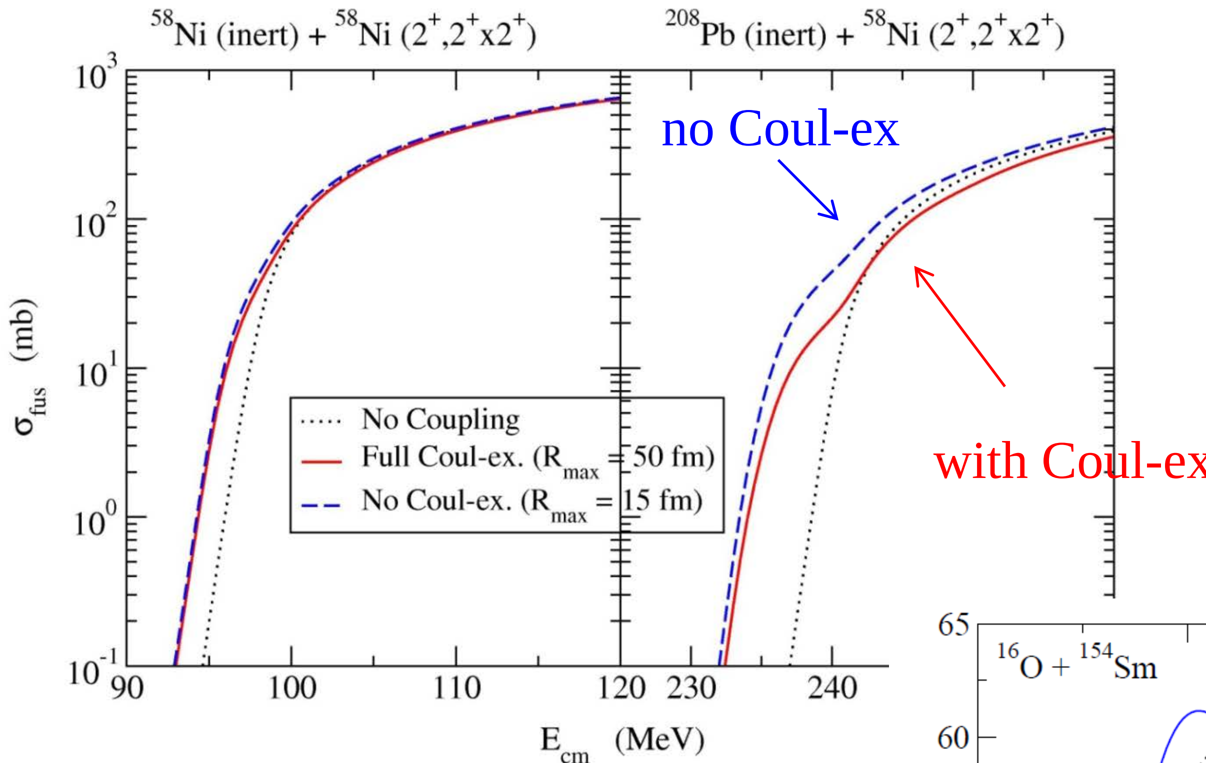
Things to do

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

Two effects of channel couplings

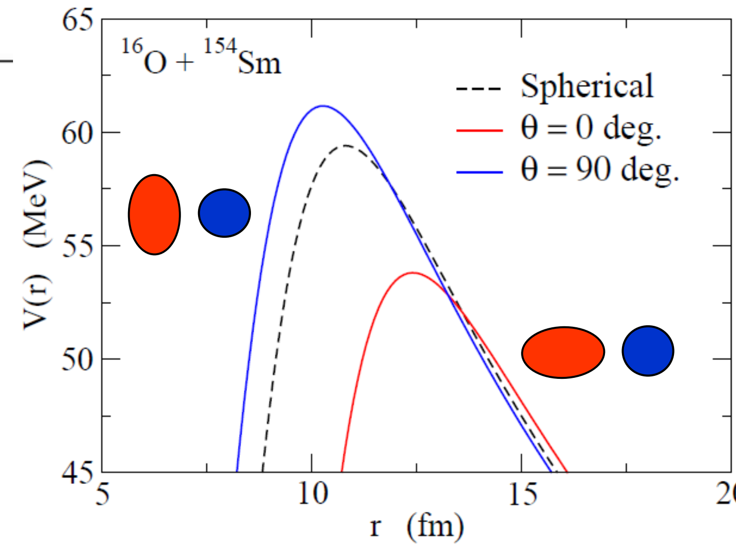
✓energy loss due to inelastic excitations





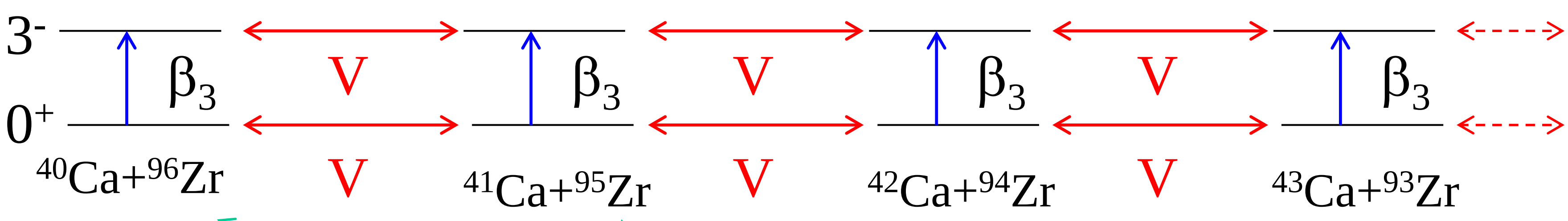
✓dynamical modification of the Coulomb barrier

⟹ large enhancement of fusion cross sections



cf. 2-level model: Dasso, Landowne, and Winther, NPA405('83)381

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



$$H = \begin{pmatrix} 0 & \beta_3 & V & 0 & 0 & 0 & \cdots \\ \beta_3 & \epsilon_3 & 0 & V & 0 & 0 & \cdots \\ V & 0 & 0 & \beta_3 & V & 0 & \cdots \\ 0 & V & \beta_3 & \epsilon_3 & 0 & V & \cdots \\ 0 & 0 & V & 0 & 0 & \beta_3 & \cdots \\ 0 & 0 & 0 & V & \beta_3 & \epsilon_3 & \cdots \\ \cdots & & & & & & \end{pmatrix}$$

$$= H_{\mathrm{inel}} \begin{pmatrix} \mathbf{1} & 0 & 0 & \cdots \\ 0 & \mathbf{1} & 0 & \cdots \\ 0 & 0 & \mathbf{1} & \cdots \\ \cdots & & & \end{pmatrix} + V \begin{pmatrix} 0 & \mathbf{1} & 0 & \cdots \\ \mathbf{1} & 0 & \mathbf{1} & \cdots \\ 0 & \mathbf{1} & 0 & \cdots \\ \cdots & & & \end{pmatrix}$$

(**1** is the N-dimensional unit matrix.)

$$
H = \left(\begin{array}{cc|cc|ccc}
0 & \beta_3 & V & 0 & 0 & 0 & \cdots \\
\beta_3 & \epsilon_3 & 0 & V & 0 & 0 & \cdots \\
\hline
V & 0 & 0 & \beta_3 & V & 0 & \cdots \\
0 & V & \beta_3 & \epsilon_3 & 0 & V & \cdots \\
\hline
0 & 0 & V & 0 & 0 & \beta_3 & \cdots \\
0 & 0 & 0 & V & \beta_3 & \epsilon_3 & \cdots \\
\hline
\cdots & & & & & &
\end{array}\right)
$$

Basis states: $\left|n \otimes n_{\mathrm{tr}}\right\rangle$

↑ inel. ↑ transfer partition

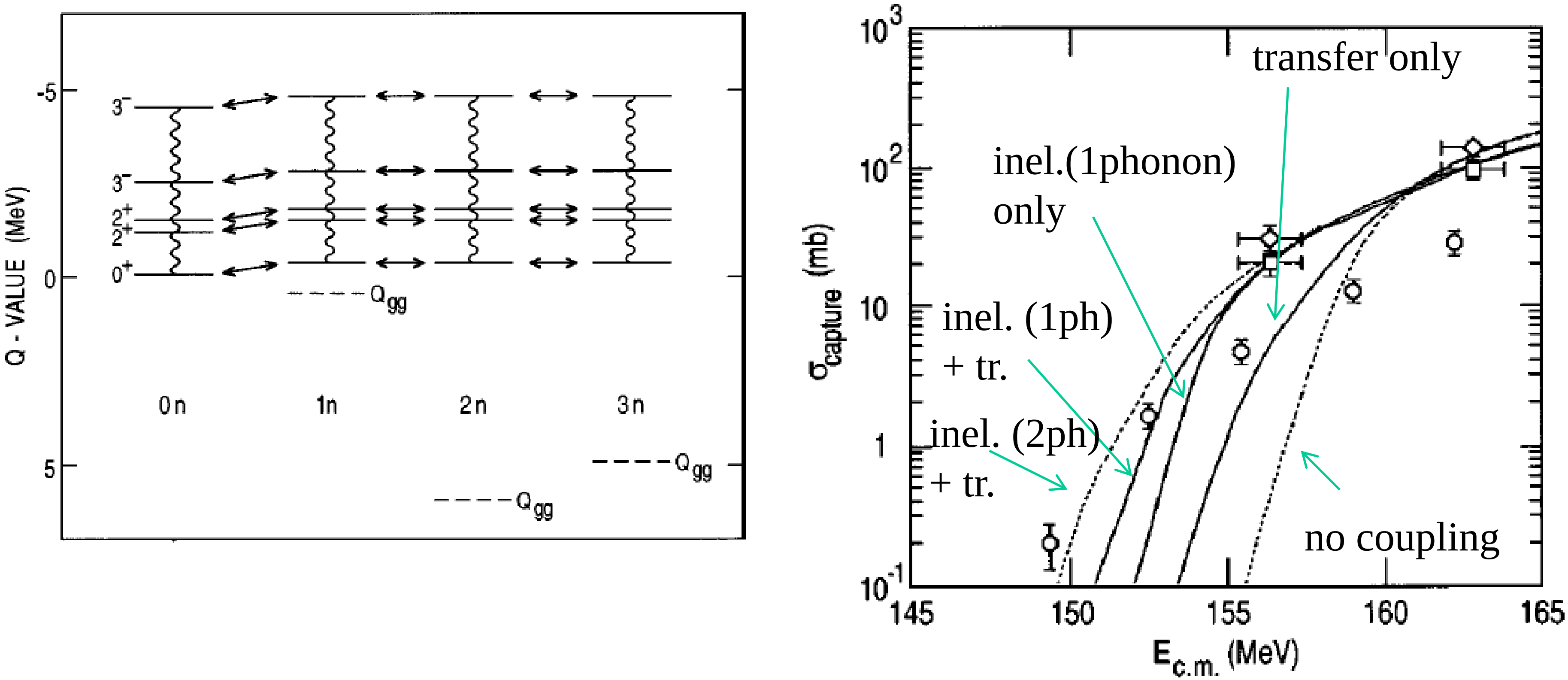
$$
\langle n \otimes n_{\mathrm{tr}} | H | n' \otimes n'_{\mathrm{tr}} \rangle = (H_{\mathrm{inel}})_{nn'}\,\delta_{n_{\mathrm{tr}},n'_{\mathrm{tr}}} + \delta_{n,n'}(V\delta_{n_{\mathrm{tr}},n'_{\mathrm{tr}}+1} + V\delta_{n_{\mathrm{tr}},n'_{\mathrm{tr}}-1})
$$

One can diagonalize first "the transfer space" $(V\delta_{n_{\mathrm{tr}},n'_{\mathrm{tr}}+1} + V\delta_{n_{\mathrm{tr}},n'_{\mathrm{tr}}-1})$ to introduce the eigen-channels for the transfer coupling: $\left|n \otimes \alpha\right\rangle$

With these,

$$
\langle n \otimes \alpha | H | n' \otimes \alpha' \rangle = (H_{\mathrm{inel}})_{nn'}\,\delta_{\alpha,\alpha'} + \lambda_\alpha\,\delta_{\alpha,\alpha'}\delta_{n,n'}
$$

$^{58}Ni + ^{124}Sn$



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