Recent developments in heavy-ion fusion reactions around the Coulomb barrier

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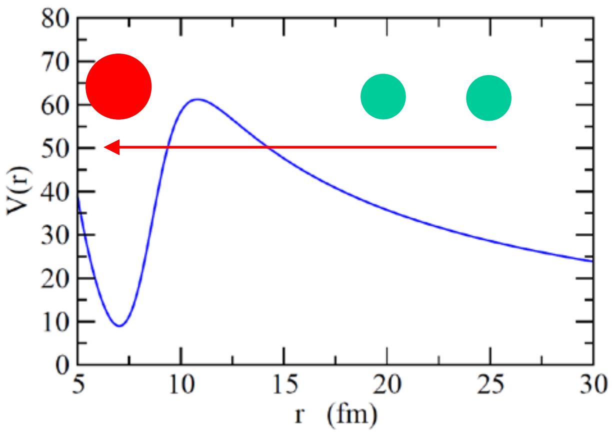
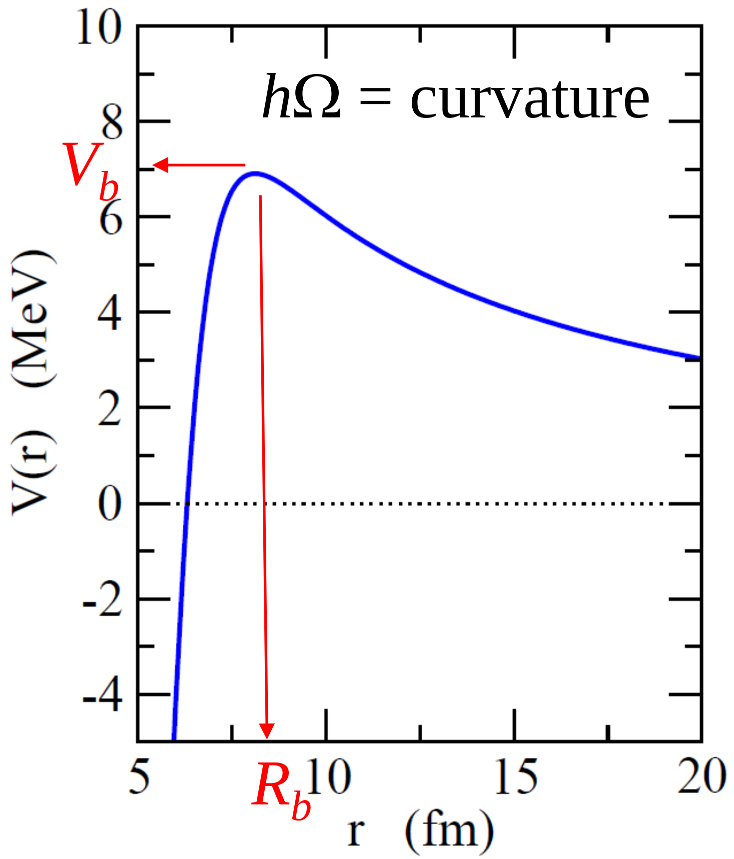
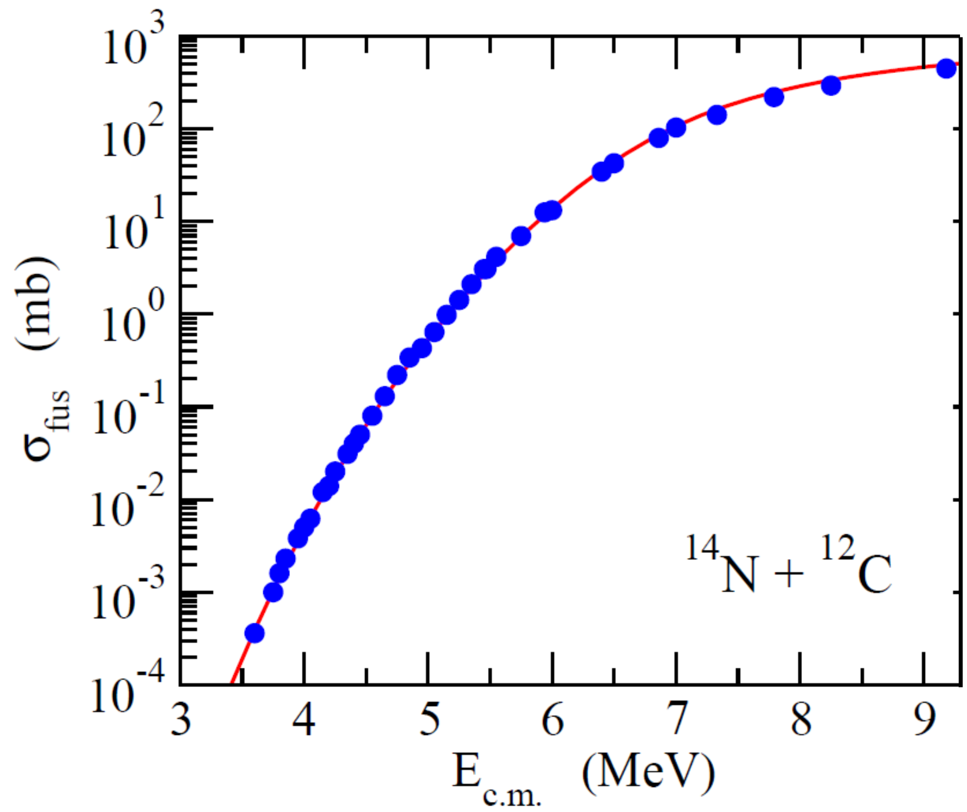


1. *Introduction: H.I. sub-barrier fusion reactions*
2. *Coupled-channels approach*
3. *C.C. calculation with "beyond-mean-field" method*
4. *Summary*

Introduction: heavy-ion sub-barrier fusion reactions

potential model: $V(r)$ + absorption





Generalized Wong formula [N. Rowley and K.H., PRC91('15)044617]

$$\sigma_{\text{fus}}(E) \sim \frac{\hbar\Omega}{2E} R_b^2 \ln\left[1 + \exp\left(\frac{2\pi}{\hbar\Omega}(E - V_b)\right)\right] + (osc.)$$

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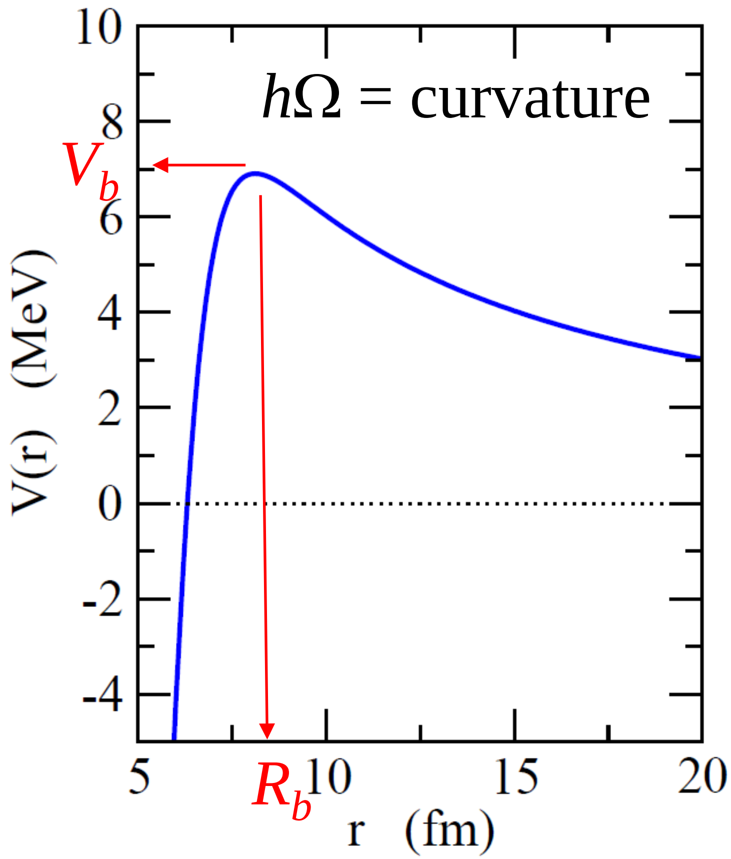

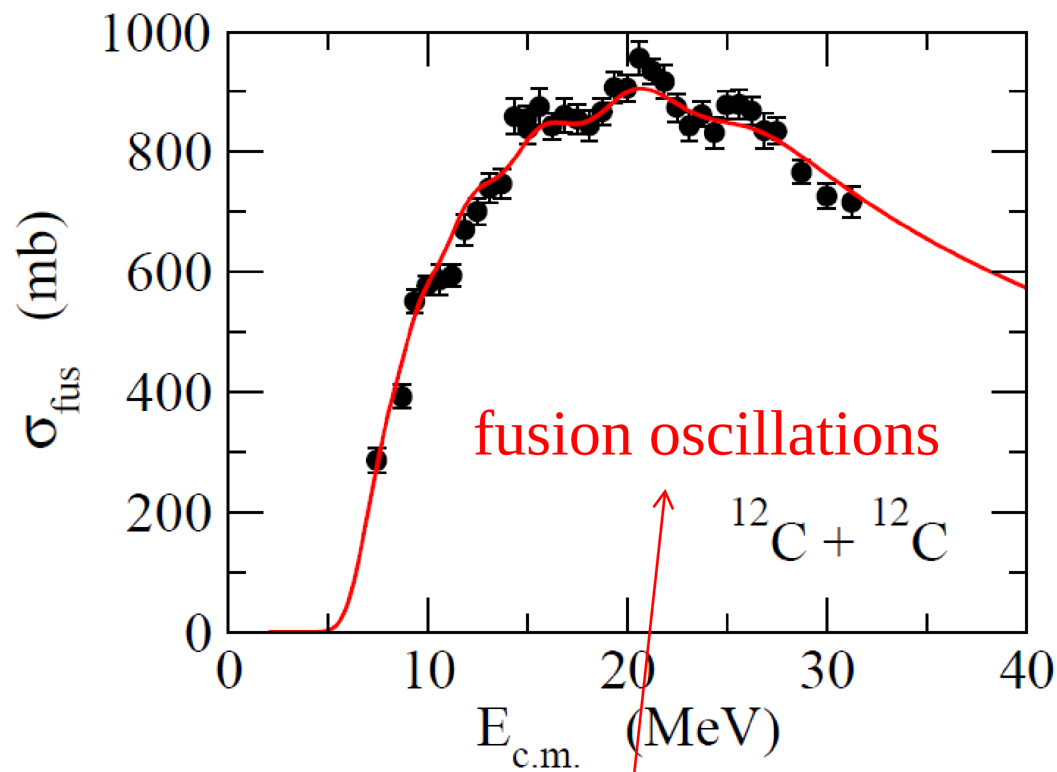

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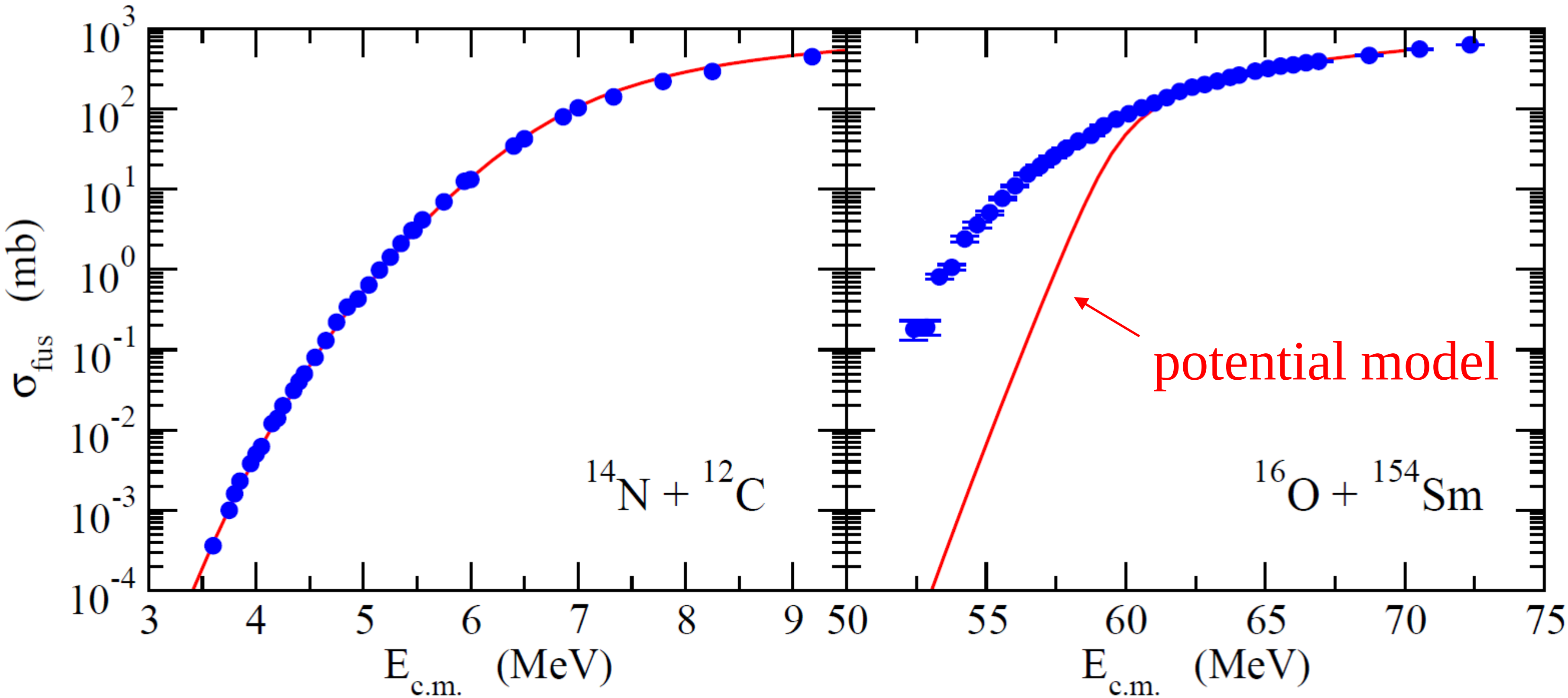
Introduction: heavy-ion sub-barrier fusion reactions

Discovery of large sub-barrier enhancement of σ_{fus} (~ the late 70's)

potential model: $V(r)$ + absorption

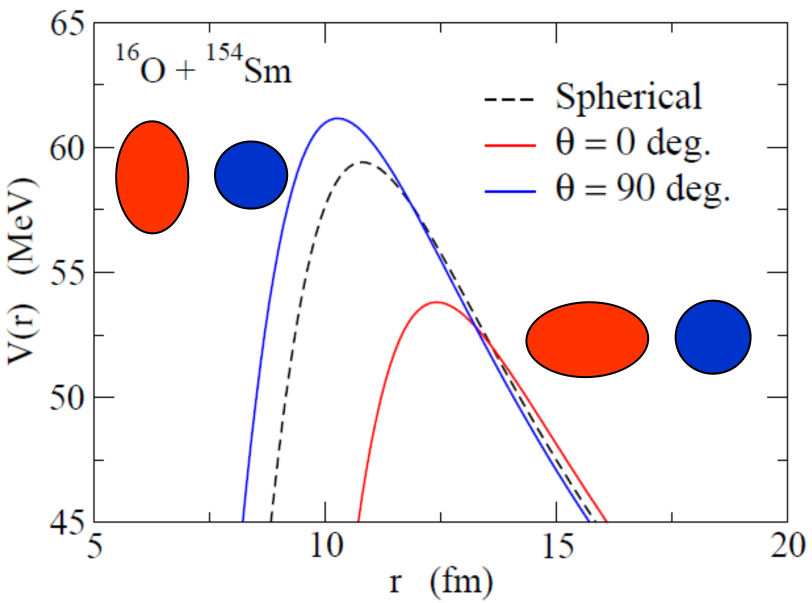


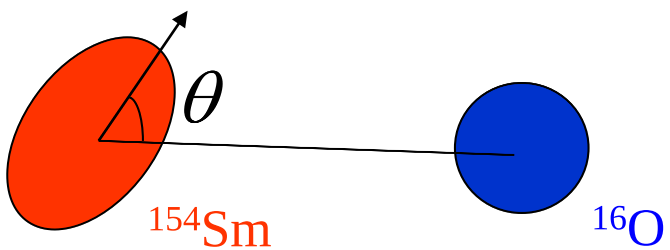
cf. seminal work:

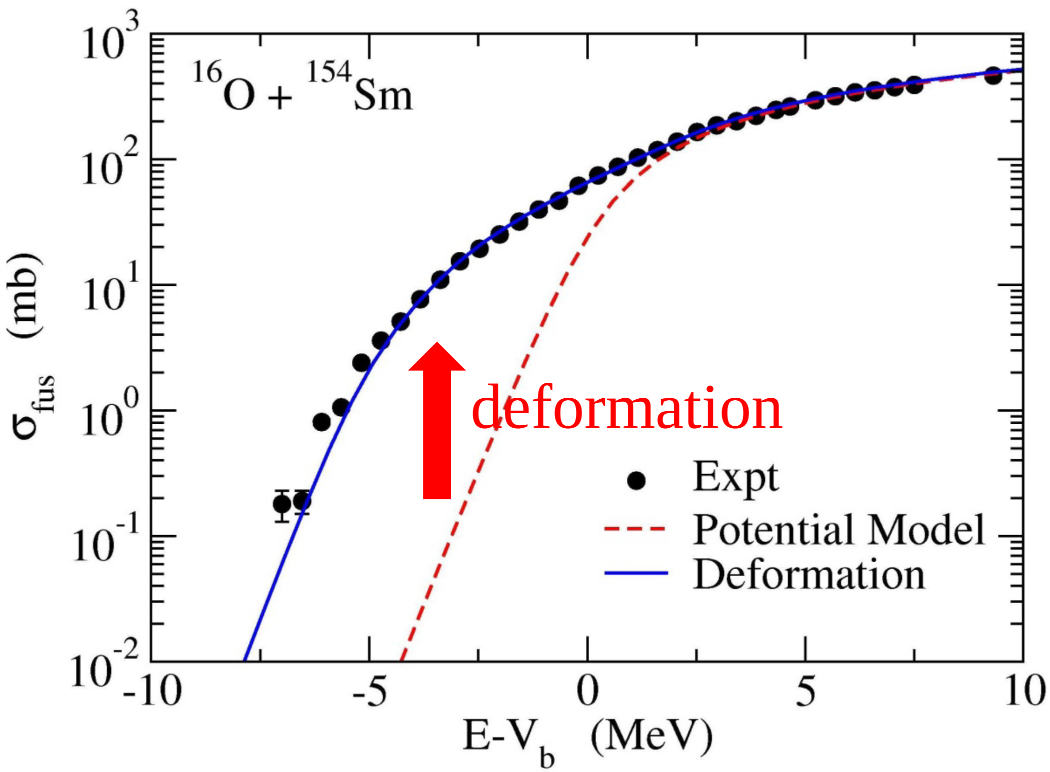
R.G. Stokstad et al., PRL41('78) 465

Effect of nuclear deformation

^{154}Sm : a deformed nucleus with $\beta_2 \sim 0.3$





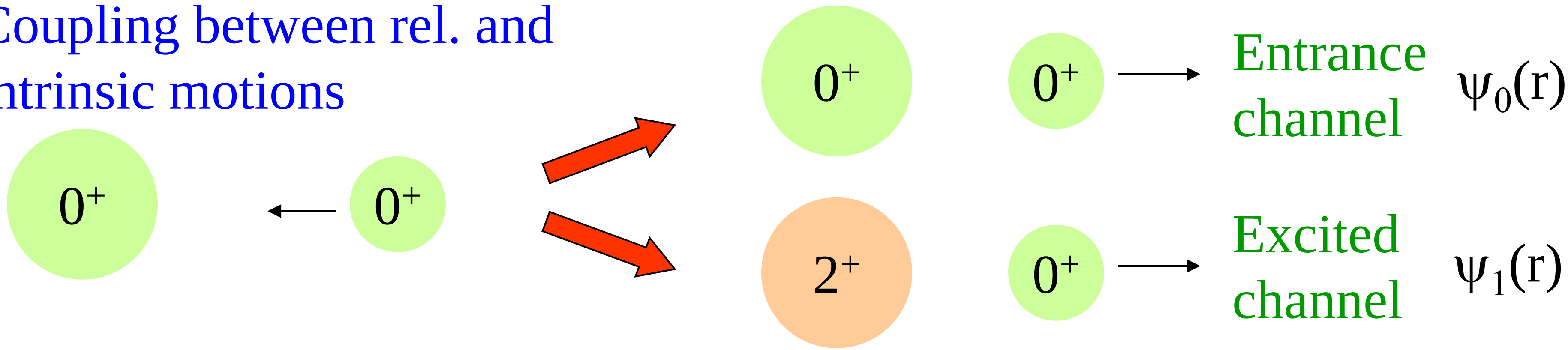


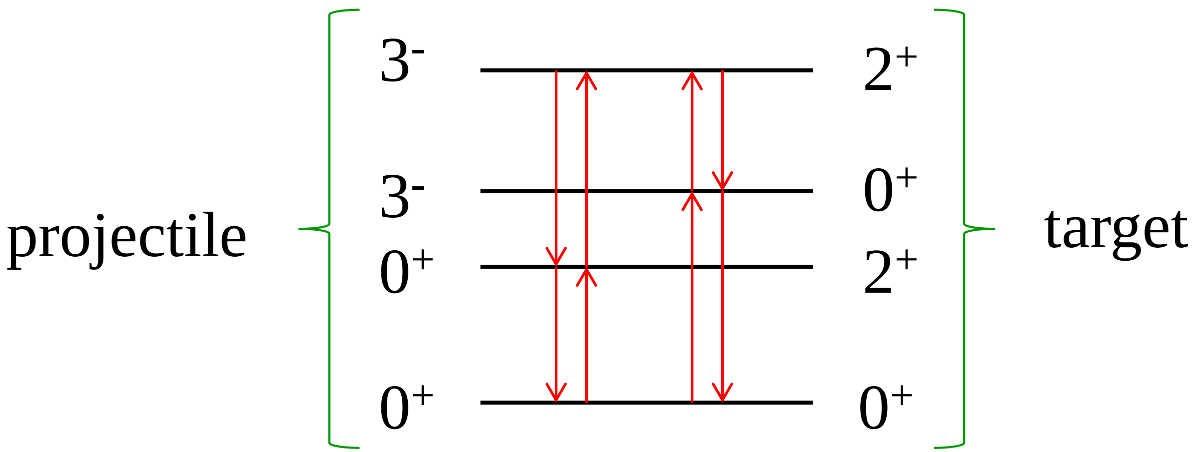
$$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos\theta)\sigma_{\text{fus}}(E;\theta)$$

Fusion: strong interplay between nuclear structure and nuclear reaction

Coupled-Channels method

Coupling between rel. and intrinsic motions





$$\Psi(\boldsymbol{r},\xi)=\sum_k \psi_k(\boldsymbol{r})\phi_k(\xi)$$

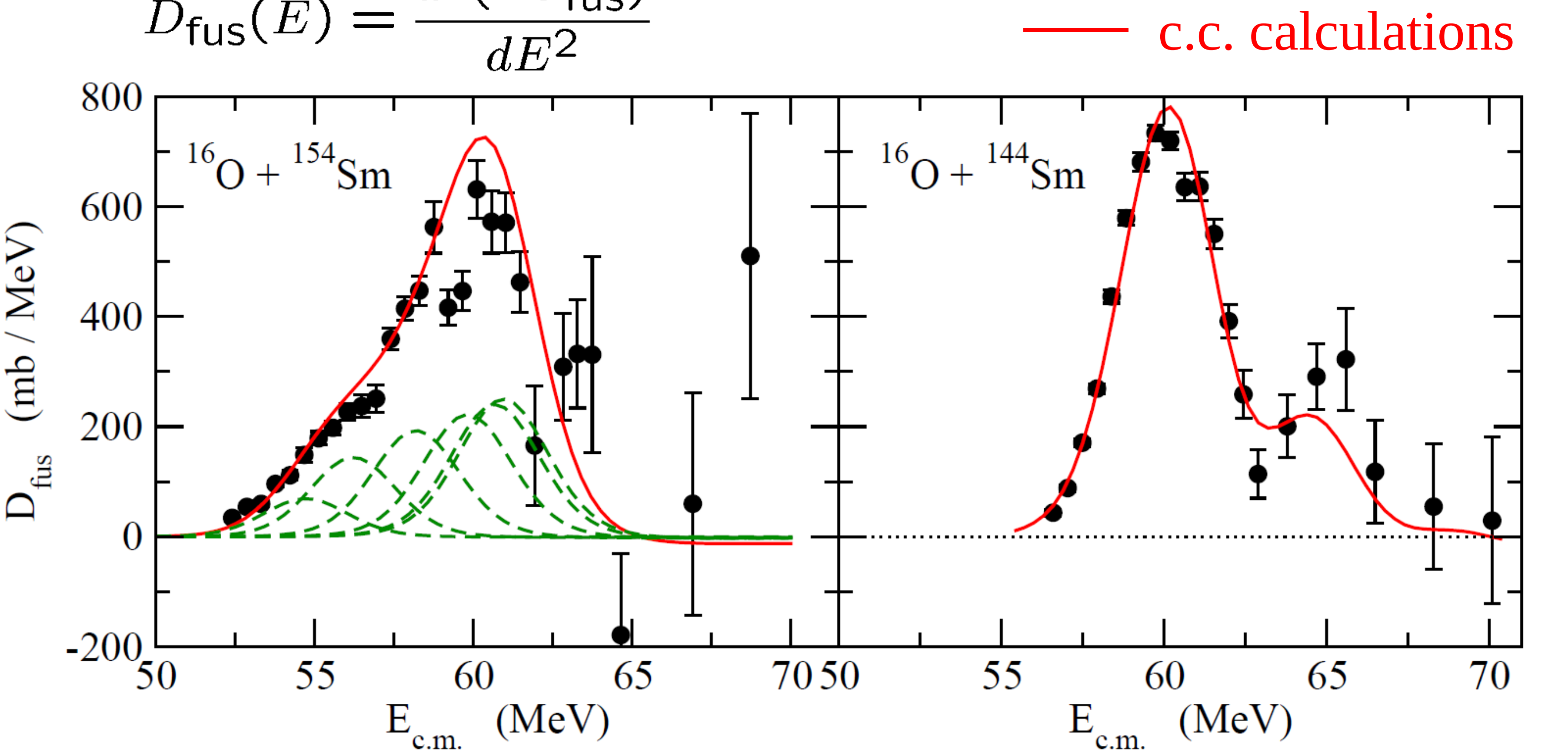
coupled Schroedinger equations for $\psi_k(r)$

C.C. approach: a standard tool for sub-barrier fusion reactions

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

✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

$$D_{\rm fus}(E) = \frac{d^2(E\sigma_{\rm fus})}{dE^2}$$

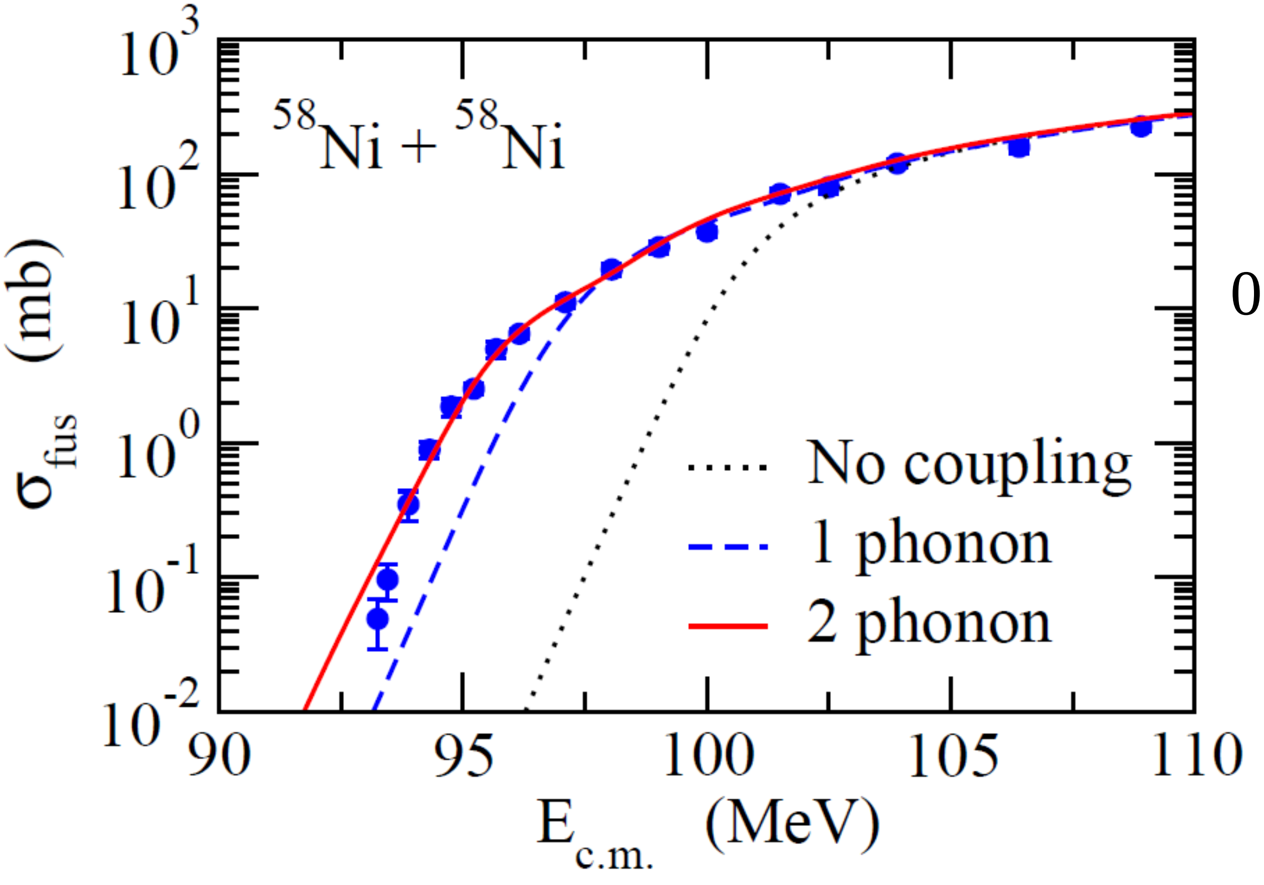


K.H., N. Takigawa, PTP128 ('12) 1061

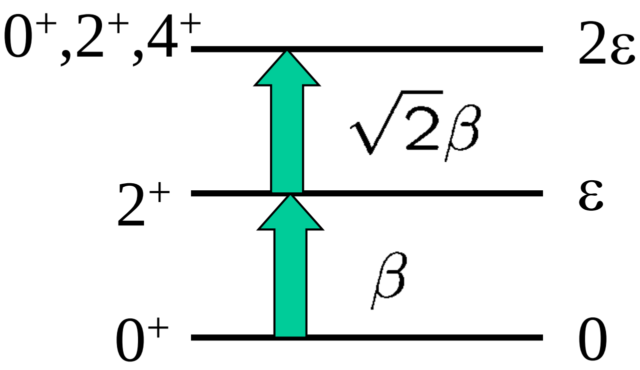
Semi-microscopic modeling of sub-barrier fusion

K.H. and J.M. Yao, PRC91('15) 064606

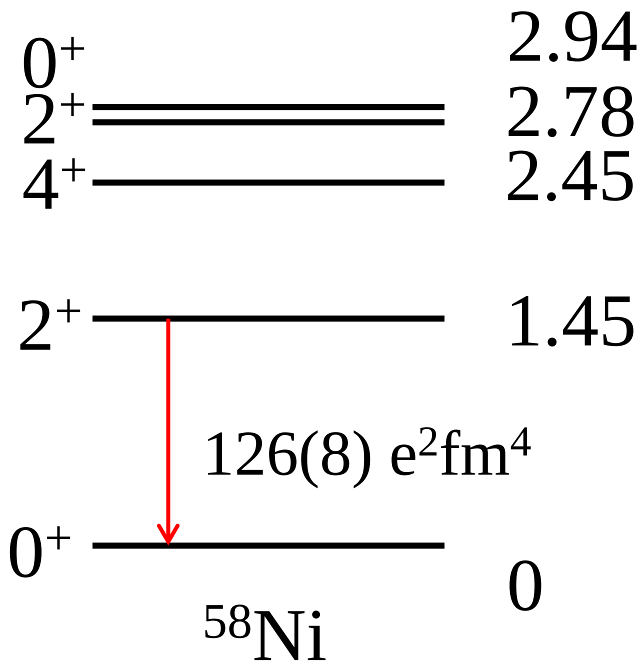
multi-phonon excitations



simple harmonic oscillator



Anharmonic vibrations



$Q(2_1^+)$ = -10 +/- 6 $e$fm^2

- Boson expansion
- Quasi-particle phonon model
- Shell model
- Interacting boson model
- Beyond-mean-field method

$$|JM\rangle = \int d\beta \, f_J(\beta) \hat{P}^J_{M0} |\Phi(\beta)\rangle$$

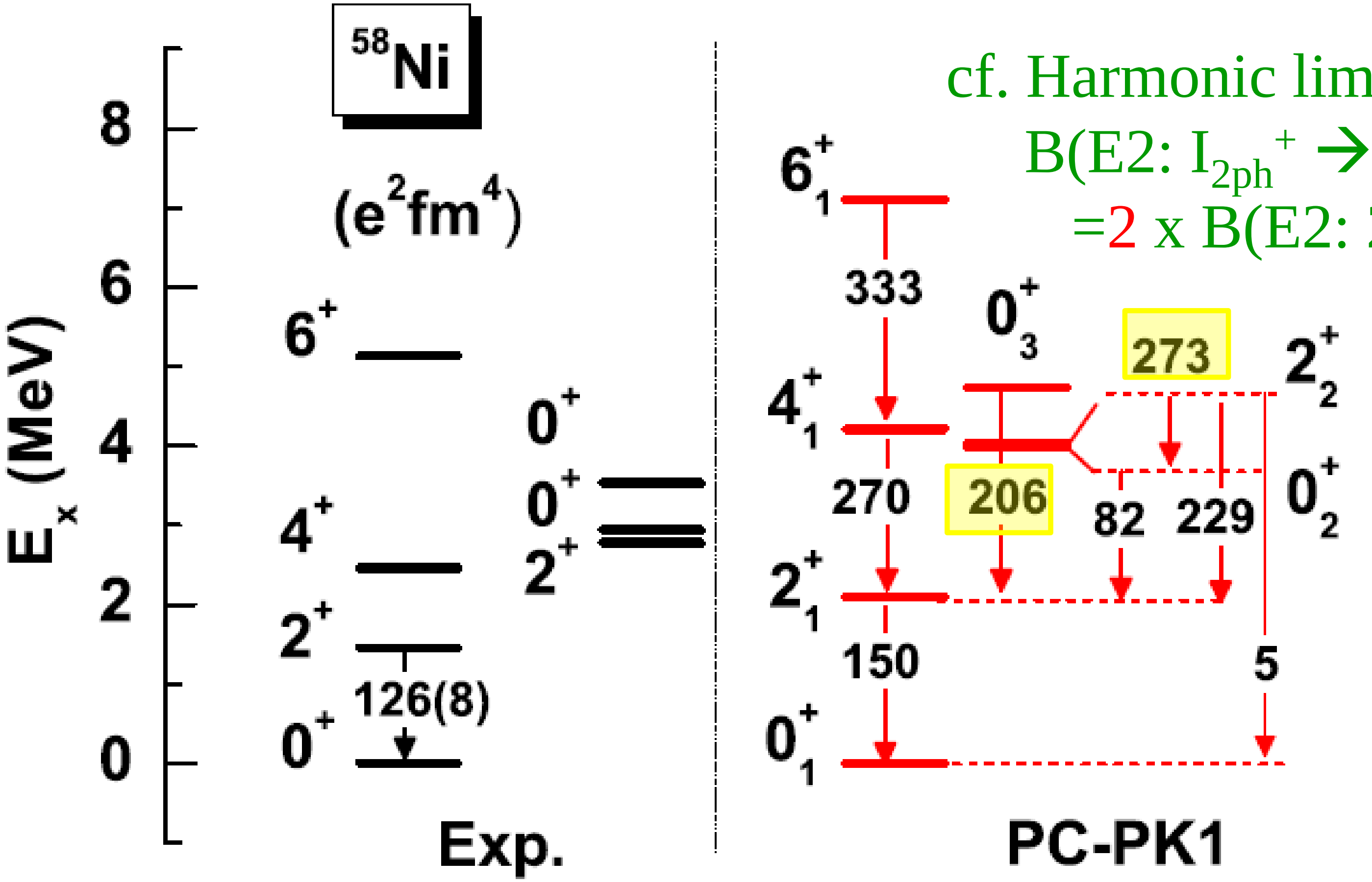
✓ MF + ang. mom. projection
+ particle number projection
+ generator coordinate method (GCM)

M. Bender, P.H. Heenen, P.-G. Reinhard, Rev. Mod. Phys. 75 ('03) 121

J.M. Yao et al., PRC89 ('14) 054306

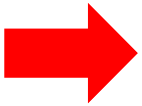
Recent beyond-MF (MR-DFT) calculations for ^{58}Ni

K.H. and J.M. Yao, PRC91 (‘15) 064606
J.M. Yao, M. Bender, and P.-H. Heenen, PRC91 (‘15) 024301



cf. Harmonic limit:
$B(E2: I_{2ph}^+ \rightarrow 2_1^+)$
$= 2 \times B(E2: 2_1^+ \rightarrow 0_1^+)$

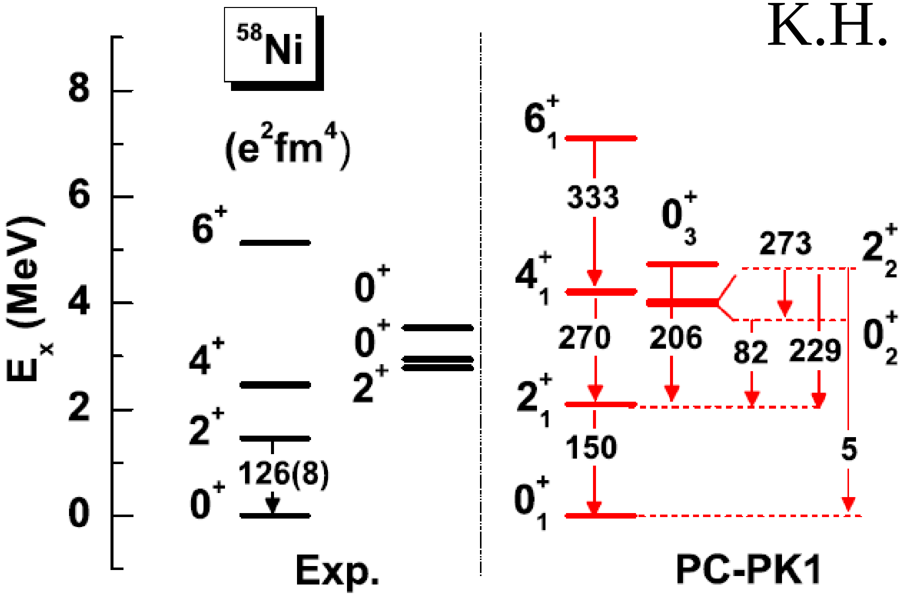
- ✓ A large fragmentation of $(2^+ \times 2^+)_{J=0}$
- ✓ A strong transition from 2_2^+ to 0_2^+



effects on sub-barrier fusion?

Semi-microscopic coupled-channels model for sub-barrier fusion

K.H. and J.M. Yao, PRC91 (‘15) 064606



microscopic
multi-pole operator

✓ $$V_{\rm coup} \sim -R_T\frac{dV_N}{dr}\alpha_\lambda\cdot Y_\lambda(\hat{\boldsymbol{r}}) \to -R_T\frac{dV_N}{dr}Q_\lambda\cdot Y_\lambda(\hat{\boldsymbol{r}})$$

✓ M(E2) from MR-DFT calculation ← among higher members of phonon states

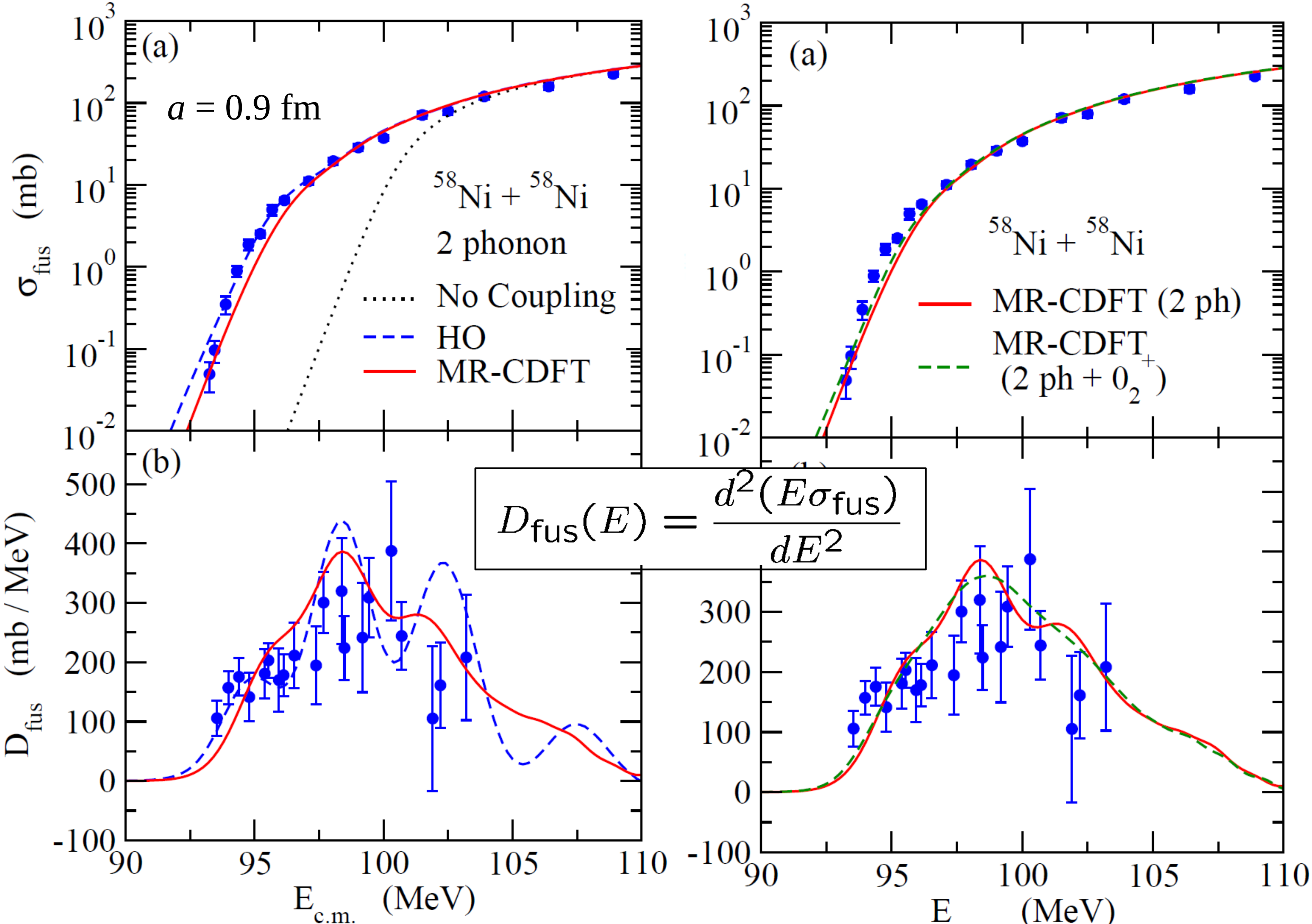
✓ scale to the empirical B(E2; $2_1^+ \to 0_1^+$)

✓ still use a phenomenological potential

✓ use the experimental values for E_x

✓ β_N and β_C from M_n/M_p for each transition

✓ axial and reflection symmetries (no 3^+ and 3^- states)



$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$

K.H. and J.M. Yao, PRC91 ('15) 064606

Summary

Coupled-channels calculations for sub-barrier fusion

- ➢ Light systems: potential model
  - ✓ Generalized Wong formula
  - ✓ fusion oscillations
- ➢ C.C. calculations with MR-DFT method
  - ✓ anharmonicity
  - ✓ truncation of phonon states
  - ✓ octupole vibrations and tri-axiality
    : in progress

more flexibility:

- application to transitional nuclei
- a good guidance to a Q-moment of excited states