"Tsukuba CCS-RIKEN joint Workshop on microscopic theories of nuclear structure and dynamics, 2016.12.12-16

Beyond-mean-field theory for multi-octupole excitations in ^{208}Pb and subbarrier fusion of ^{16}O + ^{208}Pb

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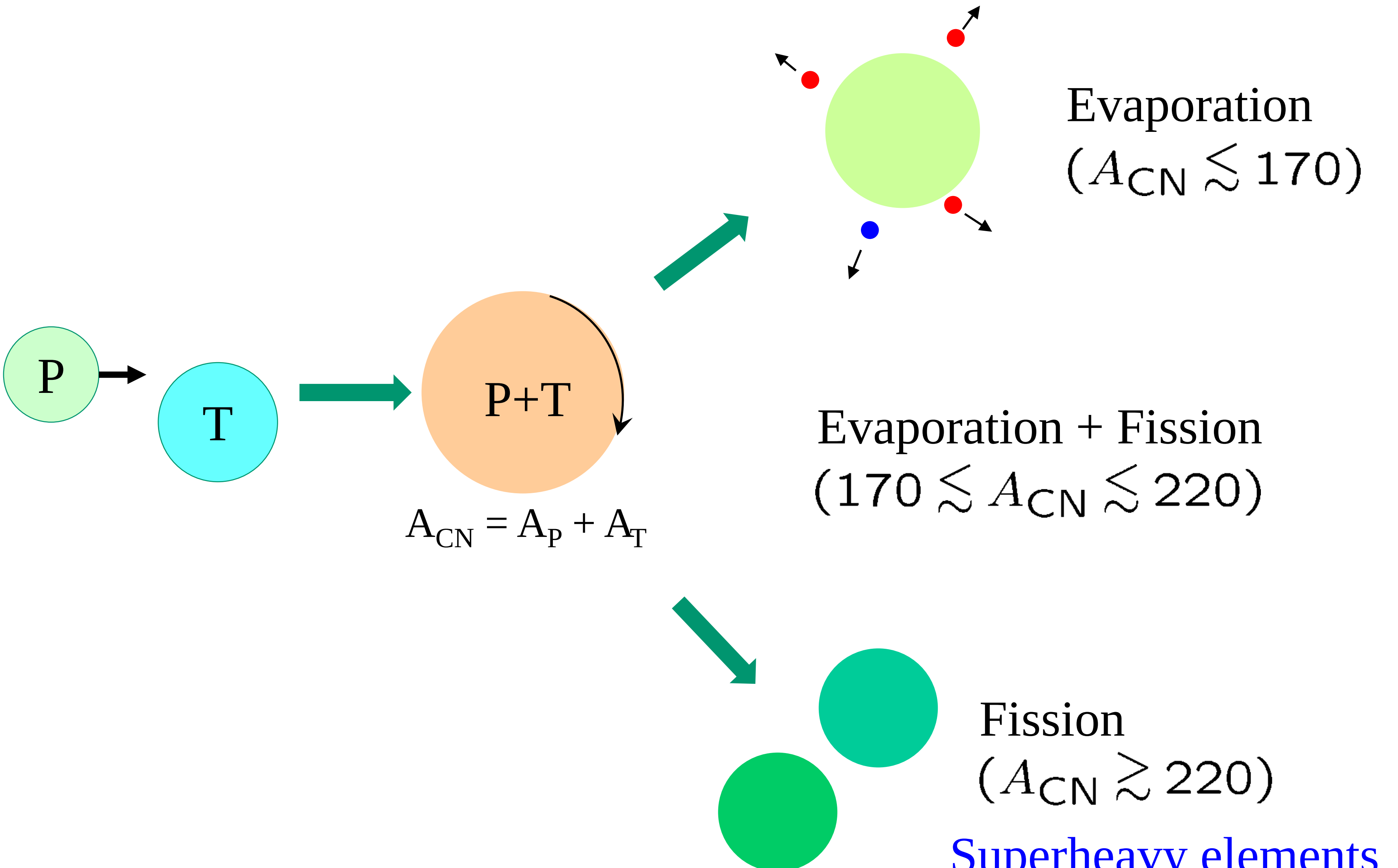
TOHOKU UNIVERSITY

1. *Introduction: Heavy-ion subbarrier fusion reactions*
2. *Coupled-channels approach with "beyond-mean-field" method*
3. *Octupole excitations in fusion of ^{16}O + ^{208}Pb*
4. *Summary*

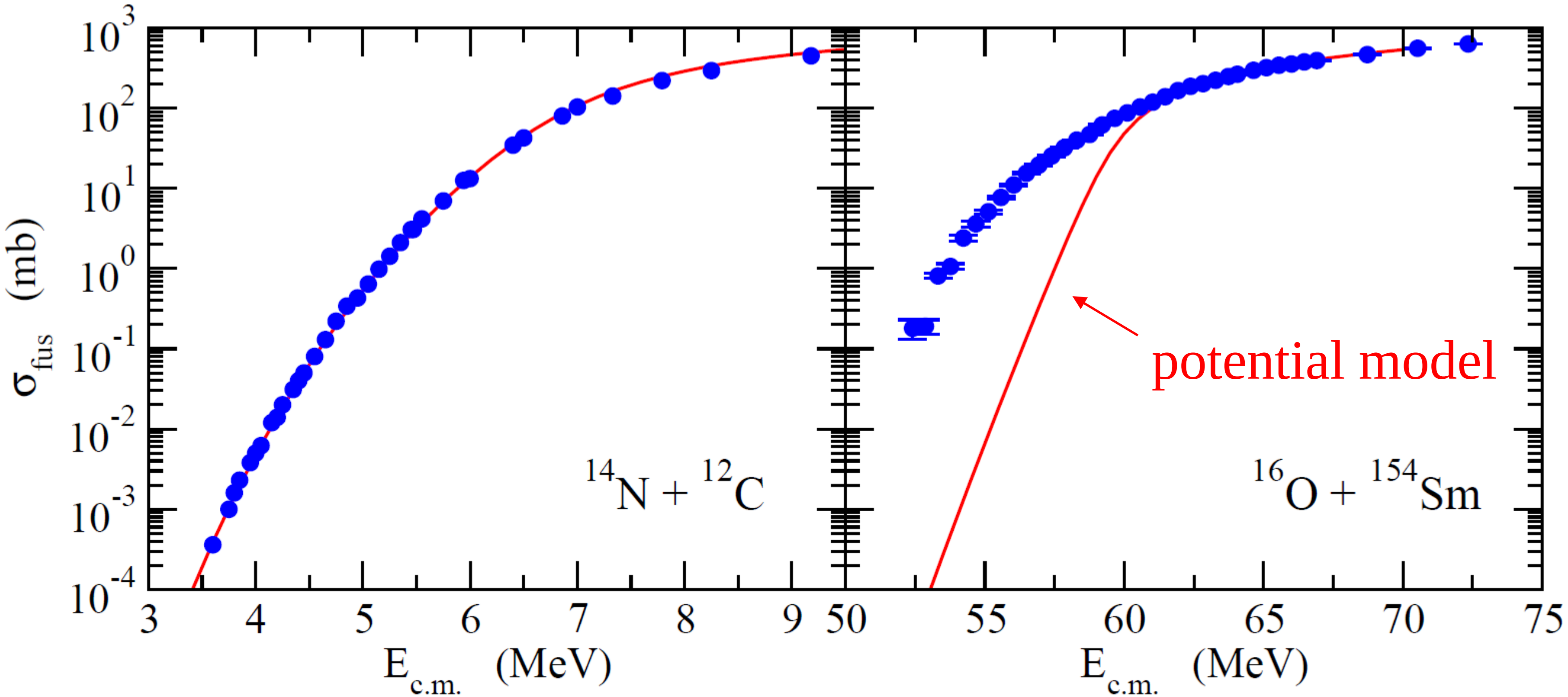
Introduction: Heavy-ion fusion reactions

Fusion: compound nucleus formation



Discovery of large sub-barrier enhancement of σ_{fus}

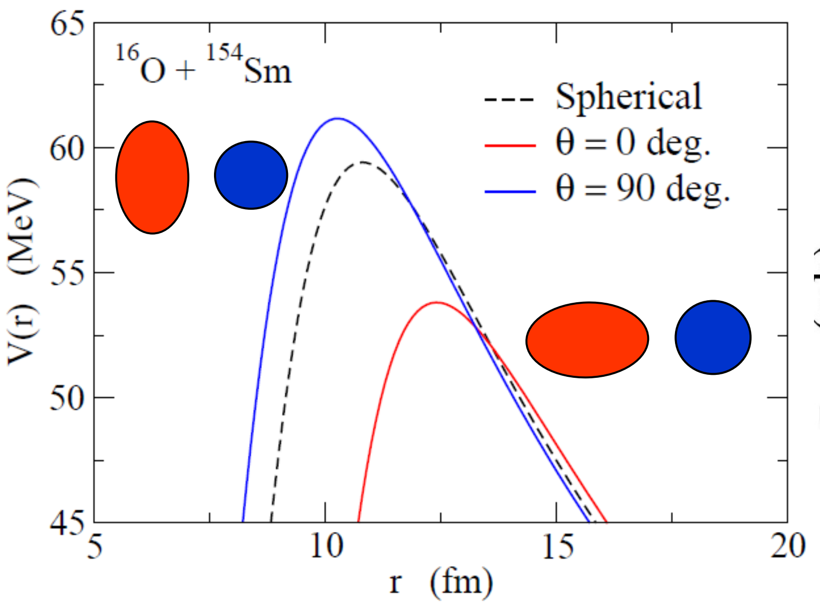
potential model: $V(r)$ + absorption

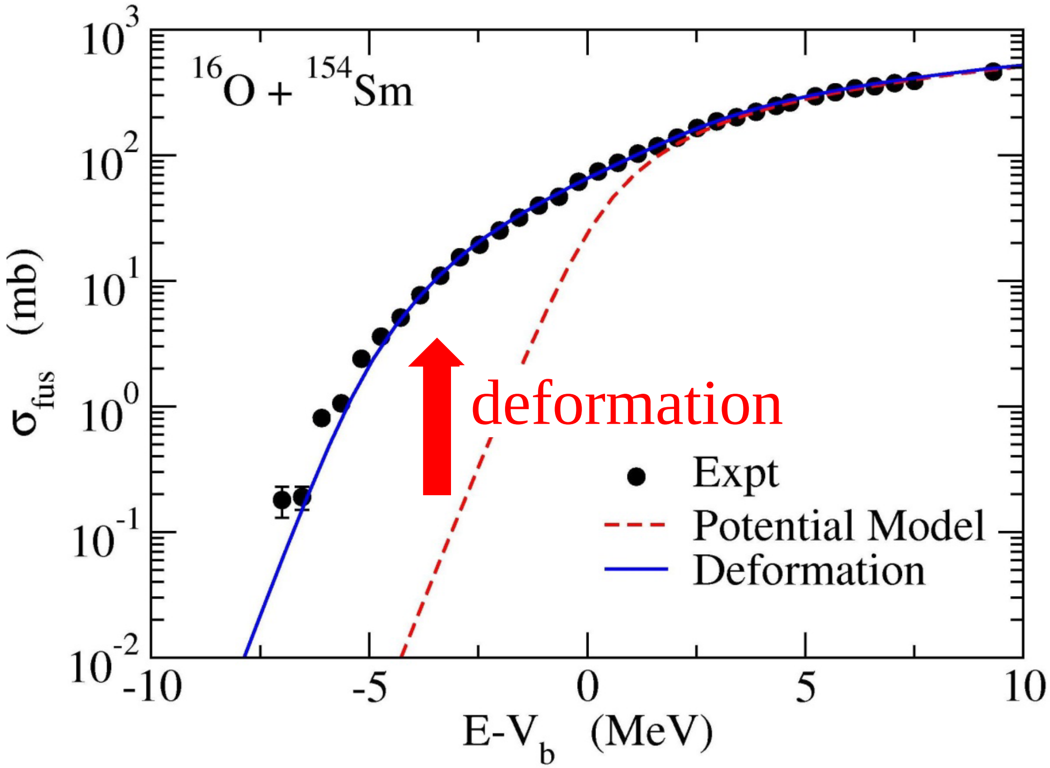


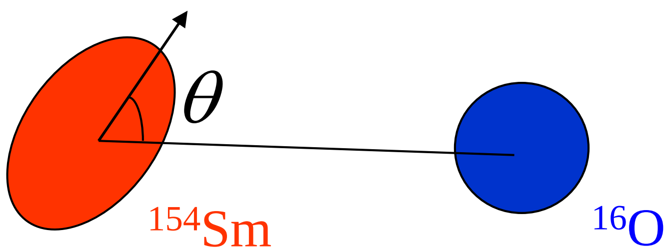
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

Effect of nuclear deformation

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

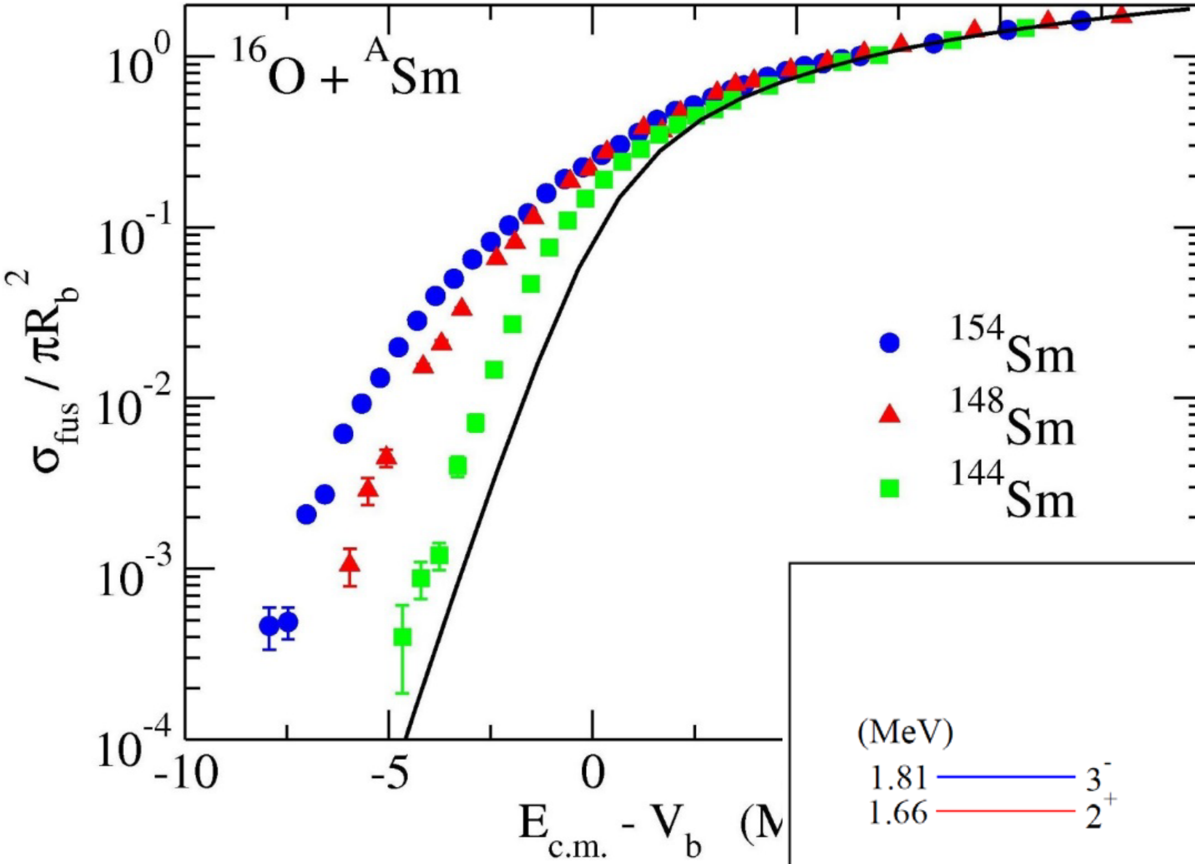


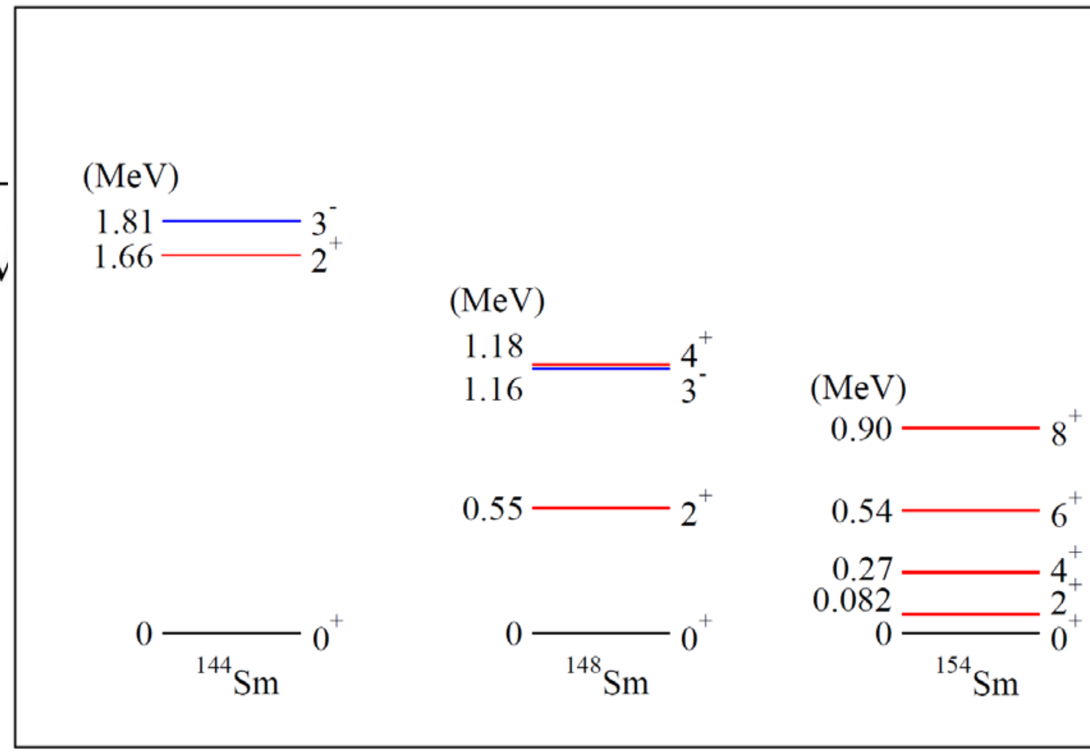




$$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos\theta)\sigma_{\text{fus}}(E;\theta)$$

Fusion: strong interplay between nuclear structure and nuclear reaction

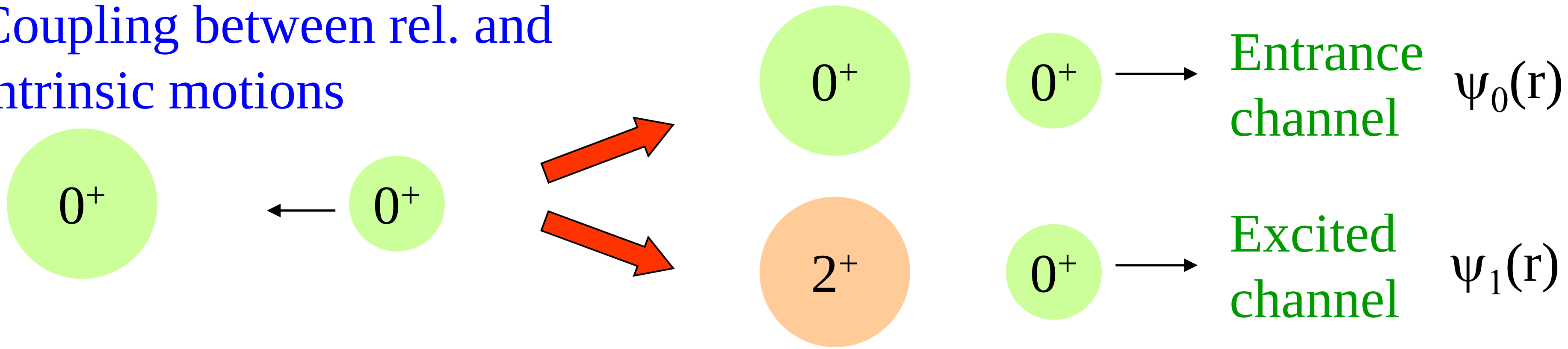


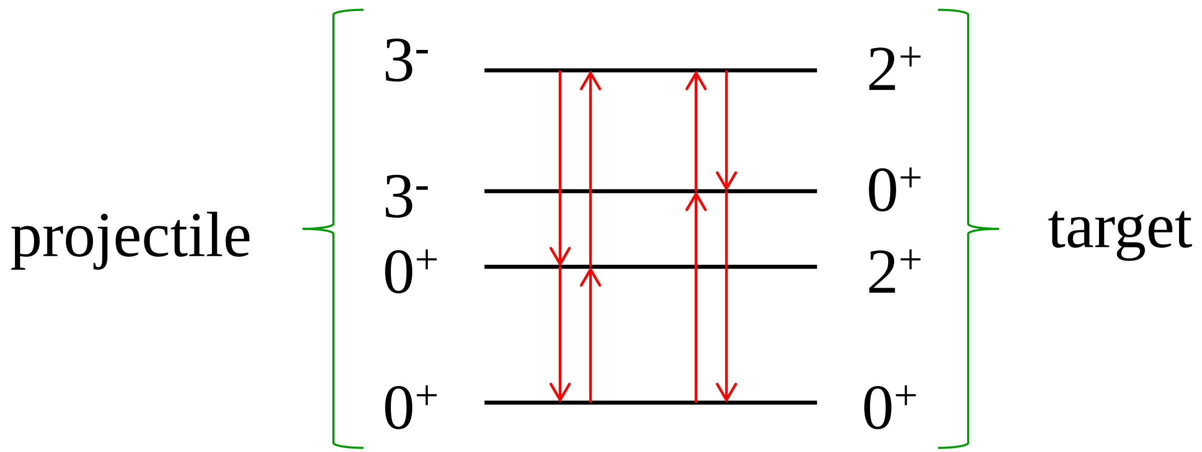


Strong target dependence
at $E < V_b$

Coupled-Channels method

Coupling between rel. and intrinsic motions





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

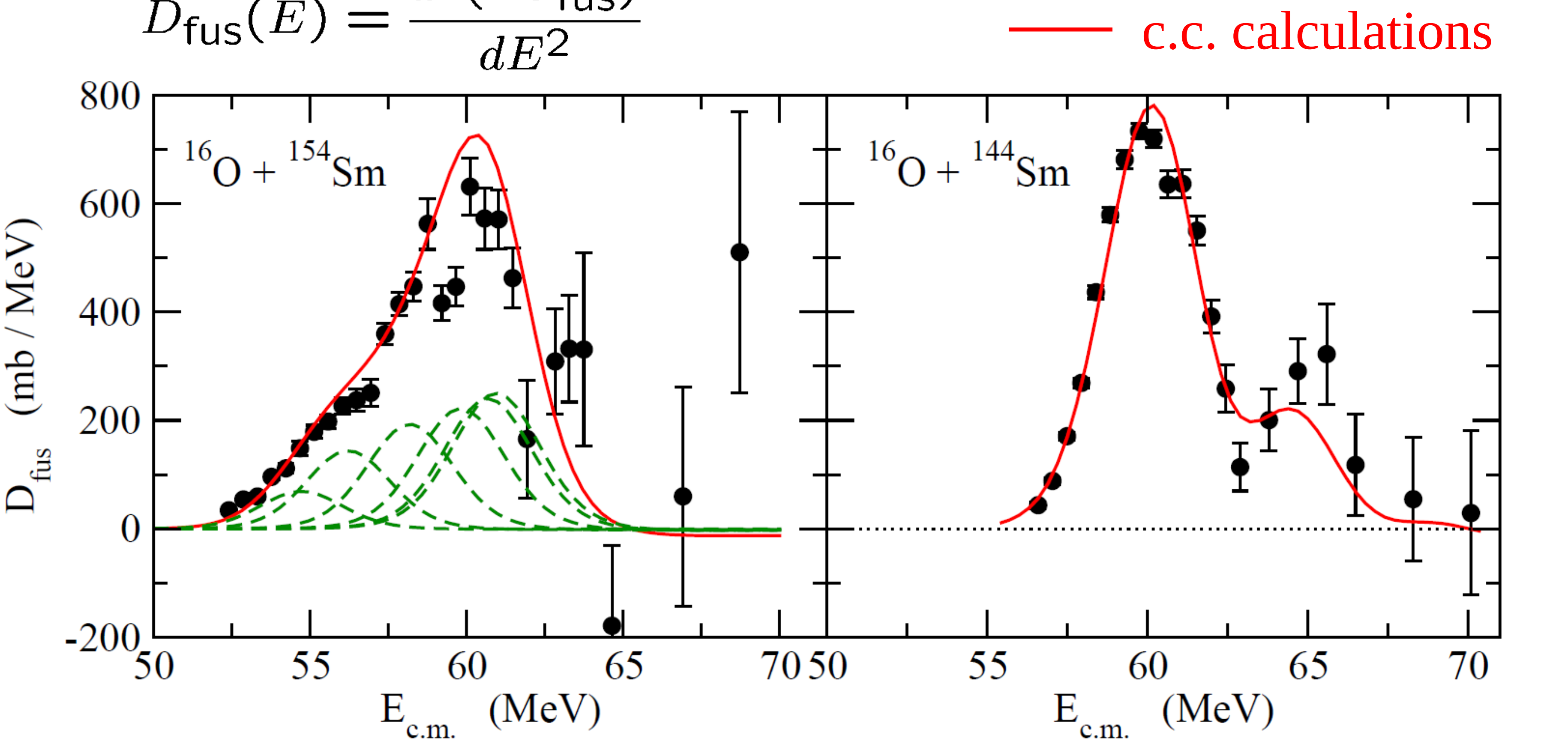
coupled Schroedinger equations for $\psi_k(r)$

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))

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

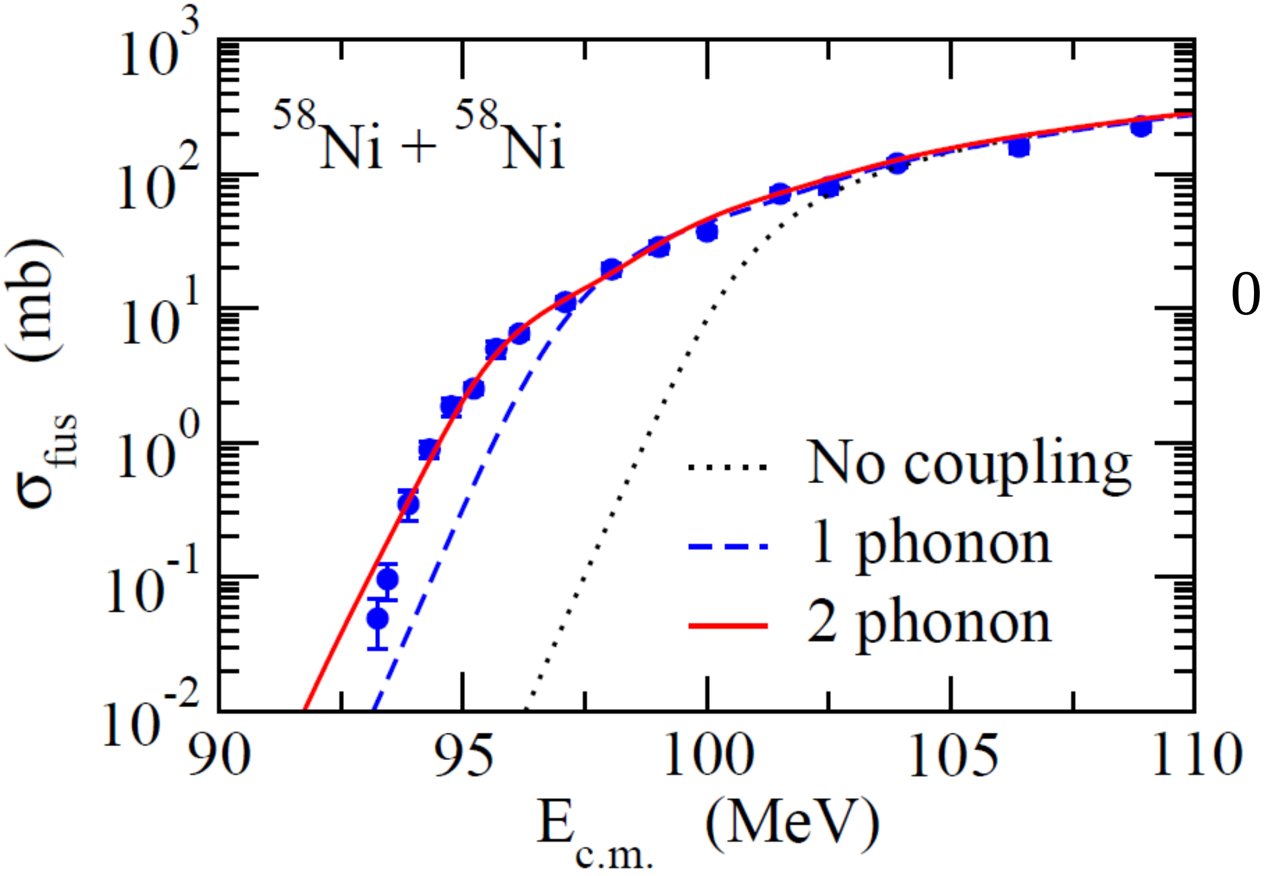


K.H., N. Takigawa, PTP128 ('12) 1061

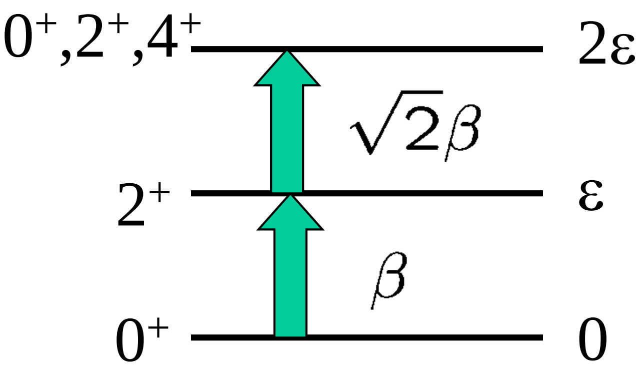
Semi-microscopic modeling of sub-barrier fusion

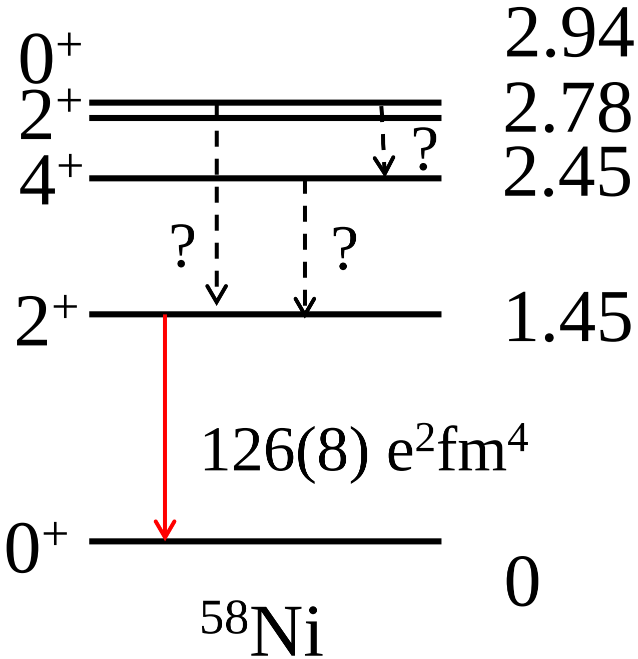
K.H. and J.M. Yao, PRC91('15) 064606

multi-phonon excitations



simple harmonic oscillator





$Q(2_1^+) = -10 +/- 6\ e\mathrm{fm}^2$

Simple harmonic oscillator
: justifiable?

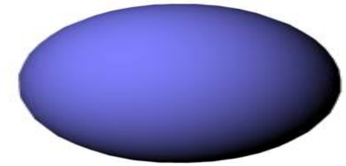
↓

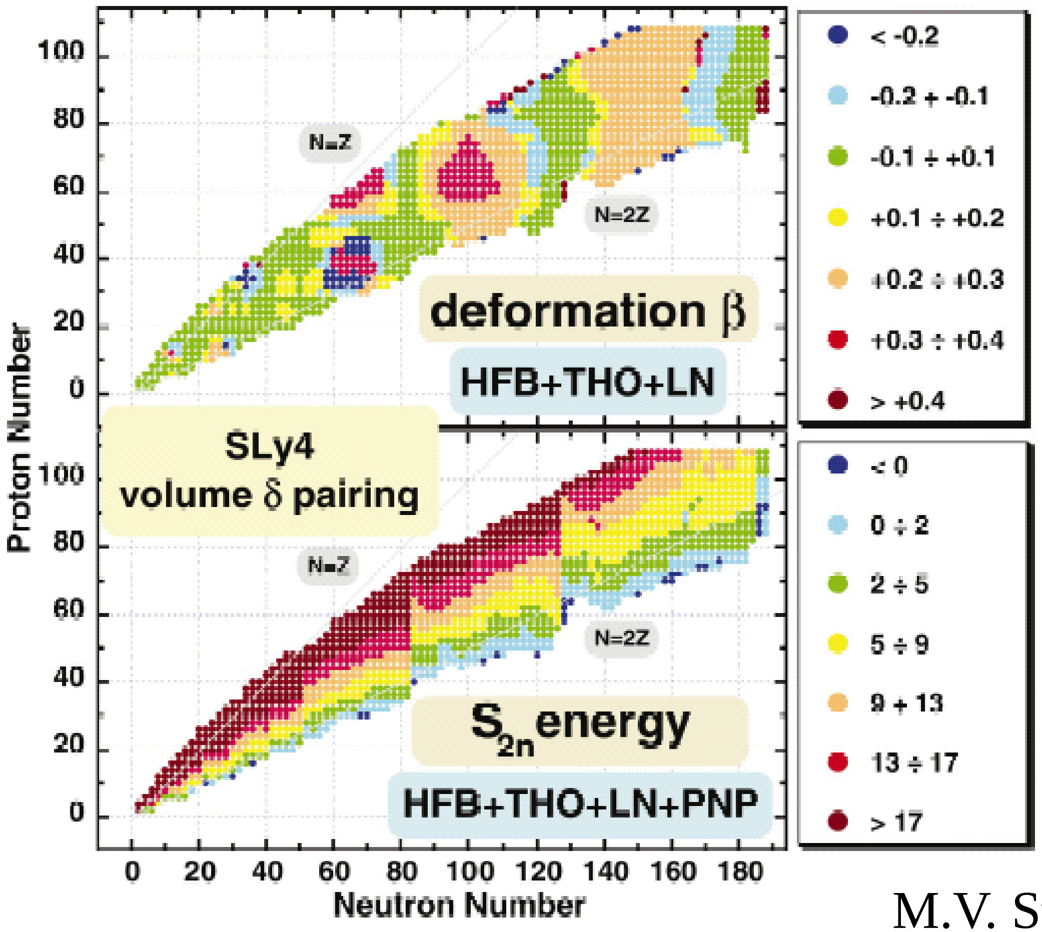
beyond mean-field approach
to account for anharmonicity

cf. GCM: large amplitude
collective motions

Self-consistent mean-field (Hartree-Fock) method:

- independent particles in a mean-field potential
- global theory for **the whole nuclear chart**
- intuitive picture for nuclear deformation
- optimized shape can be automatically determined





M.V. Stoitsov et al., PRC68('03)054312

Mean-field approximation and beyond

Drawbacks of the mean-field approximation : nuclear spectrum

✓ body-fixed frame formalism → intuitive picture of nuclear def.

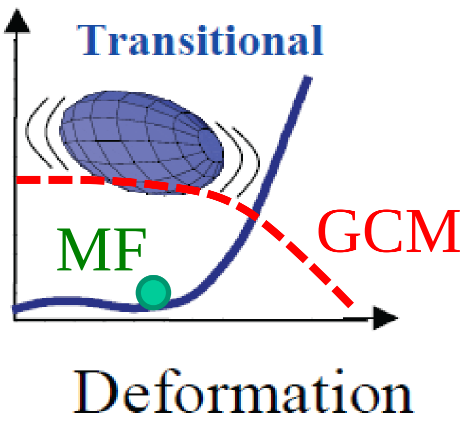
✓ spectrum: lab-frame ← transformation from intrinsic to lab. frames

nuclear spectrum: requires to go beyond the mean-field approximation

$$|\Psi_{IM}(\beta)\rangle = \hat{P}^I_{MK}\hat{P}^N\hat{P}^Z\,|\Psi_{\mathsf{MF}}(\beta)\rangle$$

angular momentum + particle number projections

✓ quantum fluctuation



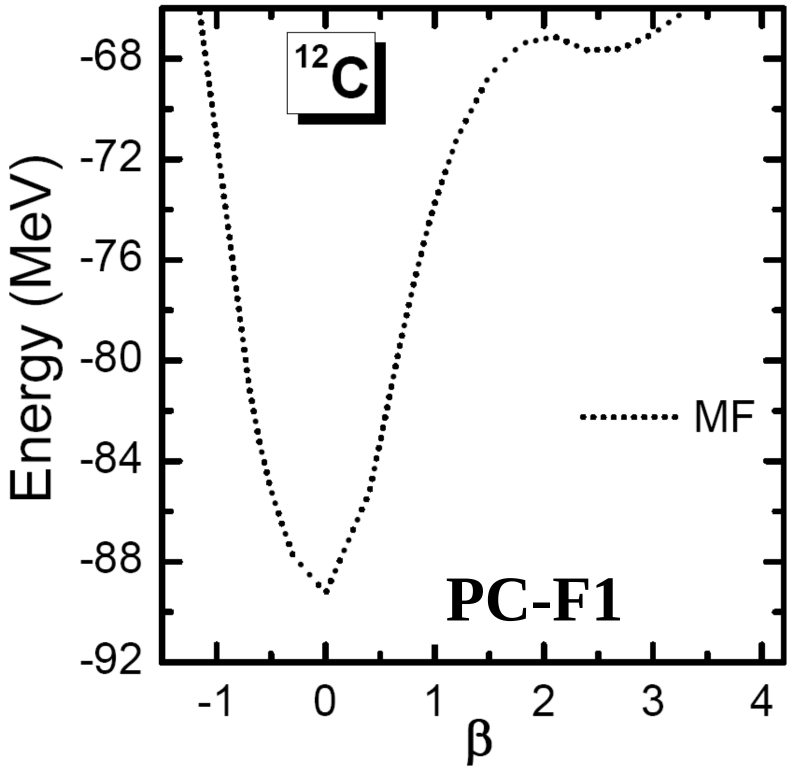
$$|\Phi_{IM}\rangle = \int d\beta\, f(\beta)|\Psi_{IM}(\beta)\rangle$$

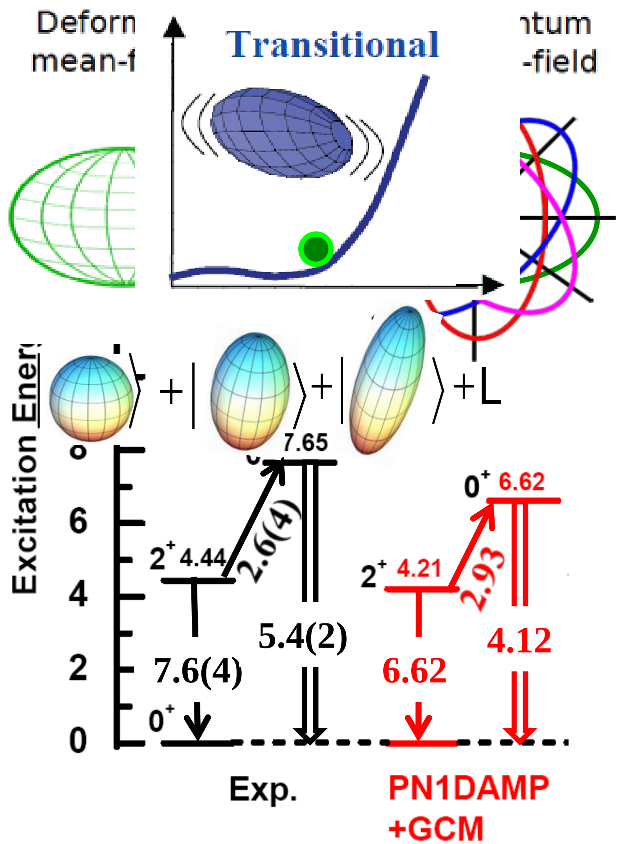
generator coordinate method (GCM)

single → multi Slater determinants

◻ Beyond MF: Illustration with ^{12}C : (GCM+PNP+AMP)

$$|\Phi_{IM_I}\rangle = \sum_{\beta} F^I(\beta)\hat{P}^I_{M_I K}\hat{P}^N\hat{P}^Z|\varphi(\beta)\rangle$$

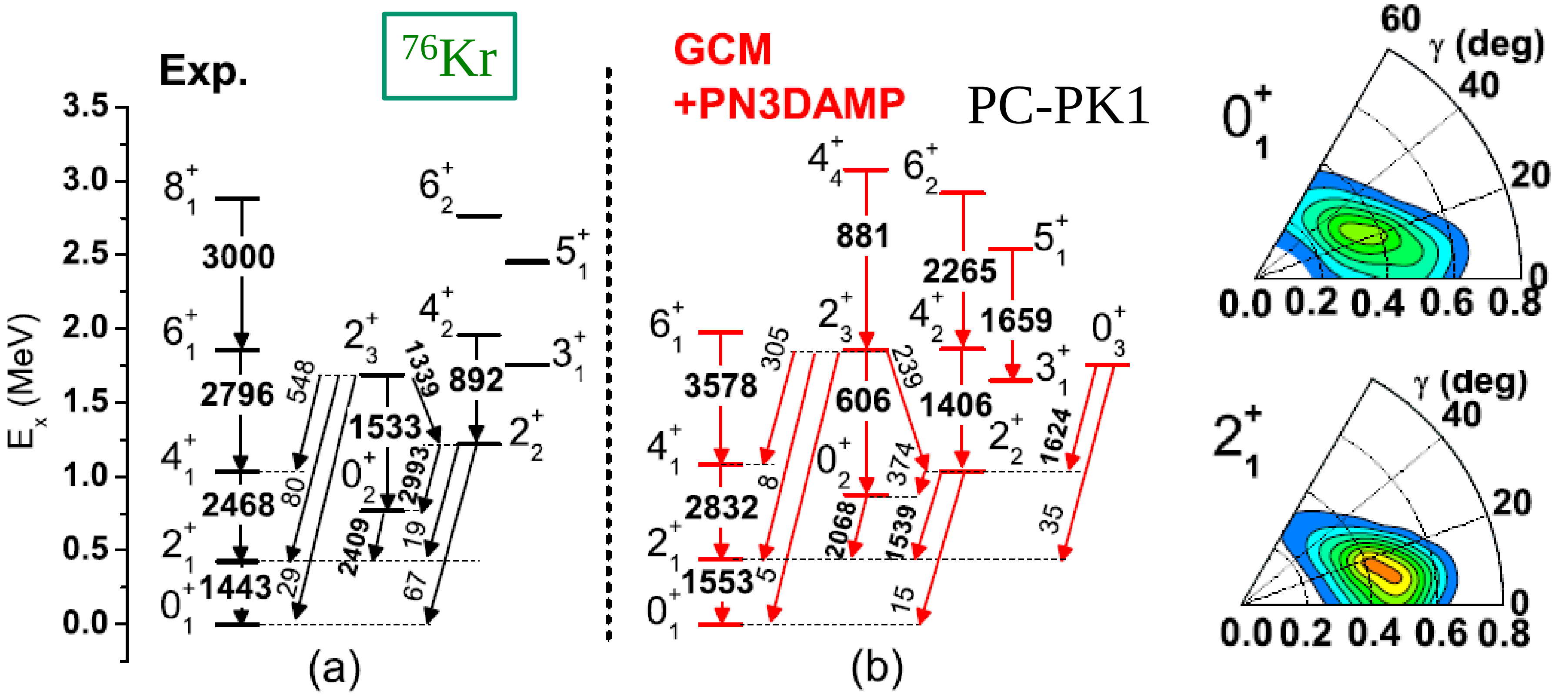




➢ Low-lying spectrum is reproduced rather well.

beyond mean-field approximation

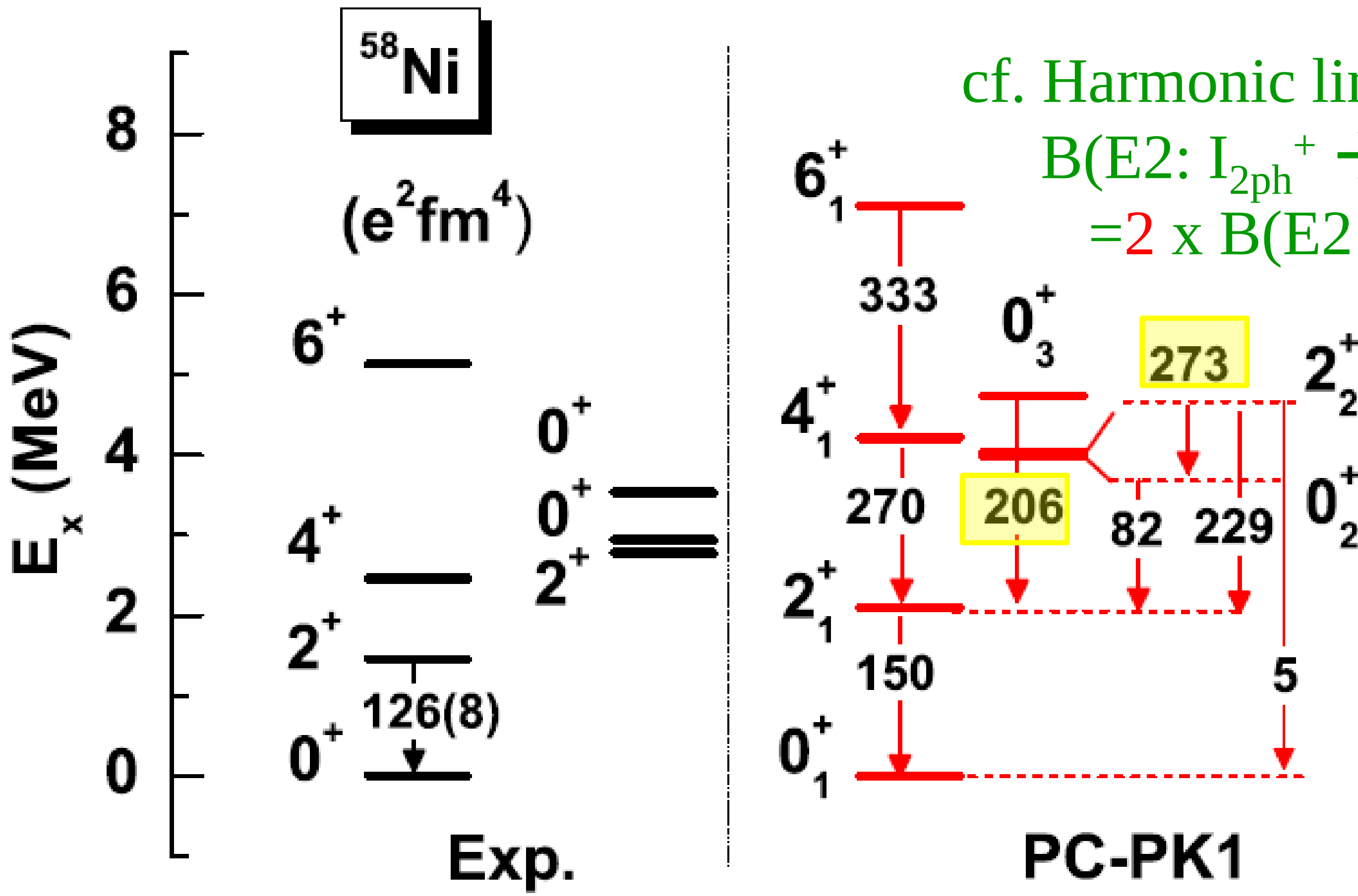
- ✓ angular momentum + particle number projections
- ✓ quantum fluctuation (GCM)



J.M. Yao, K.H., Z.P. Li, J. Meng, and P. Ring, 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



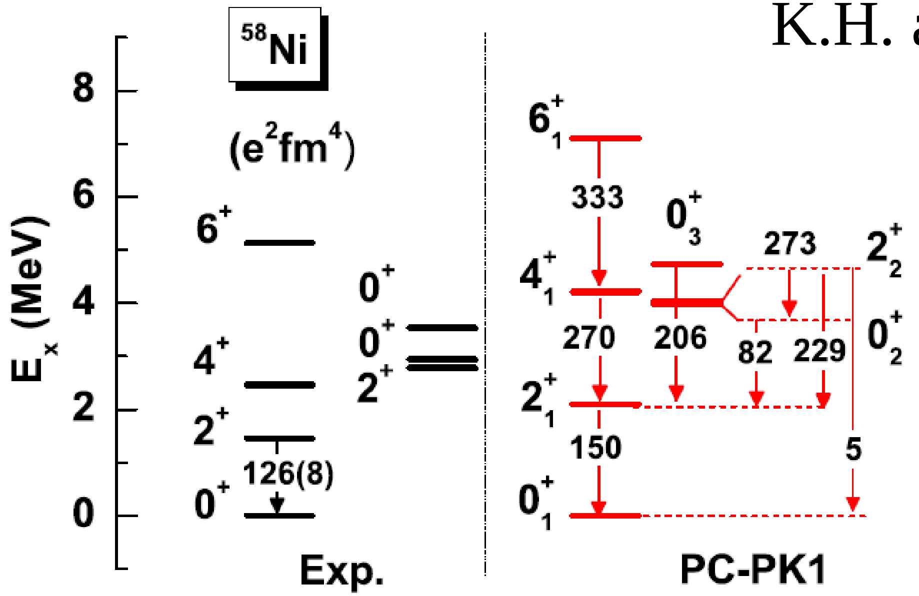
cf. Harmonic limit:
B(E2: $I_{2ph}^+ \rightarrow 2_1^+$)
$= 2 \times$ B(E2: $2_1^+ \rightarrow 0_1^+$)

- ✓ 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

✓ $$V_{\rm coup}(r,\xi) \sim F_\lambda(r)\, Q_\lambda \cdot Y_\lambda(\hat{\boldsymbol{r}})$$

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

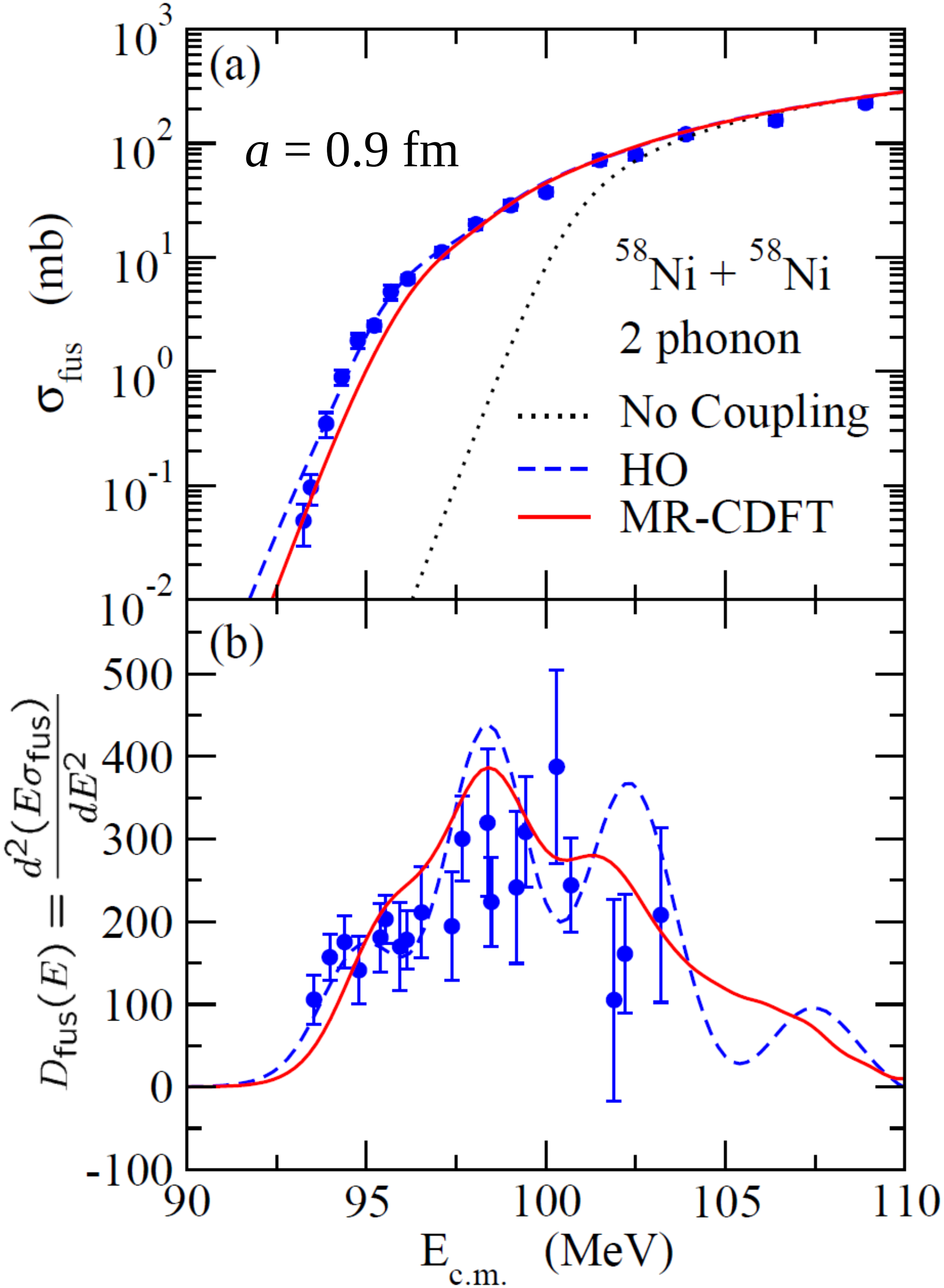
✓ scale to the empirical B(E2; $2_1^+ \to 0_1^+$)

✓ 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 symmetry (no 3^+ state)



^{58}Ni+^{58}Ni

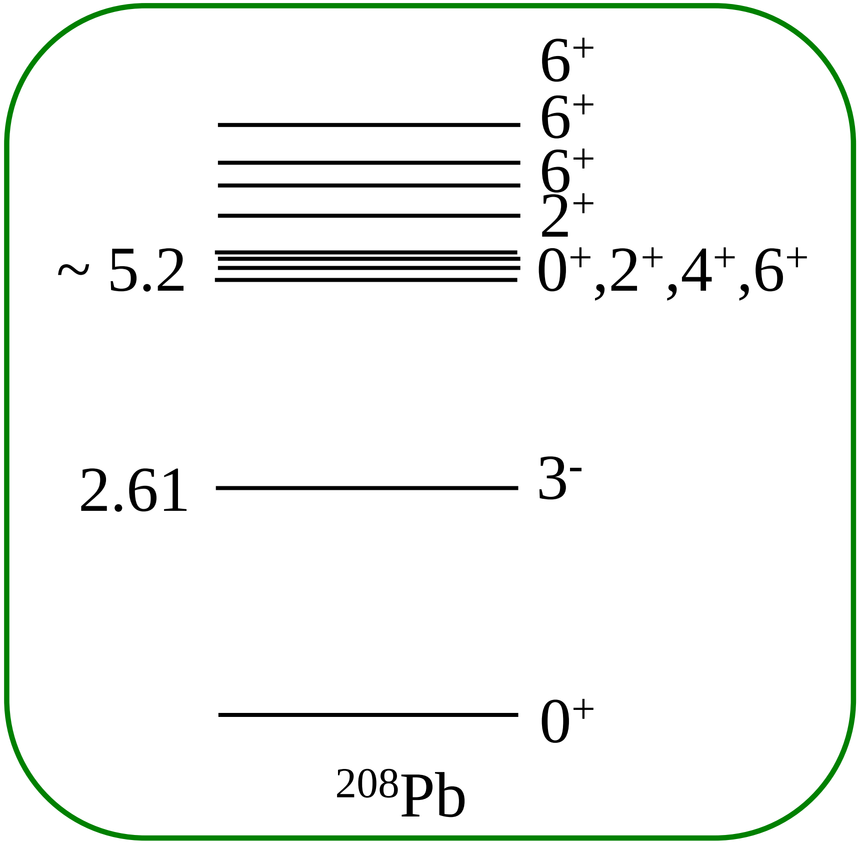
anharmonicity of 2^+ phonon
→ only a minor improvement

Next, more non-trivial case with 2^+ - 3^- coupling:
anharmonicity of oct. vib. in ^{208}Pb

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

Application to ^{16}O + ^{208}Pb fusion reaction

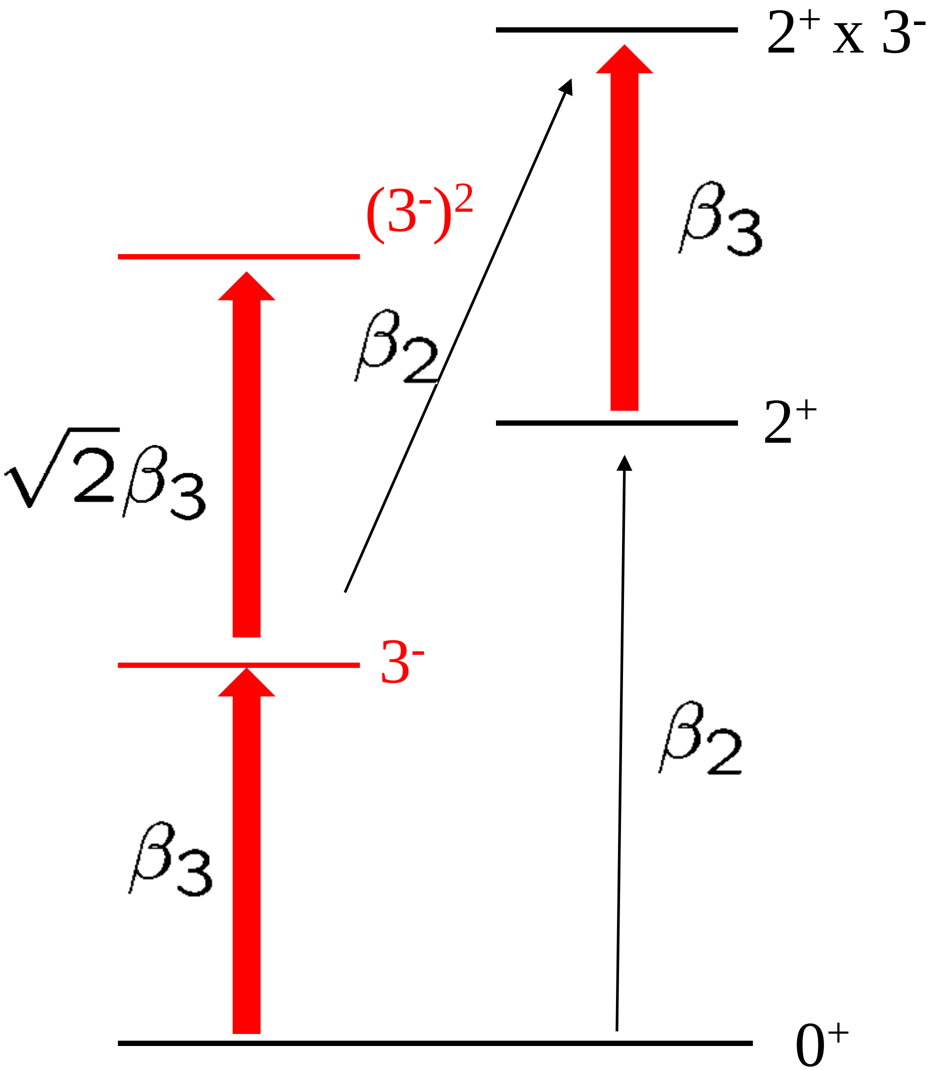
double-octupole phonon states in ^{208}Pb

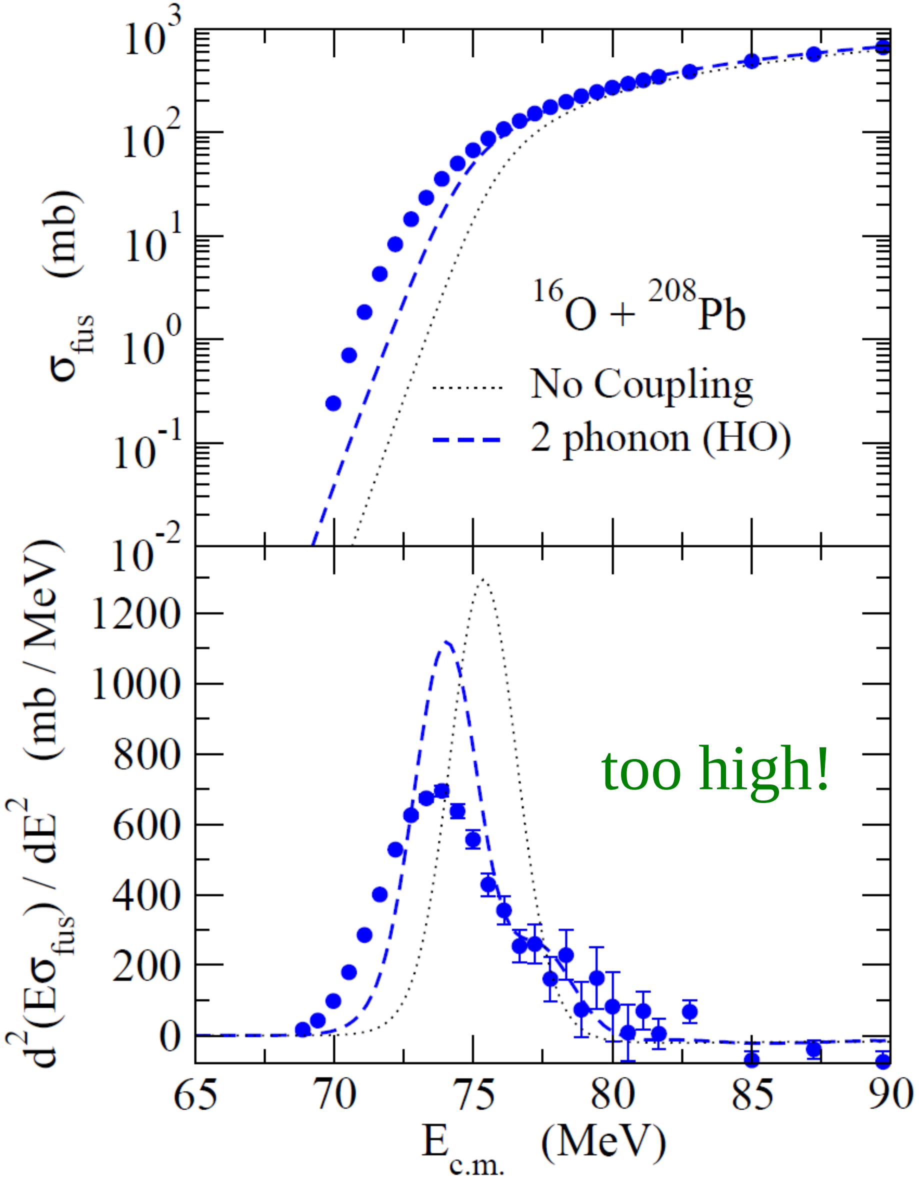


M. Yeh, M. Kadi, P.E. Garrett et al., PRC57 (‘98) R2085
K. Vetter, A.O. Macchiavelli et al., PRC58 (‘98) R2631
V. Yu. Pnomarev and P. von Neumann-Cosel, PRL82 (‘99) 501
B.A. Brown, PRL85 (‘00) 5300

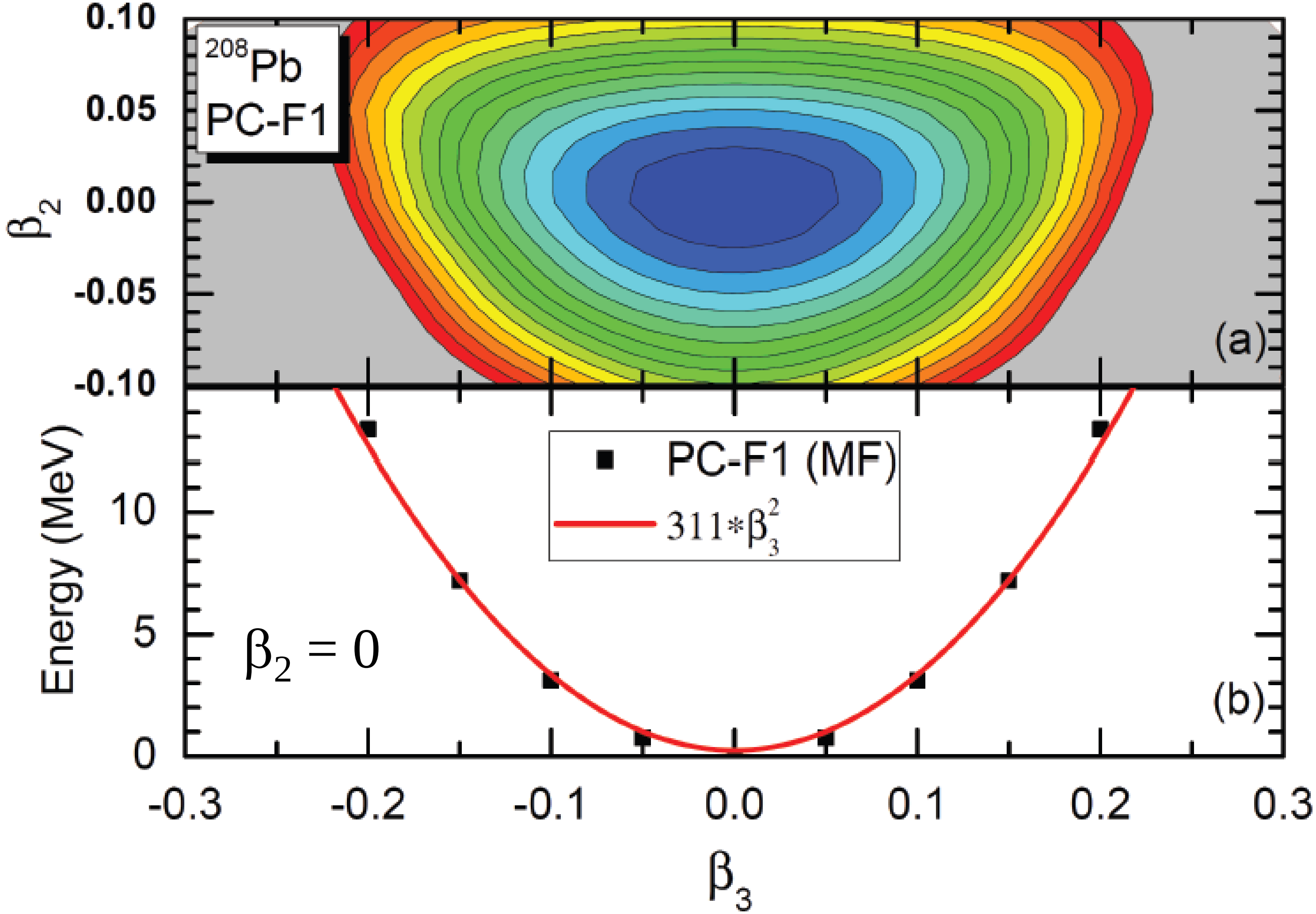
large fragmentations, especially 6^+ state

Application to $^{16}O + ^{208}Pb$ fusion reaction



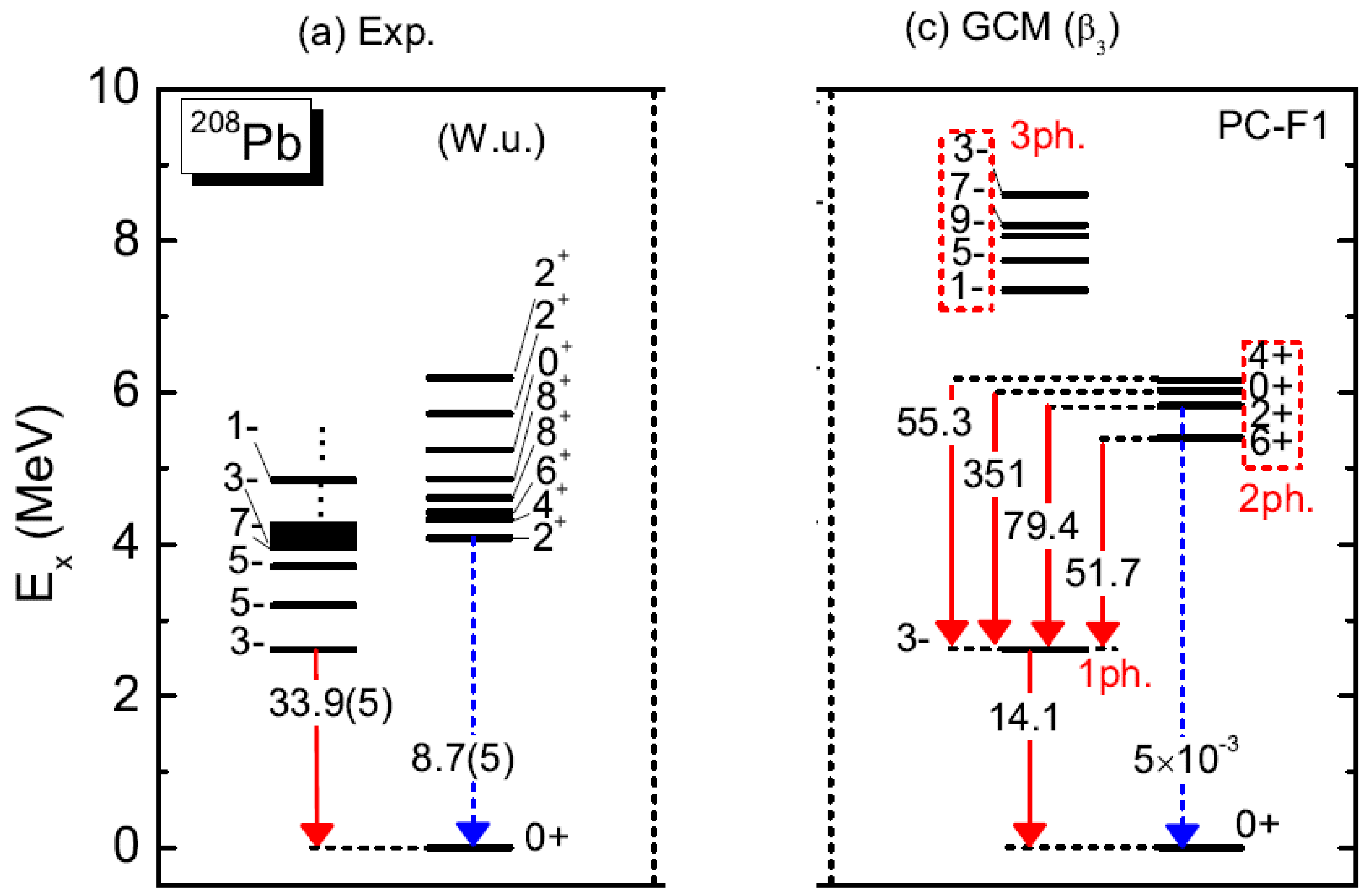


cf. C.R. Morton et al., PRC60('99) 044608 potential energy surface of ^{208}Pb (RMF with PC-F1)



J.M. Yao and K.H., PRC94 ('16) 11303(R)

Expt. data β_2=0, fluctuation in β_3



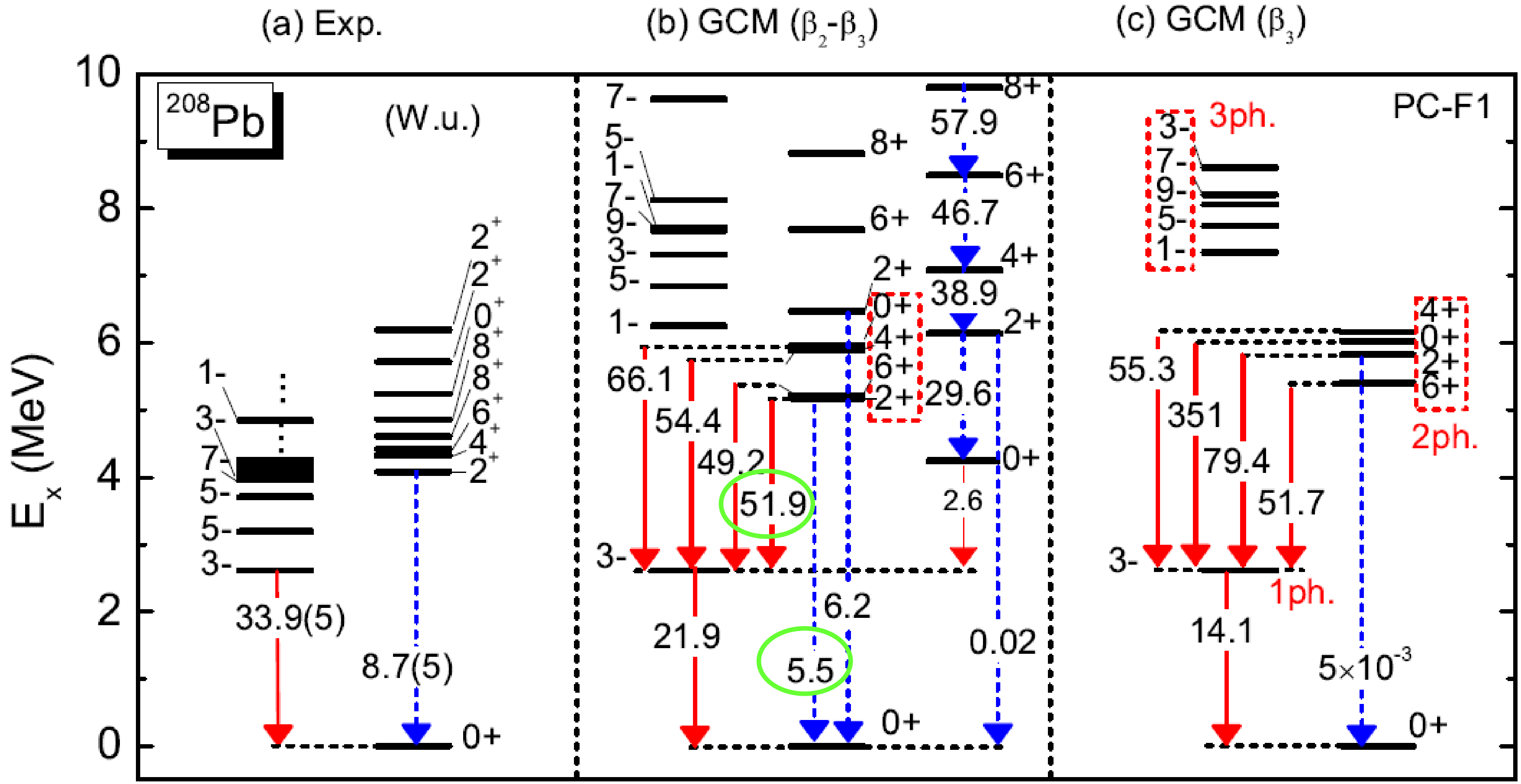
- ➢ $E_{2ph} \sim E_{1ph}$
- ➢ large anharmonicity in B(E3);

  cf. H.O.: $B(E3: I_{2ph} \rightarrow 3_1^-) = 2\, B(E3: 3_1^- \rightarrow g.s.)$
- ➢ underestimate B(E3) (and B(E2))

expt. data

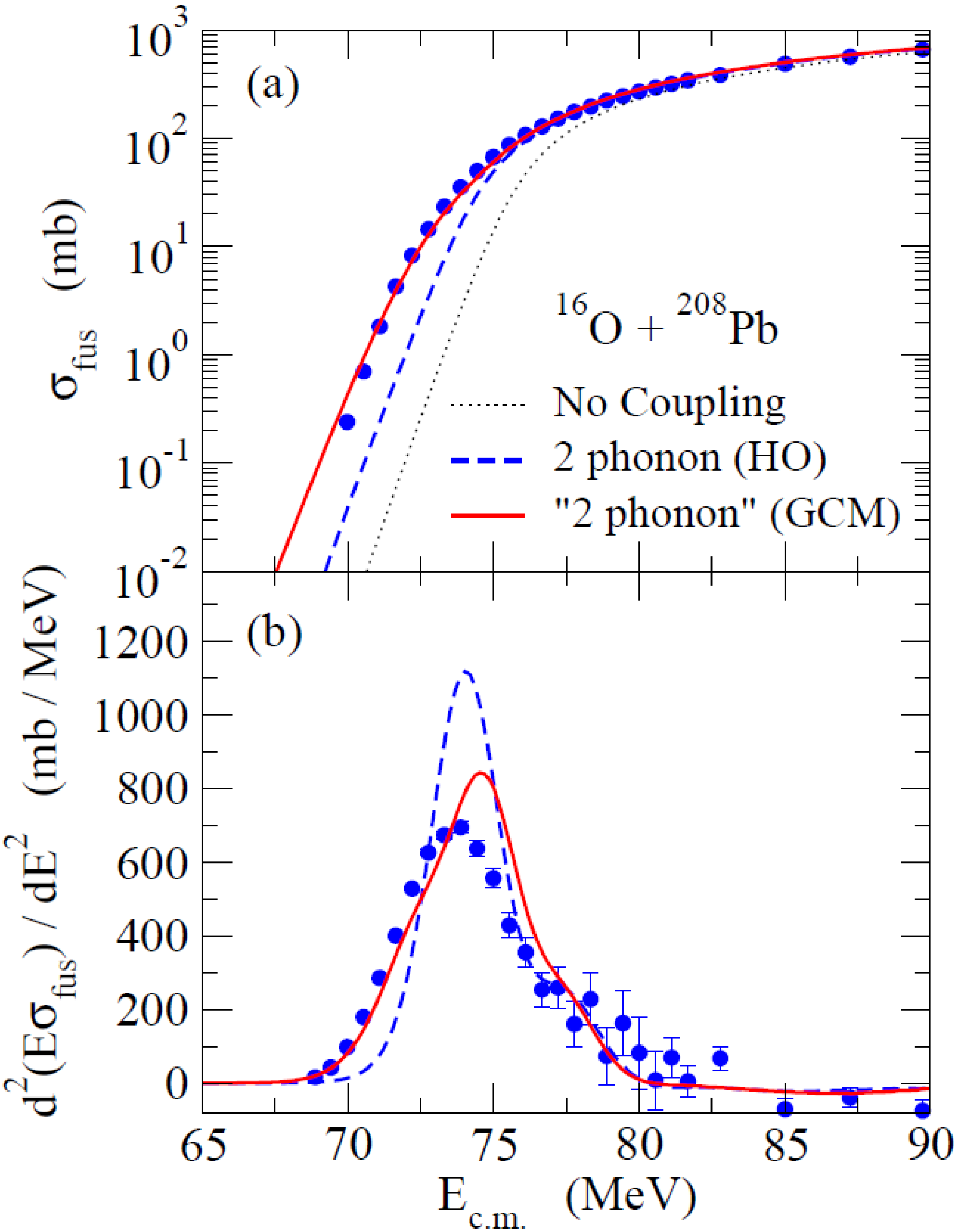
fluctuation both in β_3 and β_2

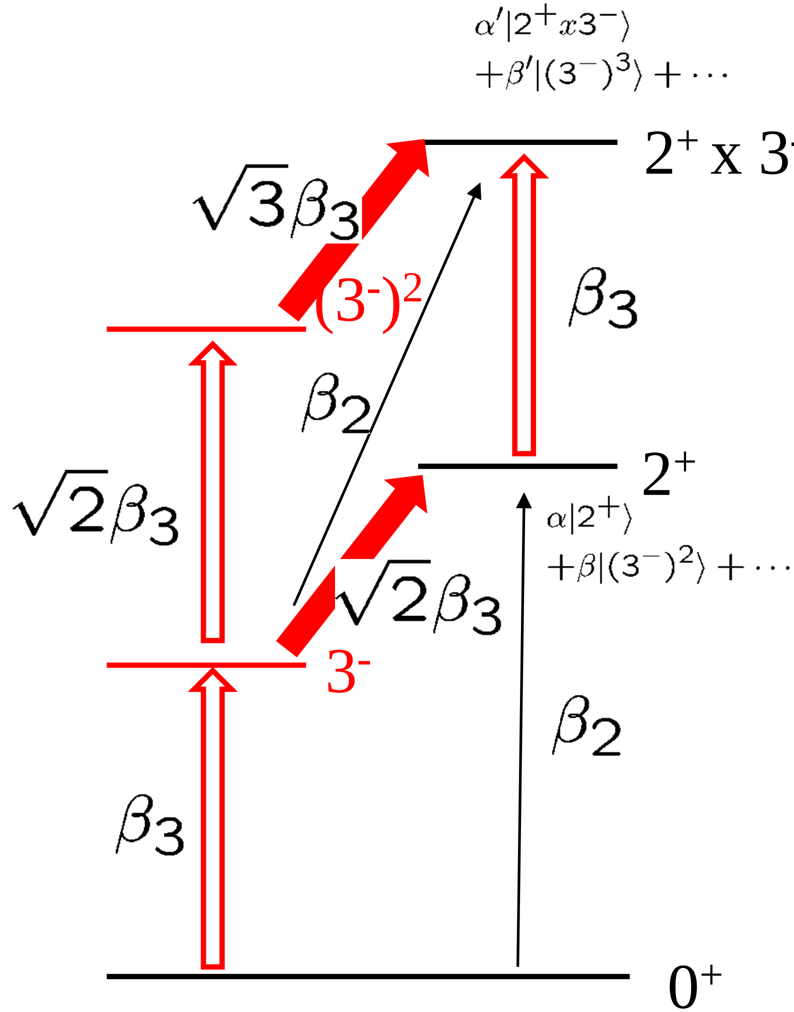
fluctuation in β_3 frozen at β_2=0



2_1^+ state: strong coupling both to g.s. and 3_1^-

$$\longrightarrow \quad |2_1^+\rangle = \alpha|2^+\rangle_{\rm HO} + \beta|[3^- \otimes 3^-]^{(I=2)}\rangle_{\rm HO} + \cdots$$





J.M. Yao and K.H.,
PRC94 ('16) 11303(R)

Summary

Heavy-ion subbarrier fusion reactions

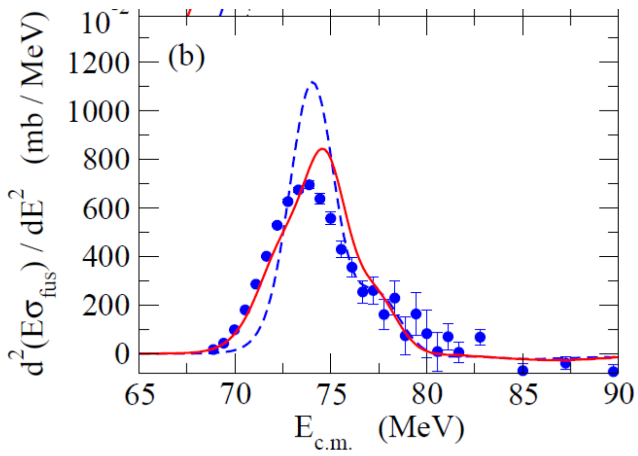
✓strong interplay between reaction and structure
cf. fusion barrier distributions

➢C.C. calculations combined with beyond-MF method

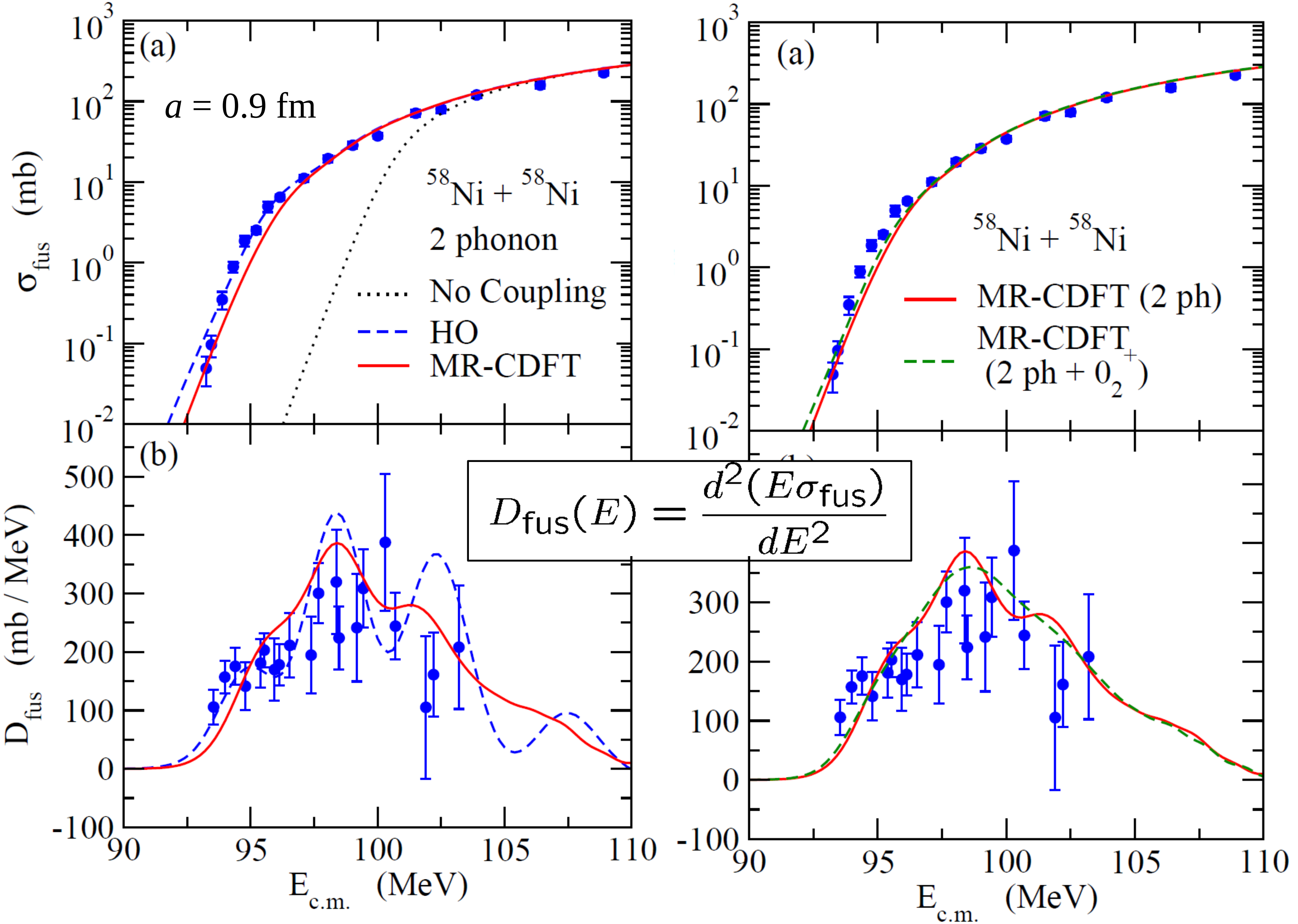
✓ anharmonicity
✓ octupole vibrations: $^{16}O + ^{208}Pb$

more flexibility:

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



C.C. with shell model?



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

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