Role of non-collective excitations in fusion reaction and quasi-elastic scattering around the Coulomb barrier

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- **Introduction**
- **Coupled-channels method**
- **Results**
- **Summary**

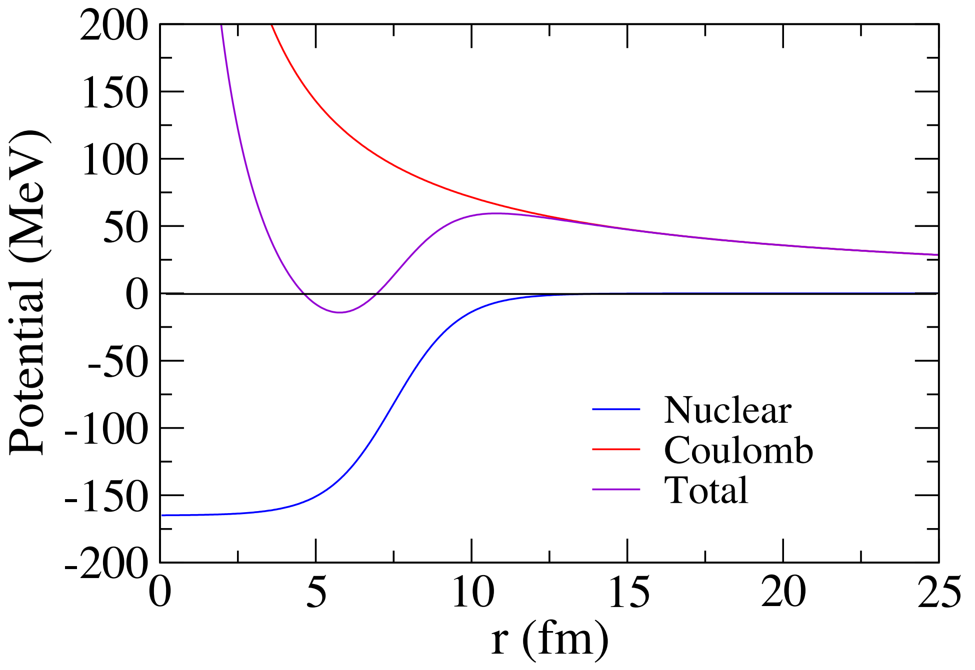
Introduction

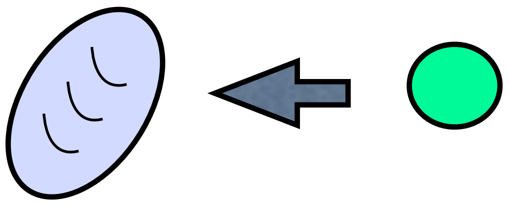
Low energy heavy-ion reactions

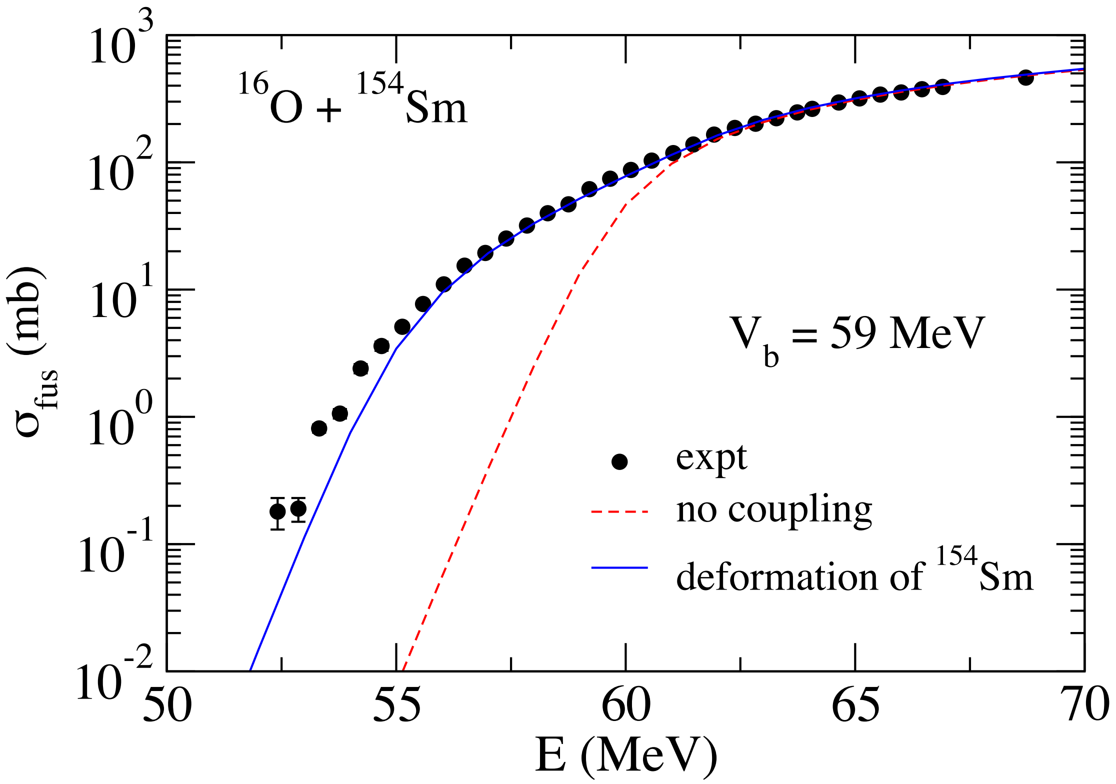
- heavy-ion reactions near the Coulomb barrier

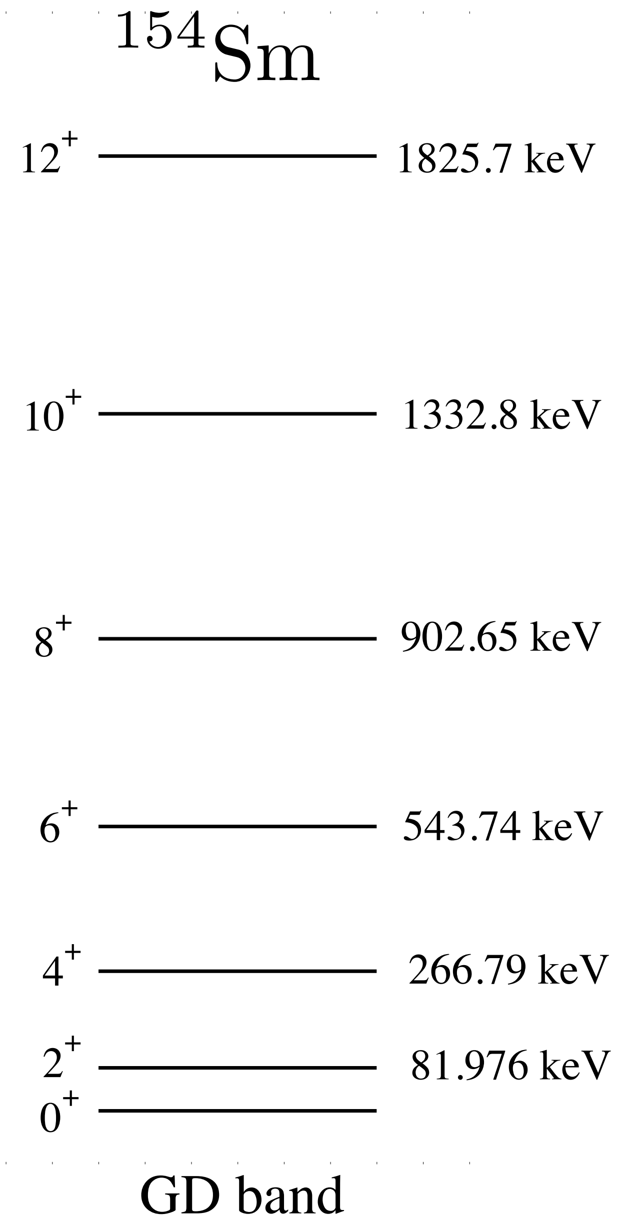
➡ channel coupling effect

e.g. large enhancement of subbarrier fusion cross sections

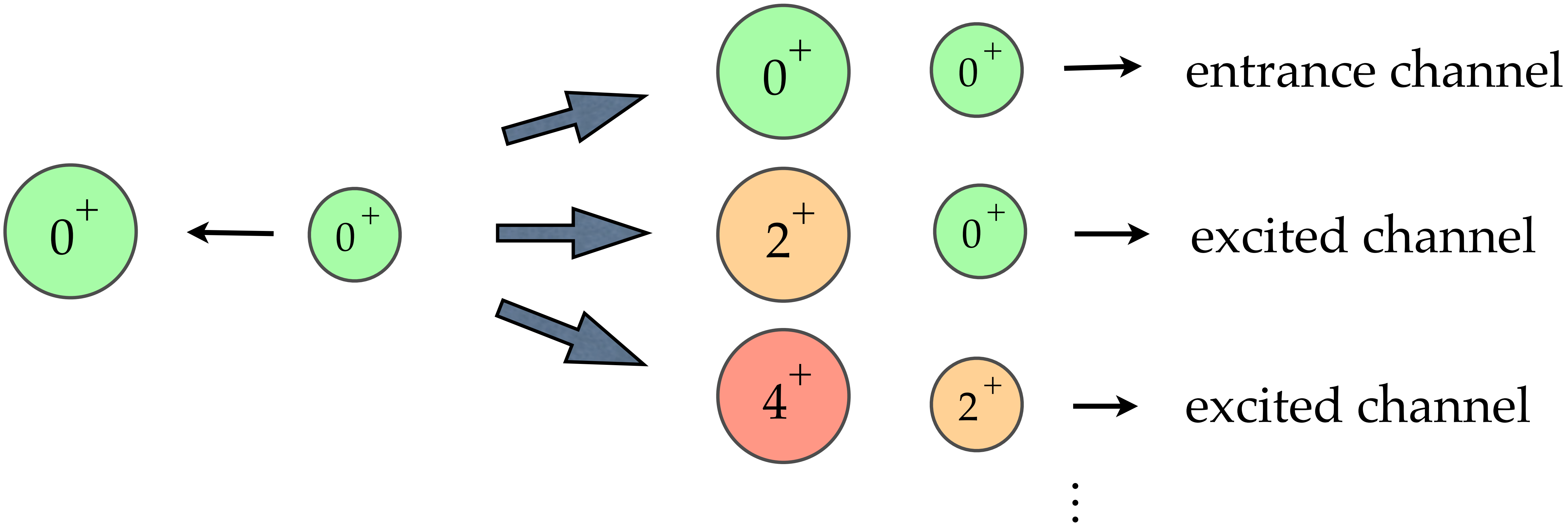








- Coupled-Channels method



entrance channel

excited channel

excited channel

Quantum theory that takes into account excitations of colliding nuclei during the collision

⇨ conventionally, collective excitations(vibration and/or rotation) are taken into account

⇩

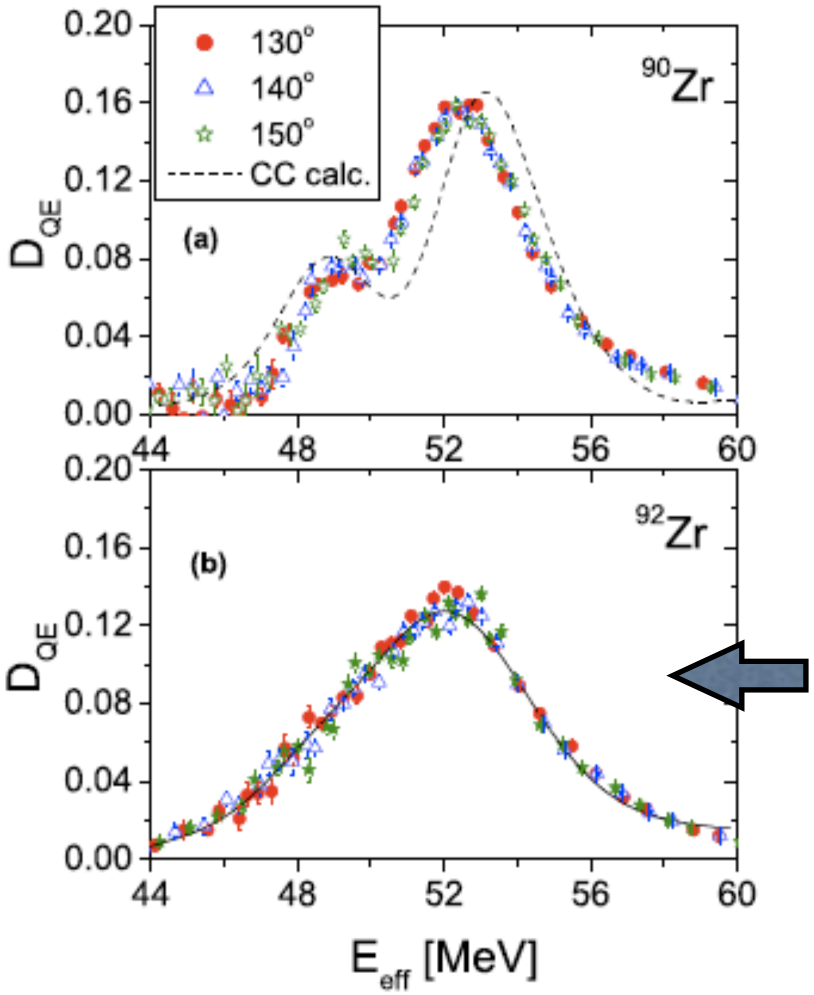
successfully accounted for heavy-ion fusion reactions and quasi-elastic scattering(elastic + inelastic + transfer)

^{20}Ne + ^{90,92}Zr quasi-elastic scattering

experimental barrier distributions show different behavior (much more smeared distribution for ^{20}Ne + ^{92}Zr system)

on the other hand,

coupled-channels calculation with collective excitations results in similar barrier distributions



$$D_{\rm qel} = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

E.Piasecki *et al.*, PRC **80**, 054613 (2009)

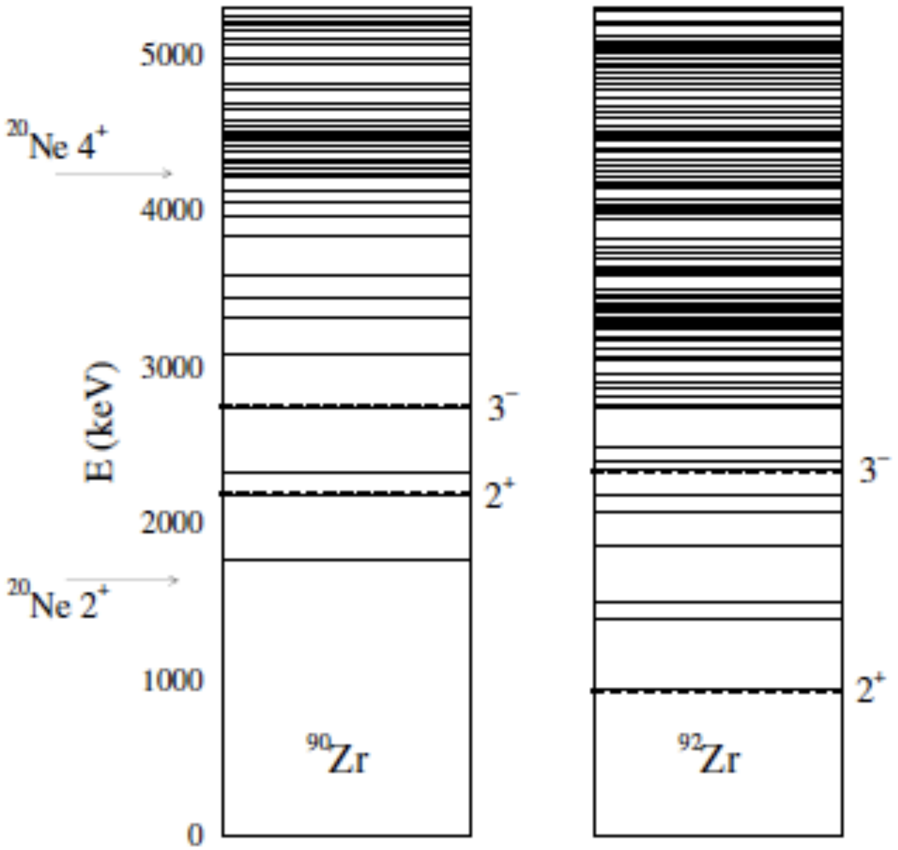
much more smeared

Energy spectrum for Zr isotopes

different level density

$$\begin{cases} ^{90}\text{Zr} : \text{N} = 50 \text{ (shell closure)} \\ ^{92}\text{Zr} : \text{N} = 50 + 2 \end{cases}$$

many non-collective excitations in ^{92}Zr

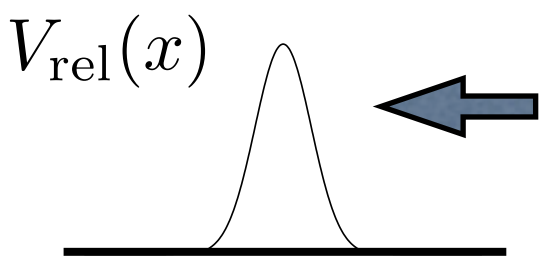


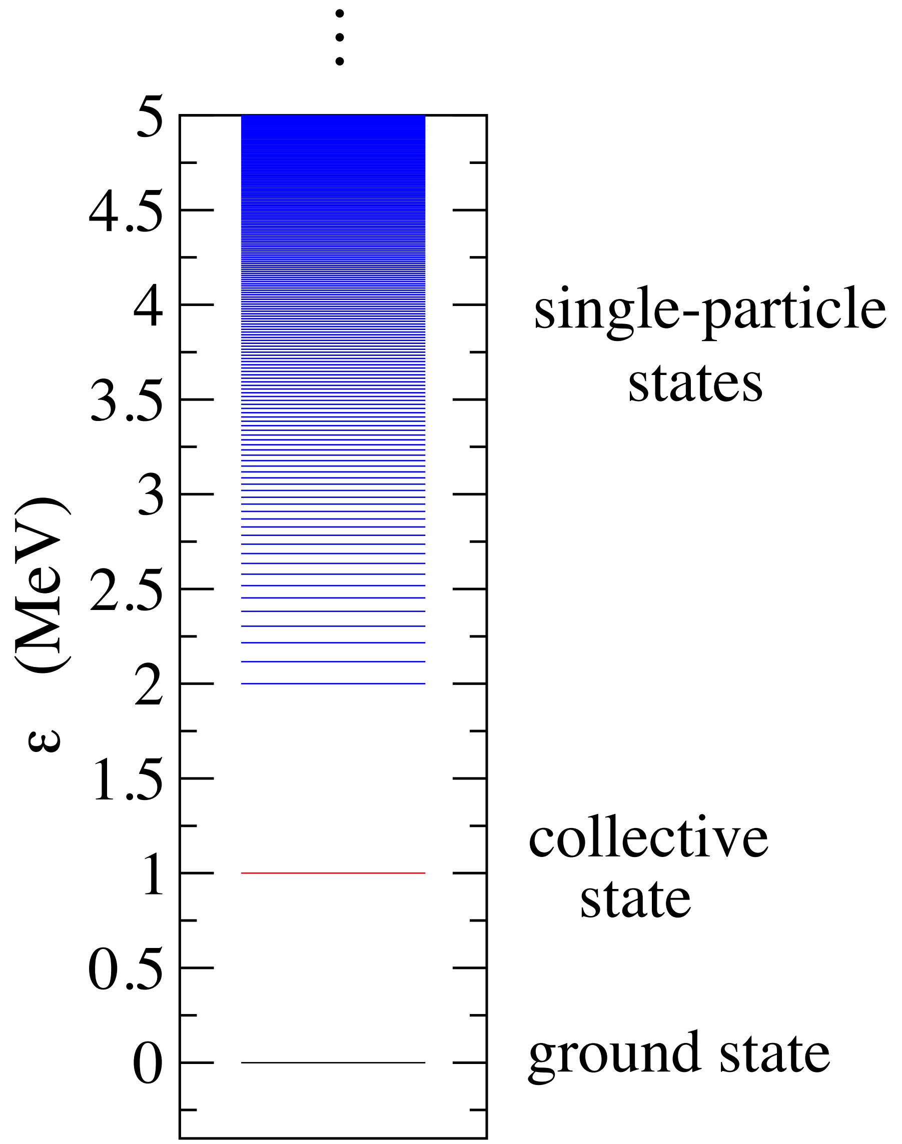
role of non-collective excitations ?

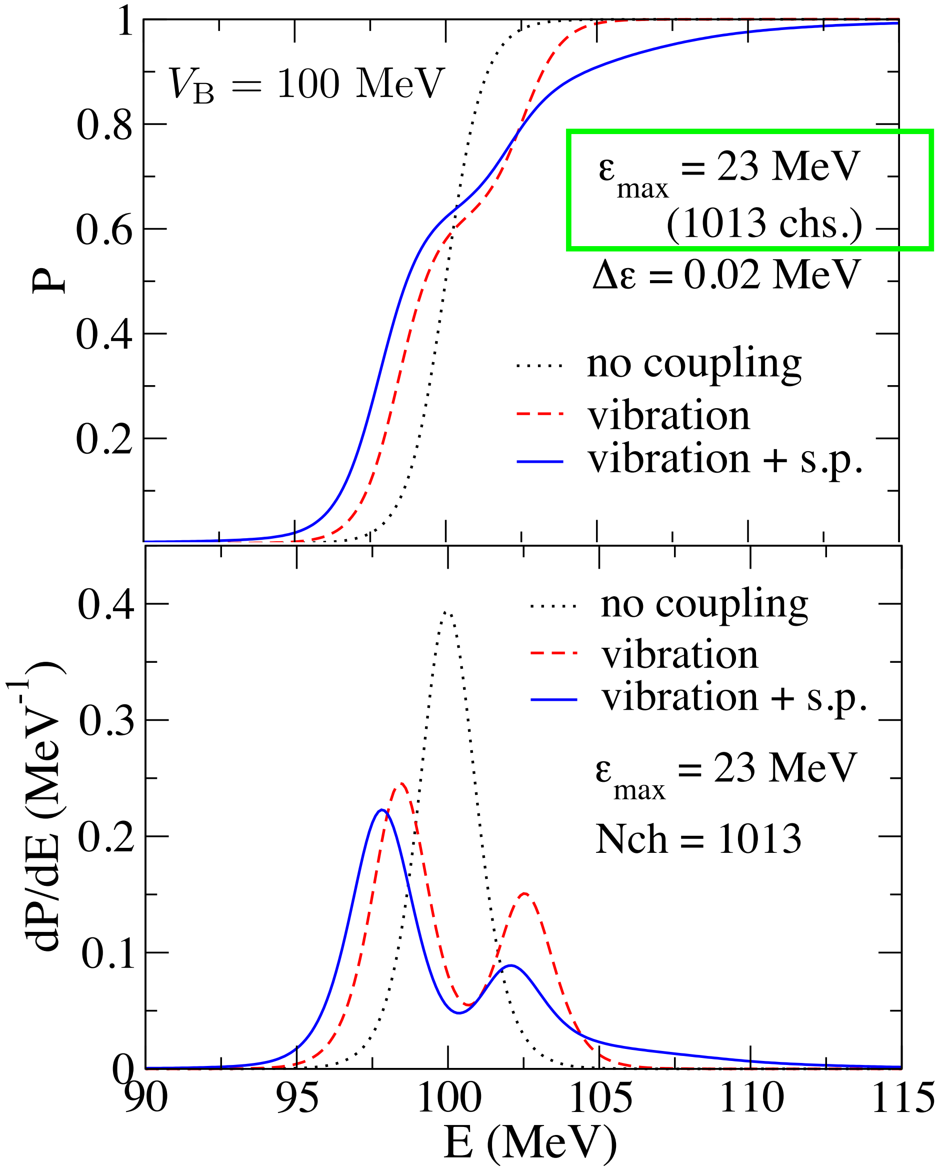
(not explicitly taken into account in the c.c. calculation)

Non-collective excitations in one-dimensional model

description of non-collective excitations based on
random matrix theory







large dimensional
coupled-channels
calculation

S.Y., K.Hagino and N.Rowley,
PRC82('10)023606

* non-coll. excitations ⇒ suppress the penetrability above the barrier

⇒ smear the barrier distribution

Coupled-channels method

2. Coupled-channles method

coupled-channels equations(in the isocentrifugal approximation):

$$\boxed{\left[\frac{d^2}{dr^2}+k^2-\frac{J(J+1)}{r^2}-\frac{2\mu}{\hbar^2}\left(V_{\mathrm{C}}(r)+V_{\mathrm{N}}(r)+\epsilon_n\right)\right]u_n^J(r)=\sum_m\frac{2\mu}{\hbar^2}V_{nm}(r)u_m^J(r)}$$

$$k=\sqrt{\frac{2\mu E}{\hbar^2}}$$

$$V_{\mathrm{N}}(r)=V_{\mathrm{N}}^{(0)}(r)+iW_{\mathrm{N}}(r)=-\frac{V_0}{1+\exp((r-R_{\mathrm{N}})/a)}-i\frac{W_0}{1+\exp((r-R_{\mathrm{W}})/a_{\mathrm{W}})}$$

ϵ_n : excitation energy of the *n*-th channel

boundary conditions

$u_n^J(r)$: regular at the origin $\qquad k_n = \sqrt{\frac{2\mu(E-\epsilon_n)}{\hbar^2}}$

$$u_n^J(r) \to \delta_{n,0} H_J^{(-)}(k_n r) - \sqrt{k_0/k_n}\, S_{n0}^J H_J^{(+)}(k_n r) \qquad (r \to \infty)$$

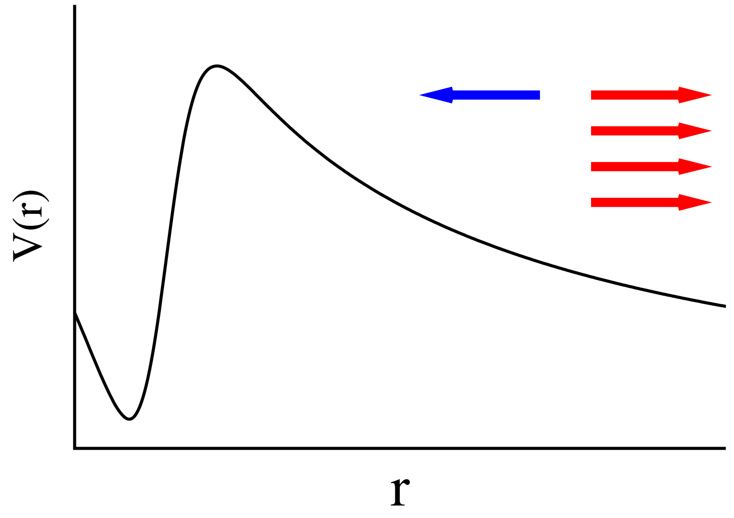
$H_J^{(\pm)}(kr)$: outgoing(imcoming) Coulomb wave functions

S_{n0}^J : S-matrix ➡ scattering amplitude

differential cross section for the *n*-th channel : $\frac{d\sigma_n}{d\Omega} = \frac{k_n}{k_0}|f_{\rm N}^n(\theta) + \delta_{n,0} f_{\rm C}(\theta)|^2$

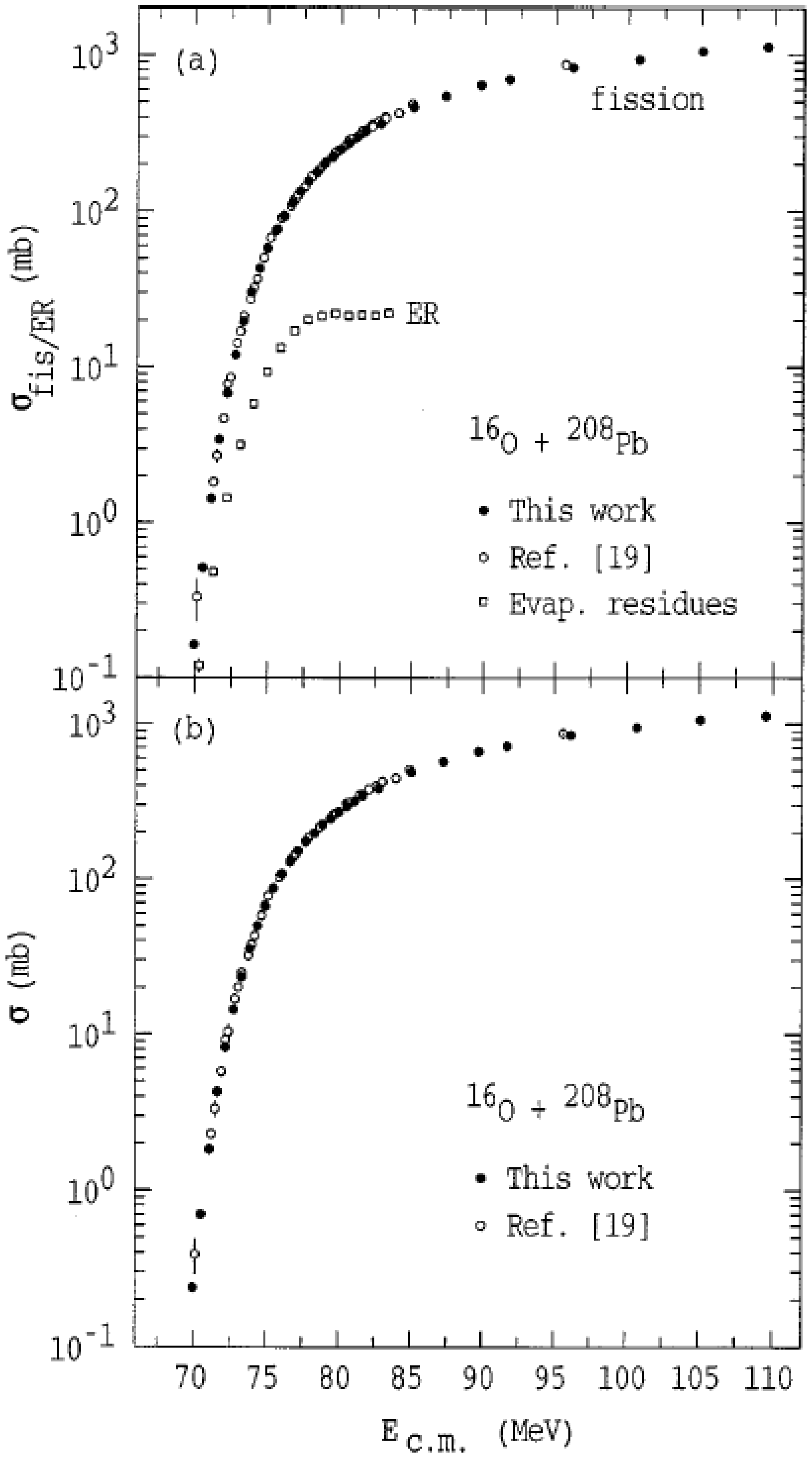
quasi-elastic cross section : $\sigma_{\rm qel}(E,\theta) = \sum_n \frac{d\sigma_n}{d\Omega}$

quasi-elastic barrier distribution : $D_{\rm qel}(E,\theta) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}}{\sigma_{\rm R}}\right)$

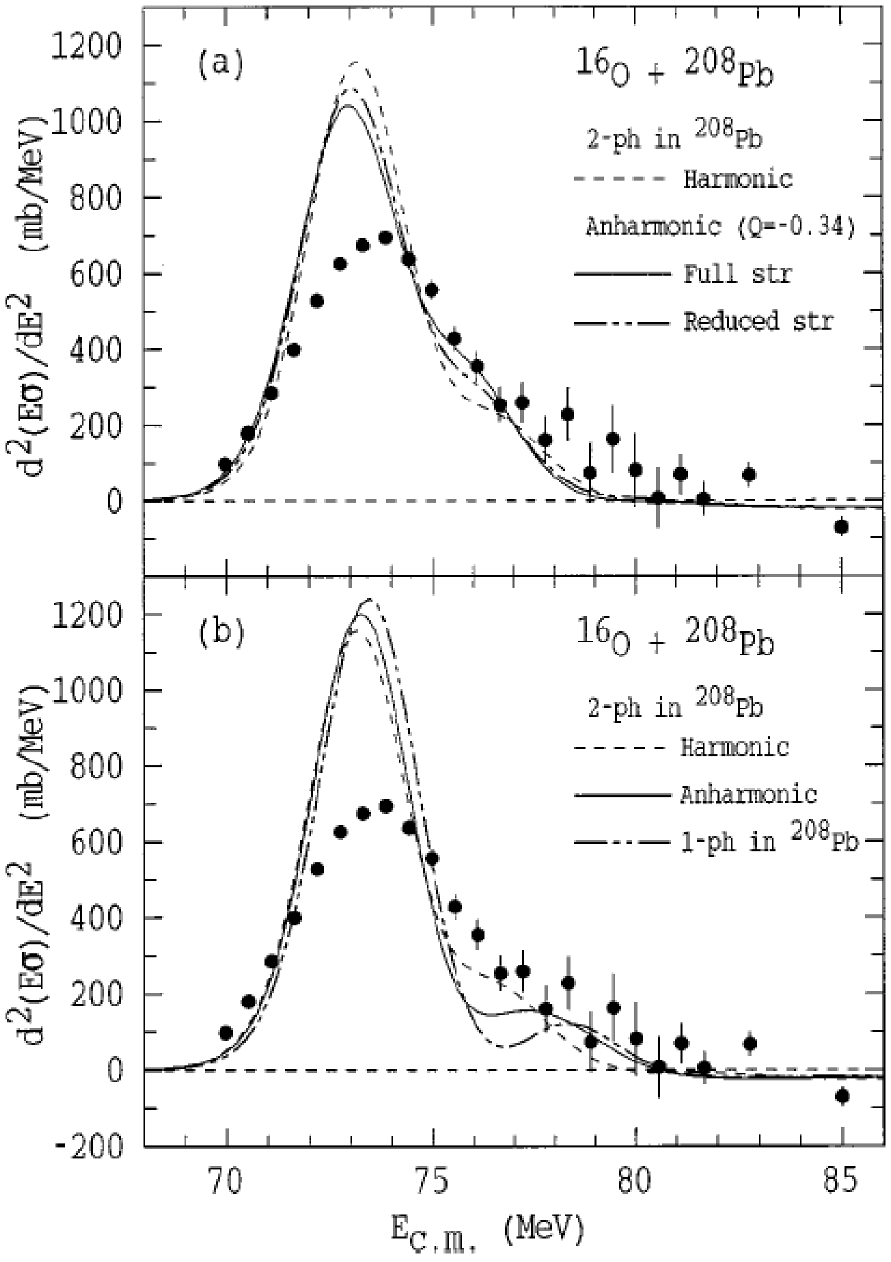


^{16}O + ^{208}Pb fusion reaction and quasi-elastic scattering with non-coll. excitations

precise fusion data



fusion barrier distribution



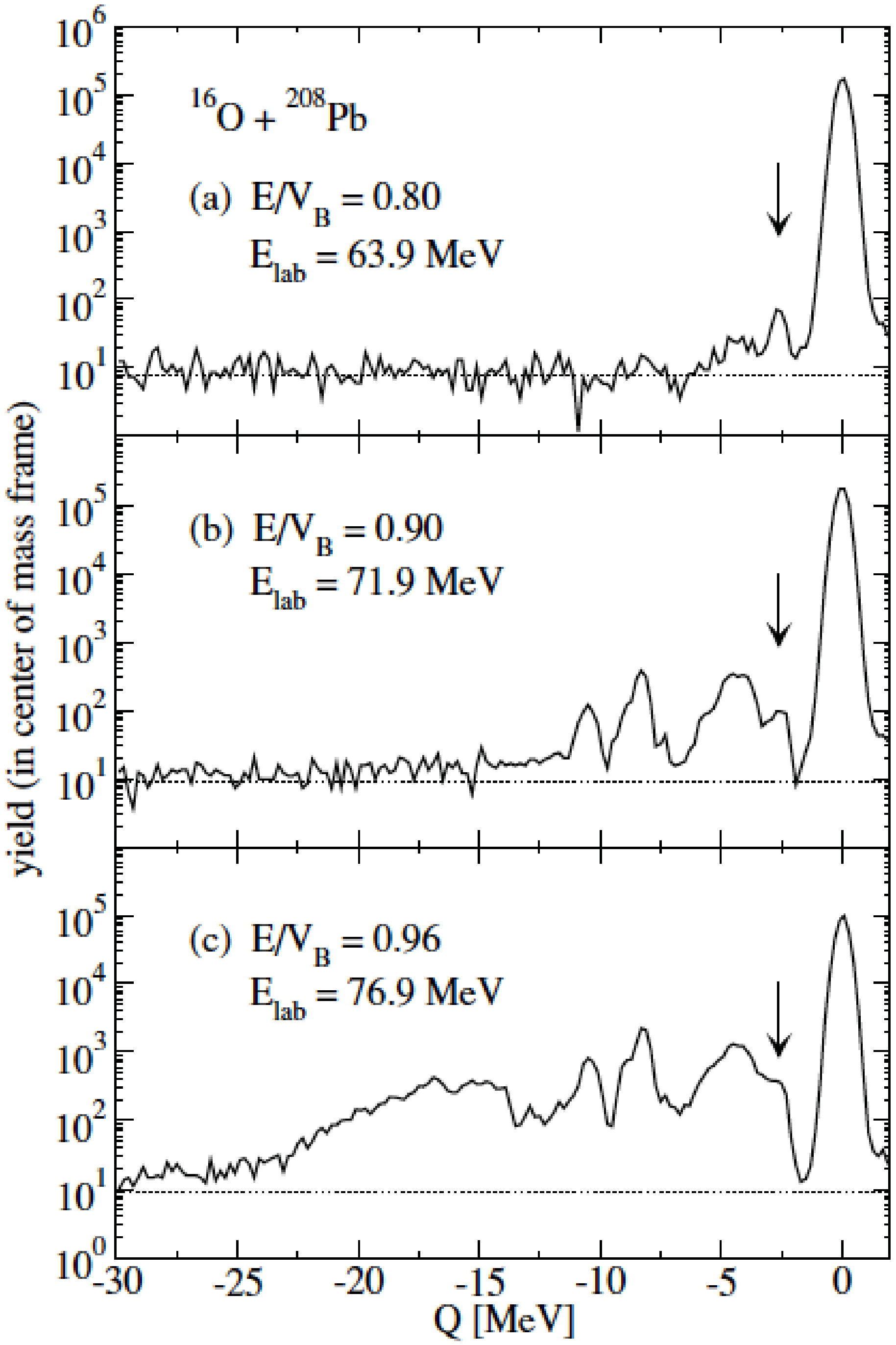
C. R. Morton *et al.*, PRC60, 044608(1999)

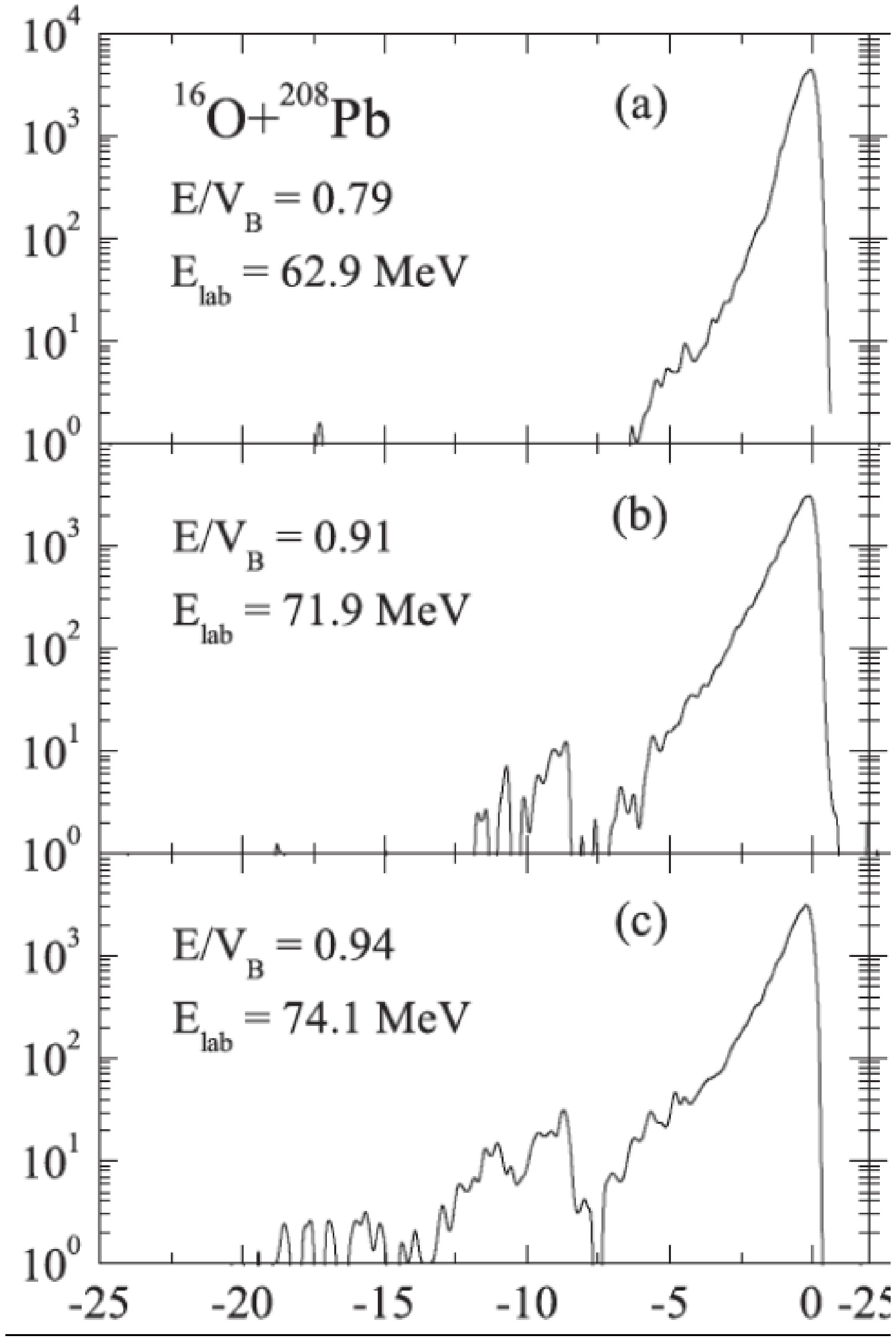
analysis with collective excitations

⟶ no satisfactory description has obtained

$^{16}O + {}^{208}Pb$ fusion reaction and quasi-elastic scattering with non-coll. excitations

Energy dependence of Q-value distribution



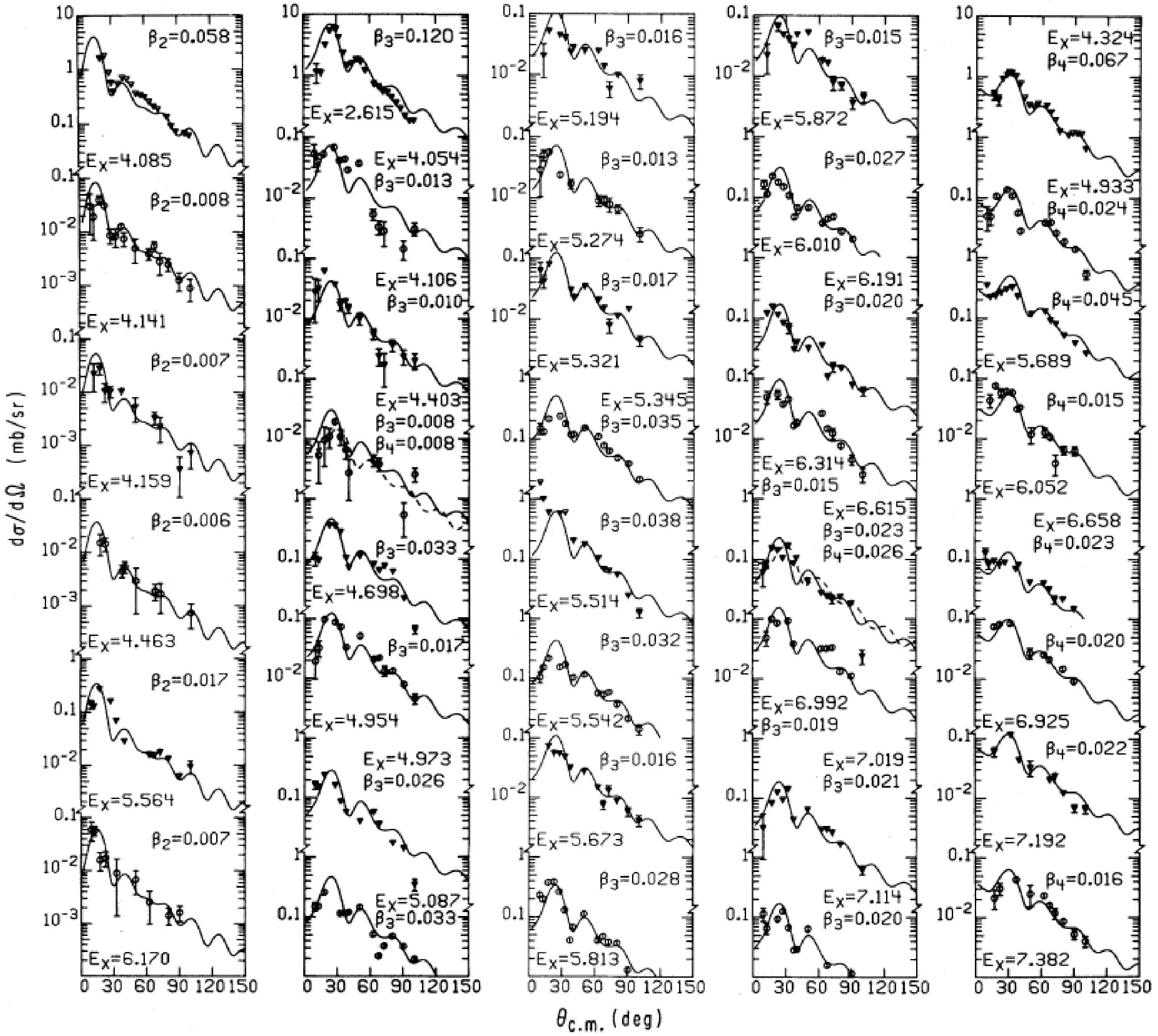


M. Ever *et al*. PRC**78**(2008)034614

C. J. Lin *et al*., PRC**79** (2009)064603

^{16}O + ^{208}Pb fusion reaction and quasi-elastic scattering with non-coll. excitations

high precision proton inelastic scattering experiment of ^{208}Pb



W.T.Wagner, *et al.* PRC**12** 757(1975)

DWBA analysis

energy E^* and deformation parameter β_λ of excited states up to about 7 MeV

couplings to these non-collective excitations
(with coupling form factor for vibrational coupling)

Results

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

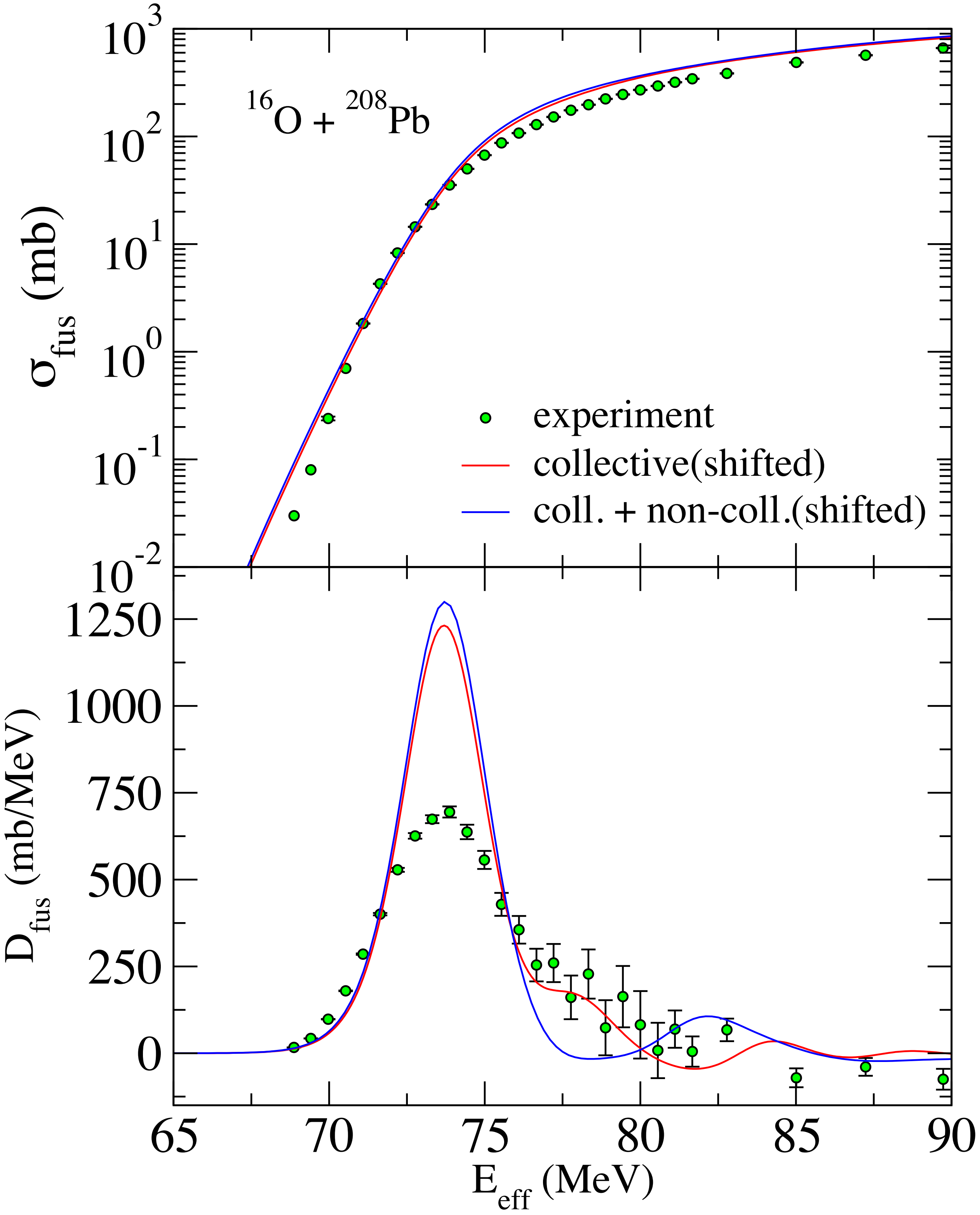
with 70 non-coll. states

※ collective states

^{208}Pb : 3^- : 2.615 MeV, $\beta_3 = 0.122$

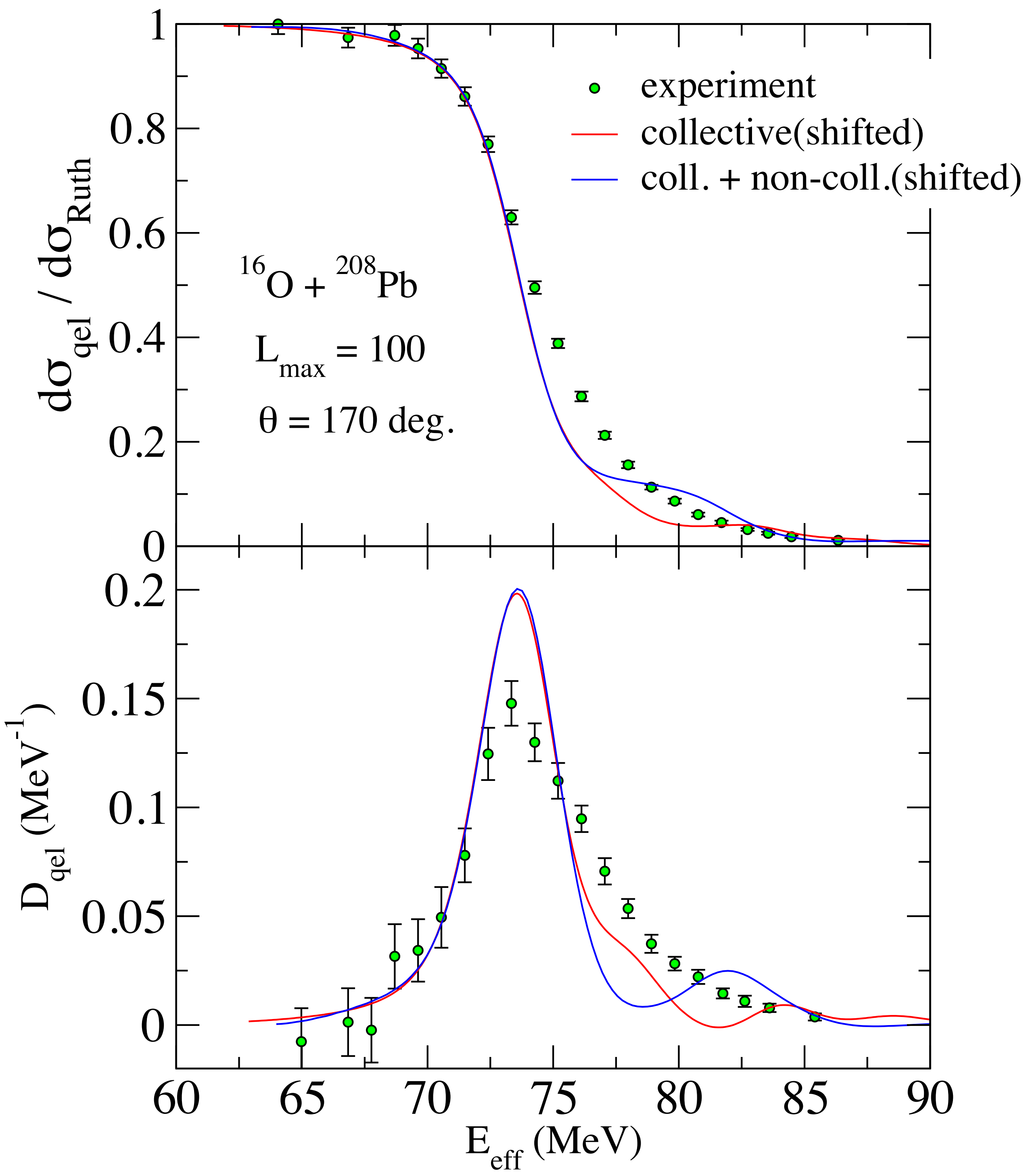
5^- : 3.198 MeV, $\beta_5 = 0.058$

^{16}O : 3^- : 6.13 MeV, $\beta_3 = 0.733$



- ✓ barrier distribution becomes single peak structure due to the non-collective excitations(smearing effect)
- ✓ non-collective excitations do not improve the agreement

^{16}O + ^{208}Pb quasi-elastic scattering



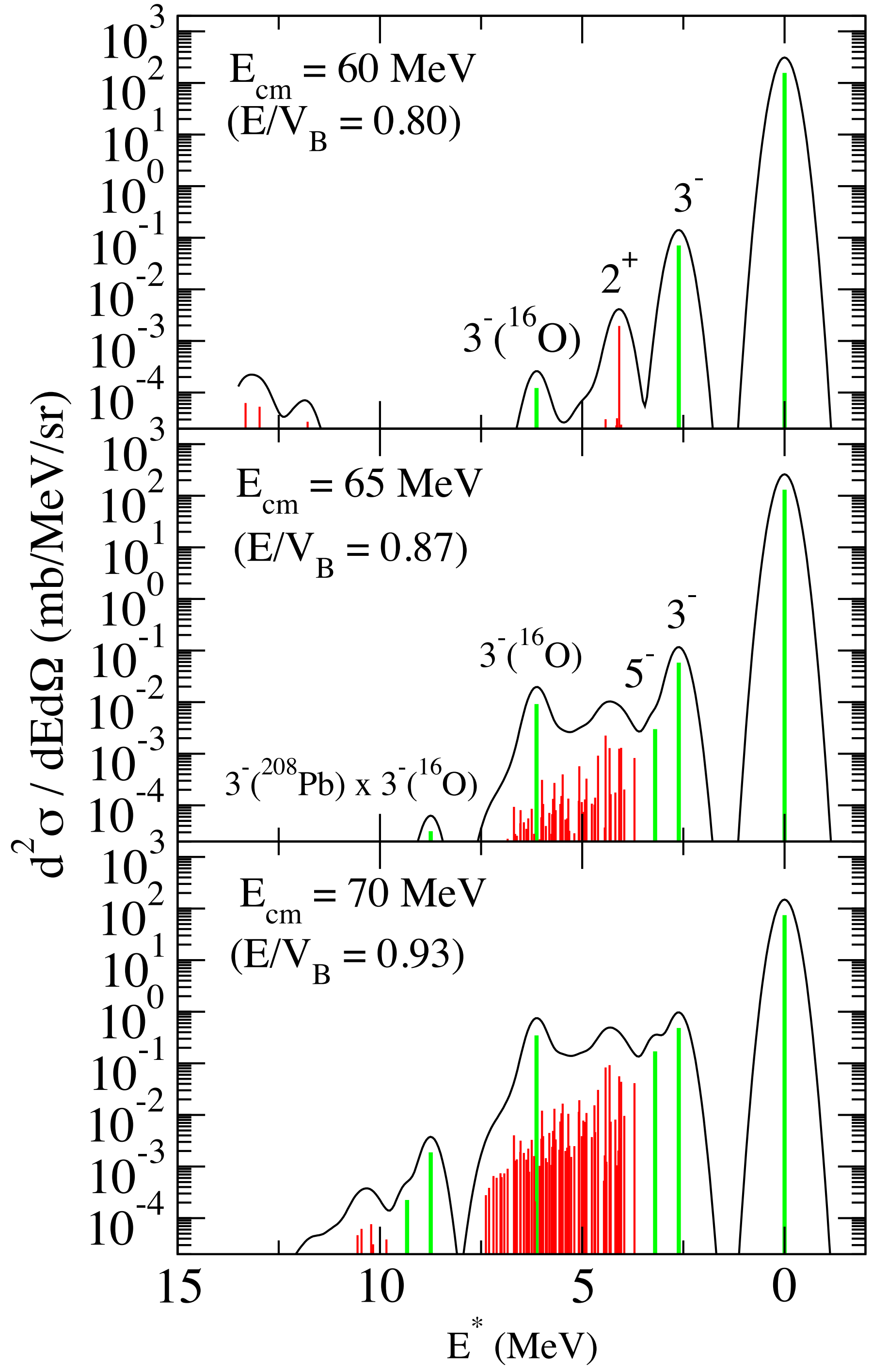
- smearing effect as in the case for fusion
- non-collective excitations do not improve the agreement between experimental barrier distributions also in this case

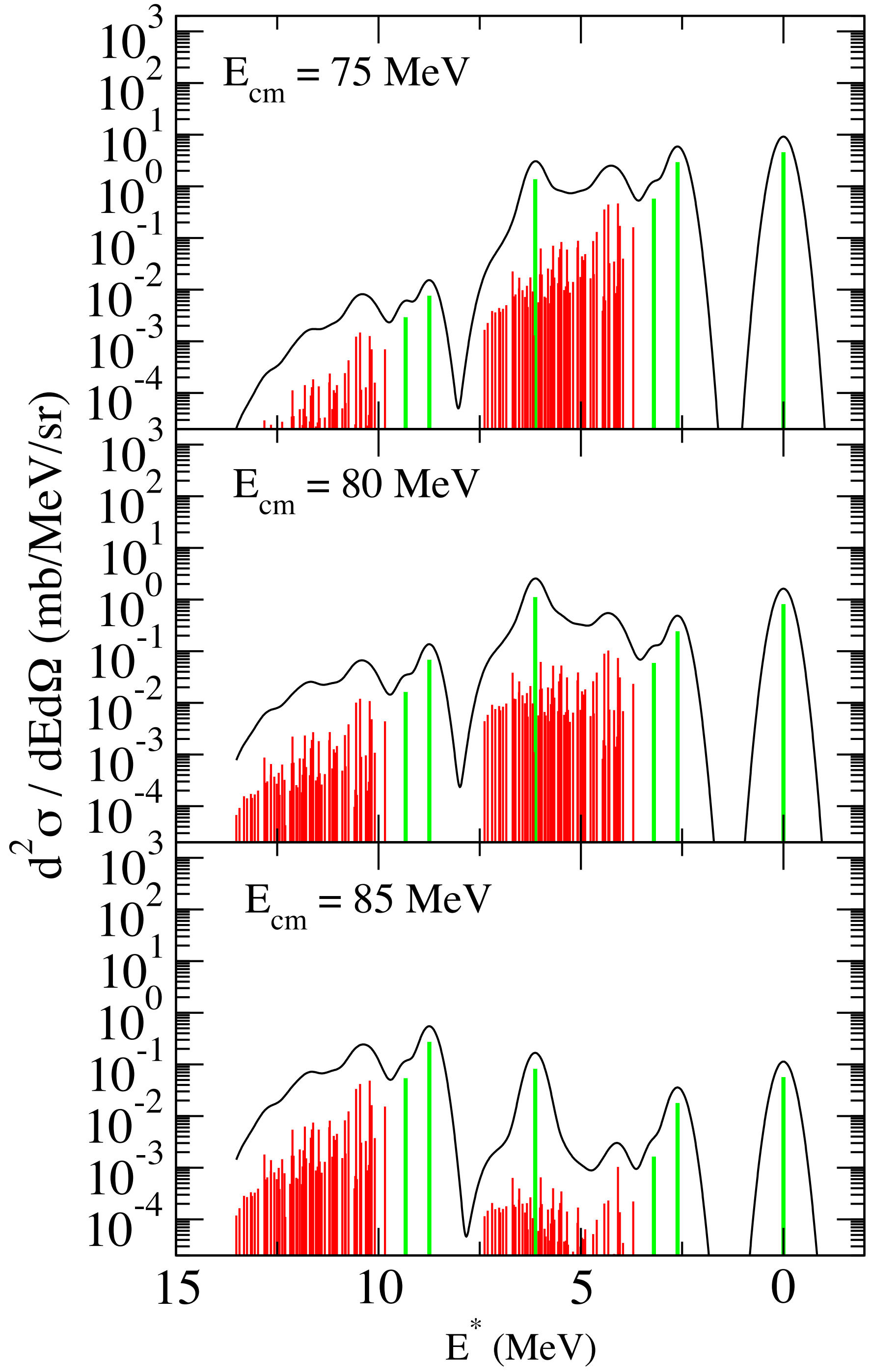
^{16}O + ^{208}Pb

$$F(E^*) = \sum_n f_n \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(E^*-\epsilon_n)^2}{2\sigma^2}}$$

Energy dependence of Q-value distribution ($\theta = 170°$)

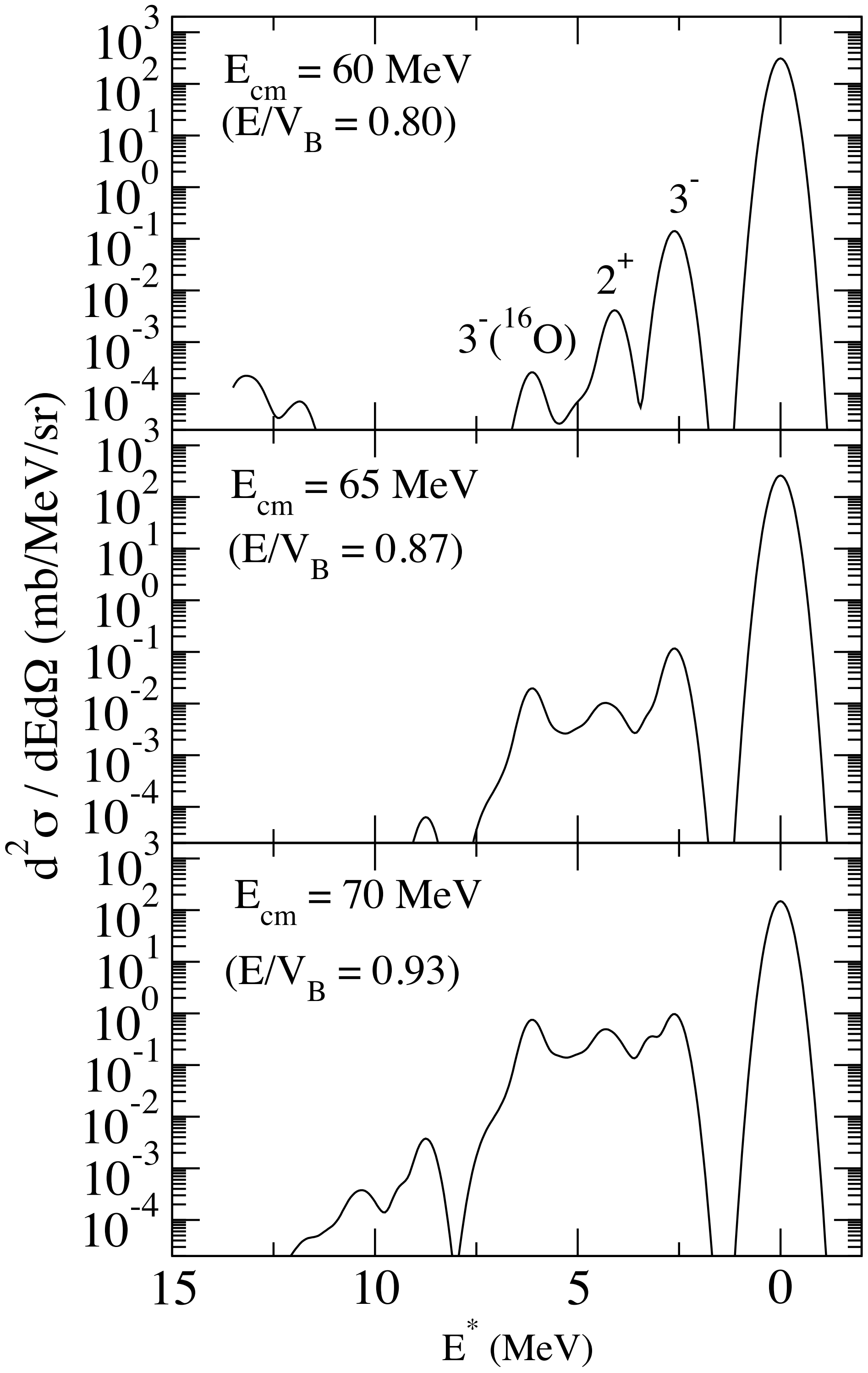
($\sigma = 0.2$ MeV)



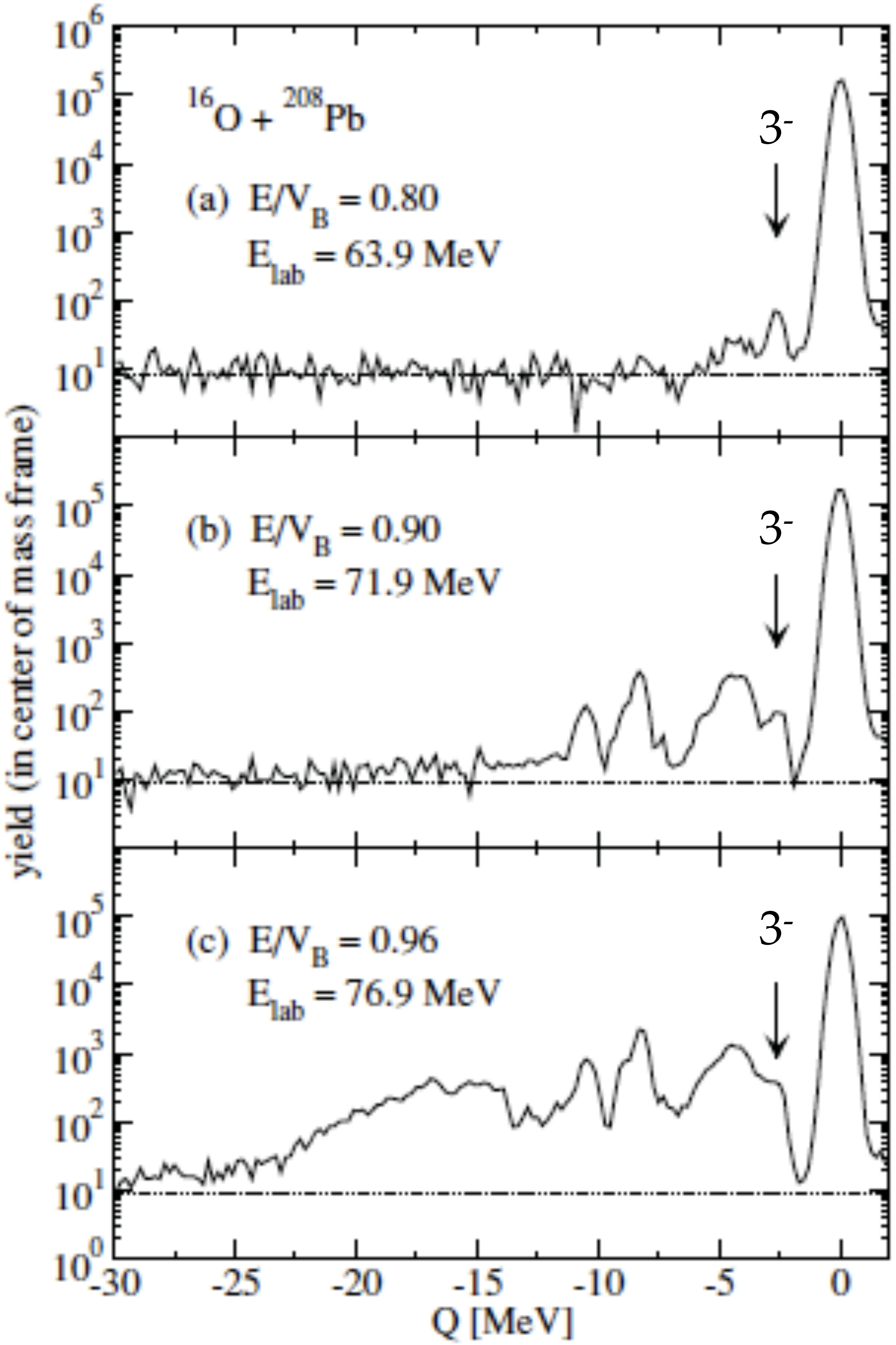


non-collective excitations becomes more and more important as the incident energy increases

$^{16}O + ^{208}Pb$



experiment



M. Ever et al. Phys.Rev.C 78('08)034614

obtained Q-value distributions are consistent with the experimental data

Summary

Low-energy heavy-ion reaction (fusion reaction and quasi-elastic scattering) taking into account non-collective excitations

- ✓ Conventional coupled-channels calculation failed to reproduce quasi-elastic barrier distributions for ^{20}Ne + ^{90,92}Zr
- ✓ Coupled-channels calculation with non-collective excitations is applied to ^{16}O + ^{208}Pb system for fusion reaction and quasi-elastic scattering
- ✓ Non-collective excitations in this calculation do not improve the fusion and quasi-elastic barrier distribution
- ✓ Energy dependence of the Q-value distribution is consistent with experimental data

Future perspectives

- Application to ^{20}Ne + ^{90,92} Zr systems for which nuclear information about the non-collective excitations has not been obtained
- Description of non-collective excitations based on random matrix theory