# Heavy-ion fusion reactions for superheavy elements

Kouichi Hagino
Tohoku University, Sendai, Japan

萩野浩一
東北大学(仙台、日本)

1. H.I. sub-barrier fusion reactions
2. Coupled-channels approach and barrier distributions
3. Application to superheavy elements
4. Hot fusion reactions of a deformed target
5. Summary and discussions

Recent review article:
K. Hagino and N. Takigawa, Prog. Theo. Phys.128 ('12)1061.

# Introduction of Tohoku University and Sendai


Sendai（仙台）:

- ✓ the largest town in the Tohoku region
- ✓ population: about 1 million

city of trees

MIYAGI HISTORY

摄于1906年3月,左第一人为鲁迅,即将离开仙台时与同班同学的合影。

# 历史和鲁迅

## 史迹,鲁迅生活过的地方

约400年前,作为伊达六十万石的城邑而发展起来,
与中国著名文学家鲁迅有深缘的仙台,
还有受伊达政宗藩主之命支仓常长一行
罗马旅行的出发地石卷。
向您介绍宫城县各地的历史风情。

回忆仙台时代生活的段落。写于1926年,引自《朝花夕拾》。

鲁迅最初寄宿的"佐藤屋"旧址,现在的米袋一丁目。

藤野嚴九郎教授
藤野严九郎教授

藤野教授

· 鲁迅和东北大学

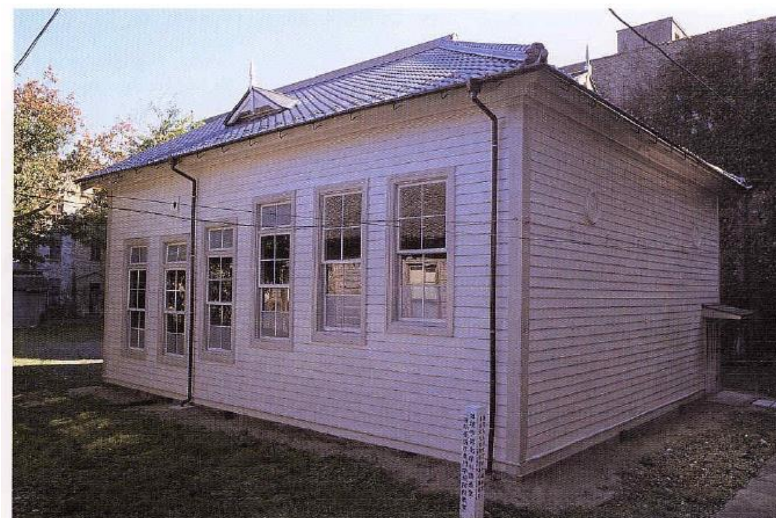
東北大学

鲁迅(原名:周树人)1881年9月25日出生于清朝(现在的中华人民共和国)的长江下游浙江省绍兴县。1902年1月毕业南京的江南陆师学堂附属矿务铁路学堂之后,同年4月作为清朝留学生来我国留学,先就读于东京的弘文学院普通速成科。在此学院鲁迅学习了日语和基础科目。

应鲁迅的要求,1904年5月20日当时的清朝·杨公使向仙台医学专门学校(现在的东北大学医学部)提出了就鲁迅的入学要求进行妥善处理的照会信。

仙台医学专门学校对此以文部省有关入学规则为依据进行探讨之后,决定允许免试入学。并于5月23日给杨公使寄送了入学许可通知书。

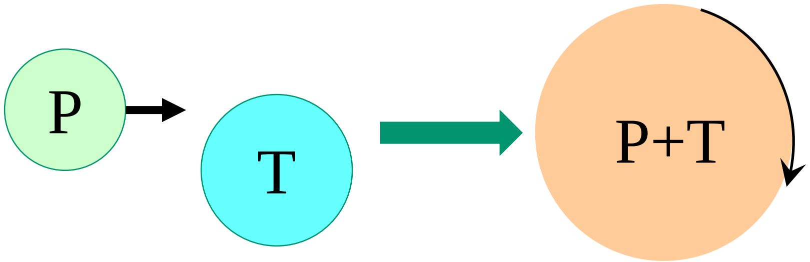
同年9月,鲁迅进入了仙台医学专门学校。



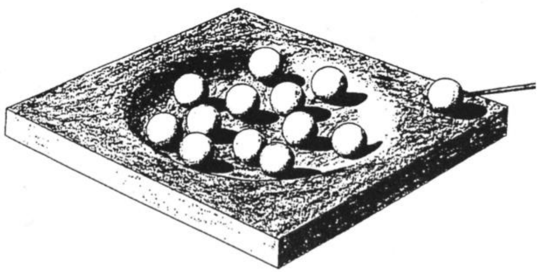
鲁迅が学んだ仙台医学専門学校階段教室外景
(鲁迅曾就读的仙台医学专门学校教学楼外景)

鲁迅阶梯教室

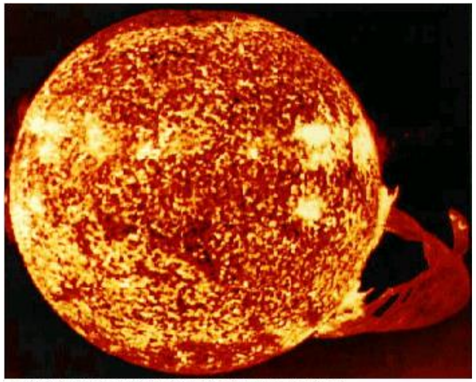
# Fusion reactions: compound nucleus formation



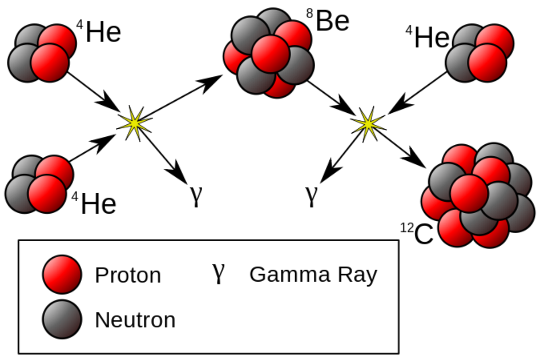

compound nucleus



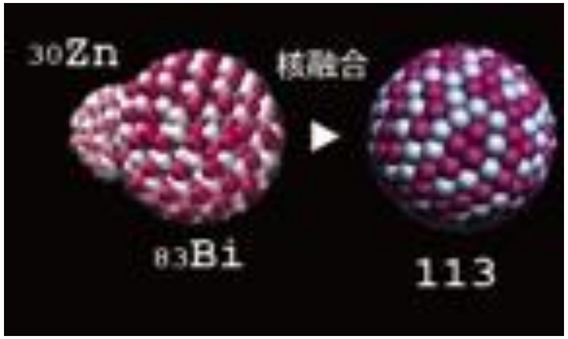
cf. Bohr '36



energy production in stars




nucleosynthesis

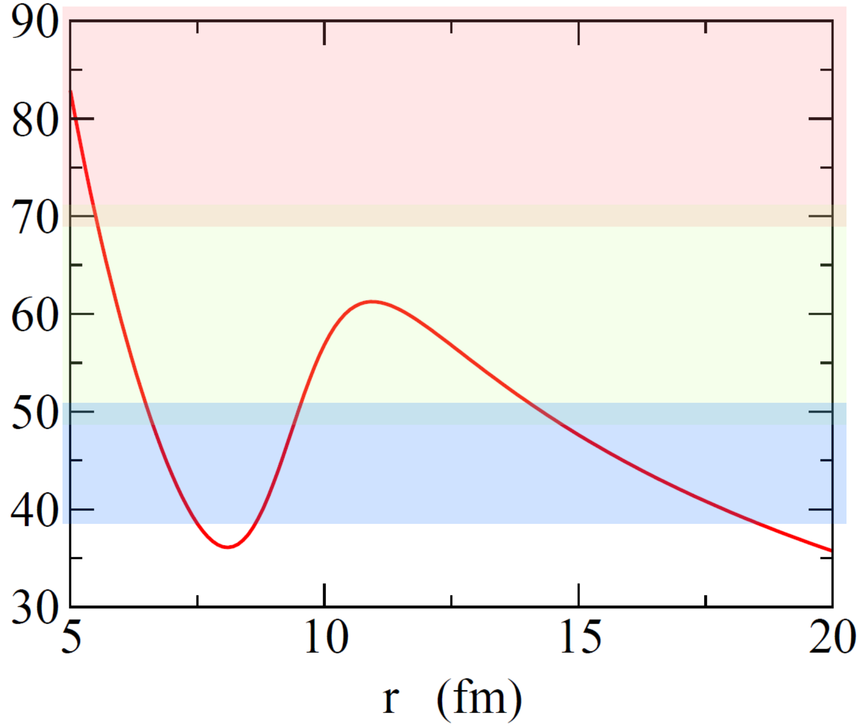



superheavy elements

Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

# Fusion reactions: compound nucleus formation




fusion reactions
in the sub-barrier energy region
$(|E - V_b| \lesssim 10\text{MeV})$

1. Coulomb force : long range, repulsive
2. Nuclear force : short range, attractive

⇒ Coulomb barrier

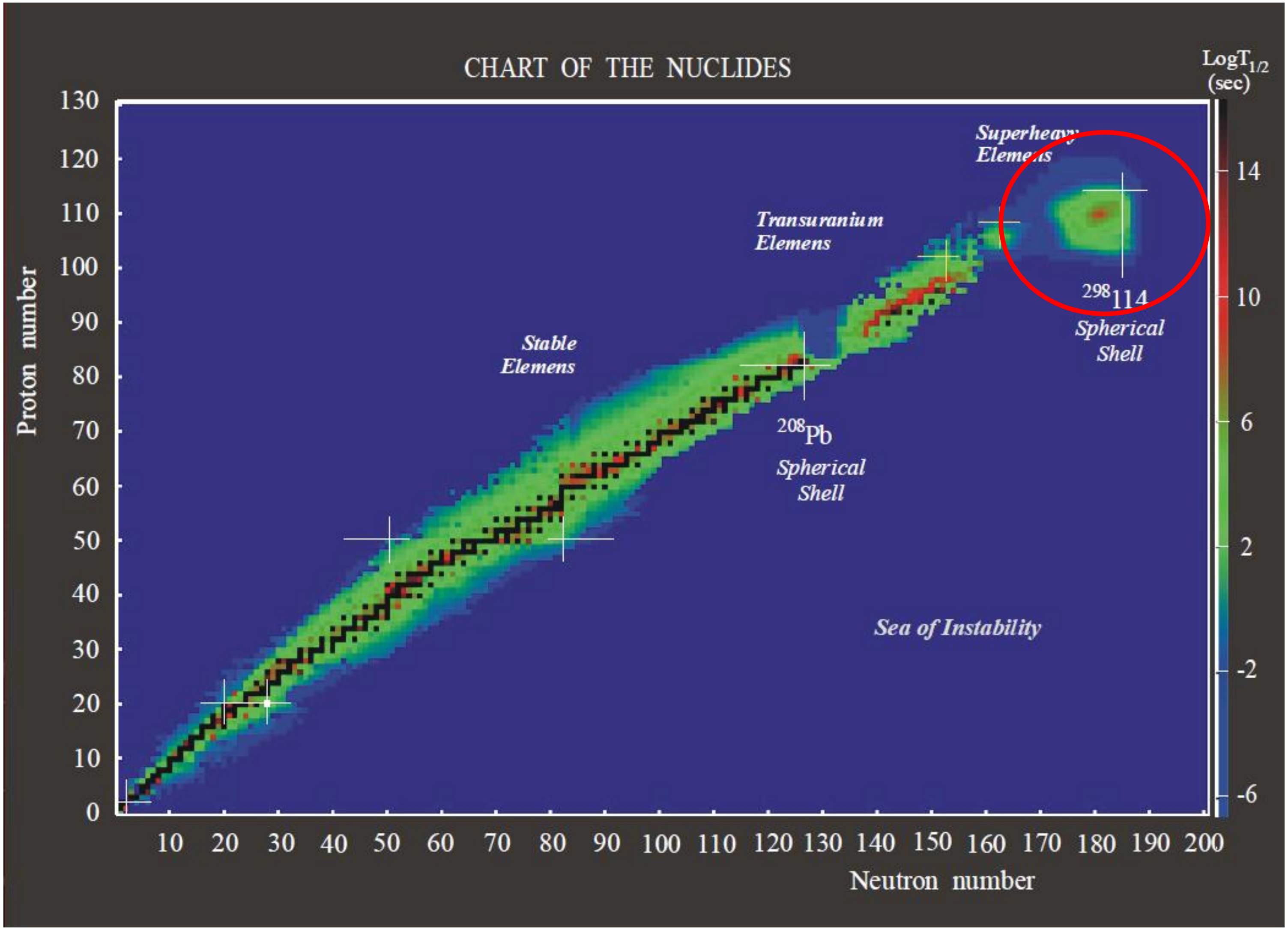
Why sub-barrier fusion?

two obvious reasons:

i) Superheavy elements
ii) Nuclear Astrophysics

# Fusion reactions for SHE

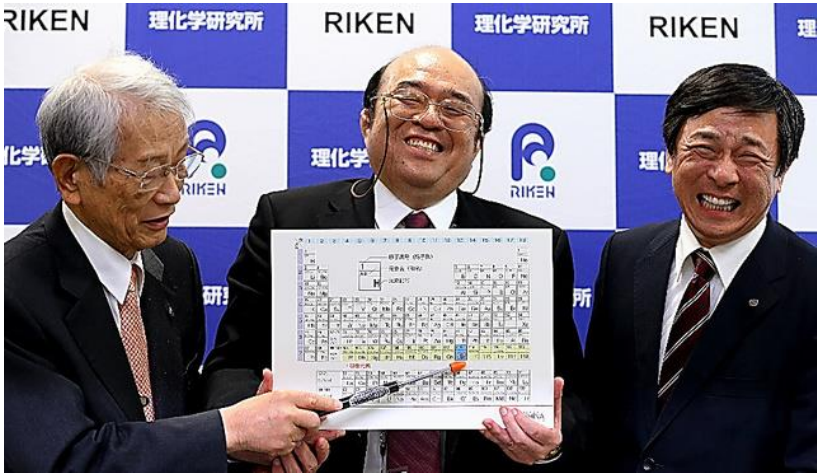
the island of stability



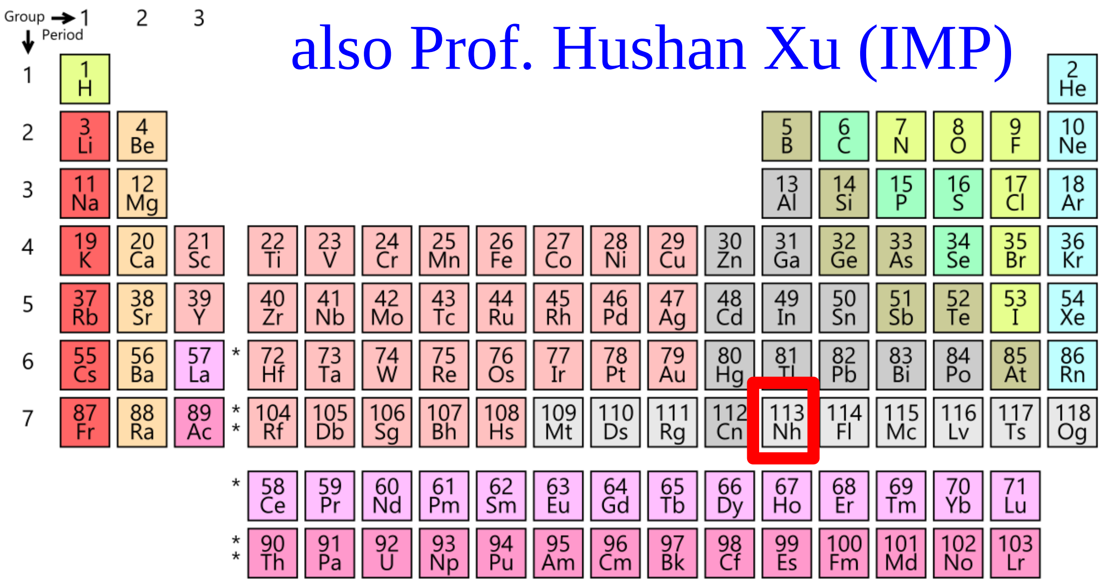
# Fusion reactions for SHE

## the element 113: Nh


November, 2016

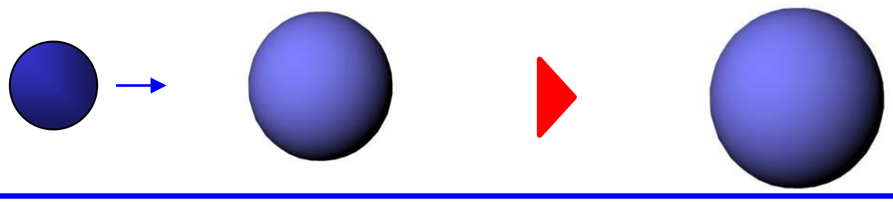



also Prof. Hushan Xu (IMP)




Wikipedia

$^{70}_{30}$Zn $^{209}_{83}$Bi $^{279}_{113}$Nh*



Heavy-ion fusion reaction

# Why sub-barrier fusion?

two obvious reasons:

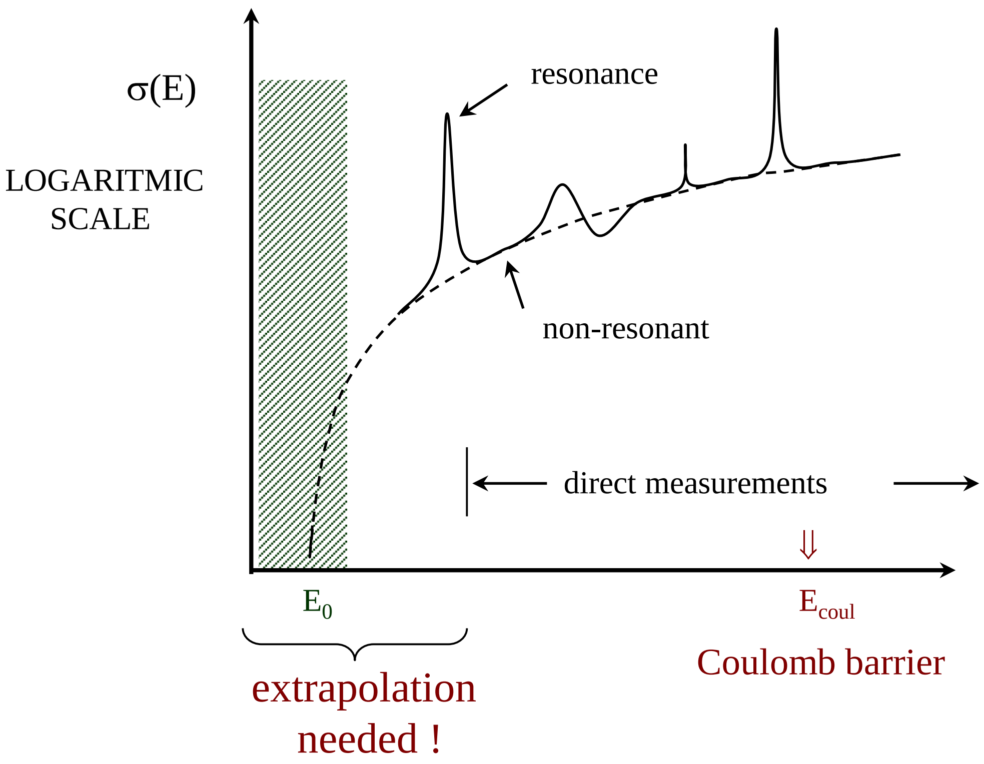
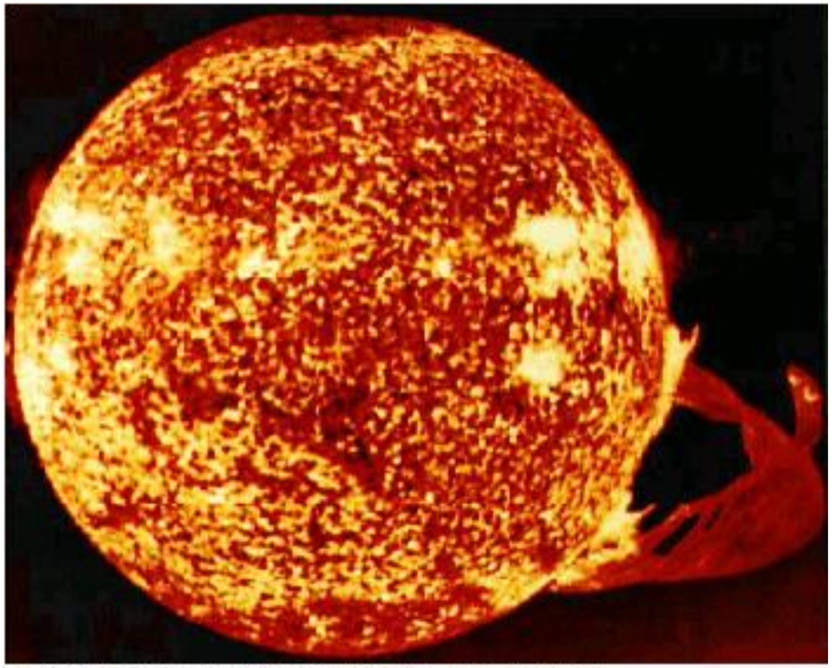



figure: M. Aliotta



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

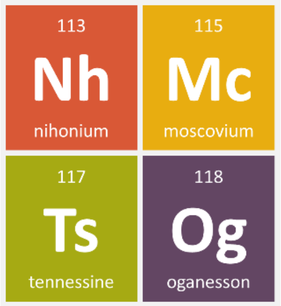
nuclear astrophysics
(nuclear fusion in stars)

cf. extrapolation of data

# Why sub-barrier fusion?

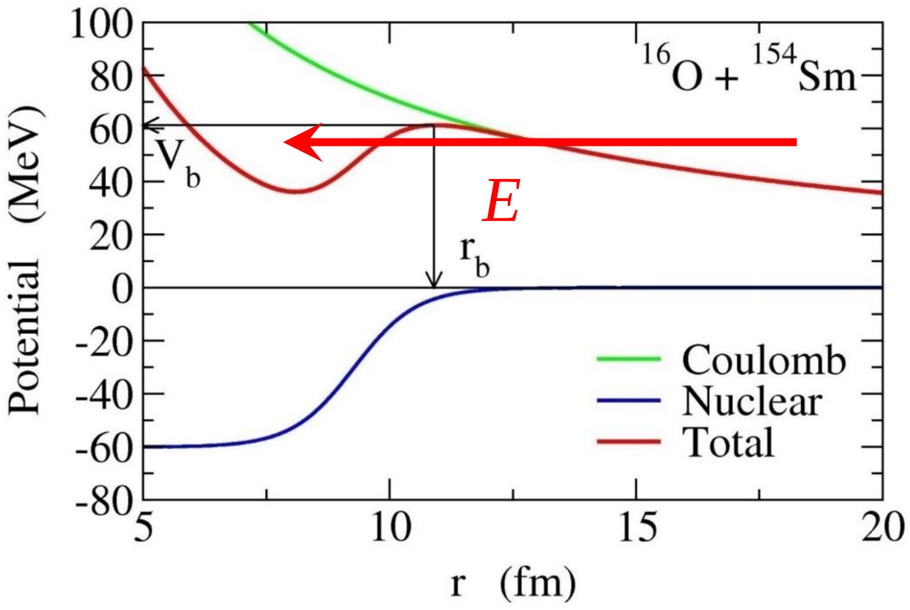
Two obvious reasons:

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




Other reasons:

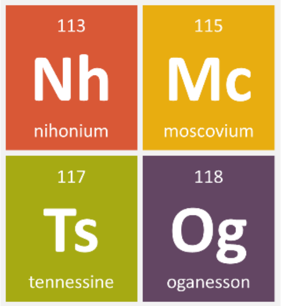
◆ **many-particle tunneling**



# Why sub-barrier fusion?

Two obvious reasons:

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




Other reasons:

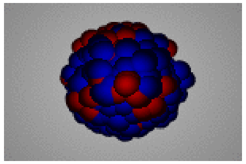
◆ reaction mechanism

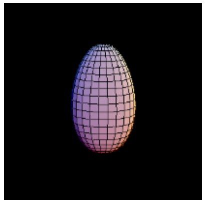
**strong interplay between reaction and nuclear structure**

cf. high $E$ reactions: much simpler reaction mechanism

◆ **many-particle tunneling**

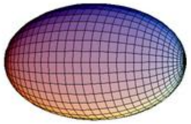
✓ many types of intrinsic degrees of freedom

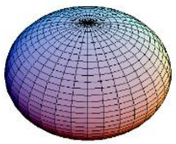




✓ energy dependence of tunneling probability

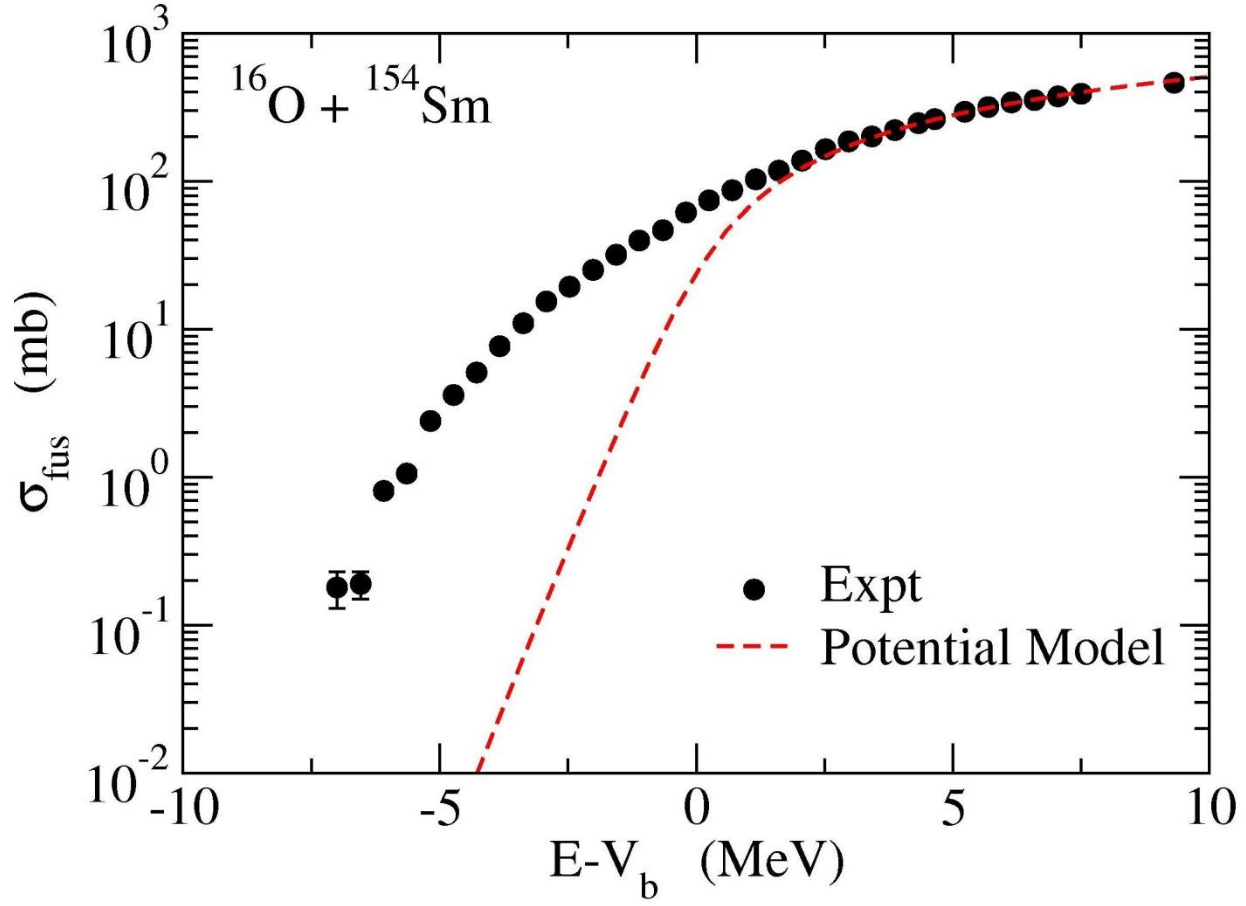
cf. alpha decay: fixed energy





H.I. fusion reaction = an ideal playground to study quantum tunneling with many degrees of freedom

# Discovery of large sub-barrier enhancement of $\sigma_{fus}$

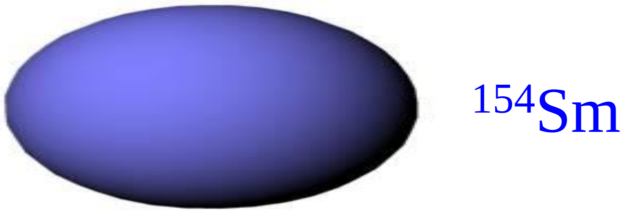


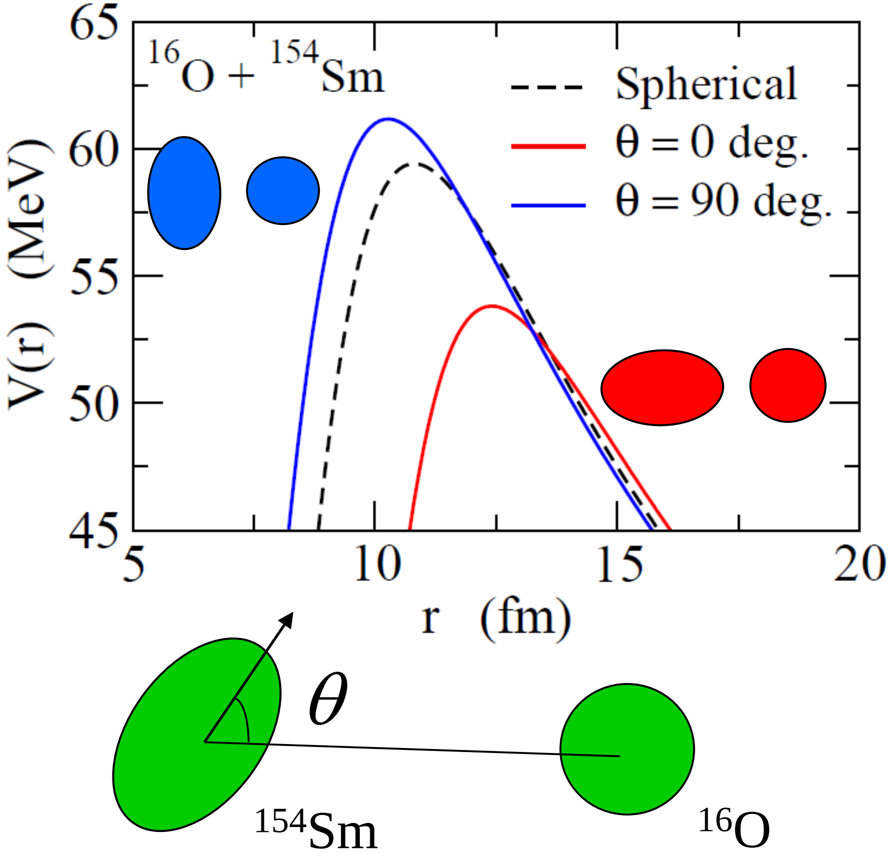

potential model: $V(r)$ + absorption

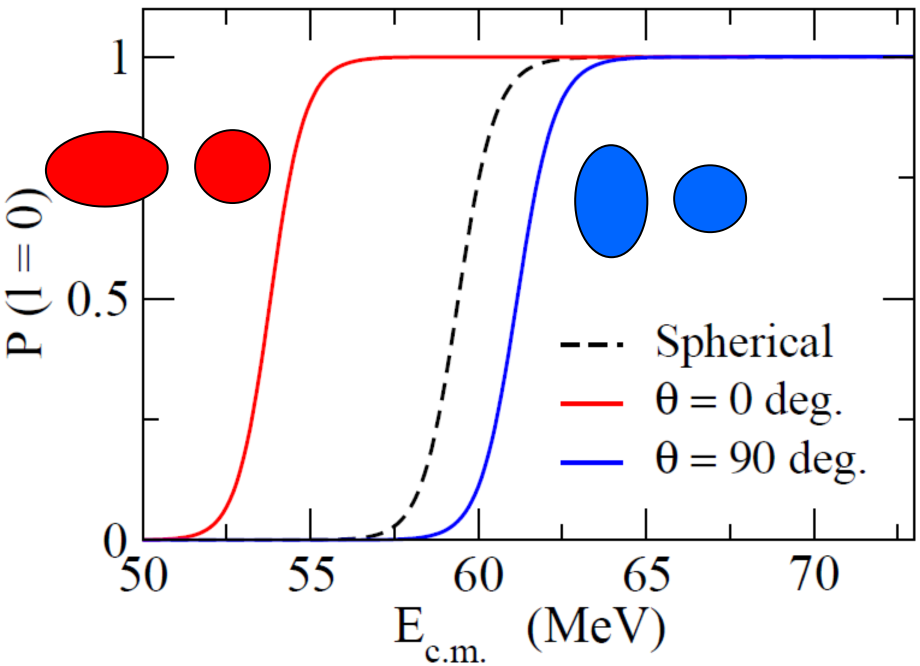
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

# Effects of nuclear deformation

$^{154}$Sm : a typical deformed nucleus



# Effects of nuclear deformation

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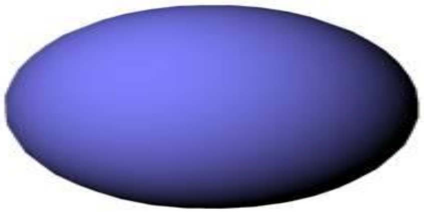
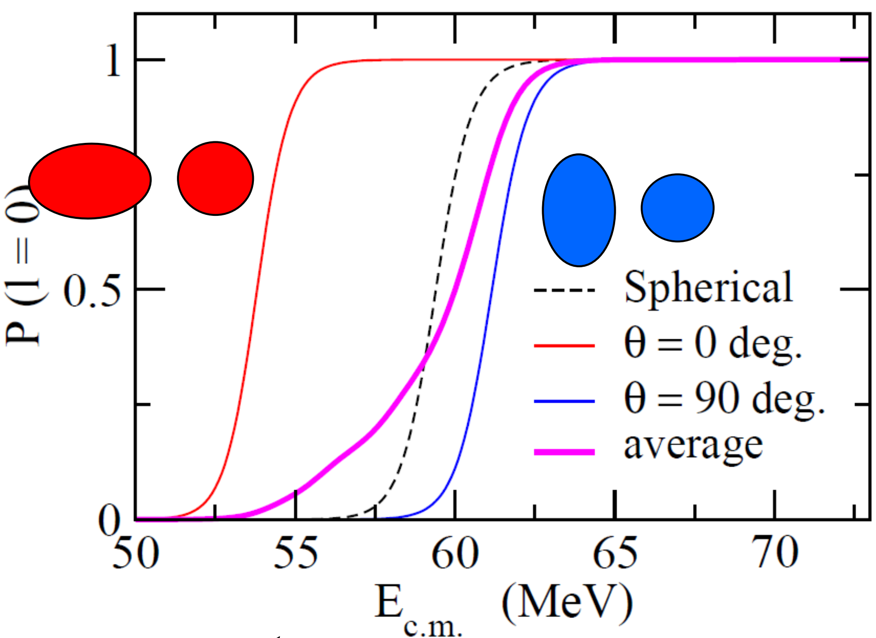
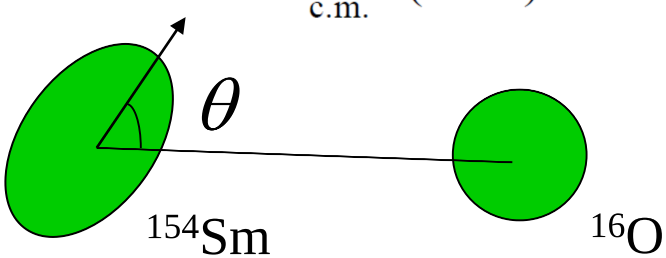
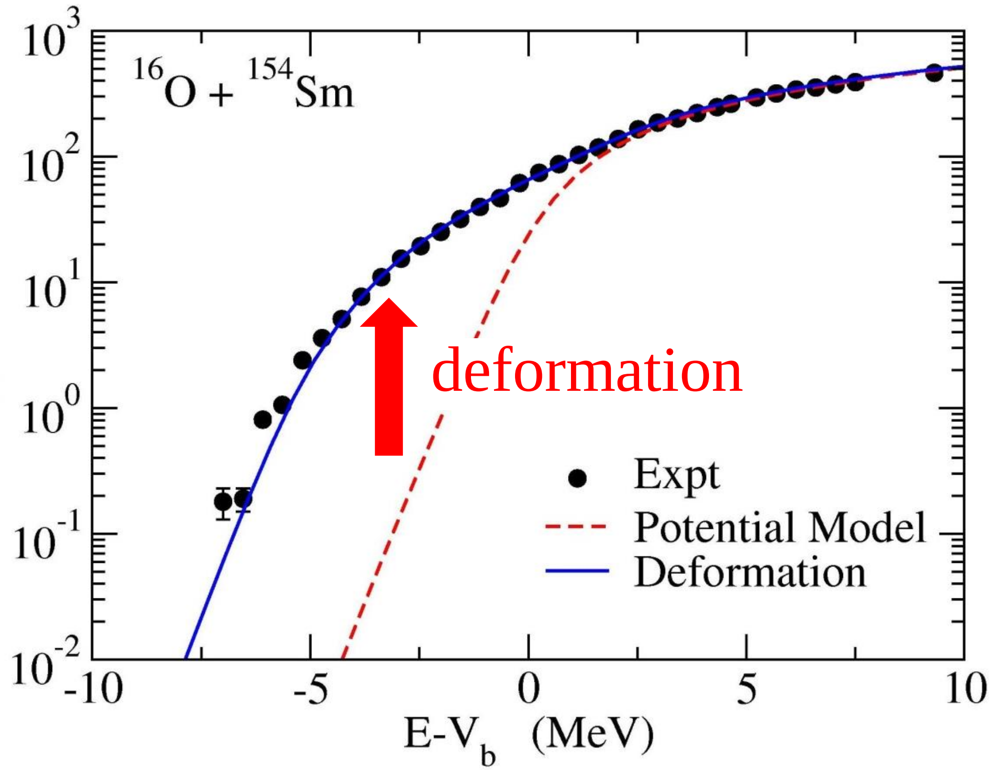


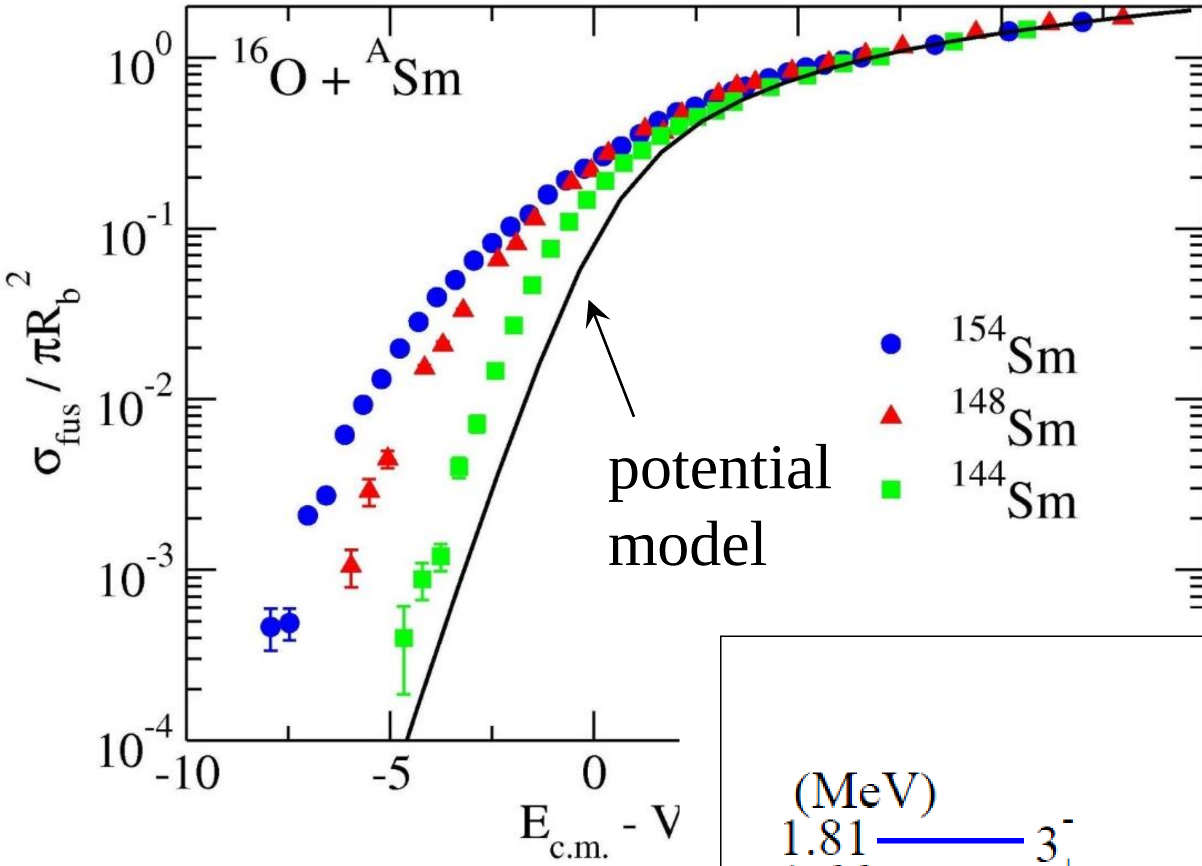



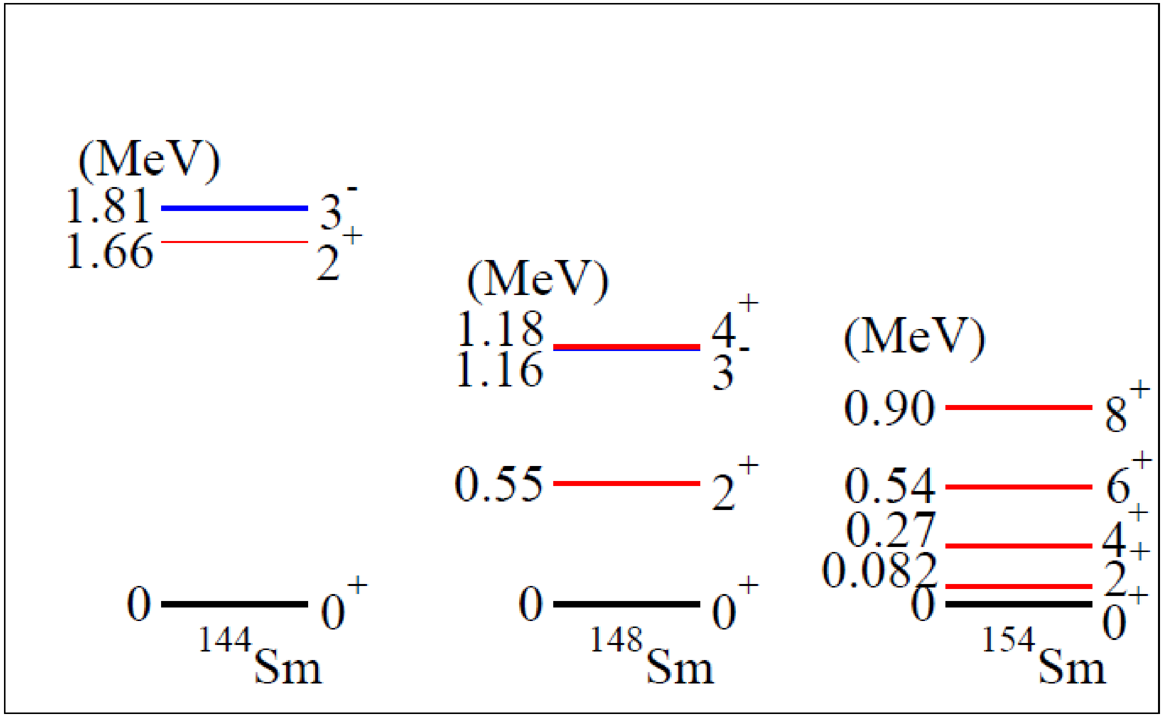

$$\sigma_{\rm fus}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm fus}(E;\theta)$$




Fusion: strong interplay between nuclear structure and reaction



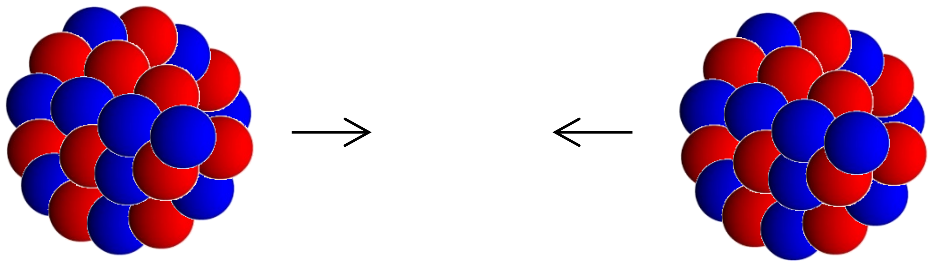

enhancement of fusion cross sections
: a general phenomenon




strong correlation with nuclear spectrum
→ coupling assisted tunneling

# Coupled-channels method: a quantal scattering theory with excitations

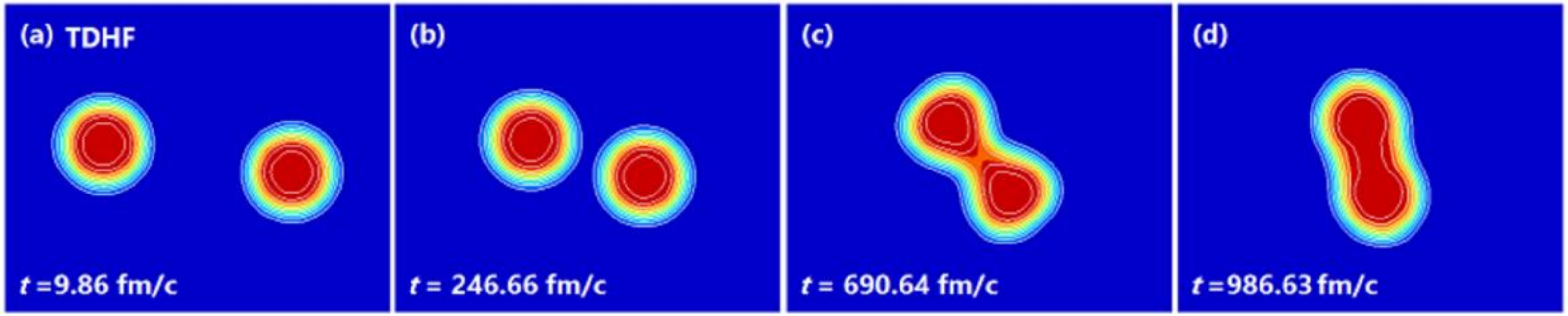
many-body problem



still very challenging

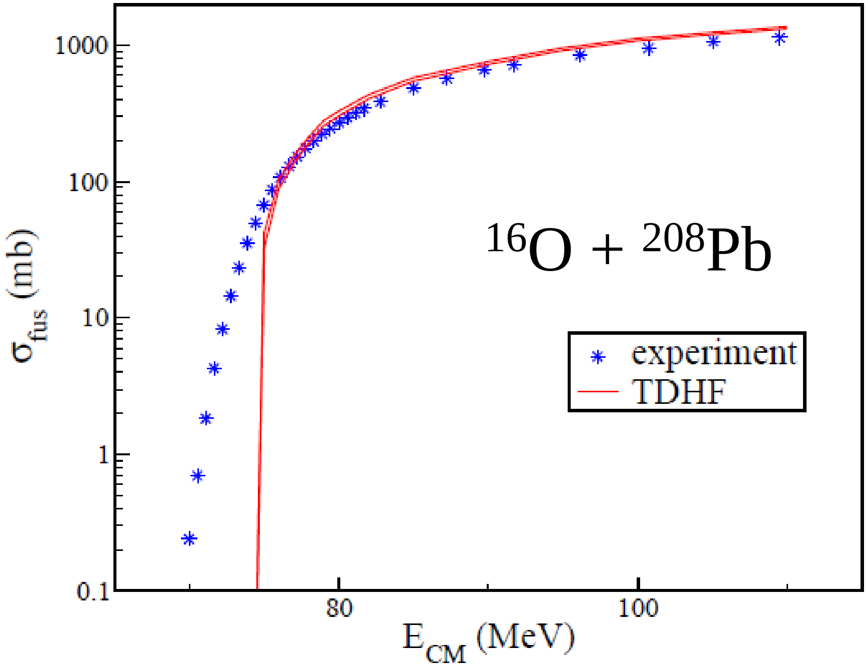
# TDHF simulation

TDHF = Time Dependent Hartree-Fock




S. Ebata, T. Nakatsukasa, JPC Conf. Proc. 6 ('15) 020056

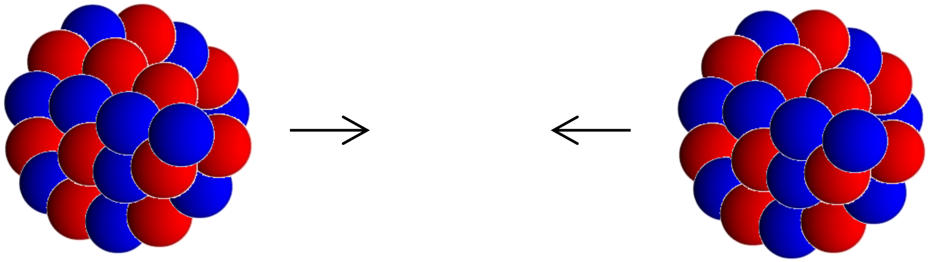
"ab-initio", but no tunneling




C. Simenel,
EPJA48 ('12) 152

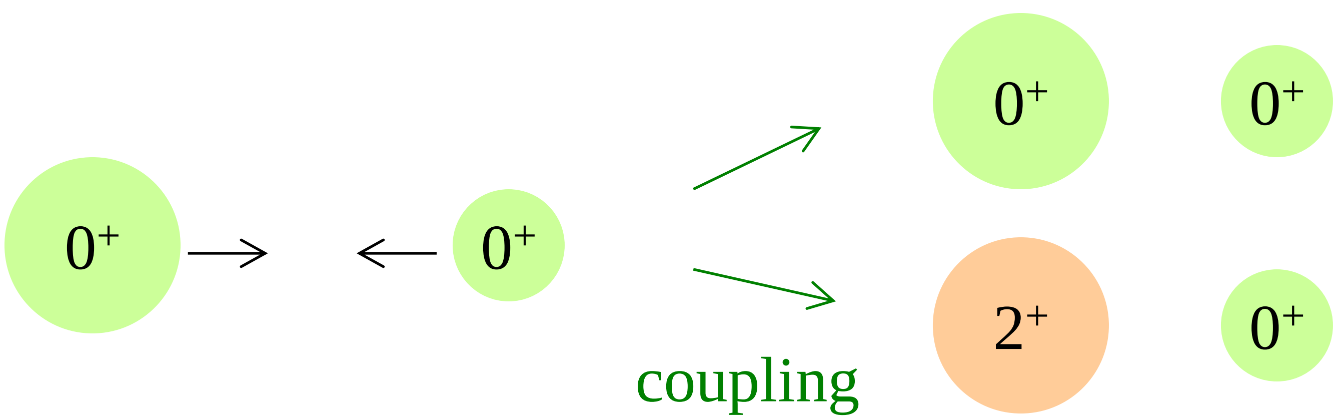
# Coupled-channels method: a quantal scattering theory with excitations

many-body problem



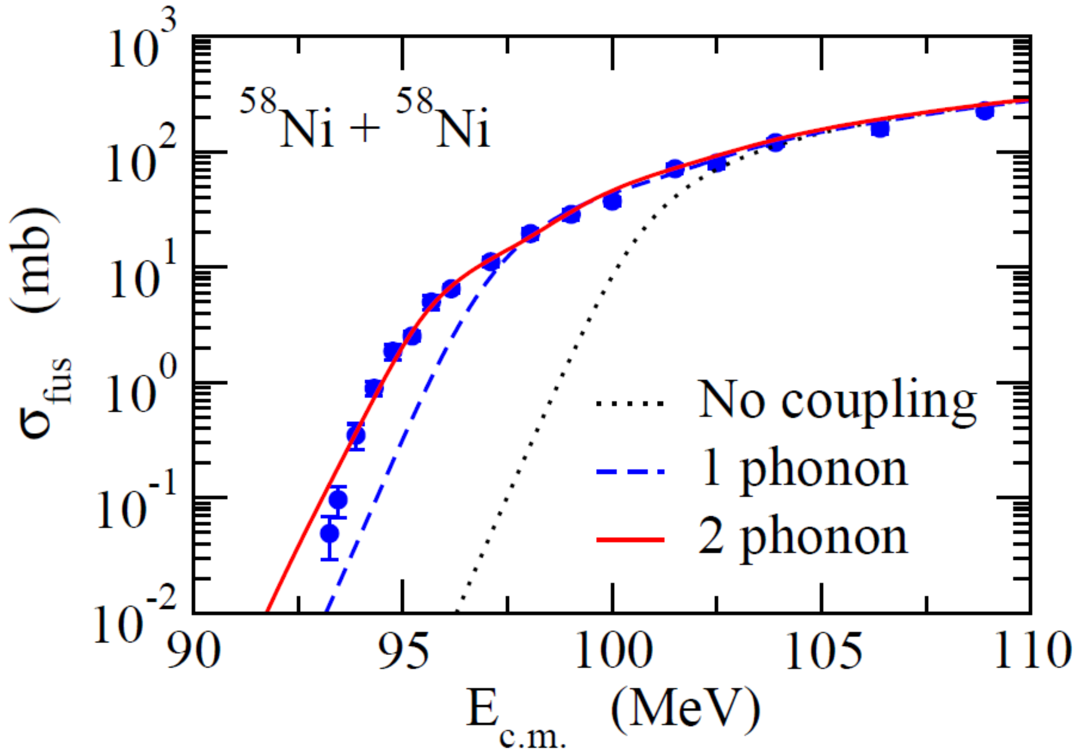
still very challenging

two-body problem, but with excitations
(coupled-channels approach)

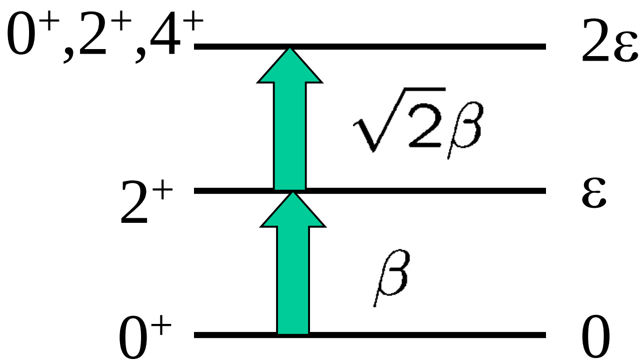



scattering theory with excitations

# An example of coupled-channels calculation




simple harmonic oscillator

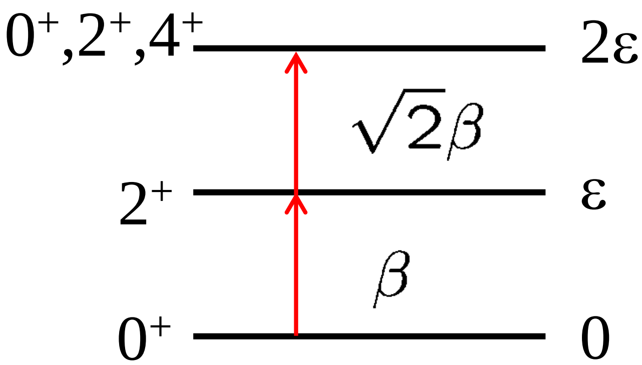


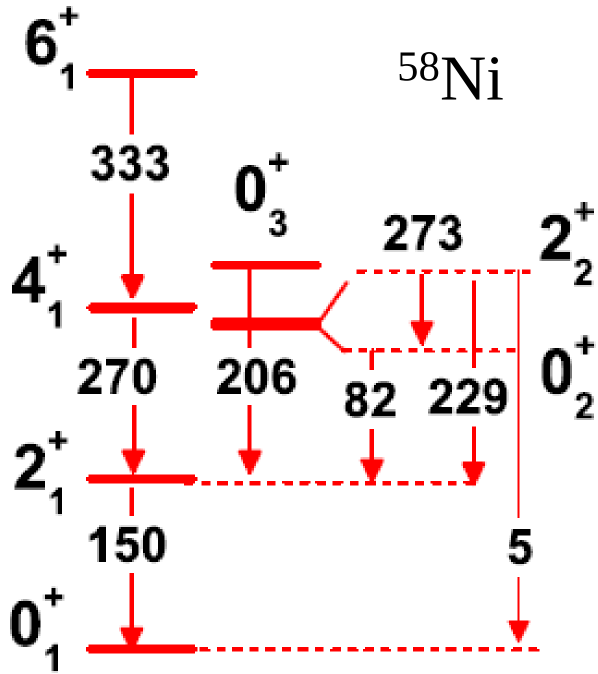
# Further development: semi-microscopic modelling

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

Coupled-channels
+ microscopic nuclear structure
  calculations
  (GCM, Shell Model, IBM…..)

simple harmonic
oscillator

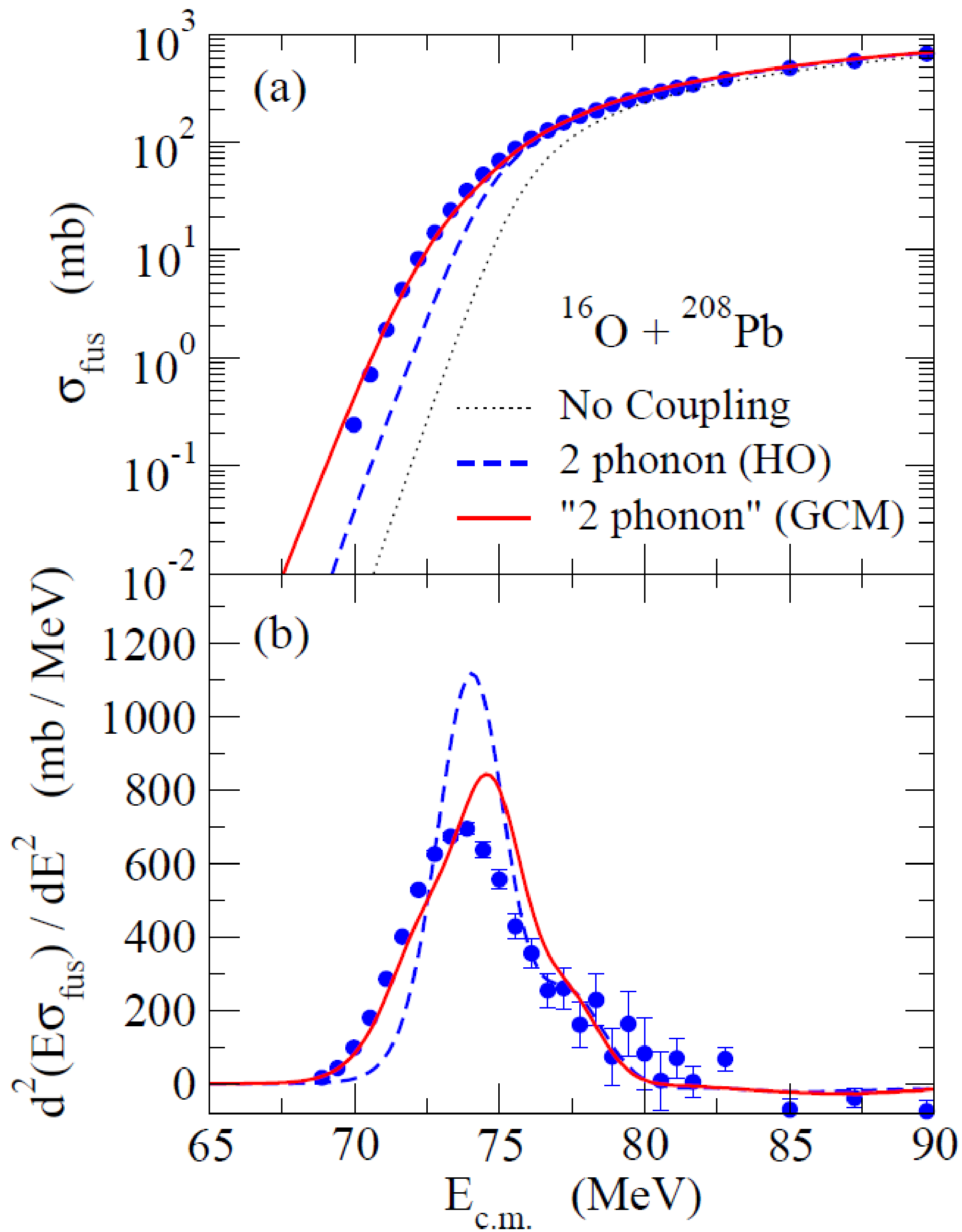


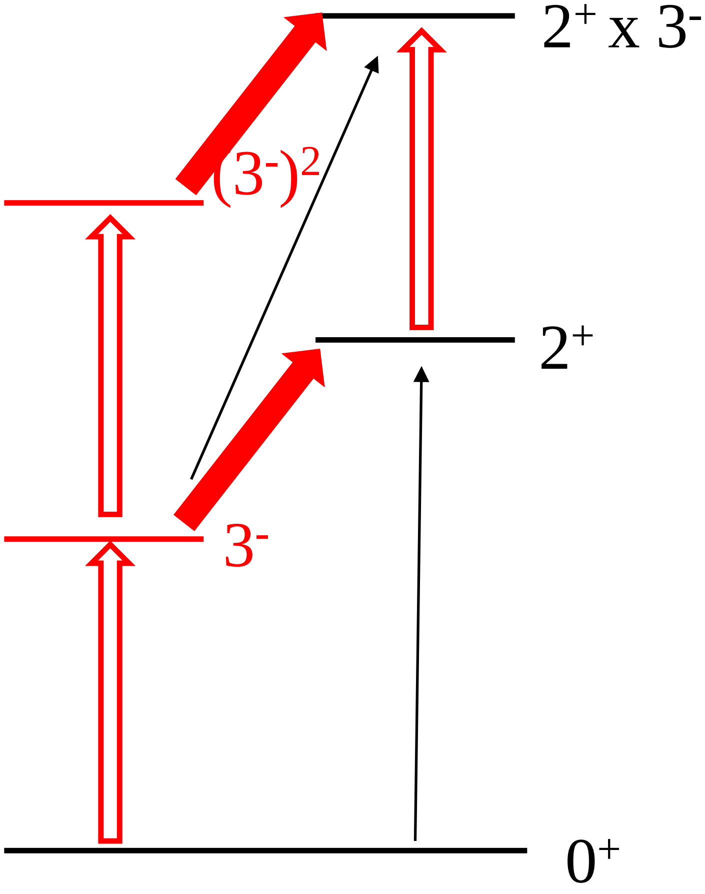




relativistic MF + GCM

anharmonicity of phonon spectra

# CCFULL with RMF+GCM



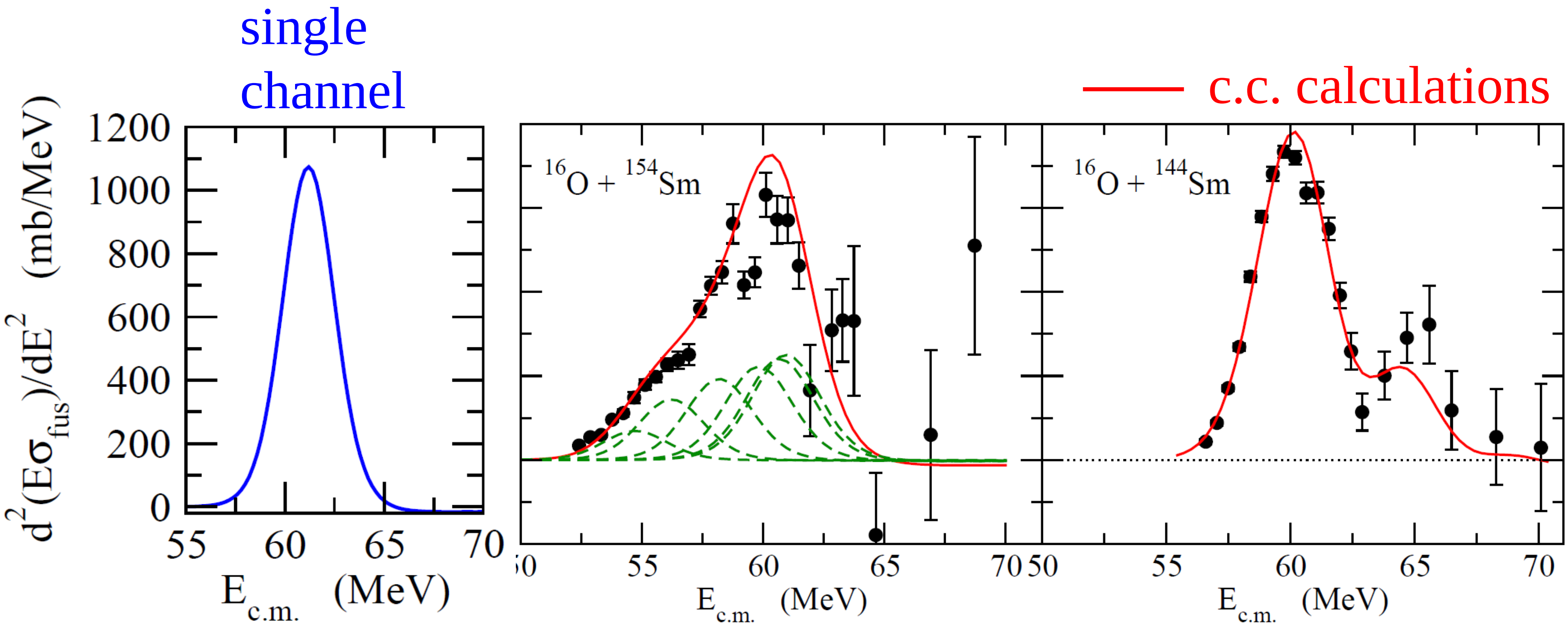

J.M. Yao and K.H., PRC94 (‘16) 11303(R)

# 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)]

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




K.H., N. Takigawa, PTP128 (‘12) 1061

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

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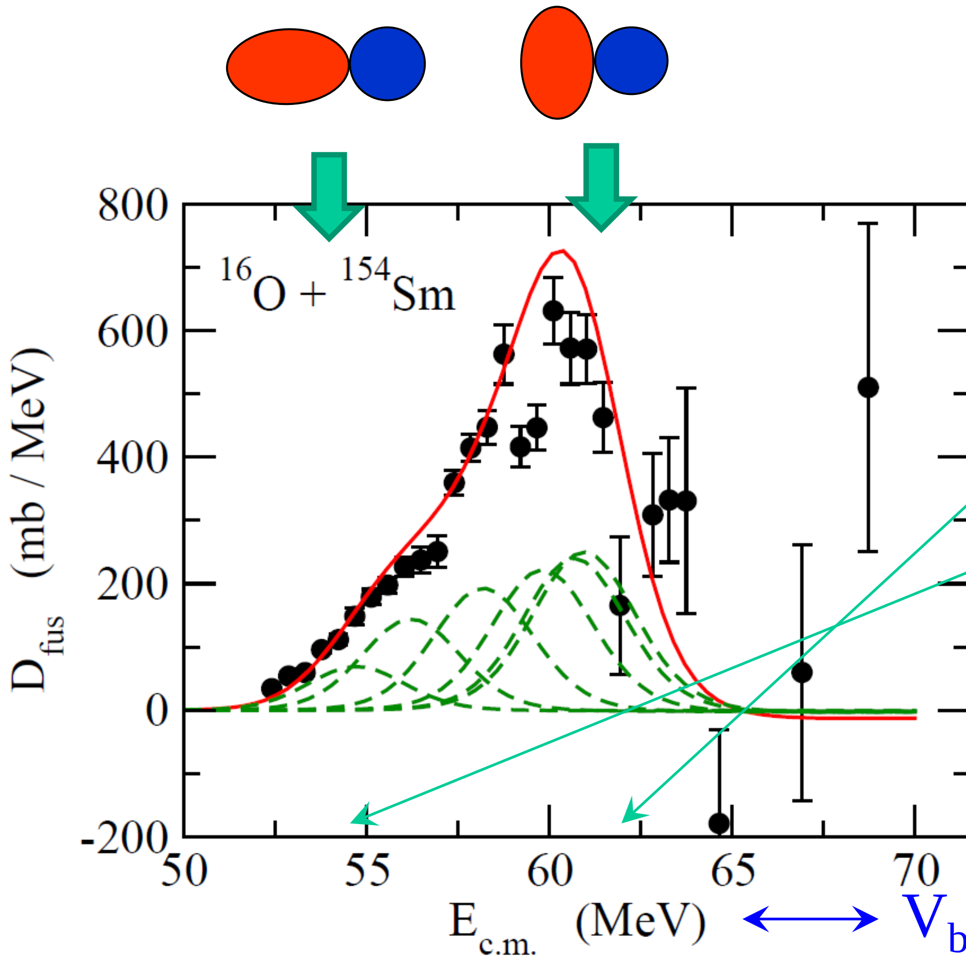
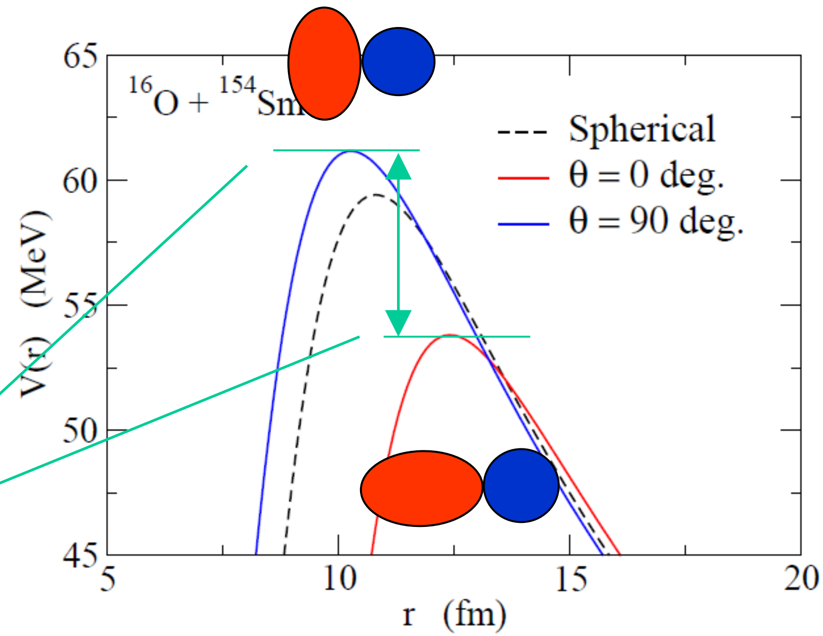


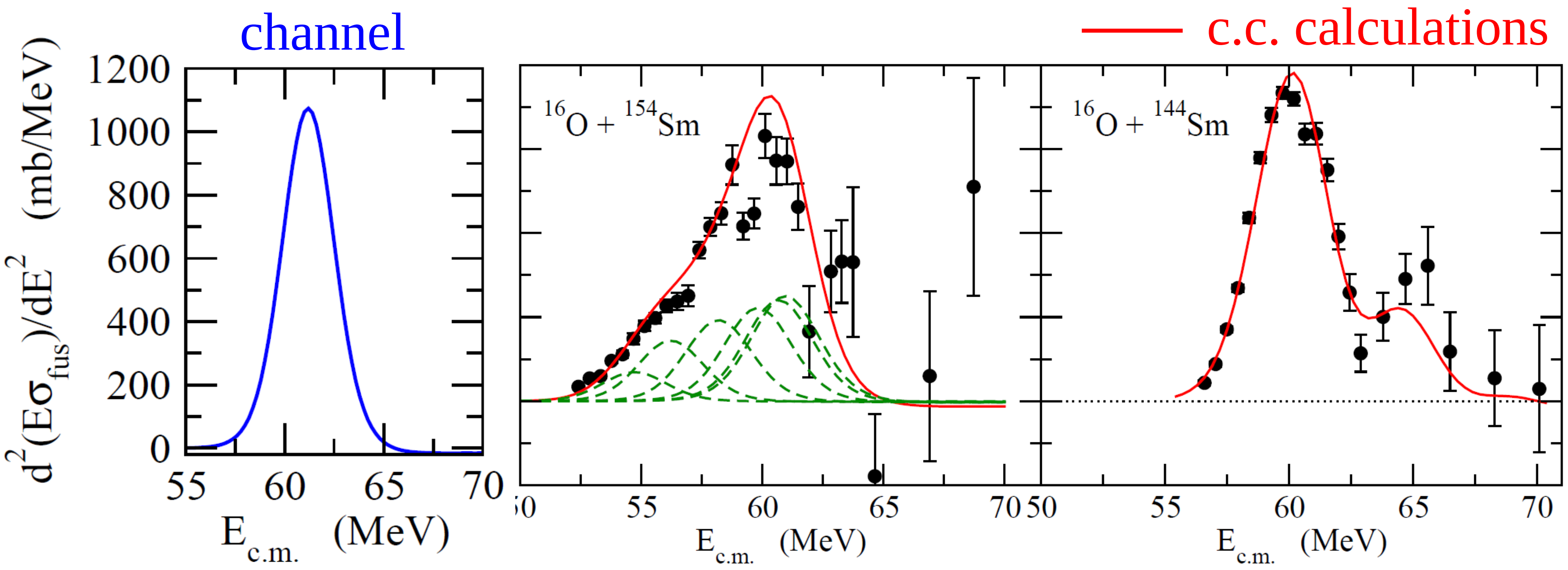

Data: J.R. Leigh et al.,
PRC52 ('95) 3151

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

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

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

single channel




a nice tool to understand the reaction dynamics

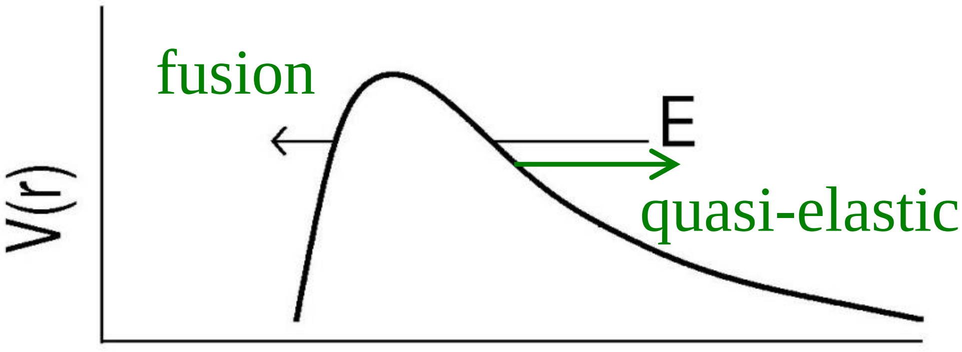
K.H., N. Takigawa, PTP128 ('12) 1061

# Recent application to SHE : Quasi-elastic B.D.

hot fusion reactions

$^{48}$Ca + actinide target → SHE

= deformation ⇒ reaction dynamics with barrier distributions?




$$P + R = 1$$

Quasi-elastic scattering
: reflected flux at the barrier

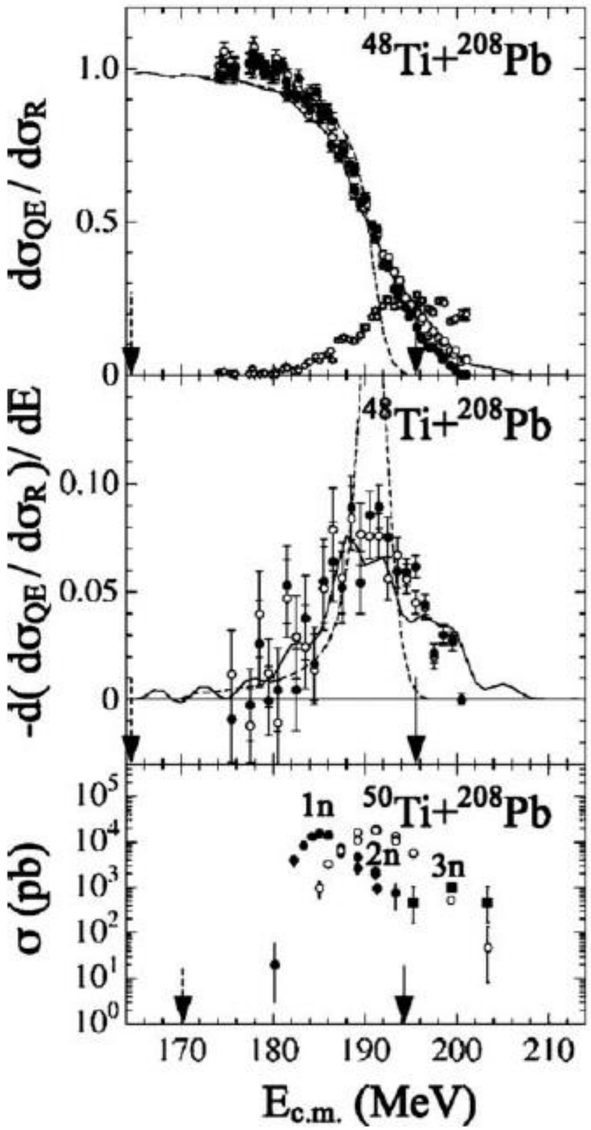
- a sum of elastic, inelastic, and transfer
- easier to measure than capture

Quasi-elastic barrier distribution

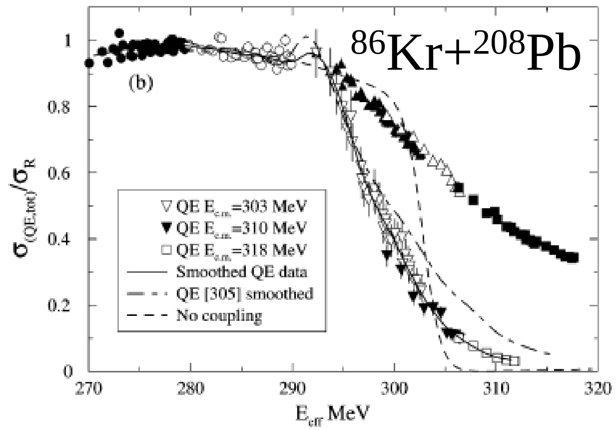
$$D_{\rm qel}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

H. Timmers et al., NPA584('95)190
K.H. and N. Rowley, PRC69('04)054610

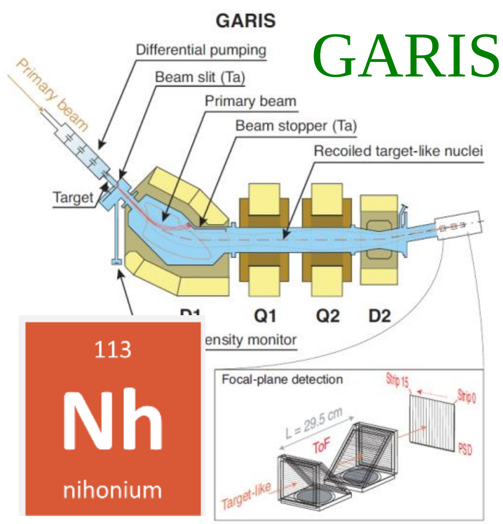
# previous attempts



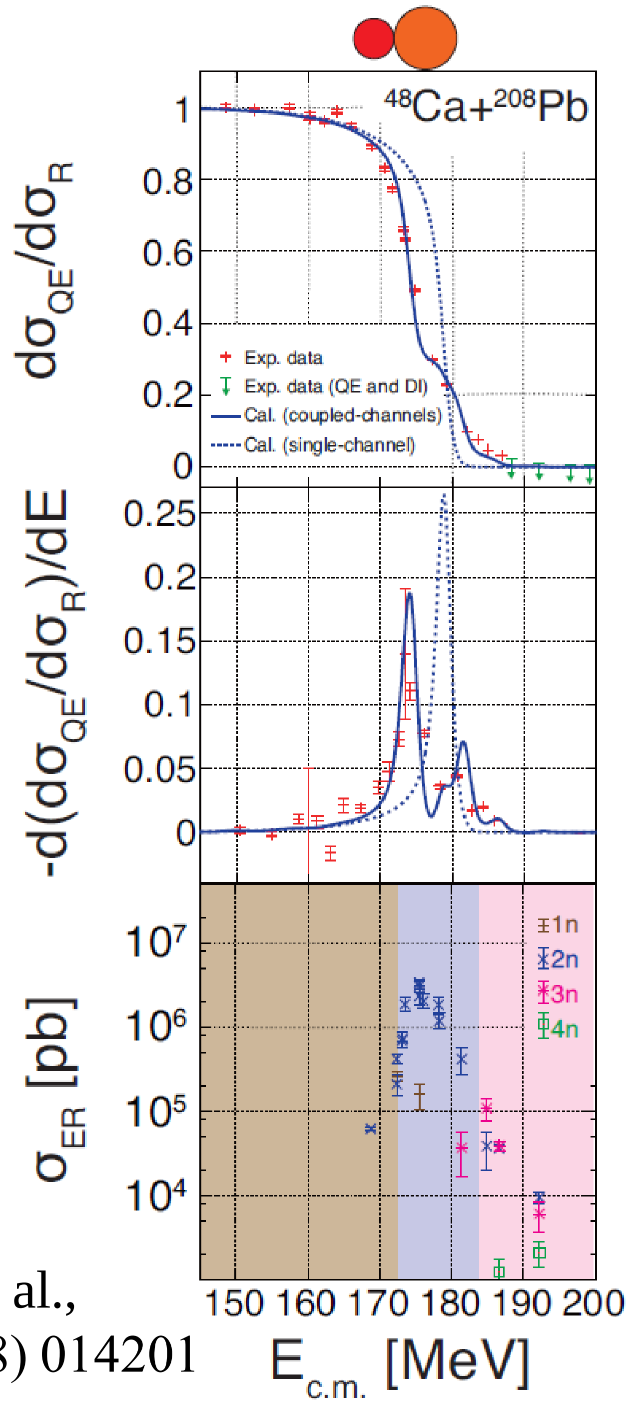

S. Mitsuoka et al.,
PRL99 (‘07) 182701




S.S. Ntshangase et al.,
PLB651 (‘07) 27




GARIS



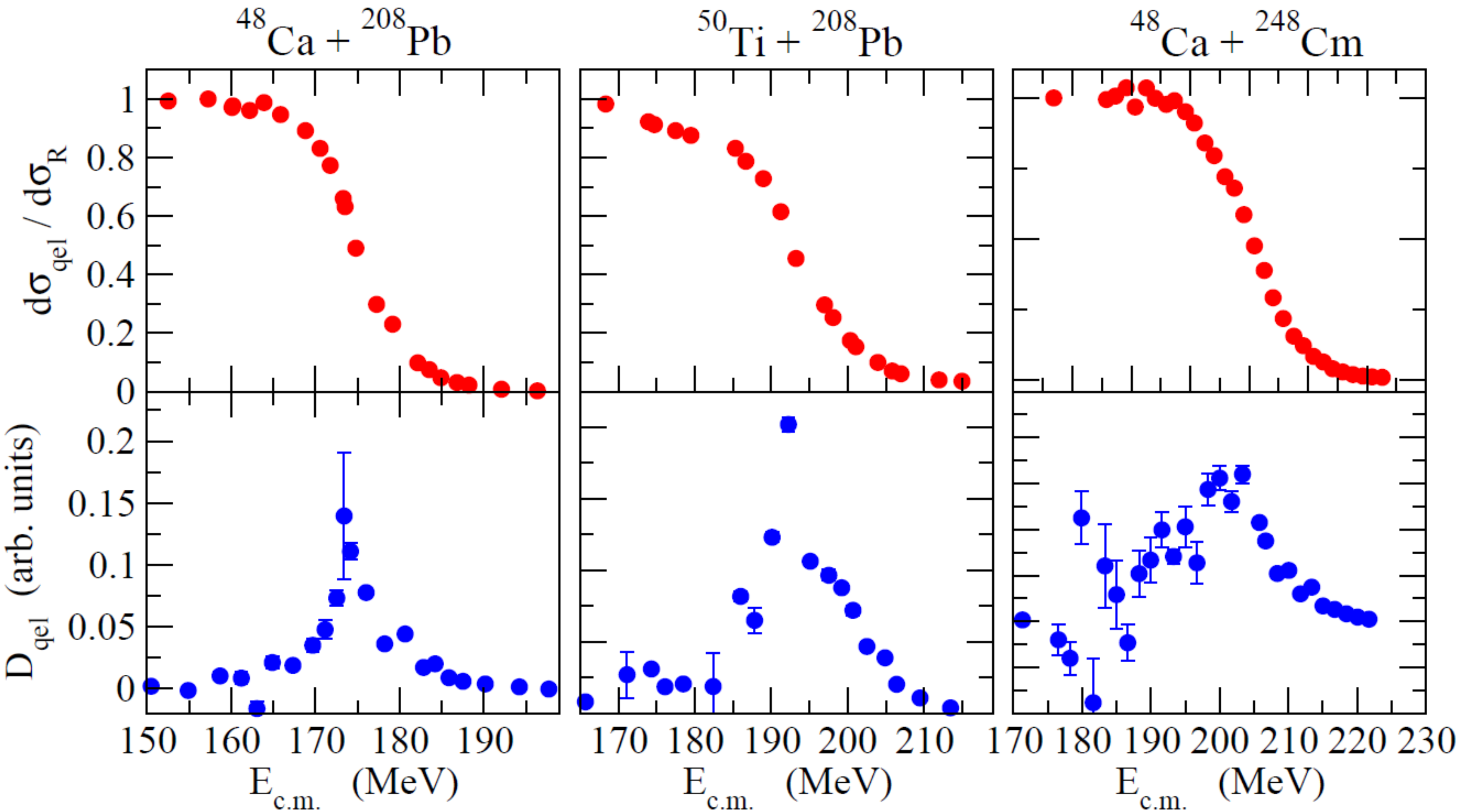

T. Tanaka et al.,
JPSJ 87 (‘18) 014201

# Measurements of barrier distributions with GARIS

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

K.H. and N. Rowley, PRC69 ('04) 054610

T. Tanaka et al.,
JPSJ 87 ('18) 014201.



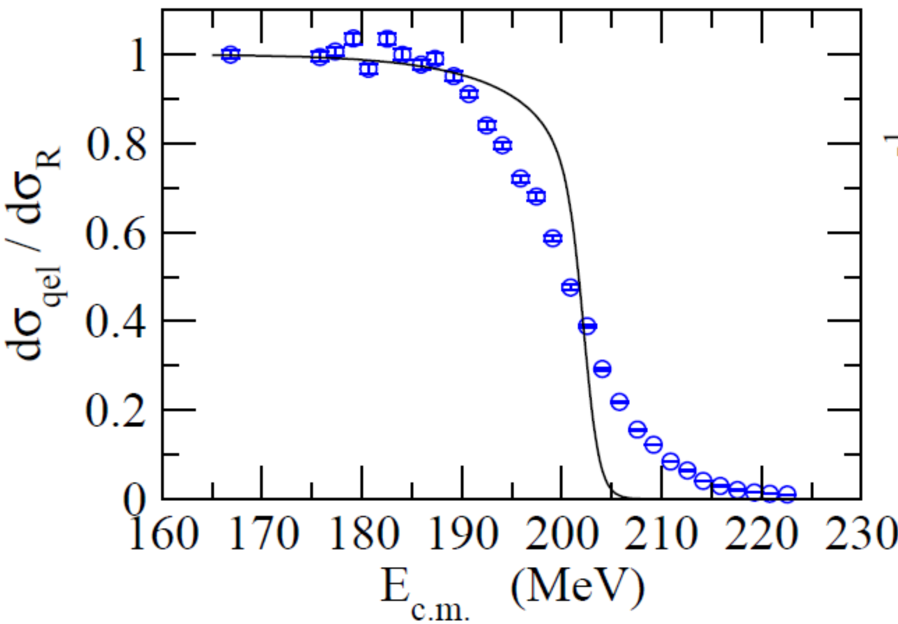
# Analysis for a hot fusion reaction $^{48}Ca + ^{248}Cm$

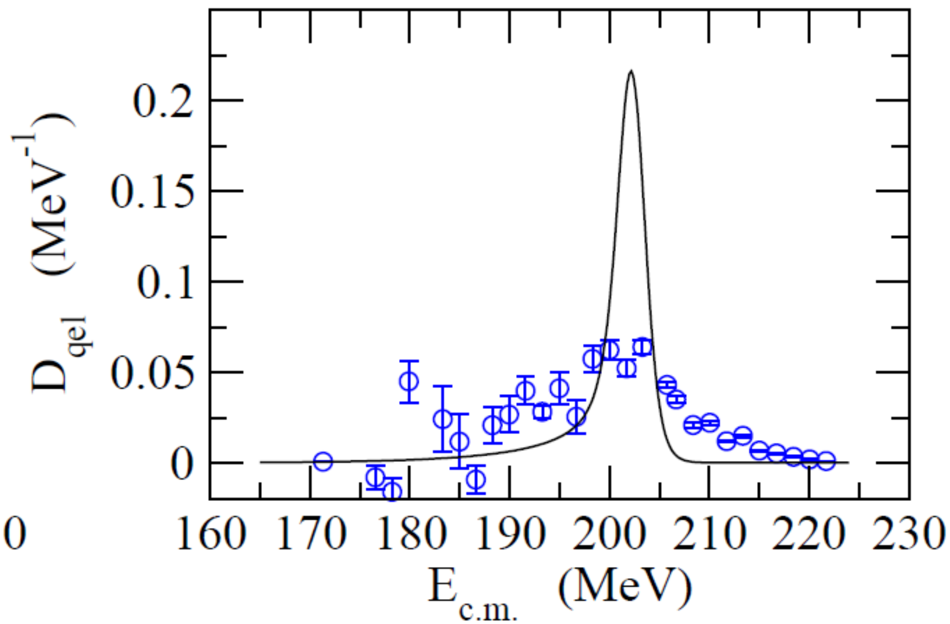
K.H. and T. Tanaka (2017)
(T. Tanaka et al., JPSJ 87 ('18) 014201)

$$^{48}\text{Ca} + ^{248}\text{Cm} \rightarrow {}^{296}_{116}\text{Lv}^*$$

single-channel calculation
(spherical $^{248}Cm$)

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



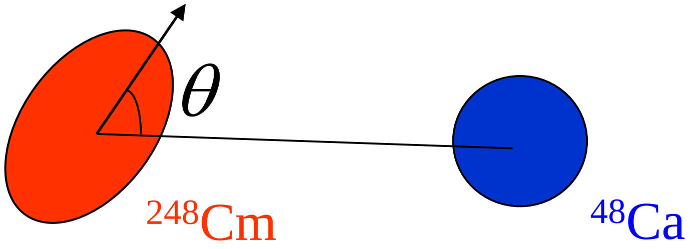
# Analysis for a hot fusion reaction $^{48}$Ca + $^{248}$Cm

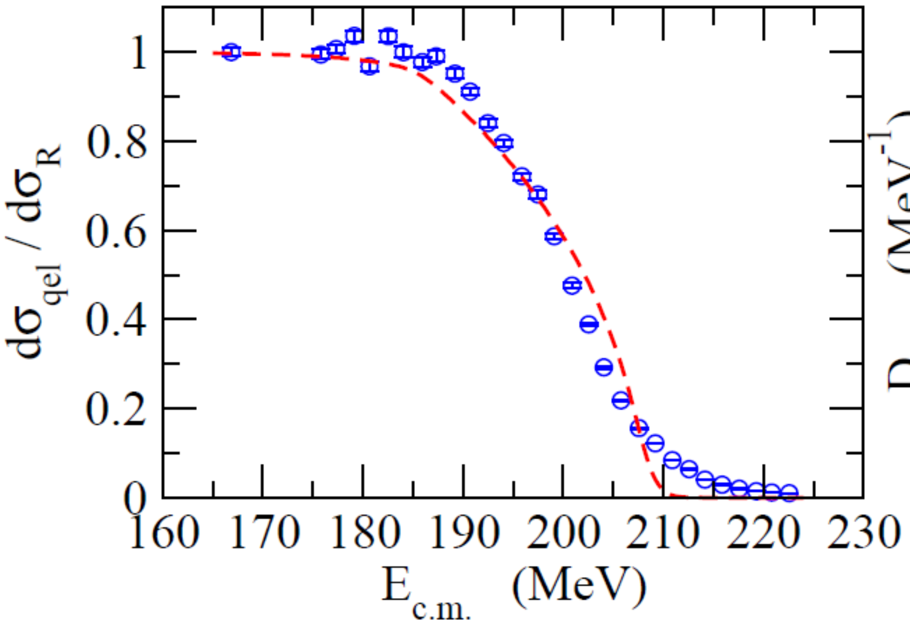
K.H. and T. Tanaka (2017)

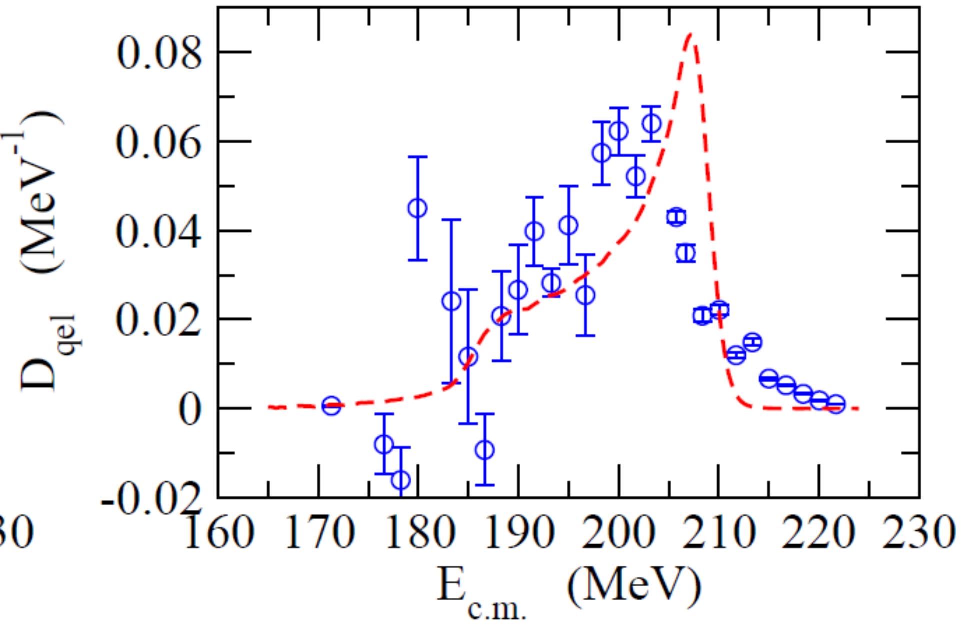
$^{48}\mathrm{Ca} + {}^{248}\mathrm{Cm}\ (\beta_2 = 0.297,\ \beta_4 = 0.04) \rightarrow {}^{296}_{116}\mathrm{Lv}^*$

[$\beta_2$ and $\beta_4$ from P. Moller]

$$\frac{d\sigma_{\rm qel}}{d\Omega} = \int_0^1 d(\cos\theta)\left(\frac{d\sigma_{\rm el}}{d\Omega}\right)_\theta$$



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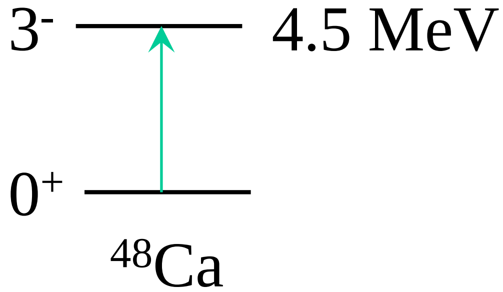
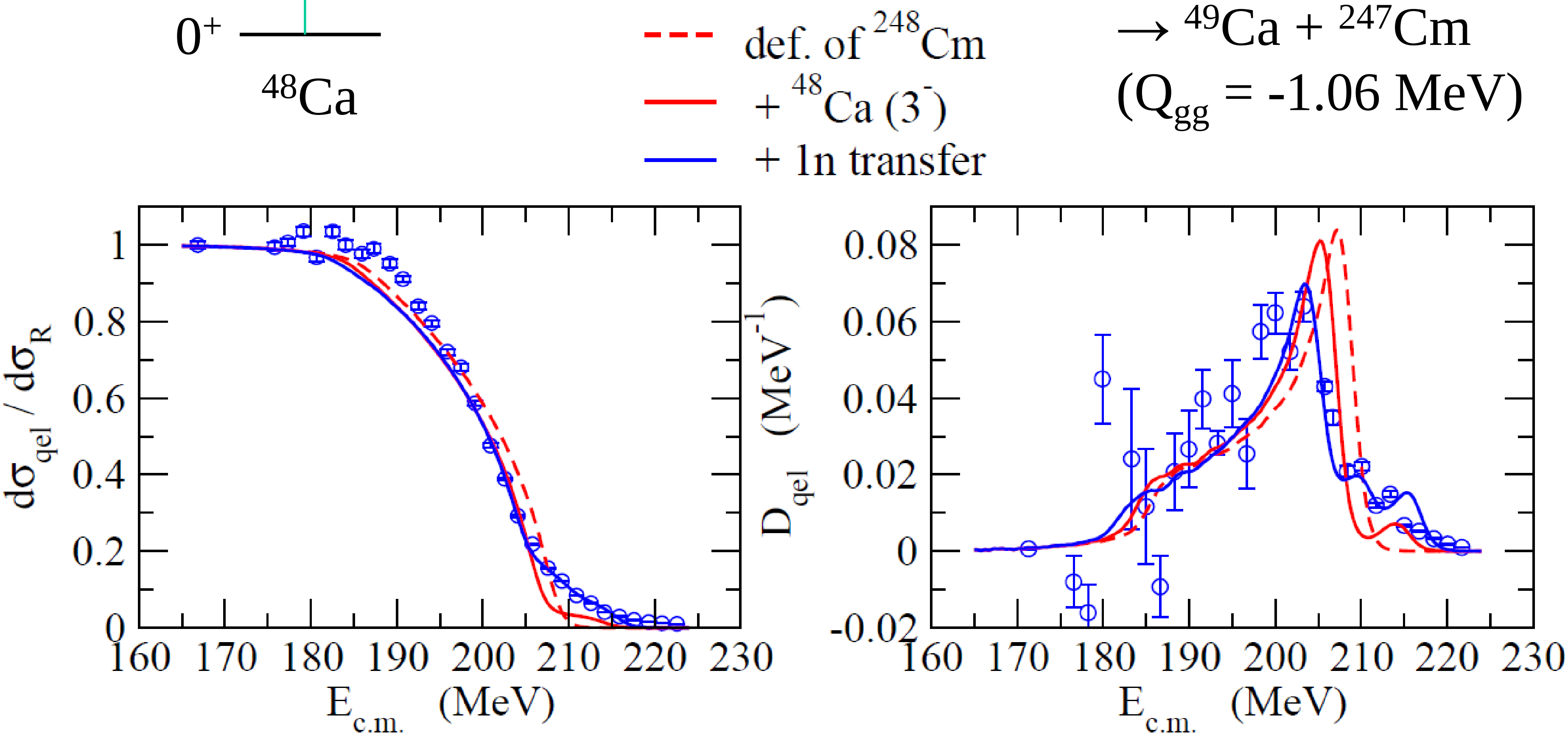



1n transfer

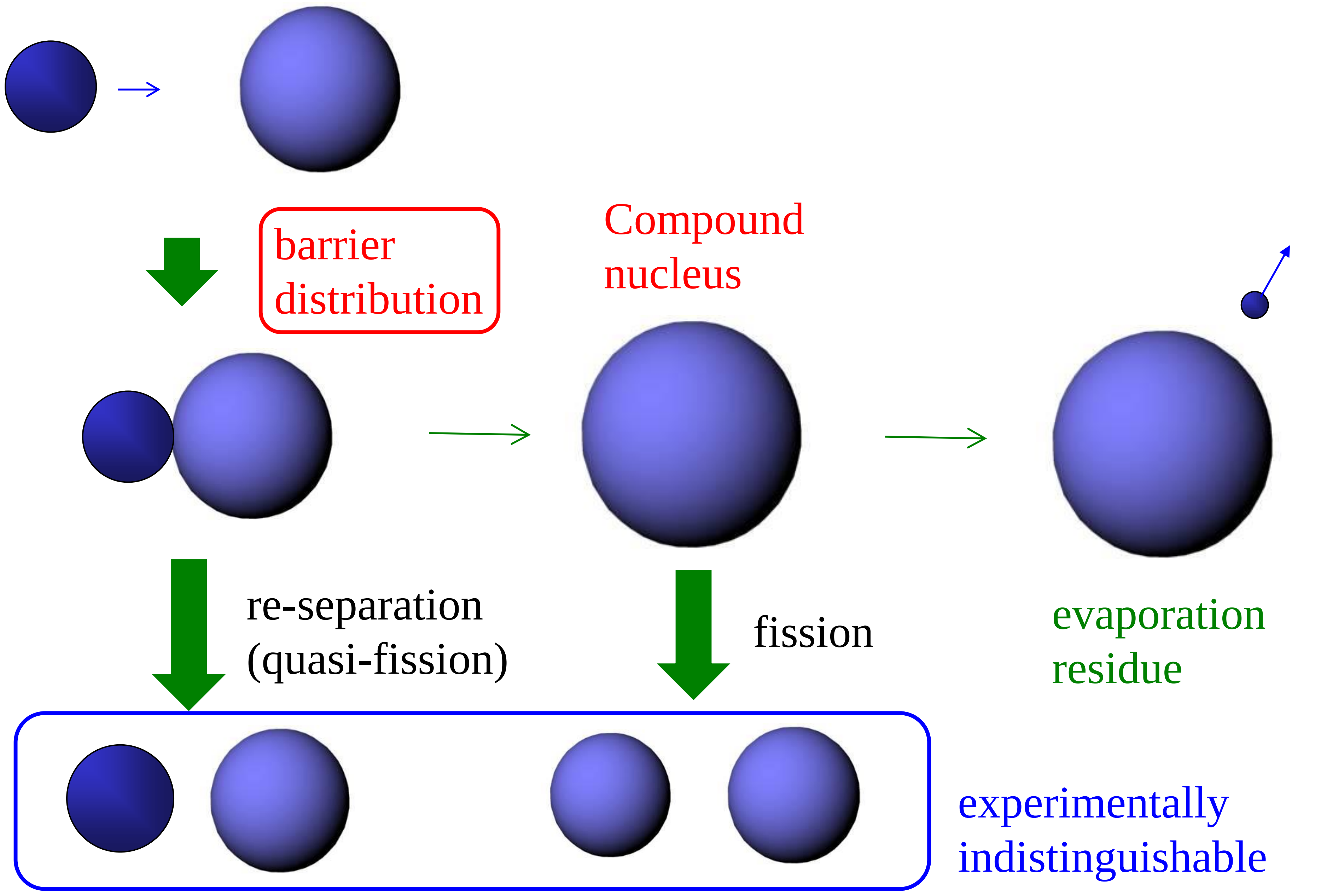
$^{48}$Ca + $^{248}$Cm

$\rightarrow$ $^{49}$Ca + $^{247}$Cm

($Q_{gg}$ = -1.06 MeV)



# Connection to the ER cross sections



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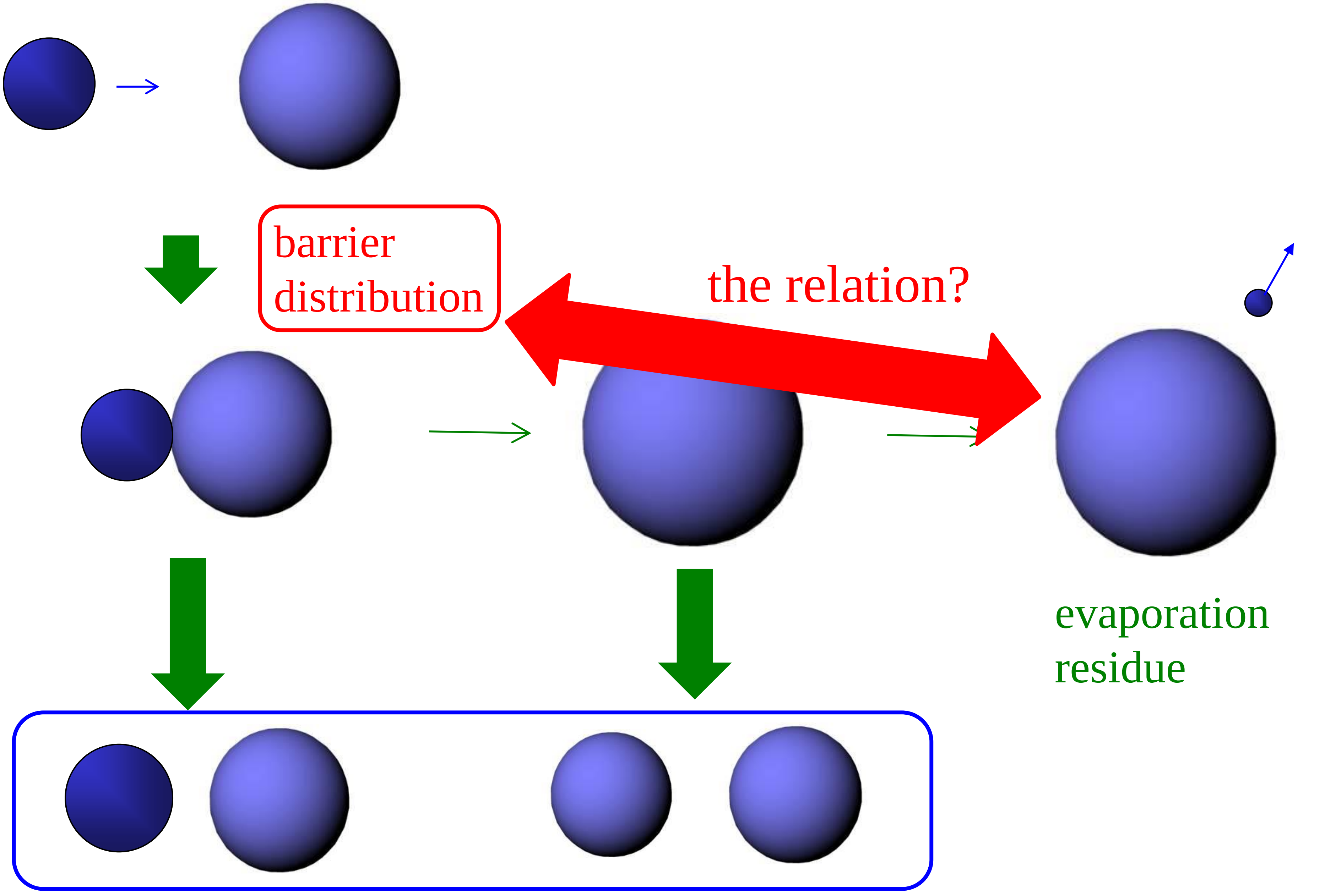

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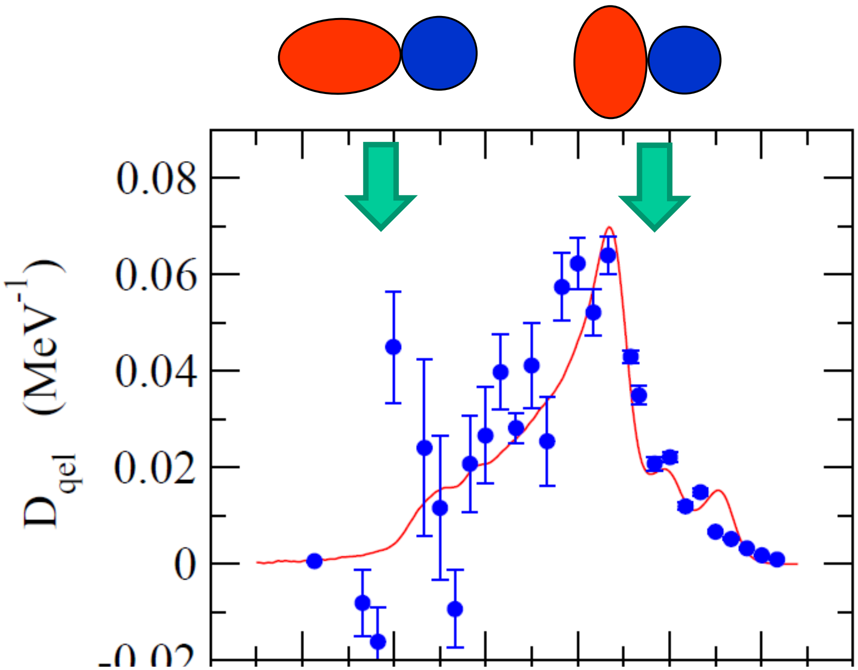
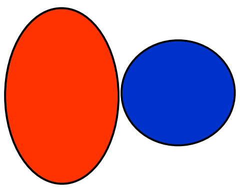



$^{48}Ca + ^{248}Cm \rightarrow ^{296}_{116}Lv^*$

notion of compactness:
D.J. Hinde et al., PRL74 (‘95) 1295



= more compact at the touching
→ favorable for CN

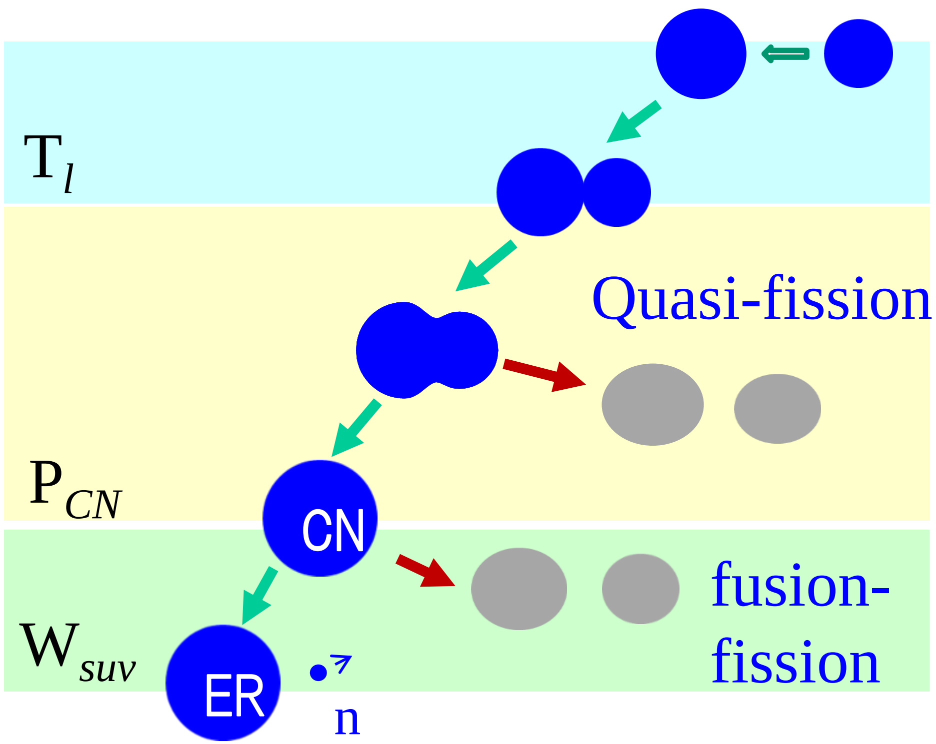
# Extension of the fusion-by-diffusion model

K.H., PRC98 (‘18) 014607

Fusion-by-diffusion model

W.J. Swiatecki et al., Acta Phys. Pol. B34 (‘03) 2049

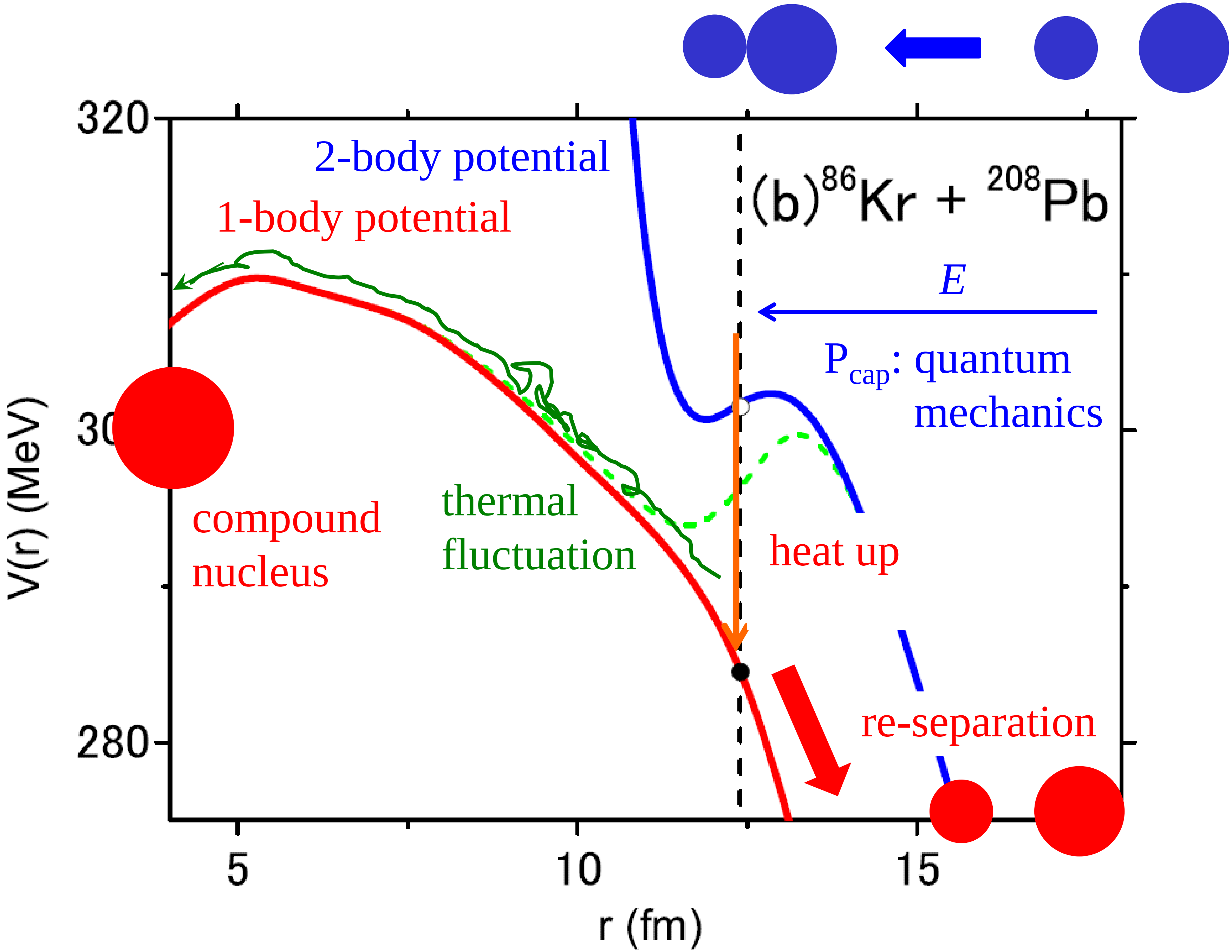
PRC71 (‘05) 014602



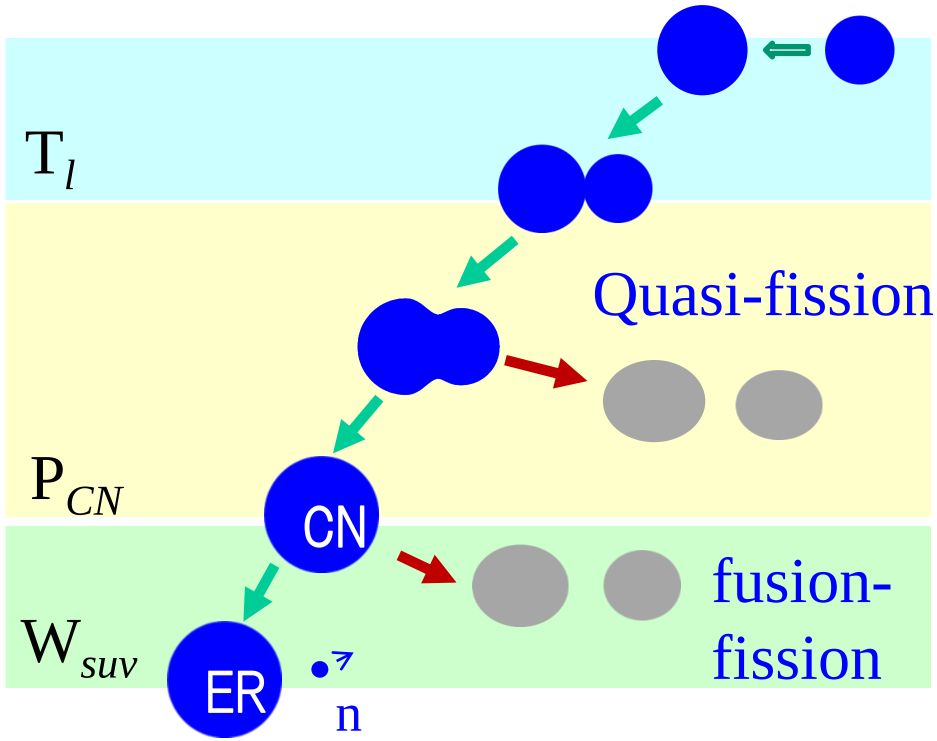

simplified C.C.

diffusion of a 1D parabolic barrier (inner barrier)

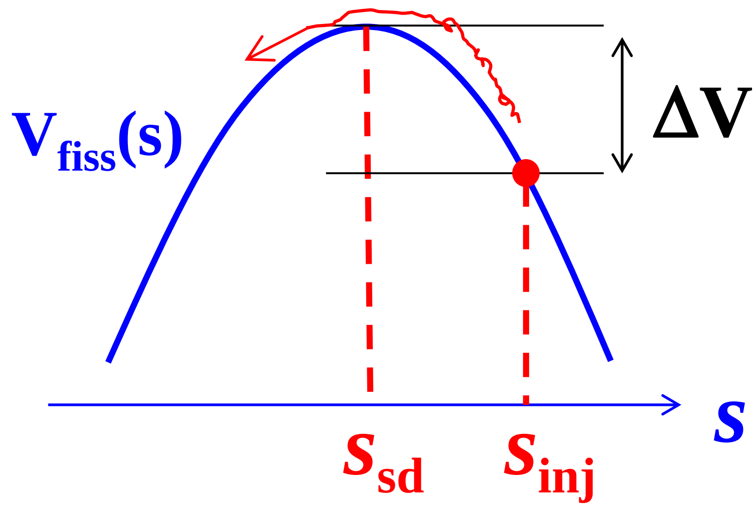
statistical model



320
280
5
10
15
r (fm)
V(r) (MeV)
2-body potential
1-body potential
(b) 86Kr + 208Pb
E
Pcap: quantum mechanics
compound nucleus
thermal fluctuation
heat up
re-separation

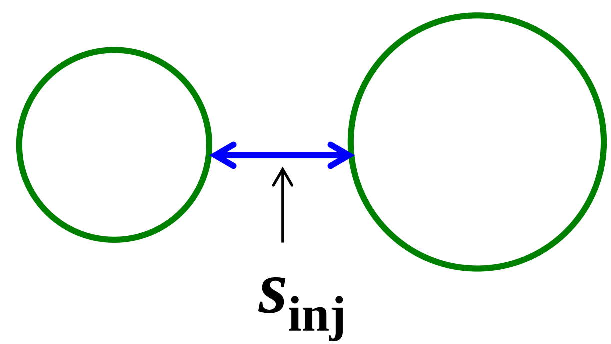



diffusion of a 1D parabolic barrier




Langevin in the overdamped limit:

$$P_{\mathrm{CN}}(E) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\Delta V}{T}\right)\right]$$



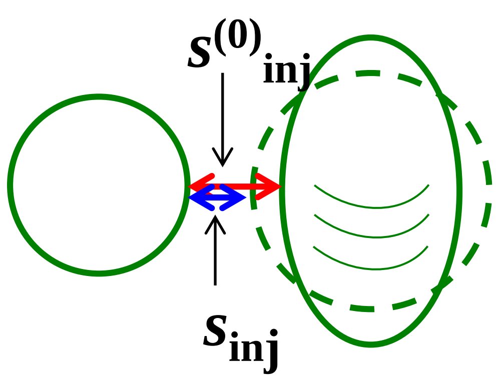
# Extension of the fusion-by-diffusion model

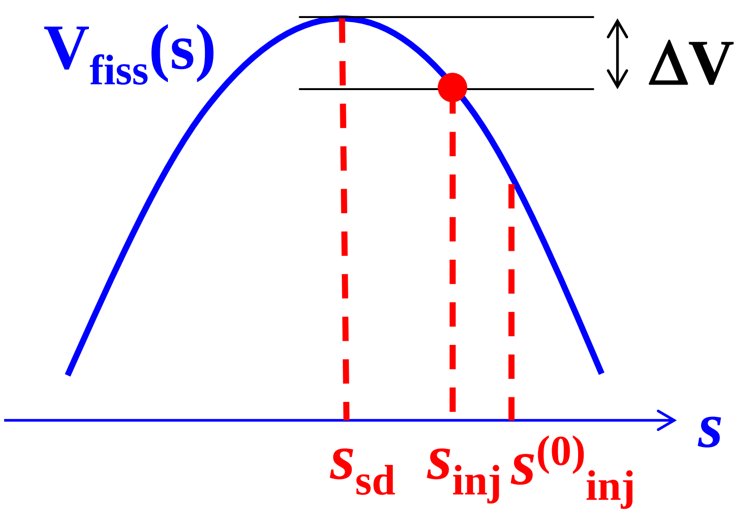
K.H., PRC98 ('18) 014607

$$s_{\mathrm{inj}}(\theta) = s_{\mathrm{inj}}^{(0)} + R_T \sum_{\lambda} \beta_{\lambda T} Y_{\lambda 0}(\theta)$$

$$P_{\mathrm{CN}}(E,\theta) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\Delta V(\theta)}{T(\theta)}\right)\right]$$

θ = π/2 (side collision)



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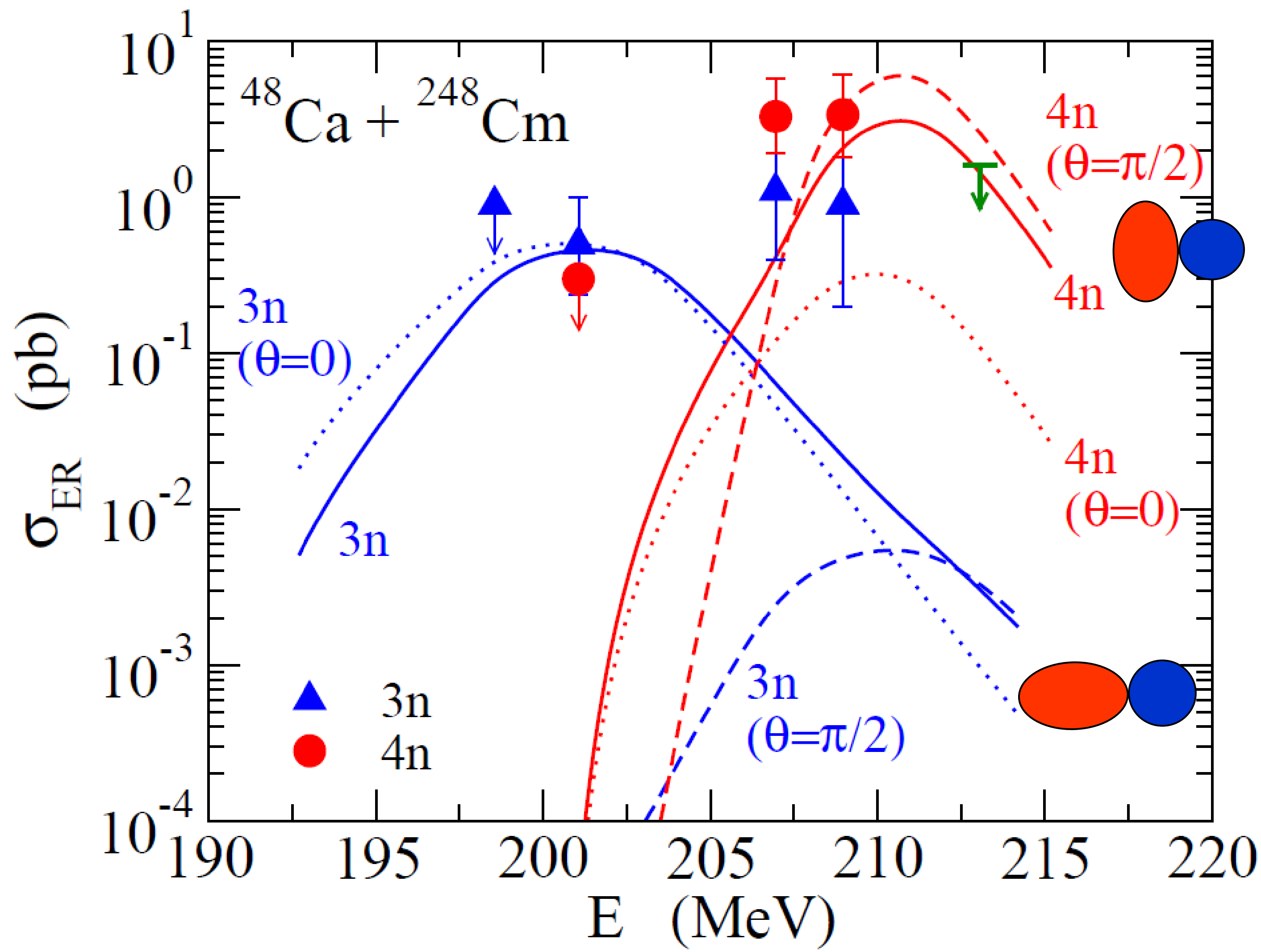
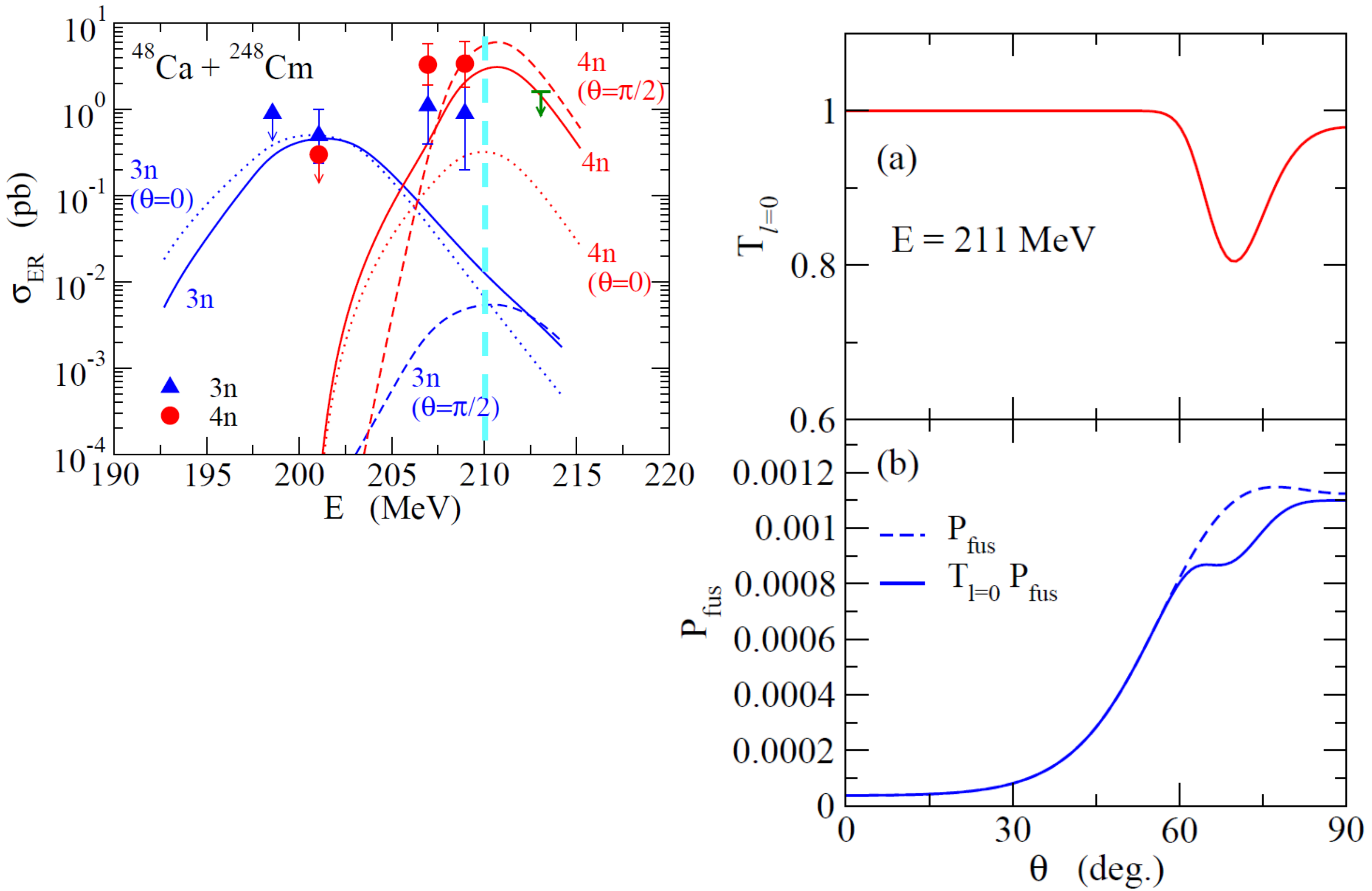
K.H., PRC98 ('18) 014607



$$\sigma_{\rm ER}(E) = \frac{\pi}{k^2} \sum_l (2l+1) \int_0^1 d\cos\theta \, T_l(E,\theta) P_{\rm fus}(E,l,\theta) W_{\rm sur}(E^*,l)$$



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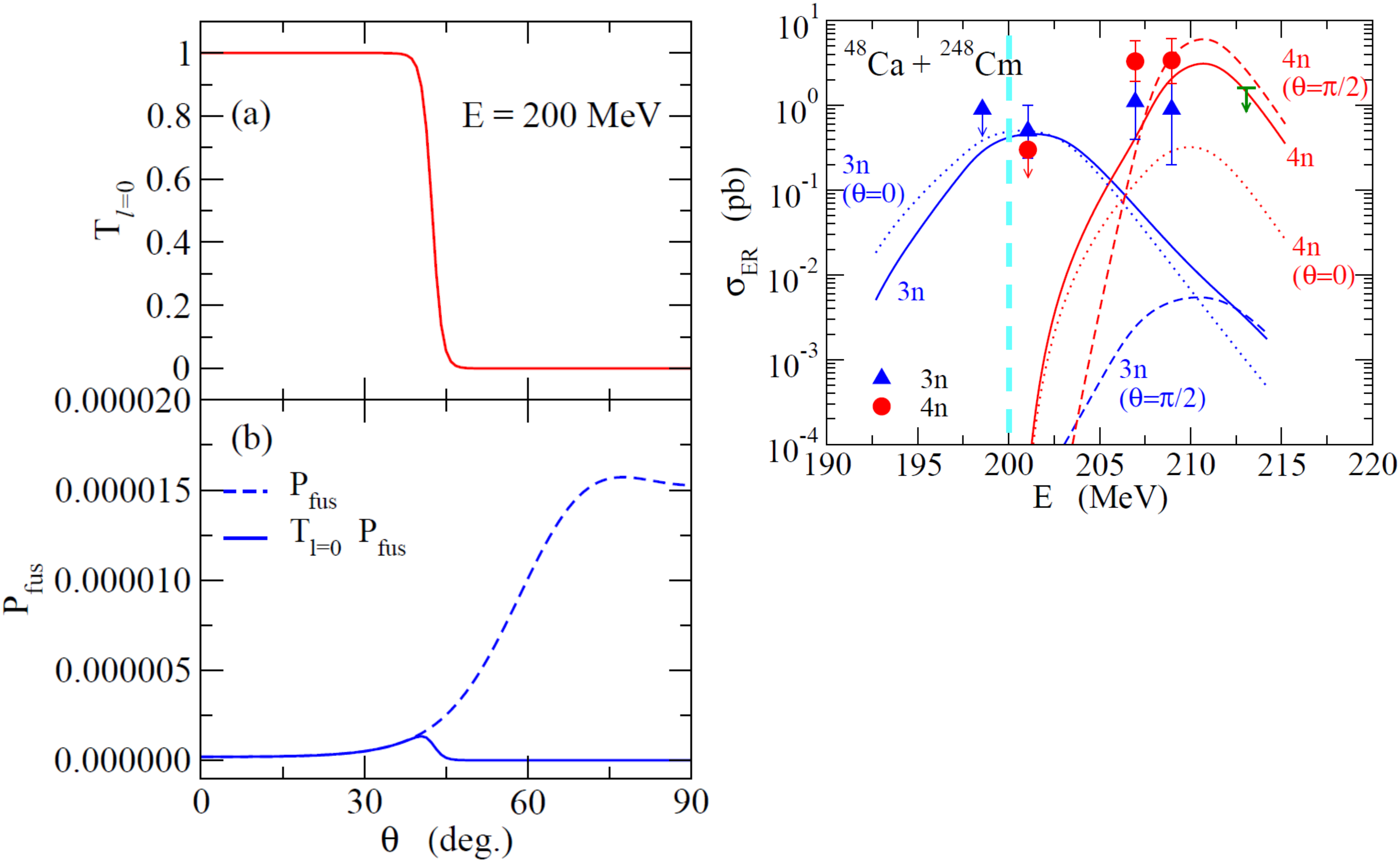
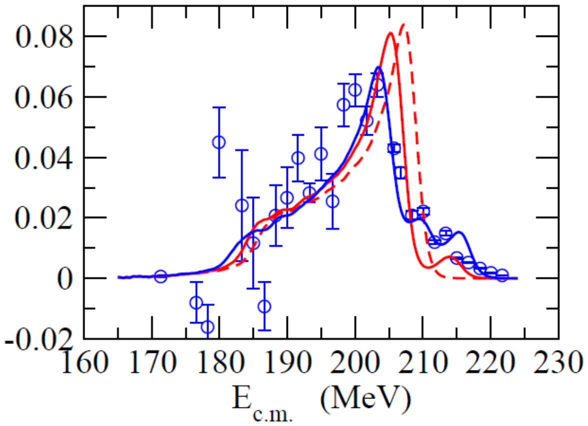


# Summary and discussions

Reaction dynamics for SHE formation reactions

- Recent measurement of barrier distributions with GARIS
  - ✓ $^{48}Ca + ^{248}Cm$
  - ✓ coupled-channels analysis
  - ✓ notion of compactness: ER formation with side collisions

more data coming soon

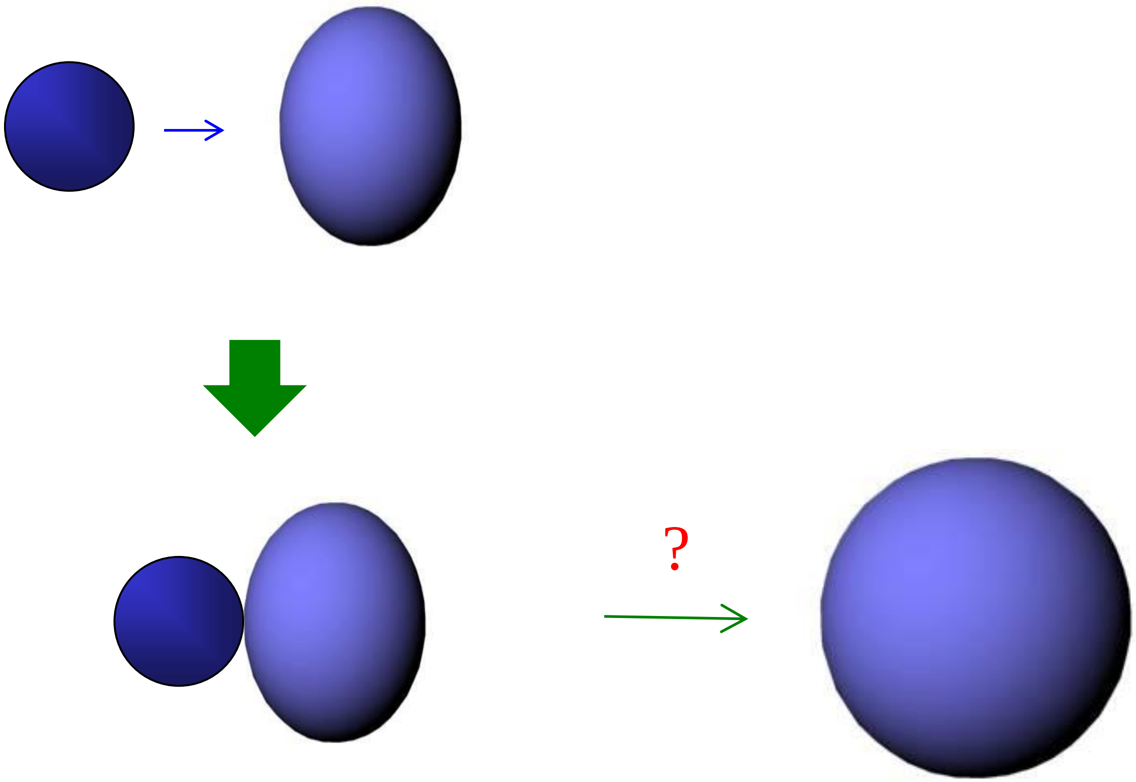



- Open problems
  - ✓ reaction dynamics?

quantum theory for friction

cf. M. Tokieda and K.H., PRC95 ('17) 054604

# A more challenging problem




heat up

disappearance of quantum effects
(shell effect and deformation)

quantum theory for friction

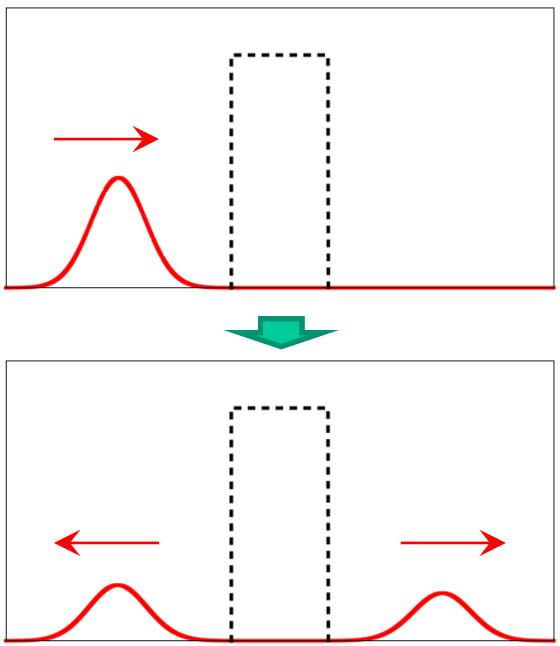
Quantum friction    classical eq. of motion    $\dot{p} = -V'(x) - \gamma p$

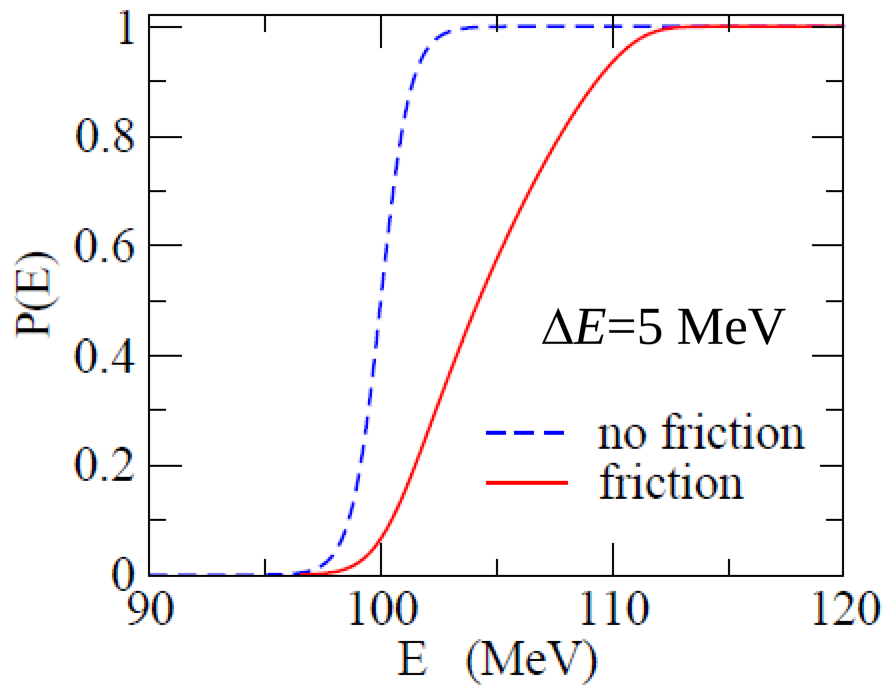
a quantization: Kanai model   E. Kanai, PTP 3 (1948) 440)

$$H = \frac{p^2}{2m} + V(x) \to \frac{\pi^2}{2m} e^{-\gamma t} + e^{\gamma t} V(x) \qquad (\pi = e^{\gamma t} p)$$

$$\Rightarrow \quad \frac{d}{dt}\langle p \rangle = -\langle V'(x) \rangle - \gamma \langle p \rangle$$

time-dep. wave packet approach






M. Tokieda and K.H., PRC95 ('17) 054604

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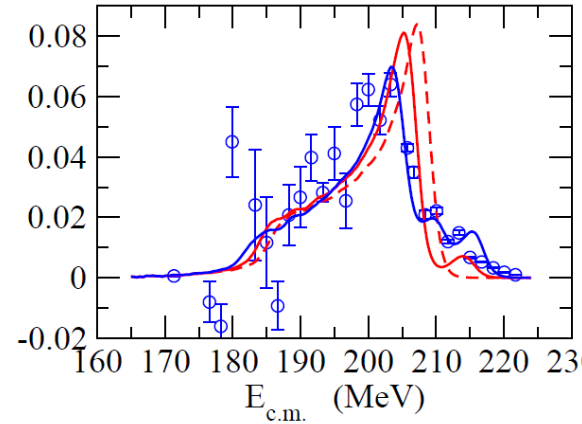



more data coming soon

➢ Open problems

- ✓ reaction dynamics?

quantum theory for friction

cf. M. Tokieda and K.H., PRC95 ('17) 054604

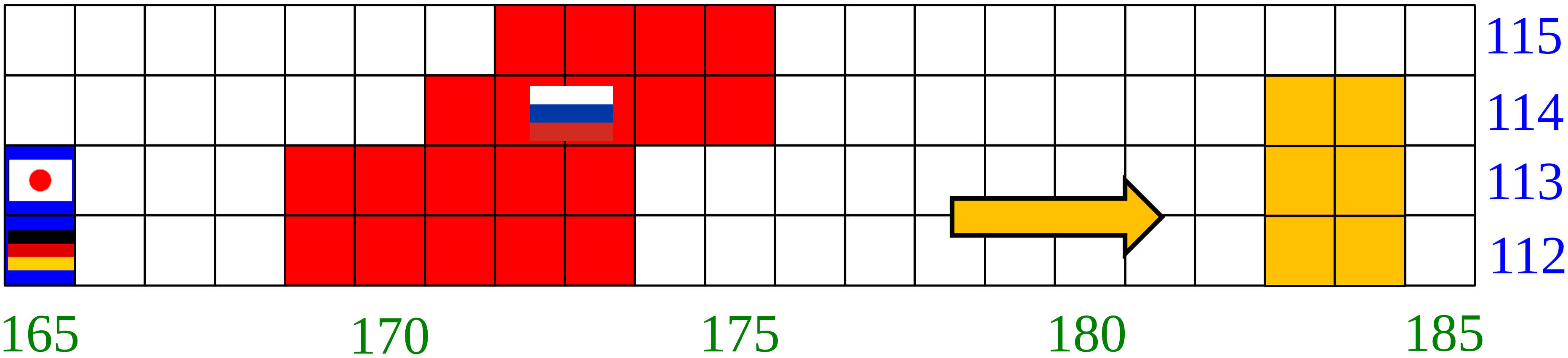
- ✓ shape evolution with a deformed target?

how does the deformation disappear during heat-up?

- ✓ towards island of stability

reaction dynamics with <u>neutron-rich</u> beams?

## Towards the island of stability




neutron-rich beams: indispensable

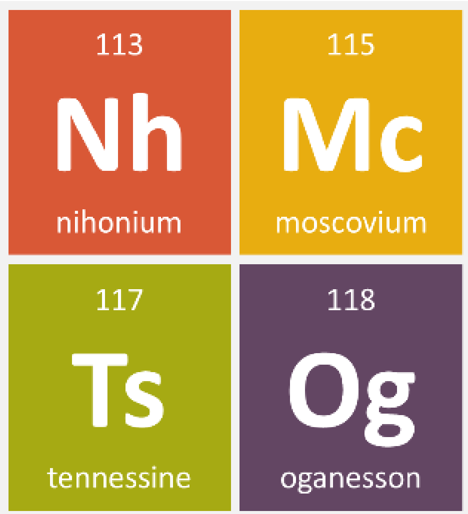
- how to deal with low beam intensity?
- reaction dynamics of neutron-rich beams?
  - ✓ capture: role of breakup and (multi-neutron) transfer?
  - ✓ diffusion: neutron emission during a shape evolution?
  - ✓ survival: validity of the statistical model?

structure of exotic nuclei

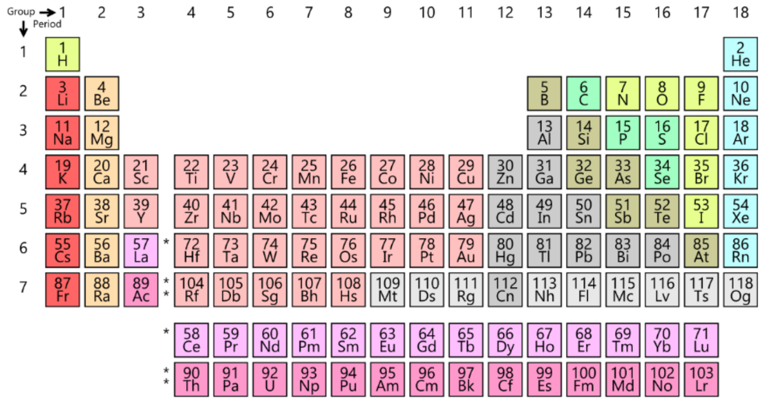
developments of physics of exotic nuclei with SHE interests formation of SHE

chemistry of SHE

the origin of (S)HE

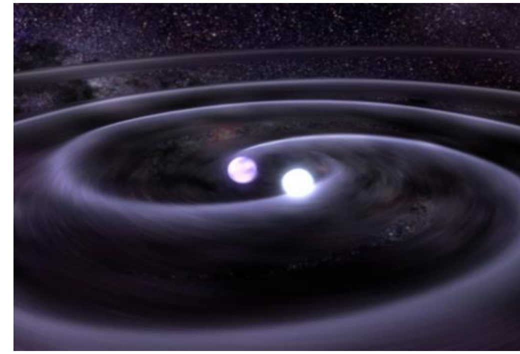


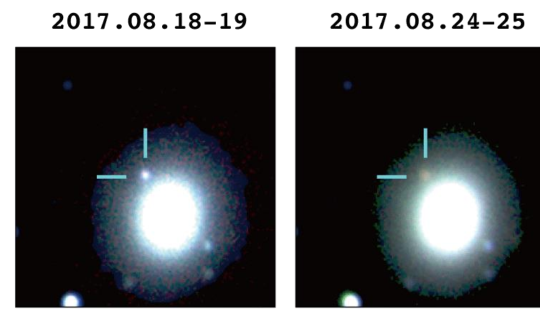

heavy-ion fusion reactions



2019 IYPT

International Year
of the Periodic Table
of Chemical Elements






r-process nucleosynthesis

**SHE: quantum many-body systems with a strong Coulomb field**

→ comprehensive understanding of SHE

# FUSION20

November 16-20, 2020
Shizuoka, Japan

Kouichi Hagino (co-chair)   Tohoku University
Katsuhisa Nishio (co-chair) JAEA

# 謝謝！