Effects of octupole deformation on nuclear fusion with ^{144}Ba and ^{224}Ra

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1. Motivation
   - EDM's and SM
   - The role of octupole deformation
   - Is fusion of any help?
2. Formalism
   - Fusion within CC
   - Full rotor
   - Quadrupole rotor + Octupole vibration
3. Results
   - ^{16}O+^{144}Ba,^{224}Ra
4. Conclusions

Electric dipole moments and the Standard Model

⇒ This is not the first CP-(T-)violation we deal with:

- Observations on neutral Kaons
- The Cabibbo-Kobayashi-Maskawa matrix has therefore three mixing angles and one CP-violating complex phase
- Always related to the weak force and a change in quark flavour

⇒ Any permanent dipole moment will imply T-(and P-)violation (e,n,nuclei,atoms)

- Large effort on constraining maximum possible EDM on ^{199}Hg atoms
- Static Octupole deformation in ^{225}Ra should contribute to the atomic EDM

✓ It might give some extra violation non related to the weak force

Why do we need Octupole deformation?

⇒ The contribution to the atomic EDM can be measured through the Schiff moment

$$S \approx \sum_i \frac{\langle g.s.|S_z|i\rangle\langle i|V_{PT}|g.s\rangle}{E_0 - E_i}$$

✓ With octupole deformation in ^{225}Ra you may have an almost degenerate couple of states $1/2^+$ and $1/2^-$, different projections of the same intrinsic state.

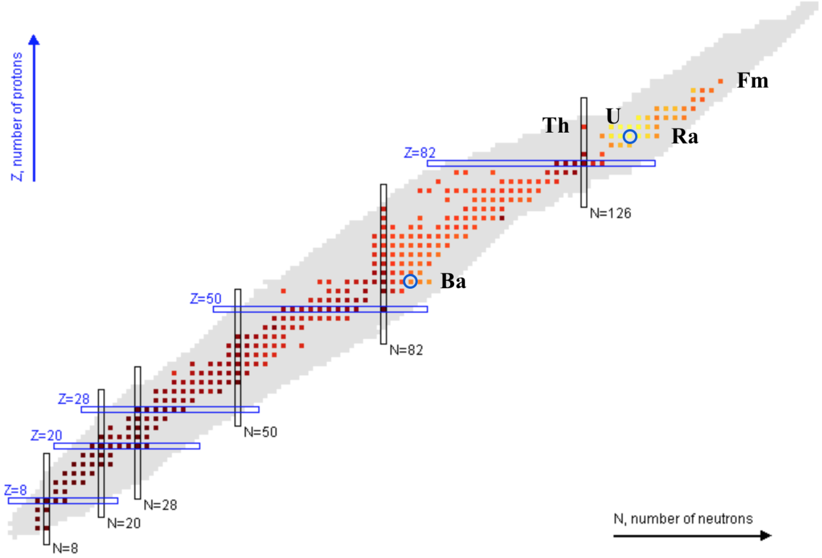
Dobaczewski and Engle PRL 94, 232502 (2005);
Spevak, Auerbach and Flambaum PRC 56, 1357 (1997).

What is needed?

- Experimental precision
  - $\mathcal{B}(E3)$
  - ΔE
- How to distinguish experimentally deformation from vibration?
  - Spectrum
  - $\mathcal{B}(E1)$

✓ Theoretical predictions for Ra,Ba,Th... agree
X Nature will never create an ideal rotor
X It always comes together with quadrupole deformation

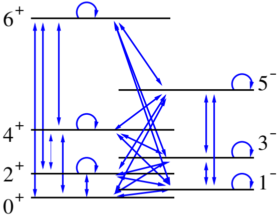
"Going Peer Shaped" Gaffney *et al.* Nature 497, 199 (2013)
P. A. Butler and W. Nazarewicz RMP 68,349 (1996).



NNDC Brookhaven Lab

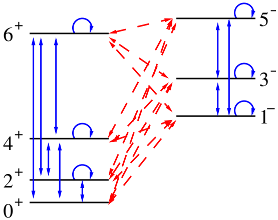
Spectrum

- Ideal axial rotor without R-symmetry



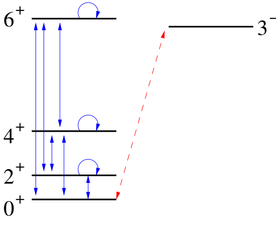
(a)

- Strongly coupled vibration



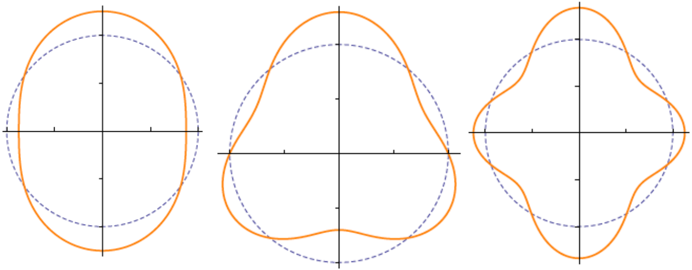
(b)

- Uncoupled vibration



(c)

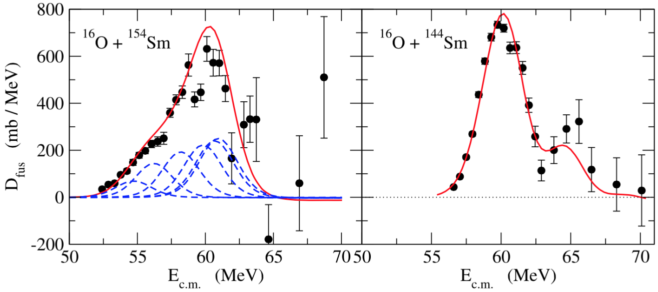
Also large $\mathcal{B}(E1)$ values can be obtained with vibration



Can subbarrier fusion help?

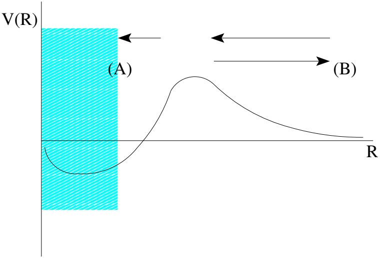
✓ Useful for distinguishing prolate/oblate, deformation or vibration, γ-soft

X Experimentally demanding



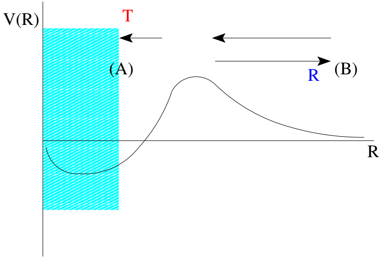
Hagino and Takigawa PTP 128, 1061 (2012)

Incoming Wave Boundary Condition (IWBC)



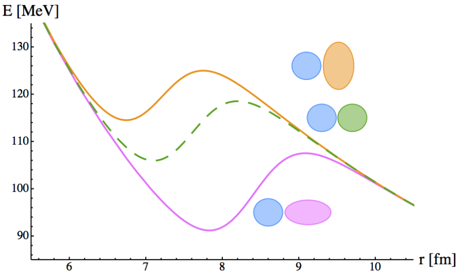
$$\chi_\beta(R) \xrightarrow{R\to\infty} \delta_{\beta 1} H_\ell^{(-)}(k_\beta R) + r_\beta H_\ell^{(+)}(k_\beta R);$$
$$\chi_\beta(R = R_{min}) = t_\beta H_\ell^{(-)}(k_\beta R),$$

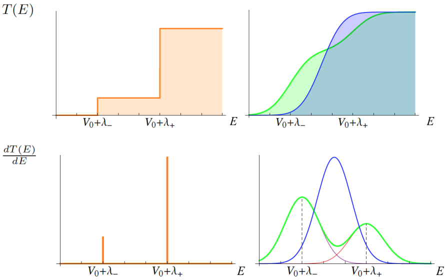
Incoming Wave Boundary Condition (IWBC)



$$\chi_\beta(R) \xrightarrow{R\to\infty} \delta_{\beta 1} H_\ell^{(-)}(k_\beta R) + r_\beta H_\ell^{(+)}(k_\beta R);$$

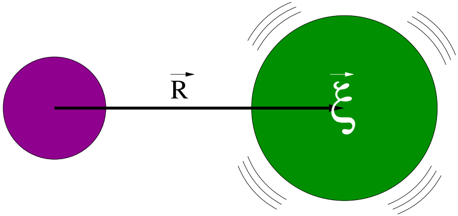
$$\chi_\beta(R = R_{min}) = t_\beta H_\ell^{(-)}(k_\beta R),$$





$$\frac{dT}{dE} = \frac{1}{\pi R_0^2} \frac{d^2[E\sigma]}{dE^2}$$

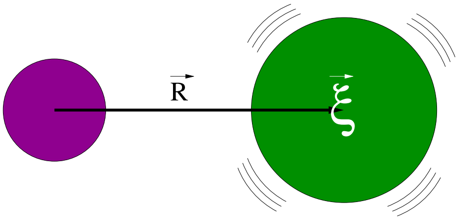
Coupled-Channels



$$\Psi^{(+)} = \sum_{\beta} \frac{\chi_\beta(R)}{R} \phi_\beta(\xi).$$

$$\frac{d^2\chi_\beta}{dR^2} + \frac{2\mu_\beta}{\hbar^2}[E_\beta - V_\beta^{eff}(R)]\chi_\beta = \frac{2\mu_\beta}{\hbar^2} \sum_{\alpha\neq\beta} V_{\beta\alpha}^{coup}(R)\chi_\alpha$$

Coupled-Channels



$$V^{coup}_{\beta\alpha}(R) = \langle \phi_\alpha(\xi) | V(R,\xi) | \phi_\beta(\xi) \rangle$$

Textbook General Rotor potential (B&M)

$$V(R - R_0) \Rightarrow V(R - R_0(\theta))$$

$$R_0(\theta) = R_0(1 + \sum_\lambda \beta_\lambda Y_{\lambda 0}(\theta))$$

$$V(R,\theta) = \sum_\lambda V_\lambda(R) Y_{\lambda 0}(\theta) \quad \Leftrightarrow \quad V_\lambda(R) = \int V(R,\theta) Y_{\lambda 0} d\Omega$$

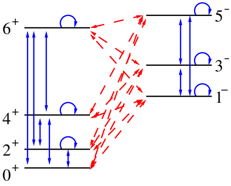
$$V_{\alpha\beta}^{coup} = c.g. \cdot V_\lambda(R)$$

Donner & Greiner Z. für Phys. 197, 440 (1966)

$$R_0(\theta) = R_0(1 + \beta_2 Y_{20}(\theta) + \sum_\mu \alpha_{3\mu} Y_{3\mu}) = R_2(\theta) + R_3(\alpha_{3\mu})$$

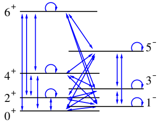
$$V(R - R_2 - R_3) \approx V(R - R_2(\theta)) - R_0 \frac{dV(R - R_2(\theta))}{dR} \sum_\mu \alpha_{3\mu} Y_{3\mu}$$

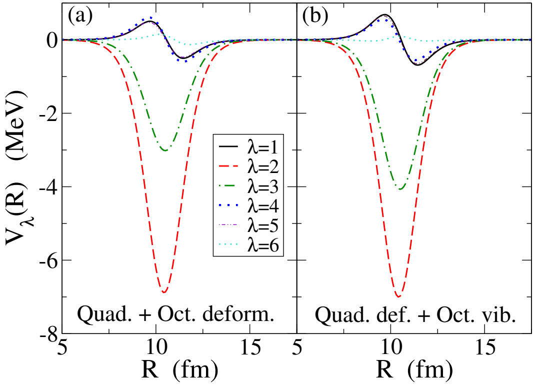
Also parallel to GDR on deformed nuclei

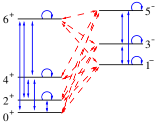


(b)

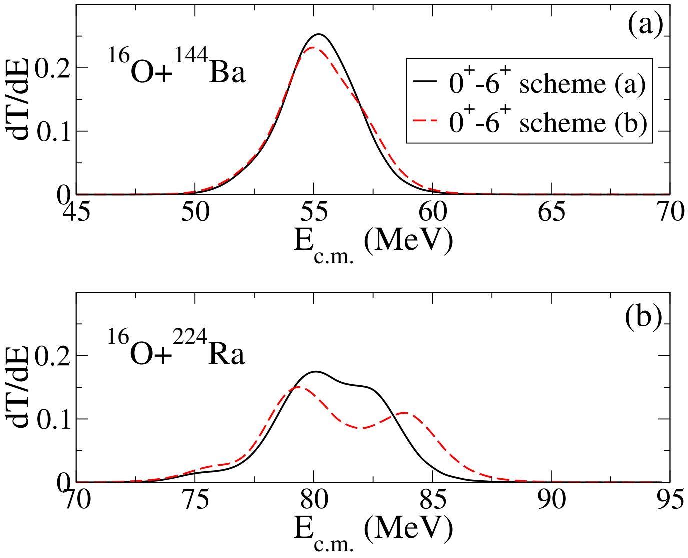
Form Factors for $^{16}O+^{144}Ba$







Kumar, Lay, Vitturi arXiv:1501.0681v2 (subm. to PRC)


(a)
^{16}O+^{144}Ba
0$^+$-6$^+$ scheme (a)
0$^+$-6$^+$ scheme (b)
dT/dE
0
0.1
0.2
45
50
55
60
65
70
E$_{c.m.}$ (MeV)
(b)
^{16}O+^{224}Ra
dT/dE
0
0.1
0.2
70
75
80
85
90
95
E$_{c.m.}$ (MeV)

Conclusions

Conclusions

- Barrier distributions show quantitative but not qualitative differences proportional to β_3

X Not enough to clearly separate deformation from vibration, maybe a complimentary probe in an optimistic future

- However, and up to our knowledge, it is the first time this is done for fusion with the coupled-channel method

Bad News (or Uncertainties)

- Akyüz-Winther potential is used since no better Optical Potential nor elastic data is available
- Both β_2, β_3 should be well known

Next steps

Good News (or things to be done)

- Check other octupole-deformed cases (Th)
- Dependence on the projectile (Q values?)
- What about ^{225}Ra

✓ We can also calculate quasielastic cross sections (done for ^{232}Th)

$$T \Longleftrightarrow \sigma_F$$
$$R \Longleftrightarrow \sigma_{qel}$$

More (not so funny) things to do

- Excitations of the projectile

Thank you!!