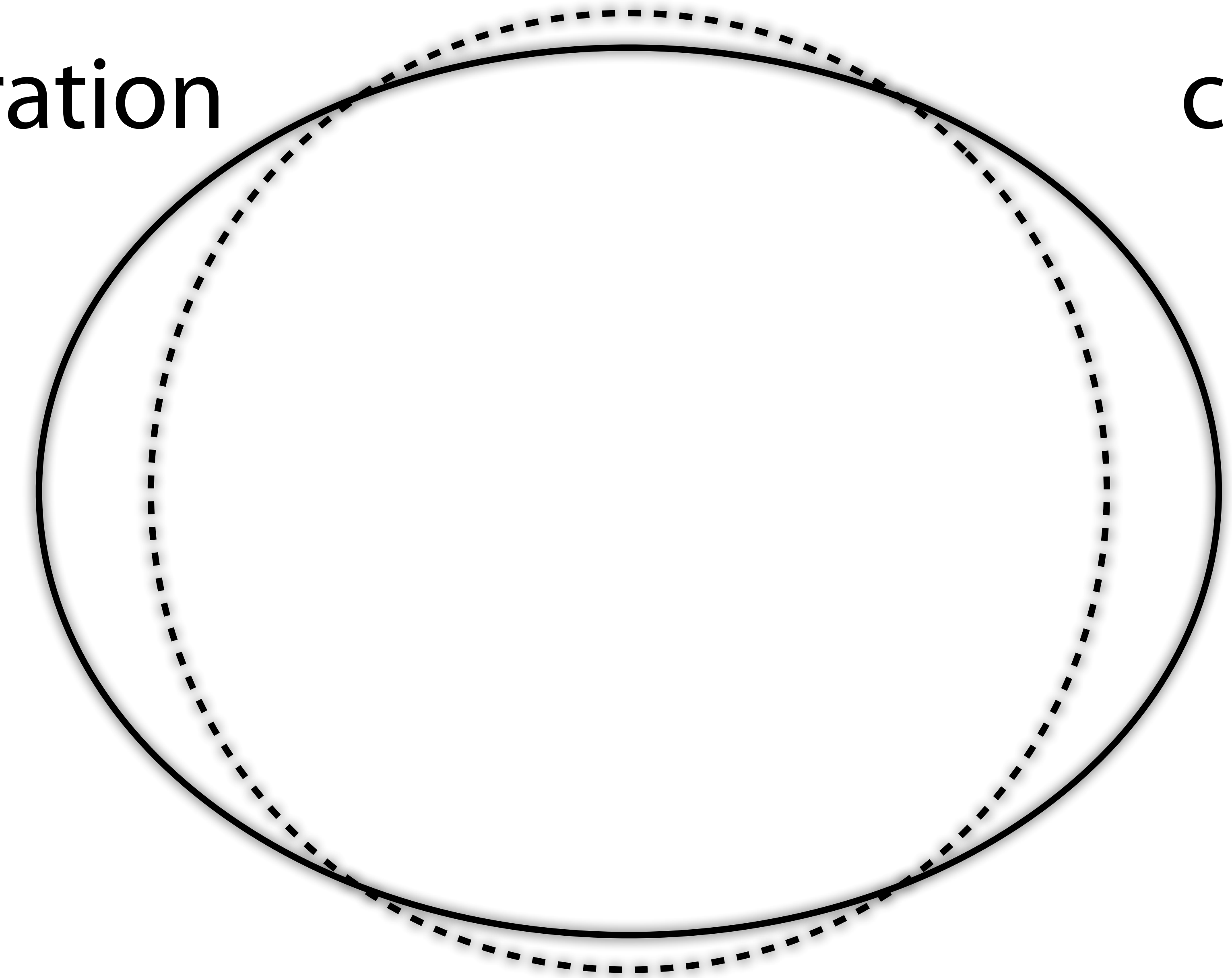
Collective motions in nuclei: vibration

Vibrational modes of excitation

surface vibration

classical picture



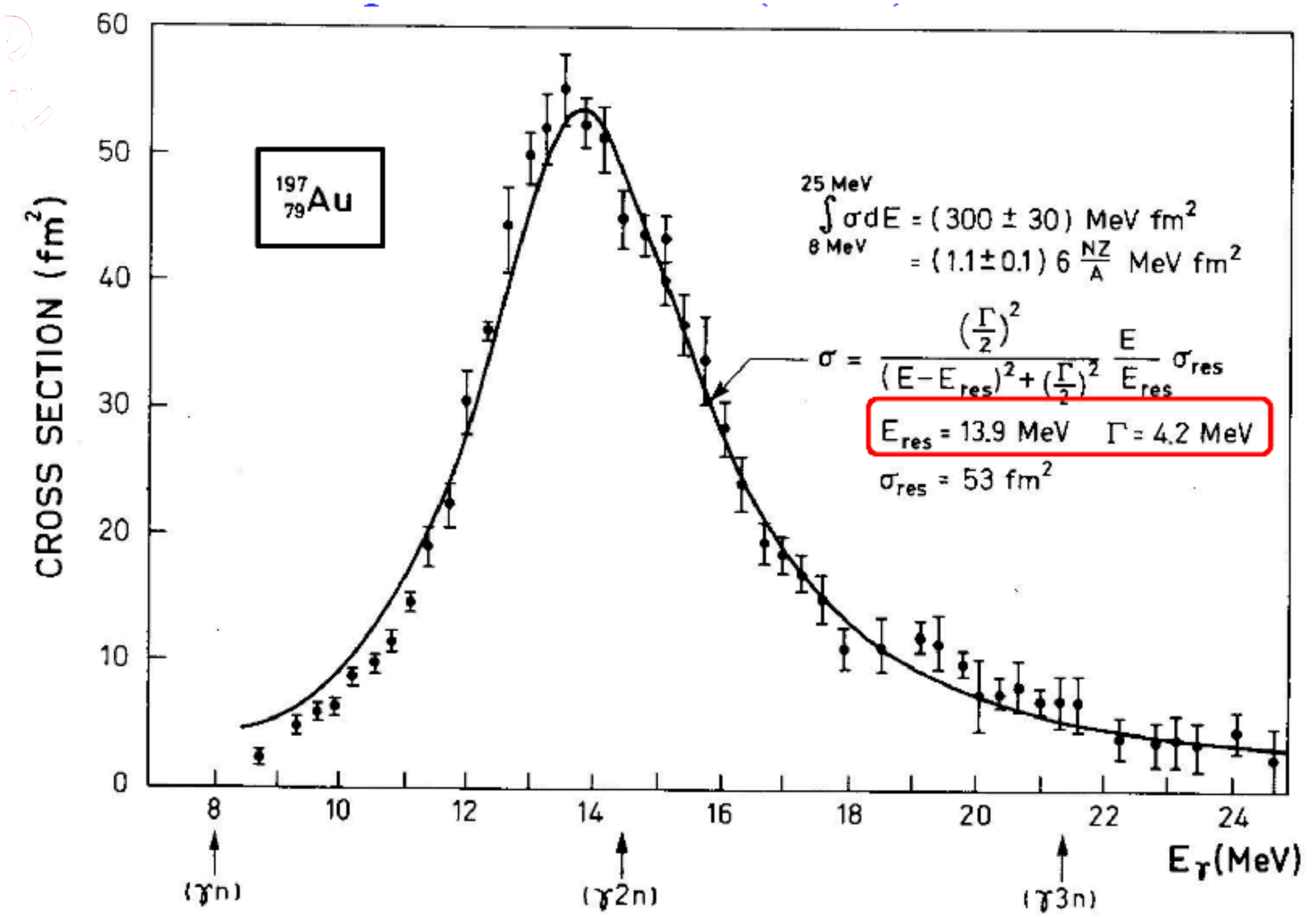


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

change of density in time

time-dependent DFT

Excitations in the HF approximation

$$H_{\mathrm{MF}} = \sum_i \varepsilon_i a_i^\dagger a_i$$

$$= \sum_m \varepsilon_m d_m^\dagger d_m - \sum_i \varepsilon_i b_i^\dagger b_i$$

1p1h
one-particle–one-hole state

$$H_{\mathrm{MF}} d_k^\dagger b_l^\dagger |\Phi_{\mathrm{HF}}\rangle = (\varepsilon_k - \varepsilon_l) d_k^\dagger b_l^\dagger |\Phi_{\mathrm{HF}}\rangle$$

2p2h
two-particle–two-hole state

$$H_{\mathrm{MF}} d_{k_1}^\dagger d_{k_2}^\dagger b_{l_1}^\dagger b_{l_2}^\dagger |\Phi_{\mathrm{HF}}\rangle = (\varepsilon_{k_1} + \varepsilon_{k_2} - \varepsilon_{l_1} - \varepsilon_{l_2}) d_{k_1}^\dagger d_{k_2}^\dagger b_{l_1}^\dagger b_{l_2}^\dagger |\Phi_{\mathrm{HF}}\rangle$$

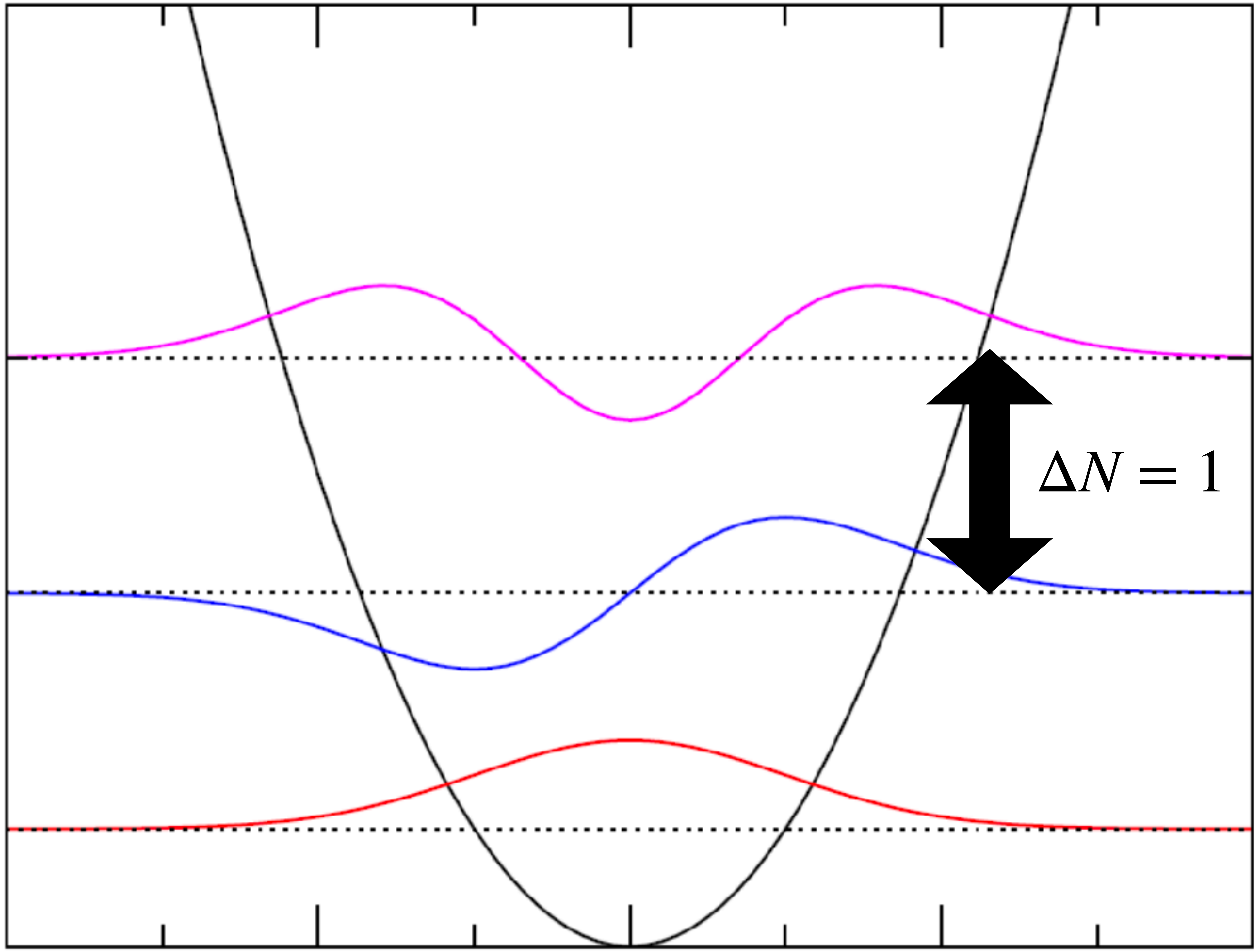
cf.

$$H_{\mathrm{MF}} d_k^\dagger |\Phi_{\mathrm{HF}}\rangle = \varepsilon_k d_k^\dagger |\Phi_{\mathrm{HF}}\rangle$$

$d_k^\dagger |\Phi_{\mathrm{HF}}\rangle$ is an eigenstate of (A+1)-body system

$$H_{\mathrm{MF}} b_l^\dagger |\Phi_{\mathrm{HF}}\rangle = -\varepsilon_l b_l^\dagger |\Phi_{\mathrm{HF}}\rangle$$

$b_l^\dagger |\Phi_{\mathrm{HF}}\rangle$ is an eigenstate of (A-1)-body system



negative-parity 1p1h excitation

$$\hbar\omega = 41 \times A^{-1/3}\,(\mathrm{MeV})$$

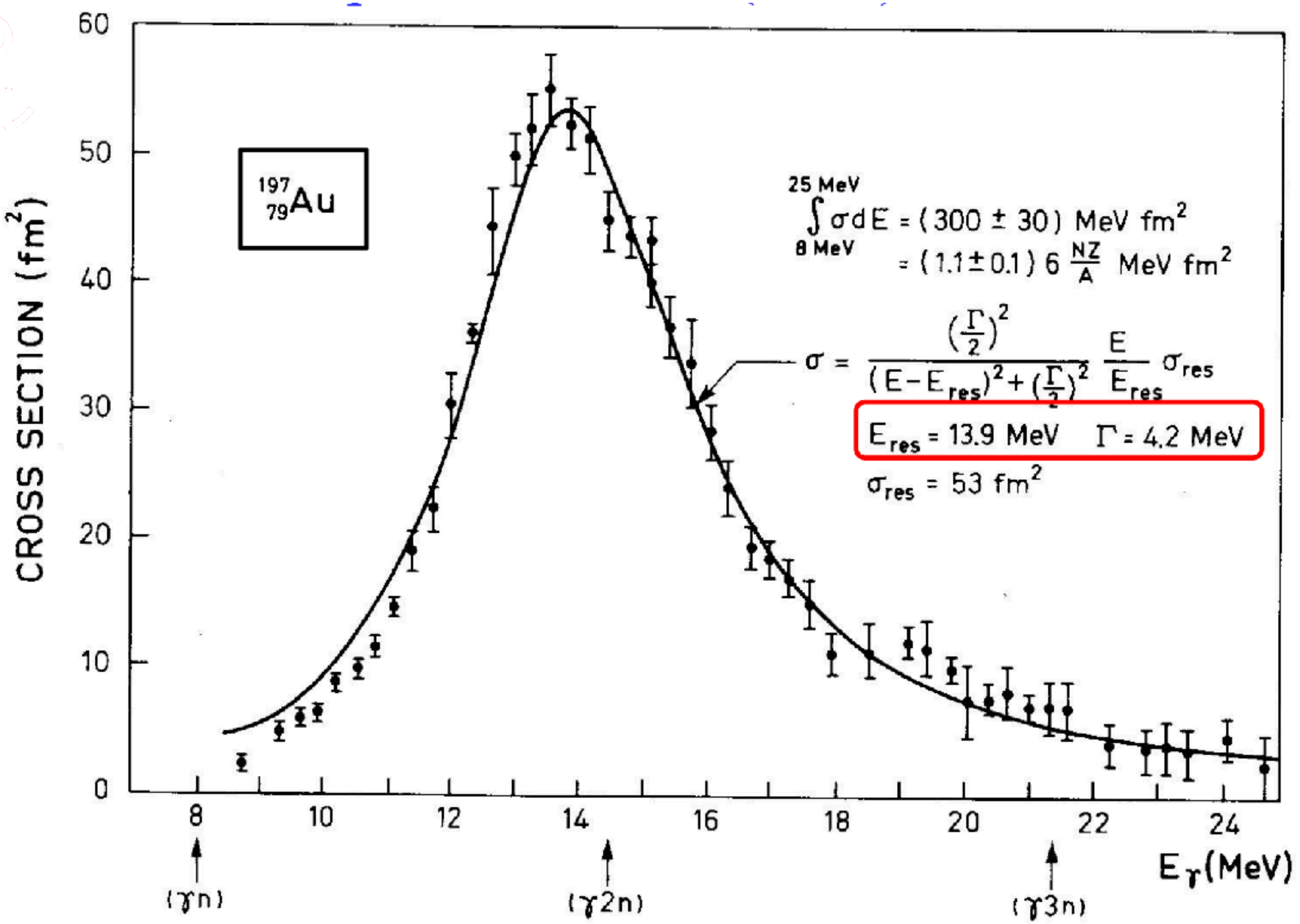


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

$$41 \times 197^{-1/3} = 7.05\,\mathrm{MeV}$$

just a half !?

Collective vibrations

<u>coherent superposition</u> of ph excitations due to the residual interaction

Tamm–Dancoff approximation (TDA)

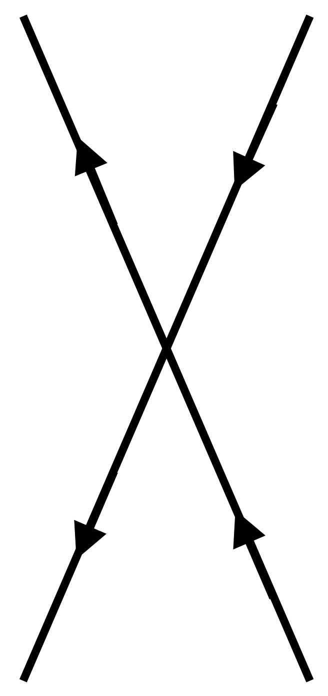
$$H = H_{\mathrm{MF}} + \sum v : c^\dagger c^\dagger c c :$$

$$|\lambda\rangle = \sum_{ph} C^\lambda_{ph} d^\dagger_p b^\dagger_h |\Phi_{\mathrm{HF}}\rangle := \Gamma^\dagger_\lambda |\Phi_{\mathrm{HF}}\rangle$$

$d^\dagger b^\dagger d b$ part of

$$c^\dagger c^\dagger c c \sim a^\dagger a^\dagger a a \sim \begin{pmatrix} d^\dagger \\ b \end{pmatrix} \begin{pmatrix} d^\dagger \\ b \end{pmatrix} \begin{pmatrix} d \\ b^\dagger \end{pmatrix} \begin{pmatrix} d \\ b^\dagger \end{pmatrix}$$

$$H^{\mathrm{TDA}} = H_{\mathrm{MF}} + \sum_\lambda E_\lambda \Gamma^\dagger_\lambda \Gamma_\lambda$$



Tamm–Dancoff equation (eigenvalue problem)

$$\sum_{p'h'} [(\varepsilon_{p'} - \varepsilon_{h'})\delta_{pp'}\delta_{hh'} + \bar{v}_{ph'hp'}] C^\lambda_{p'h'} = E_\lambda C^\lambda_{ph}$$

Collective vibrations

coherent superposition of ph excitations due to the residual interaction

RPA: Random Phase Approximation to include the ground-state correlations

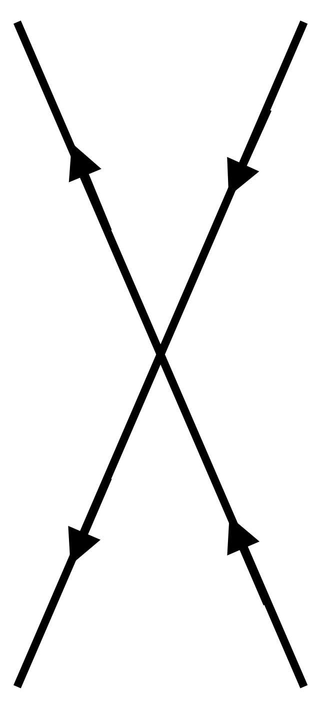
$$H|\lambda\rangle = E_\lambda|\lambda\rangle$$

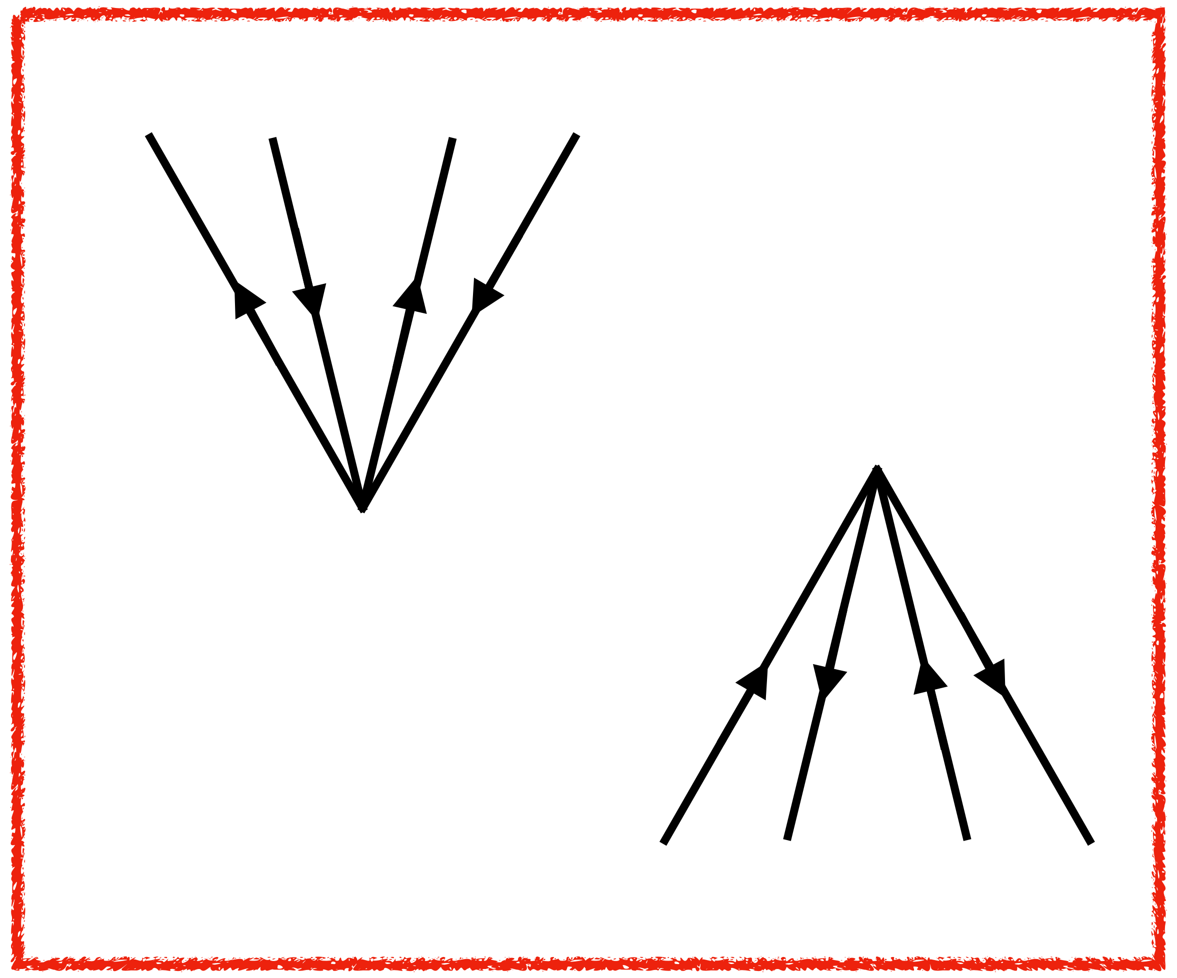
$$|\lambda\rangle = \Gamma^\dagger_\lambda|0\rangle \qquad \Gamma_\lambda|0\rangle = 0$$

TDA: $\Gamma^\dagger_\lambda = \sum_{ph} C^\lambda_{ph} d^\dagger_p b^\dagger_h$

RPA: $\Gamma^\dagger_\lambda = \sum_{ph} [X^\lambda_{ph} d^\dagger_p b^\dagger_h - \underline{Y^\lambda_{ph} b_h d_p}]$

backward-going amplitude





$d^\dagger b^\dagger db, d^\dagger d^\dagger b^\dagger b^\dagger, ddbb$ parts of

$$c^\dagger c^\dagger cc \sim a^\dagger a^\dagger aa \sim \begin{pmatrix} d^\dagger \\ b \end{pmatrix}\begin{pmatrix} d^\dagger \\ b \end{pmatrix}\begin{pmatrix} d \\ b^\dagger \end{pmatrix}\begin{pmatrix} d \\ b^\dagger \end{pmatrix}$$

RPA Hamiltonian

$$H^{\mathrm{RPA}} = E_{\mathrm{HF}} + \Delta E_{\mathrm{HF}} + \sum_{\lambda} \Omega_\lambda \Gamma^\dagger_\lambda \Gamma_\lambda$$

$$\Gamma^\dagger_\lambda = \sum_{ph} [X^\lambda_{ph} d^\dagger_p b^\dagger_h - Y^\lambda_{ph} b_h d_p] =: \sum_{ph} [X^\lambda_{ph} A^\dagger_{ph} - Y^\lambda_{ph} A_{ph}]$$

$$[H, \Gamma^\dagger_\lambda] = \Omega_\lambda \Gamma^\dagger_\lambda, \qquad [H, \Gamma_\lambda] = -\Omega_\lambda \Gamma_\lambda$$

like harmonic oscillator

⬍

RPA equation: $$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix} = \Omega_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix}$$

$$A_{php'h'} = \langle \Phi_{\mathrm{HF}} | [A_{ph}, [H, A^\dagger_{p'h'}]] | \Phi_{\mathrm{HF}} \rangle = (\varepsilon_p - \varepsilon_h)\delta_{pp'}\delta_{hh'} + \bar{v}_{ph'hp'},$$

$$B_{php'h'} = -\langle \Phi_{\mathrm{HF}} | [A_{ph}, [H, A_{p'h'}]] | \Phi_{\mathrm{HF}} \rangle = \bar{v}_{pp'hh'}$$

$$[A_{ph}, A^\dagger_{p'h'}] = [b_h d_p, d^\dagger_{p'} b^\dagger_{h'}] = \delta_{pp'}\delta_{hh'} - \underline{\delta_{pp'} b^\dagger_{h'} b_h + \delta_{hh'} d^\dagger_{p'} d_p}$$ deviation from the boson

quasi-boson approx. $\langle \Phi_{\mathrm{RPA}} | [A_{ph}, A^\dagger_{p'h'}] | \Phi_{\mathrm{RPA}} \rangle \approx \langle \Phi_{\mathrm{HF}} | [A_{ph}, A^\dagger_{p'h'}] | \Phi_{\mathrm{HF}} \rangle = \delta_{pp'}\delta_{hh'}$

normalization $$\langle \lambda | \lambda' \rangle = \delta_{\lambda\lambda'} = \langle \Phi_{\mathrm{RPA}} | [\Gamma_\lambda, \Gamma^\dagger_{\lambda'}] | \Phi_{\mathrm{RPA}} \rangle \approx \langle \Phi_{\mathrm{HF}} | [\Gamma_\lambda, \Gamma^\dagger_{\lambda'}] | \Phi_{\mathrm{HF}} \rangle = \sum_{ph} (X^{\lambda *}_{ph} X^{\lambda'}_{ph} - Y^{\lambda *}_{ph} Y^{\lambda'}_{ph})$$

Extension to the superfluid systems

superposition of two-quasiparticle excitations $\Gamma_\lambda^\dagger = \sum_{\mu\nu} [X_{\mu\nu}^\lambda a_\mu^\dagger a_\nu^\dagger - Y_{\mu\nu}^\lambda a_\nu a_\mu]$

$$H' = H - \lambda N$$

$$[H', \Gamma_\lambda^\dagger] = \Omega_\lambda \Gamma_\lambda^\dagger, \qquad [H', \Gamma_\lambda] = -\Omega_\lambda \Gamma_\lambda$$

like harmonic oscillator

⬍

Quasiparticle RPA equation:

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix} = \Omega_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix}$$

$$A_{\mu\nu,\mu'\nu'} = \langle \Phi_{\mathrm{HFB}} | [a_\nu a_\mu, [H', a_{\mu'}^\dagger a_{\nu'}^\dagger]] | \Phi_{\mathrm{HFB}} \rangle$$

$$B_{\mu\nu,\mu'\nu'} = -\langle \Phi_{\mathrm{HFB}} | [a_\nu a_\mu, [H', a_{\nu'} a_{\mu'}]] | \Phi_{\mathrm{HFB}} \rangle$$

Transition matrix elements

one-body operator $\hat{F} = \sum_{ij} F_{ij} c_i^\dagger c_j = \sum_{\mu\nu} F^{20}_{\mu\nu} a_\mu^\dagger a_\nu^\dagger + F^{02}_{\mu\nu} a_\nu a_\mu + \cdots$

matrix elements $\langle 0 | \hat{F} | \lambda \rangle = \langle 0 | \hat{F} \hat{\Gamma}_\lambda^\dagger | 0 \rangle = \langle 0 | [\hat{F}, \hat{\Gamma}_\lambda^\dagger] | 0 \rangle \approx \langle \Phi_{\mathrm{HFB}} | [\hat{F}, \hat{\Gamma}_\lambda^\dagger] | \Phi_{\mathrm{HFB}} \rangle$

quasi-boson approx.

$$\langle 0 | \hat{F} | \lambda \rangle = \langle 0 | \hat{F} \hat{\Gamma}_\lambda^\dagger | 0 \rangle \approx \langle \Phi_{\mathrm{HFB}} | \hat{F} \hat{\Gamma}_\lambda^\dagger | \Phi_{\mathrm{HFB}} \rangle$$

the ground-state correlation cannot be considered by replacing $|0\rangle$ with $|\Phi_{\mathrm{HFB}}\rangle$

collectivity: strong transition strength w.r.t. the single particle-hole ex.

Low-energy states: sensitive to the details of the shell structure around the Fermi level

High-energy state: corresponding to the classical picture of surface vibration

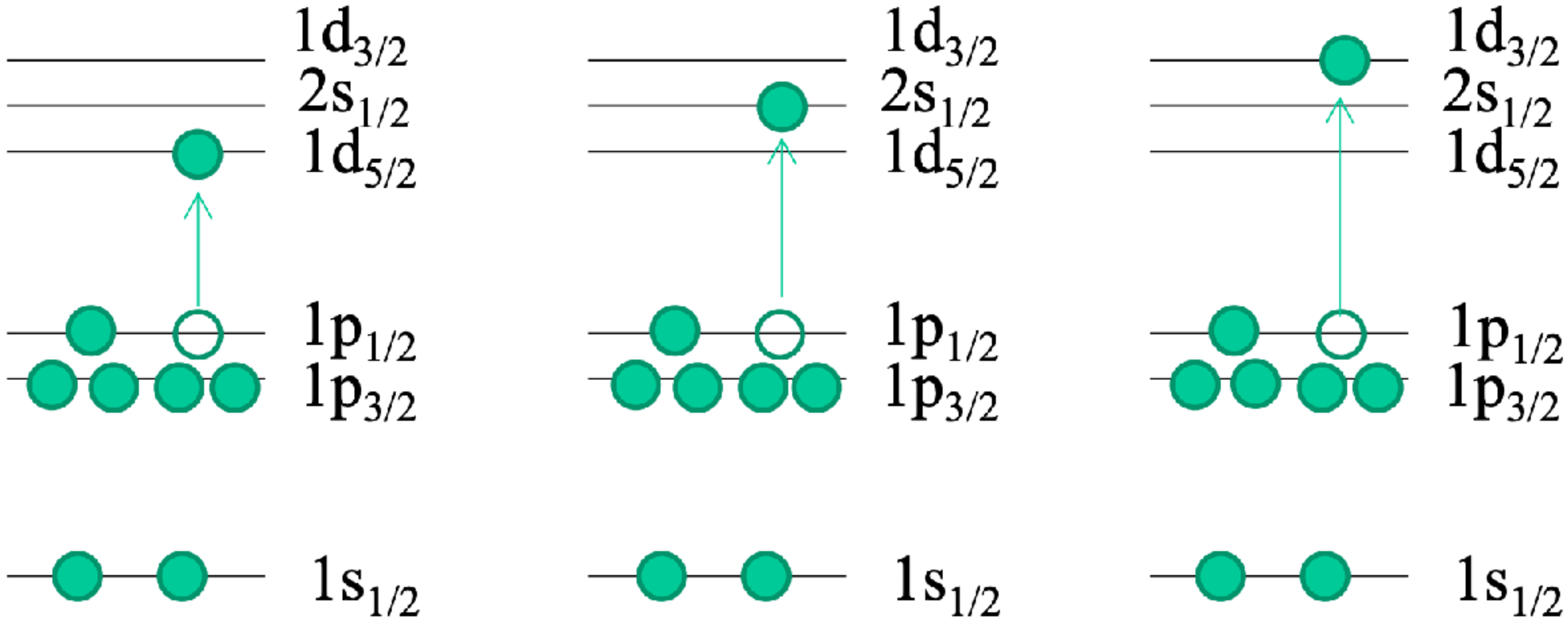
"Giant Resonances"

Some examples

TDA $$|\lambda\rangle = \sum_{ph} C^{\lambda}_{ph} d^{\dagger}_{p} b^{\dagger}_{h} |\Phi_{\mathrm{HF}}\rangle := \Gamma^{\dagger}_{\lambda} |\Phi_{\mathrm{HF}}\rangle$$

TDA eq. $$\sum_{p'h'} [(\varepsilon_{p'} - \varepsilon_{h'})\delta_{pp'}\delta_{hh'} + \bar{v}_{ph'hp'}]C^{\lambda}_{p'h'} = E_{\lambda} C^{\lambda}_{ph}$$

model space consisting of three configurations $\varepsilon_p - \varepsilon_h = \epsilon, \bar{v}_{ph'hp'} = g$



TDA for a simple case

$$H = \begin{pmatrix} \epsilon & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & \epsilon \end{pmatrix} + g \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

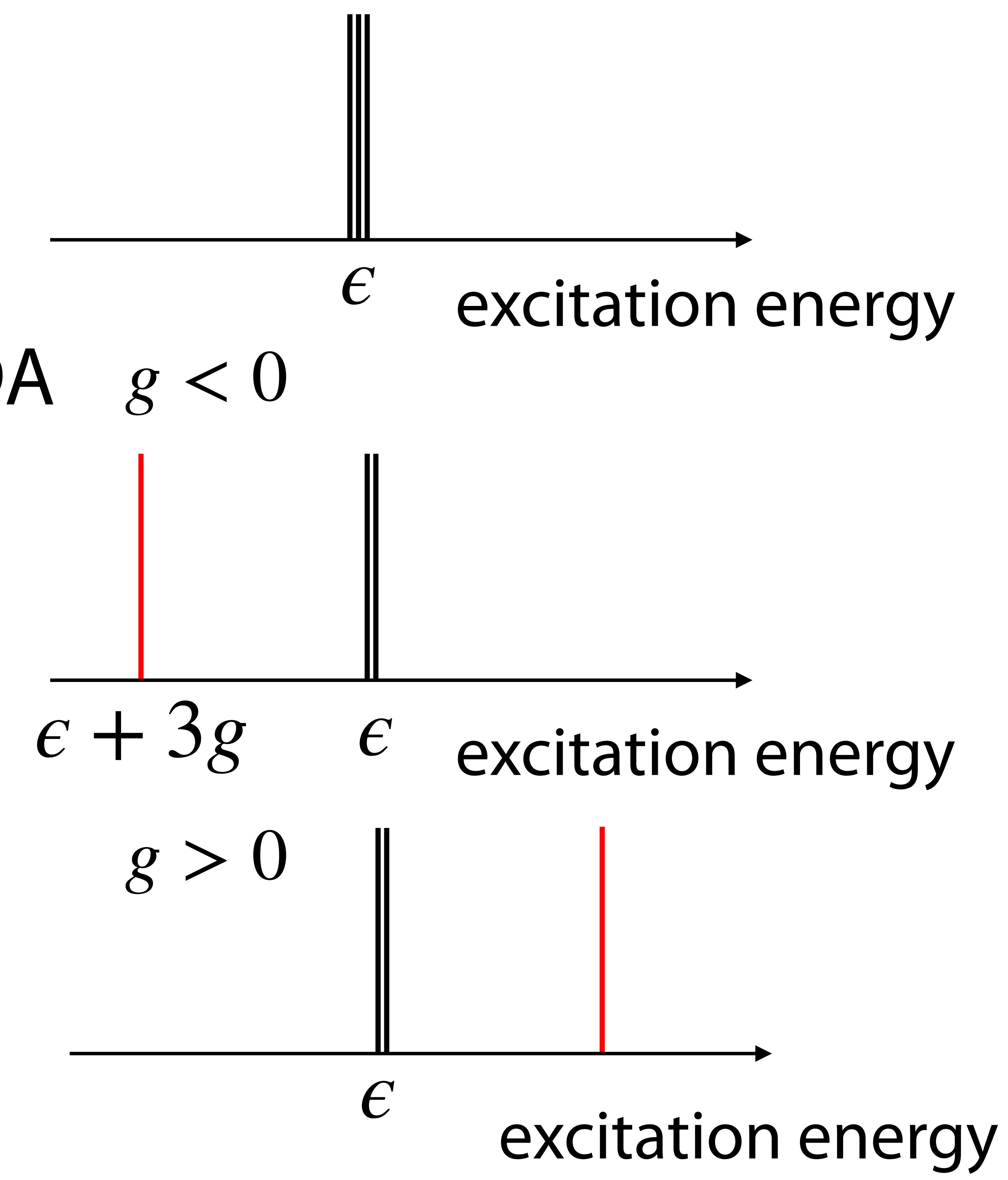
diagonalization

$$\lambda = \epsilon, \epsilon, \epsilon + 3g$$

when the interaction is attractive $g < 0$ (repulsive $g > 0$)

➡ low-energy state (high energy state)

unperturbed = mean field



TDA for a simple case

what is the structure of the collective state?

$$\lambda = \epsilon + 3g$$

$$\begin{pmatrix} \epsilon + g & g & g \\ g & \epsilon + g & g \\ g & g & \epsilon + g \end{pmatrix} \cdot \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = (\epsilon + 3g) \cdot \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

in-phase contribution of three ph excitations

=coherent superposition

the other states: $\frac{1}{\sqrt{6}} \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix}, \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}$

incoherent

TDA for a more realistic case

separable interaction: $\bar{v}_{ph'hp'} = \lambda D_{ph} D^*_{p'h'}$

QQ interaction: $D_{ph} = \langle ph | r^2 Y_{2\mu} | 0 \rangle = Q_{2\mu,ph}$

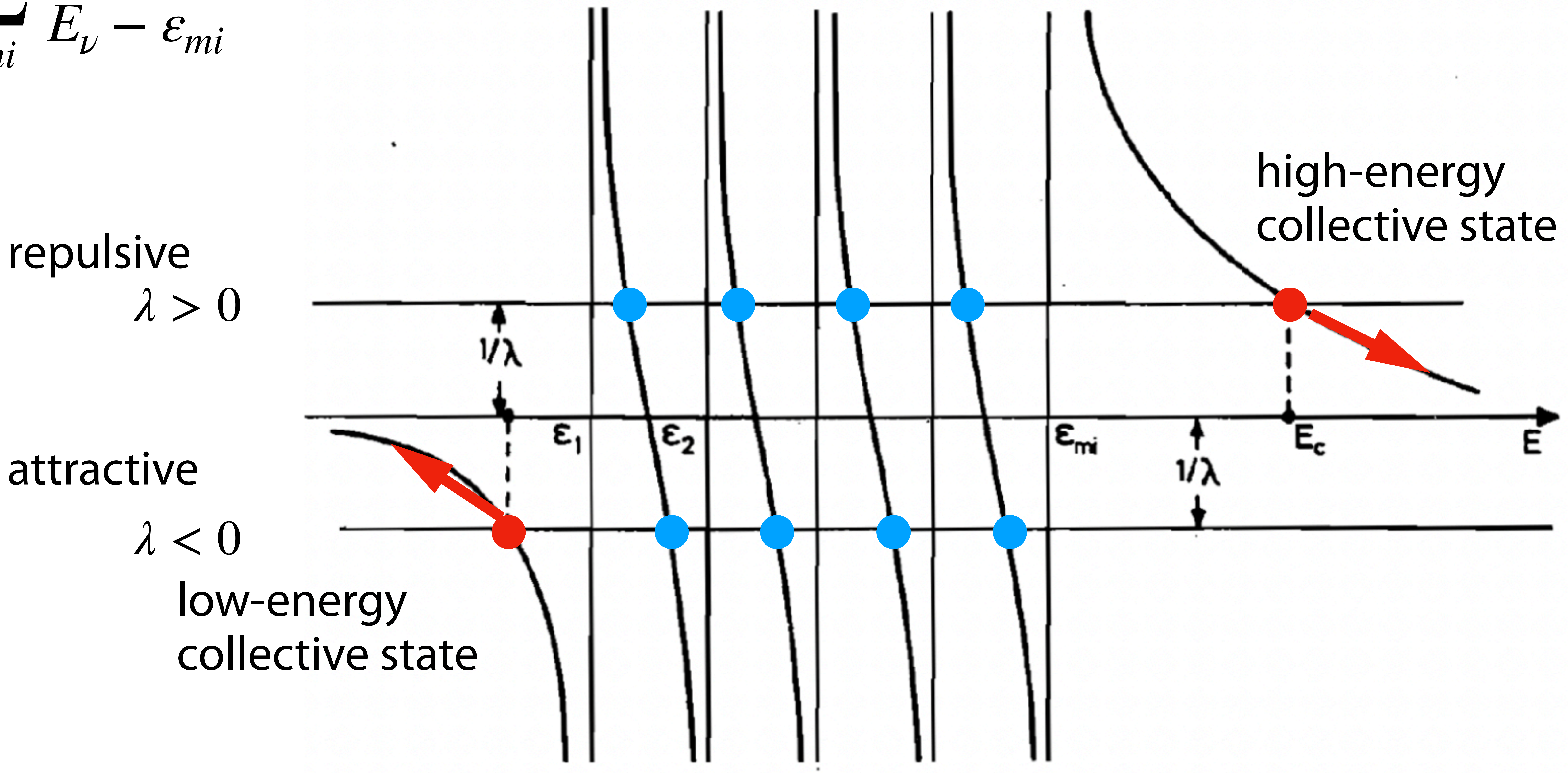
TDA equation $(E_\nu - \varepsilon_p + \varepsilon_h) C^\nu_{ph} = \lambda D_{ph} \sum_{p'h'} D^*_{p'h'} C^\nu_{p'h'}$

$$\Rightarrow \quad \frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E_\nu - \varepsilon_{ph}}, \qquad \varepsilon_{ph} = \varepsilon_p - \varepsilon_h$$

$$C^\nu_{ph} = \mathcal{N} \frac{D_{ph}}{E_\nu - \varepsilon_{ph}}, \quad \mathcal{N}^{-2} = \sum_{ph} \frac{|D_{ph}|^2}{(E_\nu - \varepsilon_{ph})^2},$$

TDA for a more realistic case

$$\frac{1}{\lambda} = \sum_{mi} \frac{|D_{mi}|^2}{E_\nu - \varepsilon_{mi}}$$



RPA with a separable interaction

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix} = \Omega_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix}$$

$$A_{php'h'} = \langle \Phi_{\rm HF} | [A_{ph}, [H, A^\dagger_{p'h'}]] | \Phi_{\rm HF} \rangle = (\varepsilon_p - \varepsilon_h)\delta_{pp'}\delta_{hh'} + \bar{v}_{ph'hp'},$$

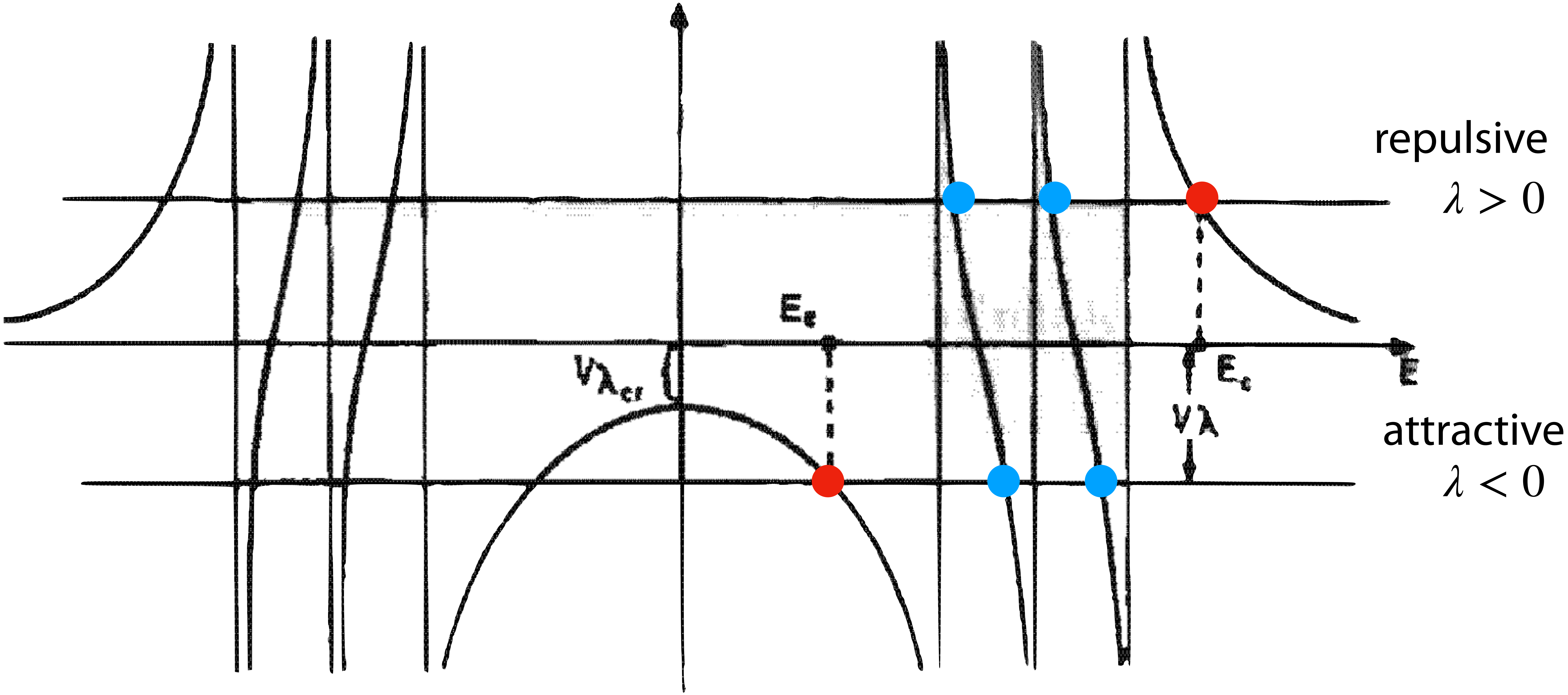
$$B_{php'h'} = -\langle \Phi_{\rm HF} | [A_{ph}, [H, A_{p'h'}]] | \Phi_{\rm HF} \rangle = \bar{v}_{pp'hh'}$$

$$\bar{v}_{ph'hp'} = \lambda D_{ph} D^*_{p'h'}$$

$$\bar{v}_{pp'hh'} = \lambda D_{ph} D_{p'h'}$$

$$\Rightarrow \quad \frac{1}{\lambda} = \sum_{ph} |D_{ph}|^2 \frac{2\varepsilon_{ph}}{\Omega_\nu^2 - \varepsilon_{ph}^2}, \qquad \varepsilon_{ph} = \varepsilon_p - \varepsilon_h$$

RPA with a separable interaction



Some features of RPA with $\lambda < 0$

① the low-energy state can have an imaginary solution

degenerated unperturbed states: $\varepsilon_{ph} = \epsilon$

$$E_{\mathrm{coll}}^2 = \epsilon^2 + 2\epsilon\lambda \sum_{ph} |D_{ph}|^2$$

$$\lambda_{\mathrm{crit}} = -\frac{\epsilon}{2\sum_{ph}|D_{ph}|^2}$$

② the low-energy state has an energy lower than in TDA

$$E_{\mathrm{coll}}^{\mathrm{TDA}}(\lambda_{\mathrm{crit}}) = \frac{\epsilon}{2}$$

$$E_{\mathrm{coll}}^{\mathrm{TDA}}(2\lambda_{\mathrm{crit}}) = 0$$

RPA dispersion

$$\frac{1}{\lambda} = \sum_{ph} |D_{ph}|^2 \frac{2\varepsilon_{ph}}{\Omega_\nu^2 - \varepsilon_{ph}^2}$$

TDA dispersion

$$\frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E_\nu - \varepsilon_{ph}}$$

$$E_{\mathrm{coll}}^{\mathrm{TDA}} = \epsilon + \lambda \sum_{ph} |D_{ph}|^2$$

Some features of RPA

③ larger transition strengths than in TDA

$$|\langle \nu | D | 0 \rangle|^2 = \left(\lambda^2 \sum_{ph} |D_{ph}|^2 \frac{4\varepsilon_{ph}\Omega_\nu}{(\Omega_\nu^2 - \varepsilon_{ph}^2)^2} \right)^{-1}$$

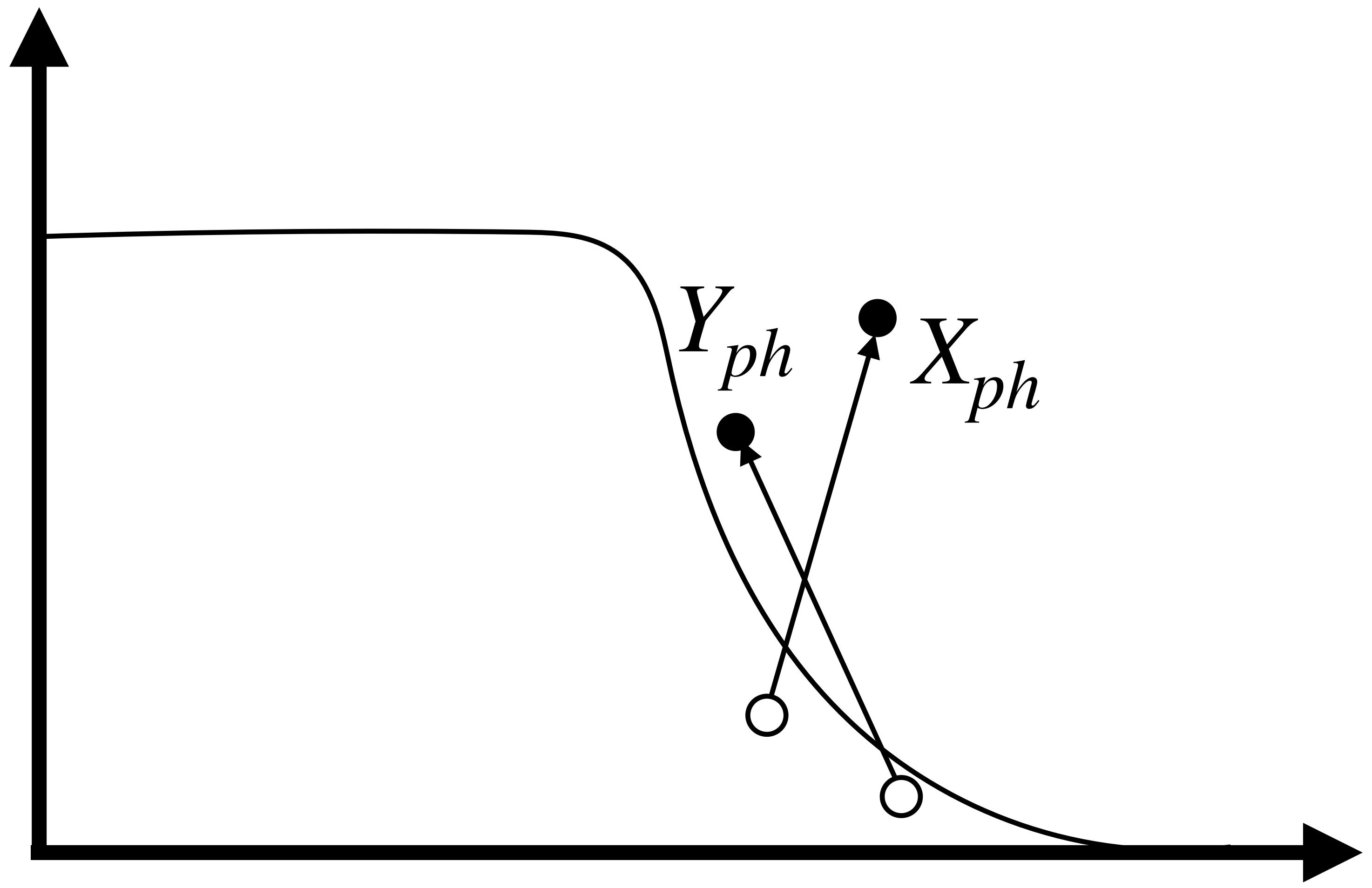
degenerate case

$$\Rightarrow \quad |\langle \nu | D | 0 \rangle|^2 = \frac{\epsilon}{E_{\rm coll}} \sum_{ph} |D_{ph}|^2$$

$$|\langle \nu | D | 0 \rangle|^2 = \sum_{ph} |D_{ph}|^2$$ for TDA

stronger collectivity than TDA thanks to the ground-state correlation

$$\Gamma_\lambda^\dagger = \sum_{ph} [X_{ph}^\lambda d_p^\dagger b_h^\dagger - \underline{Y_{ph}^\lambda b_h d_p}]$$



Sum rule

k-th moment of transition strengths $\quad m_k(F) = \sum_i (\hbar\omega_i)^k |\langle 0|\hat{F}|i\rangle|^2$

mean-energy of excited state $\quad E_\lambda = \sqrt{\frac{m_\lambda}{m_{\lambda-2}}}$

$k = 1$: energy-weighted sum rule (EWSR)

$$m_1(F) = \frac{1}{2}\langle[\hat{F},[\hat{H},\hat{F}]]\rangle = \frac{1}{2}\langle[\hat{F},[\hat{T},\hat{F}]]\rangle(1+\kappa) = \frac{\hbar^2}{2m}\int d\boldsymbol{r}\,|\nabla f(\boldsymbol{r})|^2\rho(\boldsymbol{r})(1+\kappa)$$

constant when $F \propto \sum_i r_i$

model independent

$k = -1$: dielectric theorem

$$m_{-1}(F) = \frac{1}{2}\frac{\partial^2}{\partial\lambda^2}\mathscr{E}[\mathscr{R}(\lambda)]\Big|_{\lambda=0} = \frac{1}{2}\frac{\partial}{\partial\lambda}\langle\phi(\lambda)|\hat{F}|\phi(\lambda)\rangle\Big|_{\lambda=0}$$

$|\phi(\lambda)\rangle$: HF(B) state with $-\lambda\hat{F}$

curvature of the total energy

Nuclear matter properties from the sum rule

$$m_k(F) = \sum_i (\hbar\omega_i)^k |\langle 0|\hat{F}|i\rangle|^2, \quad \hat{F} = \sum_i^A r_i^2$$

Isoscalar monopole

mean energy

$$\hat{H} \to \hat{H} + \lambda\hat{F}$$

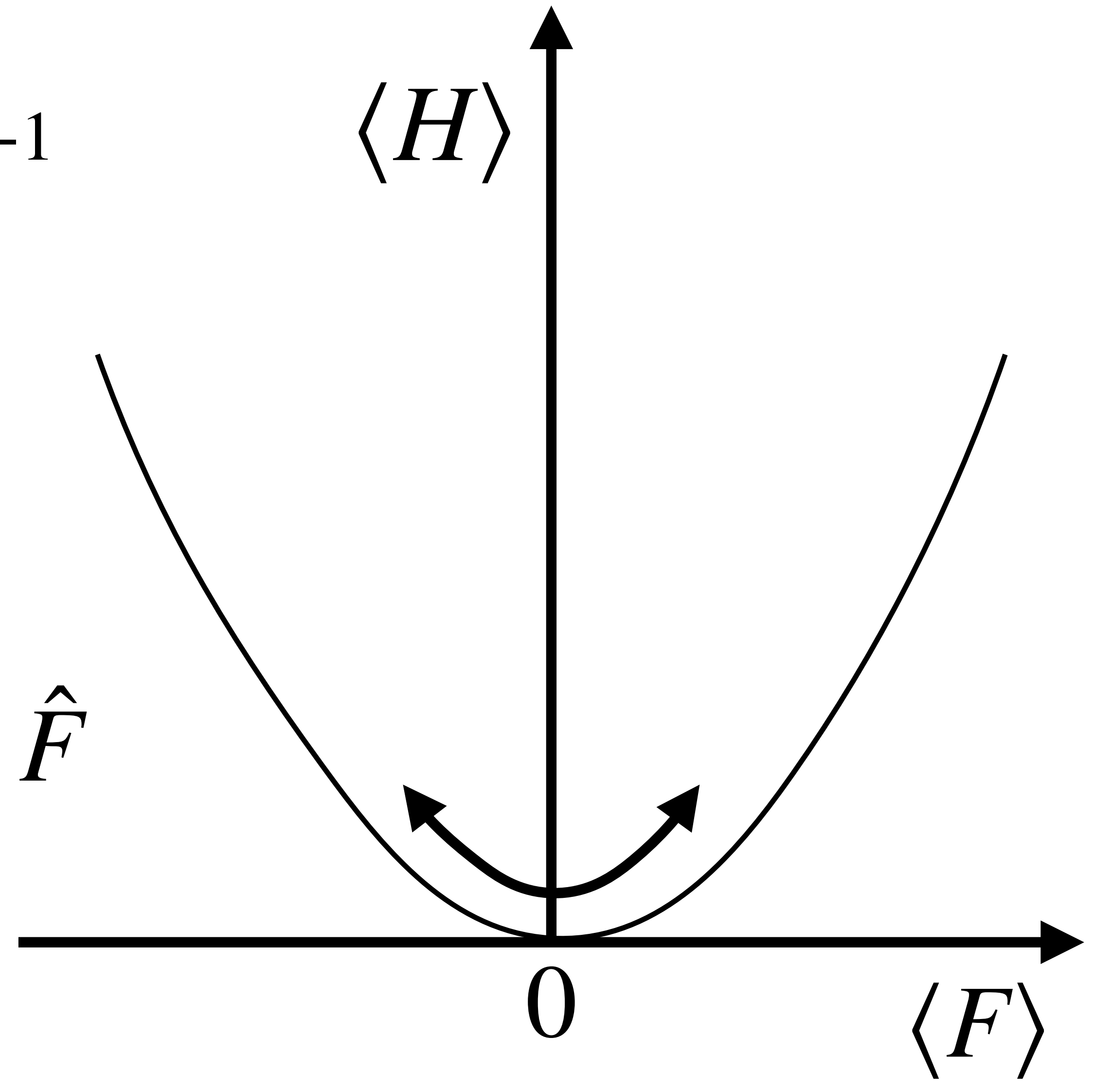
$$m_1 = \frac{1}{2}\frac{d^2}{d\eta^2}\langle\Phi_0|e^{-i\eta F} H e^{i\eta F}|\Phi_0\rangle\Big|_{\eta=0}$$

$$\bar{E} = \sqrt{\frac{m_1}{m_{-1}}}$$

$$m_1 = \frac{2\hbar^2}{m}A\langle r^2\rangle, \quad m_{-1} = \frac{1}{2}\frac{\partial^2\langle\hat{H}\rangle}{\partial\lambda^2}\Big|_{\lambda=0} = \frac{1}{2}\left(\frac{\partial^2\langle\hat{H}\rangle}{\partial\langle\hat{F}\rangle^2}\right)^{-1}$$

$$= \frac{1}{2}\chi_F$$

susceptibility in response to $\hat{F}$



$$= \sqrt{4\frac{\hbar^2}{m}\langle r^2\rangle\frac{\partial^2 E}{\partial\langle r^2\rangle^2}}$$

$$= \sqrt{4A\frac{\hbar^2}{m\langle r^2\rangle}\langle r^2\rangle^2\frac{\partial^2(E/A)}{\partial\langle r^2\rangle^2}}$$

$$=: \sqrt{K_A\frac{\hbar^2}{m\langle r^2\rangle}}$$

$$K_A = K_V + K_S A^{-1/3} + K_\tau\alpha^2 + K_C\frac{Z^2}{A^{4/3}}$$

Blaizot (1980)

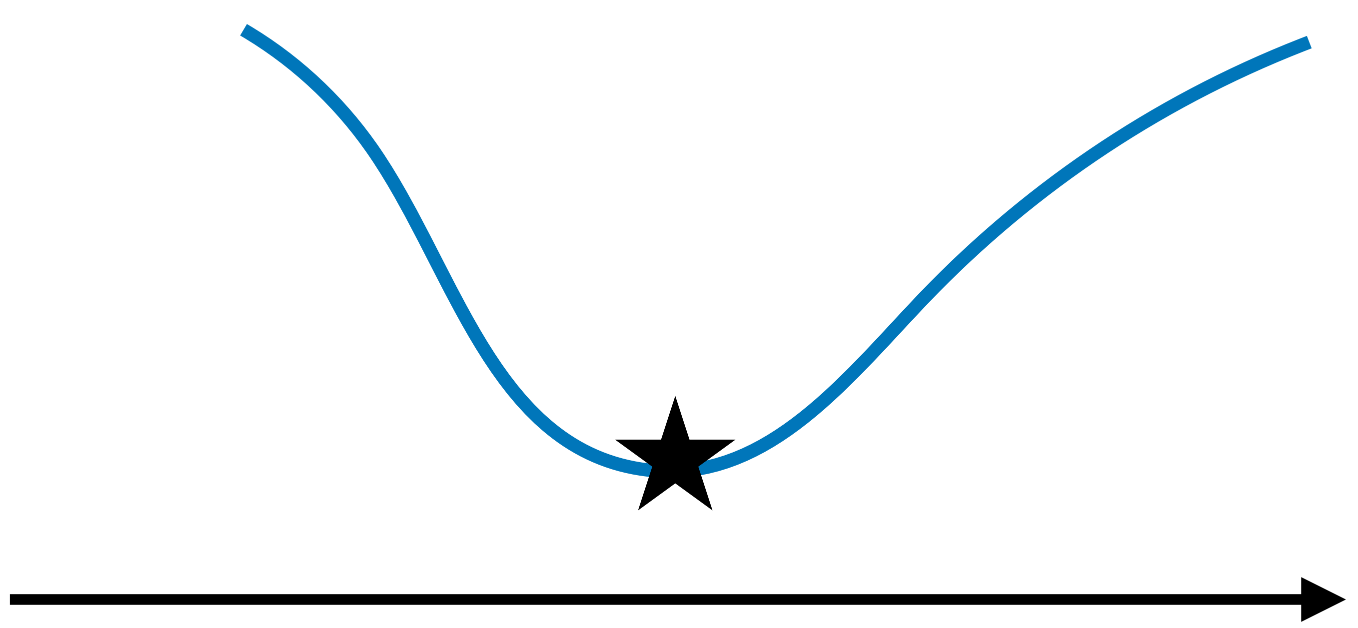
Stability of the mean-field solution

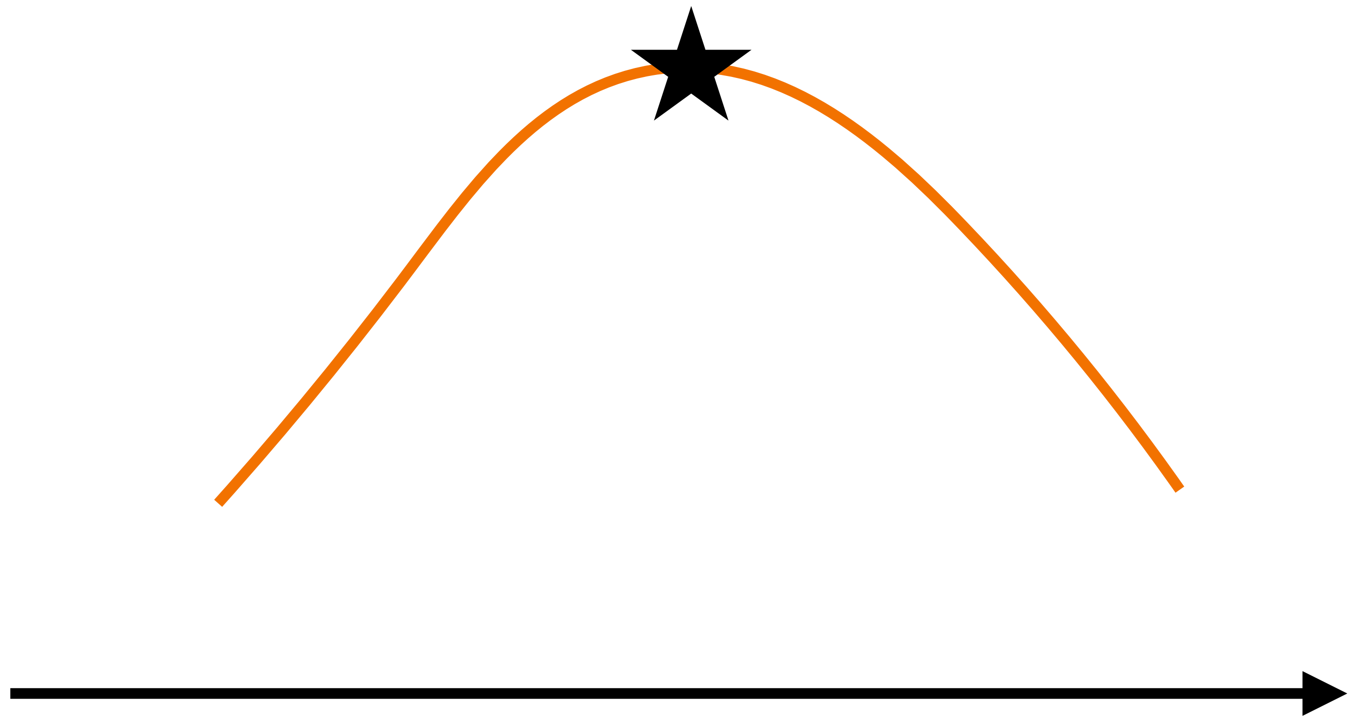
Solutions of the (Q)RPA : when X, Y, Ω is a solution, then $Y^*, X^*, -\Omega$ is also a solution

if the HF(B) is stable against any "deformation", all the Ω are real

if the HF(B) is unstable against some "deformation", Ω is imaginary

Nakada 2016, 2017





Ex.: spherical solution of HF(B) is unstable against the quadrupole deformation

➡ deformed state is energetically favored

PQ-representation of the (Q)RPA eq.

(Q)RPA eq. $[H', \Gamma_\lambda^\dagger] = \hbar\Omega_\lambda \Gamma_\lambda^\dagger, \qquad [H', \Gamma_\lambda] = -\hbar\Omega_\lambda \Gamma_\lambda$

same form in the HO potential ➡ coordinate and momentum

$$\mathscr{P}_\lambda = \frac{1}{i}\sqrt{\frac{M_\lambda \hbar \Omega_\lambda}{2}}(\Gamma_\lambda - \Gamma_\lambda^\dagger), \qquad \mathscr{Q}_\lambda = \sqrt{\frac{\hbar}{2M_\lambda\Omega_\lambda}}(\Gamma_\lambda + \Gamma_\lambda^\dagger)$$

$$[\mathscr{P}_\lambda, \mathscr{P}_{\lambda'}] = 0, \ [\mathscr{Q}_\lambda, \hat{\mathscr{Q}}_{\lambda'}] = 0 \qquad \langle \Phi_{\mathrm{HFB}} | [\mathscr{Q}_\lambda, \mathscr{P}_{\lambda'}] | \Phi_{\mathrm{HFB}} \rangle = \delta_{\lambda\lambda'}$$

(Q)RPA eq. in the PQ rep. $[H', \mathscr{P}_\lambda] = i\hbar\omega_\lambda M_\lambda \mathscr{Q}_\lambda, \qquad [H', \mathscr{Q}_\lambda] = -\frac{i\hbar}{M_\lambda}\mathscr{P}_\lambda$

$$H' = H - \lambda N = \mathrm{const} + \sum_\lambda \left(\frac{1}{2M_\lambda}\mathscr{P}_\lambda^2 + \frac{M_\lambda}{2}\Omega_\lambda^2 \mathscr{Q}_\lambda^2 \right)$$

PQ-representation of the (Q)RPA eq.

$$\mathscr{P}_\lambda = \sum_{\mu\nu} P^\lambda_{\mu\nu} a^\dagger_\mu a^\dagger_\nu + P^{\lambda *}_{\mu\nu} a_\nu a_\mu, \qquad \mathscr{Q}_\lambda = \sum_{\mu\nu} Q^\lambda_{\mu\nu} a^\dagger_\mu a^\dagger_\nu + Q^{\lambda *}_{\mu\nu} a_\nu a_\mu$$

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} P^\lambda \\ -P^{\lambda *} \end{pmatrix} = i\hbar \Omega^2_\lambda M_\lambda \begin{pmatrix} Q^\lambda \\ Q^{\lambda *} \end{pmatrix}$$

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} Q^\lambda \\ -Q^{\lambda *} \end{pmatrix} = \frac{\hbar}{i} \frac{1}{M_\lambda} \begin{pmatrix} P^\lambda \\ P^{\lambda *} \end{pmatrix}$$

normalization $\begin{pmatrix} Q^{\lambda *} & Q^\lambda \end{pmatrix} \begin{pmatrix} P^{\lambda'} \\ -P^{\lambda' *} \end{pmatrix} = i\hbar \delta_{\lambda\lambda'}$

The (Q)RPA defines the generalized coordinates and momenta on the HF(B) equilibrium.

Symmetries and the (Q)RPA

The HF(B) solutions breaks the symmetries

translational: locality

rotational: deformation

particle number: superfluidity

while the many-body Hamiltonian possesses the sym.：$[H', P] = 0, [H'_{\mathrm{MF}}, P] \neq 0$

QRPA eq. PQ rep. $[H', \mathscr{P}_\lambda] = i\hbar\omega_\lambda M_\lambda \mathscr{Q}_\lambda, \quad [H', \mathscr{Q}_\lambda] = -\frac{i\hbar}{M_\lambda}\mathscr{P}_\lambda$

⬇ $\hbar\omega_{\mathrm{sym}} = 0$

the zero-energy solution the (Q)RPA eq.

$[H', P]_{\mathrm{RPA}} = 0$

the broken sym. in the MFA is restored in the RPA

Symmetries and the (Q)RPA

$$H'_{\mathrm{RPA}} = \mathrm{const} + \frac{1}{2M_0}\mathscr{P}_0^2 + \sum_{\Omega_\lambda \neq 0}\left(\frac{1}{2M_\lambda}\mathscr{P}_\lambda^2 + \frac{M_\lambda}{2}\Omega_\lambda^2\mathscr{Q}_\lambda^2\right)$$

zero-energy solution

$$[H'_{\mathrm{RPA}}, \mathscr{P}_0] = 0$$

translational: $[H'_{\mathrm{RPA}}, R] = \frac{1}{iAm}P,\ [H'_{\mathrm{RPA}}, P] = 0,\ [R, P] = i$ $\quad M_0 = A$

rotational: $[H'_{\mathrm{RPA}}, \Omega] = \frac{1}{i\mathscr{J}}J_x,\ [H'_{\mathrm{RPA}}, J_x] = 0,\ [\Omega, J_x] = i$ $\quad M_0 = \mathscr{J}$

Thouless–Valatin moment of inertia

global U(1): $[H'_{\mathrm{RPA}}, \Theta] = \frac{1}{i\mathscr{M}}N,\ [H'_{\mathrm{RPA}}, N] = 0,\ [\Theta, N] = i$ $\quad M_0 = \mathscr{M}$

DFT for dynamics and excitations: TDDFT

$$\hat{H}(t) = \hat{T} + \hat{V}(t) + \hat{W}$$
$$= \int dx \hat{\psi}^\dagger(x)\left(-\frac{\hbar^2}{2m}\nabla^2\right)\hat{\psi}(x) + \int dx \hat{\psi}^\dagger(x) v(x,t)\hat{\psi}(x) + \frac{1}{2}\int\int dx dy \hat{\psi}^\dagger(x)\hat{\psi}^\dagger(y) w(x,y)\hat{\psi}(y)\hat{\psi}(x)$$

$$A(t_1, t_0) \equiv \int_{t_0}^{t_1} dt \langle\Psi(t)|i\hbar\partial_t - \hat{H}(t)|\Psi(t)\rangle$$

$$\frac{\delta A}{\delta\langle\Psi(t)|} = [i\hbar\partial_t - \hat{H}]|\Psi(t)\rangle = 0$$ ⟺ $|\Psi(t)\rangle$ A solution of TD Sch. eq.

E. Runge and E. K. U. Gross, PRL52(1984)997

Theorem 1: $|\Psi(t)\rangle = |\Psi[\rho, \Psi_0](t)\rangle$ ⟵ $\rho(r,t) \Longleftrightarrow v(r,t) \Longleftrightarrow \Psi(r,t)$

Action density functional $A[\rho] = \int_{t_0}^{t_1} dt \langle\Psi[\rho,\Psi_0](t)|i\hbar\partial_t - \hat{H}(t)|\Psi[\rho,\Psi_0](t)\rangle$

Theorem 2: $\frac{\delta A}{\delta\rho(r,t)} = 0$ ⟶ the exact density $\rho(r,t)$

Practical method for TDDFT: the Time Dependent Kohn-Sham equation

Reference system: without interactions

TDKS eq. $$i\partial_t \phi_i(r,t) = \left\{ -\frac{\hbar^2}{2m}\nabla^2 + v_s[\rho](r,t) \right\} \phi_i(r,t)$$

→ the exact density $\rho(r,t) = \sum_{i=1}^{N} |\phi_i(r,t)|^2$

Action density functional for the reference system

$$A_s[\rho] = B_s[\rho] - \int_{t_0}^{t_1} dt \int dr v_s[\rho](r,t)\rho(r,t)$$

$$B_s[\rho] = \int_{t_0}^{t_1} dt \langle \Psi[\rho](t) | i\partial_t - \hat{T} | \Psi[\rho](t) \rangle$$

Theorem 2 → $$\frac{\delta A_s[\rho]}{\delta \rho(r,t)} = \frac{\delta B_s[\rho]}{\delta \rho(r,t)} - v_s(r,t) = 0$$

$$v_s[\rho](r,t) = v(r,t) + \frac{\delta A_{\text{eff}}[\rho]}{\delta \rho(r,t)}$$

Interacting system

Action density functional

$$A[\rho] = B[\rho] - \int_{t_0}^{t_1} dt \int dr v(r,t)\rho(r,t)$$

$$= B_s[\rho] - \int_{t_0}^{t_1} dt \int dr v(r,t)\rho(r,t) + \{B[\rho] - B_s[\rho]\}$$

$$= B_s[\rho] - \int_{t_0}^{t_1} dt \int dr v(r,t)\rho(r,t) - A_{\text{eff}}[\rho]$$

$$B[\rho] = \int_{t_0}^{t_1} dt \langle \Psi[\rho,\Psi_0](t) | i\partial_t - \hat{T} - \hat{W} | \Psi[\rho,\Psi_0](t) \rangle$$

Theorem 2 → $$\frac{\delta A[\rho]}{\delta \rho(r,t)} = \frac{\delta B_s[\rho]}{\delta \rho(r,t)} - v(r,t) - \frac{\delta A_{\text{eff}}[\rho]}{\delta \rho(r,t)} = 0$$

$\rho(r,t)$

the exact density of the int. system

Linear-response TDDFT for vibrational modes: RPA

for t<0

$$h_0(r)\phi_i(r) = \epsilon_i\phi_i(r)$$
$$h_0(r) = h[\rho_0](r)$$
$$\rho_0(r) = \sum_i |\phi_i(r)|^2$$

$$v(r,t) = \begin{cases} 0 & \text{for} \quad t \le 0 \\ v_{\text{ext}}(r,t) & \text{for} \quad t > 0 \end{cases}$$

perturbing field oscillates at a frequency ω

$$v_{\text{ext}}(r,t) = v_{\text{ext}}(r)e^{-i\omega t} + v^*_{\text{ext}}(r)e^{i\omega t}$$

TDKS eq. for t>0

$$i\partial_t\psi_i(r,t) = \{h[\rho](r,t) + v_{\text{ext}}(r,t)\}\psi_i(r,t)$$
$$\rho(r,t) = \sum_i |\psi_i(r,t)|^2$$
$$h[\rho](r,t) = -\frac{\hbar^2}{2m}\nabla^2 + \frac{\delta A_{\text{eff}}[\rho]}{\delta\rho}$$

transition density also oscillates at a frequency ω

$$\rho(r,t) = \rho_0(r) + \delta\rho(r,t)$$
$$\delta\rho(r,t) = \sum_i \phi^*_i(r)\delta\psi_i(r,t) + \phi_i(r)\delta\psi^*_i(r,t)$$

$$\delta\rho(r,t) = \delta\rho(r)e^{-i\omega t} + \delta\rho^*(r)e^{i\omega t}$$
$$\delta\psi_i(r,t) = f_i(r)e^{-i\omega t} + g_i(r)e^{i\omega t}$$

Oscillation around the ground state:

$$\psi_i(r,t) = (\phi_i(r) + \delta\psi_i(r,t))e^{-i\epsilon_i t}$$

Linearized TDKS eq.

$$i\partial_t\delta\psi_i(r,t) = (h_0(r)-\epsilon_i)\delta\psi_i(r,t) + \left(\int dr'dt' \frac{\delta h[\rho](r,t)}{\delta\rho(r',t')}\delta\rho(r',t) + v_{\text{ext}}(r,t)\right)\phi_i(r)$$

$$X_{mi} = \int dr\phi^*_m(r)f_i(r)$$
$$Y_{mi} = \int dr\phi^*_m(r)g_i(r)$$

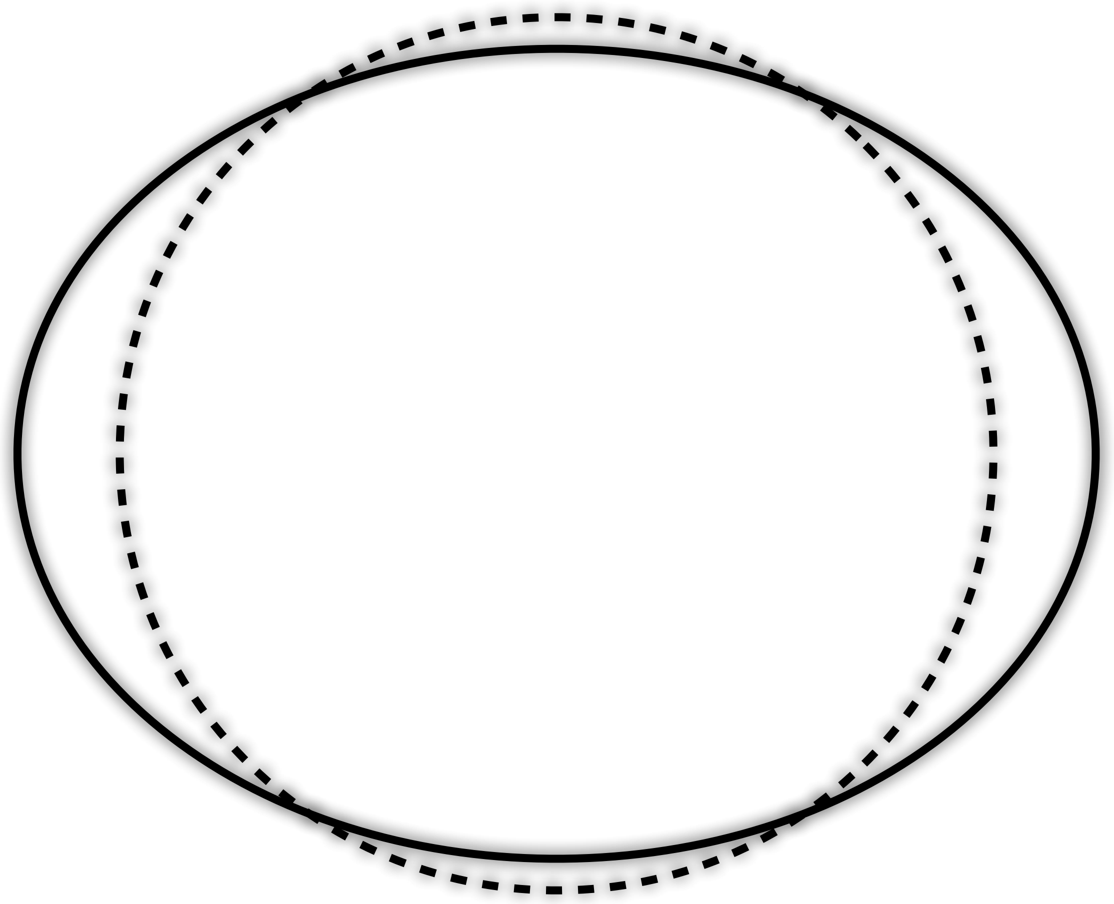
RPA eq.

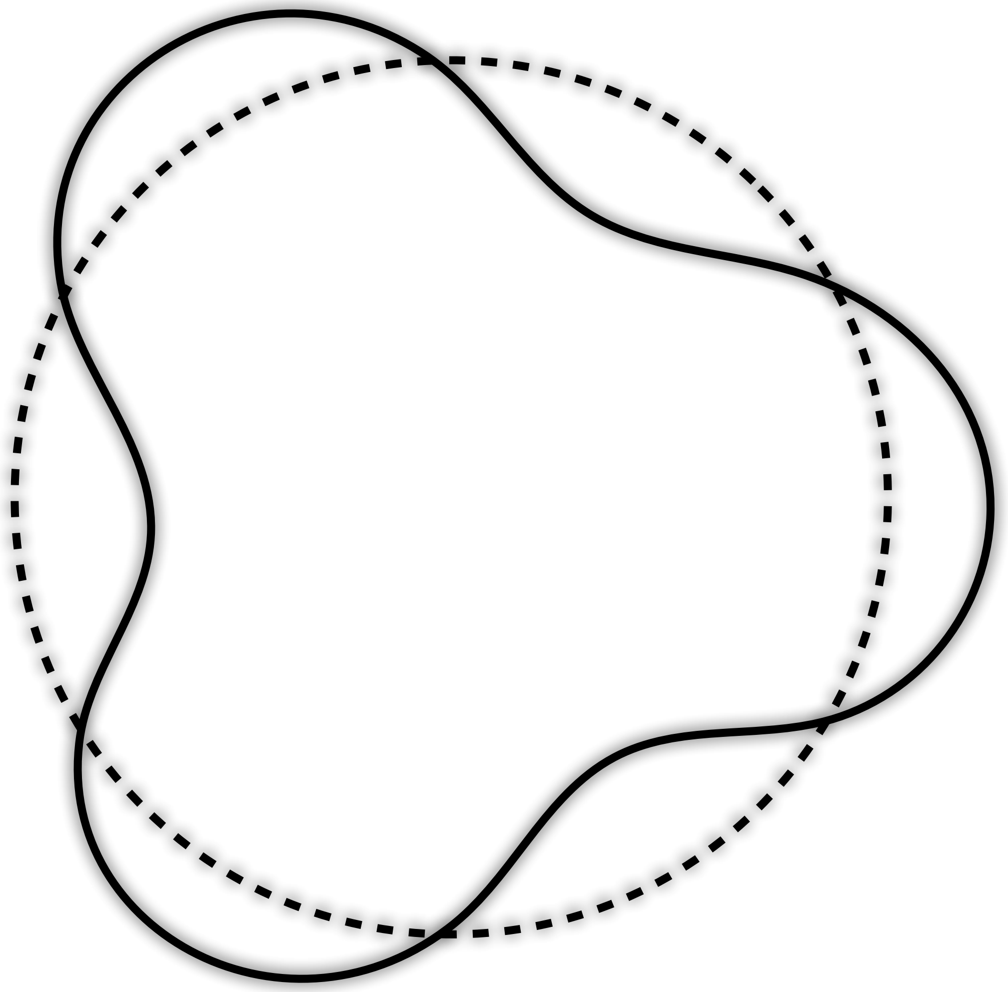
$$\omega X_{mi} = (\epsilon_m - \epsilon_i)X_{mi} + \sum_{nj}\iint drdr'\phi^*_m(r)\phi^*_j(r')\frac{\delta h}{\delta\rho}\phi_i(r)\phi_n(r')X_{nj} + \sum_{nj}\iint drdr'\phi^*_m(r)\phi^*_n(r')\frac{\delta h}{\delta\rho}\phi_i(r)\phi_j(r')Y_{nj}$$

$$-\omega Y_{mi} = (\epsilon_m - \epsilon_i)X_{mi} + \sum_{nj}\iint drdr'\phi^*_m(r)\phi^*_j(r')\frac{\delta h}{\delta\rho}\phi_i(r)\phi_n(r')Y_{nj} + \sum_{nj}\iint drdr'\phi^*_m(r)\phi^*_n(r')\frac{\delta h}{\delta\rho}\phi_i(r)\phi_j(r')X_{nj}$$

Vibrational modes of excitation

Rich variety of collective vibrations





GR is strongly excited by a one-body operator, and exhausts a **sum-rule value**

$$F = \sum_{\sigma,\sigma'} \sum_{\tau,\tau'} \int d\boldsymbol{r} r^L Y_L(\hat{r}) \psi^\dagger(\boldsymbol{r}\sigma\tau) \langle\sigma| \begin{Bmatrix} 1 \\ \vec{\sigma} \end{Bmatrix} |\sigma'\rangle \langle\tau| \begin{Bmatrix} 1 \\ \vec{\tau} \end{Bmatrix} |\tau'\rangle \psi(\boldsymbol{r}\sigma'\tau')$$

space spin isospin

Collective modes of excitation in deformed nuclei

nuclear DFT for Quasiparticle-RPA in deformed nuclei

pairing and deformation taken into account

Skyrme EDF

Matrix-QRPA
- K. Yoshida et al., PRC78(2008)064316
- C. Losa et al., PRC81(2010)064307
- J. Terasaki et al., PRC82(2010)034326

LR-TDDFT
- S. Ebata et al., PRC82(2010)034306
- G. Scamps et al., PRC89(2014)034314

FAM-QRPA
- M. Stoitsov et al., PRC84(2011)041305
- M. Kortelainen et al., PRC92(2015)051302R
- K. Washiyama et al., PRC96(2017)041304R

Gogny EDF

S. Péru et al., PRC77(2008)044313

Relativistic EDF

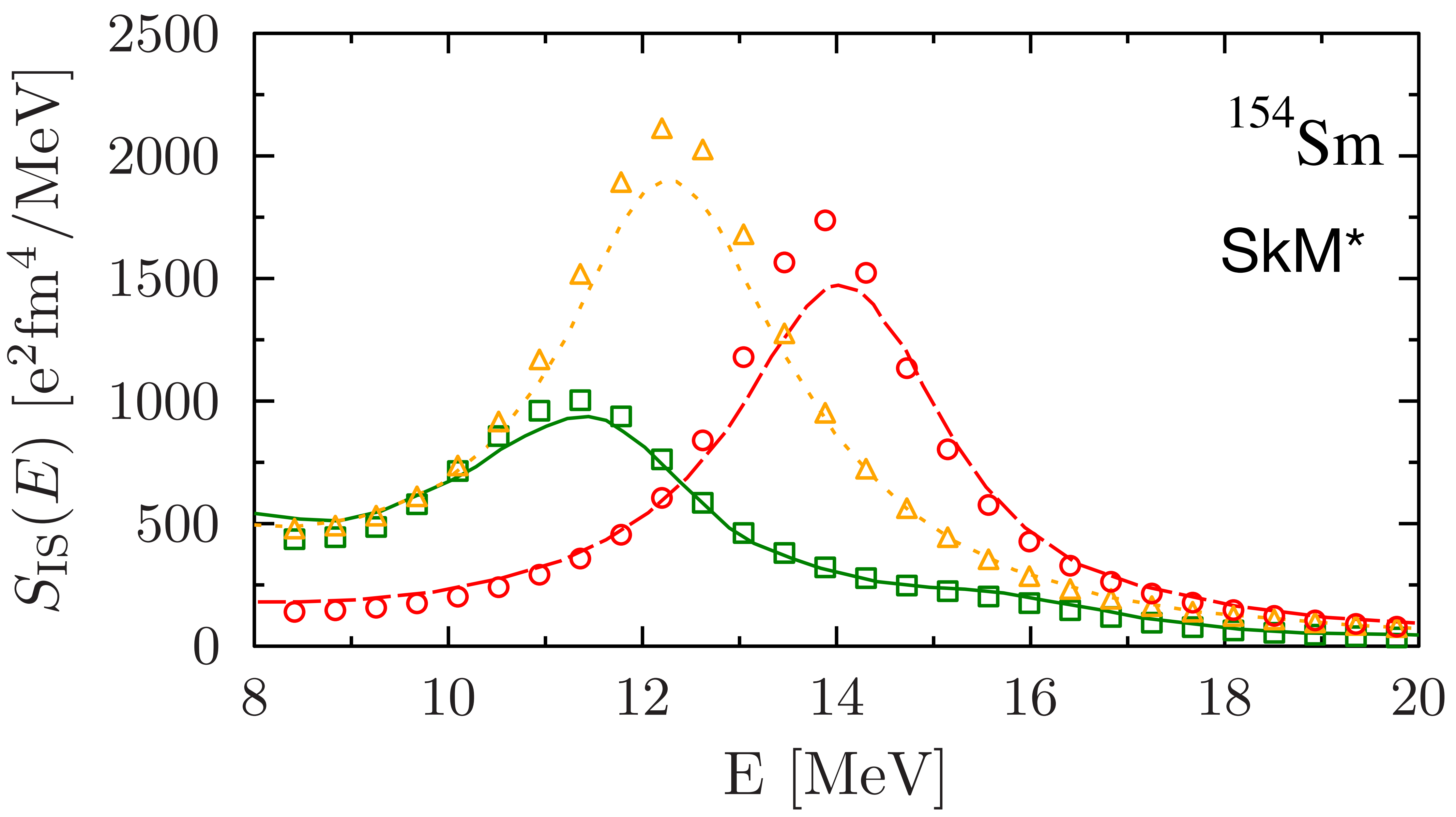
D. P. Arteaga et al., PRC79(2009)034311

T. Nikšić et al., PRC88(2013)044327

QRPA and LR-TDDFT(BCS)

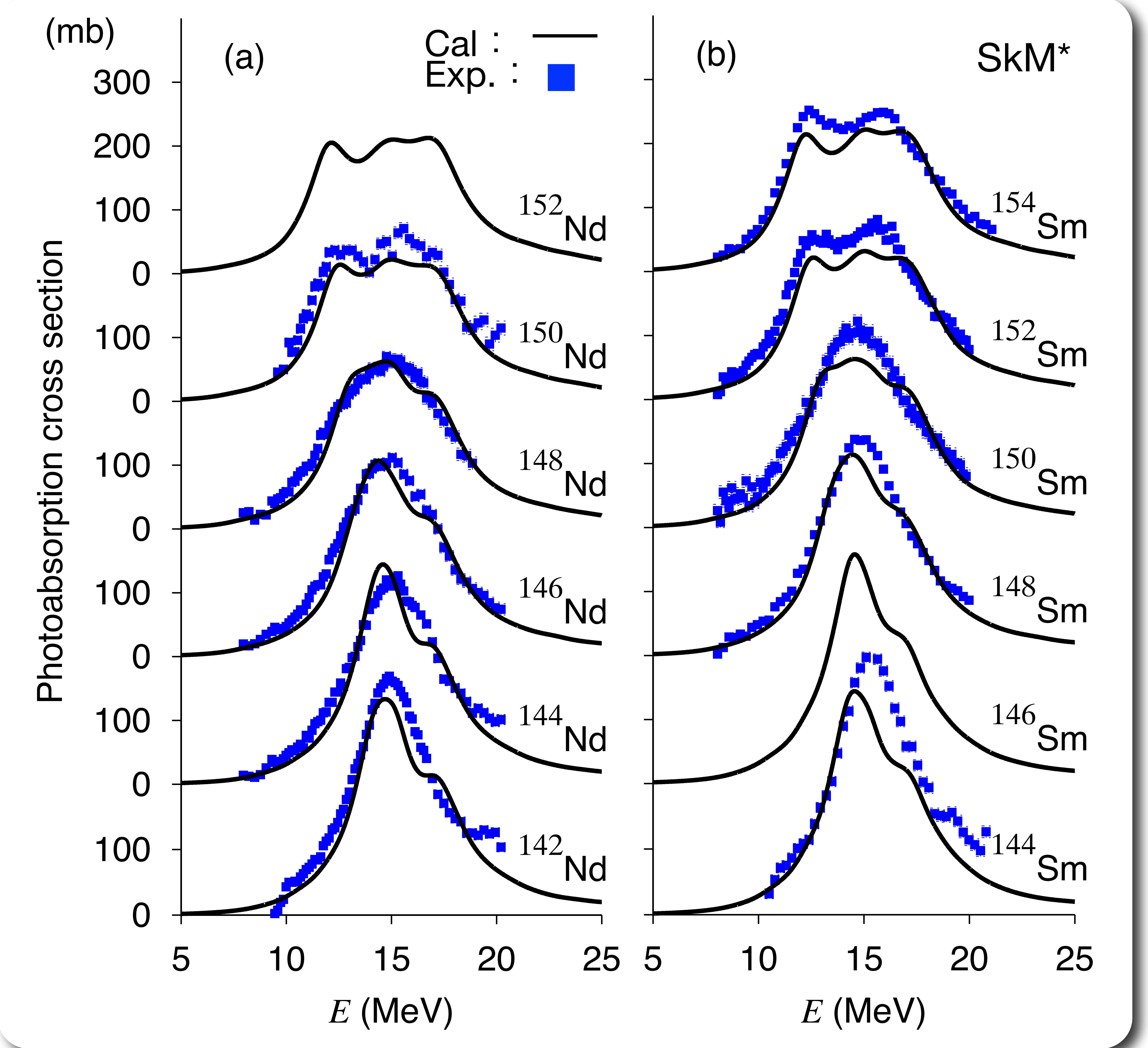
Scamps et al.

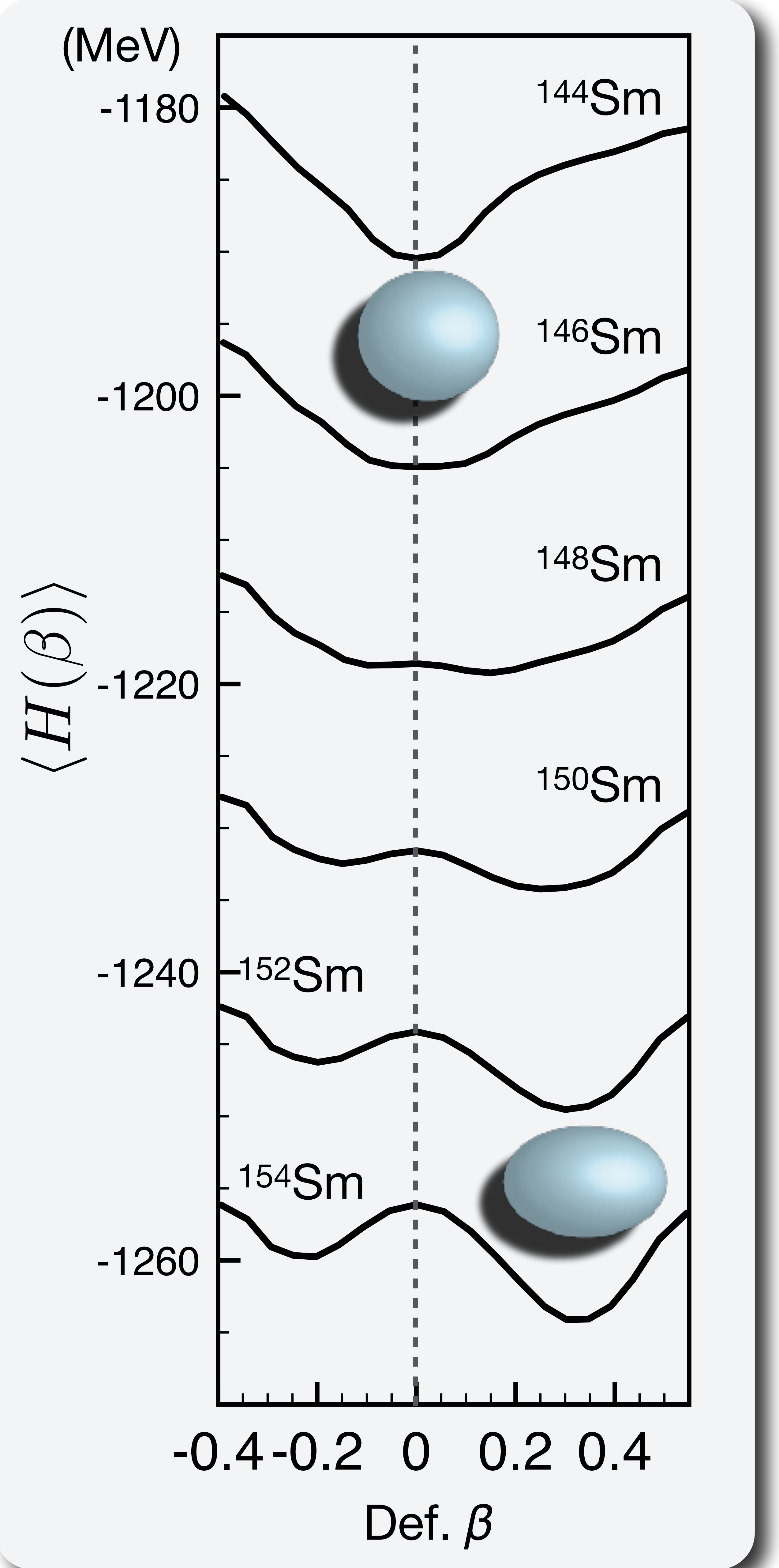
Giant Quadrupole Resonance (GQR)



KY, T. Nakatsukasa, PRC83(2011)021304R

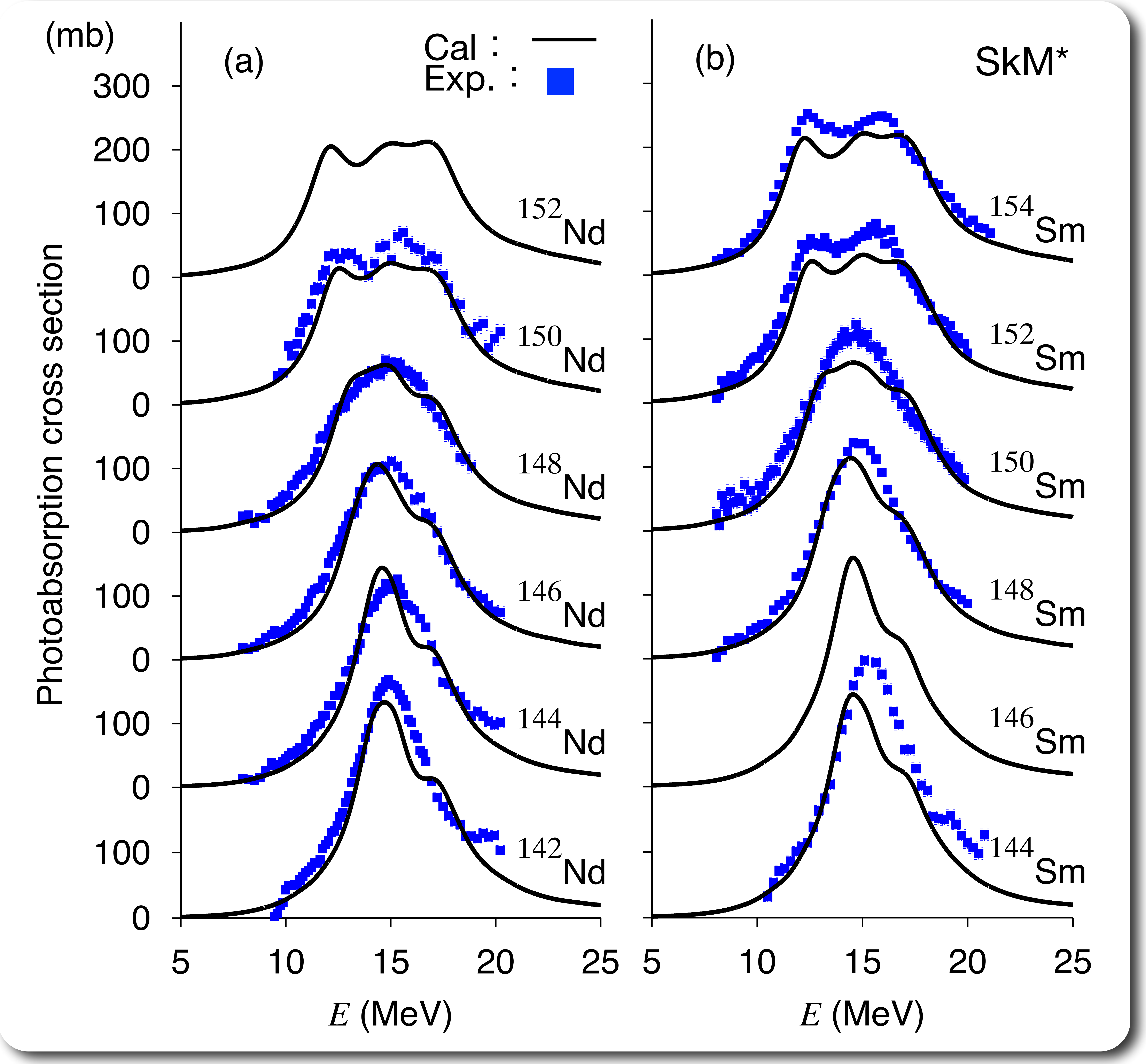
Shape evolution seen in Giant Dipole Resonance





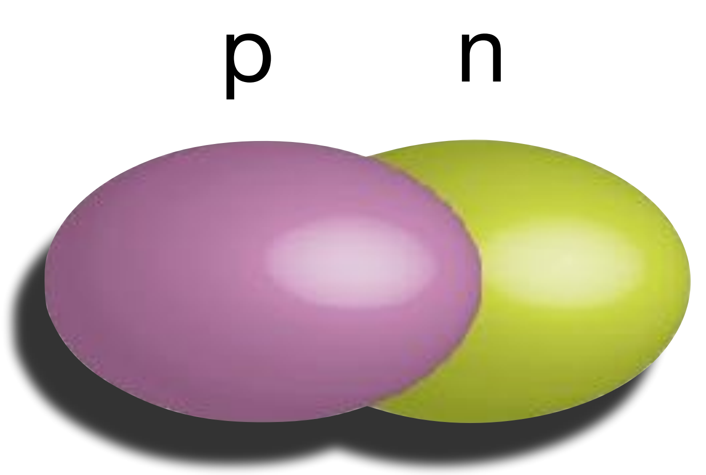
KY, T. Nakatsukasa, PRC83(2011)021304R

Shape evolution seen in Giant Dipole Resonance

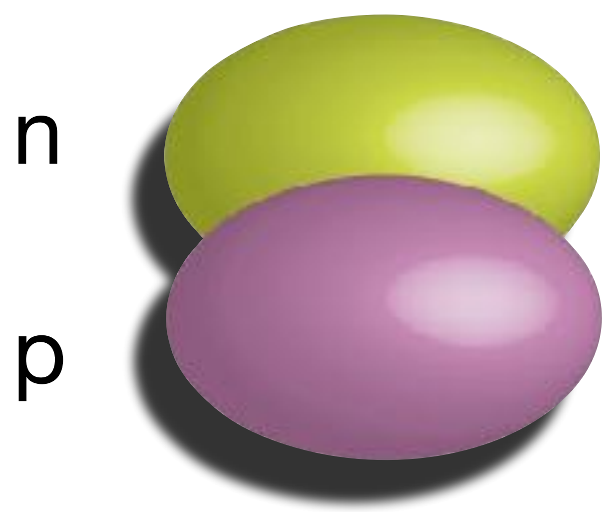


collective oscillation $\omega \propto \frac{1}{R}$

$\omega_{\parallel} \propto \frac{1}{R_{\parallel}}$ $\omega_{\perp} \propto \frac{1}{R_{\perp}}$



K=0



K=1

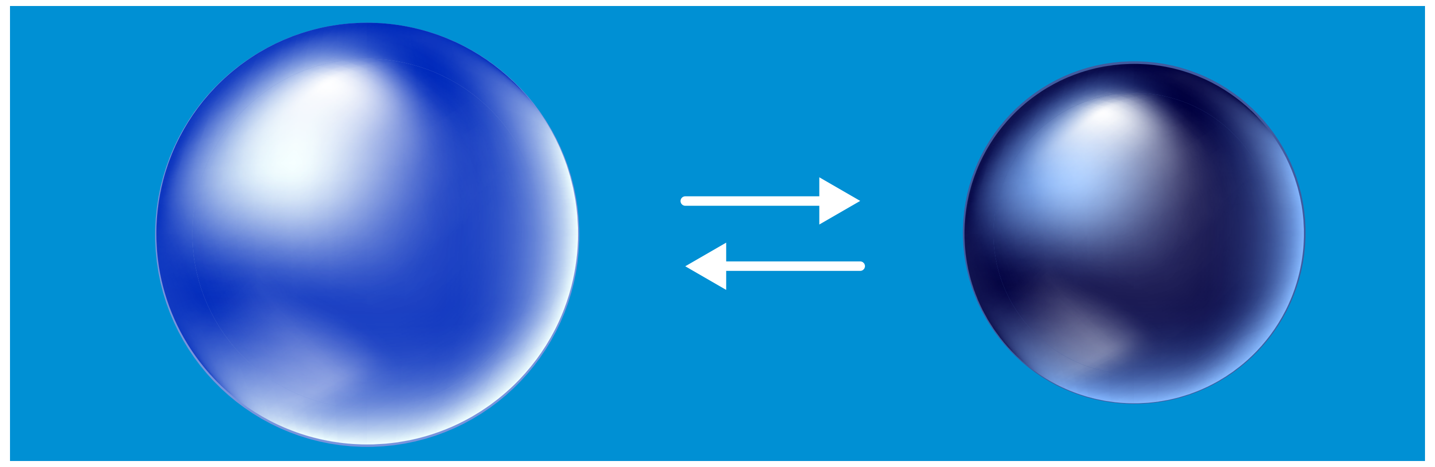
classically understood

Deformation effect in Giant Monopole Resonance?

$$F = \int d\vec{r} r^2 \psi^\dagger(\vec{r})\psi(\vec{r})$$

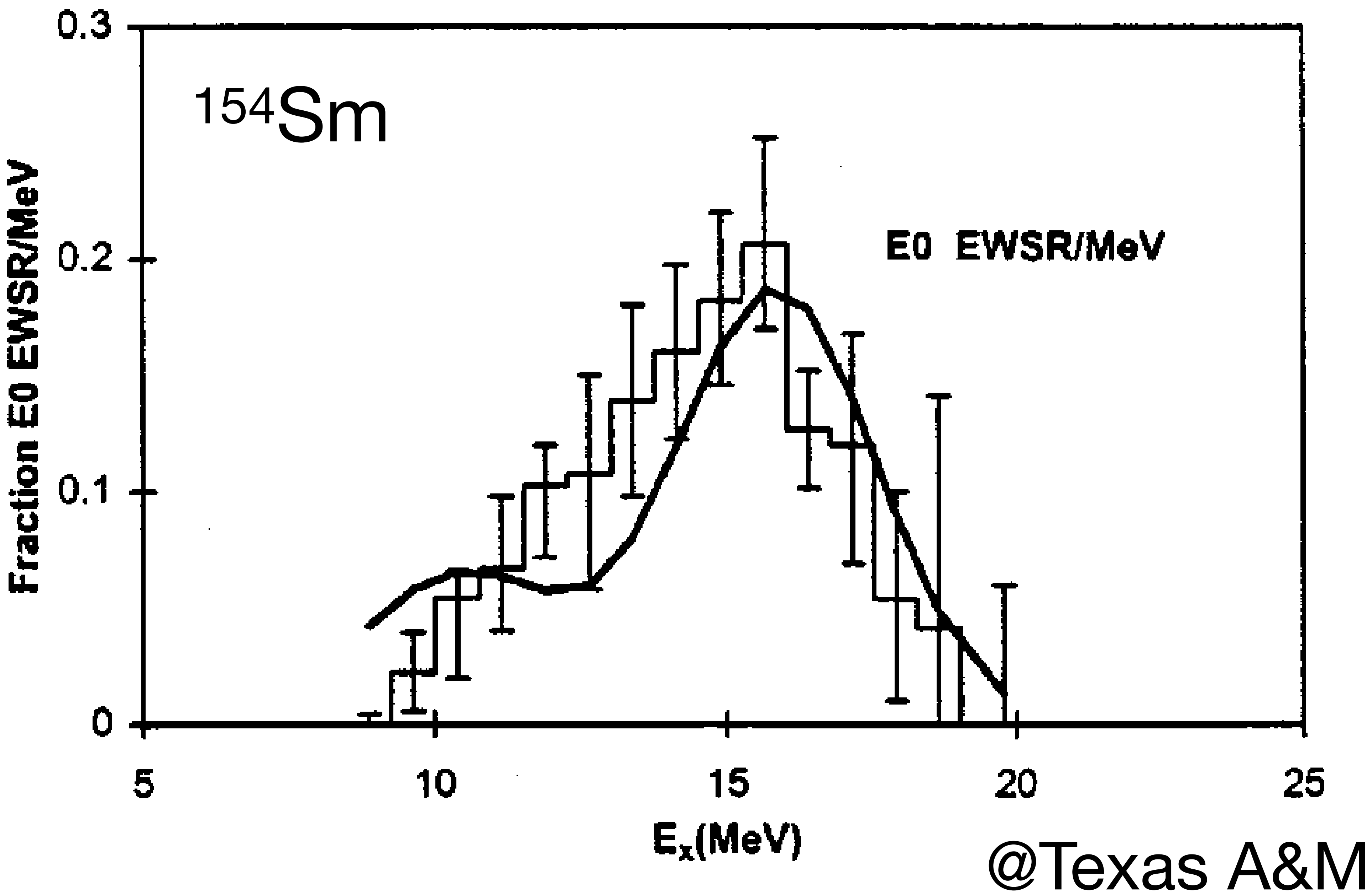
volume change ⟷ incompressibility of nuclear matter

J.-P. Blaizot,
Phys. Rep. 64(1980)171

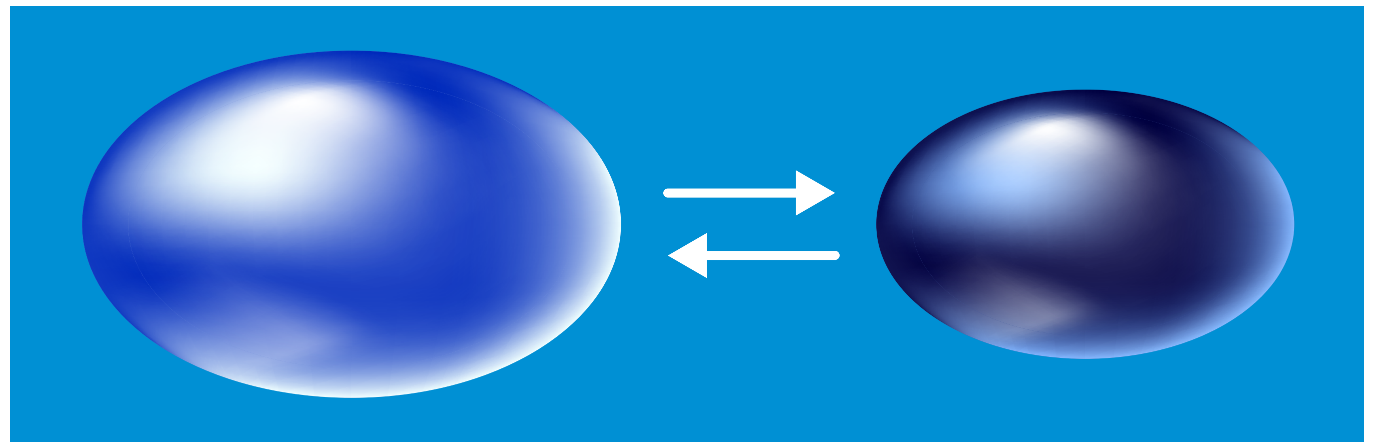


deformation splitting?

U. Garg, *et al*., PRL45(1980)1670
D. H. Youngblood, *et al*., PRC60(1999)067302



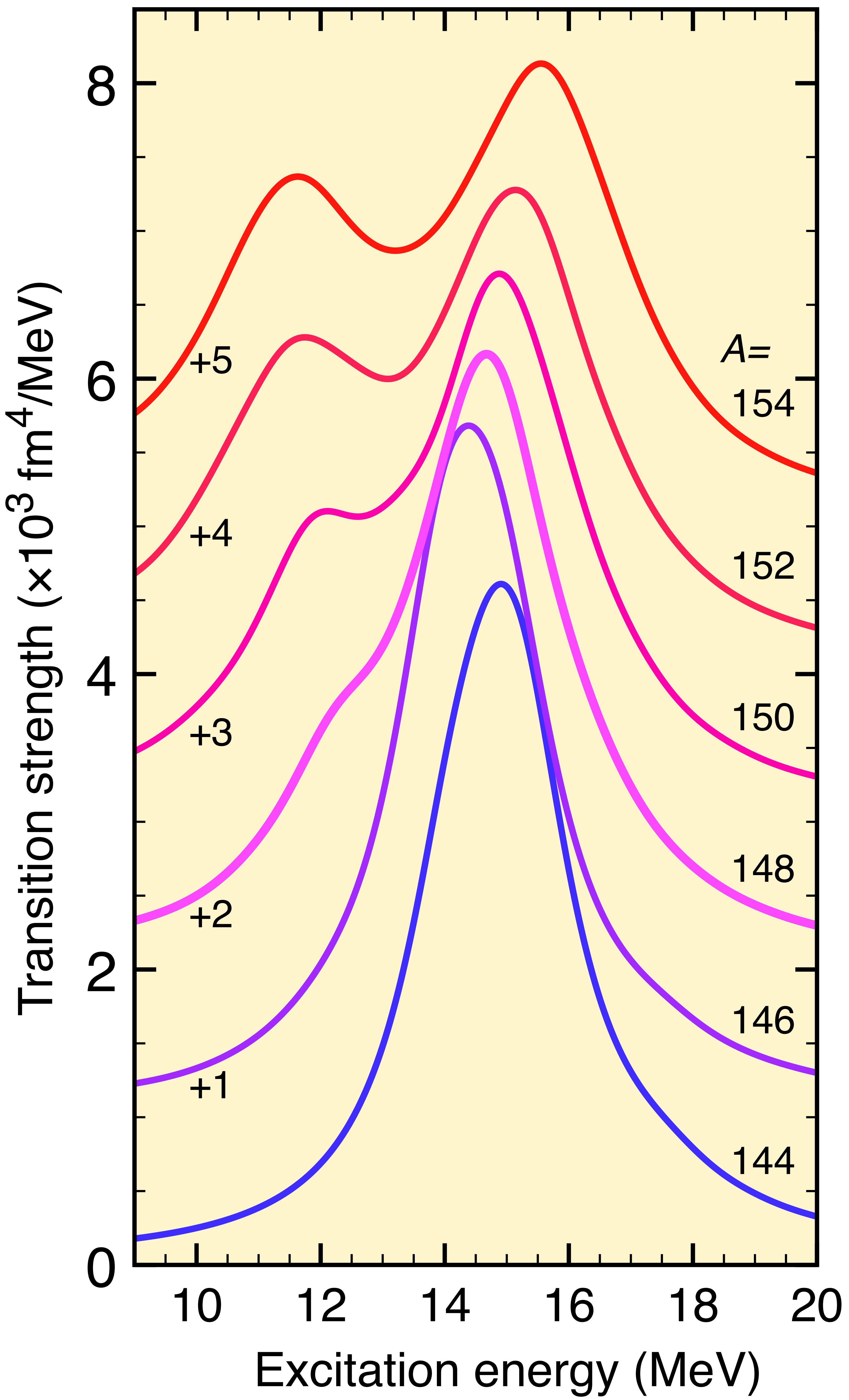
@Texas A&M Univ.

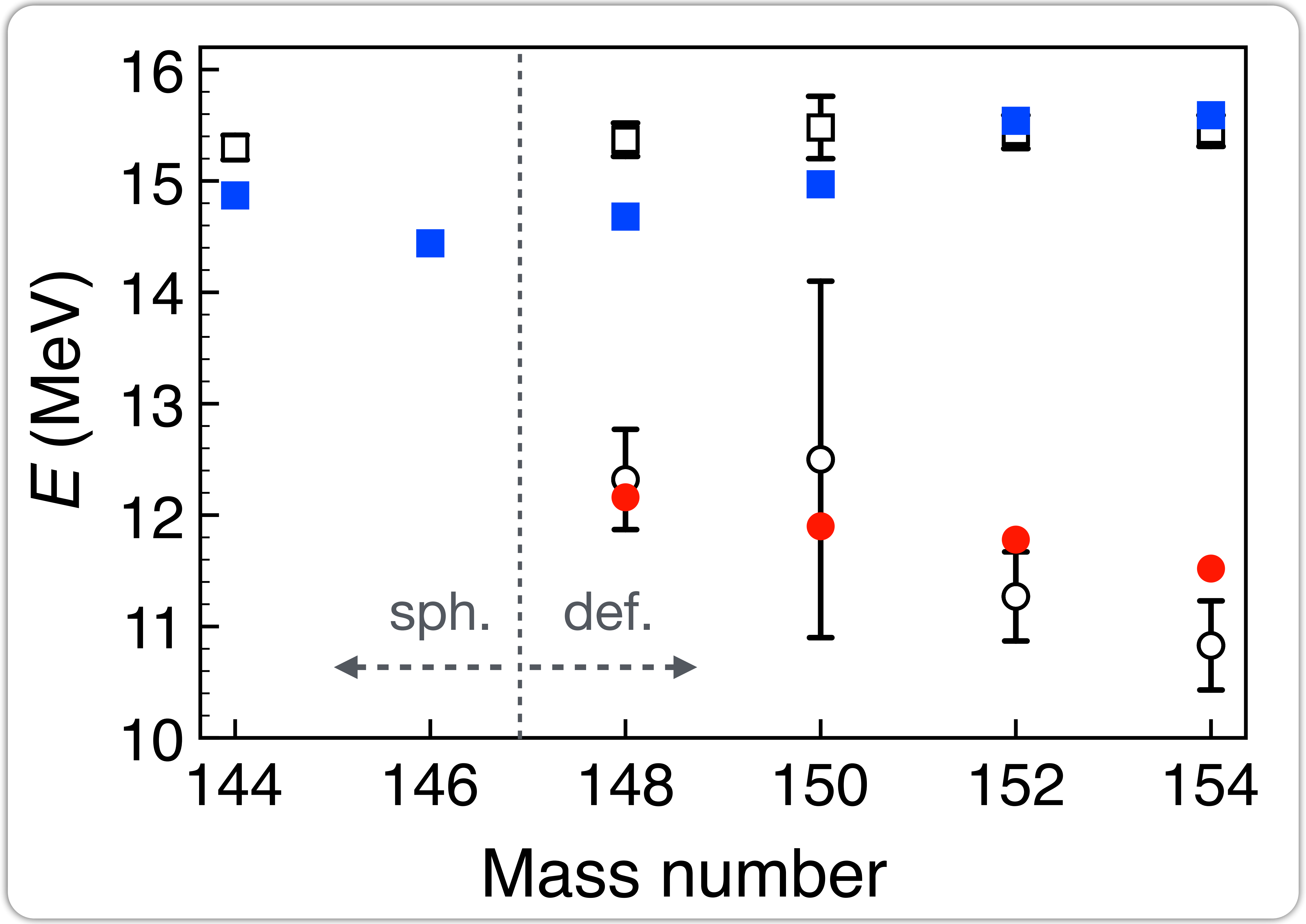


no angle dependence as in GDR

KY, T. Nakatsukasa, PRC88(2013)034309

GMR energy in the Sm (Z=62) isotopes

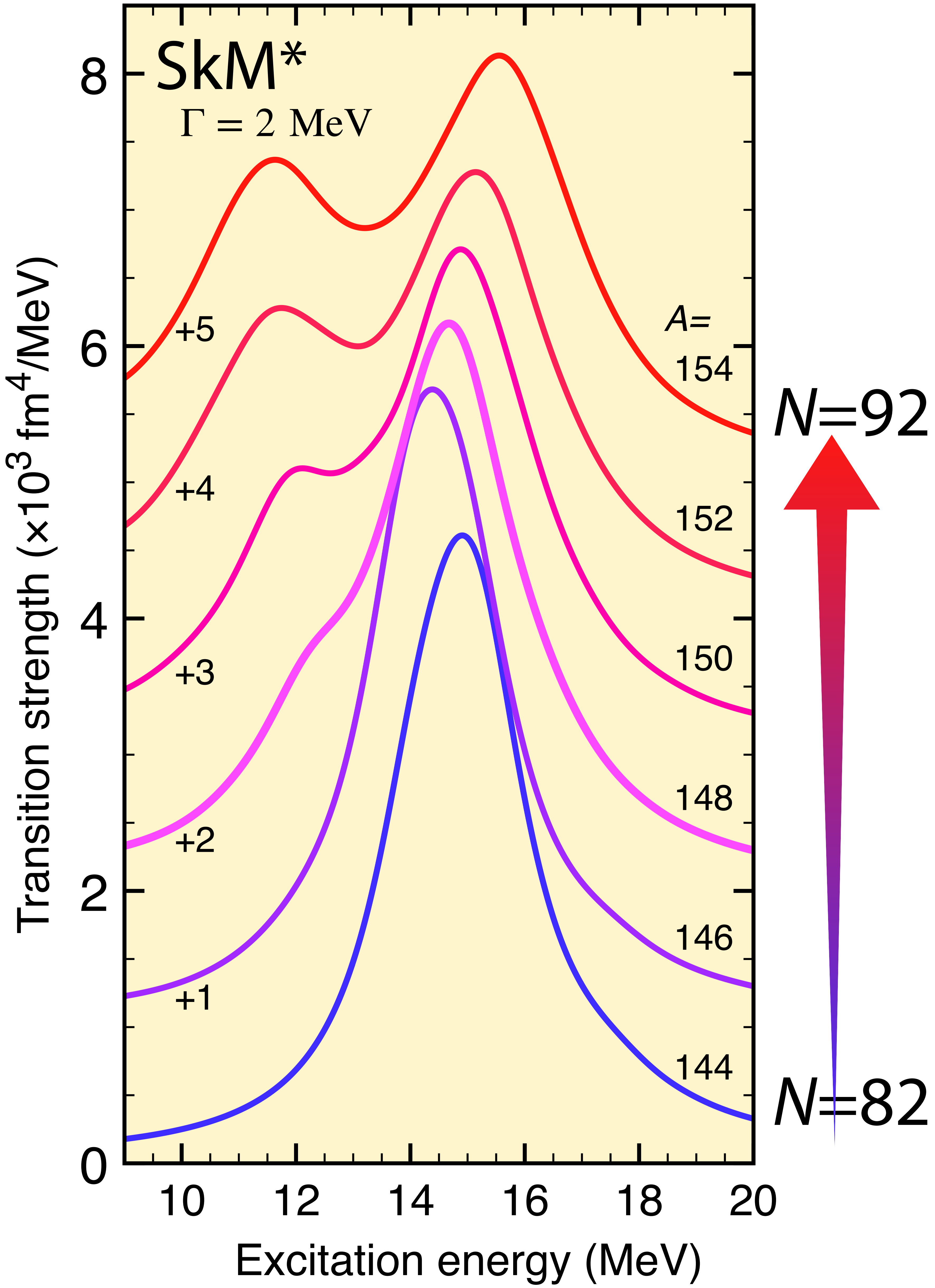




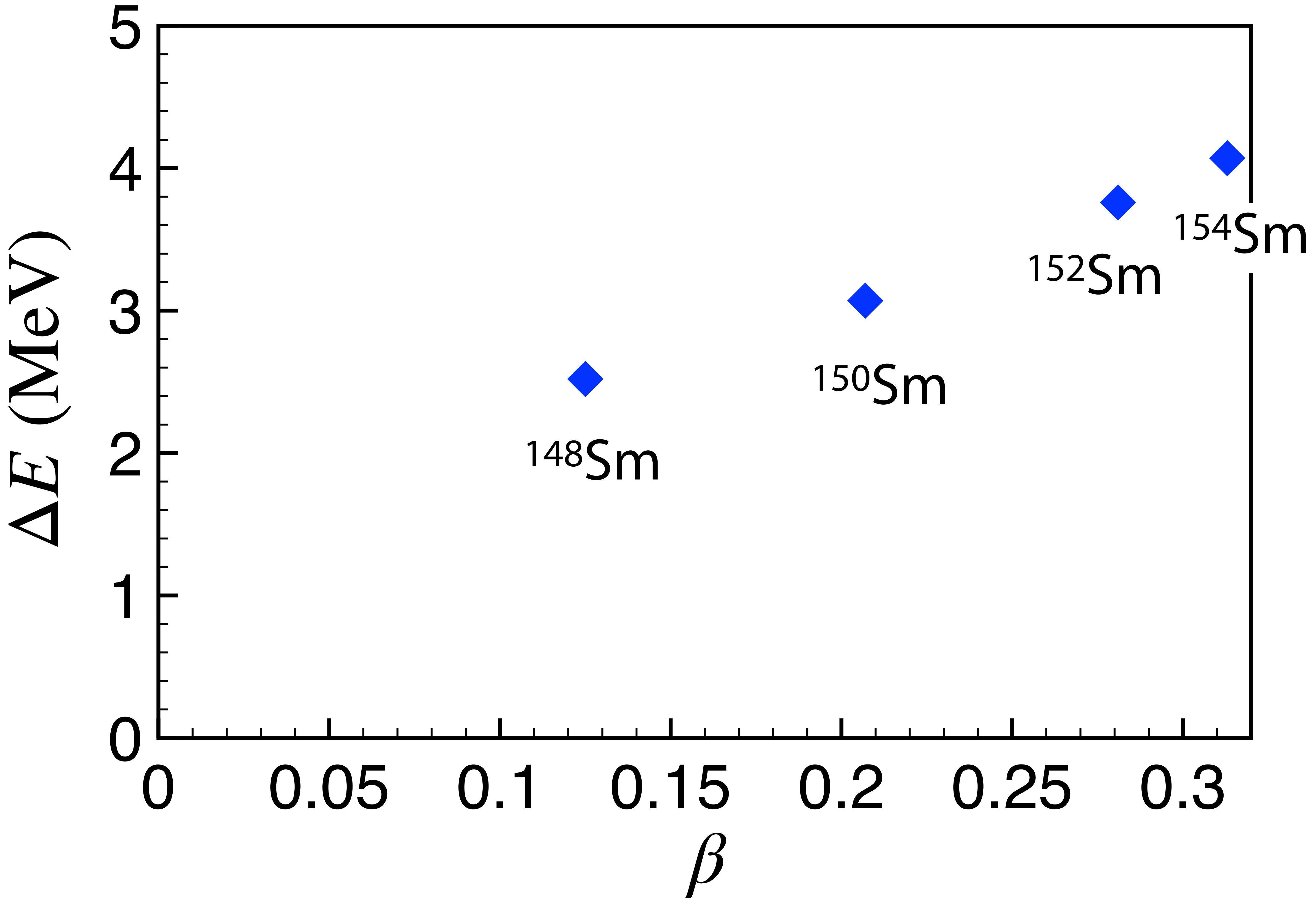
Exp.: M. Itoh, *et al.*, PRC68(2003)064602

GMR in the Sm isotopes

Yoshida–Nakatsukasa ('13)

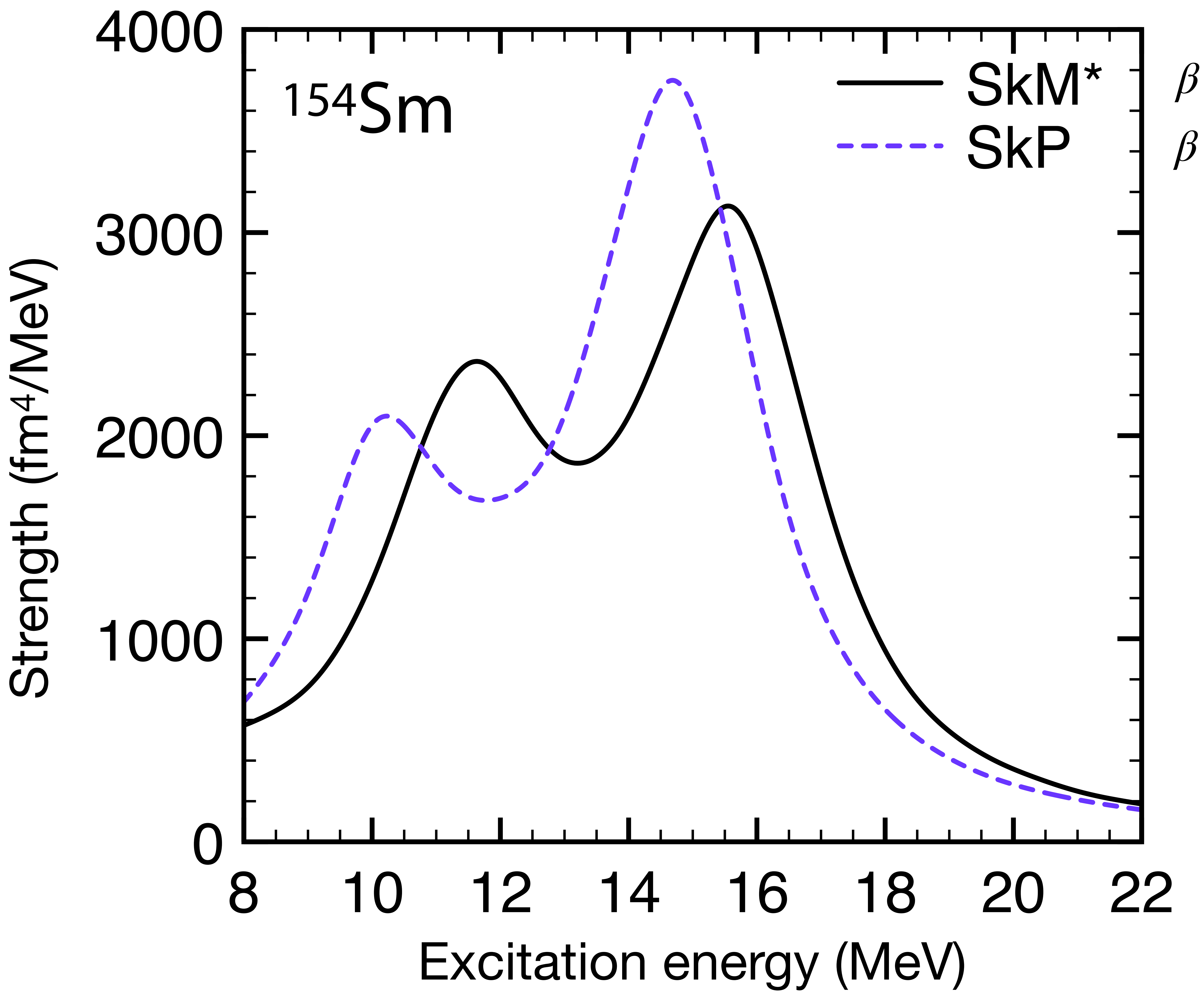


deformation splitting



GMR in the Sm isotopes

KY, T. Nakatsukasa, PRC88(2013)034309



Ratio of EWS
higher/lower

$\beta = 0.31$ 1.9

$\beta = 0.29$ 3.2

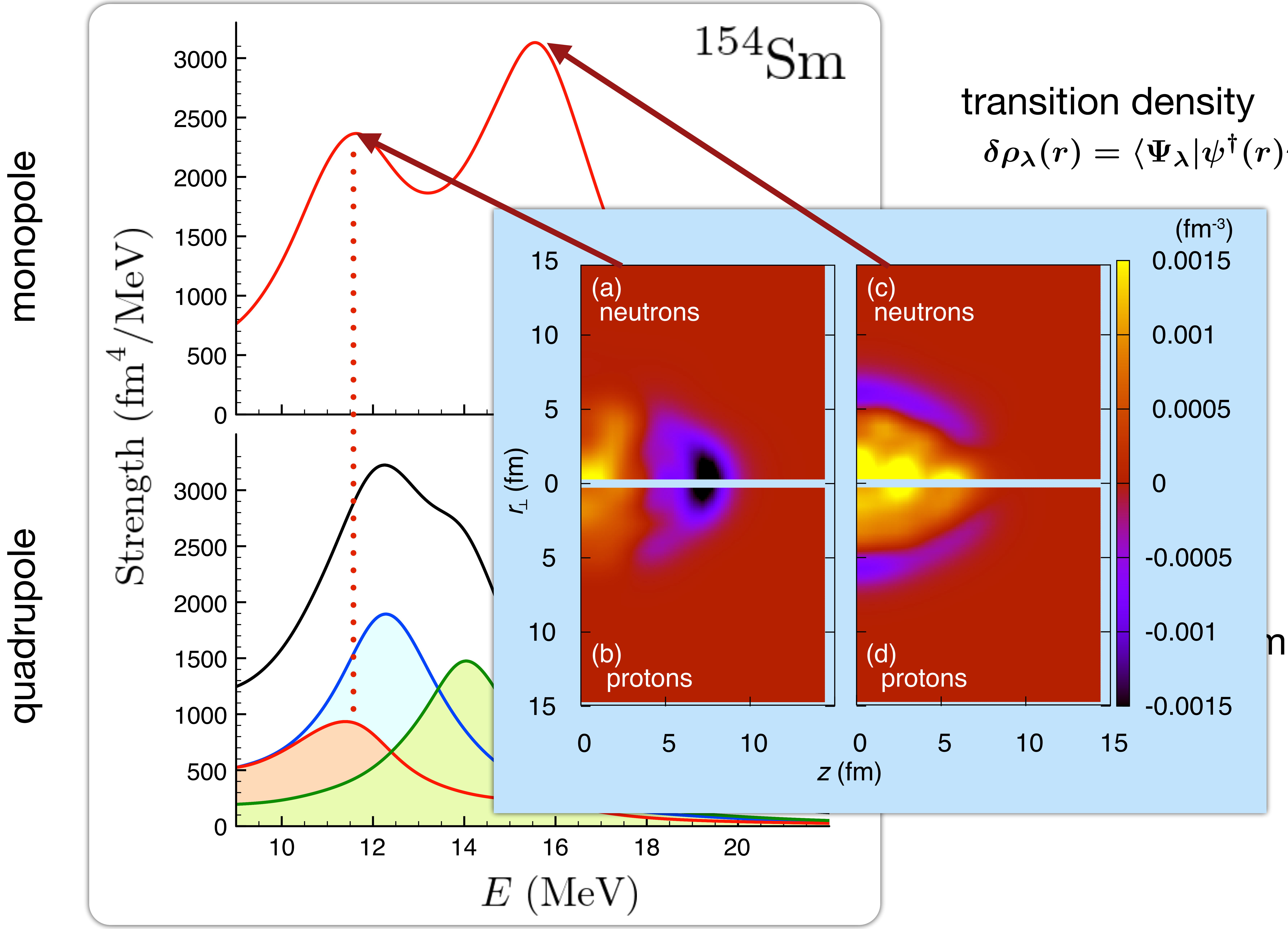
larger strengths in the lower peak
in a strongly-deformed nucleus

stronger coupling between GMR and GQR
as deformation increases

splitting energy

ratio of strengths

Coupling of GMR and GQR

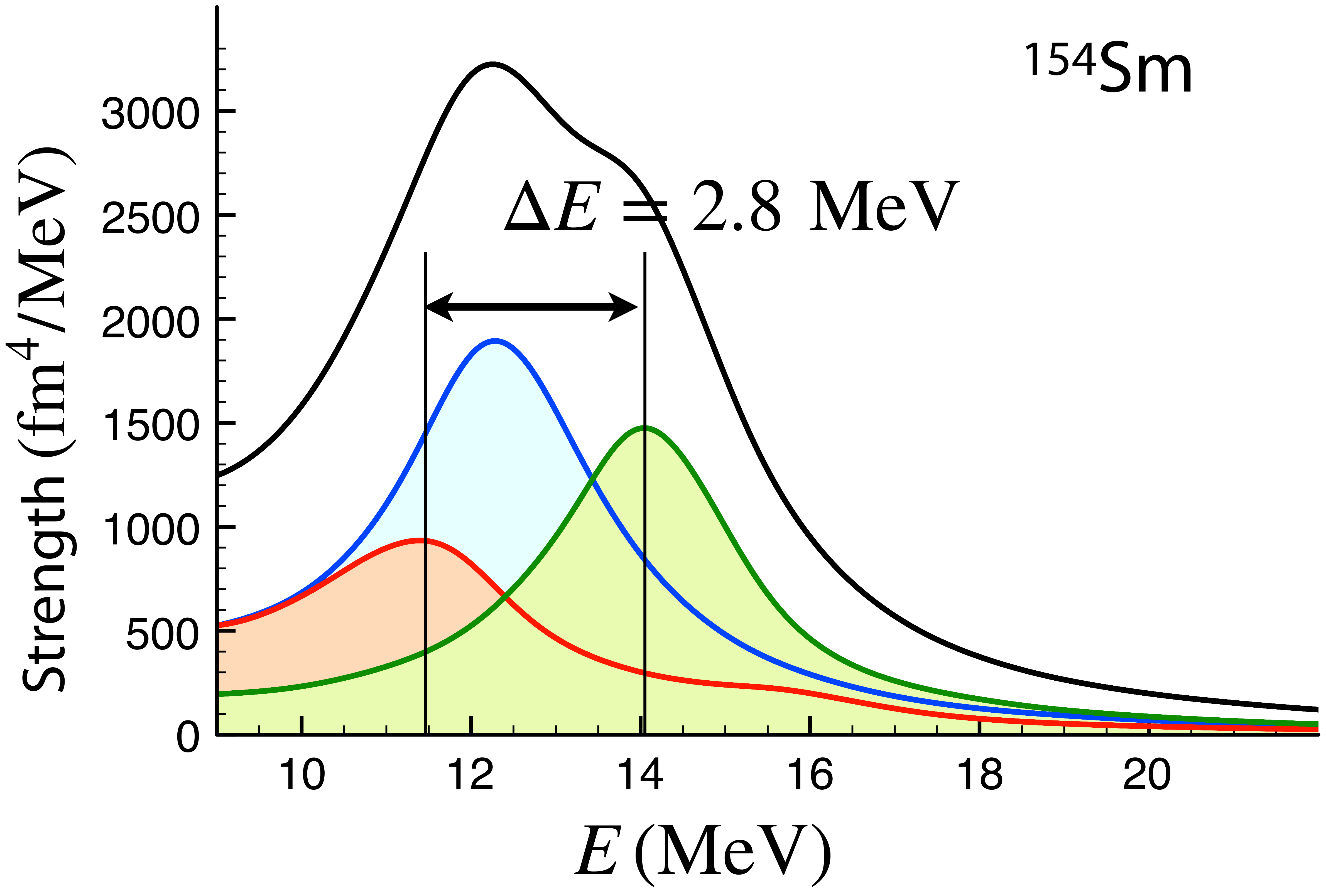


transition density

$$\delta\rho_\lambda(\boldsymbol{r}) = \langle \Psi_\lambda | \psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r}) | \Psi_0 \rangle$$

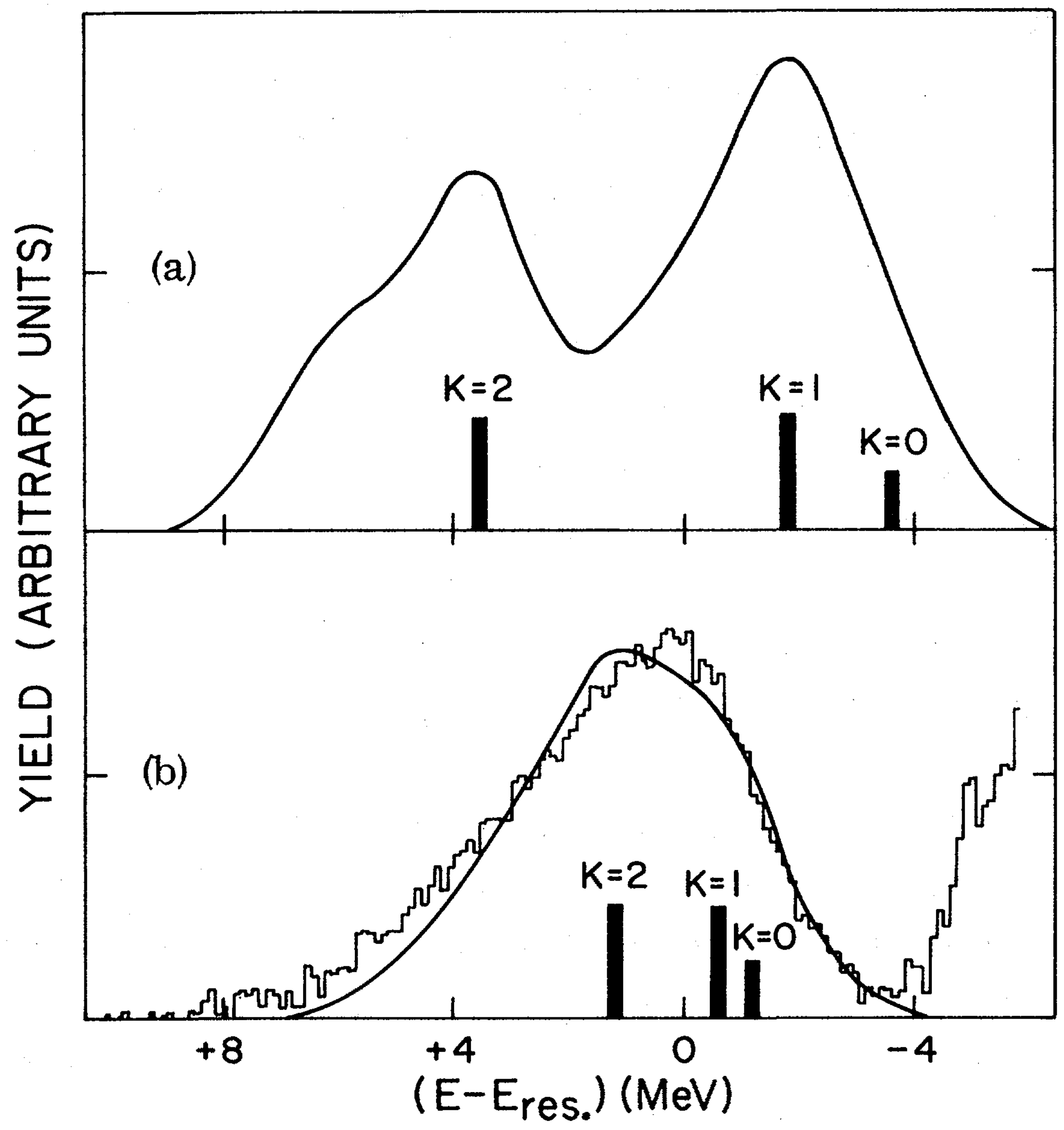
nber

Deformation splitting of the GQR



P+Q model

Kishimoto+('75)



$\Delta E \sim 6$ MeV

ordinal coordinate

$\Delta E \sim 2$ MeV

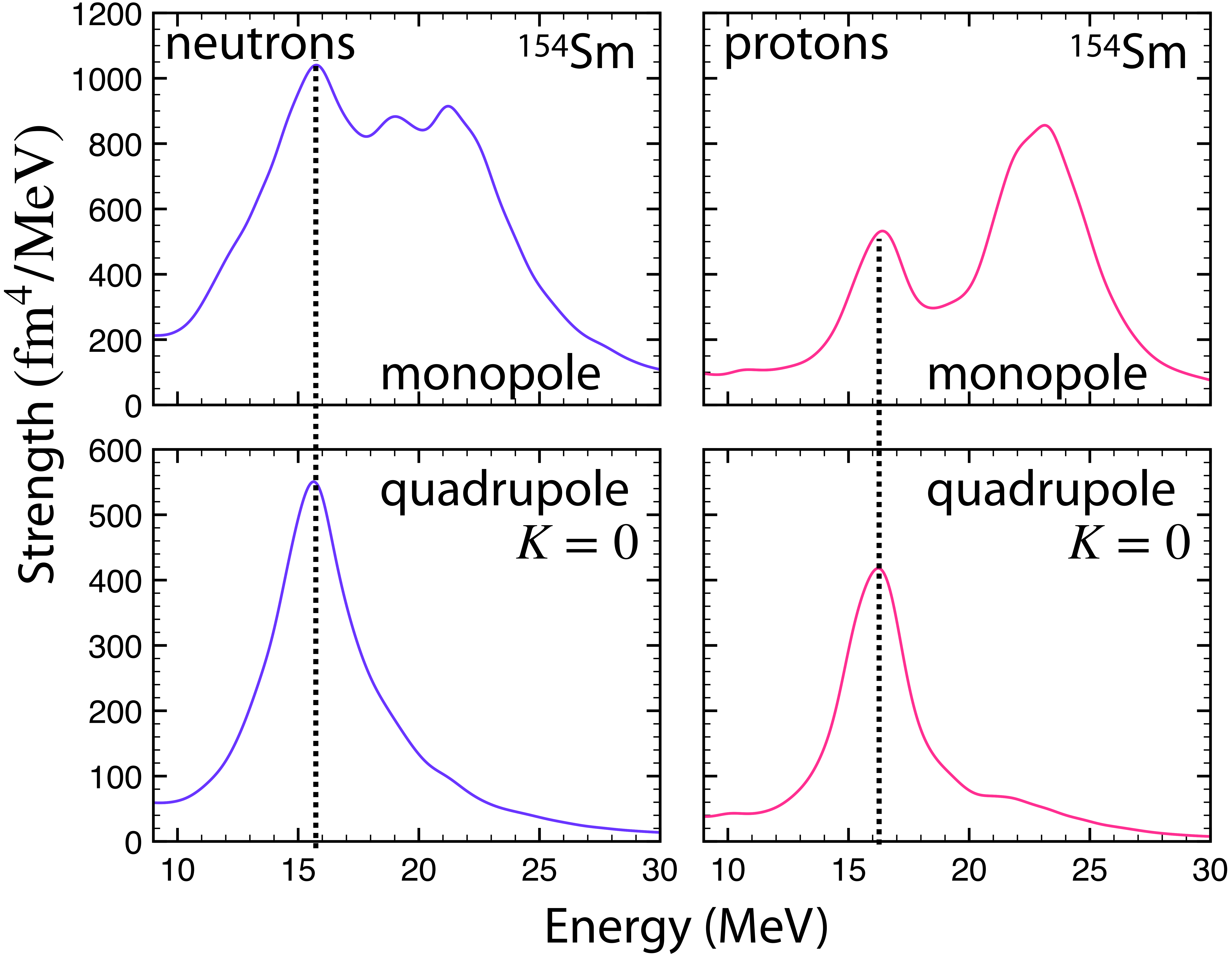
doubly-stretched coordinate

EDF-based QRPA satisfies the nuclear self-consistency

shape (density distribution) and potential

Coupling at the static level

KY, PRC104(2021)044309



Unperturbed strengths

w/o the RPA (dynamic) correlations

deformation-induced coupling

Peaks

monopole and K=0 quadrupole coincide in energy

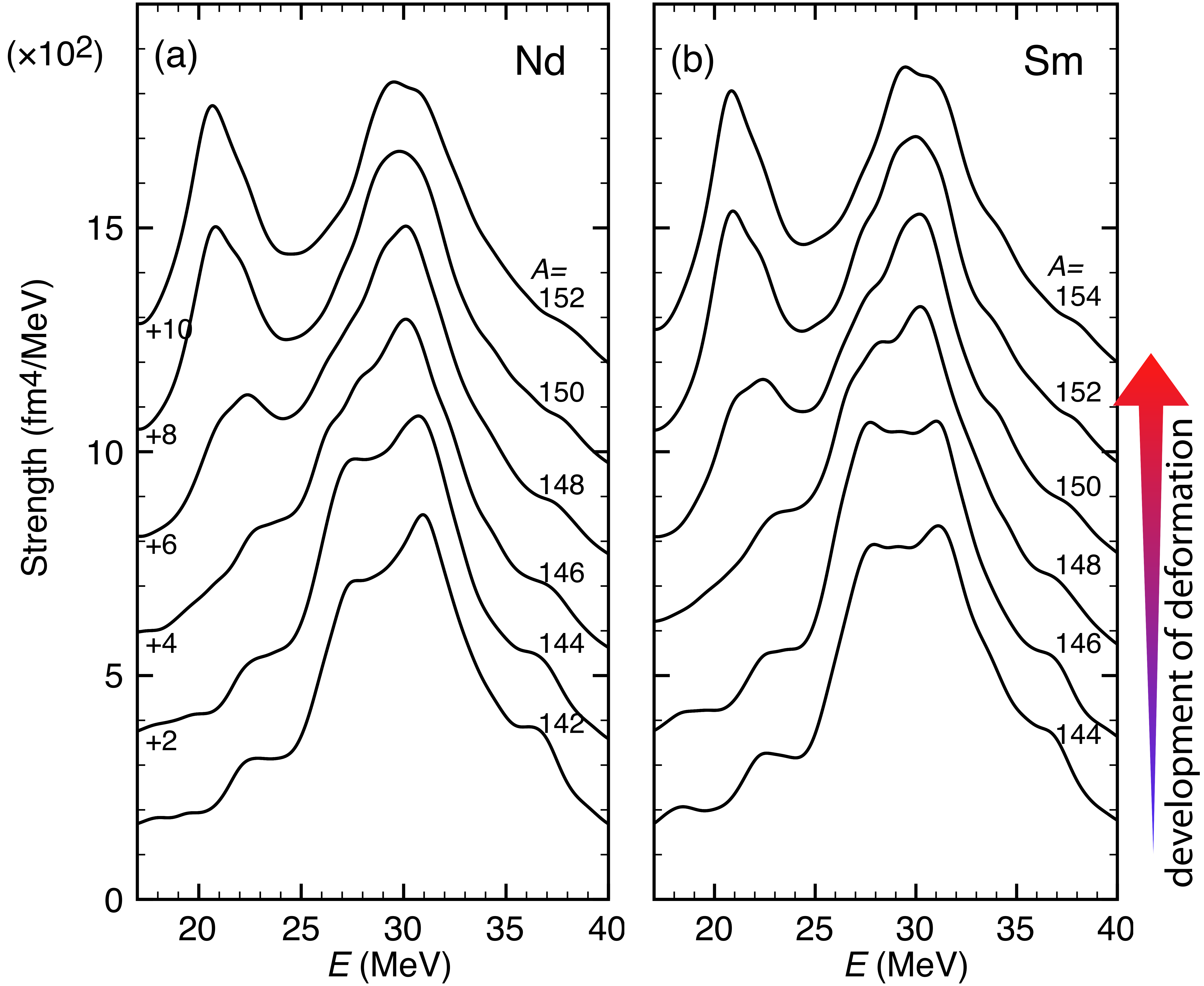
residual interactions

Coexistence persists

Isovector (IV)-GMR in deformed nuclei

KY, T. Nakatsukasa, PRC88(2013)034309

$$F = \sum_{\tau\tau'} \int d\vec{r} r^2 \psi^\dagger(\vec{r}\tau)\langle\tau|\tau_3|\tau'\rangle\psi(\vec{r}\tau')$$



emergence of
deformation "splitting"

$\Delta E \sim 10$ MeV @ ^{154}Sm

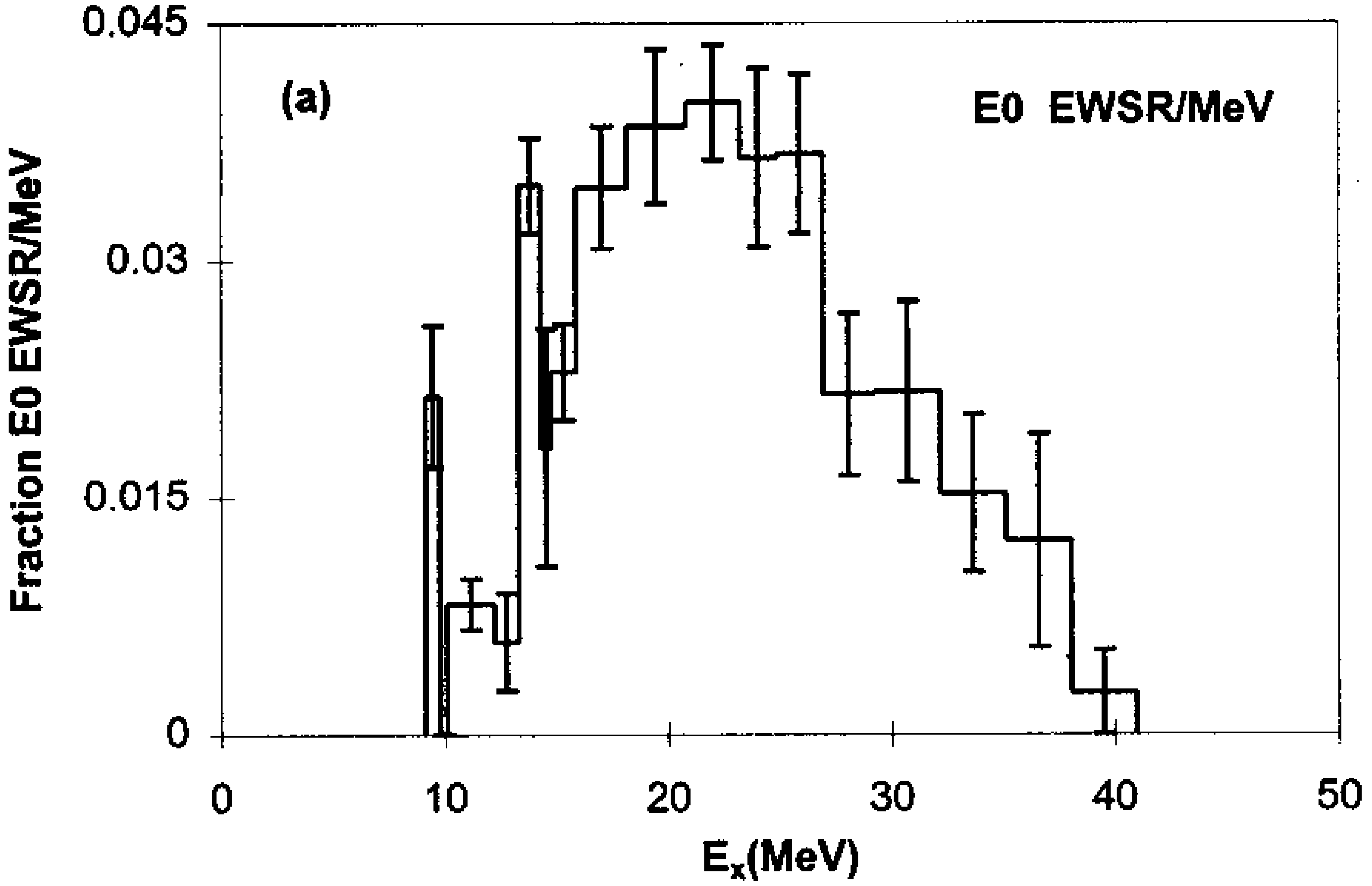
$\sim 2 \times \Delta E$(ISGMR)

due to the coupling to the $K = 0$ of IV-GQR

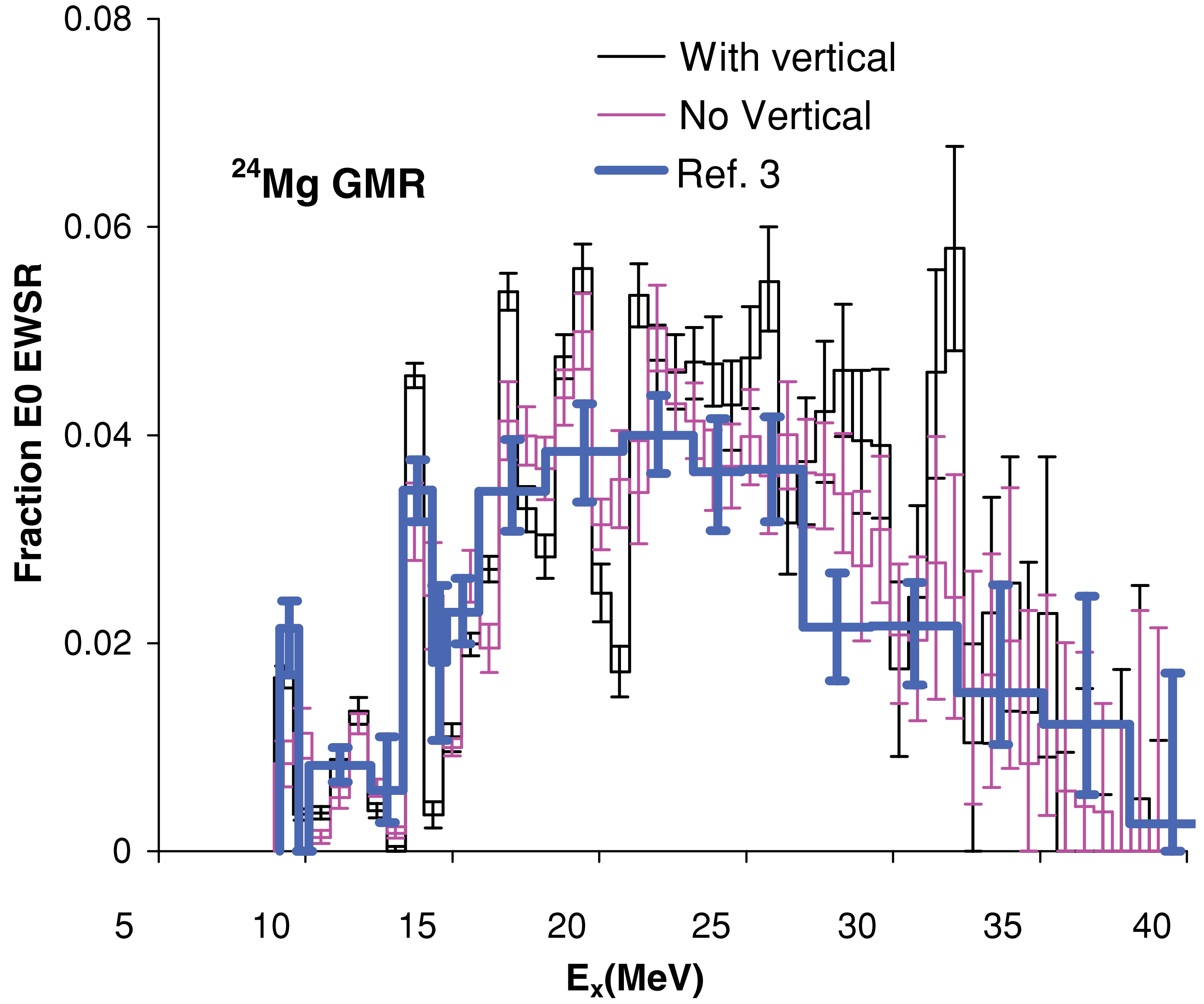
Deformation effect on GMR in light nuclei: universality

^{24}Mg @ TAMU

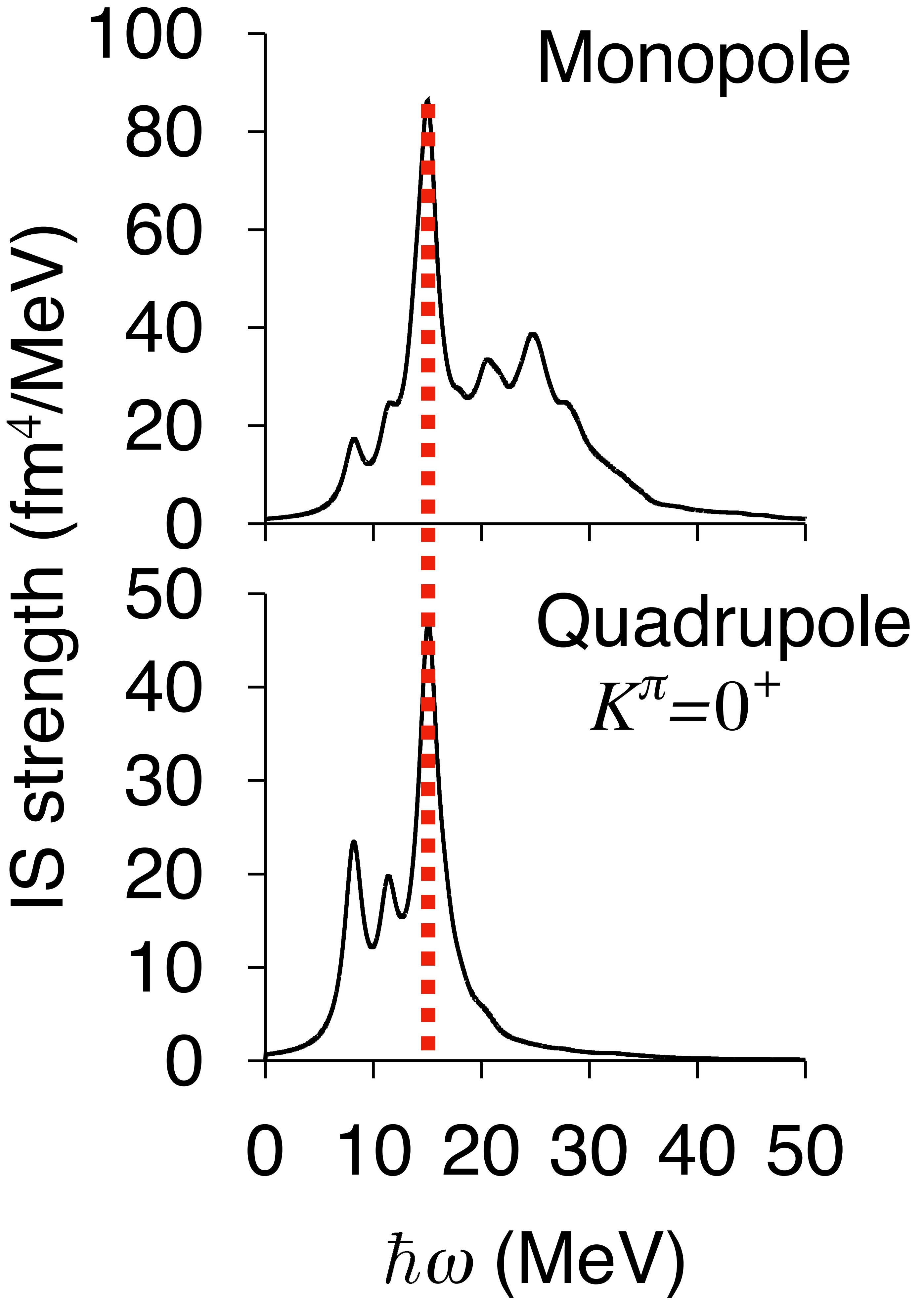
Youngblood+('99)



Youngblood+('09)



KY, Mod. Phys. Lett. A 25 (2010), 1783



occurrence of the "lower-energy (~15 MeV)" peak due to coupling to the *K*=0 of GQR

Deformation splitting in a light nucleus

Physics Letters B 748 (2015) 343–346

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Splitting of ISGMR strength in the light-mass nucleus ^{24}Mg due to ground-state deformation

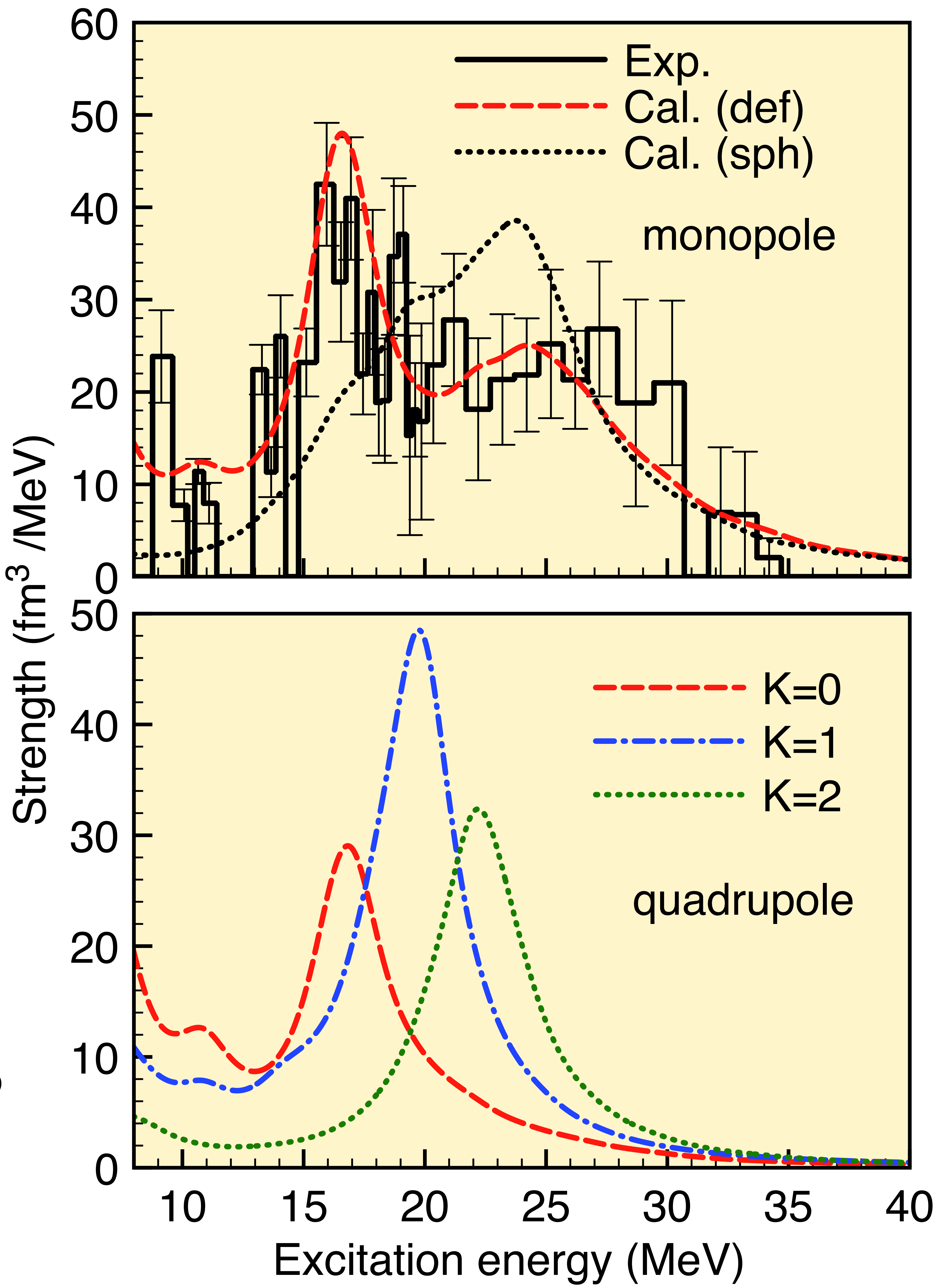
Y.K. Gupta [a,1], U. Garg [a], J.T. Matta [a], D. Patel [a], T. Peach [a], J. Hoffman [a,2], K. Yoshida [b,c], M. Itoh [d,3], M. Fujiwara [d], K. Hara [d], H. Hashimoto [d], K. Nakanishi [d], M. Yosoi [d], H. Sakaguchi [e], S. Terashima [e], S. Kishi [e], T. Murakami [e], M. Uchida [e,4], Y. Yasuda [e], H. Akimune [f], T. Kawabata [g,5], M.N. Harakeh [h]

First observation of the splitting of GMR strengths in a light system

universal feature in deformed nuclei

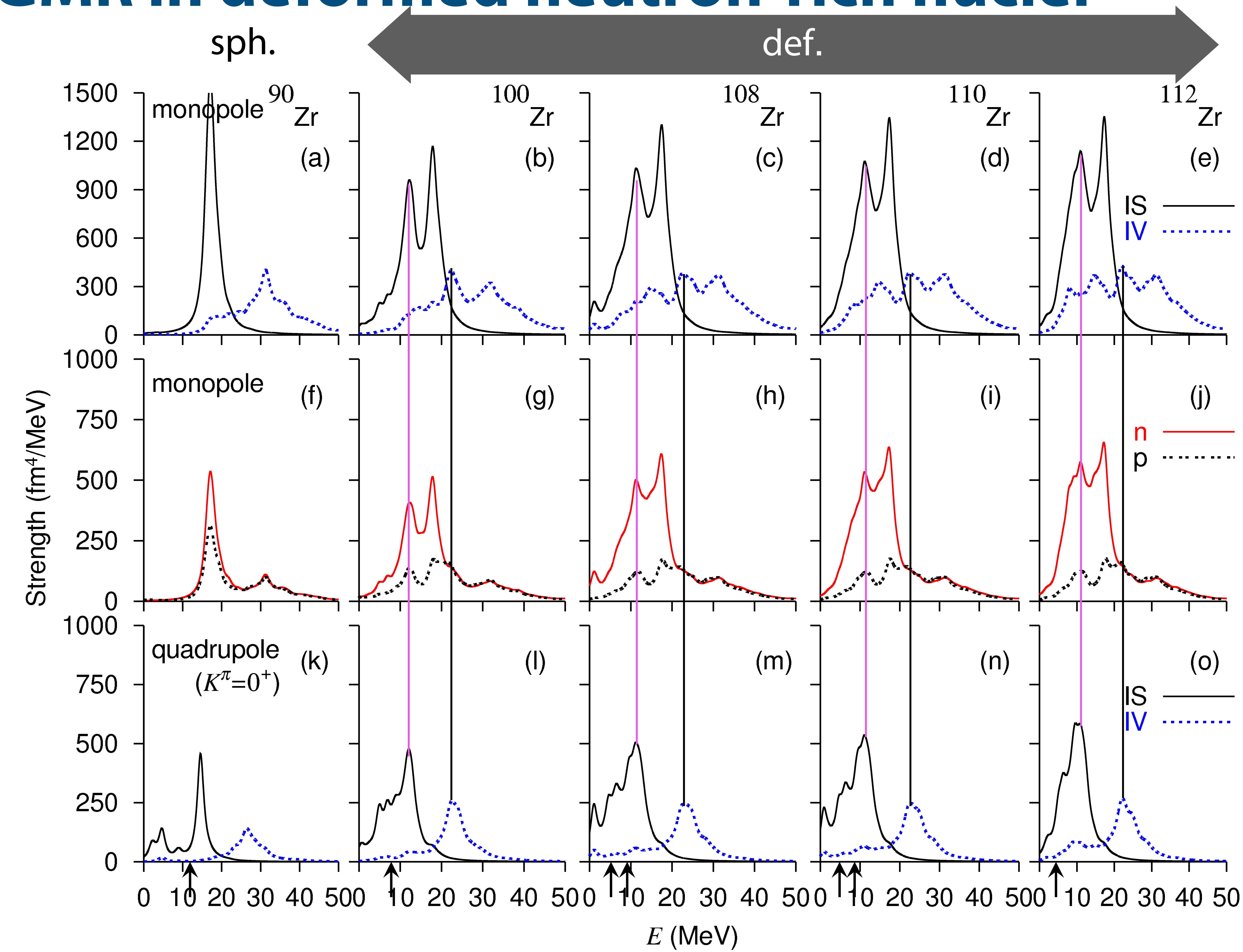
background-free high-resolution experiment @RCNP

parameter-free nuclear DFT calculation



GMR in deformed neutron-rich nuclei

KY, PRC82(2010)034324



SkM*

$\Gamma = 2$ MeV

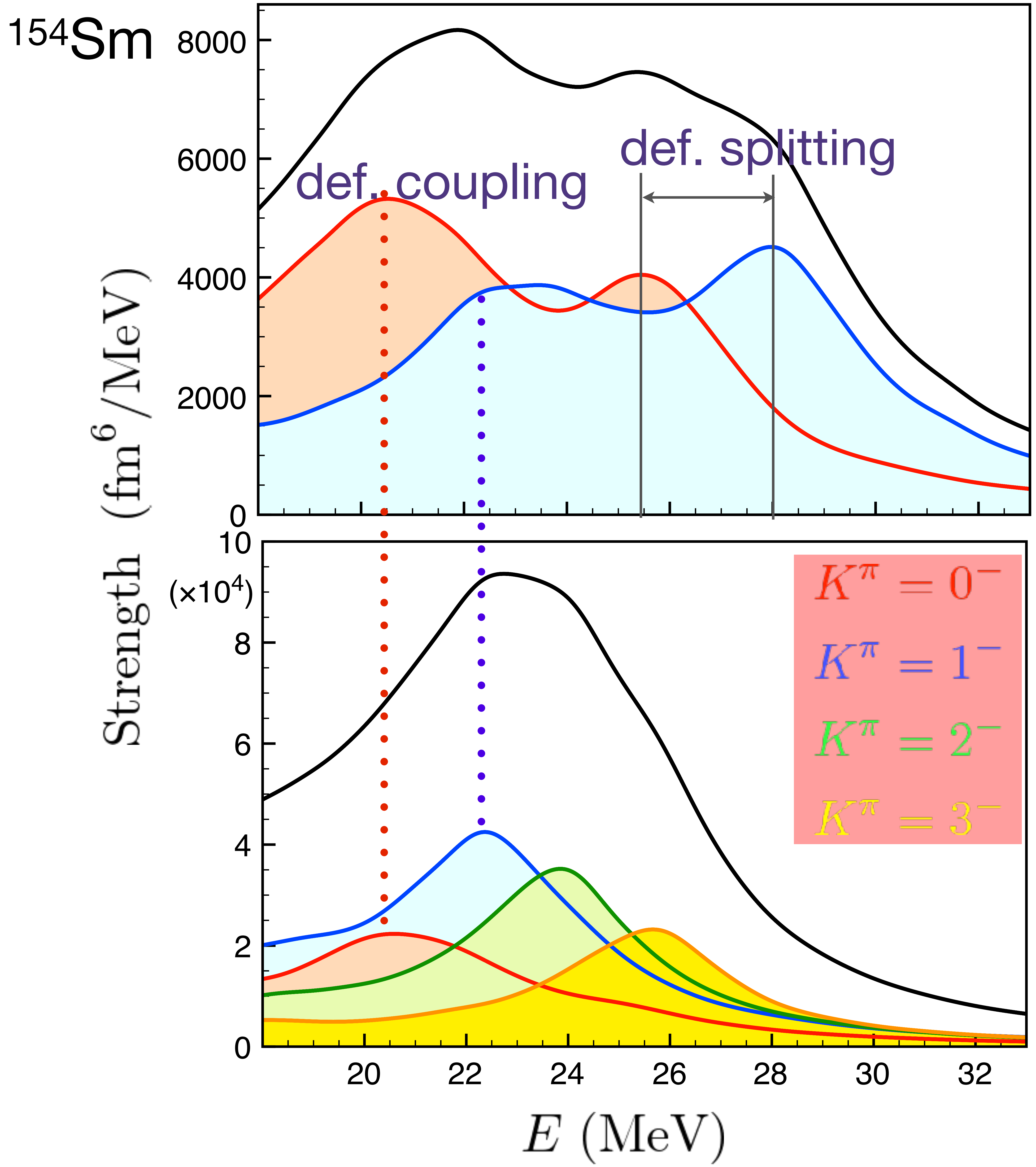
IV strengths in low energy excitation of neutrons

deformation splitting in IVGMR

Isoscalar GDR and high-energy octupole resonance

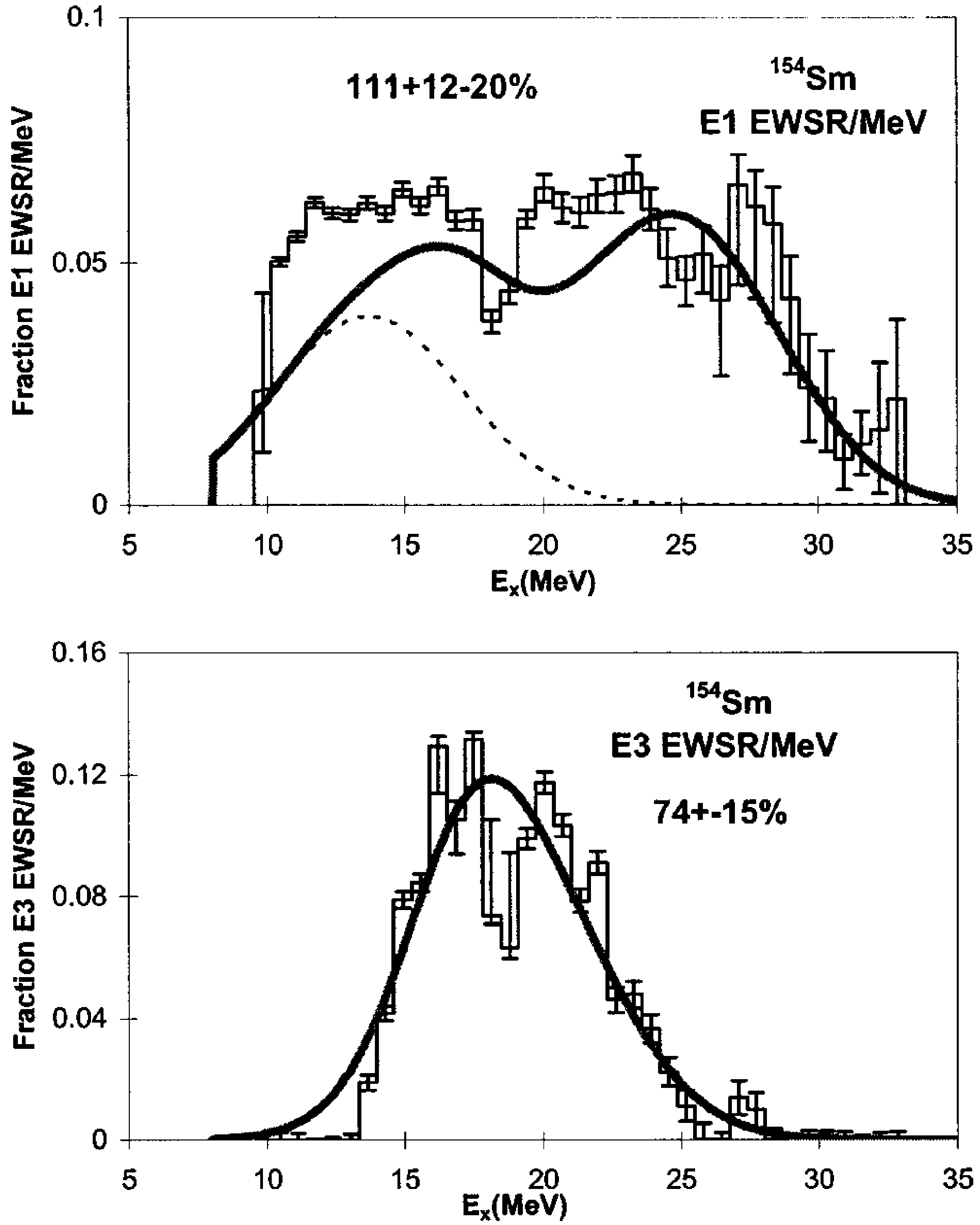
$$F = \sum_{\tau} \int d\vec{r} r^3 Y_1(\hat{r}) \psi^\dagger(\vec{r}\tau)\psi(\vec{r}\tau)$$

KY, T. Nakatsukasa, PRC88(2013)034309



large width of the ISGDR

D. H. Youngblood et al., PRC69(2004)034315



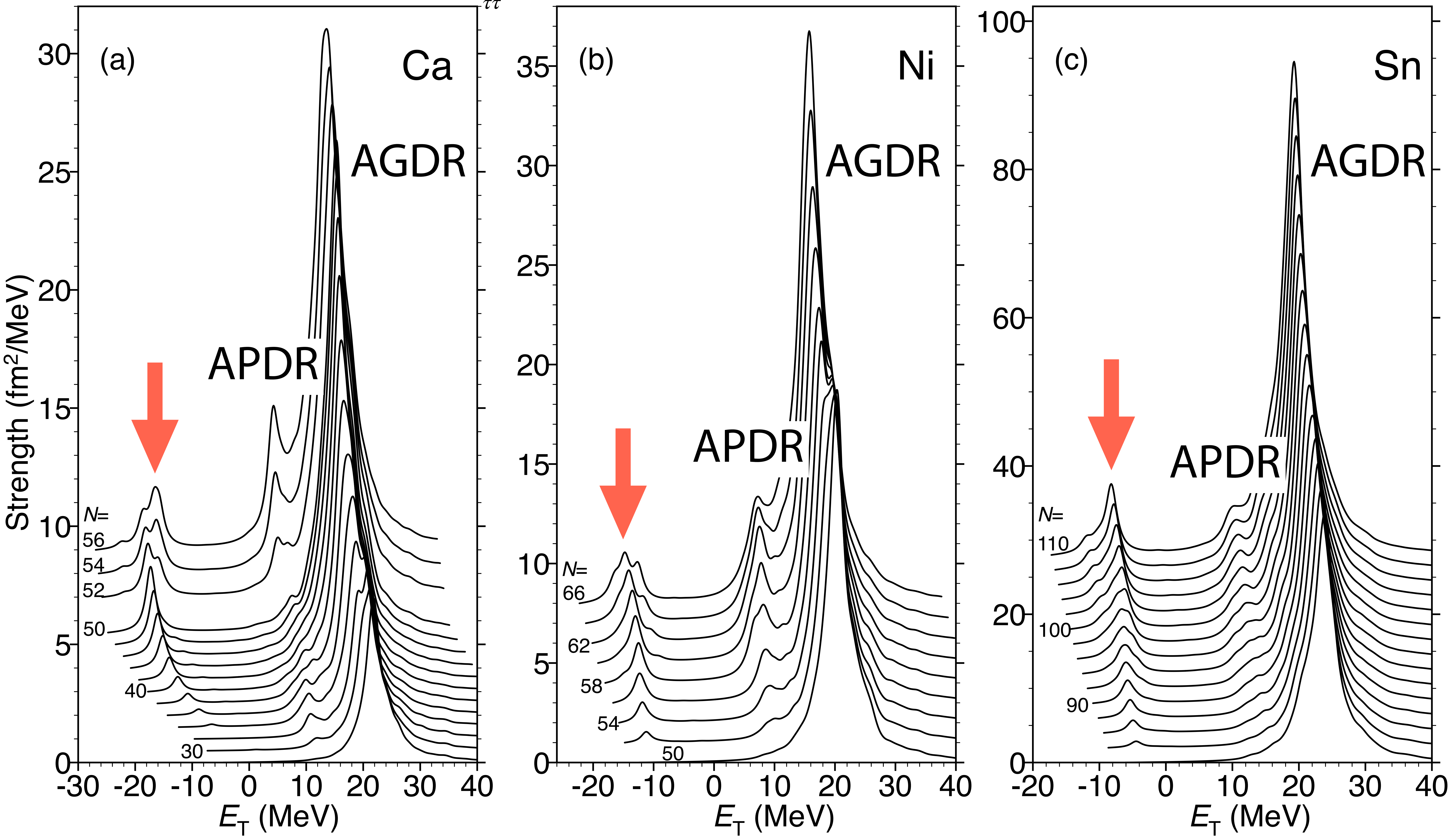
IV dipole responses: charge-exchange channel

KY, PRC96(2017)

SkM*, Γ=2.0 MeV

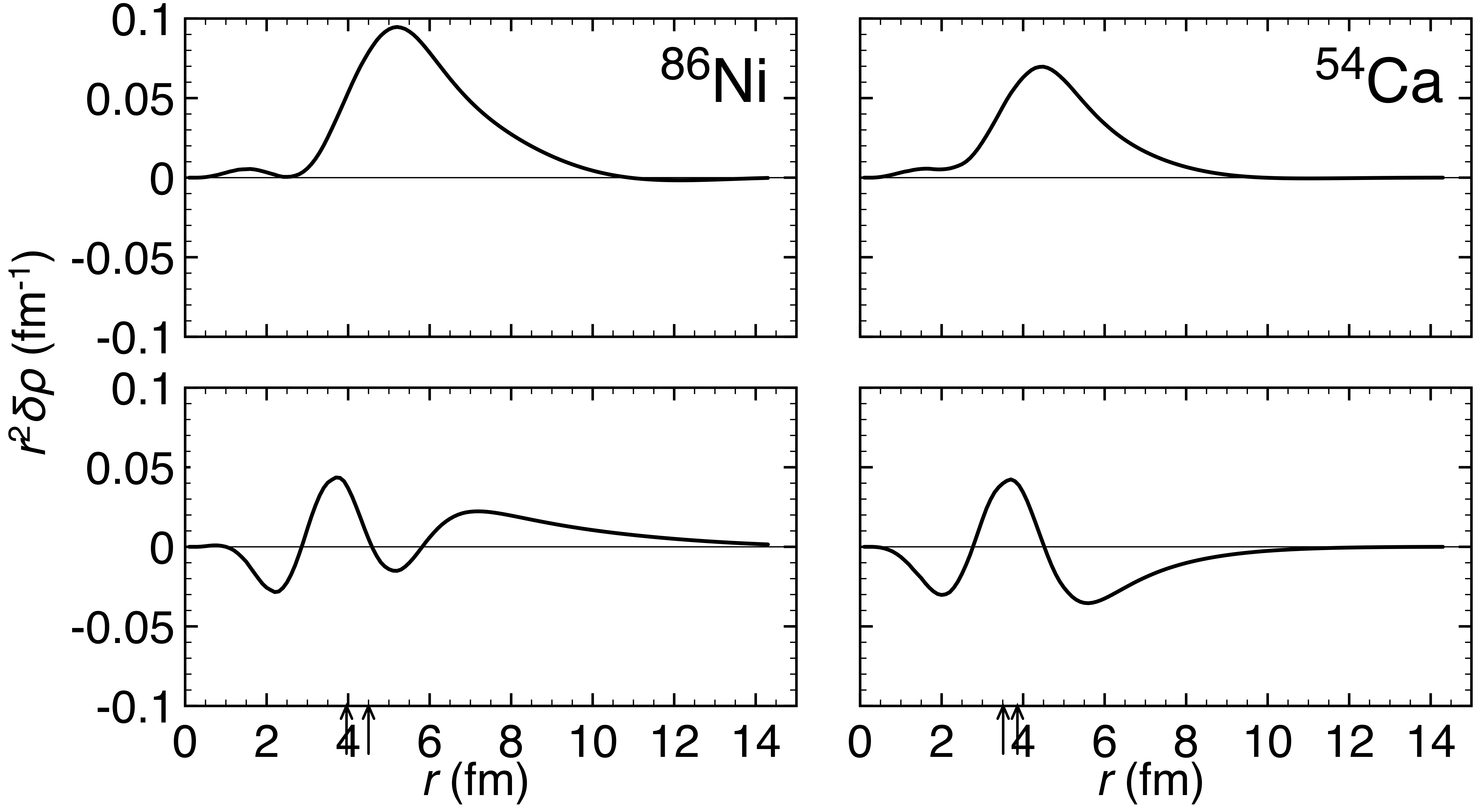
$\mu = -1$: (p, n) type

$$F = \sum_{\tau\tau'} \int d\vec{r} r^2 r Y_1(\hat{r}) \psi^\dagger(\vec{r}\tau) \langle \tau | \tau_\mu | \tau' \rangle \psi(\vec{r}\tau')$$



Anti-analog PDR and GDR

transition density



AGDR

pronounced IV character around the surface

APDR

not a simply IV mode

IS/IV mixing

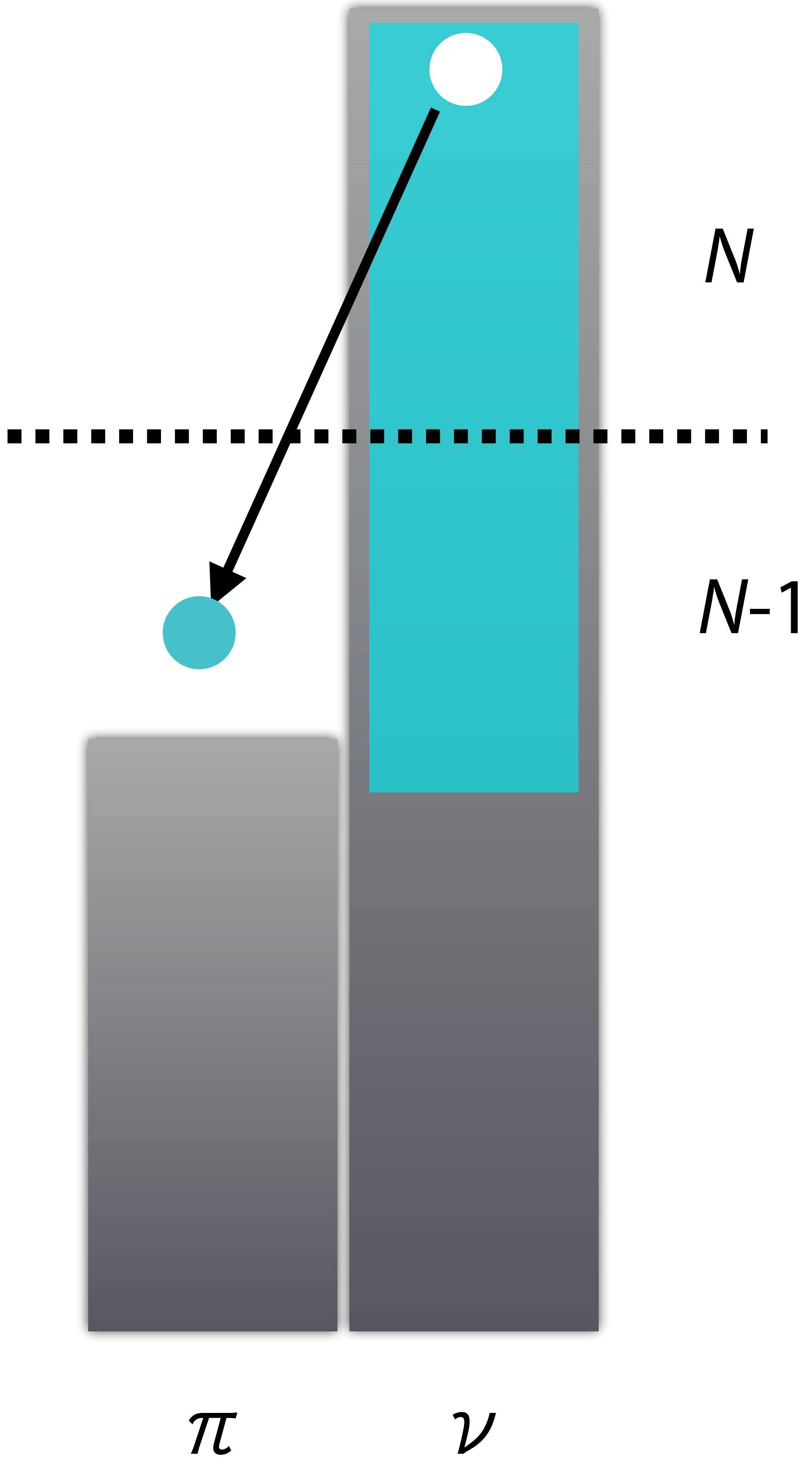
spatially extended structure

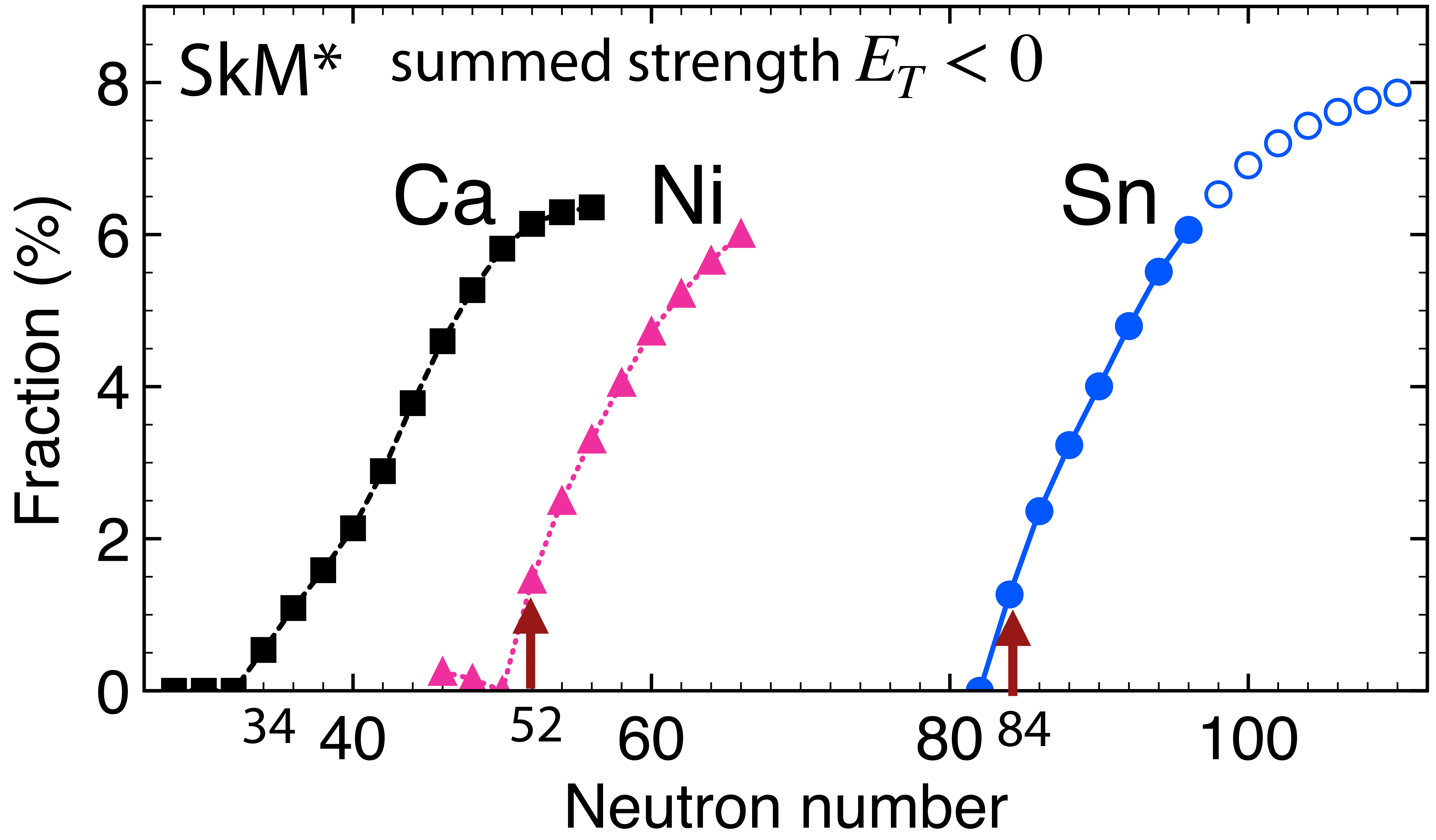
weakly-bound neutrons

Cross-shell $-1\hbar\omega_0$ excitation: lowest-lying dipole mode

protons are deeply bound

should be distinguished from the anti-analog of PDR





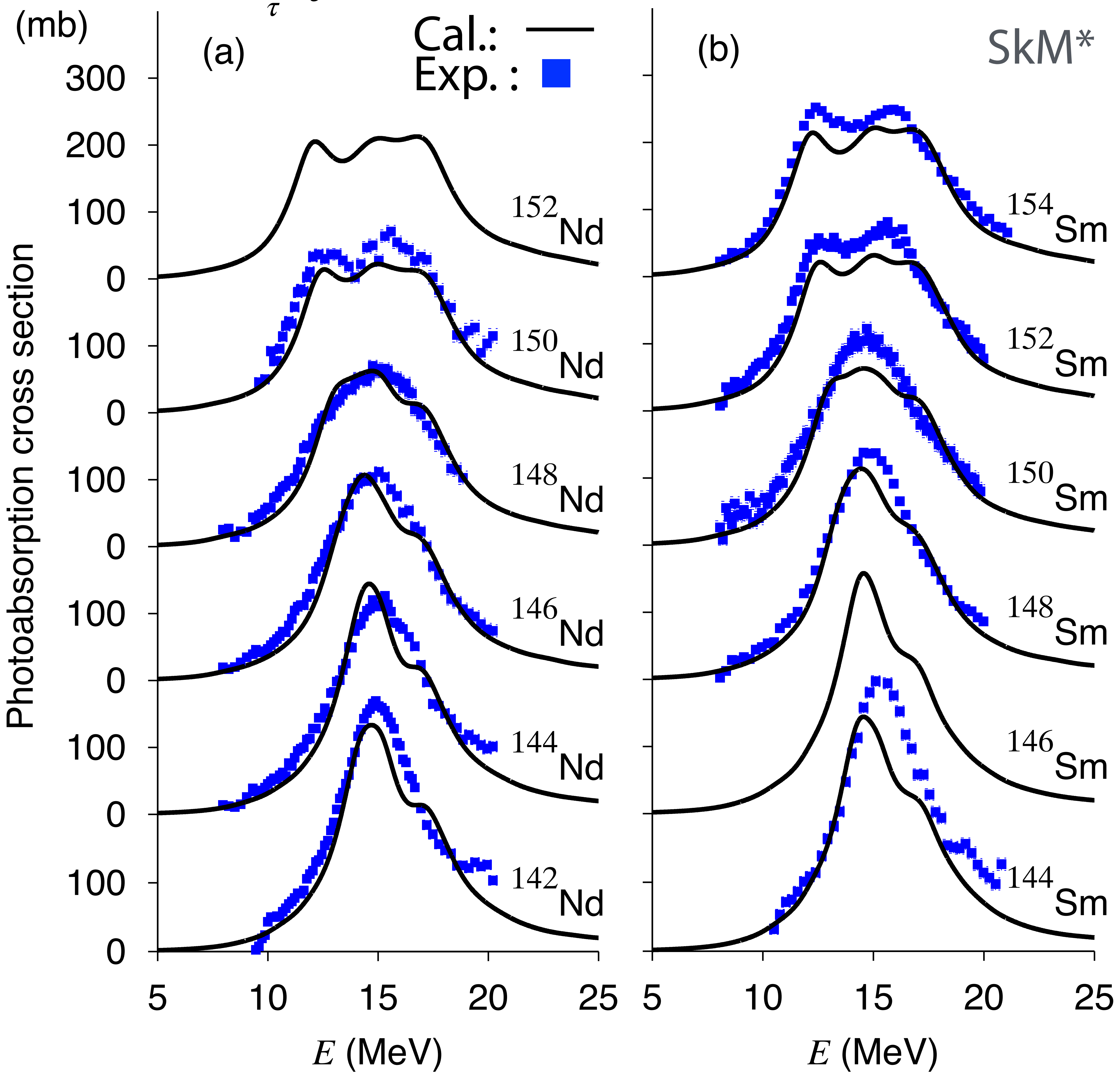
occupation of $2d_{5/2}$ occupation of $2f_{7/2}$

$\nu d_{5/2} \rightarrow \pi p_{3/2}$ $\nu f_{7/2} \rightarrow \pi d_{5/2}$

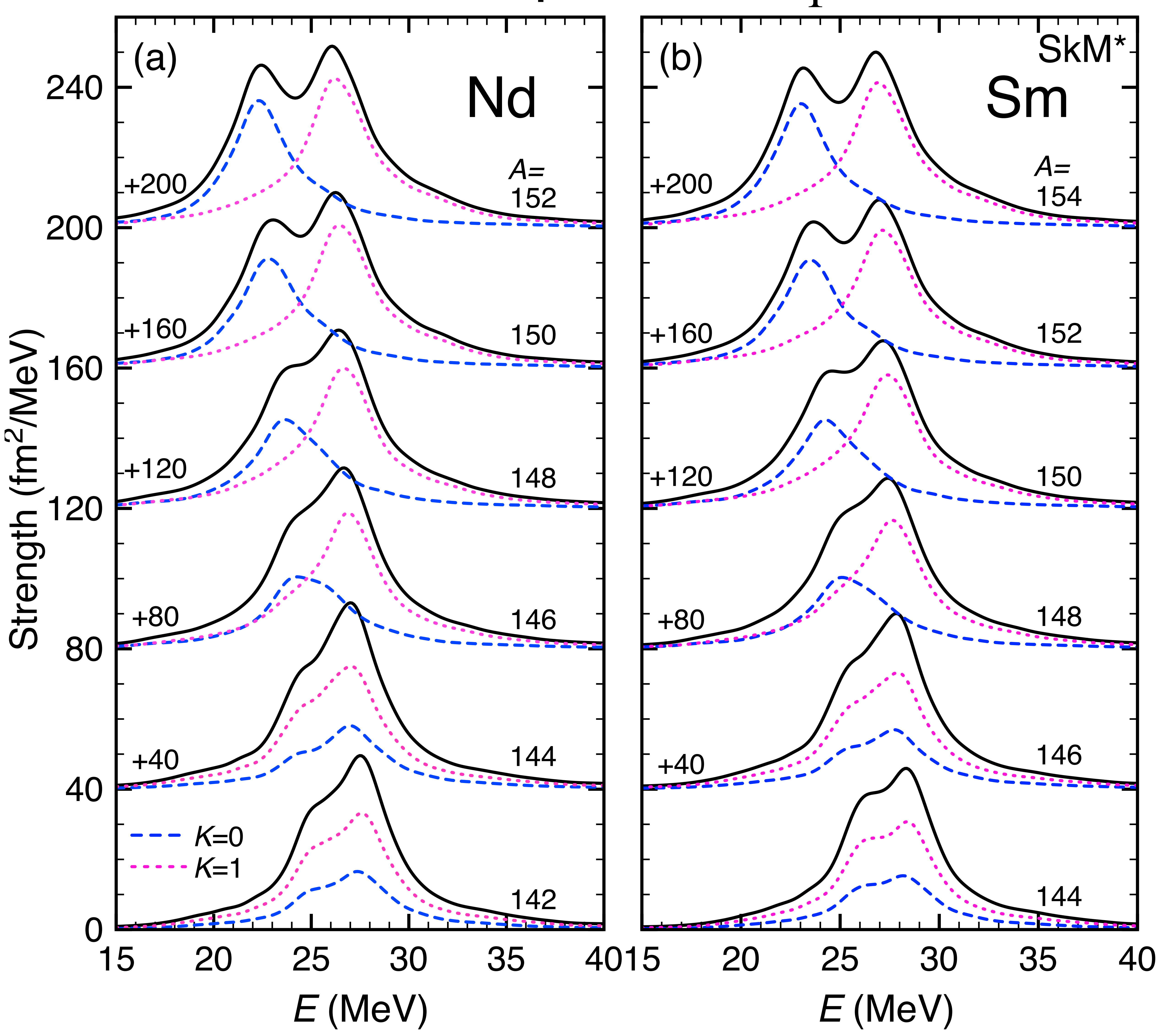
Deformation effects in IV excitations for $\tau_{\pm 1}$

KY, PRC102(2020)

$$F = \sum_\tau \int d\vec{r} r Y_1(\hat{r}) \psi^\dagger(\vec{r}\tau) \langle \tau | \tau_3 | \tau' \rangle \psi(\vec{r}\tau')$$



IV dipole for τ_{-1}



Nuclear beta decay

A semileptonic process governed by

an effective Hamiltonian for a low-energy ($\ll m_W$) charged current reaction:

$$H_{\text{eff}} = \frac{G_F V_{ud}}{\sqrt{2}} \int d\boldsymbol{x} \left[\bar{e}(\boldsymbol{x})\gamma^{\mu}(1-\gamma_5)\nu_e(\boldsymbol{x})J_{\mu}(\boldsymbol{x}) + \mathrm{H.c.} \right]$$

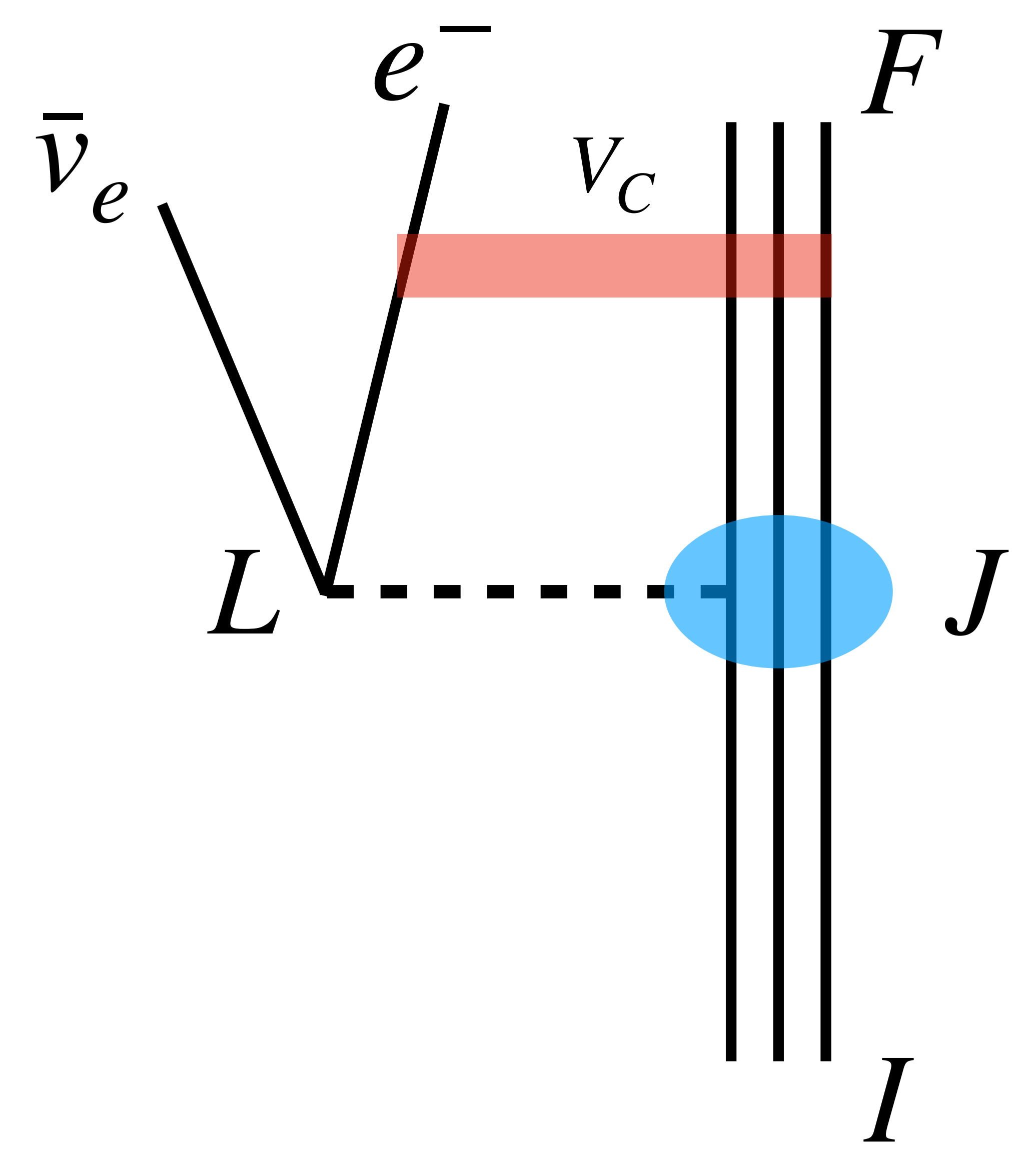
$G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$

$V_{ud} = 0.9737$

Nuclear beta decay

transition matrix element:

$$T_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} \int d\boldsymbol{x} \overline{\psi}_{e^-}(\boldsymbol{x}) \gamma^\mu (1-\gamma_5) \psi_\nu(\boldsymbol{x}) \underline{\langle F | J_\mu(\boldsymbol{x}) | I \rangle}$$



Nuclear currents involving not only the nuclear many-body wave functions but the form factors and momentum tranfer

$$J^\mu(\boldsymbol{x}) = \mathscr{V}^\mu(\boldsymbol{x}) - \mathscr{A}^\mu(\boldsymbol{x})$$

vector currents $\mathscr{V}^\mu = (V^0, \boldsymbol{V})$ axial-vector currents $\mathscr{A}^\mu = (A^0, \boldsymbol{A})$

decay rate: $$\Gamma = \frac{(G_F V_{ud})^2}{\pi^2} \int_{m_e}^{E_0} dE_e \, p_e E_e \left(E_0 - E_e\right)^2 \sum_{J,\kappa_e,\kappa_\nu} \frac{1}{2J_i+1} \left| \sum_L \langle f || \underline{\Xi_{JL}(\kappa_e, \kappa_\nu)} || i \rangle \right|^2$$

multipole operator

One-body charged-current operators: Impulse Approx.

Gamow–Teller type

spatial component

$$\boldsymbol{A}(\boldsymbol{r}) = \sum_{j=1}^{A} \delta(\boldsymbol{r}-\boldsymbol{r}_j) g_A \boldsymbol{\sigma}_j \tau_j^{\pm}$$

momentum transfer:

$$\boldsymbol{q} = \boldsymbol{p}_j' - \boldsymbol{p}_j$$

$$g_A(q^2=0) = g_A$$

$$g_V(q^2=0) = g_V$$

$$\langle f || \sum_L \Xi_{JL}(\kappa_e,\kappa_\nu) || i \rangle = \mathrm{sign}(\kappa_e) \int_0^\infty dr\, r^2 \left[\rho^{\sigma}_{J-1J}(r)\phi_a(r) + \rho^{\sigma}_{J+1J}(r)\phi_b(r) \right]$$

leptons wfs

nuclear transion density: $\rho^{\sigma}_{LJ}(r) = \langle f || \sum_{j=1}^{A} \int d\Omega_r \delta(\boldsymbol{r}-\boldsymbol{r}_j)\tau_j^{\pm} [Y_L(\hat{r}) \otimes \boldsymbol{\sigma}_j]_J || i \rangle$

usually $J=1, L=0$ is only considered

"GT"

Fermi type

time component

$$V^0(\boldsymbol{r}) = \sum_{j=1}^{A} \delta(\boldsymbol{r}-\boldsymbol{r}_j) g_V \tau_j^{\pm}$$

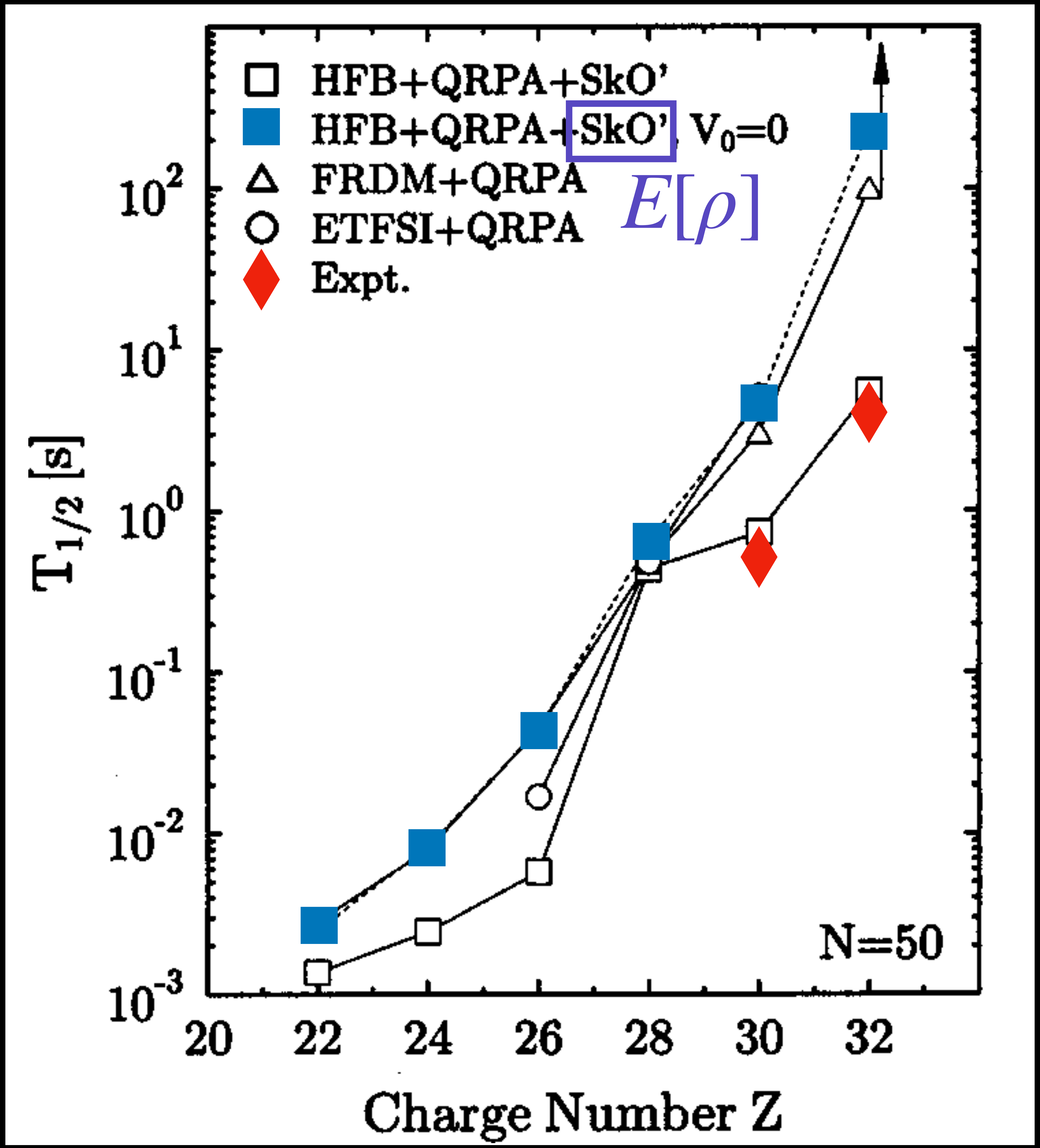
$$\langle f || \sum_L \Xi_{JL}(\kappa_e,\kappa_\nu) || i \rangle = \mathrm{sign}(\kappa_e) \int_0^\infty dr\, r^2 \rho_J(r)\phi_A(r)$$

$$\rho_J(r) = \langle f || \sum_{j=1}^{A} \int d\Omega_r \delta(\boldsymbol{r}-\boldsymbol{r}_j)\tau_j^{\pm} Y_J(\hat{r}) || i \rangle$$

usually $J=L=0$ is only considered

Pioneering microscopic work for *β*-decay based on DFT

J. Engel *et al.*, PRC60(1999)014302



Hadronic current

$$J_\mu(x) = \bar{\psi}_p(x)[V_\mu - A_\mu]\psi_n(x)$$

$$V_\mu = g_V(q^2)\gamma_\mu + \cancel{i g_M(q^2)\frac{\sigma_{\mu\nu}}{2m_n}q^\nu}$$

$$A_\mu = g_A(q^2)\gamma_\mu\gamma_5 + \cancel{i g_P(q^2)q_\mu\gamma_5}$$

quenching

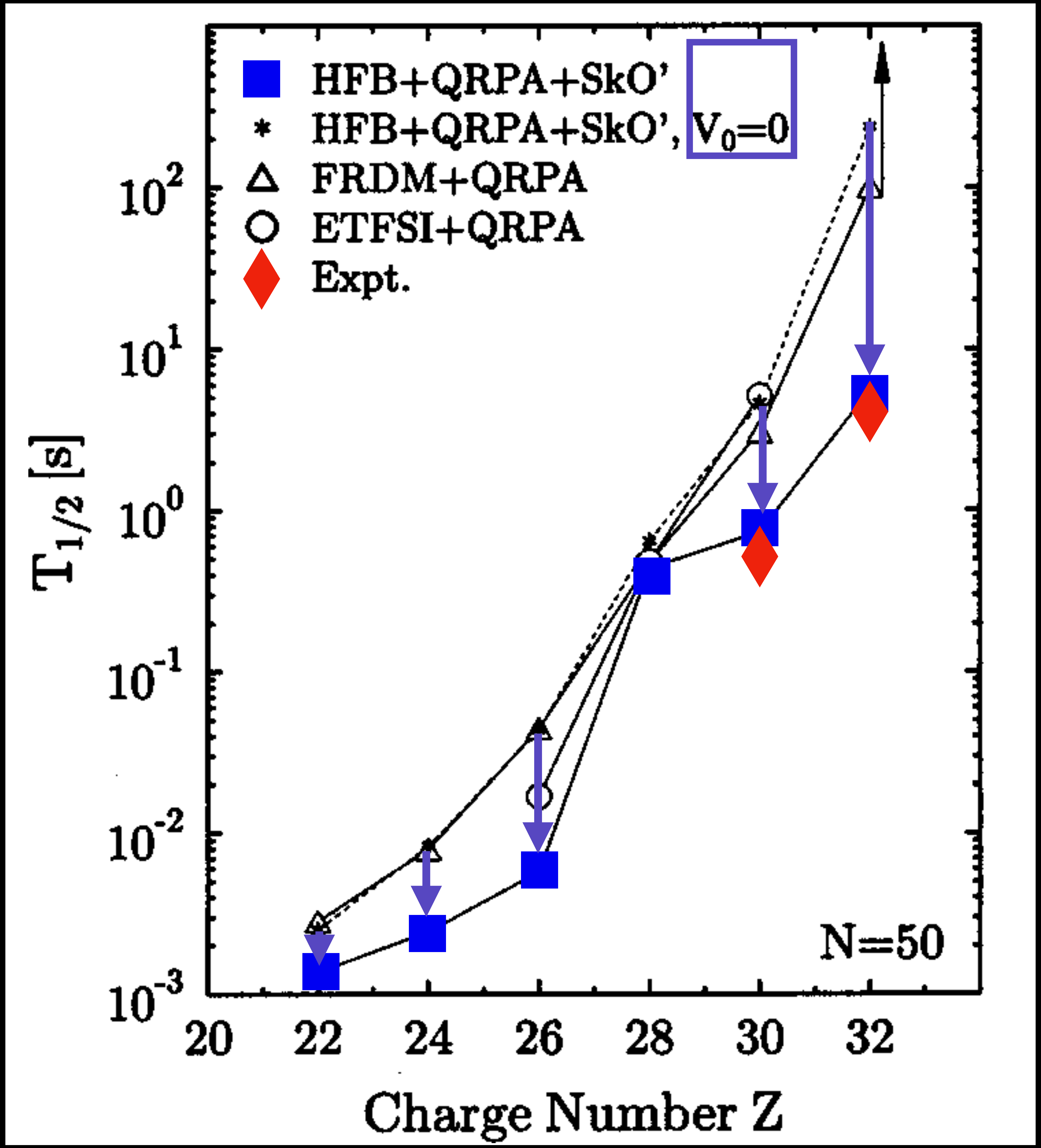
$$g_A^{\mathrm{eff}} = q g_A$$

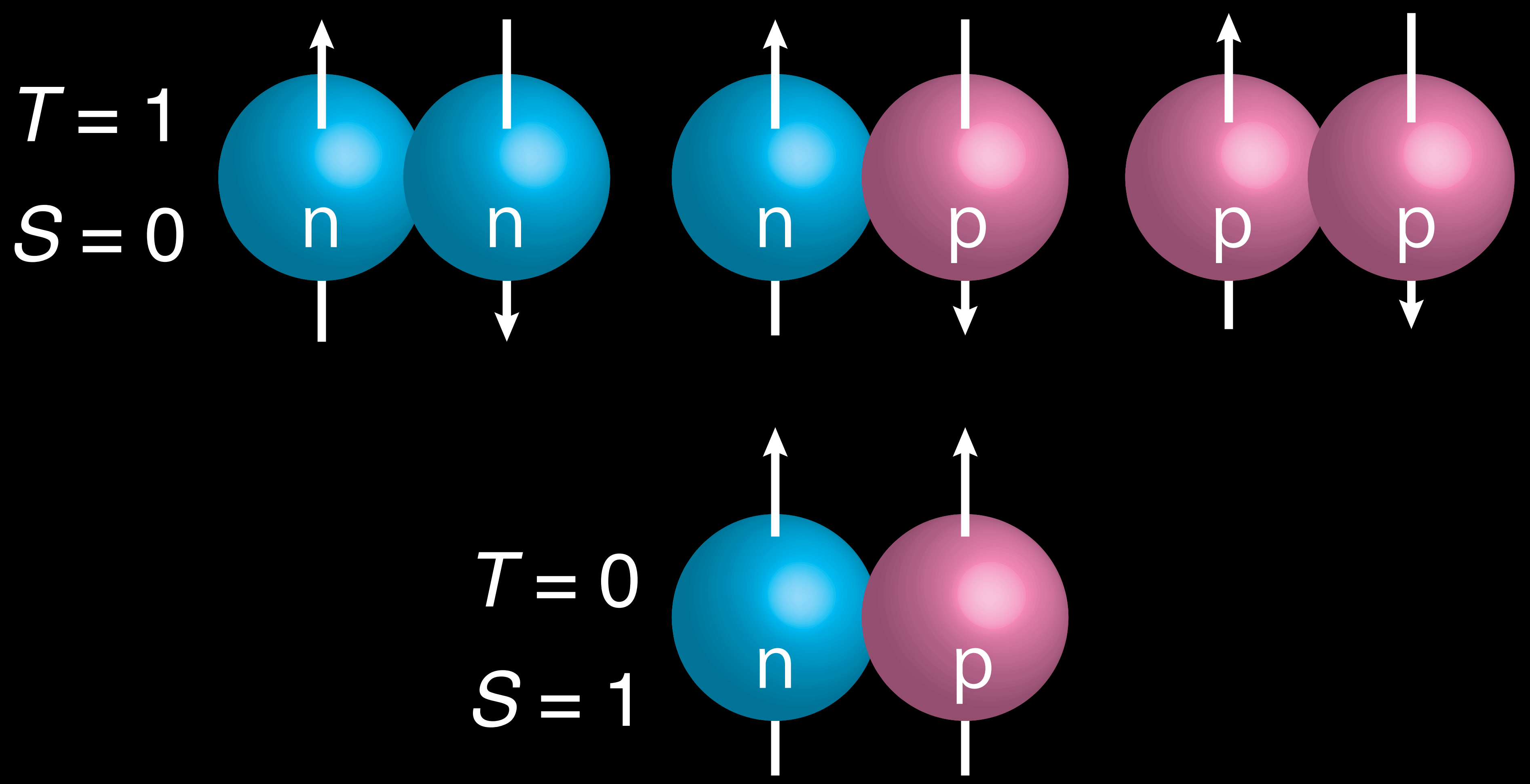
$$q \sim 0.78$$

non-nucleonic d.o.f.
two-body currents
short-range correlation
truncation of many-body space

Important role of the spin-triplet pairing revealed by the microscopic cal.

J. Engel *et al.*, PRC60(1999)014302



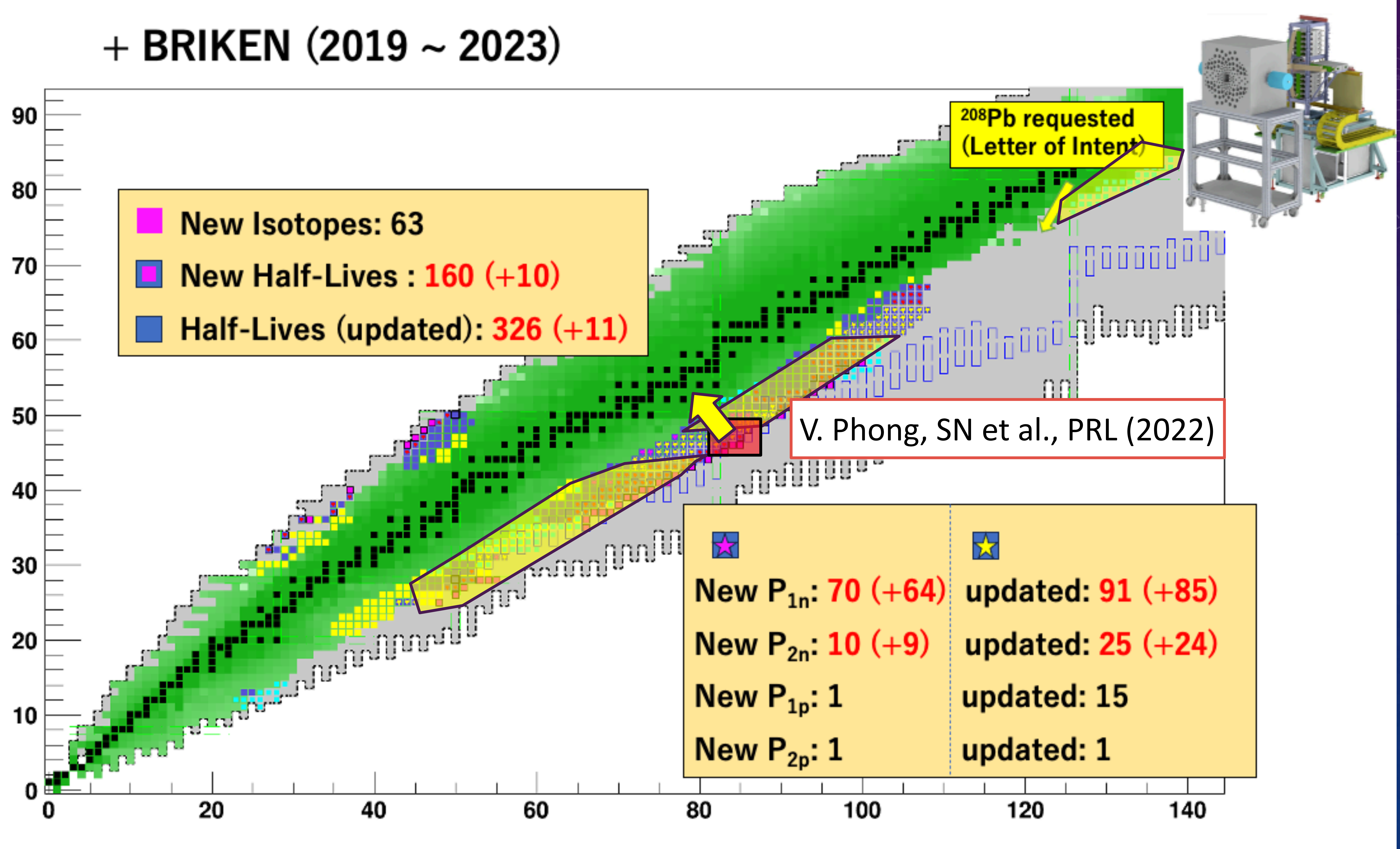


- ✓ being not included in FRDM
- ✓ shortens the half-lives
- ✓ sensitive to the shell structure

Decay Properties Surveyed

courtesy of S. Nishimura (RIKEN)

EURICA

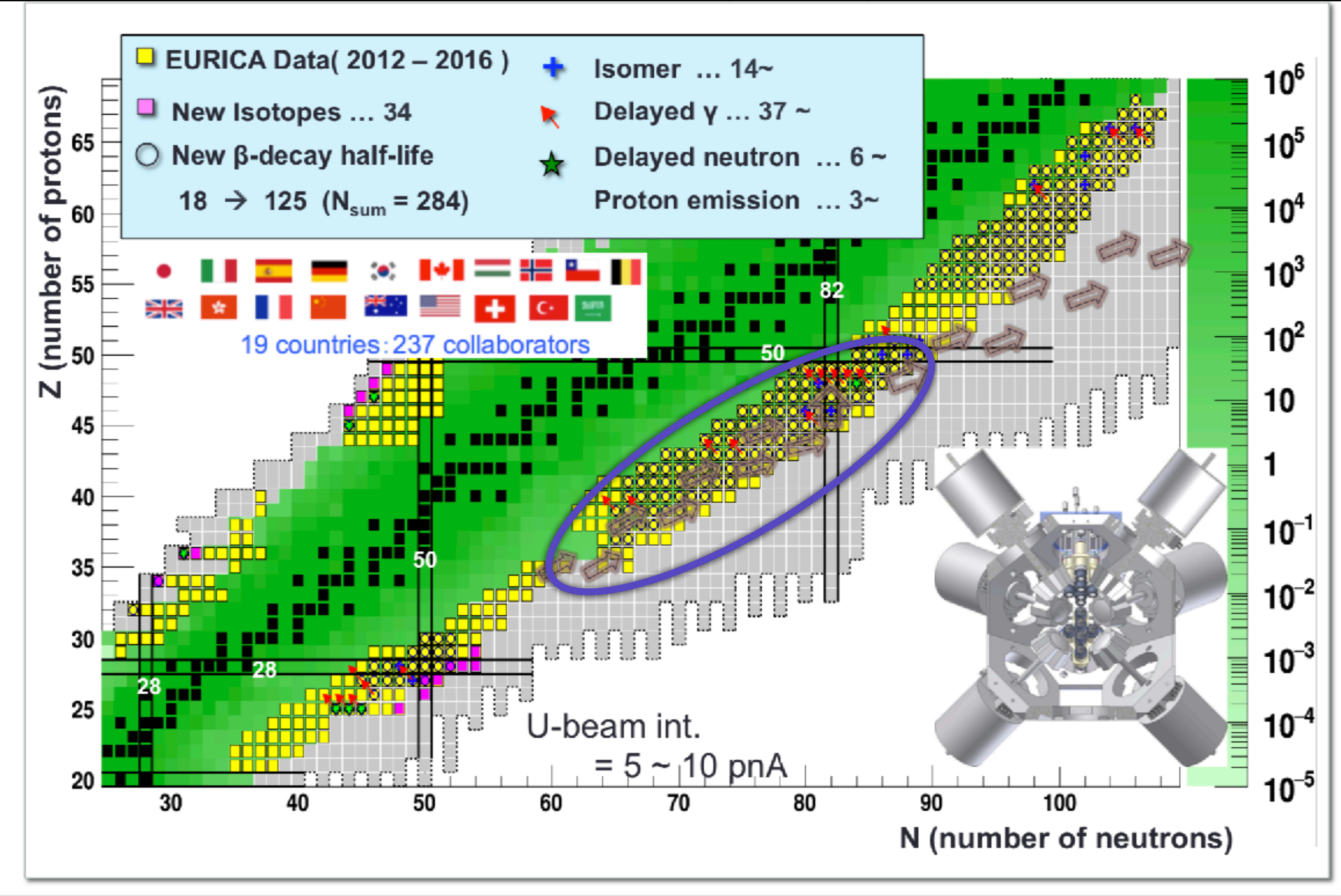


More Decay Data ($T_{1/2}$, P_{xn}) ... + ~ 200 Isotopes expected from BRIKEN

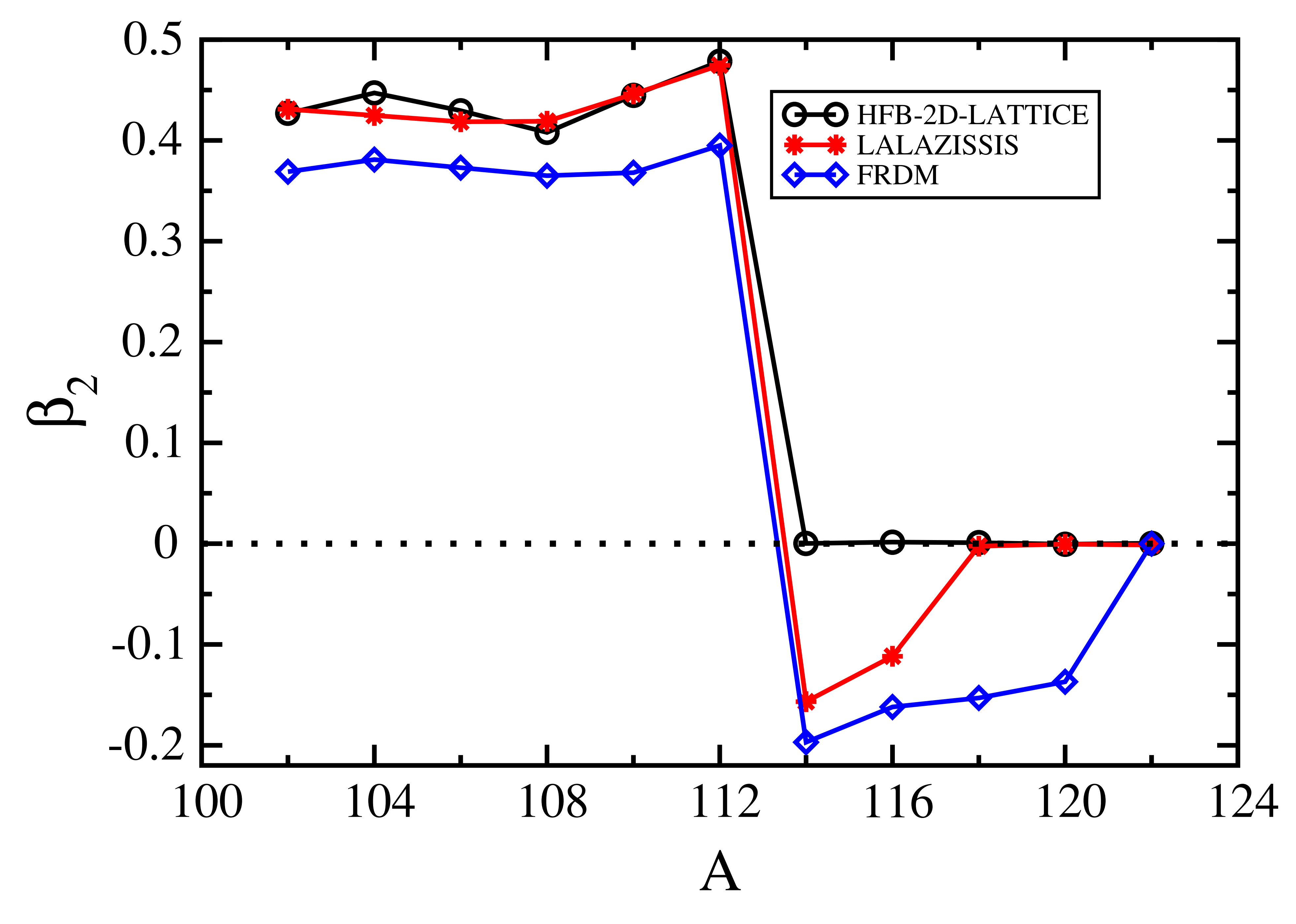
Systematic measurement of β-decay@RIBF

S. Nishimura *et al.*

β-decay half-lives of r-process nuclei



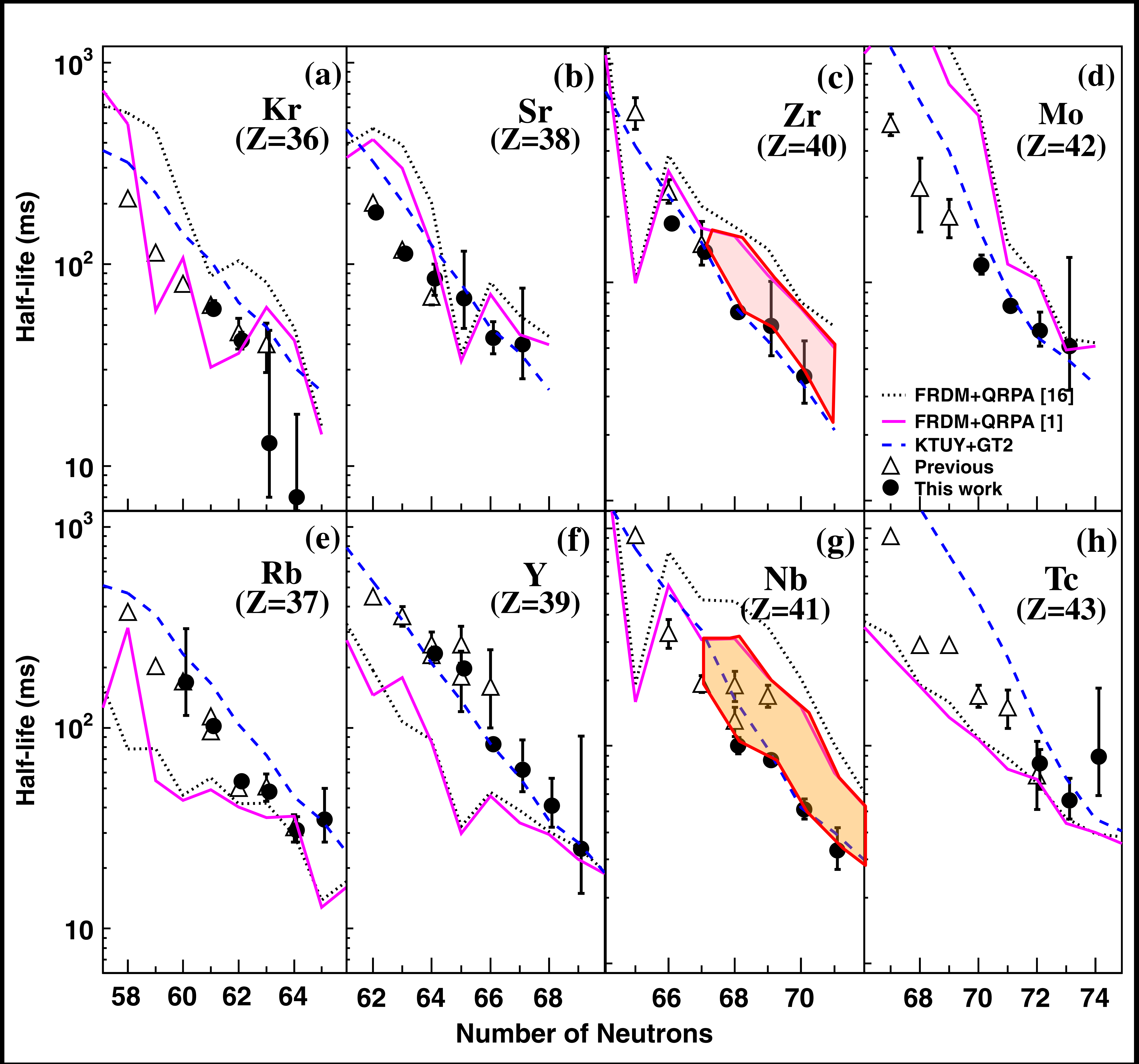
neutron-rich Zr isotopes: predicted to be well deformed by DFT cal.

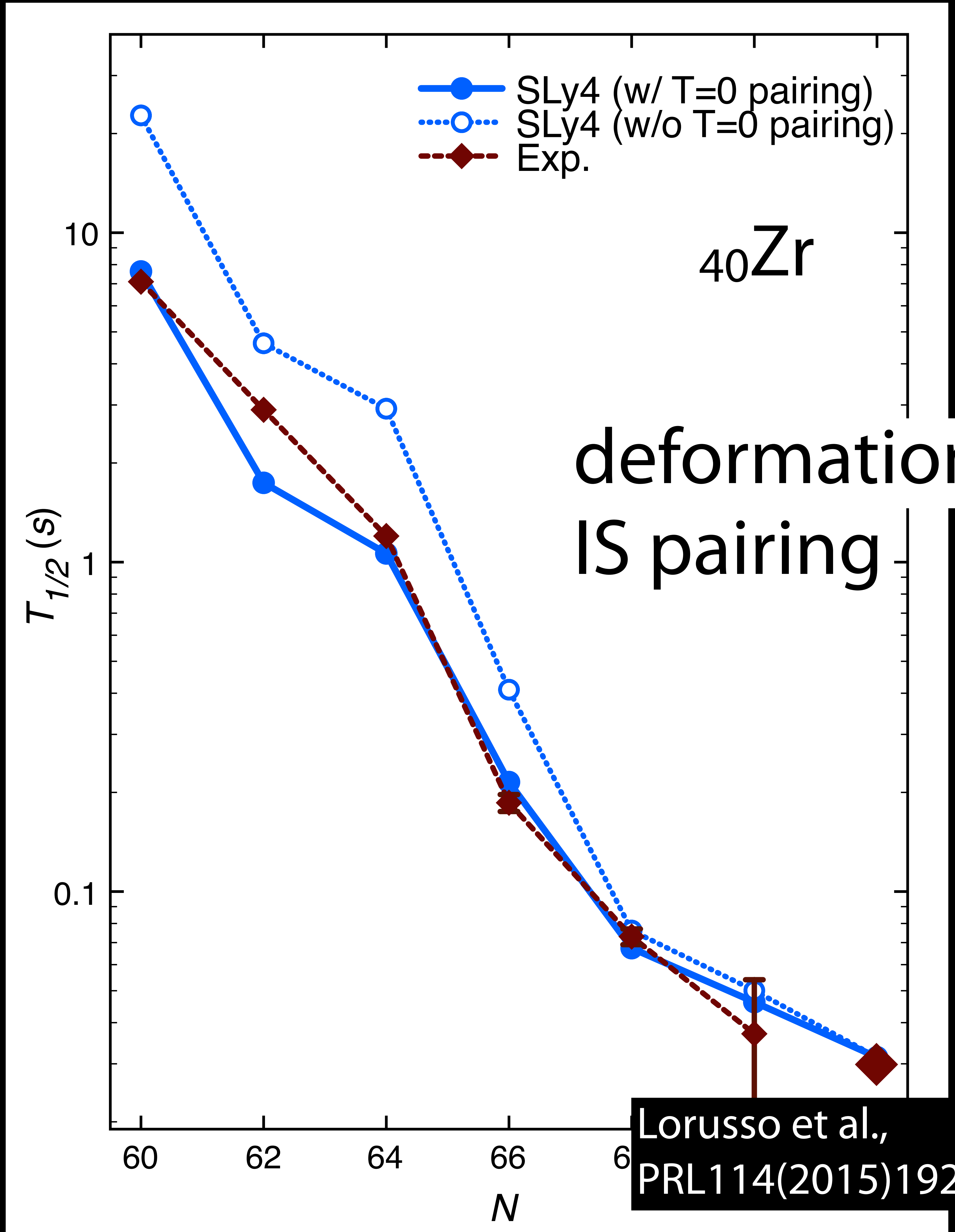


A. Blazkiewicz+, PRC71(2005)054321

Short half-lives in the Zr region

KY, PTEP(2013)113D02





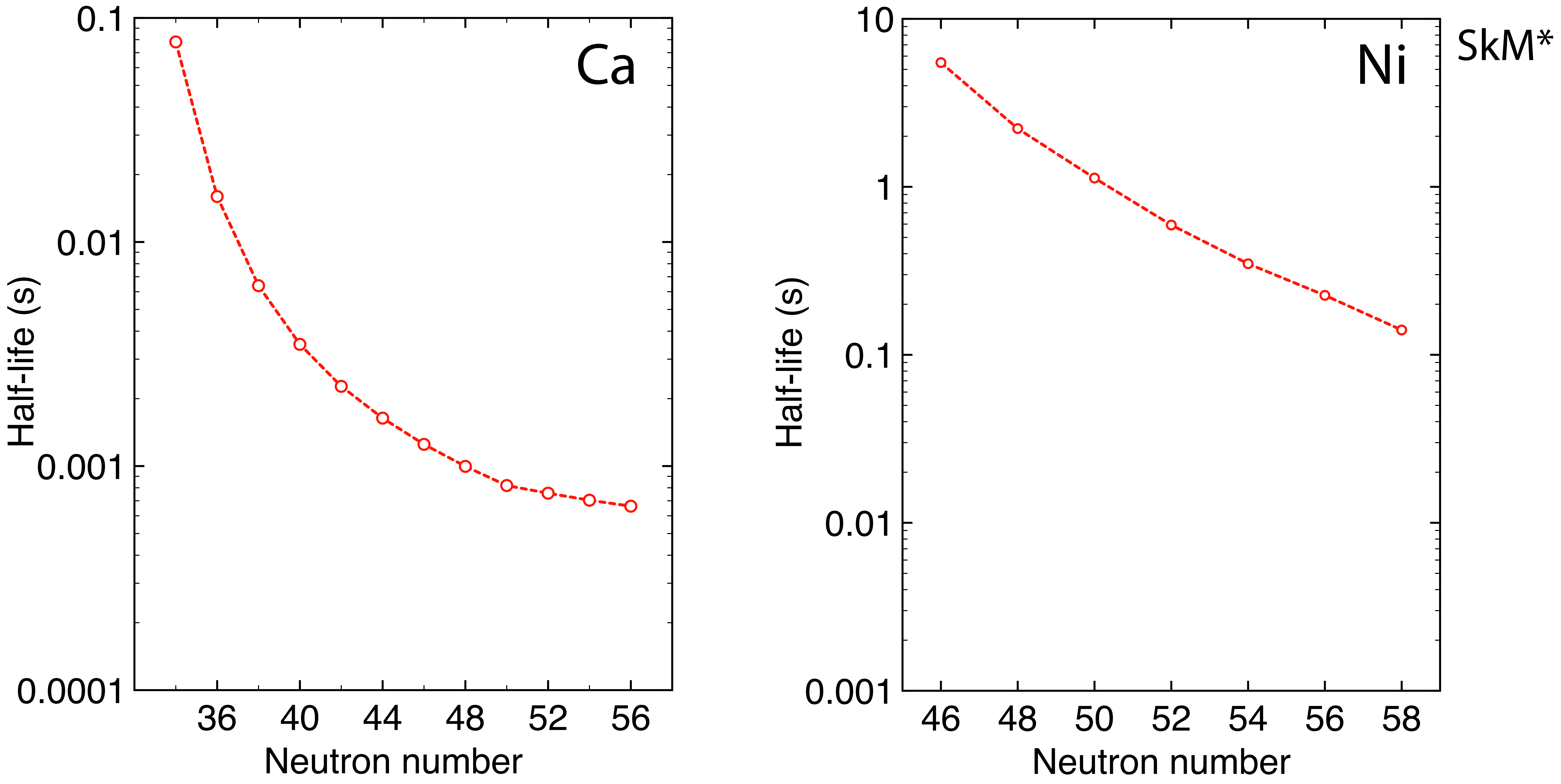
deformation
IS pairing

Lorusso et al.,
PRL114(2015)192501

Cross-shell $-1\hbar\omega_0$ excitation: impact on β-decay rate

allowed transitions only

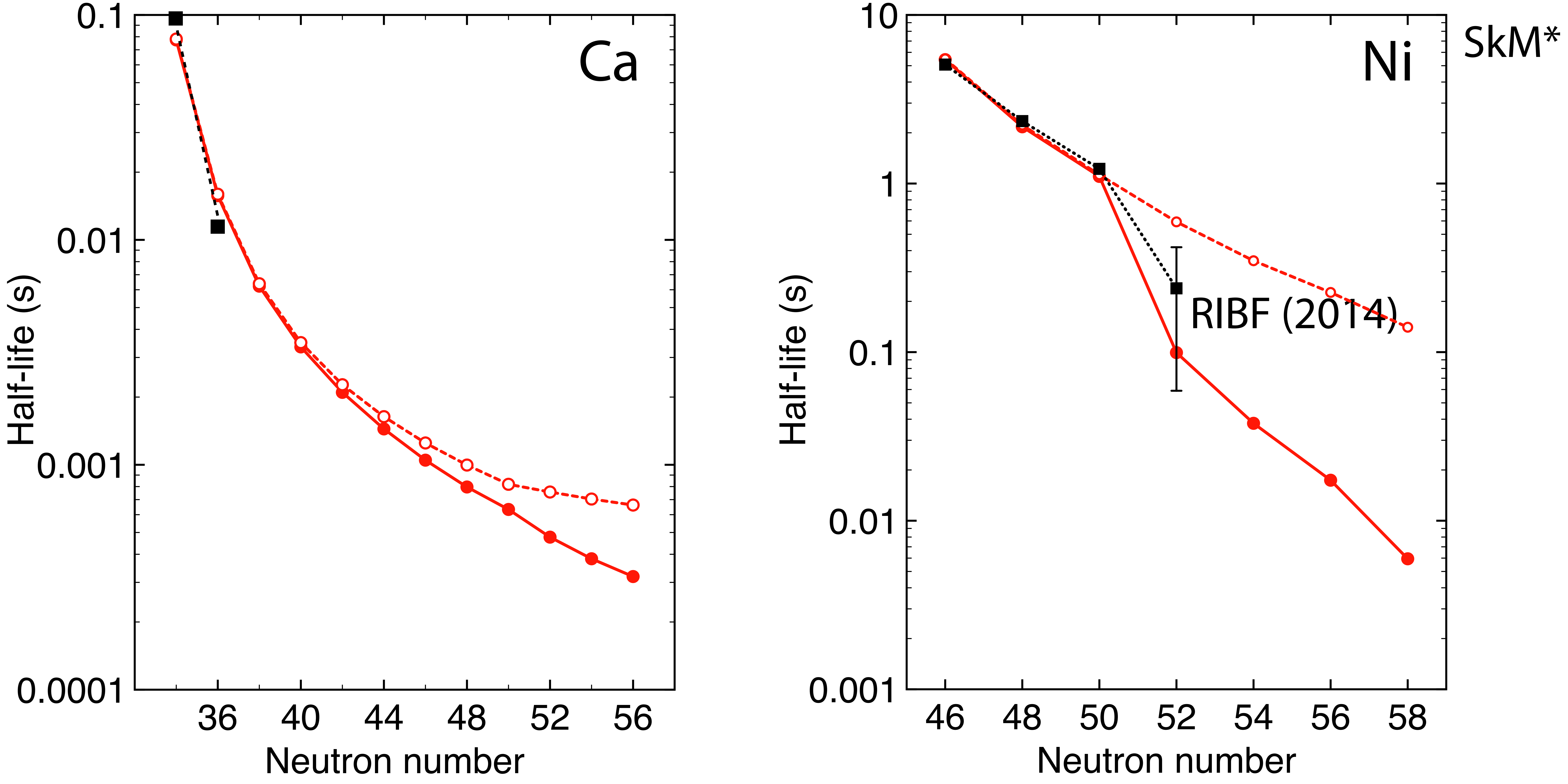
KY, PRC100(2019)



Cross-shell $-1\hbar\omega_0$ excitation: impact on β-decay rate

first-forbidden transitions (dipole+SD) included

KY, PRC100(2019)



Aim of this lecture

to understand the mean-field (MF) theory as an approximation to the quantum theory of many-body system

to understand the similarity and difference between MF theory and Density-Functional theory

to obtain physical picture characterizing the system from experimental data with the help of mean field

to understand physics behind the recent experiments