Skyrme energy-density functional approach to collective excitations in medium-mass to heavy nuclei

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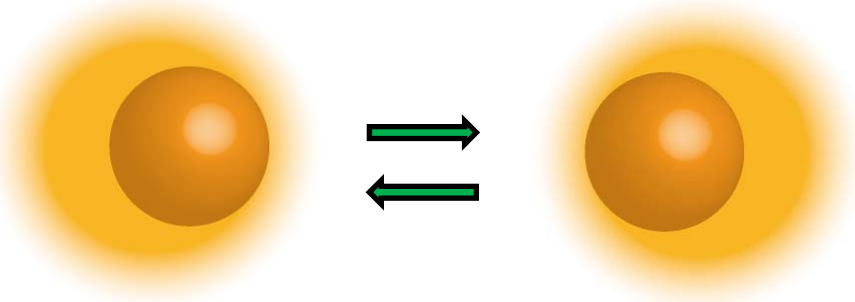
Collective modes unique to neutron-rich nuclei

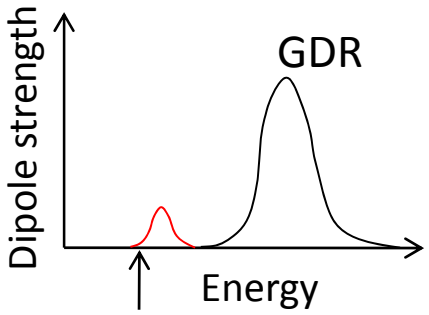
DEFORMATION

- ✓Coupling among excitation modes with different angular momenta

NEUTRON EXCESS

- ✓IS and IV mixing modes
- ✓Neutron-excitation dominant modes
- ✓Neutron-skin excitation modes
  - ✓Soft dipole mode, Pygmy resonance





Skyrme-HFB-QRPA for axially-symmetric nuclei

Minimizing the energy density $\delta\mathcal{E} = 0$ $\mathcal{E} = \mathcal{E}_{\rm kin} + \mathcal{E}_{\rm Sky} + \mathcal{E}_{\rm Coul} + \mathcal{E}_{\rm pair} + \mathcal{E}_{\rm corr}$

The coordinate-space Hartree-Fock-Bogoliubov eq. (Kohn-Sham-Bogoliubov eq.)

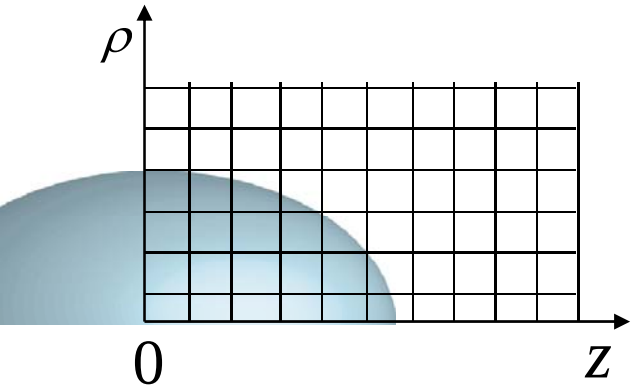
$$\begin{pmatrix} h^q(\boldsymbol{r},\sigma) - \lambda^q & \tilde{h}^q(\boldsymbol{r},\sigma) \\ \tilde{h}^q(\boldsymbol{r},\sigma) & -(h^q(\boldsymbol{r},\sigma) - \lambda^q) \end{pmatrix} \begin{pmatrix} \varphi^q_{1,i}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,i}(\boldsymbol{r},\sigma) \end{pmatrix} = E_i \begin{pmatrix} \varphi^q_{1,i}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,i}(\boldsymbol{r},\sigma) \end{pmatrix}$$

J.Dobaczewski, H.Flocard and J.Treiner, NPA422(1984)103
A.Bulgac, FT-194-1980 (Institute of Atomic Physics, Bucharest)

- Mean-field Hamiltonian $h = \dfrac{\delta\mathcal{E}}{\delta\varrho}$
- Pairing field $\tilde{h} = \dfrac{\delta\mathcal{E}}{\delta\tilde{\varrho}}$

HFB equations solved directly on the 2D lattice.

➢11-point formula for derivative



✓Simple

✓Appropriate for describing the spatially extended structure of wave functions

⟷ H.O. basis

Q(uasiparticle-)RPA

HFB equations ⟹ Quasiparticle basis (i,j,k,l)

KY, N.V.Giai, PRC78(2008)064316

The QRPA equation in a matrix form

$$\begin{pmatrix} A_{\alpha\beta\gamma\delta} & B_{\alpha\beta\gamma\delta} \\ B_{\alpha\beta\gamma\delta} & A_{\alpha\beta\gamma\delta} \end{pmatrix} \begin{pmatrix} X^i_{\gamma\delta} \\ Y^i_{\gamma\delta} \end{pmatrix} = \hbar\omega_i \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^i_{\alpha\beta} \\ Y^i_{\alpha\beta} \end{pmatrix}$$

Residual interactions

✓particle-hole channel: $\dfrac{\delta^2 \mathcal{E}_{\rm Sky}}{\delta\varrho(\boldsymbol{r}')\delta\varrho(\boldsymbol{r})}$

$$\begin{aligned} v_{ph}(\boldsymbol{r},\boldsymbol{r}') = & [a_0 + a_0'\boldsymbol{\tau}\cdot\boldsymbol{\tau}' + (b_0 + b_0'\boldsymbol{\tau}\cdot\boldsymbol{\tau}')\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}']\delta(\boldsymbol{r}-\boldsymbol{r}') \\ & + [a_1 + a_1'\boldsymbol{\tau}\cdot\boldsymbol{\tau}' + (b_1 + b_1'\boldsymbol{\tau}\cdot\boldsymbol{\tau}')\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}'][\boldsymbol{k}^{\dagger 2}\delta(\boldsymbol{r}-\boldsymbol{r}') + \delta(\boldsymbol{r}-\boldsymbol{r}')\boldsymbol{k}^2] \\ & + [a_2 + a_2'\boldsymbol{\tau}\cdot\boldsymbol{\tau}' + (b_2 + b_2'\boldsymbol{\tau}\cdot\boldsymbol{\tau}')\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}'][\boldsymbol{k}^{\dagger}\cdot\delta(\boldsymbol{r}-\boldsymbol{r}')\boldsymbol{k}] \\ & + (a_4 + a_4'\boldsymbol{\tau}\cdot\boldsymbol{\tau}')(\boldsymbol{\sigma}+\boldsymbol{\sigma}')\cdot\boldsymbol{k}^{\dagger}\times\delta(\boldsymbol{r}-\boldsymbol{r}')\boldsymbol{k} \end{aligned}$$

We neglect the two-body Coulomb interaction.

✓particle-particle channel: $\dfrac{\delta^2 \mathcal{E}_{\rm pair}}{\delta\tilde{\varrho}(\boldsymbol{r}')\delta\tilde{\varrho}(\boldsymbol{r})}$

Strength distributions

$$S_\lambda(E) = \frac{\Gamma/2}{\pi}\sum_i\sum_K \frac{|\langle i|\hat{F}_\lambda|0\rangle|^2}{(E-\hbar\omega_i)^2 + \Gamma^2/4} \qquad \Gamma = 2\ \text{MeV}$$

Deformed HFB+QRPA for heavy nuclei

Using N CPUs:

HFB equations for each angular momentum, parity and isospin

$$\begin{pmatrix} h^q(\boldsymbol{r},\sigma)-\lambda^q & \tilde{h}^q(\boldsymbol{r},\sigma) \\ \tilde{h}^q(\boldsymbol{r},\sigma) & -(h^q(\boldsymbol{r},\sigma)-\lambda^q) \end{pmatrix} \begin{pmatrix} \varphi^q_{1,i}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,i}(\boldsymbol{r},\sigma) \end{pmatrix} = E_i \begin{pmatrix} \varphi^q_{1,i}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,i}(\boldsymbol{r},\sigma) \end{pmatrix}$$

neutrons

protons

CPU 1	CPU 2	...	CPU N/2	CPU N/2+1	...	CPU N
$\Omega^\pi = 1/2^+$	$1/2^-$		$(N-2)/4^-$	$1/2^+$		$(N-2)/4^-$

Densities, Hamiltonians

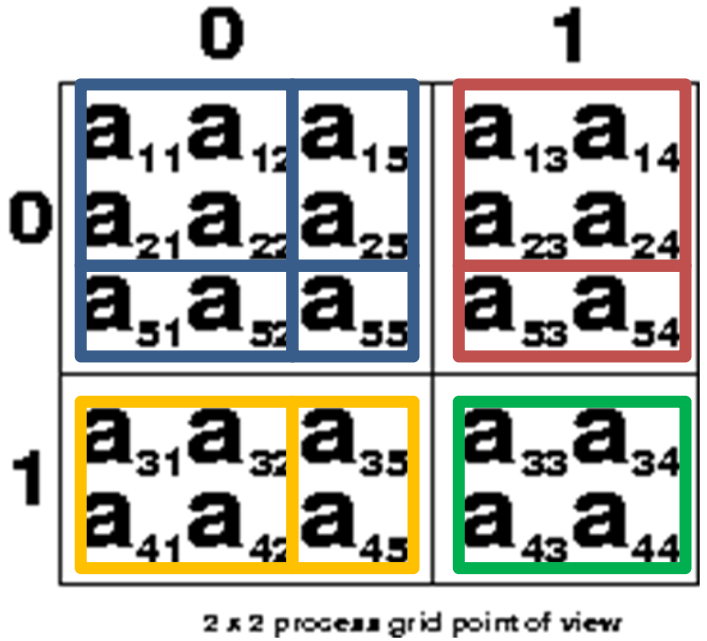
Iteration

Deformed HFB+QRPA for heavy nuclei

Distribution of the QRPA matrices

Ex. Using 4 CPUs

block matrix



original matrix (global)

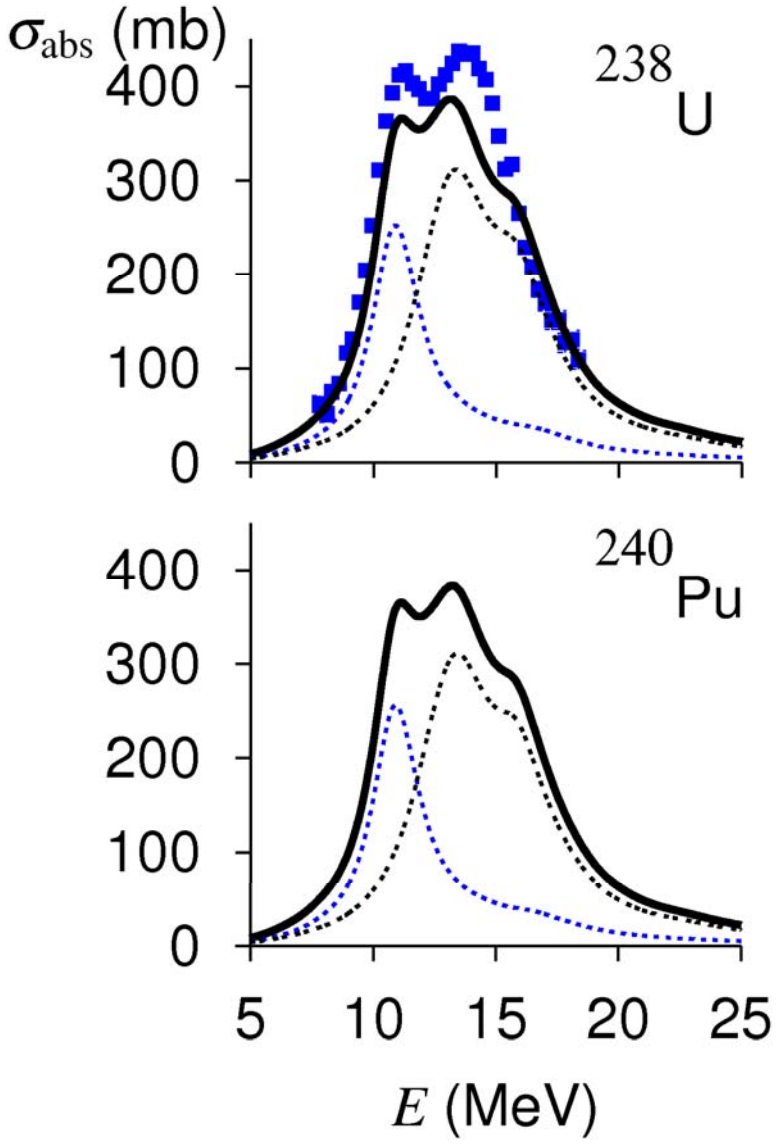
distributed matrix (local)

✓Matrix elements

✓Diagonalization ⇨ ScaLAPACK

Dipole responses in actinides

SkM* functional



HFB calc. (using 64 CPUs)

Box: $14.7\ \mathrm{fm} \times 14.4\ \mathrm{fm}$

Cut-off: $\Omega \leqq \frac{31}{2}$, $E_\alpha \leqq 60\ \mathrm{MeV}$

QRPA calc.

Cut-off: $E_\alpha + E_\beta \leqq 60\ \mathrm{MeV}$

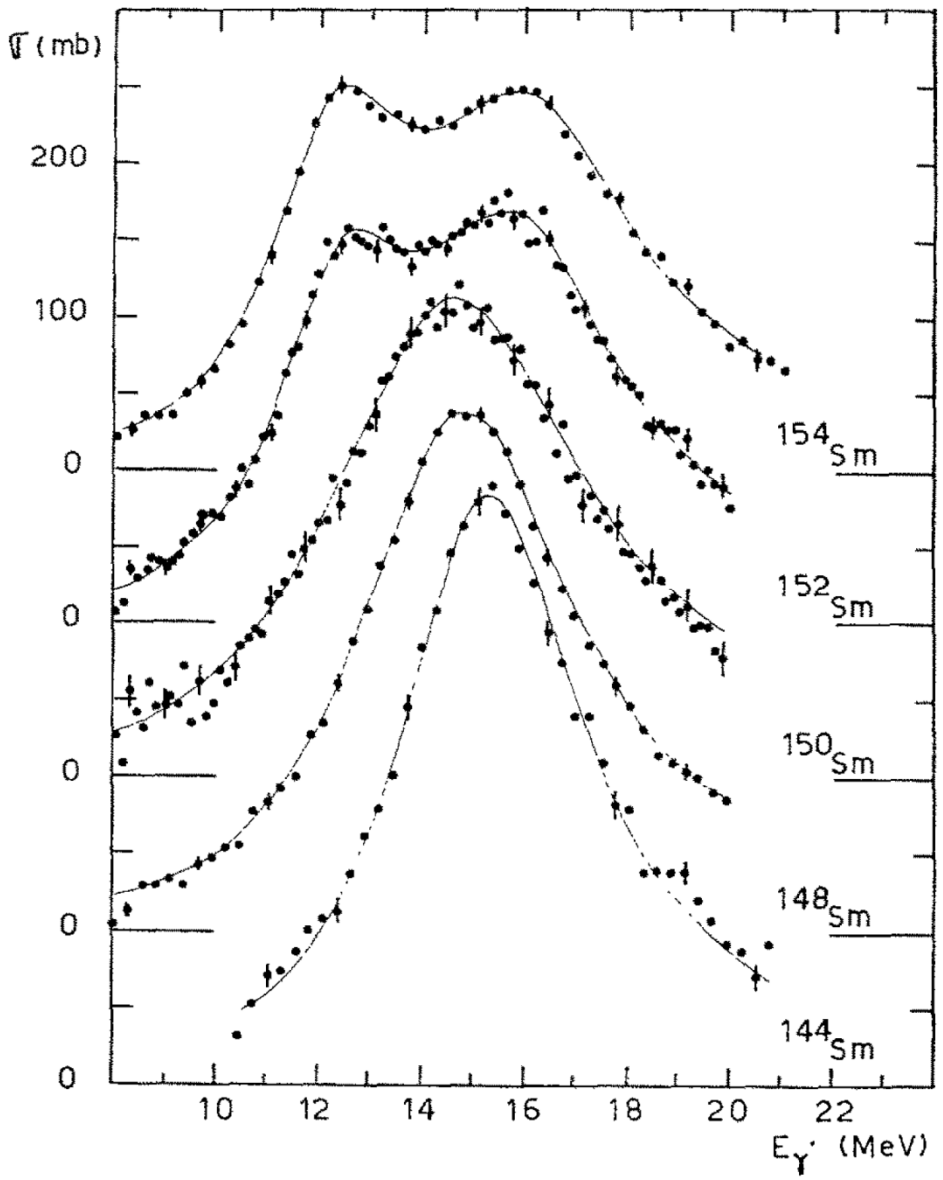
# of 2qp excitation: about 50,000

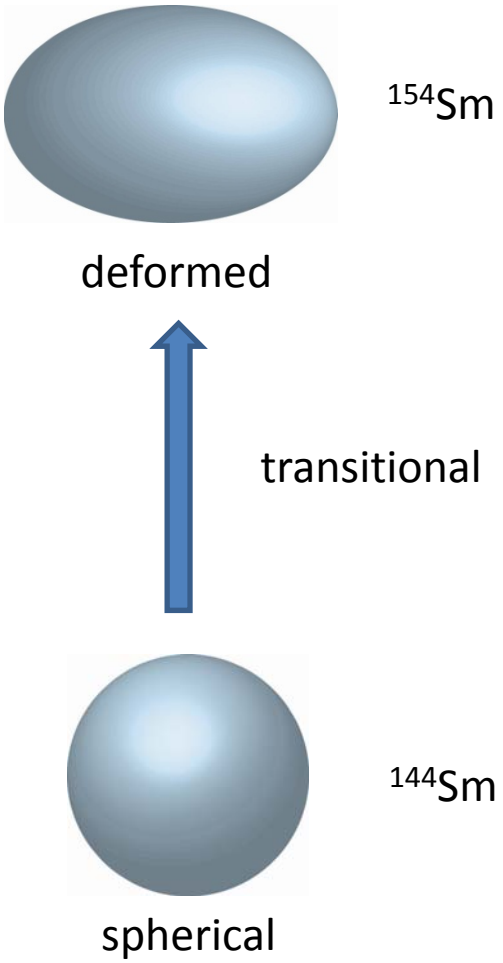
Matrix elements: 590 CPU hours
Diagonalization: 330 CPU hours

512 CPUs@RICC

Matrix elements: 69 minutes
Diagonalization: 38 minutes

Evolution of nuclear deformation in GDR





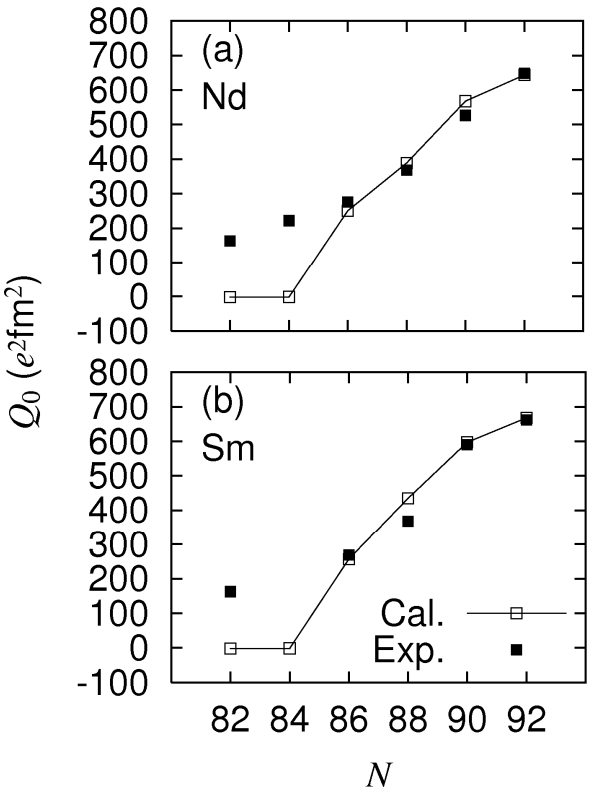
P.Carlos *et al.*, NPA225(1974)171

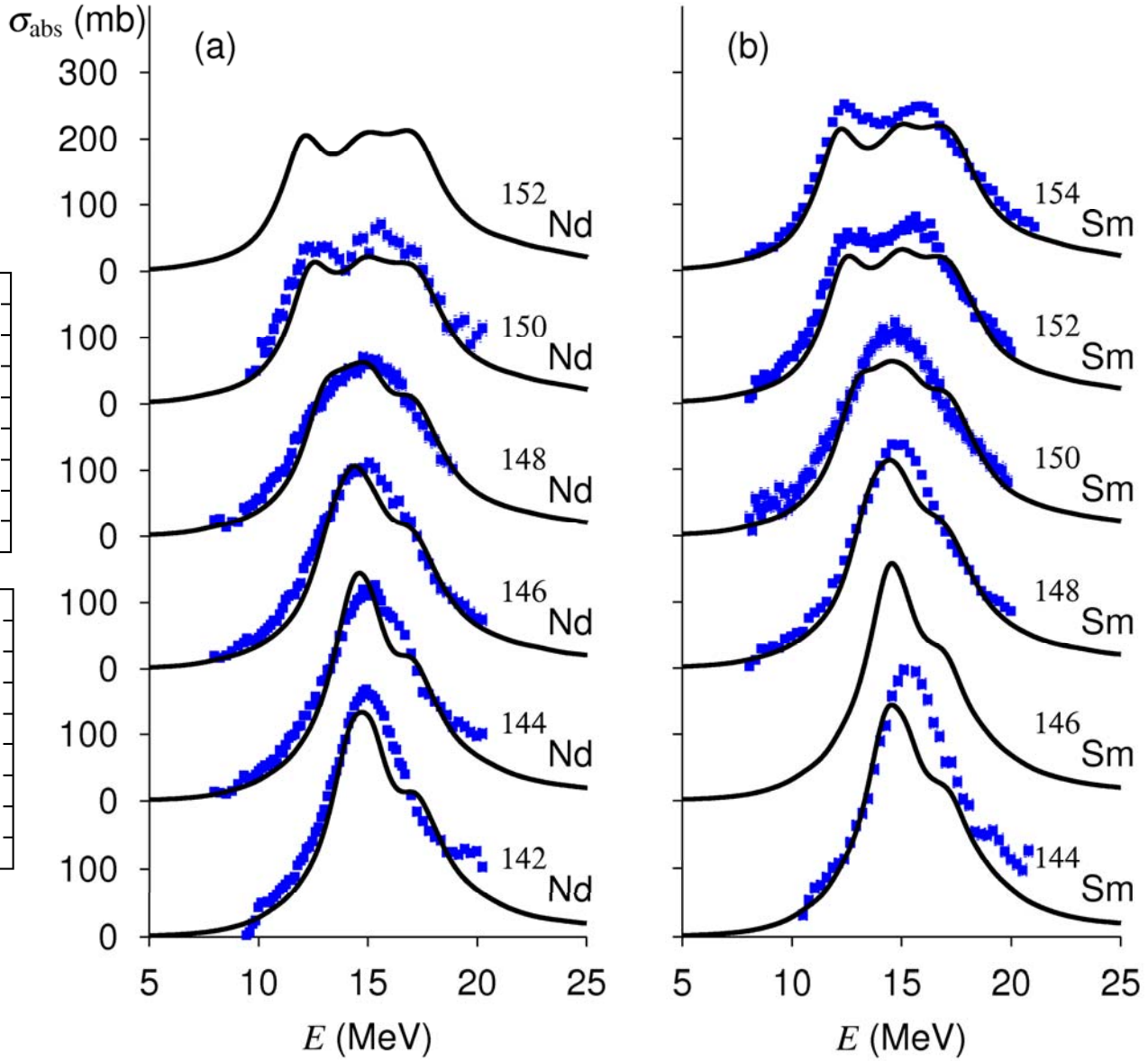
Skyrme-QRPA photoabsorption cross sections

SkM* functional

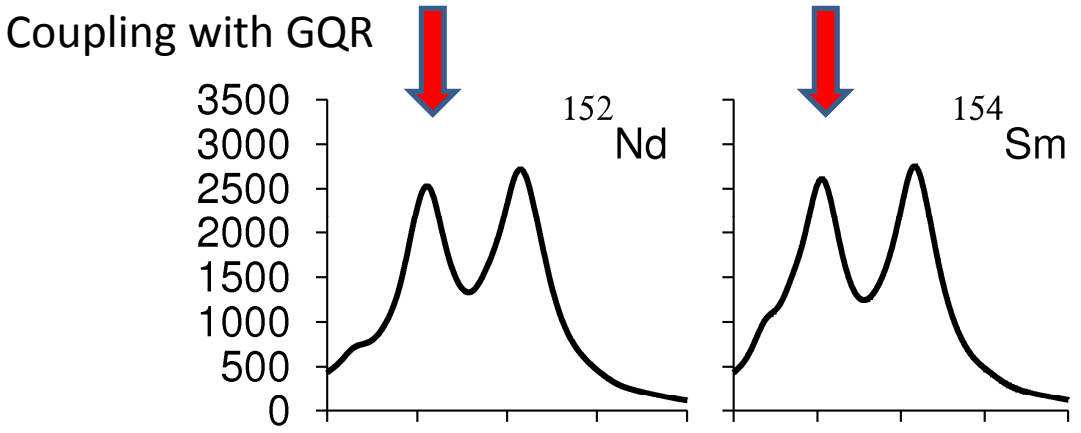
KY, T.Nakatsukasa, arXiv:1008.1520

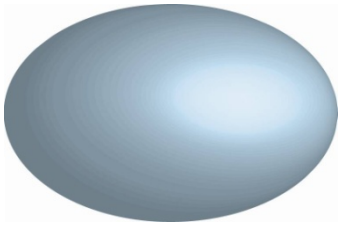
Intrinsic Q moment



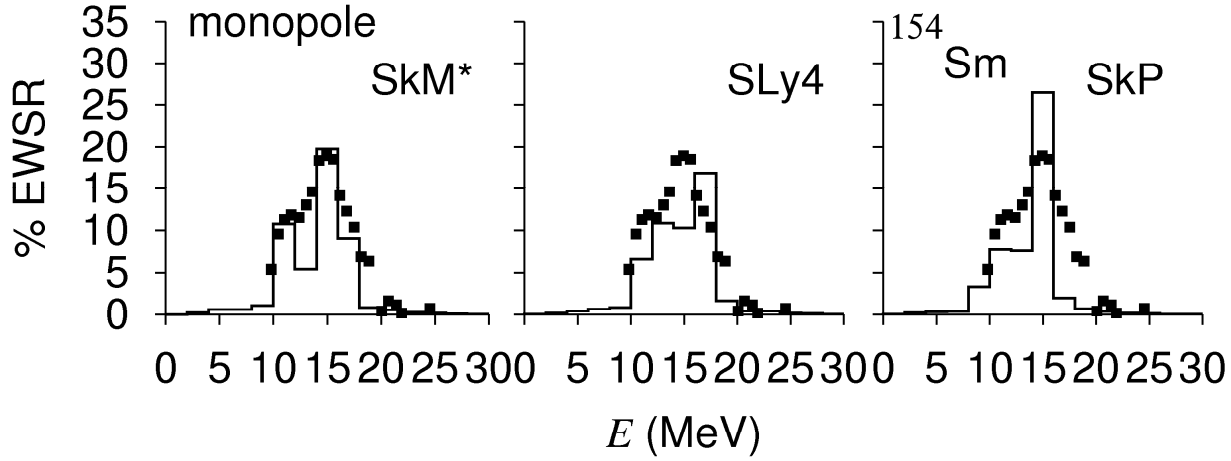


Deformation effect on ISGMR





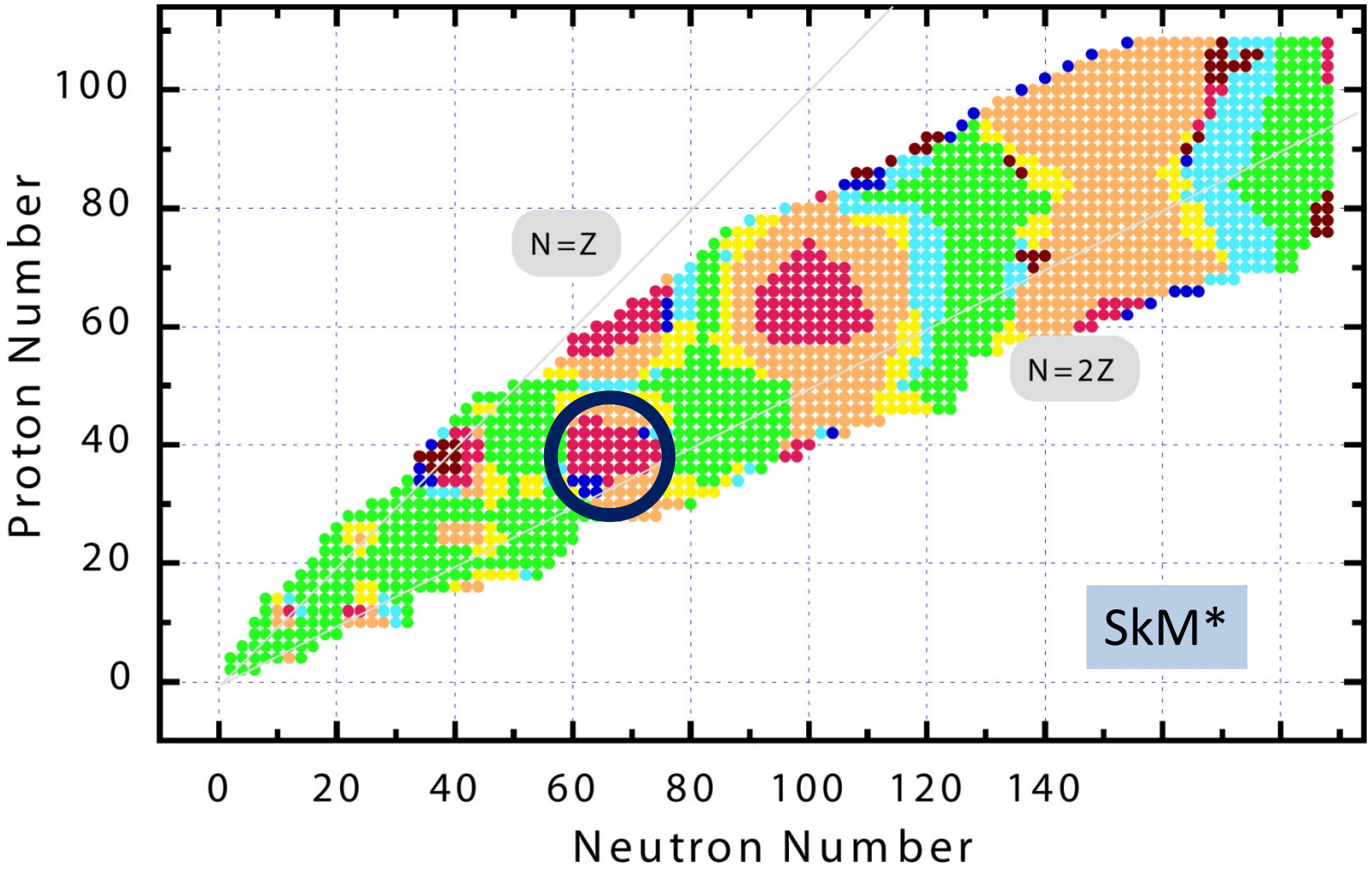
deformed



spherical

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

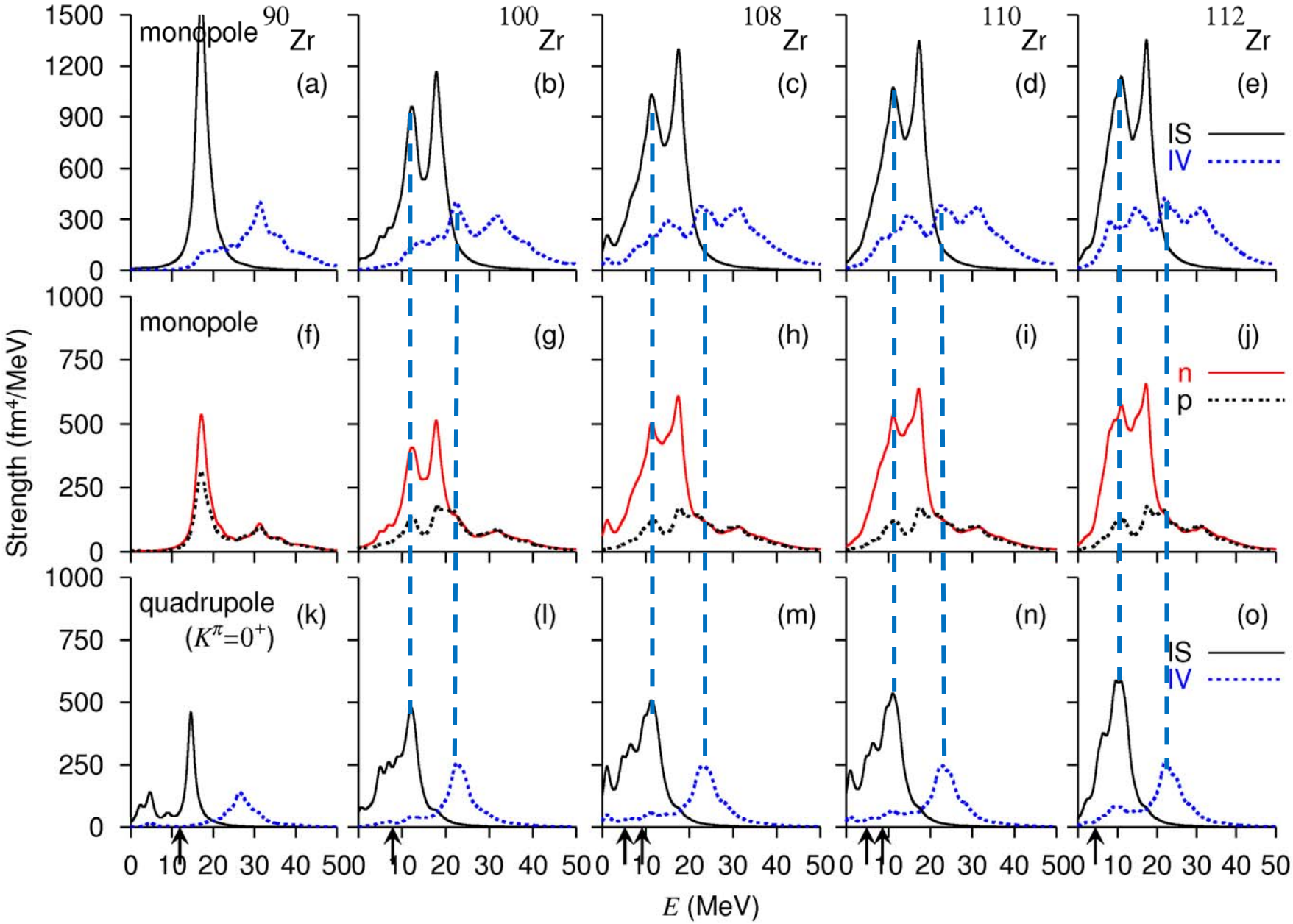
Deformation in Zr isotopes



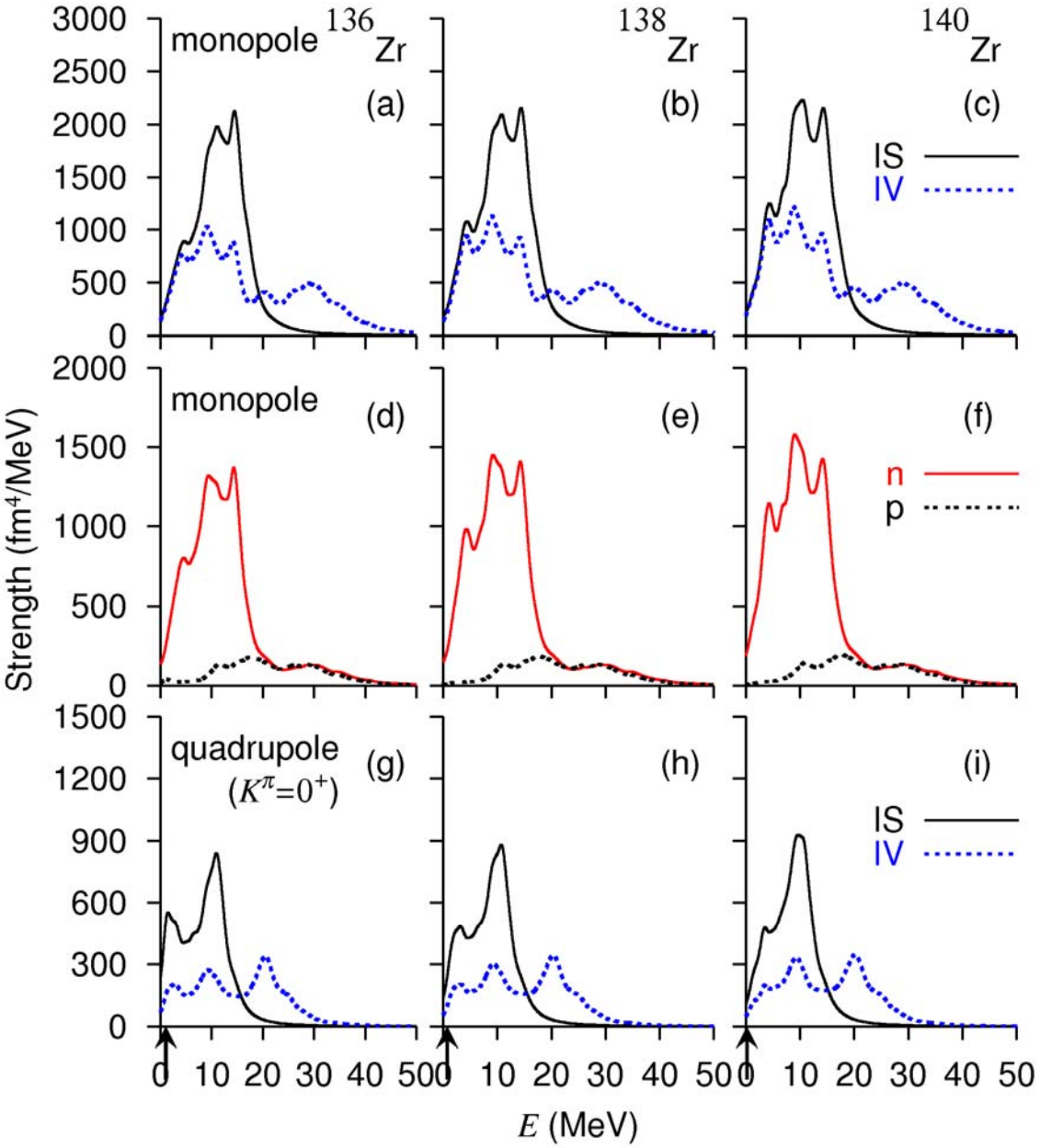
M.V. Stoitsov *et al.*, Phys. Rev. C68(2003) 054312

Strong deformation in Zr isotopes around N=70

Effects deformation and neutron excess on GMR



GMR in deformed drip-line nuclei

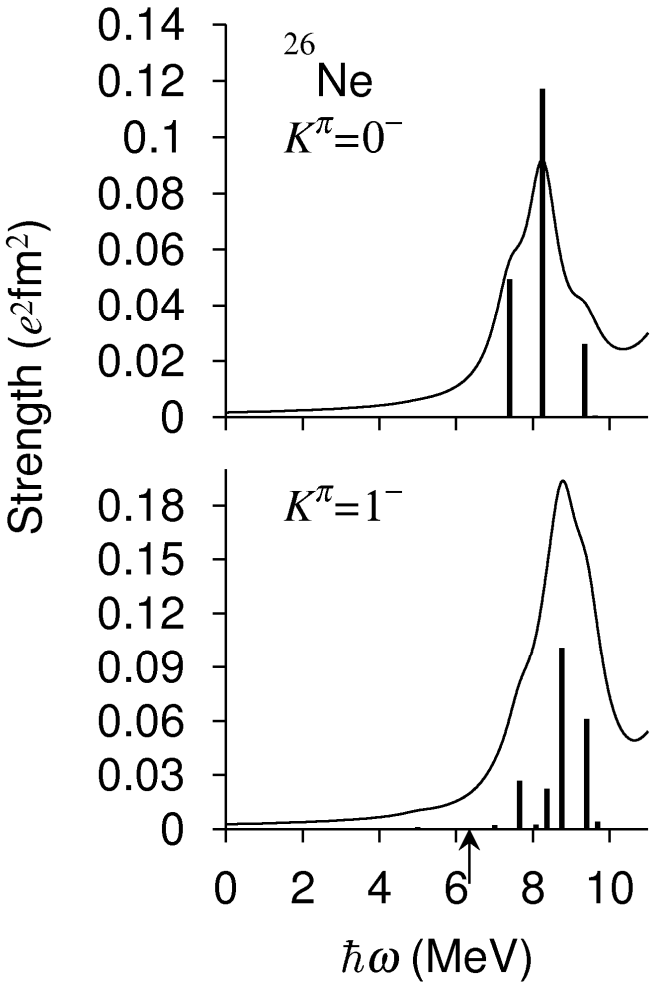


KY, arXiv:1008.1522

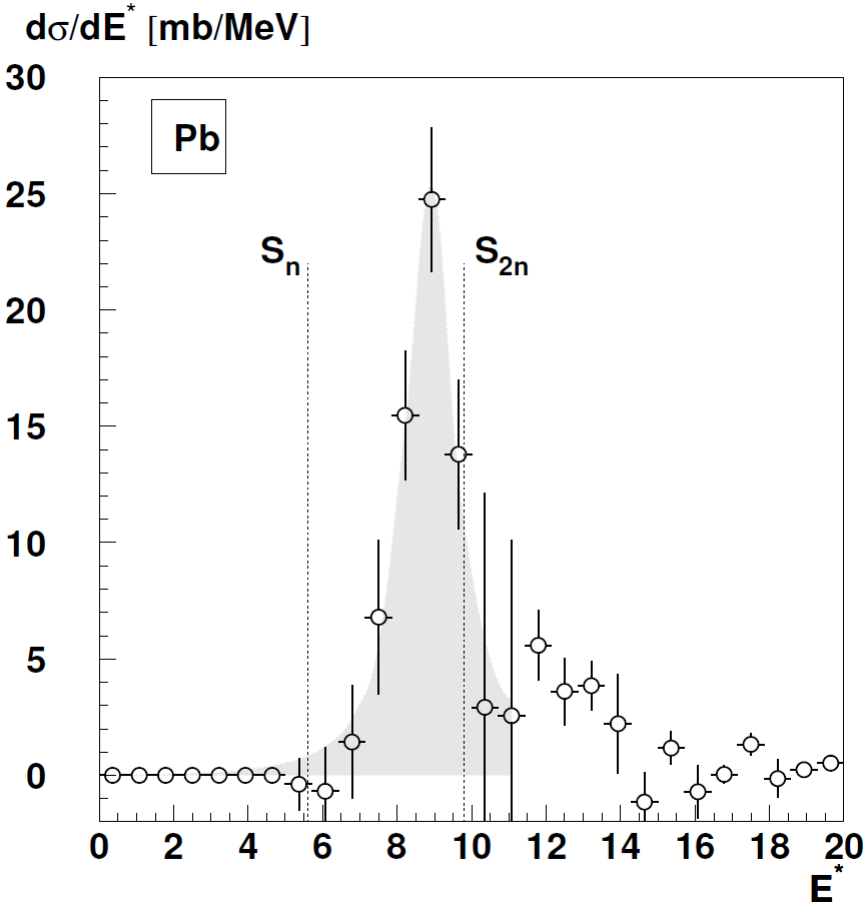
- ✓Excitation of neutrons
- ✓Threshold strength

Pygmy resonance in ^{26}Ne

KY, N.V.Giai, PRC78(2008)014305



J.Gibelin *et al.*, PRL101(2008)212503



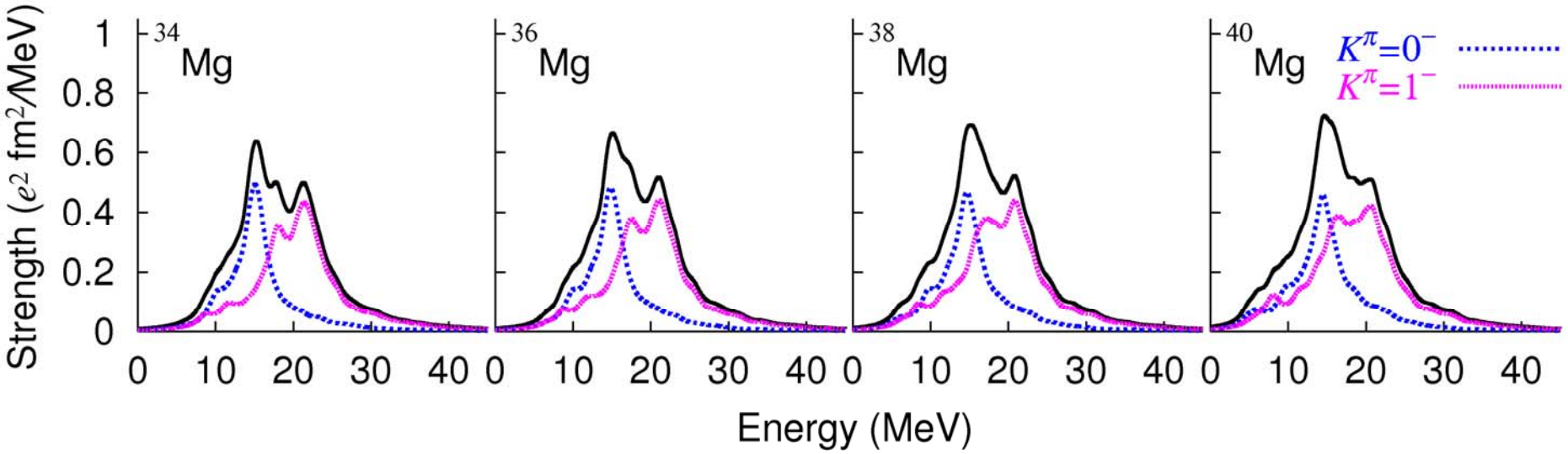
6% of the TRK sum rule (up to 10MeV)

Single-particle excitation is dominant: $\nu(2s_{1/2}^{-1}1p_{3/2})$

IV dipole excitations in neutron-rich Mg isotopes

KY, PRC80(2009)044324

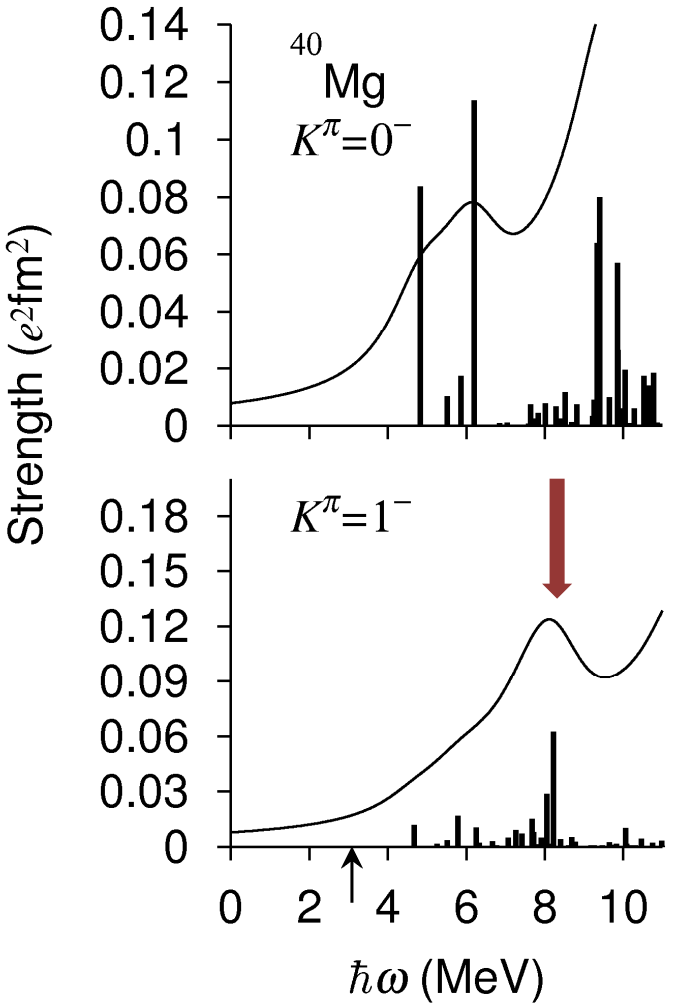
	^{34}Mg	^{36}Mg	^{38}Mg	^{40}Mg
$\beta_{2,n}$	0.35	0.31	0.29	0.28
$\beta_{2,p}$	0.41	0.39	0.38	0.36

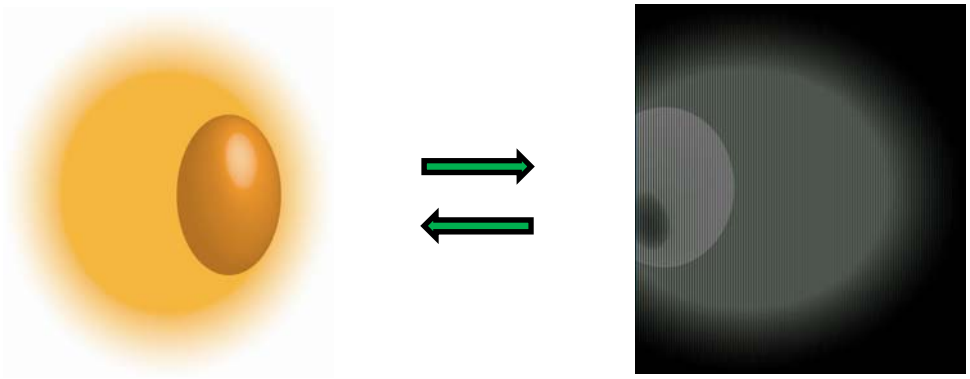


GDR: "K splitting" ➡ good indicator of deformation

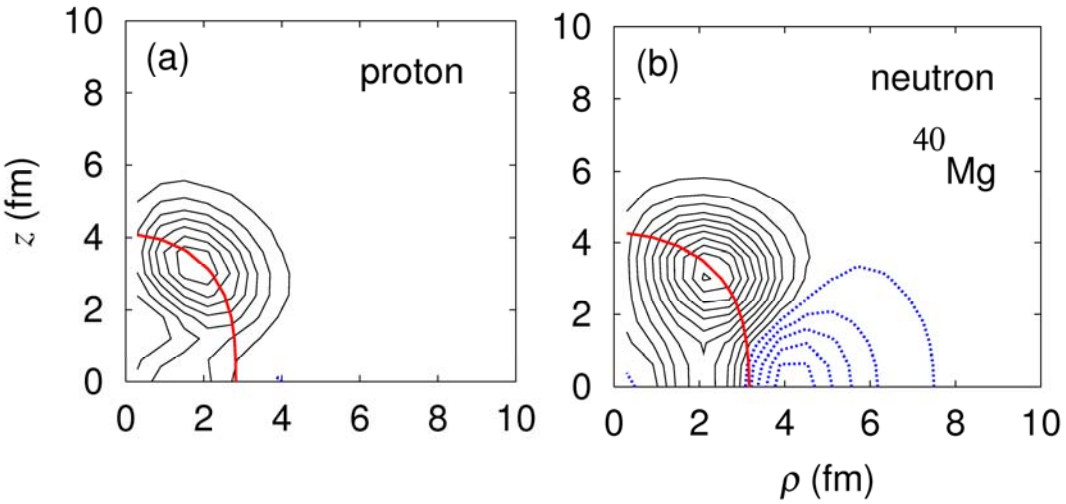
- Unique feature in neutron drip-line nuclei
  - ✓As approaching the drip line, the bump structure below 10MeV develops.

Pygmy mode in ^{40}Mg



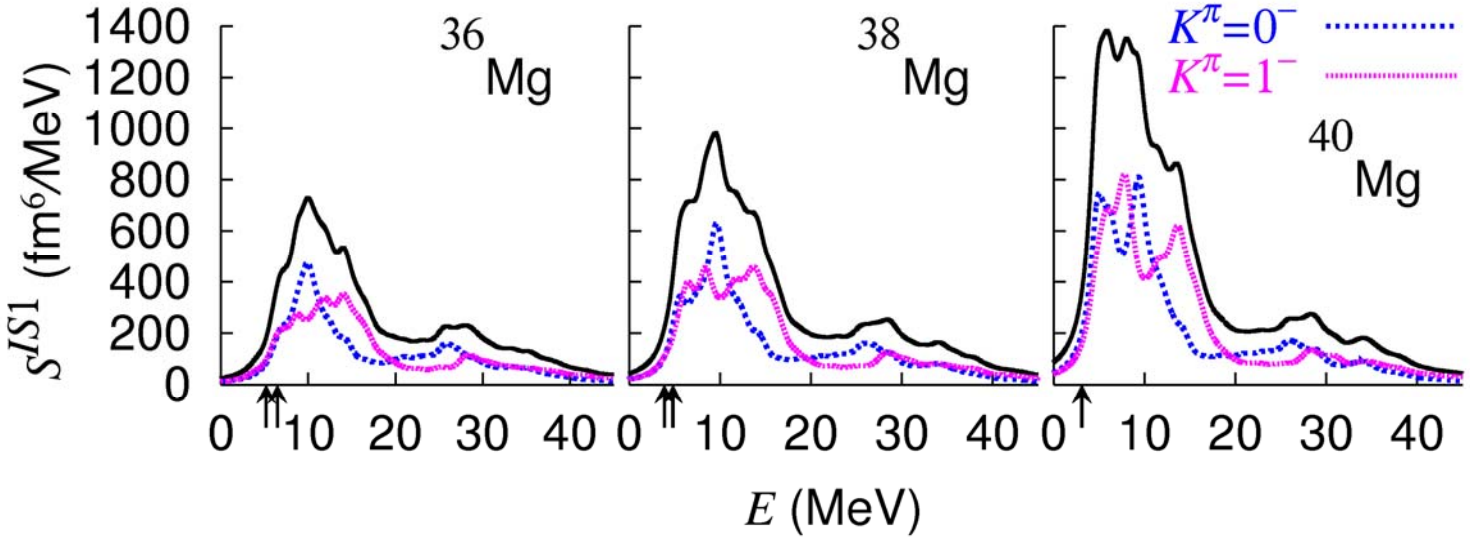


Transition density (8.2 MeV)



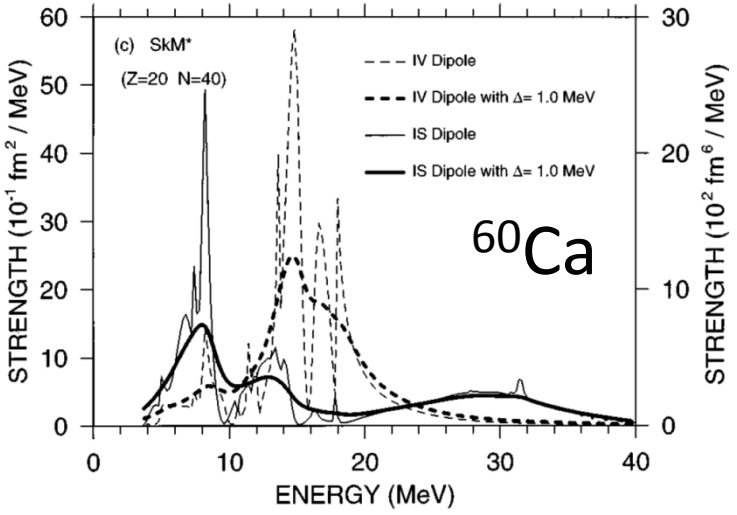
Isoscalar character of the pygmy mode

Responses for the compression dipole operator



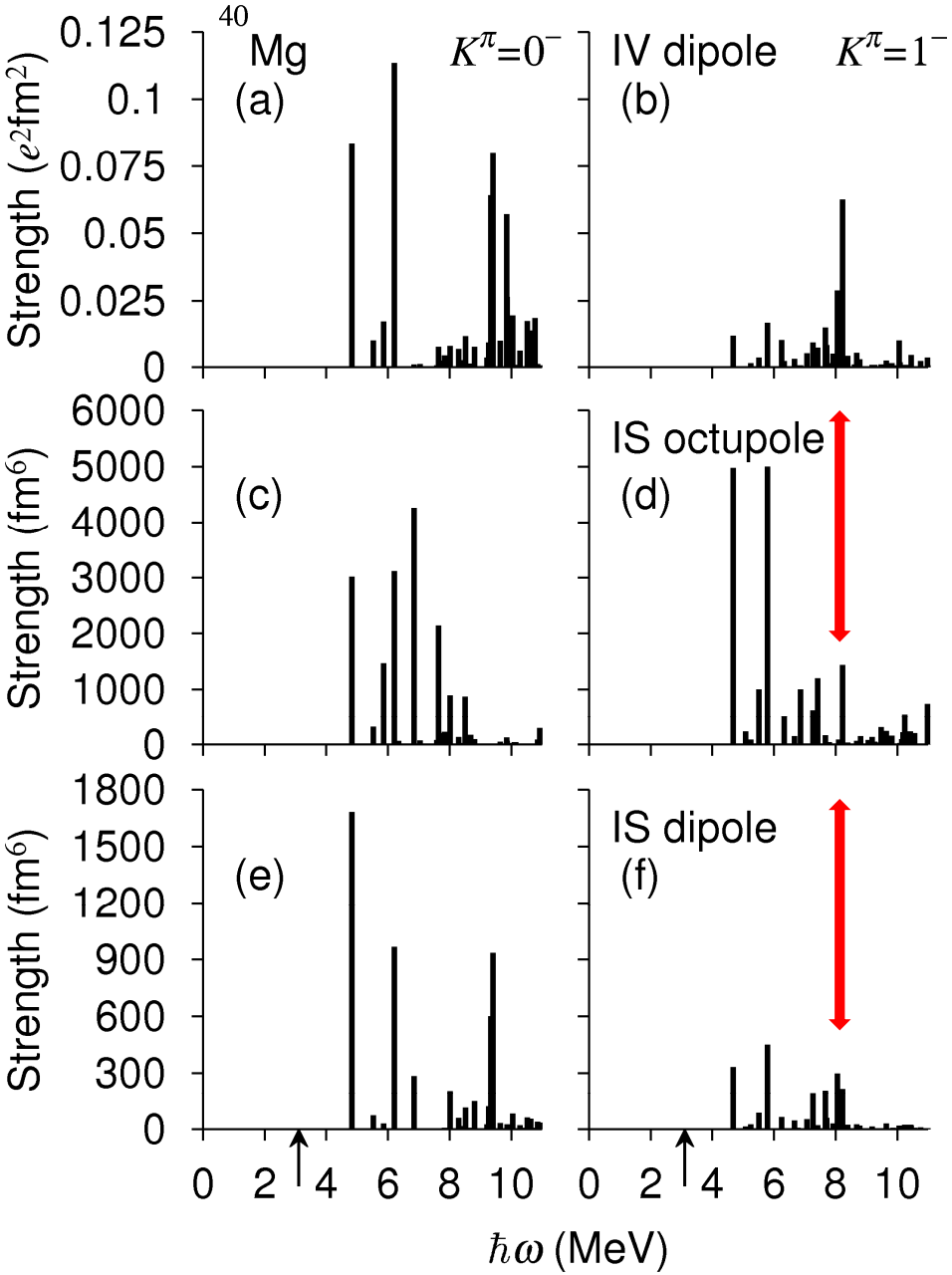
Tremendous enhancement of the transition strengths in the low-energy region

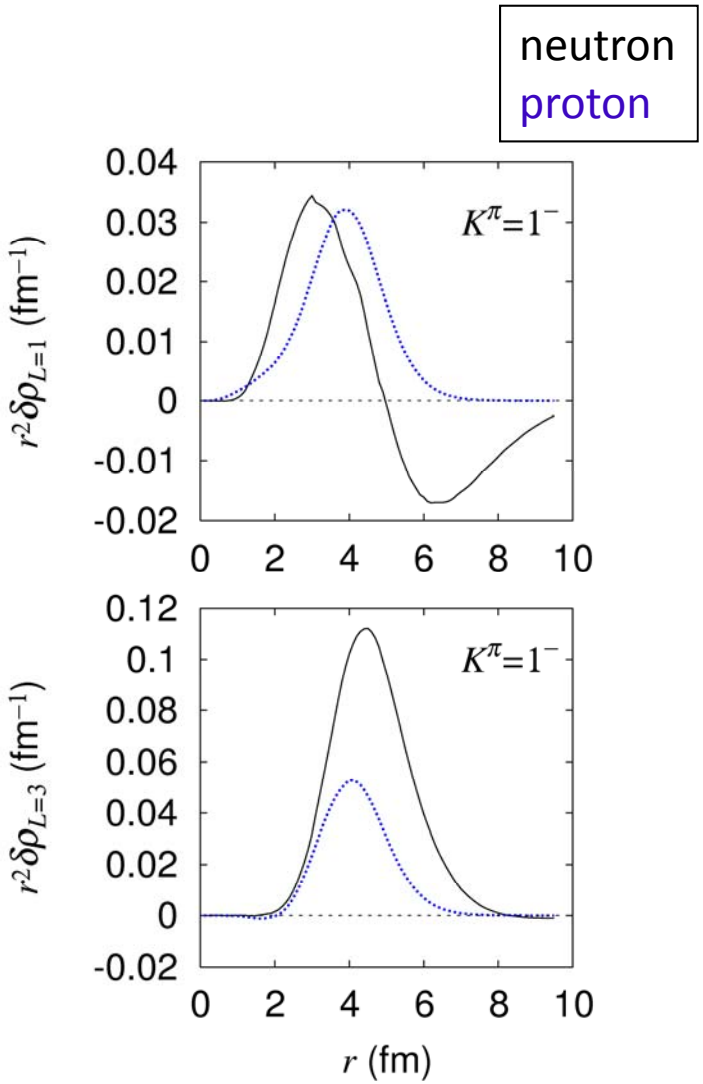
NEUTRON SKIN EFFECT (?)



I.Hamamoto, H.Sagawa, X.Z.Zhang, PRC57(1998)R1064

Mixing of different modes of excitation





$$\delta\varrho_L(r) = \int d\cos\theta d\varphi \delta\varrho(\rho, z) Y^*_{LK}(\theta, \varphi)$$

Summary

Skyrme-EDF based deformed QRPA ready for the systematic investigation of the collective excitations in nuclei located in a wide mass region from drip line to drip line

High performance computer

RICC RIKEN Integrated Cluster of Clusters

✓Nuclear deformation

→ Deformation splitting
Coupling among excitation modes with different angular momenta

GMR and the $K=0^+$ component of GQR

✓Neutron excess

→ Enhancement of the transition strengths in the low energy region

Lower peak of the ISGMR in deformed neutron-rich nuclei
Pygmy mode: IV dipole + IS octupole + IS compression dipole