# Pygmy resonance and giant resonance in deformed nuclei

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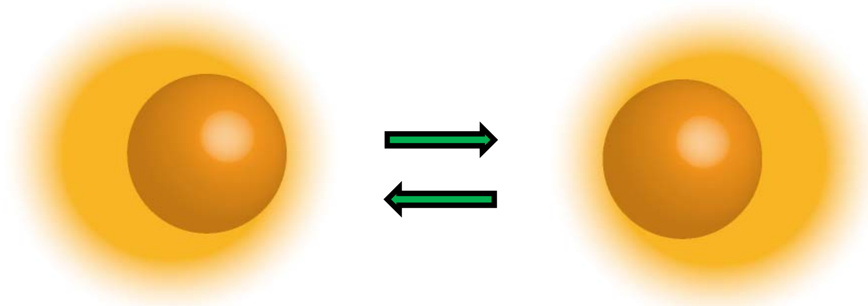
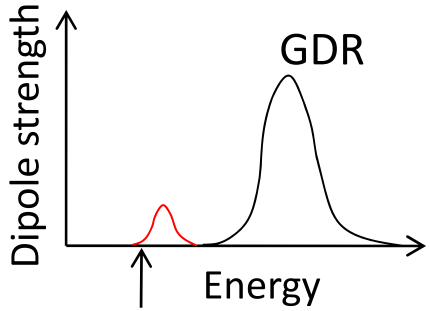
# Collective modes unique in neutron-rich nuclei

## Neutron excess

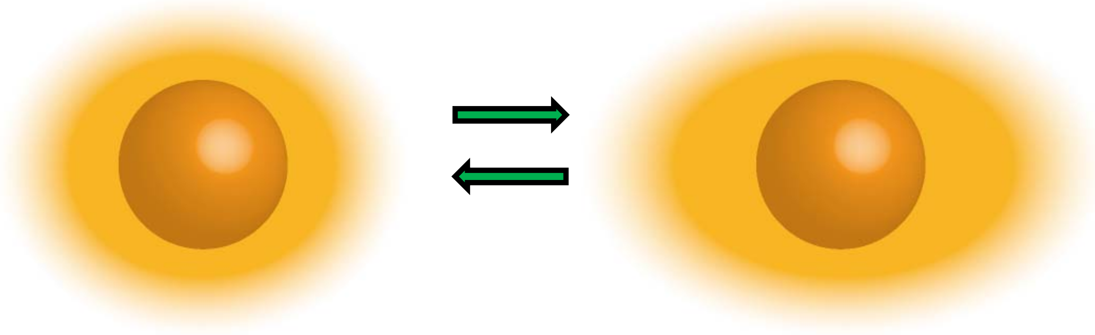
✓IS and IV mixing modes
✓Neutron-excitation dominant modes
✓Neutron-skin excitation modes

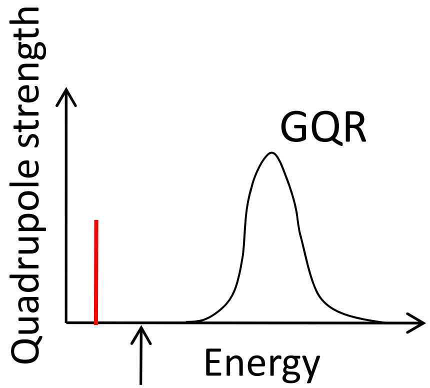
✓Soft dipole mode, Pygmy resonance






✓Neutron-skin quadrupole mode





# Skyrme Energy Density Functional (EDF)

## EDF for superfluid systems

$$\mathcal{E} = \mathcal{E}_{\text{kin}} + \mathcal{E}_{\text{Sky}} + \mathcal{E}_{\text{Coul}} + \mathcal{E}_{\text{pair}} + \mathcal{E}_{\text{corr}}$$

$$\mathcal{E}_{\text{Sky}} = \int d\boldsymbol{r}\mathcal{H}_{\text{Sky}}(\boldsymbol{r})$$

zero range: local densities

finite range: gradient terms

$$\mathcal{H}_{\text{Sky}} = \sum_{t=0,1} \Big\{ C_t^{\rho} \varrho_t^2 + C_t^{\boldsymbol{s}} \boldsymbol{s}_t^2 + C_t^{\triangle\rho} \varrho_t \triangle \varrho_t + C_t^{\triangle \boldsymbol{s}} \boldsymbol{s}_t \cdot \triangle \boldsymbol{s}_t$$
$$+ C_t^{\tau}(\varrho_t \tau_t - \boldsymbol{j}_t^2) + C_t^{T}(\boldsymbol{s}_t \cdot \boldsymbol{T}_t - \overleftrightarrow{J}_t^2) + C_t^{\nabla J}(\varrho_t \nabla \cdot \boldsymbol{J}_t + \boldsymbol{s}_t \cdot \nabla \times \boldsymbol{j}_t) \Big\}$$

$$\mathcal{E}_{\text{pair}} = \int d\boldsymbol{r}\mathcal{H}_{\text{pair}}(\boldsymbol{r})$$

$$\mathcal{H}_{\text{pair}} = \frac{1}{8}\left[t_0' + \frac{t_3'}{6}\varrho_0^{\gamma}(\boldsymbol{r})\right] \sum_{t=0,1} (\tilde{\varrho}_t^2(\boldsymbol{r}) - \tilde{\boldsymbol{s}}_t^2(\boldsymbol{r}))$$

# Skyrme-HFB-QRPA

Minimizing the energy density $\delta\mathcal{E} = 0$

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

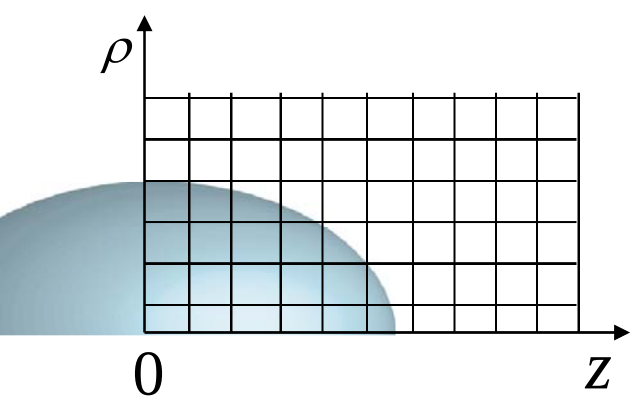
$$h = \frac{\delta\mathcal{E}}{\delta\varrho}$$

- Pairing field

$$\tilde{h} = \frac{\delta\mathcal{E}}{\delta\tilde{\varrho}}$$

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

# Skyrme-HFB-QRPA

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

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

The QRPA equation in a matrix form

$$\begin{pmatrix} A_{ijkl} & B_{ijkl} \\ B_{ijkl} & A_{ijkl} \end{pmatrix} \begin{pmatrix} X^{\lambda}_{kl} \\ Y^{\lambda}_{kl} \end{pmatrix} = \hbar\omega_{\lambda} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^{\lambda}_{ij} \\ Y^{\lambda}_{ij} \end{pmatrix}$$

Residual interactions

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

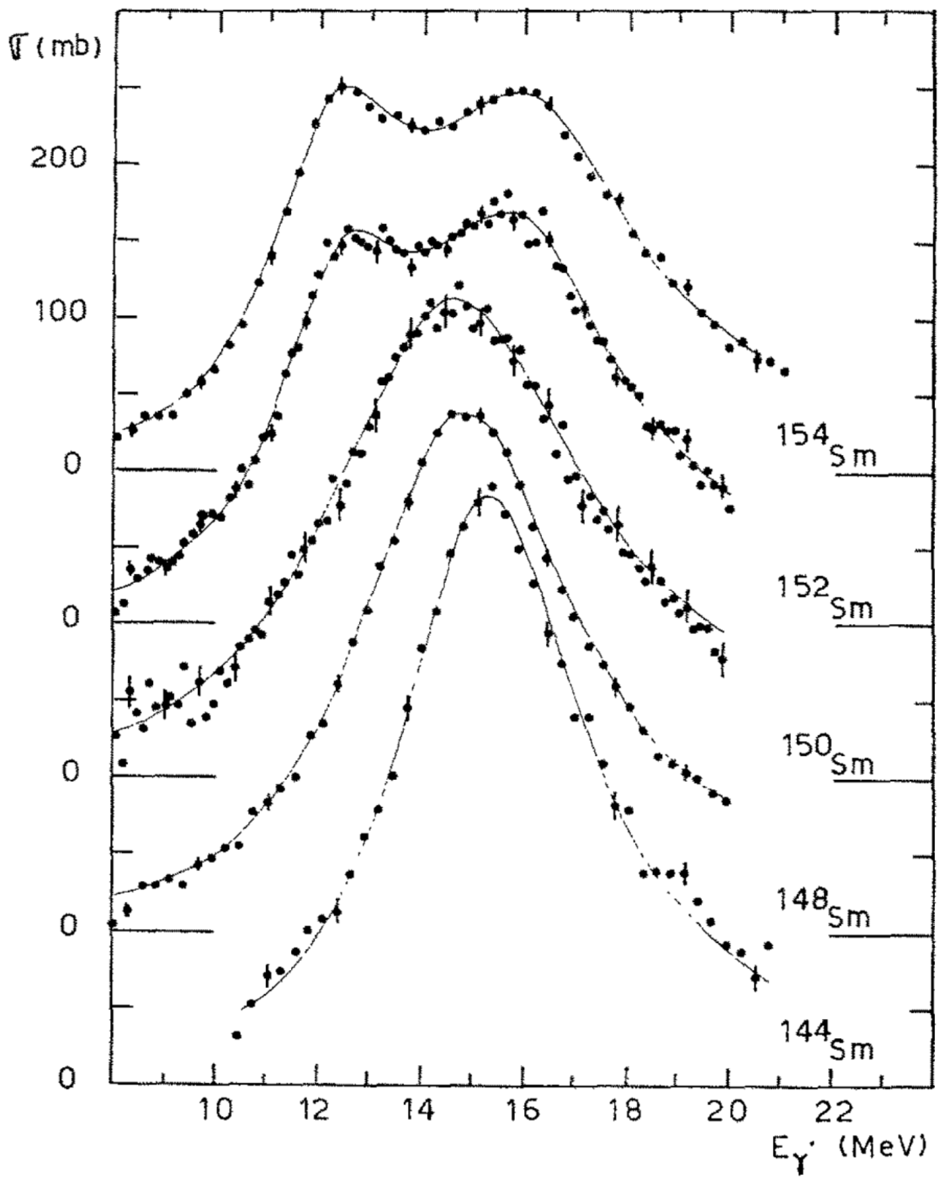
$$\begin{aligned} v_{ph}(\boldsymbol{r},\boldsymbol{r}') &= (a_0 + a_0'\tau\cdot\tau' + (b_0 + b_0'\tau\cdot\tau')\sigma\cdot\sigma')\delta(\boldsymbol{r}-\boldsymbol{r}') \\ &+ (a_1 + a_1'\tau\cdot\tau' + (b_1 + b_1'\tau\cdot\tau')\sigma\cdot\sigma') \\ &\times (\boldsymbol{k}^{\dagger 2}\delta(\boldsymbol{r}-\boldsymbol{r}')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

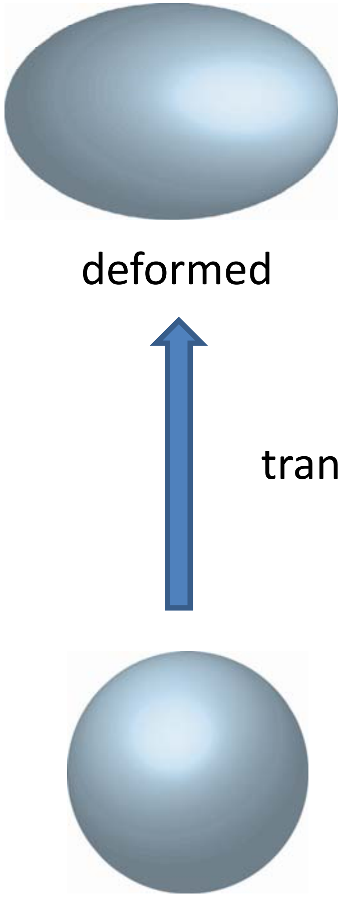
We neglect the two-body spin-orbit and Coulomb interactions.

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

$$v_{pp}(\boldsymbol{r},\boldsymbol{r}') = \frac{1-P_{\sigma}}{2}\left[t_0' + \frac{t_3'}{6}\varrho(\boldsymbol{r})\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$

# Evolution of nuclear deformation seen via GDR



$^{154}$Sm

deformed

transitional

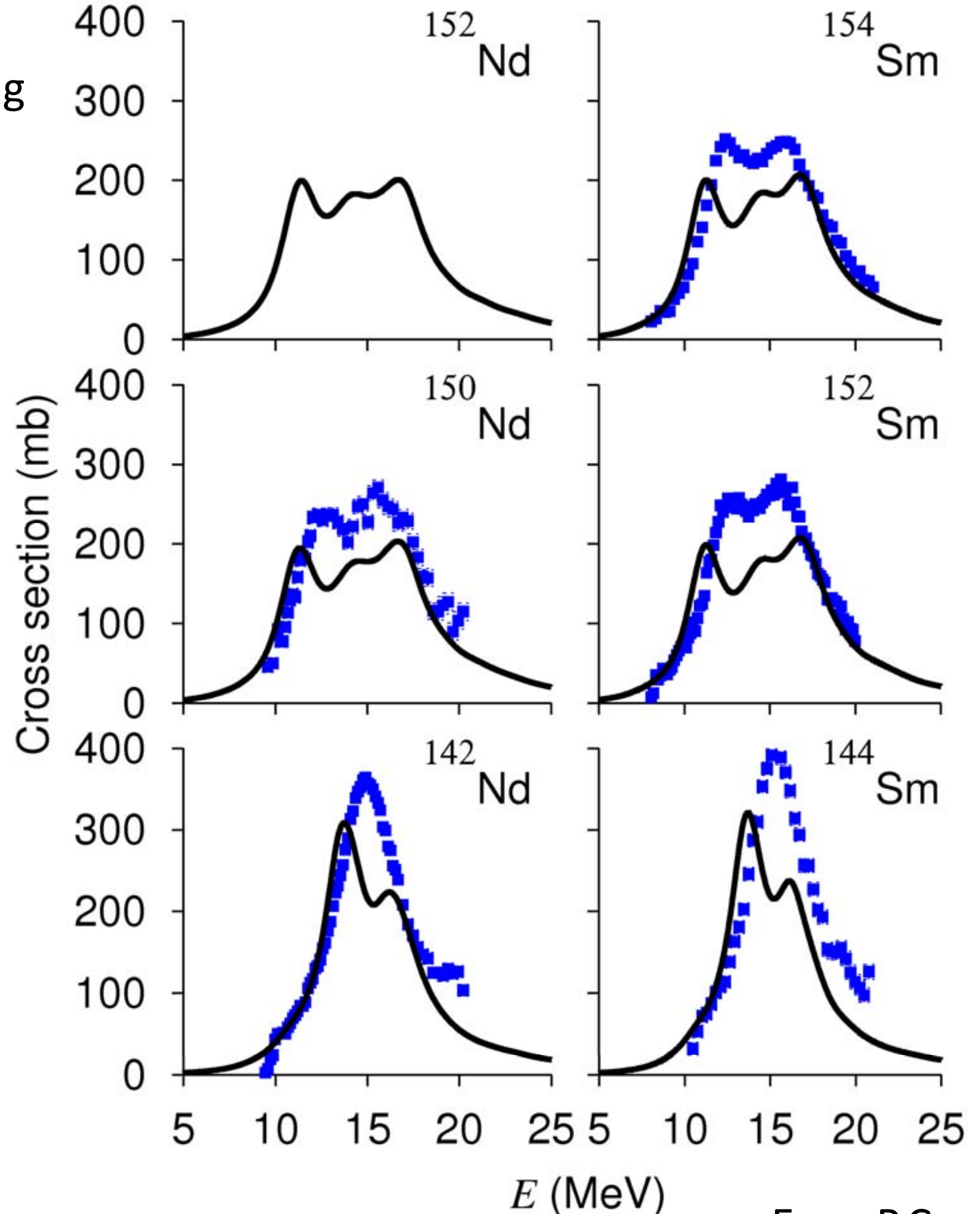
spherical

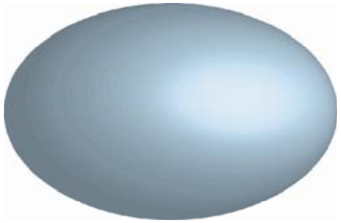
$^{144}$Sm

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

# Skyrme-QRPA photoabsorption cross sections

SkM*+
mixed-type pairing



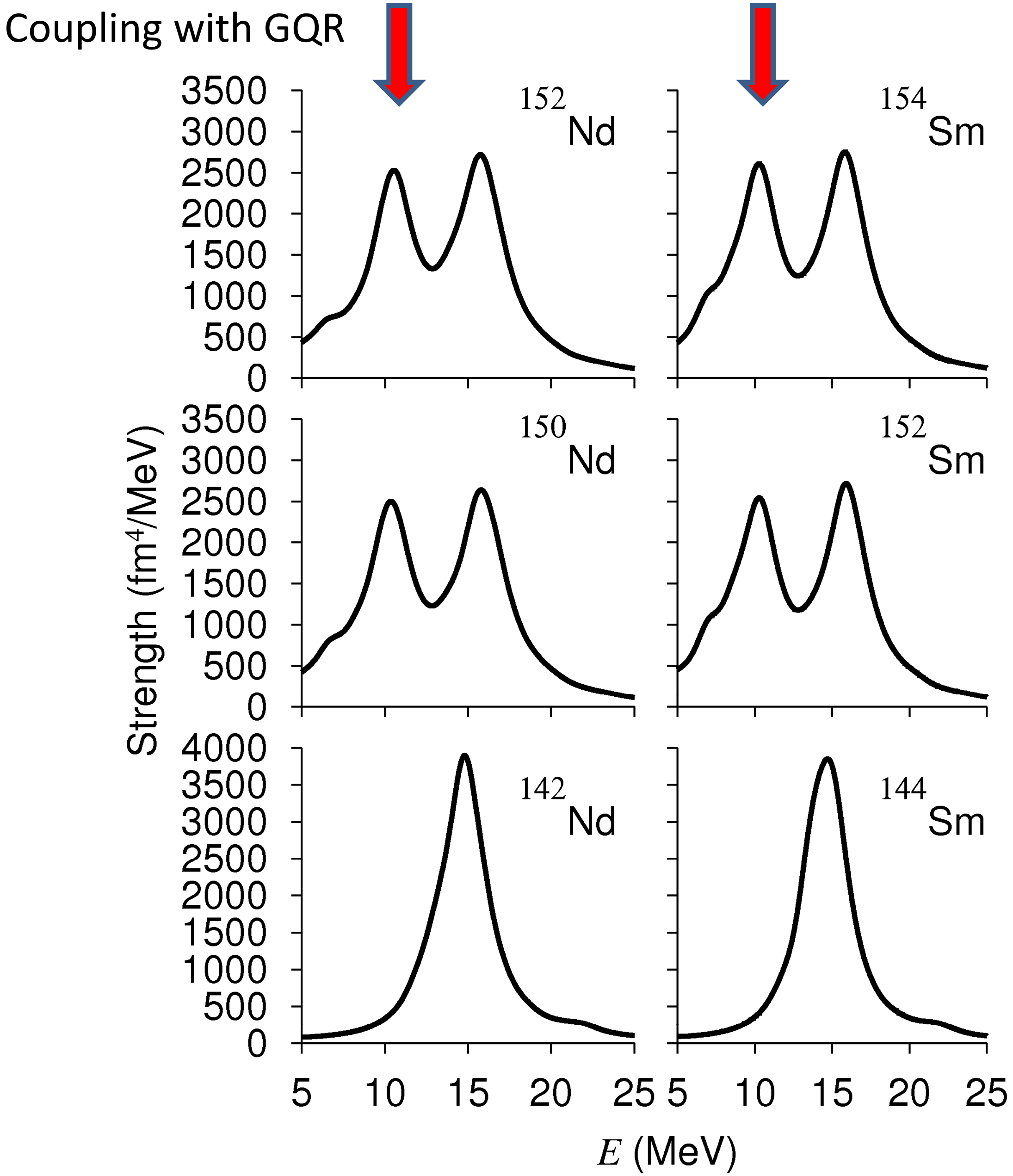



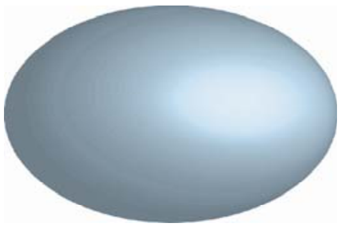
deformed

spherical

Exp.: P.Carlos et al., NPA225(1974)171

# Deformation effect on ISGMR

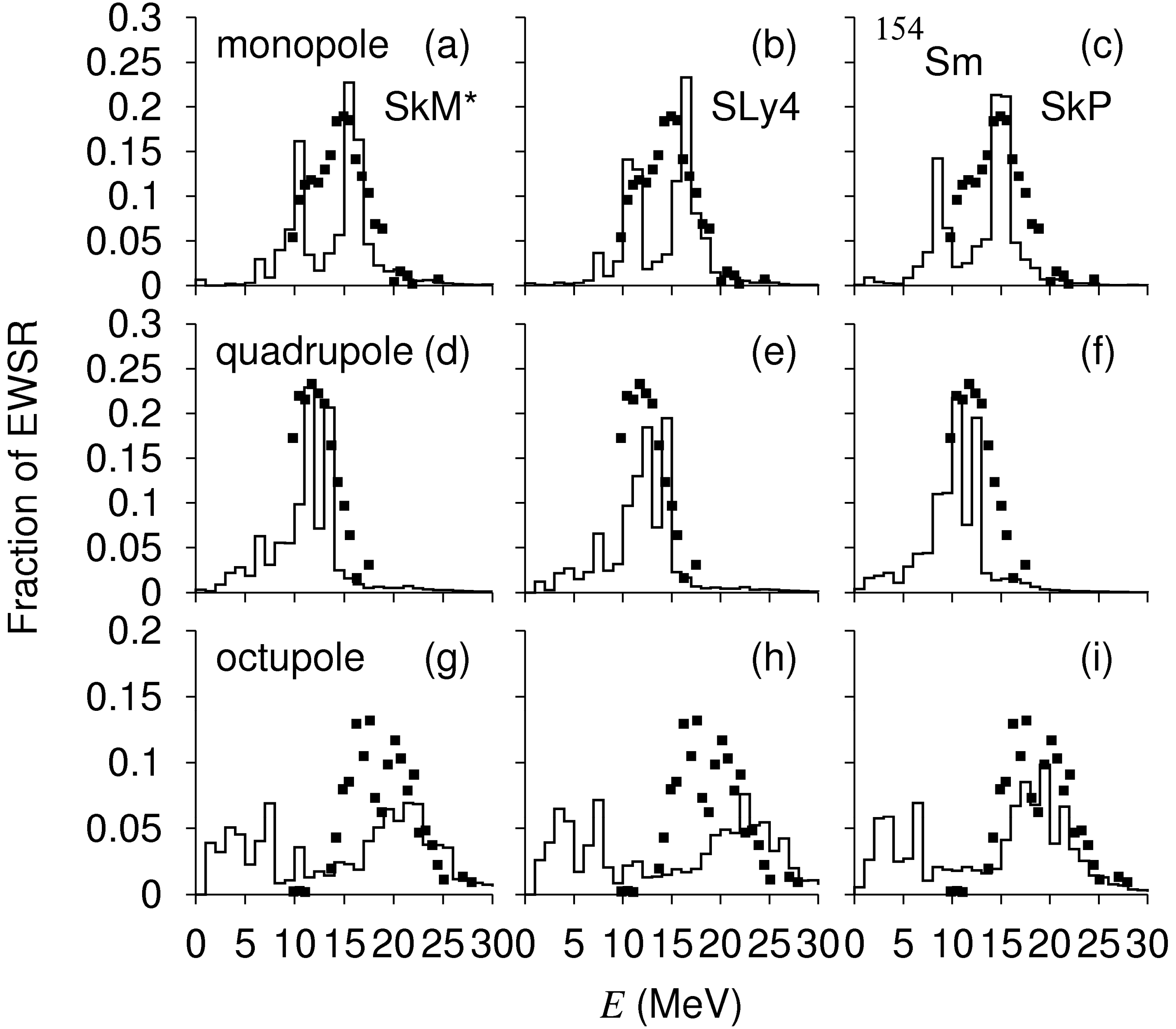


deformed

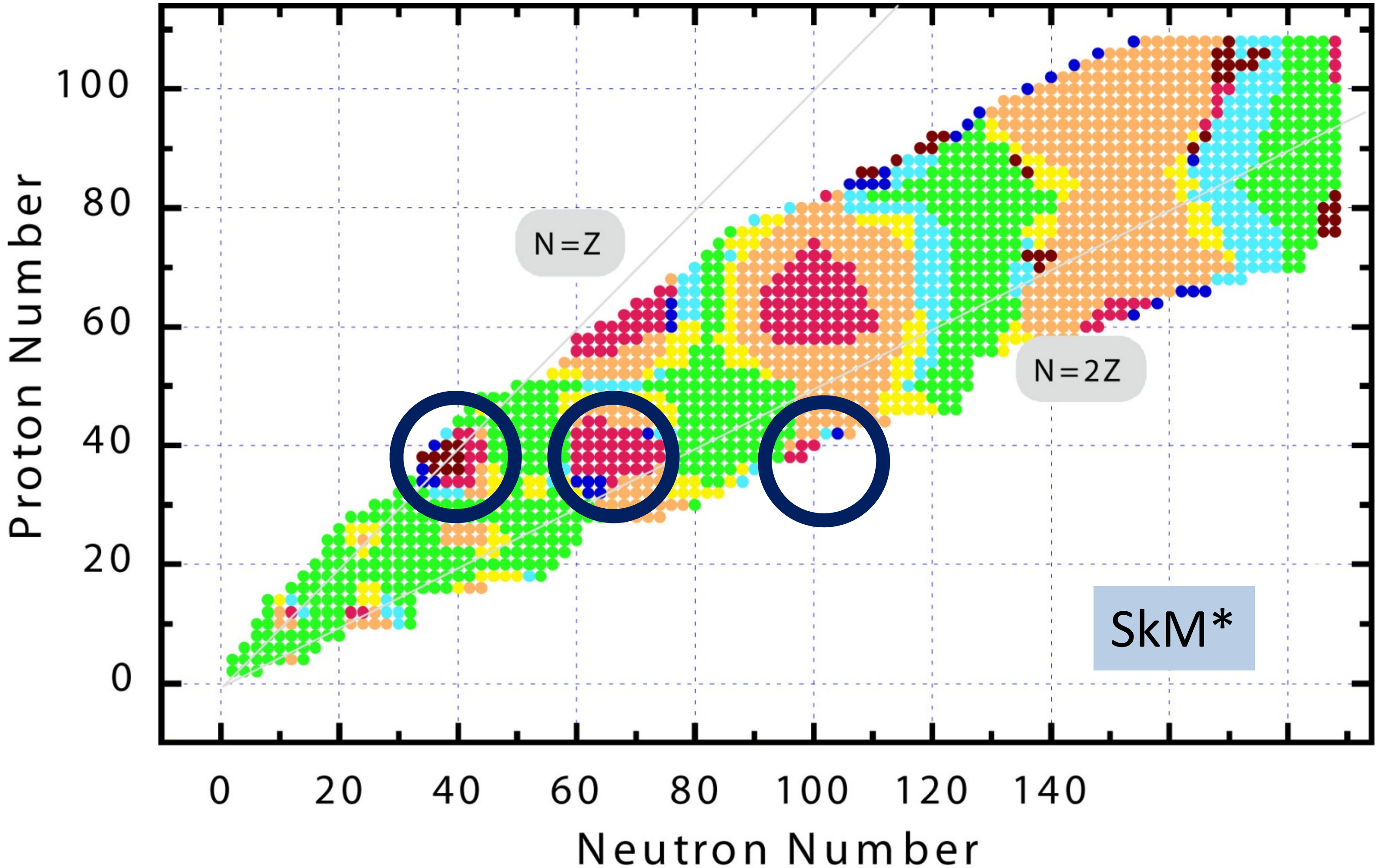
spherical

# Skyrme-functional dependence




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

# Deformation in Zr isotopes



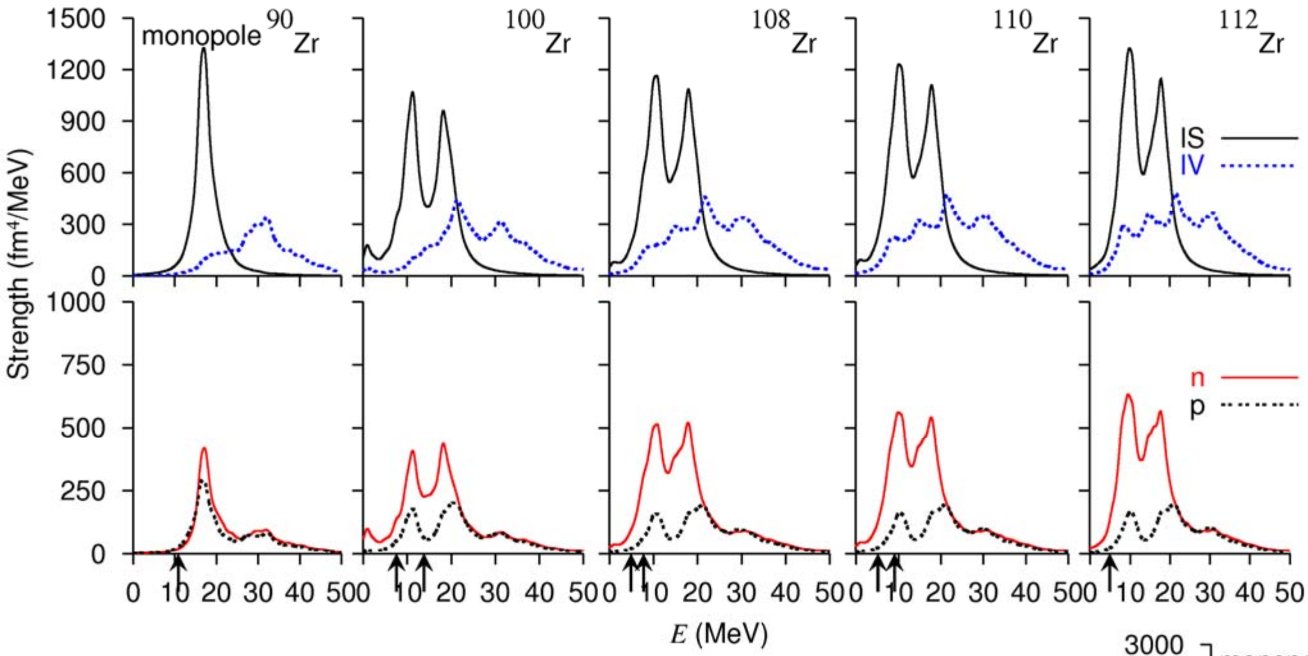

M.V. Stoitsov *et al.*, Phys. Rev. C68(2003) 054312

**Strong deformation** in Zr isotopes around N=70

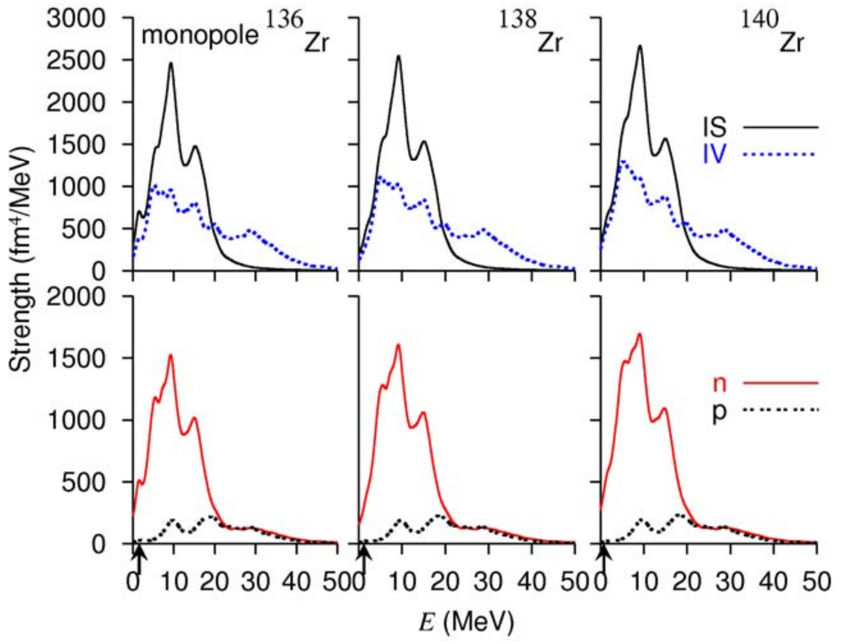
Proton drip-line region

Neutron drip-line region

# Roles of deformation and neutron excess on GMR

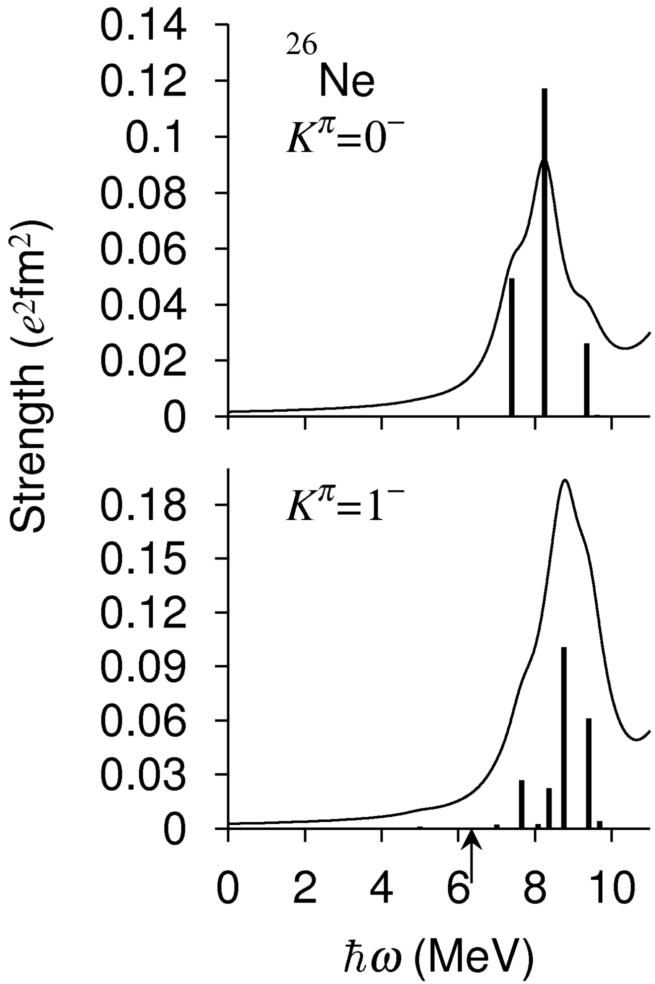



Toward a neutron drip line

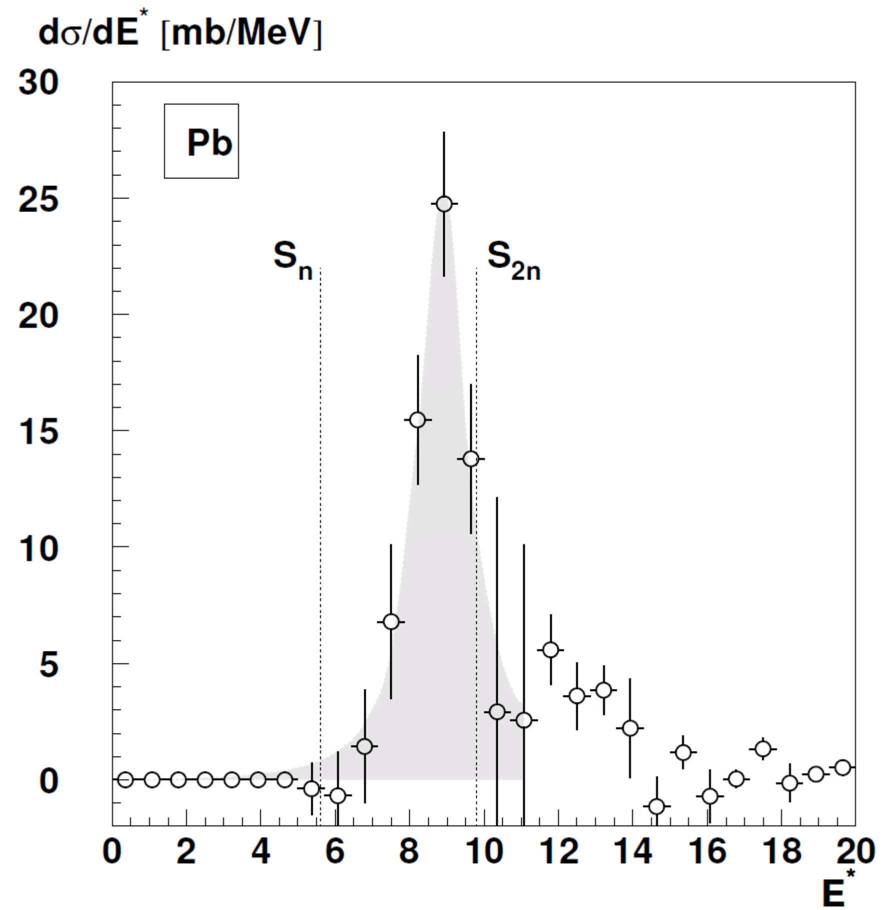


# Pygmy resonance in $^{26}$Ne

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




J.Gibelin, PRL101(2008)212503



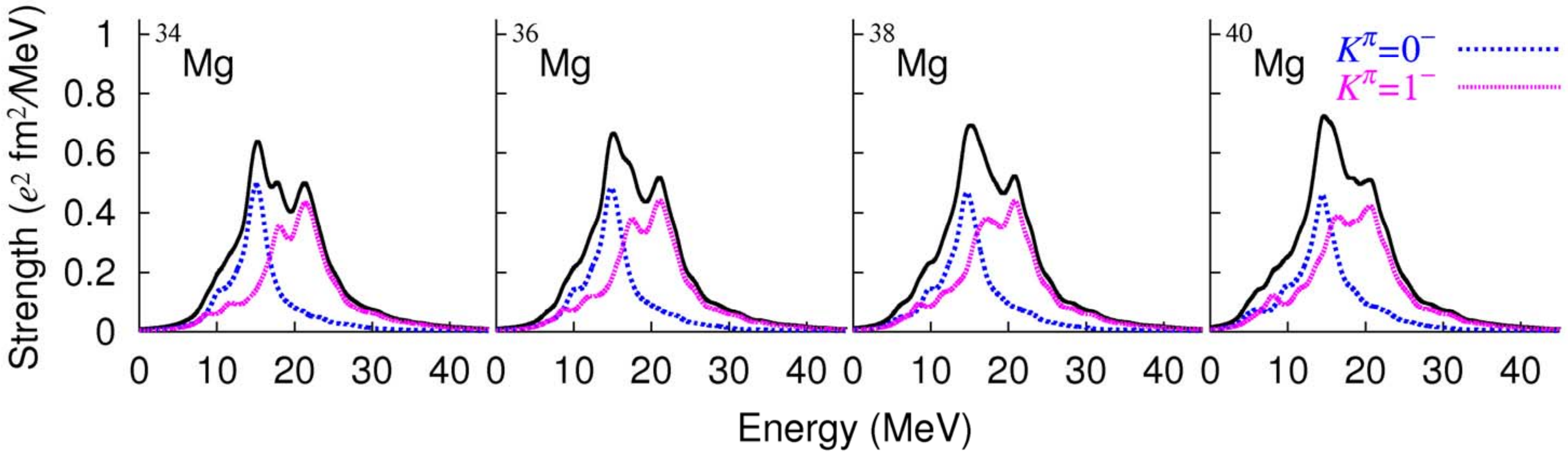

6% of the TRK sum rule (up to 10MeV)

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

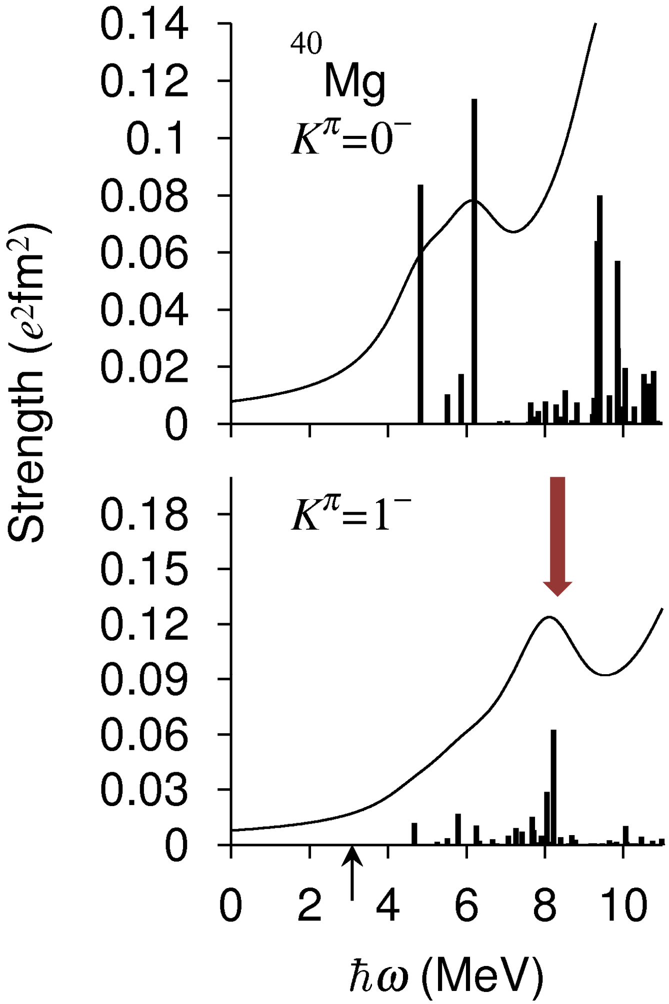
| | $^{34}$Mg | $^{36}$Mg | $^{38}$Mg | $^{40}$Mg |
|---|---|---|---|---|
| $\beta_{2,n}$ | 0.35 | 0.31 | 0.29 | 0.28 |
| $\beta_{2,p}$ | 0.41 | 0.39 | 0.38 | 0.36 |

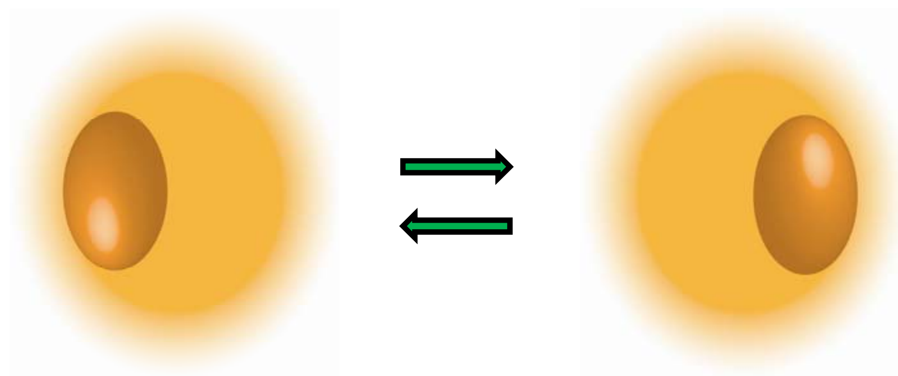



GDR: "K splitting" → good indicator of deformation

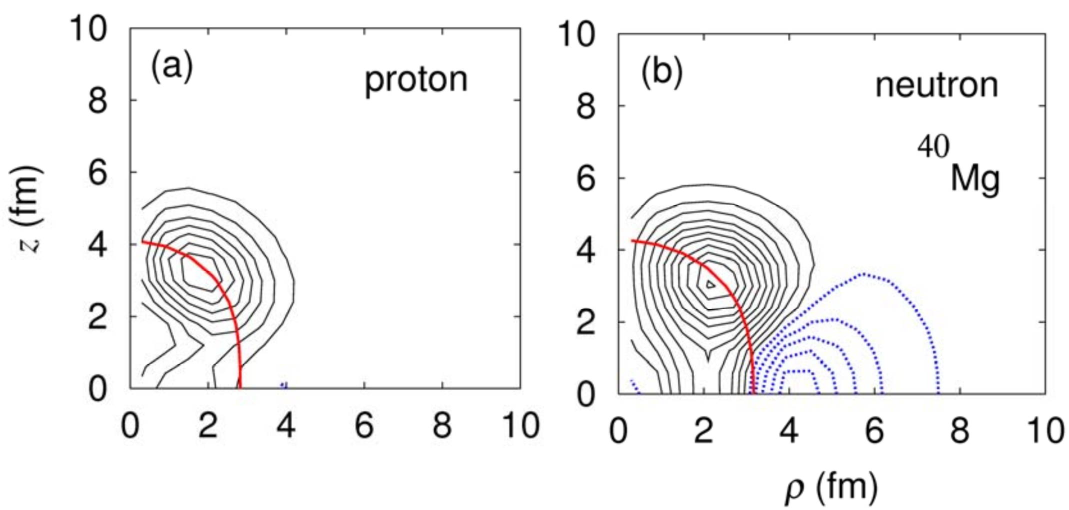
- Unique feature in neutron drip-line nuclei
  - ✓As approaching the drip line, the bump structure below 10MeV develops.

# Pygmy mode in $^{40}$Mg



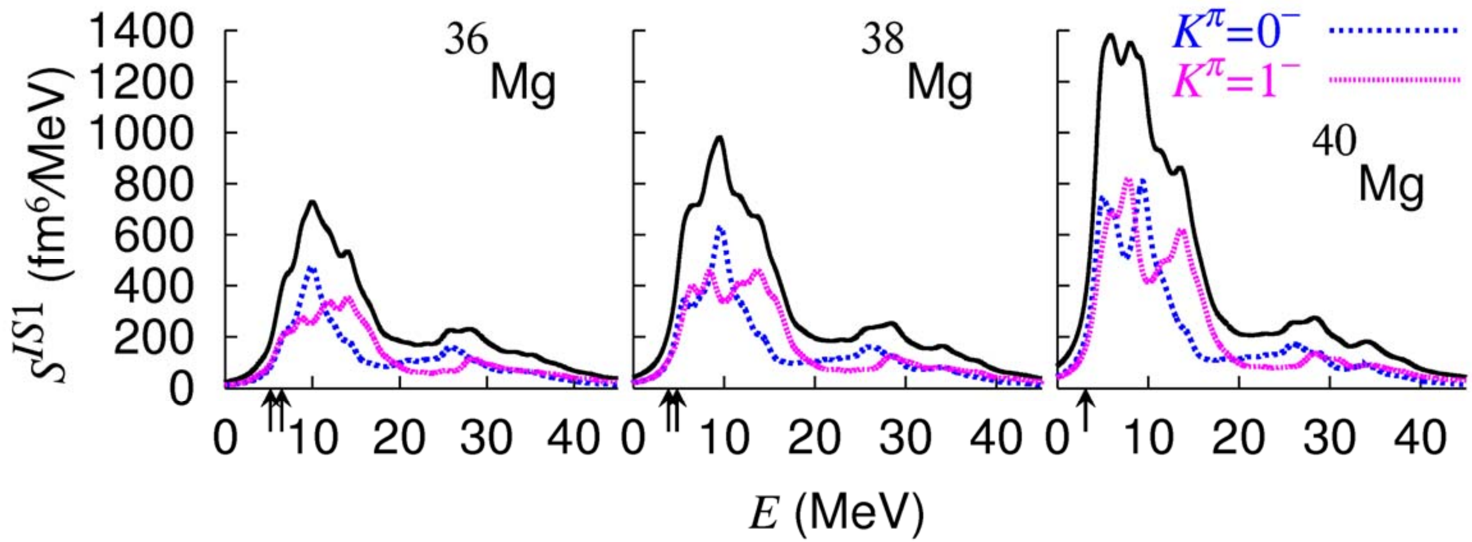



Transition density (8.2 MeV)



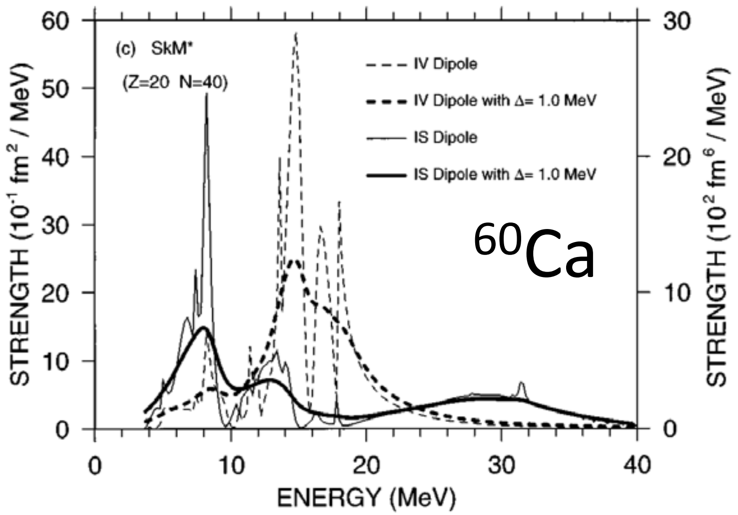
# Isoscalar character of the pygmy mode

Responses for the compression dipole operator



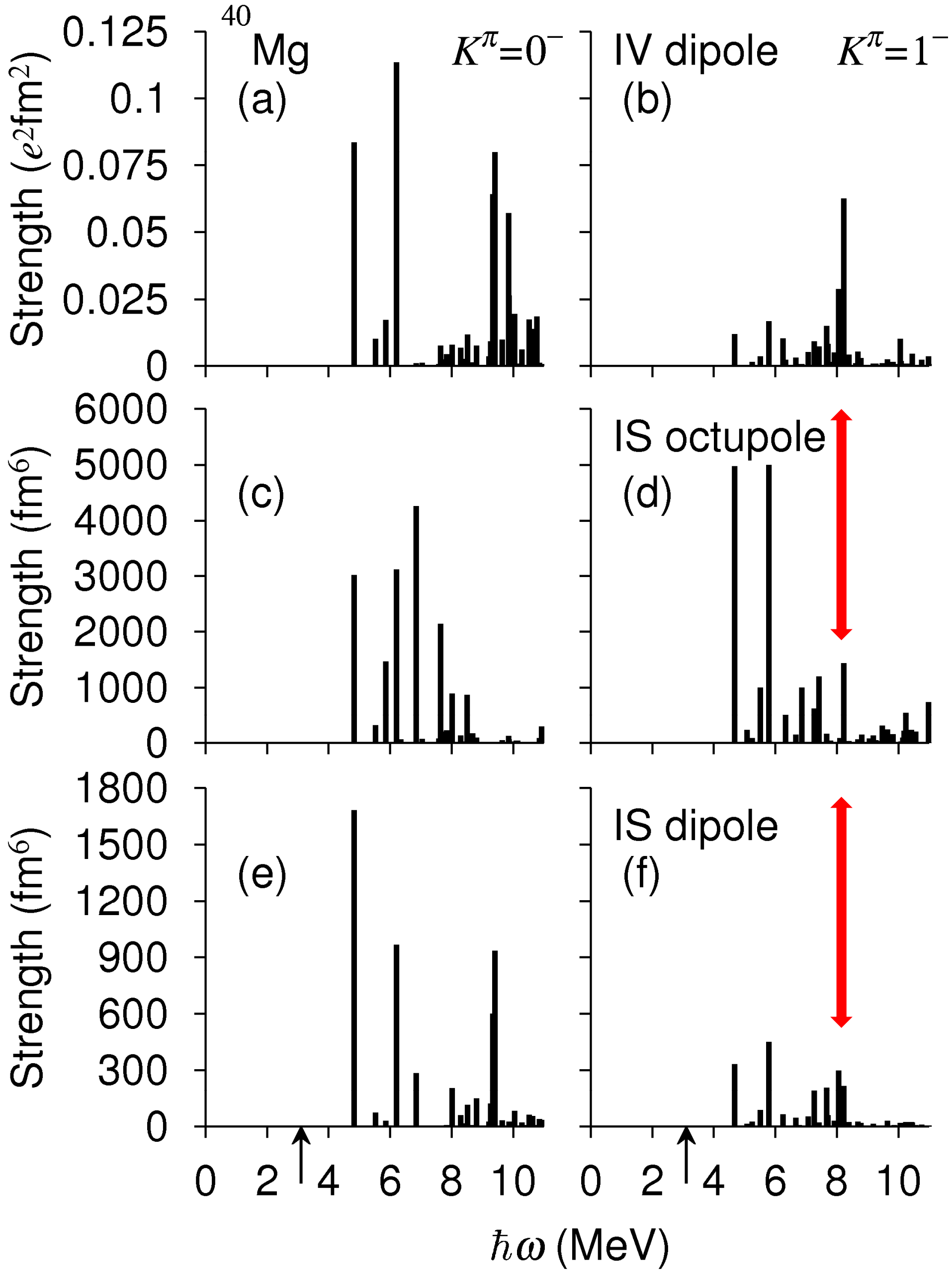

Tremendous enhancement of the transition strengths in the low-energy region

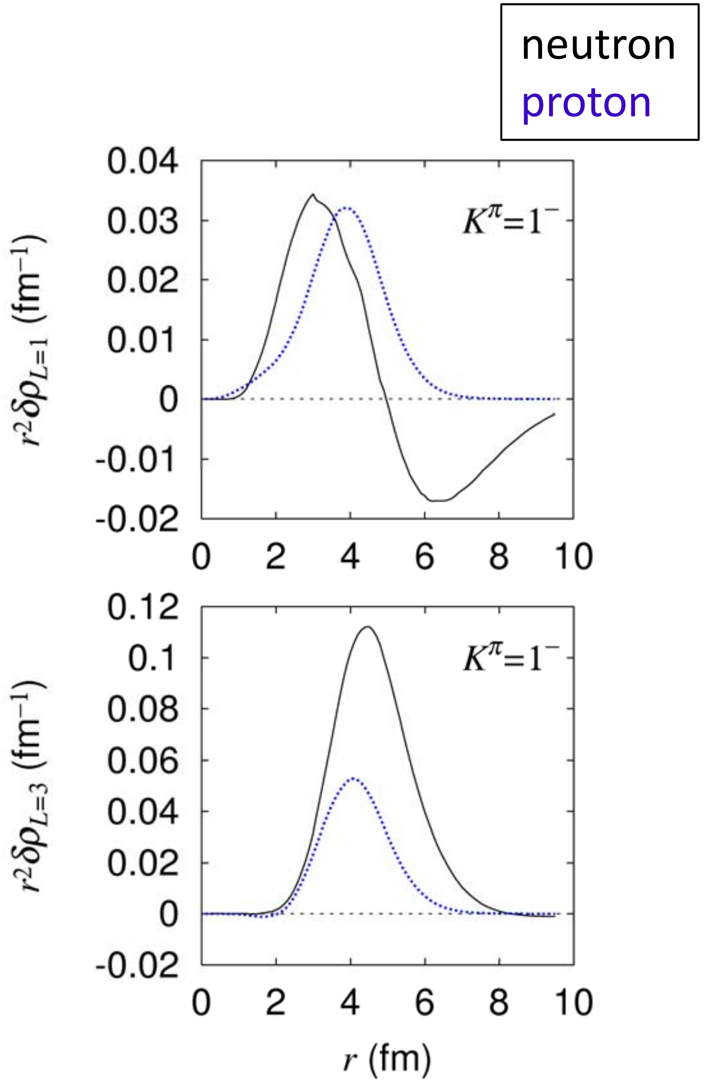
**NEUTRON SKIN EFFECT (?)**




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**

✓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 drip-line nuclei
Pygmy mode: IV dipole + IS octupole + IS compression dipole