Nuclear incompressibility from spherical and deformed nuclei

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Motivation and outline of the talk

The compressional properties of nuclei are relevant not only to pinpoint the key features of nuclear structure and build “universal” models, but also for nuclear collisions, supernova explosion, and so on.

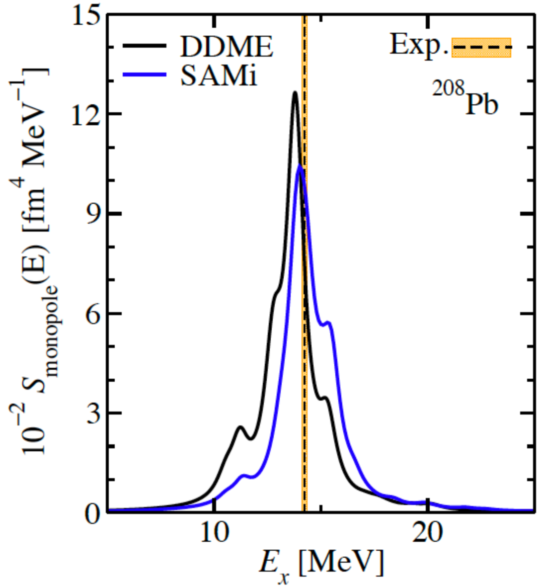
The main goal here is to understand the differences between the **compressional properties of spherical and deformed nuclei**.

- The tool of choice: energy density functionals (EDFs)
- Linear response, *viz.* self-consistent deformed QRPA
- Results for ^{24}Mg and comparison with the experimental data
- Analysis of the collective states (monopole/quadrupole coupling)
- Extraction of the nuclear incompressibility (?)

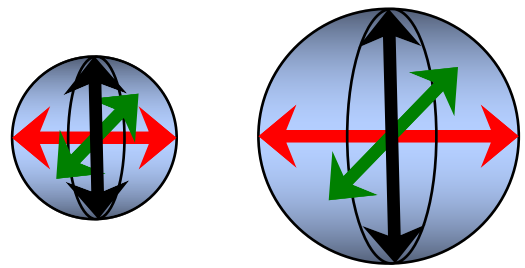
Equation of state and incompressibility of nuclear matter

The incompressibility of symmetric nuclear matter reflects the curvature of the equation of state E/A around saturation.

$$K_\infty = 9\rho_0^2 \frac{d^2}{d\rho^2}\left(\frac{E}{A}\right)_{\rho=\rho_0}$$



Breathing mode: its energy is expected to be correlated with K

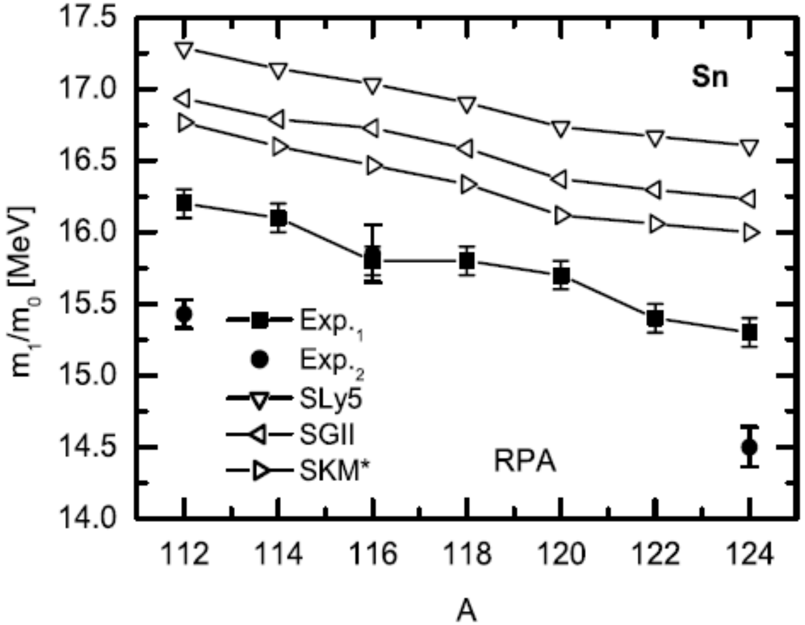


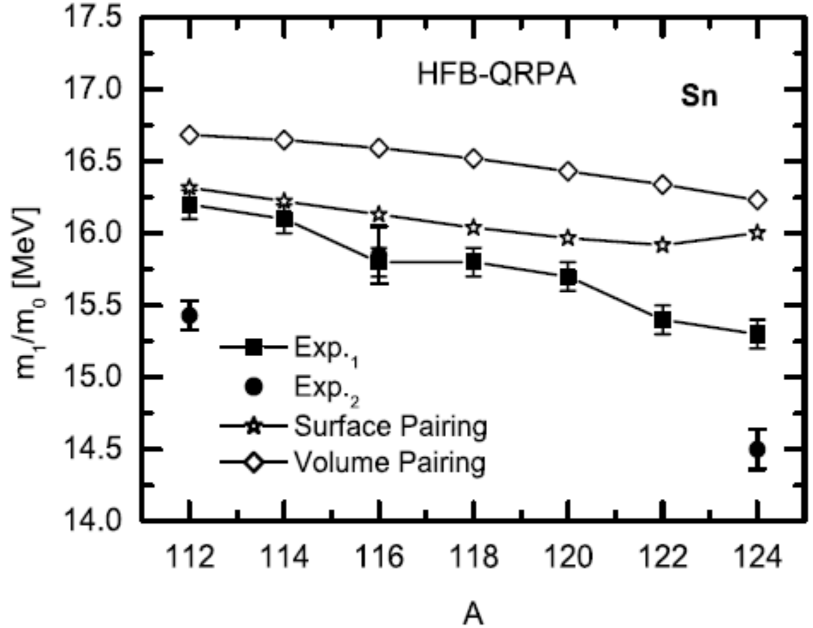
240 ± 20 MeV from ^{208}Pb and magic nuclei

The compression-mode giant resonances and nuclear incompressibility
Umesh Garg [a], Gianluca Colò [b,c,*]
Progress in Particle and Nuclear Physics 101 (2018) 55–95

Non-magic nuclei may (?) point to lower values of the nuclear incompressibility.

Superfluid nuclei





Pairing correlations **lower** the energy of the GMR (right panel) with respect to RPA (left panel).

J. Li *et al.*, Phys. Rev. C 78, 064304(2008); L. Cao *et al.*, Phys. Rev. C 86, 054313 (2012).

The effect on the incompressibility can be of the order of 10%.

E. Khan *et al.*, Phys. Rev. C 82, 024322 (2010).

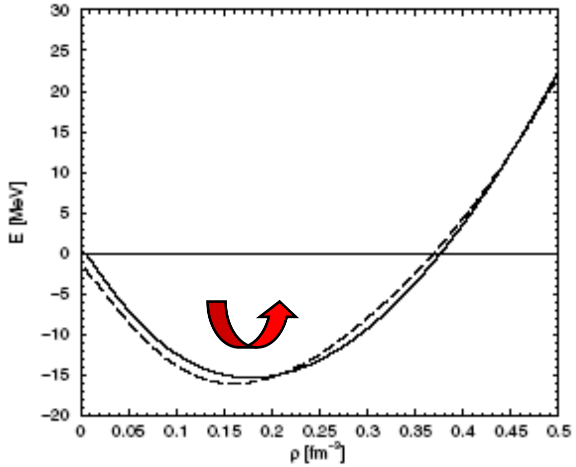
(Q)RPA using EDFs in a nutshell

Energy Density Functional

$$E = \langle \Psi | \hat{H} | \Psi \rangle = \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}]$$

$|\Phi\rangle$ **Slater determinant** $\Leftrightarrow$ $\hat{\rho}$ **1-body density matrix**

$H_{eff} = T + V_{eff}$. If V_{eff} is well designed, the resulting g.s. (minimum) energy can fit experiment at best. Hartree-Fock or Kohn-Sham.



- Within a time-dependent theory (TDHF), one can describe harmonic oscillations around the minimum.
- The restoring force is: $v \equiv \frac{\delta^2 E}{\delta \rho^2}$.

$$X_{\rm ph}|ph^{-1}\rangle - Y_{\rm ph}|hp^{-1}\rangle$$

- The linearization of the equation of the motion leads to RPA[1].

[1]Random Phase Approximation.

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \hbar\omega \begin{pmatrix} X \\ Y \end{pmatrix}$$

Deformed implementation

- The **HFB equations** with a Skyrme force and a density-dependent pairing force are solved on a harmonic oscillator basis (HFBTHO).

M. Stoitsov *et al.*, Comp. Phys. Comm. 184 (2013) 1592

- This allows to determine the **g.s. deformation.**

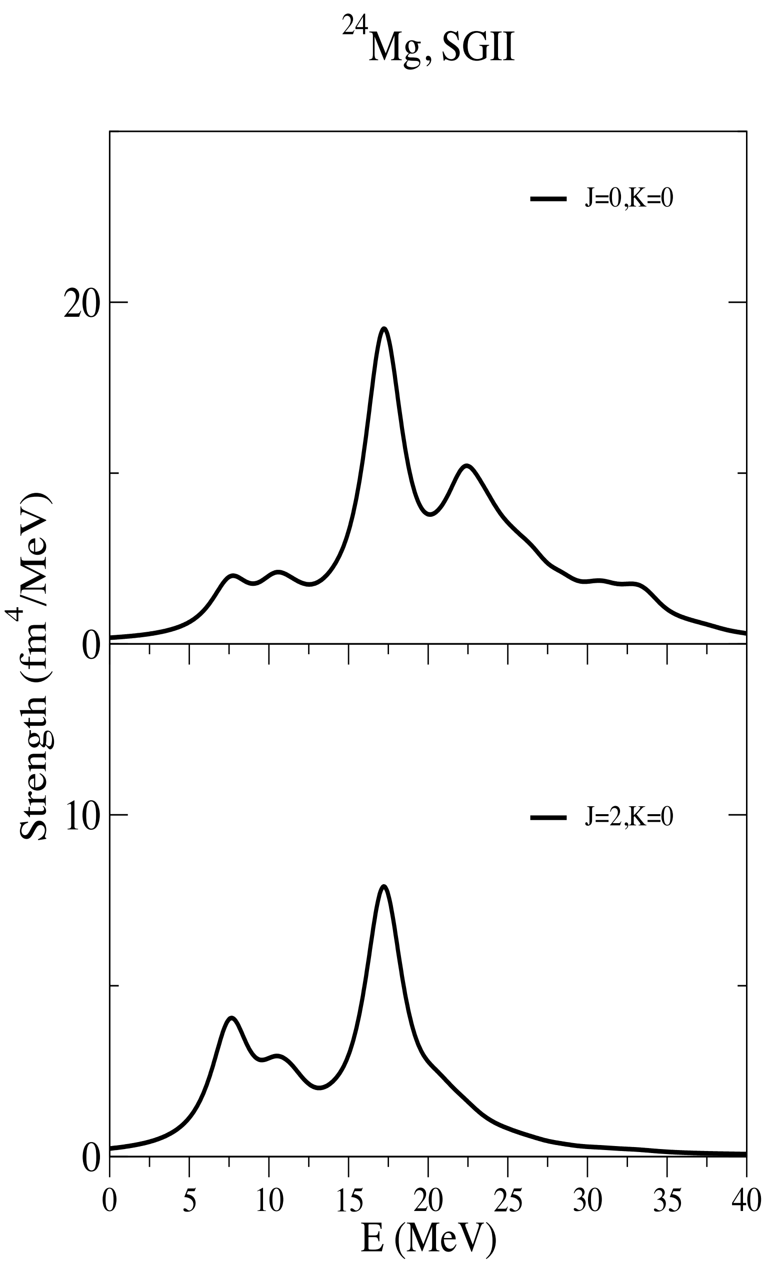
$$min_\beta \; E[\beta]$$

- The **QRPA equations** are solved on a discrete basis with **good $\mathbf{K^\pi}$.**

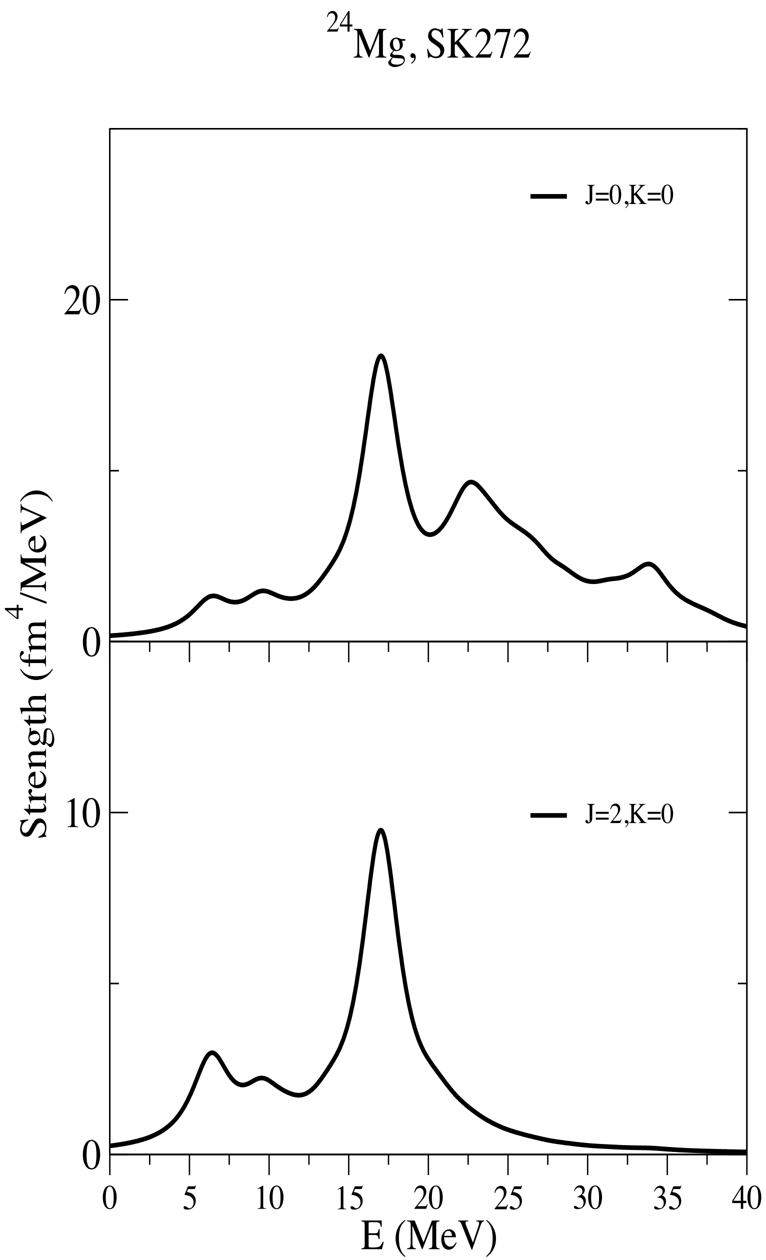
- The approach is **fully self-consistent.**

$$N_{\rm sh} = 10 - 15$$
$$\hbar\omega_0 = 1.2 \frac{41}{{\rm A}^{1/3}} \ {\rm MeV}$$
$$E_{\rm cut} = 80 \ {\rm MeV}$$

C. Losa *et al.*, Phys. Rev. C81, 064307 (2010)

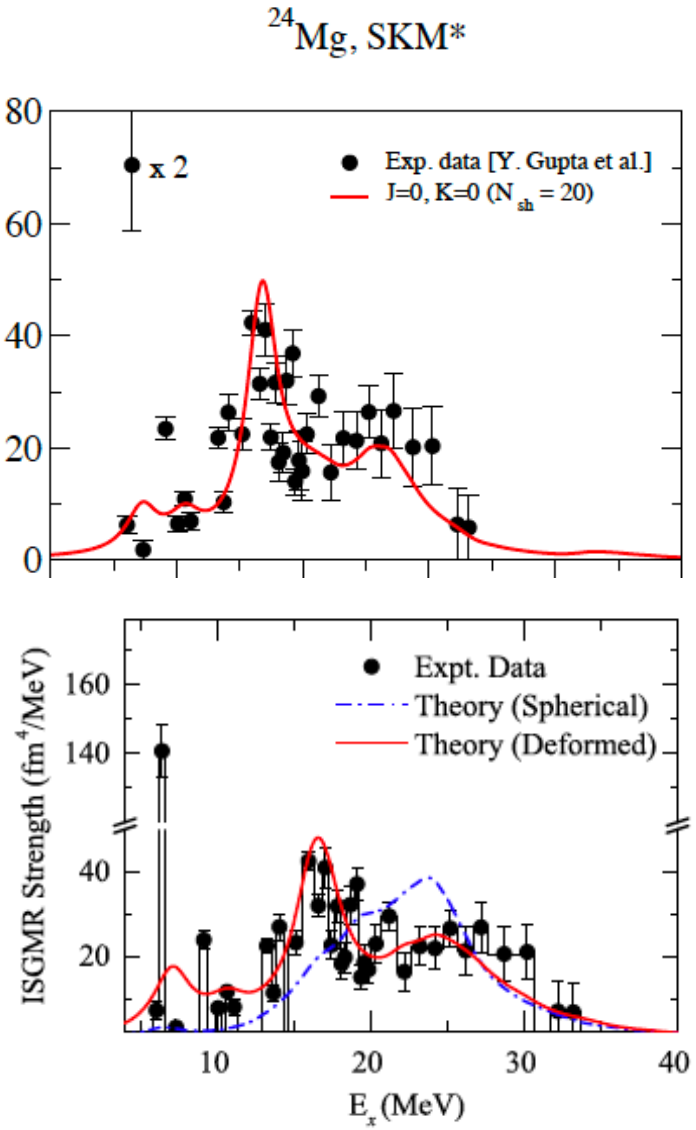


^{24}Mg, SGII
J=0,K=0
J=2,K=0
Strength (fm^4/MeV)
E (MeV)
0
5
10
15
20
25
30
35
40



^{24}Mg, SK272
J=0,K=0
J=2,K=0
Strength (fm^4/MeV)
E (MeV)
0
5
10
15
20
25
30
35
40

Comparison with experiment



We compare with RCNP data from Y. Gupta *et al.*, PRC 93, 044324 (2016).

The two-peak structure is evident.

Thanks to K. Howard.

Similar calculations by K. Yoshida was used to show that the double peak is related to deformation.

We focus on the most collective part. For the low-lying peaks, cf. M. Kimura.

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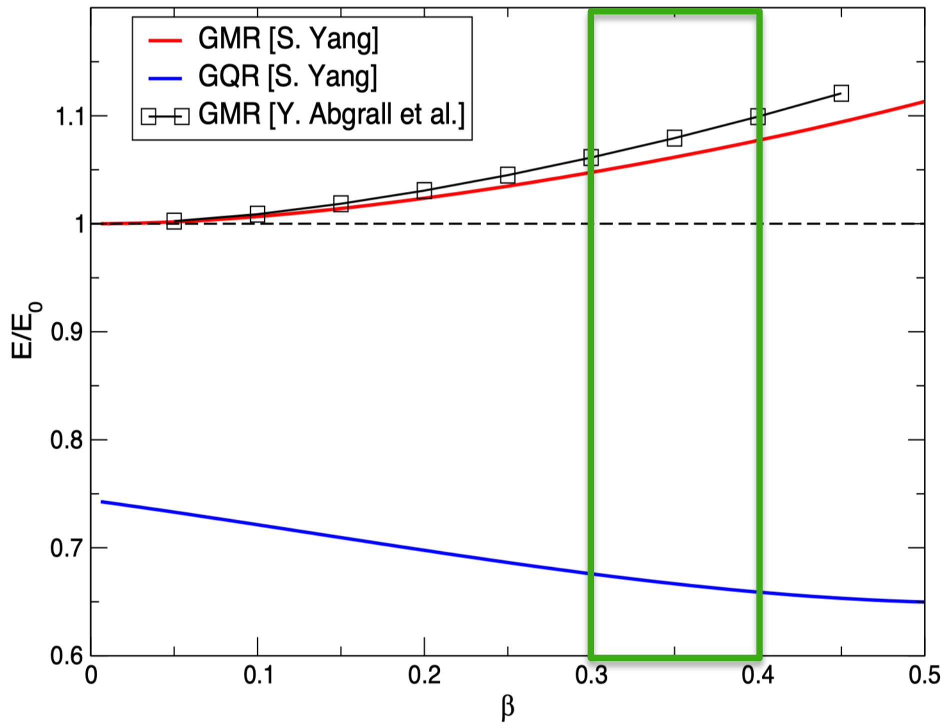
In **macroscopic models**, one starts from the "ideal" GMR and GQR of spherical nuclei and finds that two peaks arise from the **coupling of the K=0 components of GMR and GQR**.



- S. Yang, NPA 401 (1983) 303

Hydrodynamical calculations

$$E_0 \left(1 + 0.86\delta^2 - 1.25\delta^3\right)$$

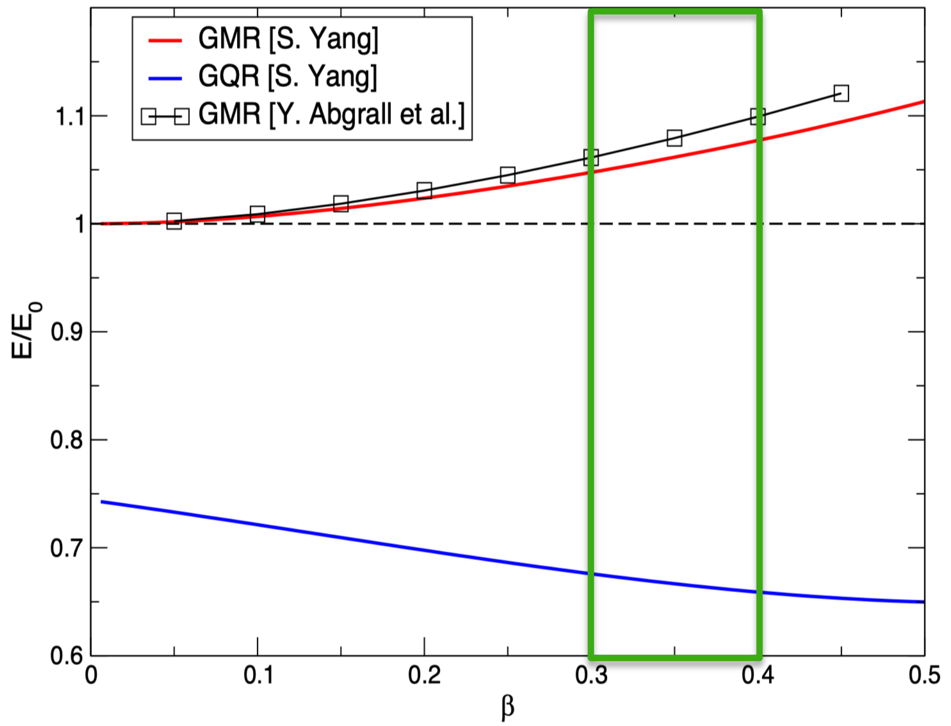
- Y. Abgrall *et al.*, NPA 436 (1980) 431

Adiabatic cranking model

Quite similar results!

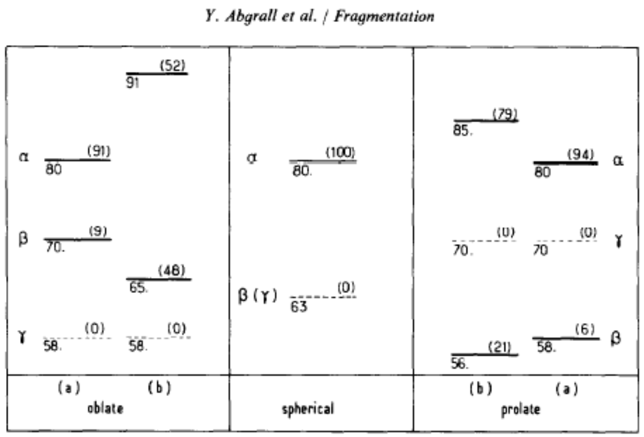
- T. Suzuki and D. Rowe, NPA 289 (1977) 461
- Y. Shimizu and K. Matsuyanagi, PTEP 72 (1984) 1017
- S. Åberg, NPA 473 (1987) 1
- D. Zawischa *et al.*, NPA 311 (1978) 445

In addition to the shifts of GMR and GQR, due to deformation, one has a **mixing** between them. For the case of the deformations under study, around 80% of the monopole strength is expected to remain in the higher peak, whereas 30% can be found in the lower peak.



- Y. Abgrall *et al.*, NPA 436 (1980) 431

Adiabatic cranking model

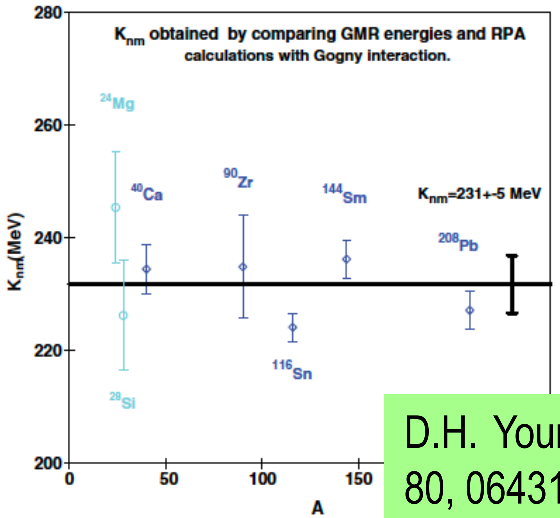


- If there is a **<u>GMR shift</u>** (and admixture) due to the GQR coupling, this is **not related to the incompressibility** of nuclear matter.

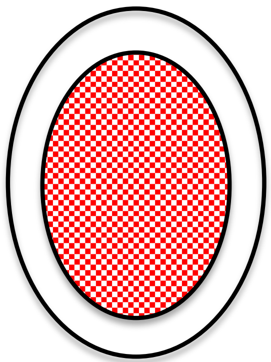
- Indeed, one does not expect different incompressibilities associated with various deformations.

- Unfortunately, **<u>within QRPA we cannot "disentangle" this effect</u>.**

- We can, however, see if the physical picture of the macroscopic model is reflected in the wave functions or transition densities.



D.H. Youngblood *et al.*, PRC 80, 064318

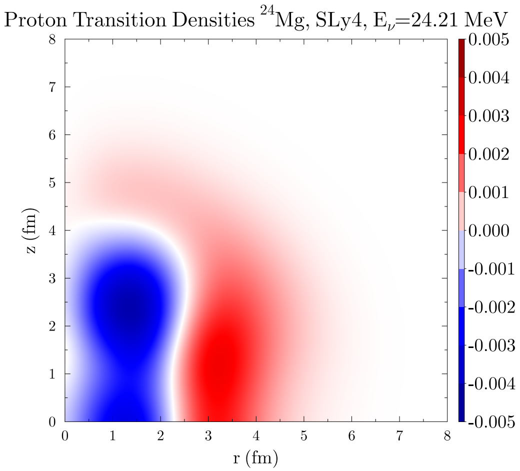


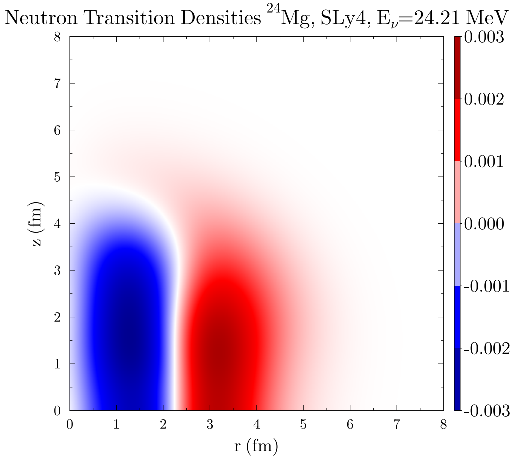
Macroscopic density change

$$\rho = \rho_0 + \delta\rho$$

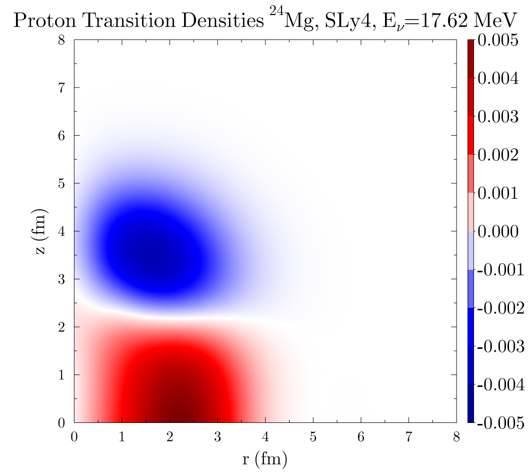
QRPA transition densities

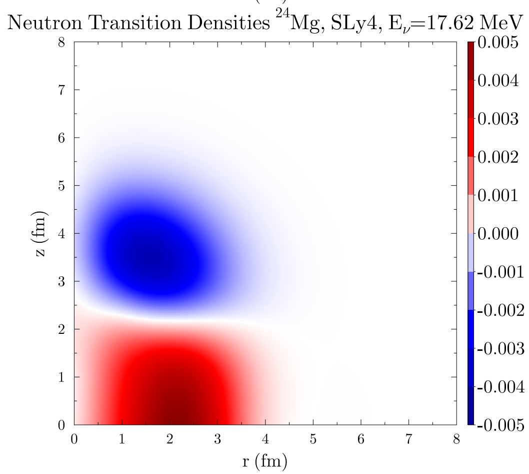
"GMR-like"



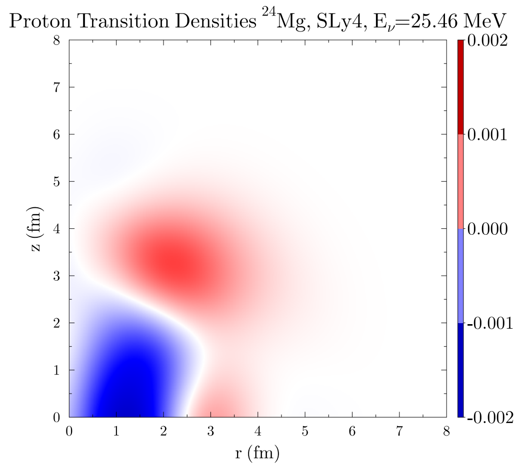


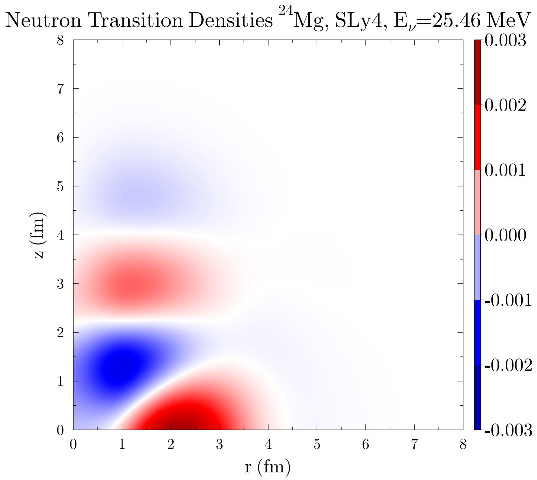
"GQR"





Non collective





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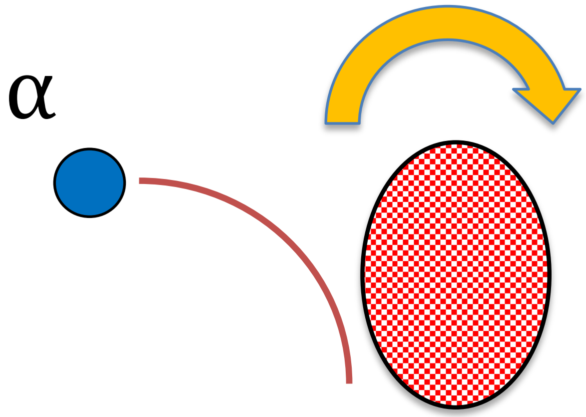
$$\rho = \rho_0 + \delta\rho$$

Projection method



The interaction time is short and the zero-point rotation is much slower.

Nevertheless, the external monopole field in the lab must be transformed into the intrinsic frame.

Or, analogously, we should project the intrinsic states into states with good J.

$$|KM\rangle \quad \rightarrow \quad |JKM\rangle = P^{J}_{KM}|KM\rangle = \int d\Omega \; \mathcal{D}^{\dagger J}_{KM}(\Omega)R(\Omega) \; |KM\rangle$$

We are implementing this projection in the axial case.
Projected strength:

$$\langle f||r^2||I\rangle = \int_0^{\pi} d(cos\beta) \; \langle f|r^2 exp(-i\beta\hat{J}_y)|i\rangle$$

Conclusion

- Consensus had been reached that **the nuclear incompressibility should be around 240 MeV, but based on few magic nuclei**
- Superfluid nuclei may point to a lower value, and there are other “anomalies”
- **We need to fit deformed nuclei into the picture**
- **The coupling between the K=0 components of the monopole and quadrupole** plays a role in determining the peak of the monopole strength
- We have shown clear indications from macroscopic models and microscopic QRPA
- **This effect should be decoupled. To this aim, we are implementing proper projection on J**
- Perspective: heavier nuclei

Thank you!