Constraints on Nuclear Functionals from Collective Vibrations

The 2nd LACM-EFES-JUSTIPEN Workshop

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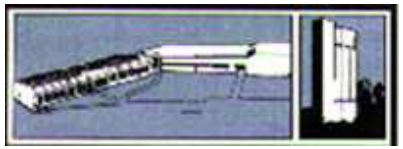
Oak Ridge, 25/1/2008



Collaborators :

- P.F. Bortignon, S. Fracasso, J. Li, L. Trippa, E. Vigezzi (Milano)
- N. Van Giai (Orsay)
- K. Bennaceur, J. Meyer (Lyon)
- P. Bonche (Saclay)

General motivation

- One of the major goals of the nuclear structure community is the definition of a universal energy functional. Cf. UNEDF within SciDAC.
- What are the inputs for the fit of a functional ? This is strongly debated at present.
- Ground-state observables are certainly the starting point but may not be enough.
- Focus of this talk: definite excited states carry unique information which can be instrumental for the mentioned fit.
- In particular: collective vibrations.

DFT and time-dependent extension

- The Hohenberg-Kohn theorem has its counterpart in the Runge-Gross theorem for the time-dependent case. (Map $V(r,t) \leftrightarrow \rho(r,t)$).

- There are of course problems in practical implementations of TDDFT, in the same way as for the static DFT.

- However, it is not the purpose here to discuss this, rather to assume that: (a) if HF(B) is the best current implementation of the static theory, then we can study the self-consistent (Q)RPA as the correspondent time-dependent theory; (b) in this way, we study ground states and excited states, testing the functionals on equal footing.

E. Runge and E. K. U. Gross, *Phys. Rev. Lett.* **52**, 997 (1984)

Until few years ago, many groups did NOT have a fully self-consistent (SC) RPA. Terms in the residual interaction were omitted. In the last years, some accurate, fully SC (Q)RPA codes have appeared.

A way to extract “exact” strength centroids or to test RPA codes is:

take m(1) from the double-commutator sum rule

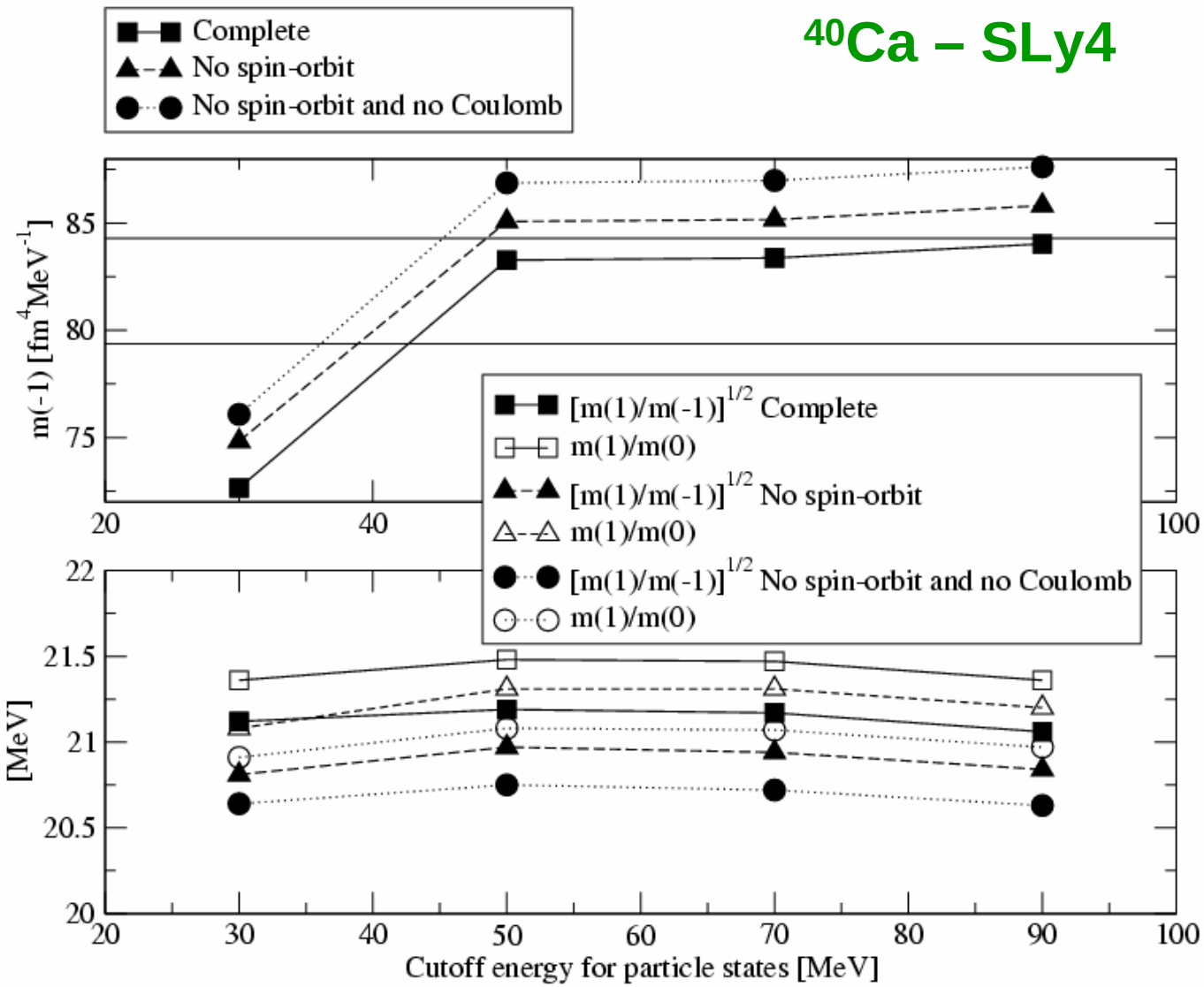
and m(-1) from contrained HF calculations (dielectric theorem).

$$H' = H + \lambda r^2,$$

$$m(-1) = -\frac{1}{2}\frac{\delta\langle r^2\rangle}{\delta\lambda} = \frac{1}{2}\frac{\delta^2\langle H\rangle}{\delta\lambda^2}$$

We have now fully SC codes for RPA, QRPA on top of HF-BCS – both for the normal channel and the charge-exchange one.

^{40}Ca – SLy4



G.C., P.F. Bortignon, S. Fracasso, N. Van Giai, *Nucl. Phys.* **A788**, 137c (2007)

The Giant Monopole Resonance and K_∞ as control on the isoscalar part of the functional

$$\frac{E}{A}[\rho] = \frac{E}{A}[\rho_0] + \frac{1}{18}K_\infty\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

Given a functional, at the same time

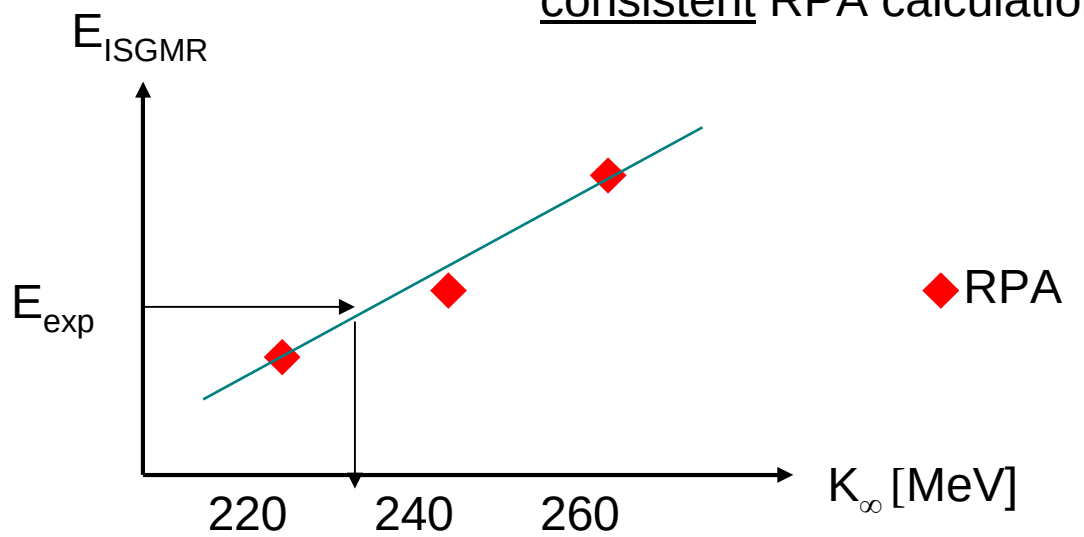
K_∞ in nuclear matter (analytic)

E_{ISGMR} (by means of <u>self-consistent</u> RPA calculations)

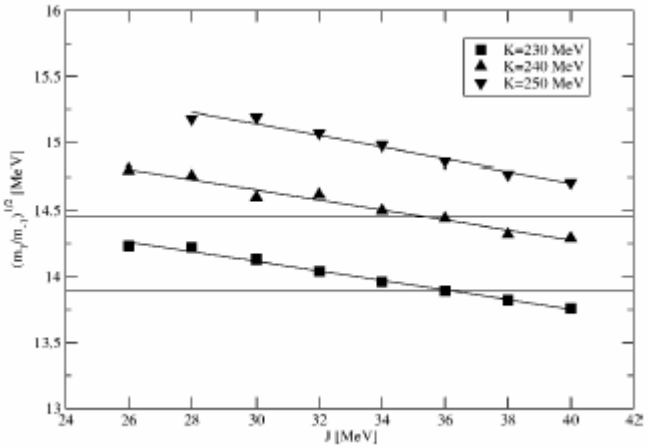
Skyrme

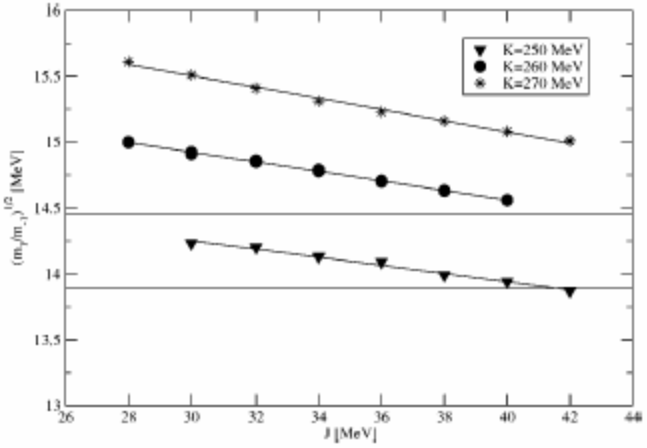
Gogny

RMF



Extracted value of K_∞





Right (left) refers to a softer (stiffer) density dependence: α=1/6 (1/3).

G.C., N. Van Giai, J. Meyer, K. Bennaceur, P. Bonche, *Phys. Rev.* **C70**, 024307 (2004)

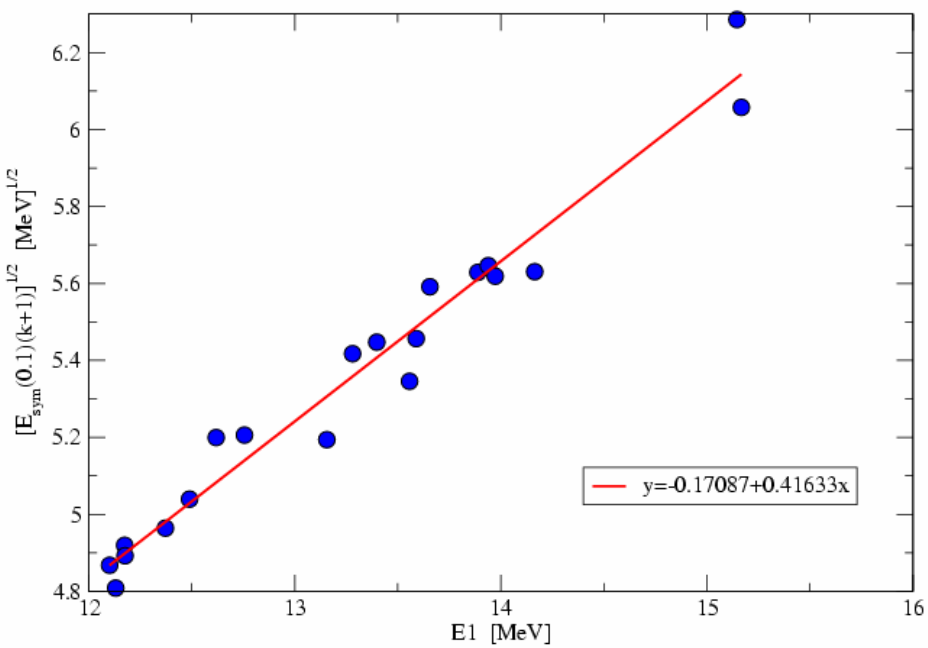
Concrete proposal #1 for the fit of functionals :

• Giant Monopole Resonance : E_{GMR} constrains K_∞ = 240 ± 20 MeV. (a) Allow in the fit this relatively broad range (one can allow 1.5σ, that is, 210 < K_∞ < 270 MeV). (b) A smaller range is possible if we have an *a priori* choice for the density dependence.

S. Shlomo, V.M. Kolomietz, G.C., *Eur. Phys. J.* **A30**, 23 (2006)

Constrain the SYMMETRY ENERGY by means of the Giant Dipole Resonance

$$\mathcal{E}(\varrho, \varrho_-) = \mathcal{E}_0(\varrho) + \varrho S(\varrho)(\frac{\varrho_-}{\varrho})^2$$



- x-axis: E_{GDR} from RPA;
- y-axis: $[S(\rho = 0.1)(1+\kappa)]^{1/2}$; κ is the enhancement factor.

L. Trippa, G.C., E. Vigezzi (submitted)

G.C., N. Van Giai, H. Sagawa, *Phys. Lett.* **B363**, 5 (1996)

The enhancement factor can be taken from experimental measurments, although with some uncertainty.

Concrete proposal #2 for the fit of functionals :

• Giant Dipole Resonance : E_{GDR} constraints $S_{0.1} \equiv S(\rho=0.1\ fm_{-3})$. The constraint, coming from a study with Skyrme, is $22.3 < S_{0.1} < 25.8$ MeV.

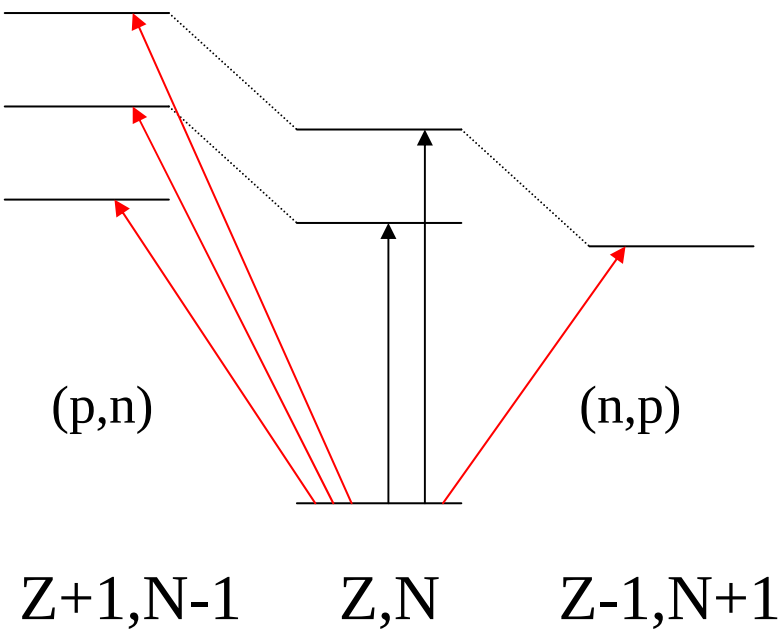
Cf. neutron stars, HI reactions…

CHARGE-EXCHANGE excitations

They are induced by charge-exchange reactions, like (p,n) or (^{3}He,t), so that starting from (N,Z) states in the neighbouring nuclei (N,Z±1) are excited.

A systematic picture of these states is missing.

However, such a knowledge would be important for astrophysics, or neutrino physics

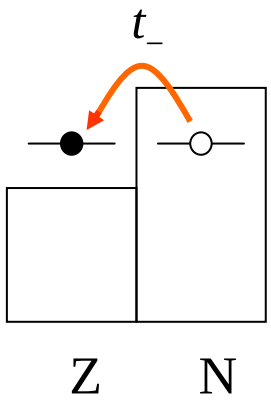


"Nuclear matrix elements have to be evaluated with uncertainities of less than 20-30% to establish the neutrino mass spectrum."

K. Zuber, workshop on double-β, decay, 2005

- Isobaric Analog Resonance (IAR)

$\Delta L = 0, \quad \Delta S = 0$

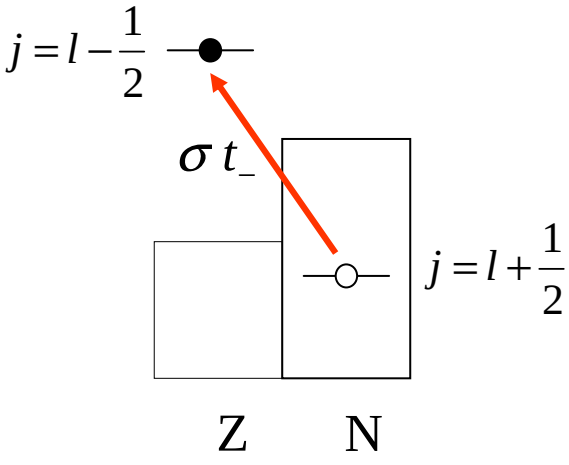


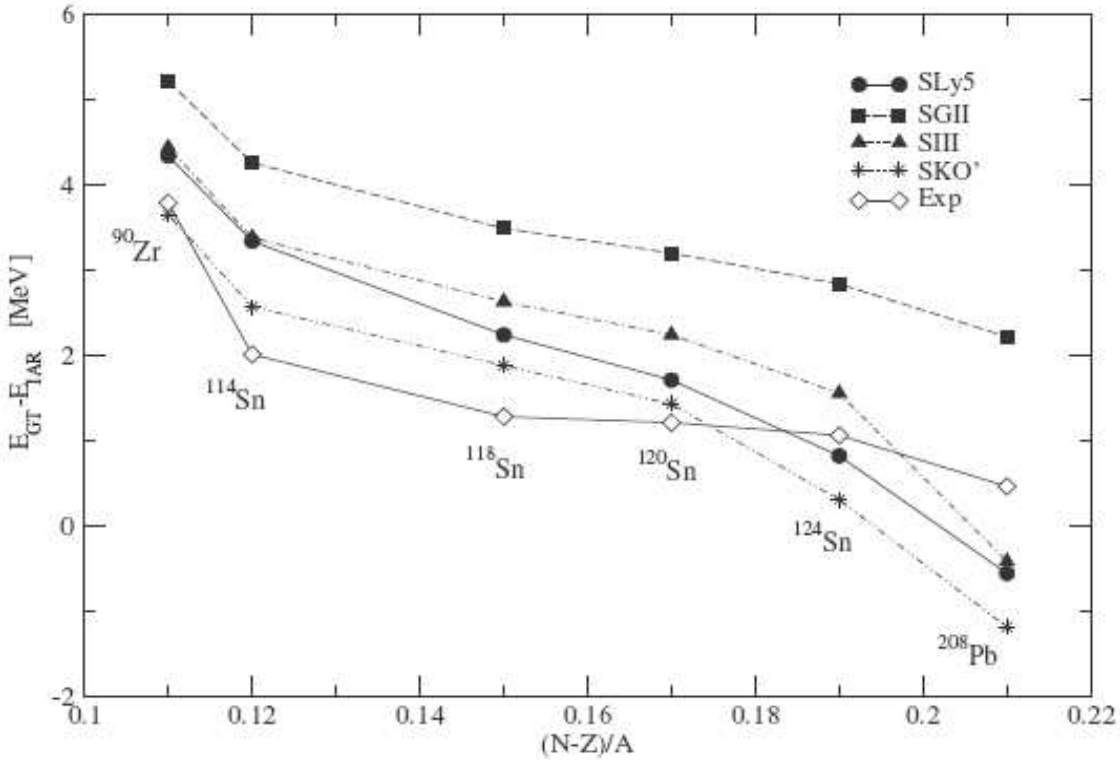
Strict connection with the isospin symmetry : if H commutes with isospin, the IAR must lie at zero energy.

H includes parts which provide explicit symmetry breaking: the Coulomb interaction, charge-breaking terms in the NN interaction, e.m. spin-orbit.

- Gamow-Teller Resonance (GTR)

$\Delta L = 0, \quad \Delta S = 1$

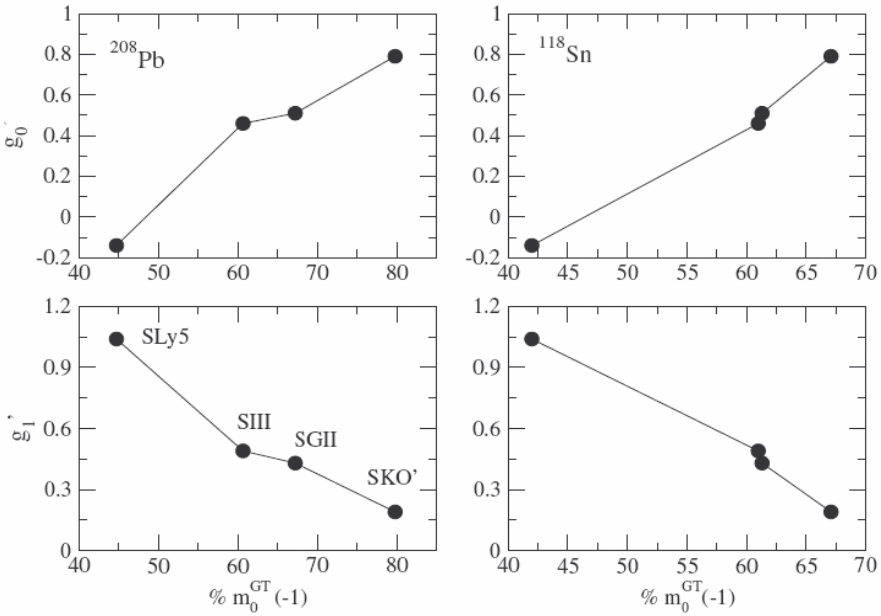




$$E_{\mathrm{GTR}} - E_{\mathrm{IAR}} = \Delta E_{ls} + 2\frac{\kappa_{\sigma\tau} - \kappa_{\tau}}{A}(N - Z)$$

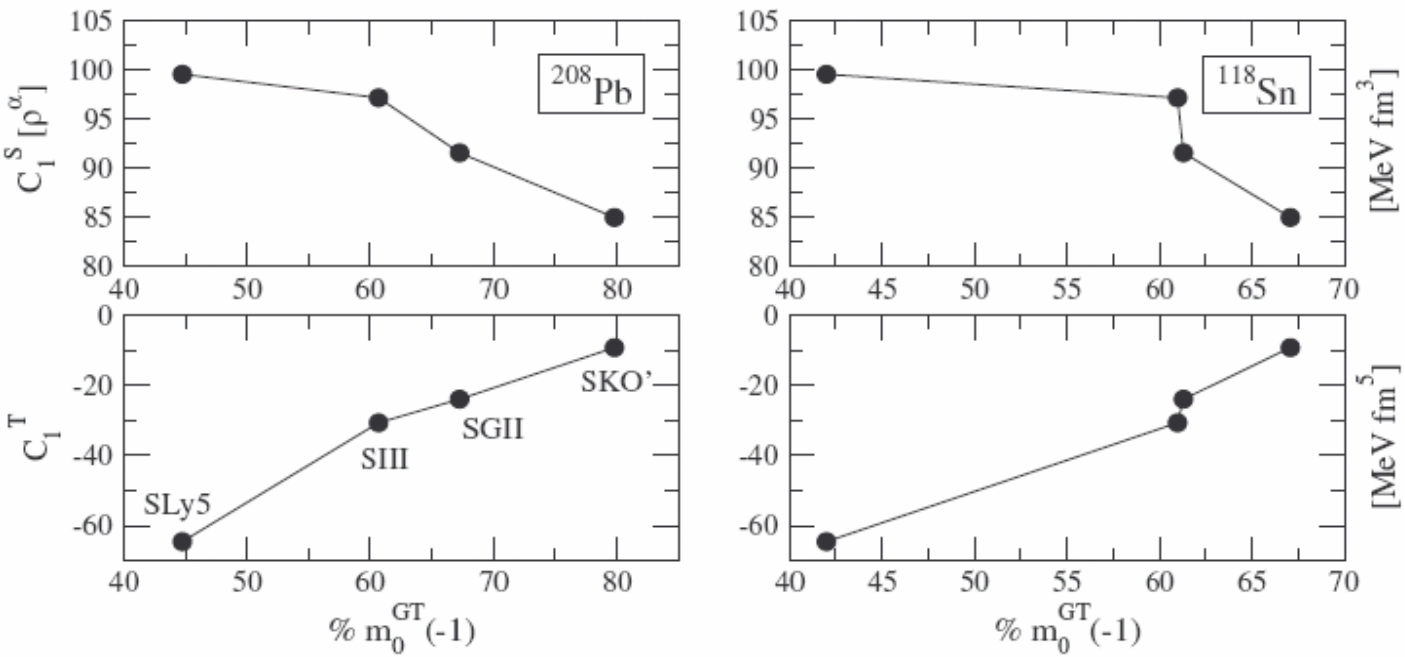
The behavior of the Skyrme parametrizations is systematic, not only as far as the centrod energy is concerned but also for the fraction of strength: while SGII, SIII and SkO' produce a main GTR which absorbs about 60% of 3(N-Z), this number is about 40% for SLy4.

S. Fracasso,G.C., *Phys. Rev.* **C76**, 044307 (2007)



Concrete proposal #3 for the fit of functionals :

- Giant Gamow-Teller Resonance : imposing that it exhausts about 60% of the 3(N-Z) sum rule constraints the spin-isospin part of the functional.



Conclusions

- The relevance of definite energies or collectivities of vibrational states, as “benchmarks” for functionals or quantities to be fitted, has been discussed.
- Certainly, some collective states are well correlated with definite parts of the functional.
- Other calculations (e.g., low-lying 2^+) are useful, but the purpose here is to propose a hierarchy in which well-defined correlations are used as criterion to prefer certain benchmarks with respect to others.

The IV monopole ($r^2\tau$)

G. Colò and N. Van Giai, "Where is the non spin-flip isovector monopole resonance in ^{208}Tl ?", Phys. Rev. C53 (1996) 2201.

We are still waiting to know where it lies… <u>We miss an idea about a really selective probe</u>. Yet it can give access to:

- isospin mixing in the ground-state
- symmetry energy

$$\frac{\sum_n |\langle n| \sum_i r_i^2 \tau_z(i) |0\rangle|^2}{E_n - E_0}$$

$$\sim \vec{T} \cdot \vec{t} = T_z t_z + 1/2(T_+ t_- + T_- t_+)$$