10th International Spring Seminar on Nuclear Physics, 21-25 May 2010

New Quests in Nuclear Structure

Tensor effects in shell evolution at Z, N = 8, 20 and 28 using non relativistic and relativistic mean field

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Outline

- Tensor force within the mean field approach
- Non relativistic mean field: Skyrme and Gogny cases. Relativistic mean field: Relativistic Hartree-Fock (RHF)

- Structure evolution far from stability: gap evolution at magic numbers. Does the tensor force play an important role?

- Results: Evolution of the gaps at Z, N = 8, 20 and 28. No pairing. No beyond-mean-field effects. Qualitative trends

- Conclusions and perspectives

Regions where the tensor effects can be easily isolated in the evolution of the gaps

Inclusion of these observables in the parameter fitting procedures in mean-field approaches where the tensor force is explicitly considered.

Moreno-Torres, Grasso, Liang, De Donno, Anguiano, Van Giai, in preparation

More global view

- Odd nuclei. Time-odd terms

- Tensor effects in excited states

- **De Donno, et al., PRC 79, 044311 (2009), Gogny force, low-lying magnetic excitations**

- **Li-Gang Cao, et al., PRC 80, 064304 (2009), self-consistent RPA, quadrupole, octupole and magnetic dipole**

Tensor force in Skyrme case

Skyrme, Phil. Mag. 1, 1043 (1956); Skyrme, Nucl. Phys. 9, 615 (1958)

$$\begin{aligned} v_{\mathrm{T}} = \frac{T}{2} &\left[\left((\boldsymbol{\sigma}_1 \cdot \mathbf{k}')(\boldsymbol{\sigma}_2 \cdot \mathbf{k}') - \frac{1}{3}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\mathbf{k}'^2 \right) \delta(\mathbf{r}_1 - \mathbf{r}_2) \right] \\ &+ \frac{T}{2}\delta(\mathbf{r}_1 - \mathbf{r}_2) \left[\left((\boldsymbol{\sigma}_1 \cdot \mathbf{k})(\boldsymbol{\sigma}_2 \cdot \mathbf{k}) - \frac{1}{3}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\mathbf{k}^2 \right) \right] \\ &+ U \left[(\boldsymbol{\sigma}_1 \cdot \mathbf{k}')\delta(\mathbf{r}_1 - \mathbf{r}_2)(\boldsymbol{\sigma}_2 \cdot \mathbf{k}) - \frac{1}{3}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \times (\mathbf{k}' \cdot \delta(\mathbf{r}_1 - \mathbf{r}_2)\mathbf{k}) \right] \end{aligned}$$

σ are the spin matrices

$\mathbf{k} = (\nabla_1 - \nabla_2)/2i$ acts on the right and $\mathbf{k}' = -(\nabla_1 - \nabla_2)/2i$ acts on the left. T and U provide the intensity of the tensor force in even and odd states of relative motion, respectively.

Variation of the energy density (contributions depending on *J*)

(spherical symmetry and time-reversal invariance)

$$\Delta H = \frac{1}{2}\alpha\left(J_n^2 + J_p^2\right) + \beta J_n J_p$$

J -> spin-orbit density

$$\alpha_{\mathrm{T}} = \frac{5}{12}U$$

$$\beta_{\mathrm{T}} = \frac{5}{24}(T+U)$$

The parameters of the J^2 terms are two:

$$\alpha = \alpha_C + \boxed{\alpha_T} \qquad \beta = \beta_C + \boxed{\beta_T}$$

α_C and β_C are related to the central exchange part and are expressed in terms of the other parameters of the Skyrme interaction:

$$\alpha_C = \frac{1}{8}(t_1 - t_2) - \frac{1}{8}(t_1 x_1 + t_2 x_2) \qquad \beta_C = -\frac{1}{8}(t_1 x_1 + t_2 x_2)$$

The spin–orbit potential is modified by the new contributions

$$U_{SO}^{q} = \frac{W_0}{2}\left(2\frac{d\rho_q}{dr} + \frac{d\rho_{q'}}{dr}\right) + \left(\alpha J_q + \beta J_{q'}\right)$$

J -> spin-orbit density

$$J_q(r) = \frac{1}{4\pi r^3}\sum_i \left(2j_i + 1\right)\left[j_i\left(j_i + 1\right) - l_i\left(l_i + 1\right) - \frac{3}{4}\right]v_i^2(r)$$

Tensor effects are zero in a spin-saturated nucleus

First analysis: Stancu, Brink, Flocard, Phis. Lett. B 68, 108 (1977)

1) If the tensor parameters are estimated from the realistic interaction the agreement with the experimental values of some spin-orbit splittings deteriorates

2) If α_T and β_T are treated as free parameters minor improvements are found

Triangle defined by:

$0 \leq \beta \leq 80$

$-80 \leq \alpha \leq 0$

More recently… with Skyrme…some references

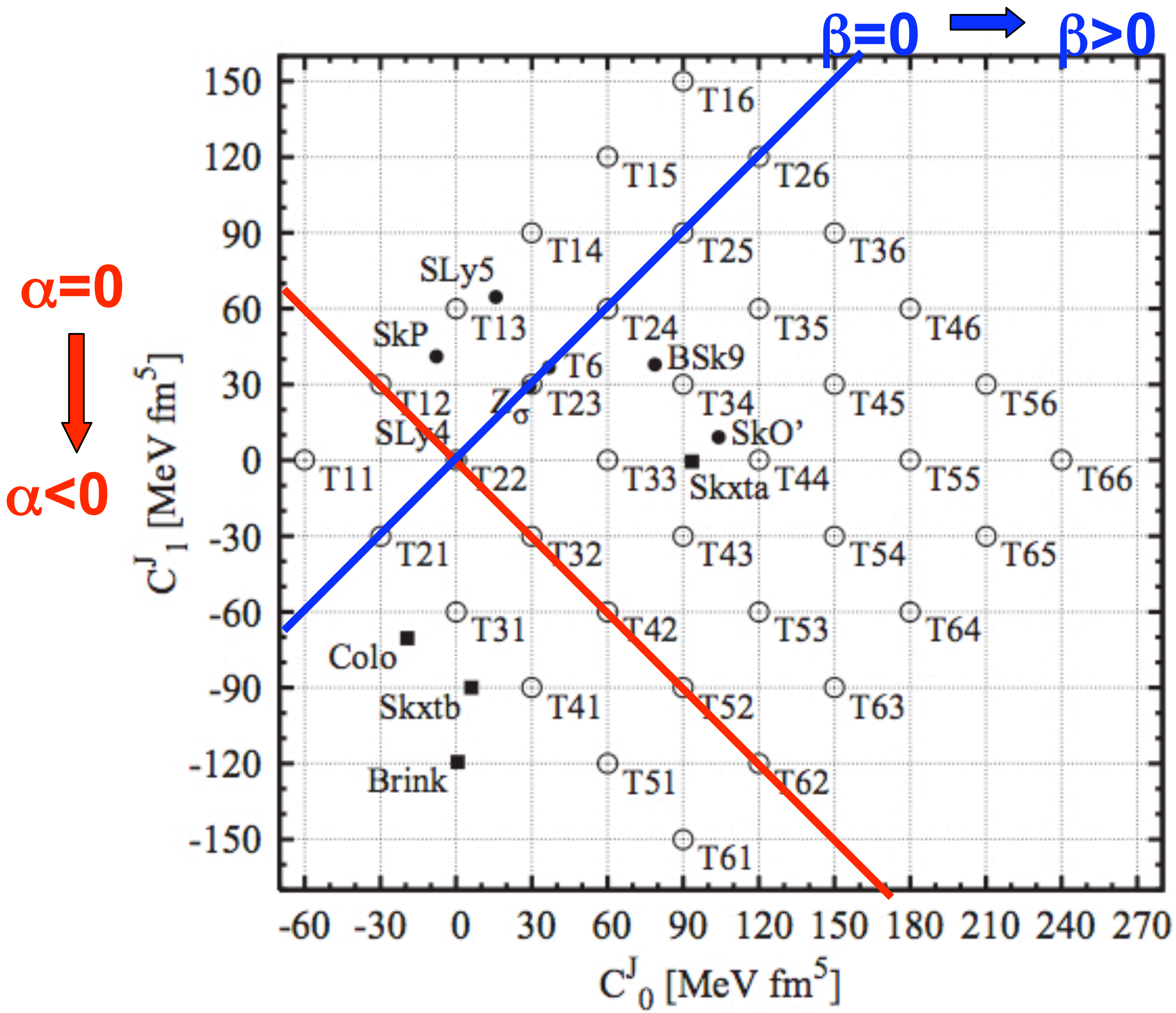
-Brown, et al., PRC74, 061303 (2006): (starting point: finite-range G matrix potential. The strength of the zero-range tensor is first calibrated to this and then refitted to nuclear properties (different sign of α))

-Brink and Stancu, PRC75, 064311 (2007): extension of the previous analysis to exotic nuclei. Fit * (values outside the triangle). Conclusion: the Skyrme energy functional with the zero-range tensor force is adequate to describe the evolution of shell effects

-Colò et al., PLB646, 227 (2007): fit * of the tensor parameters on top of the Sly5 interaction which already takes into account the exchange part of the tensor force
$(\alpha_T,\beta_T)=(-170,100)$ MeV fm^5

* J.P. Schiffer, et al., Phys. Rev. Lett. 92 (2004) 162501.

Lesinski et al. parametrizations PRC76, 014312 (2007)



C_0 = 1/2 ($\alpha+\beta$)

C_1 = 1/2 ($\alpha-\beta$)

Gogny case (from the usual tensor operator S_{12}, a term depending on the tensor force is added only in the isospin channel $\tau_1 \bullet \tau_2$)

$$v_T = F_T \, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \underbrace{3 \left(\frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{r}_{12})(\boldsymbol{\sigma}_2 \cdot \mathbf{r}_{12})}{(\mathbf{r}_{12})^2} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \right)}_{S_{12}} f_G(r)$$

where $F_T = 50.79506$ MeV and $f_G(r)$ is a gaussian function, with a range of 1.2 fm

The parameter F_T has been fixed assuming that the volume integral reproduces that of AV8'. The range of the gaussian f_G has been chosen equal to the longest range of the central part

The parametrization GT2, used here, has been introduced by Otsuka and collaborators (fitted at the HF level)

Otsuka, Matsuo, and Abe, Phys. Rev. Lett. 97, 162501 (2006)

Tensor in RHF

In the relativistic framework, the tensor correlations are deduced from the pion-nucleon and ρ-nucleon tensor interactions. The part of the Lagrangian containing the pion and ρ-meson fields is written as

$$
\begin{aligned}
\mathcal{L}_{\pi+\rho} = & +\frac{1}{2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} - \frac{1}{2}m_\pi^2\vec{\pi}\cdot\vec{\pi} - \frac{f_\pi}{m_\pi}\bar{\psi}\gamma_5\gamma^\mu\partial_\mu\vec{\pi}\cdot\vec{\tau}\psi \\
& -\frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^\mu\cdot\vec{\rho}_\mu - g_\rho\bar{\psi}\gamma^\mu\vec{\rho}_\mu\cdot\vec{\tau}\psi \\
& +\frac{f_\rho}{2M}\bar{\psi}\sigma_{\mu\nu}\partial^\nu\vec{\rho}^\mu\cdot\vec{\tau}\psi,
\end{aligned}
$$

where $\vec{R}^{\mu\nu} \equiv \partial^\mu\vec{\rho}^\nu - \partial^\nu\vec{\rho}^\mu$. In the parametrization PKA1 the coupling strengths f_π, g_ρ, and f_ρ are exponentially density-dependent.

W. H. Long, N. V. Giai, and J. Meng, Phys. Lett. B **640**, 150 (2006).

W. H.Long, N. V. Giai, and J. Meng, Europhys. Lett. **82**, 12001 (2008).

W. H. Long, H. Sagawa, N. V. Giai, and J. Meng, Phys. Rev. C **76**, 034314 (2007).

How the experimental gaps are evaluated. Approximation. Separation energies

$$E_{\rm gap}(Z_{\rm magic}, N) = \epsilon_a - \epsilon_b.$$

a -> abobe (first unoccupied)

b -> below (last occupied)

$$\begin{aligned}\epsilon_b(Z_{\rm magic}, N) &= -(E(Z_{\rm magic}, N) - E(Z_{\rm magic} - 1, N)) \\ &= -S_p(Z_{\rm magic}, N) \\ \epsilon_a(Z_{\rm magic}, N) &= -(E(Z_{\rm magic} + 1, N) - E(Z_{\rm magic}, N)) \\ &= -S_p(Z_{\rm magic} + 1, N),\end{aligned}$$

S_p -> separation energy

Wigner energy correction in N≈Z nuclei

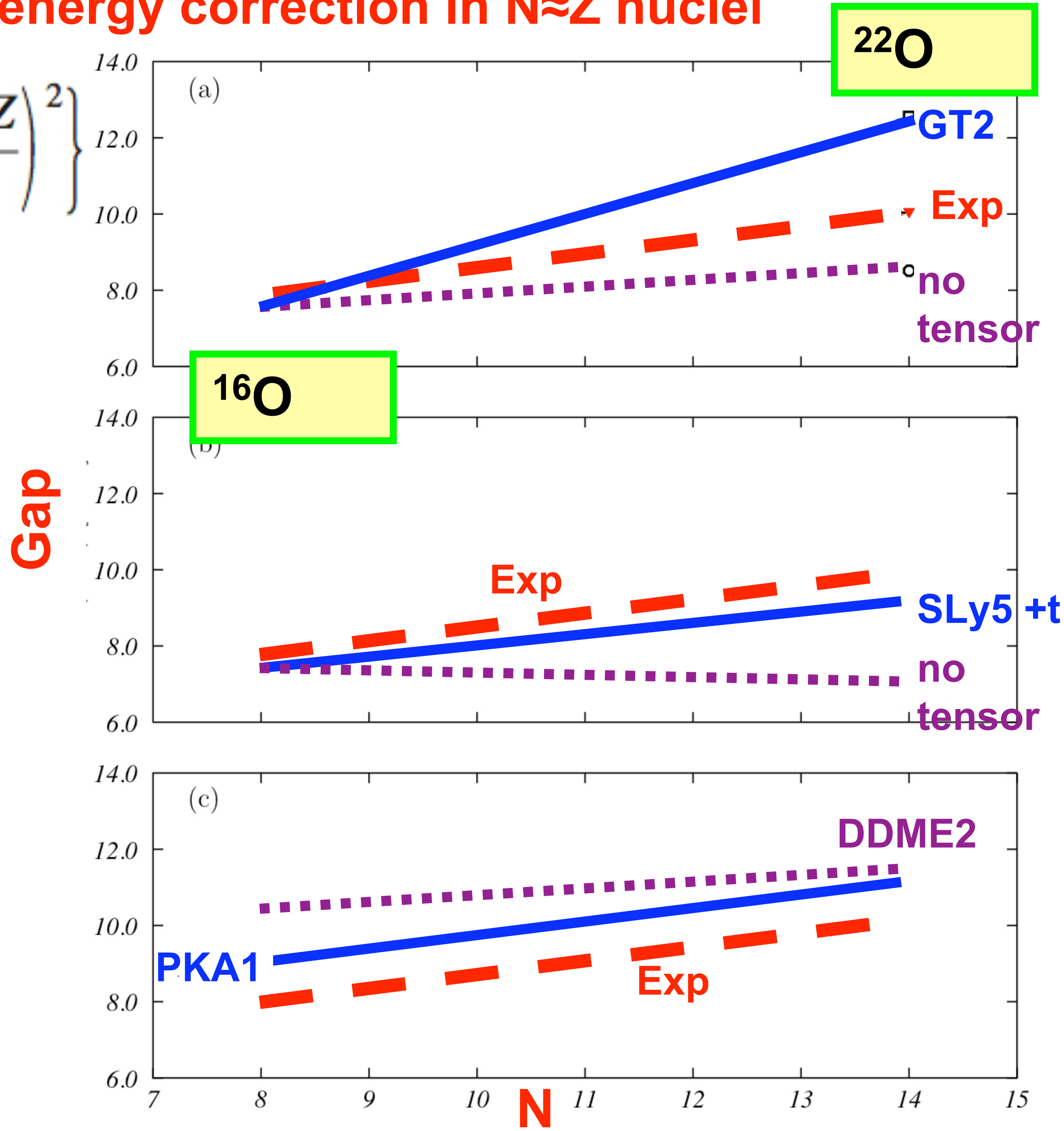
Z=8

$$E_W = V_W \exp\left\{-\lambda\left(\frac{N-Z}{A}\right)^2\right\}$$

V_W = -2.327 MeV

λ = 400

Goriely et al., PRC 66, 024326 (2002)



Analysis of the mean-field results (simpler case of Skyrme)

$^{16}O \rightarrow {}^{22}O$

Neutron d5/2 state is filled

$$\Delta W_{so}^{(q)} = \cancel{\alpha J_q} + \beta J_{q'}$$

p p n

Effect on proton gap. The gap is calculated between proton p1/2 and proton d5/2 states.

- β is positive

- Neutron spin-orbit density is positive

- Proton spin-orbit splitting is reduced

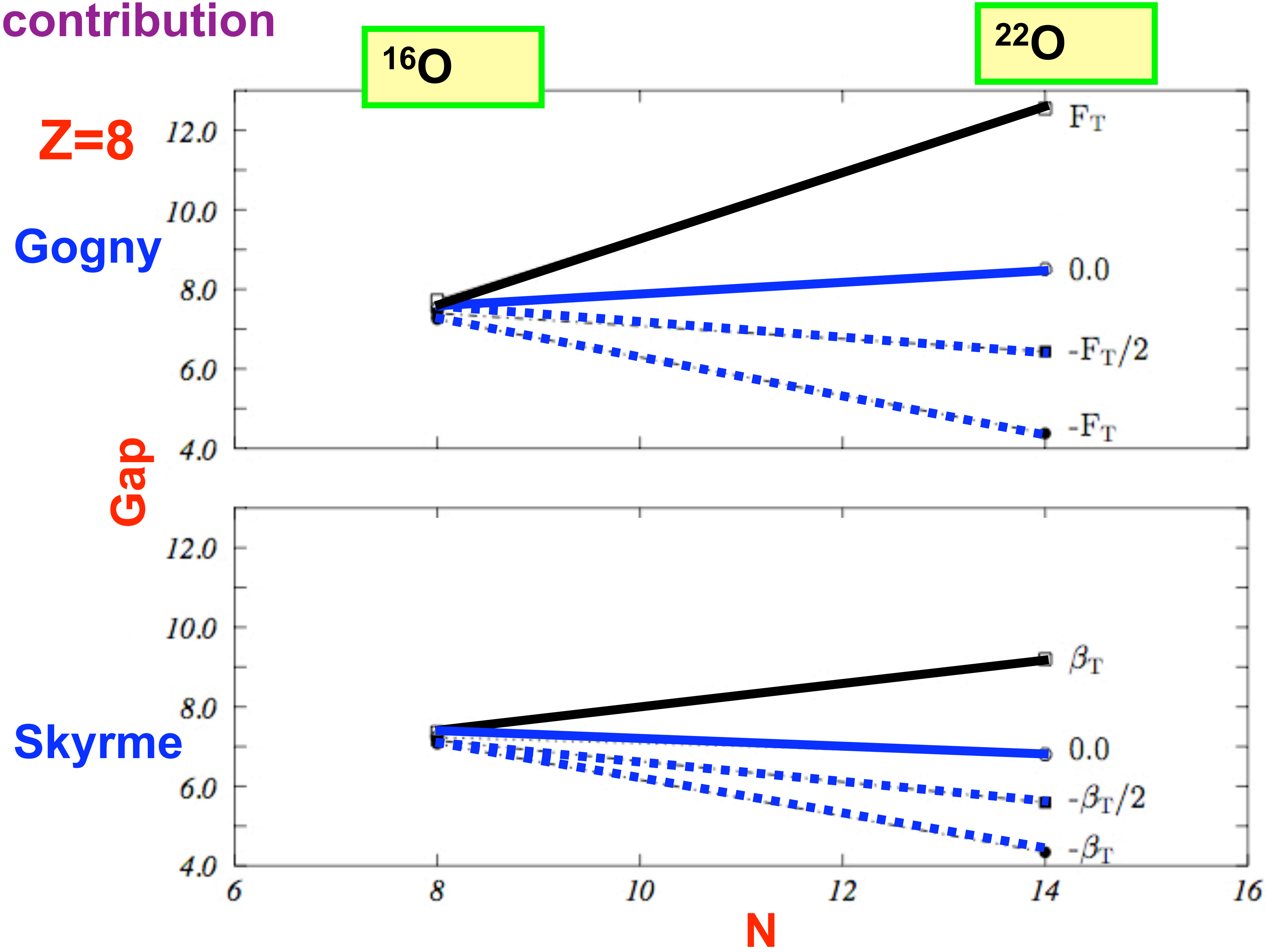
Z = 8 -> spin-saturated for protons. J_p ~0

- p p1/2 energy is reduced (attraction with neutron d5/2)

-p d5/2 energy is increased (repulsion with neutron d5/2).

- The gap is expected to increase

The tensor effect is clear: the slope depends on the tensor contribution



N, Z = 28…what to expect ?
Skyrme: α and β (spin-unsaturated for both protons and neutrons)

- How to disentangle the effect of proton (neutron) filling on neutron (proton) gaps?

- Proton (neutron) gap calculated between f7/2 and p3/2. Both states are j>: ambiguity

Conclusions and Perspectives

1) **Tensor effects clearly visible in the gap evolution at N, Z = 8 and 20 within mean field approaches.**

2) **N, Z = 8 and 20: fits of tensor parameters have to be performed.**

3) **Pairing correlations are not included**

4) **Beyond-mean-field effects (particle-vibration coupling) are not taken into account**