Investigation of tensor-force effect on exotic nuclei by the HFB method

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Outline

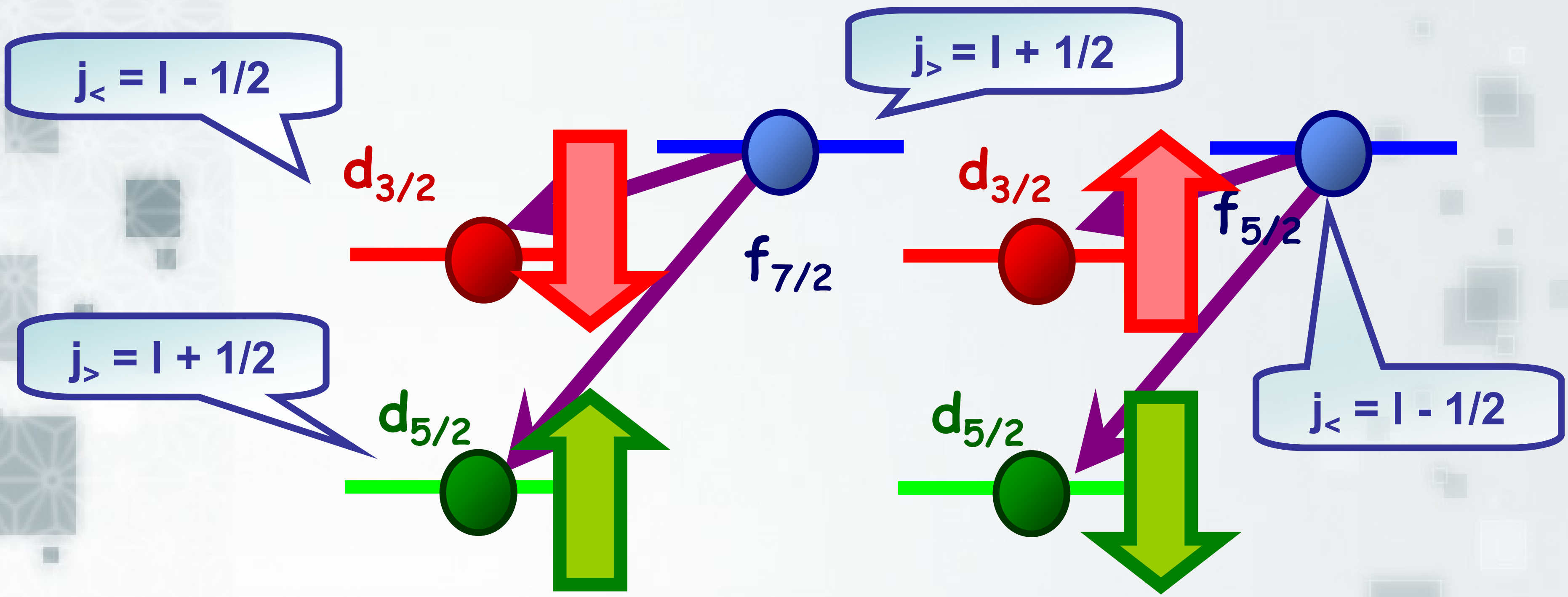
- Motivation
- Method
  - HFB + Gogny
  - How to implement the tensor force
  - How to adjust parameters
- Results and discussion
  - Ni isotopes
  - Sb isotopes
  - Bi isotopes
  - Kr isotopes
- Summary

Motivation

- We investigate nuclear structures from viewpoint of the tensor force.
- The "tensor force" is a missing part in usual mean-field calculations such as Skyrme and Gogny.
- There are some experimental data which cannot be explained by those usual methods.
  - Sb isotopes: PRL 92, 16 (2004),
  - Ca and Ar: PRL 97, 092501 (2006)
  - ^{17}F and ^{23}F: PLB 638, 146 (2006)
  - and so on…
- We can see interesting differences between the tensor force and spin-orbit force.
- And we expect that the tensor force plays a crucial role in exotic nuclear region as well as the spin-orbit force.

Tensor-force effect

$$S_{12} = \frac{3}{r^2}(\boldsymbol{\sigma}_1 \cdot \mathbf{r})(\boldsymbol{\sigma}_2 \cdot \mathbf{r}) - (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$$



HFB calculation with steepest gradient method

- Spherical symmetry

$$\beta_k^\dagger = \sum_l (c_l^\dagger U_{lk} + c_l V_{lk})$$

$$\beta_k = \sum_l (c_l^\dagger V_{lk}^* + c_l U_{lk}^*)$$

- Basis
  - spherical HO basis

$$\hat{H} = \sum \varepsilon_{\alpha\beta} c_\alpha^\dagger c_\beta + \frac{1}{4}\sum \bar{v}_{\alpha\beta\gamma\delta} c_\alpha^\dagger c_\beta^\dagger c_\delta c_\gamma$$

- Hamiltonian
  - Gogny force

$$0 = \delta\langle\Phi|(\hat{H} - \lambda_N \hat{N} - \lambda_Z \hat{Z})|\Phi\rangle$$

$$N = \langle\Phi|\hat{N}|\Phi\rangle, Z = \langle\Phi|\hat{Z}|\Phi\rangle$$

- Iteration
  - steepest gradient meth

$$\begin{aligned}\delta E &= \langle\Phi'|\hat{H}|\Phi'\rangle - \langle\Phi|\hat{H}|\Phi\rangle \\ &= \delta Z^* \frac{\partial E}{\partial Z^*} + \delta Z \frac{\partial E}{\partial Z} \\ &= \delta Z^* H^{20} + \delta Z H^{20*}\end{aligned}$$

Gogny force

J. Decharge and D. Gogny. PRC 21, 4 (1980)

$$V_{12} = \sum_{i=1,2} (W_i + B_i P_\sigma - H_i P_\tau - M_i P_\sigma P_\tau) \exp(-r_{12}^2/\mu_i^2)$$
$$+ iW_0(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \overleftarrow{\mathbf{k}} \times \delta(\mathbf{r}_{12}) \overrightarrow{\mathbf{k}}$$
$$+ t_3(1 + x_3 P_\sigma)\delta(\mathbf{r}_{12})\rho^\alpha$$

- Coulomb force and CM correction.
- Two Gaussians as central force.
- Good binding energies and other properties of nuclei
- Good pairing property (Sn isotopes)

But…

- No tensor force

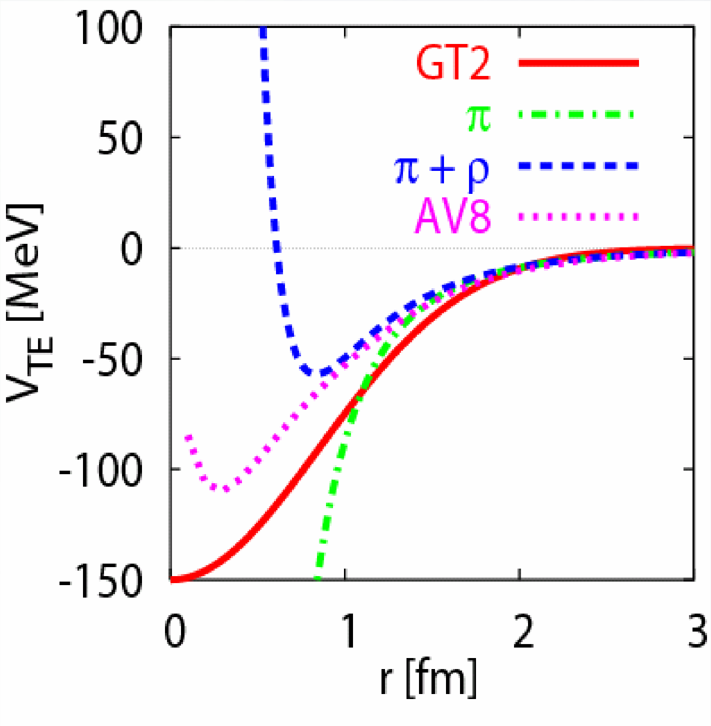
Gogny + Tensor

T. Otsuka et al., PRL 97, 162501 (2006)

$$
\begin{aligned}
V_{12} = \sum_{i=1,2} & (W_i + B_i P_\sigma - H_i P_\tau - M_i P_\sigma P_\tau) \exp(-r_{12}^2/\mu_i^2) \\
& + iW_0(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \overleftarrow{\mathbf{k}} \times \delta(\mathbf{r}_{12}) \overrightarrow{\mathbf{k}} \\
& + t_3(1 + x_3 P_\sigma)\rho^\alpha \delta(\mathbf{r}_{12}) \\
& + (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) V_T^0 \exp(-r_{12}^2/\mu_T^2) S_{12}
\end{aligned}
$$

- Tensor force.
- Parameters are readjusted.
- Single Gaussian.

Radial dependences of the tensor force



Triplet-Even

$$\mu_T = 1.2[\mathrm{fm}]$$
$$V_T^0 = 50.8[\mathrm{MeV}]$$

- Similar dependence between GT2 and AV8'.
- Short-range dependence of GT2 is somehow different from others.
- This difference is irrelevant.
- Because the tensor force cannot affect on s-wave states.

Parameters

- **D1S**
  - J. F. Berger, et al., Nucl. Phys. A428, 23c (1984)
- **GT1,2 (our earlier study)**
  - T. Matsuo, Ph.D. Thesis, University of Tokyo (2004)
  - T. Otsuka et al., PRL 97, 162501 (2006)
- **GT3**
  - **New parameter set**

$$W_1, B_1, H_1, M_1$$
$$W_2, B_2, H_2, M_2$$
$$t_3, x_3, \alpha$$
$$W_0$$

- Nuclear Matter properties
- Binding energies of some nuclei
- Pairing property

Nuclear matter properties

$$k_F \simeq 1.34 \quad [\mathrm{fm}^{-1}]$$

$$-E/A \simeq 16.0 \quad [\mathrm{MeV}]$$

$$K = k_F^2 \frac{\partial^2 (E/A)}{\partial k_f^2}$$

$$\frac{k_F}{M^*} = \frac{\partial \varepsilon}{\partial k_F}$$

$$a_s = \frac{1}{2} \frac{\partial^2 (E/A)}{\partial^2 \eta_s}$$

$$a_t = \frac{1}{2} \frac{\partial^2 (E/A)}{\partial^2 \eta_t}$$

$$a_{st} = \frac{1}{2} \frac{\partial^2 (E/A)}{\partial^2 \eta_{st}}$$

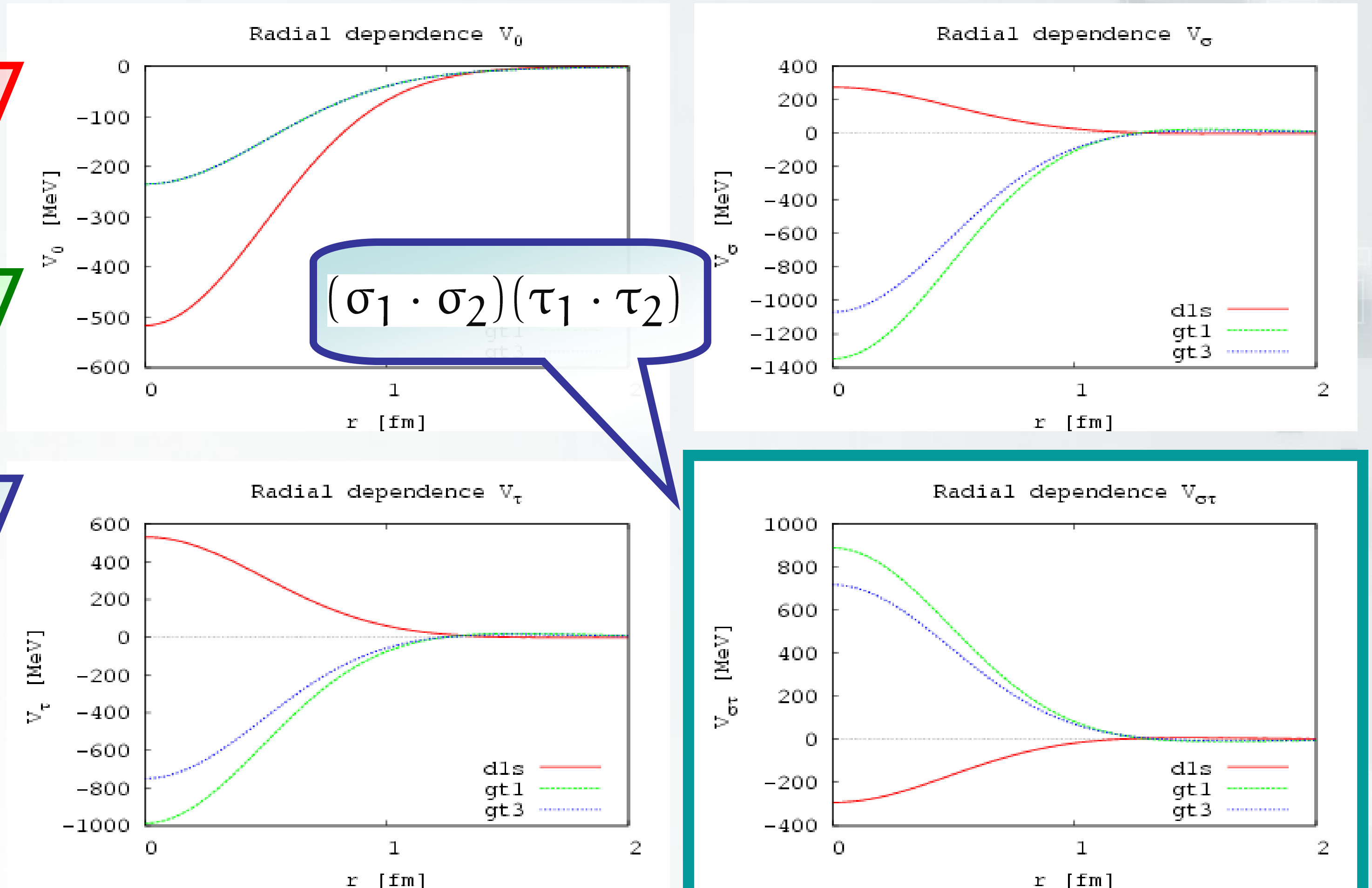
	D1S	GT1	GT2	GT3
kF	1.342	1.336		
-E/A	16.01	16.02		
K	202.8	228.1		
M*/M	0.697	0.672		
as	26.18	35.19	38.40	24.31
at	31.13	31.29	33.94	28.60
ast	29.12	26.64	24.69	31.17

Radial dependences of central force

D1S

GT1

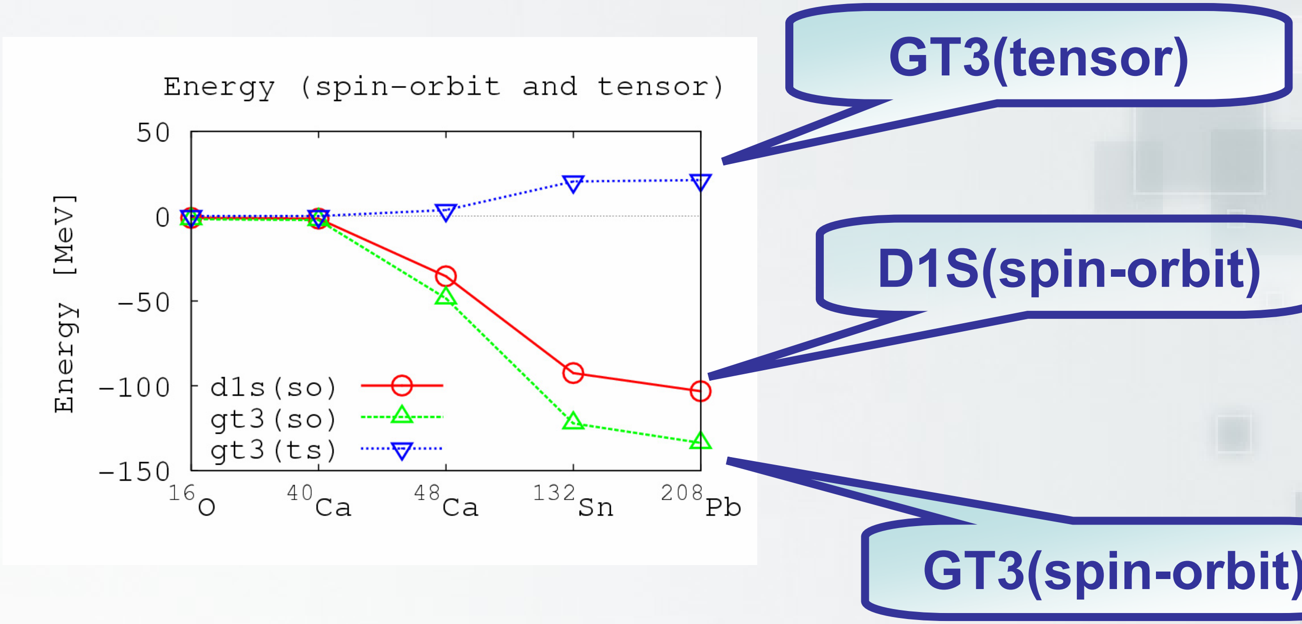
GT3



Neutron $p_{1/2} - p_{3/2}$ splitting of ^{16}O

- Spin-orbit force mainly contributes to this splitting
- No contribution of the tensor force
- D1S $\quad W_0 \simeq 130 \rightarrow 6$ [MeV]
- GT3 $\quad W_0 \simeq 160 \rightarrow 8$ [MeV]
  - Larger gap
  - ^{28}O can be bound using W = 130, but cannot be bound using W = 160

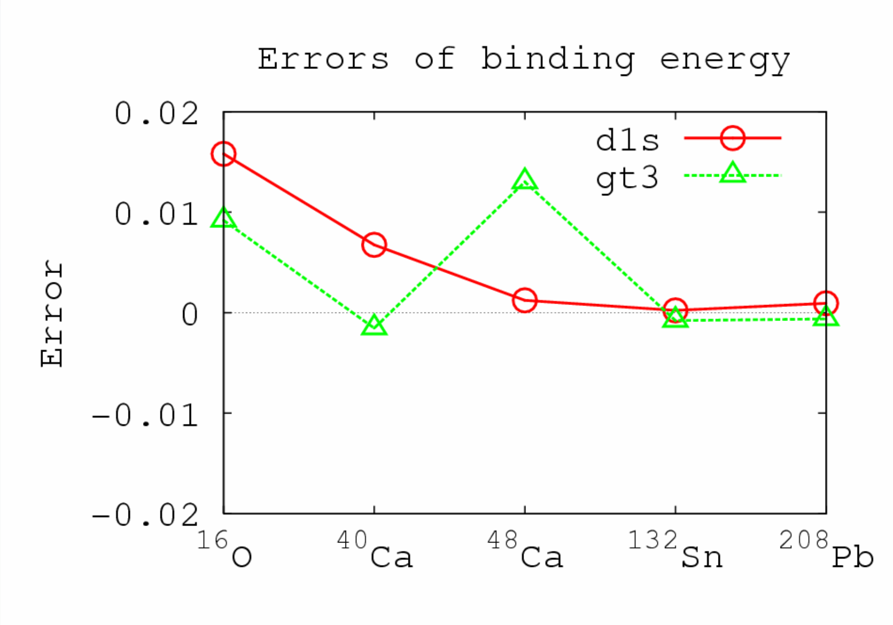
Contributions to binding energies



- D1S(spin-orbit) =
  GT3(spin-orbit) + GT3(tensor)
- Contribution
  - spin-orbit force: more bound
  - tensor force: less bound

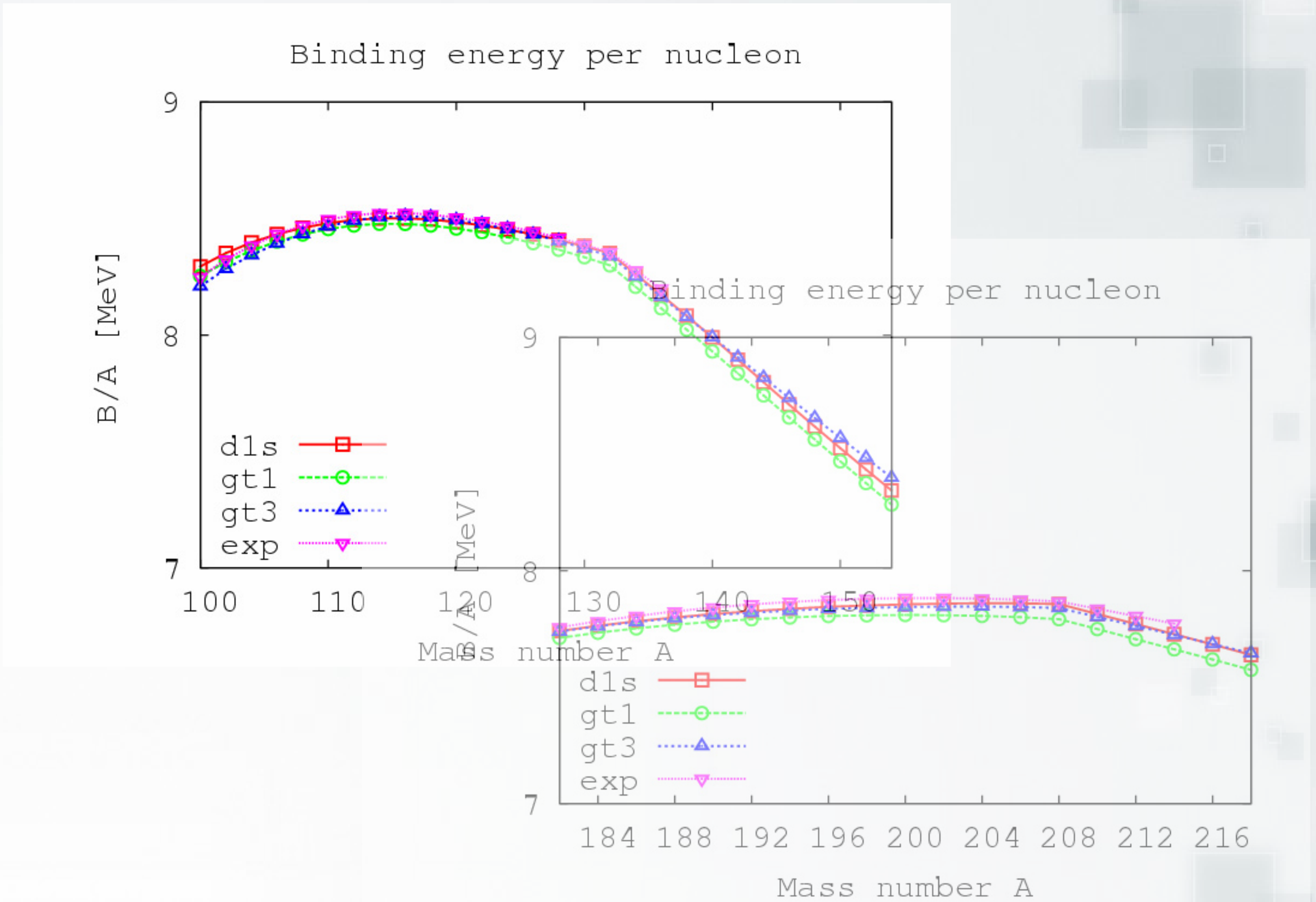
Binding energy

$$\text{Error} = \frac{BE_{\text{calc}} - BE_{\text{exp}}}{BE_{\text{exp}}}$$



- B.E. errors
  - ^{16}O, ^{40}Ca, ^{48}Ca (bad result), ^{132}Sn, ^{208}Pb
- Fine tuning will be necessary

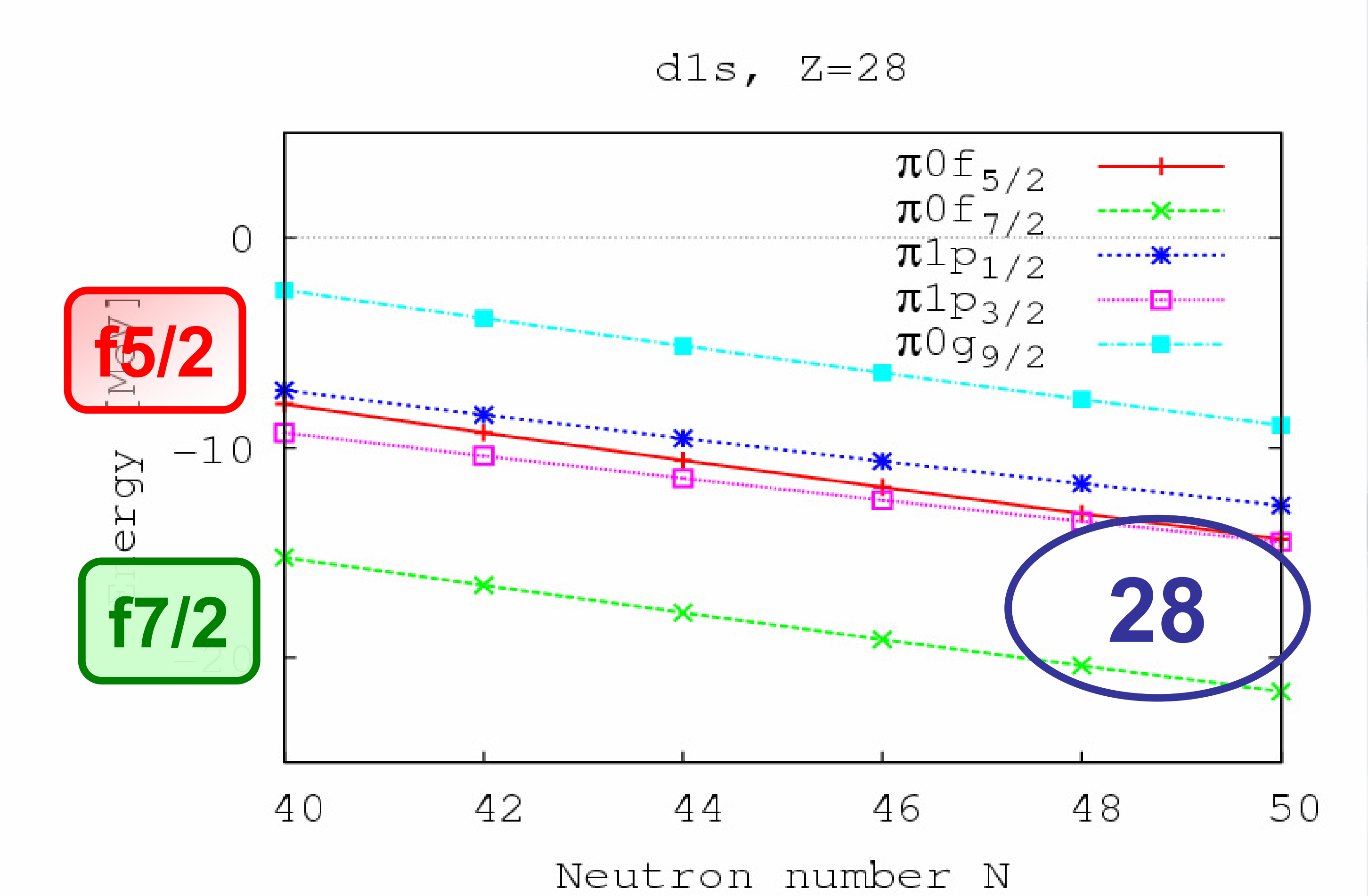
B.E. of Sn and Pb isotopes



Results

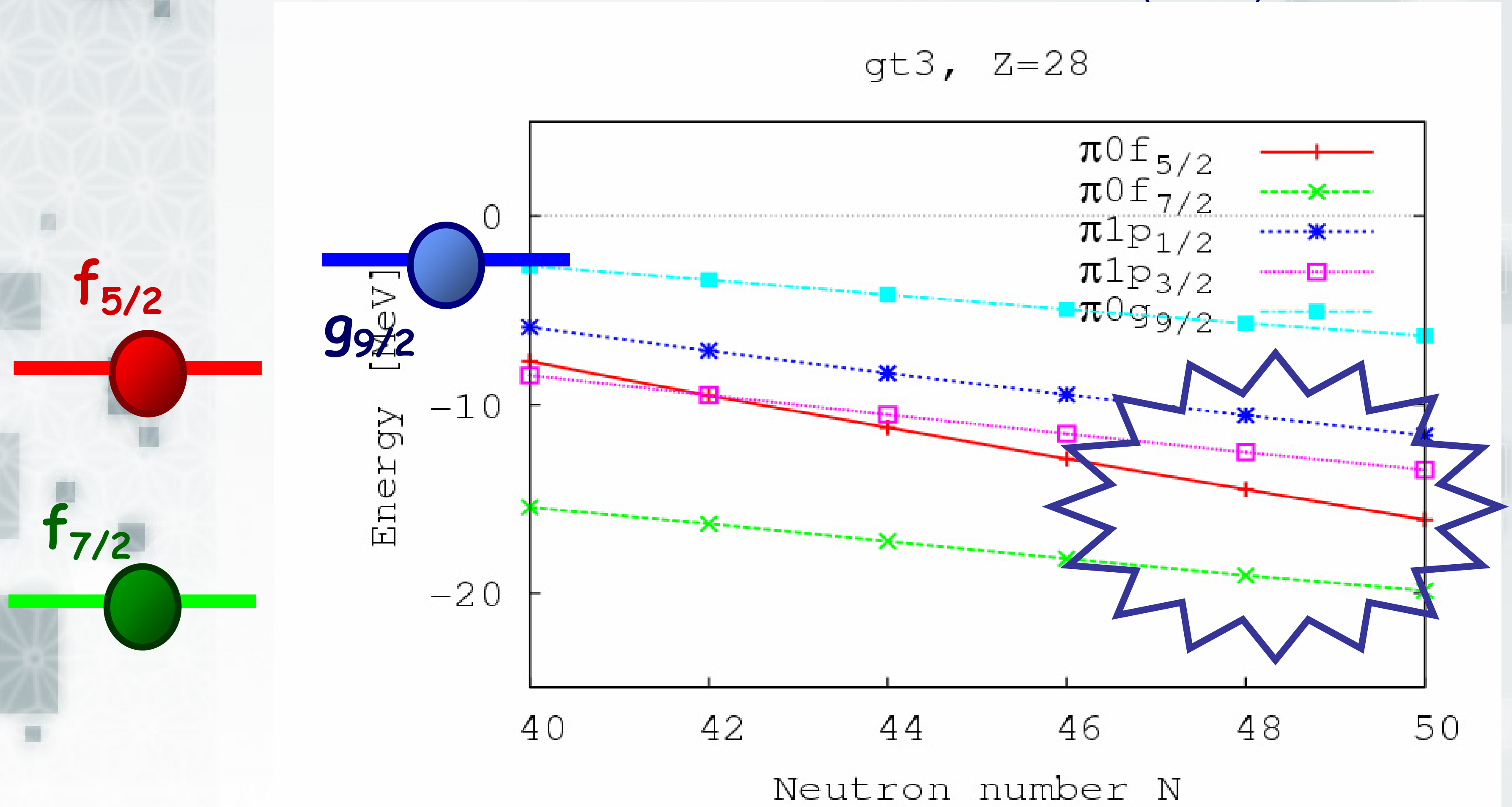
- Ni isotopes
  - Magic number Z=28
- Sb isotopes
  - h11/2 and g7/2 gap
- Bi isotopes
  - i13/2 and h9/2 gap
- Kr isotopes
  - two-neutron separation energy

Proton single-particle energies of Ni isotopes, D1S



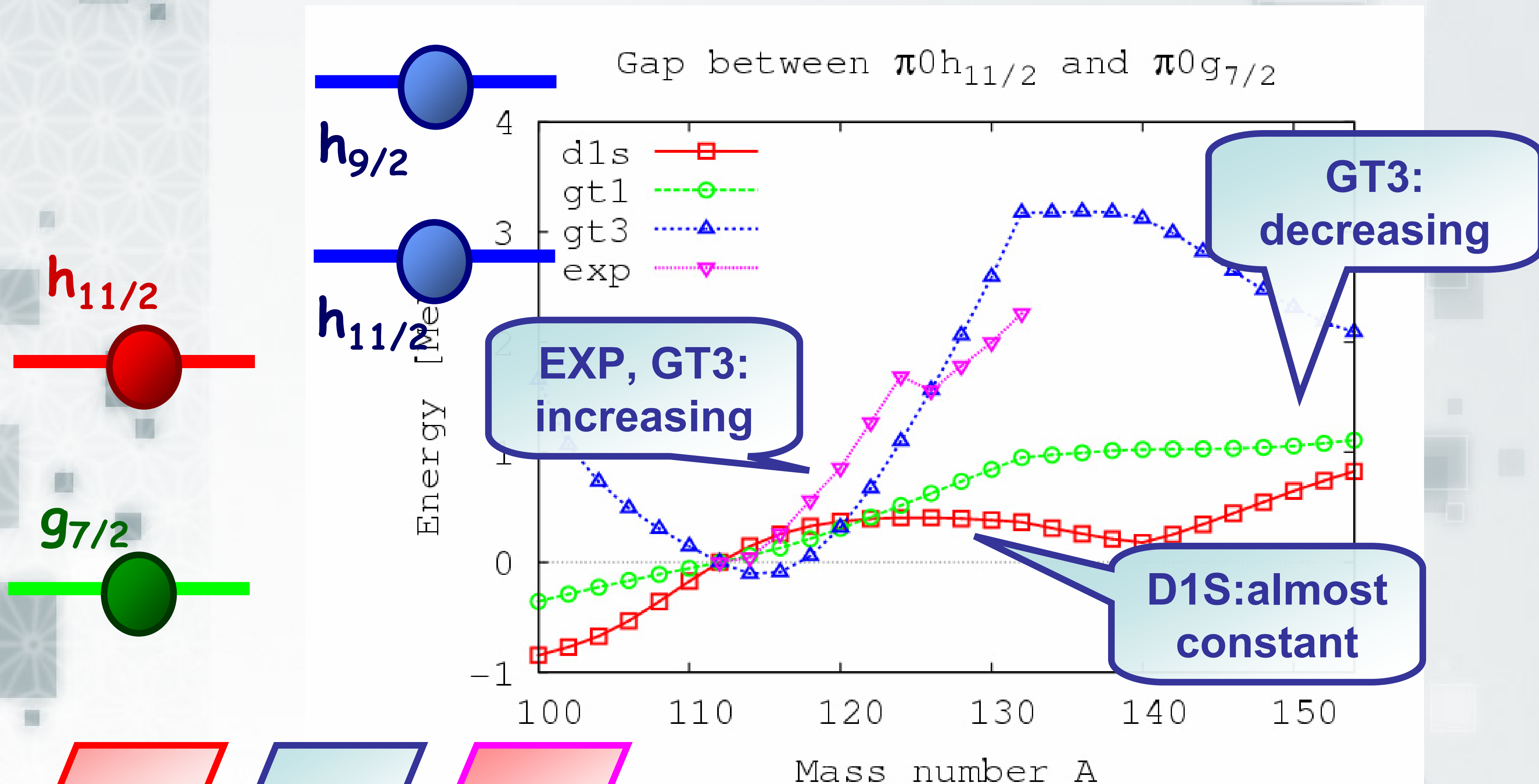
Proton single-particle energies of Ni isotopes, GT3

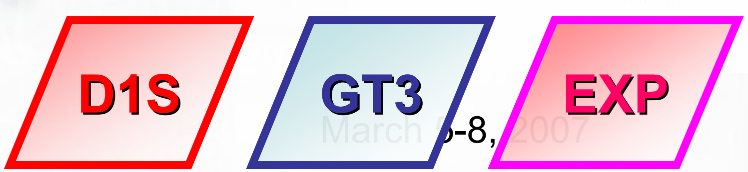
HF calc :T. Otsuka et al., PRL 97, 162501 (2006)



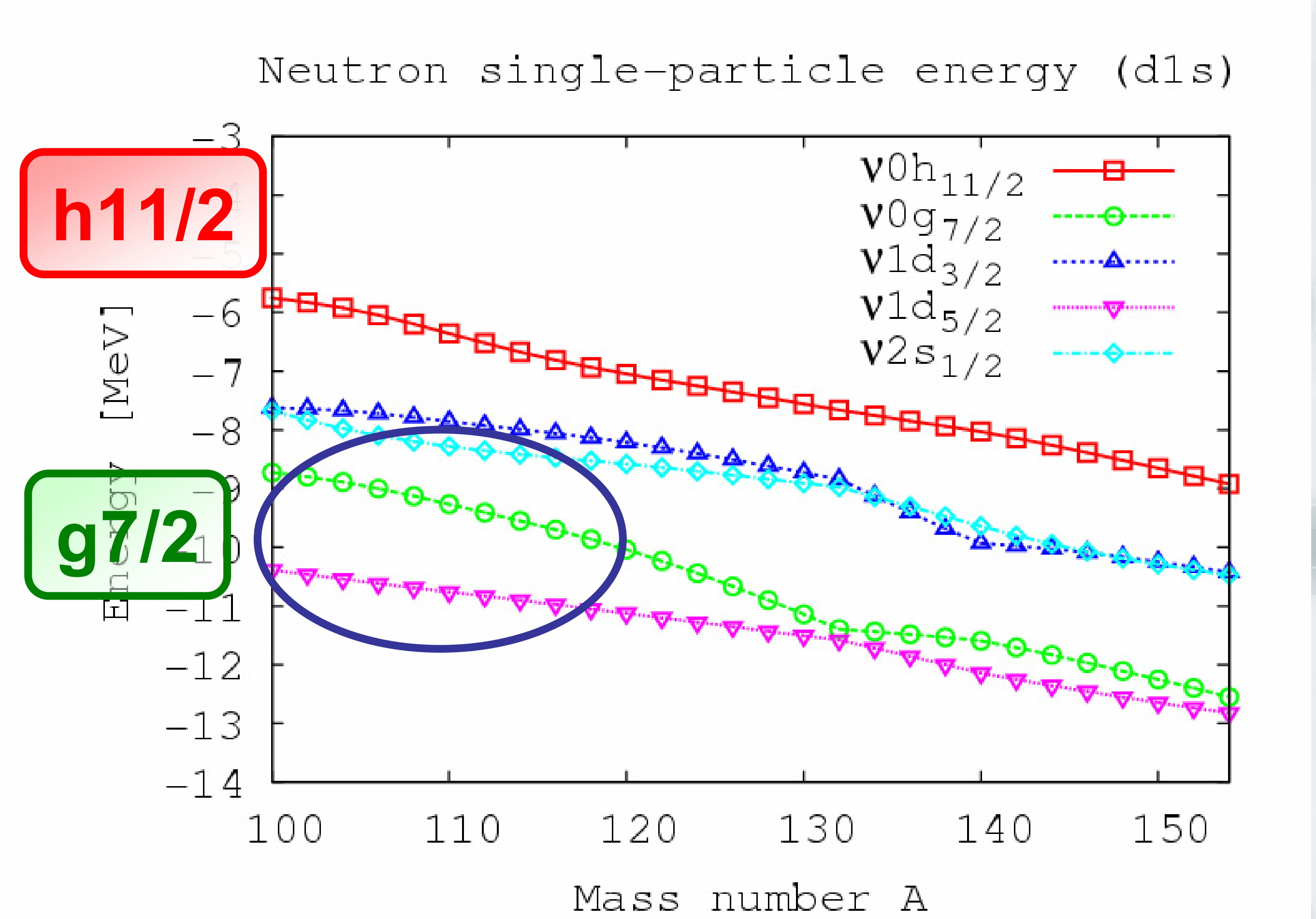
Sb isotopes

Exp: Schiffer et al., PRL 92, 16 (2004)

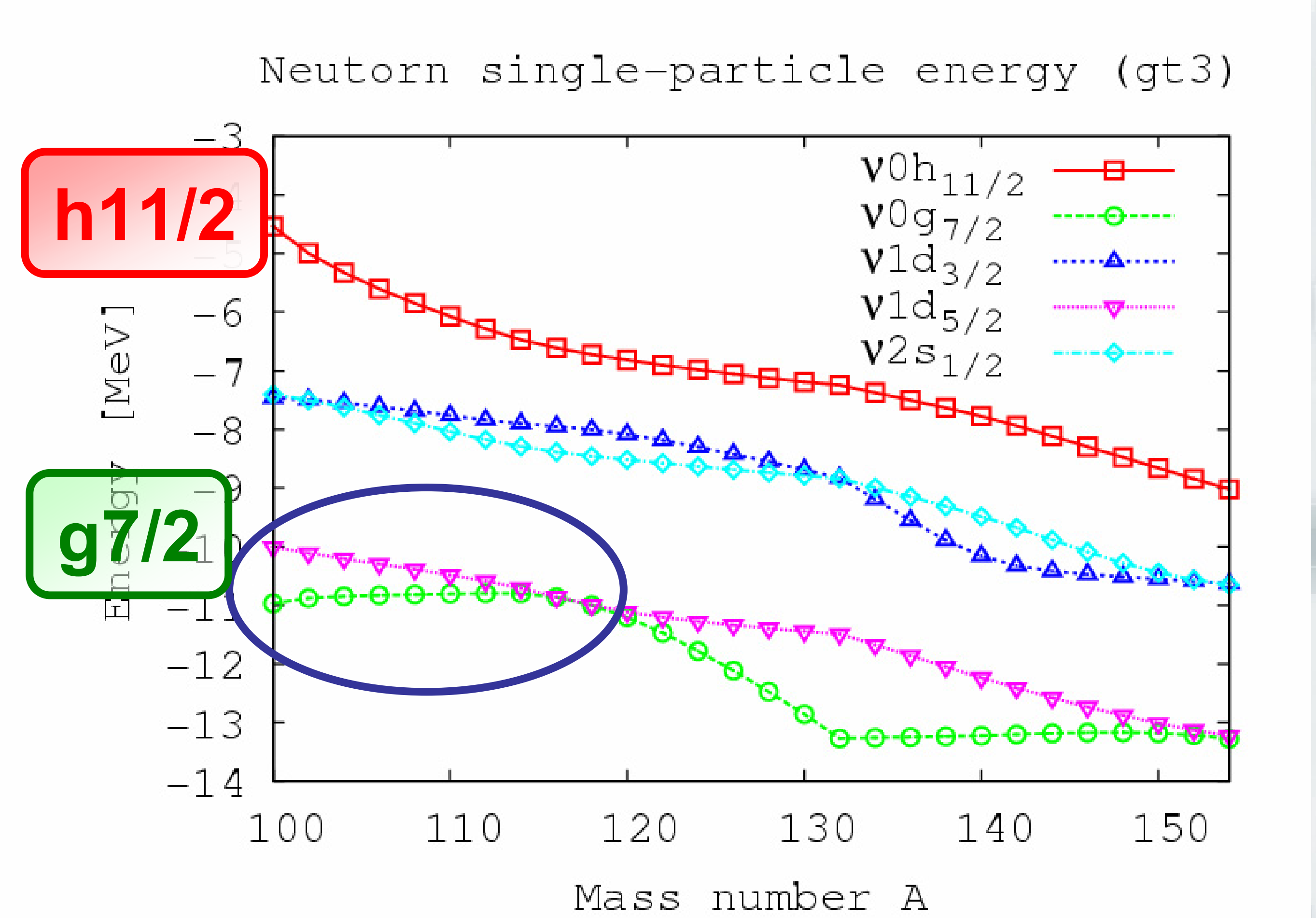




Neutron single-particle energies, D1S, Z=50

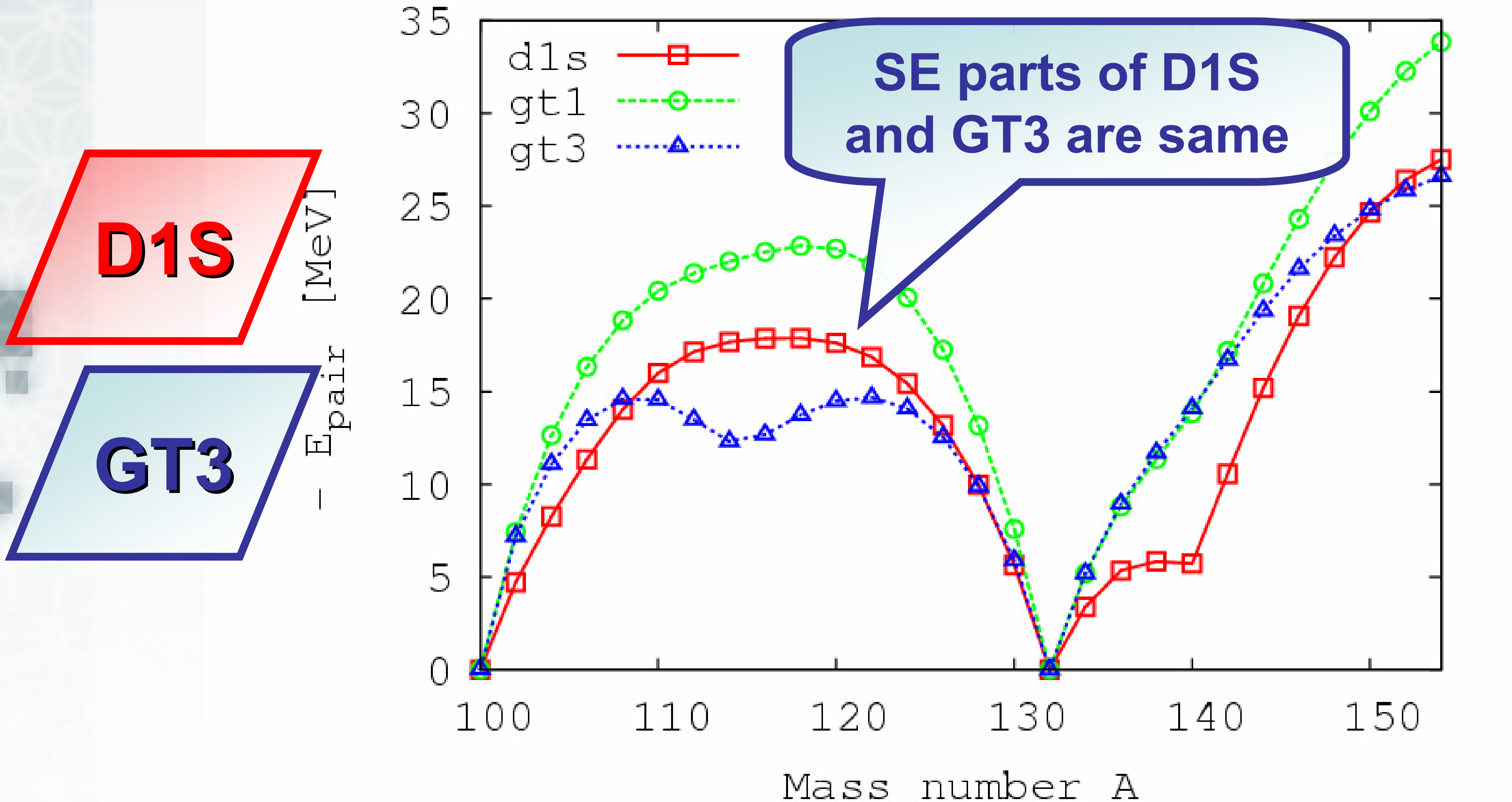


Neutron single-particle energies, GT3, Z=50



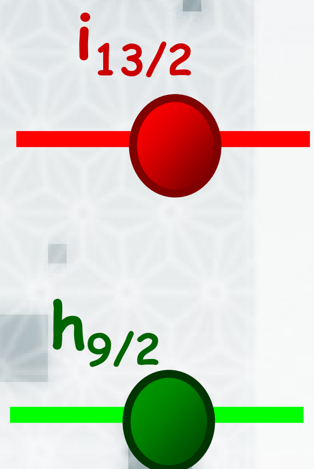
Pairing property (Sn, Z=50)

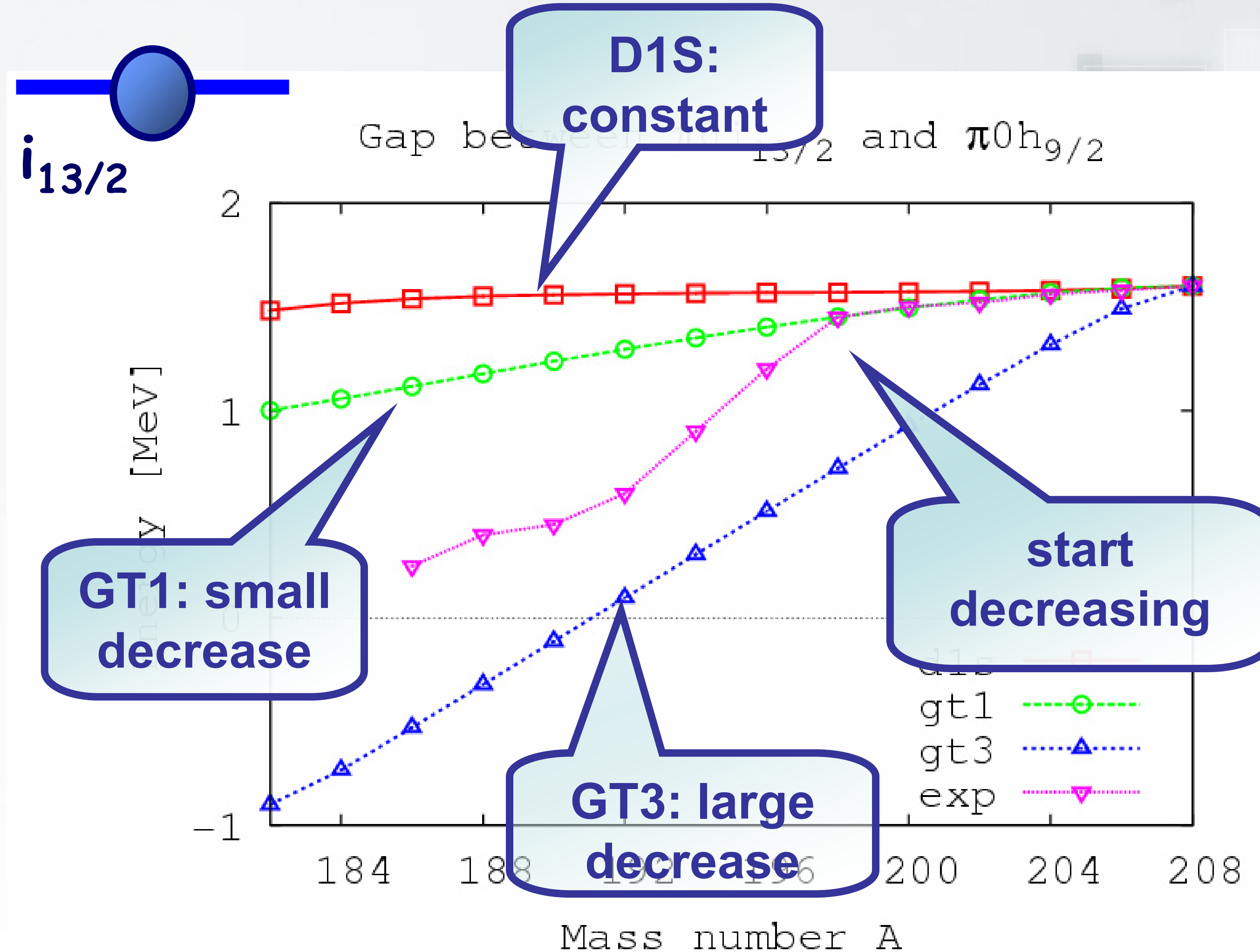
$$E_{pair} = -\frac{1}{2}\mathrm{Tr}\left(\Delta\kappa^*\right)$$



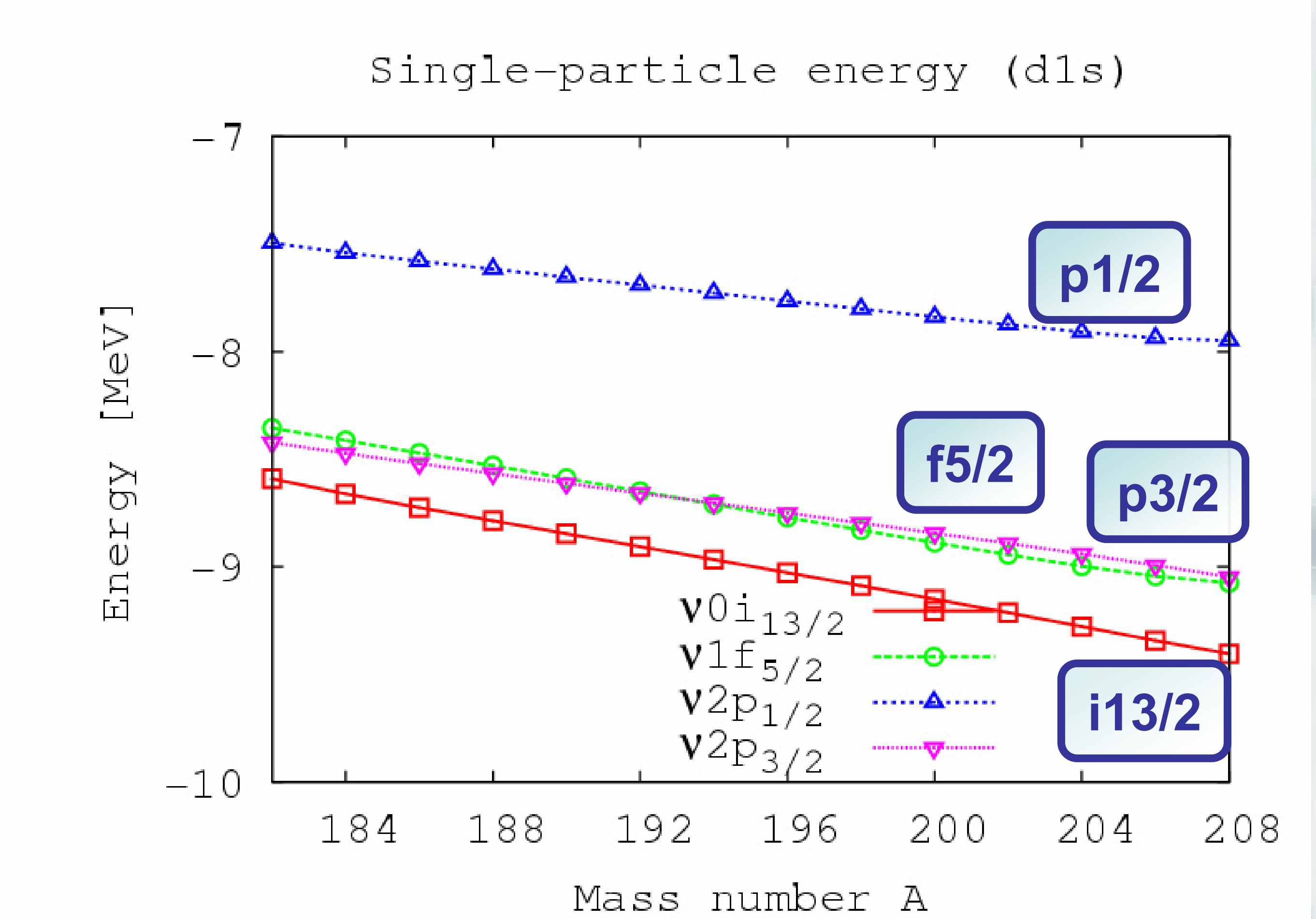
Bi isotopes

Exp: Eur. Phys. J 15, 329 (2002)

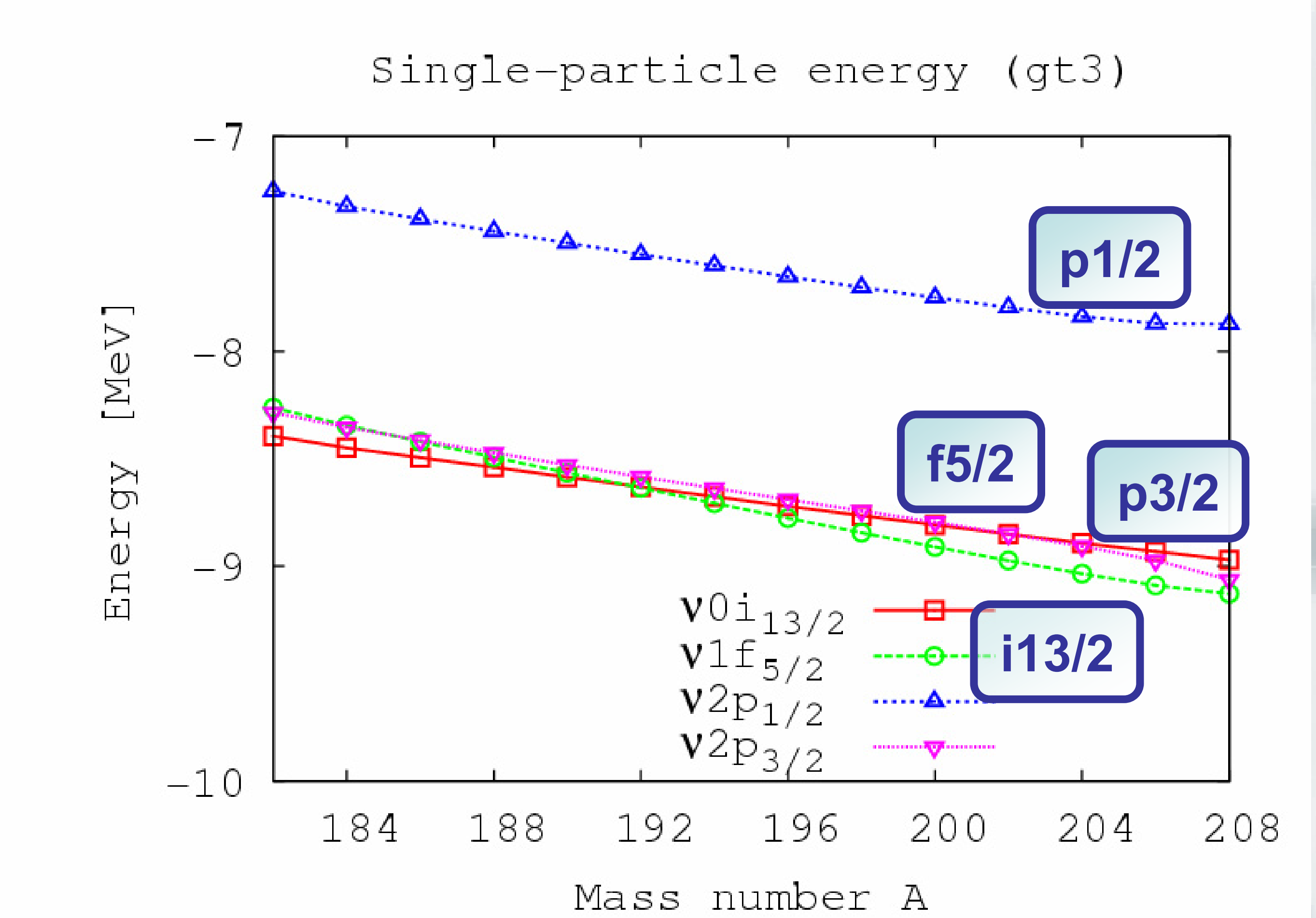




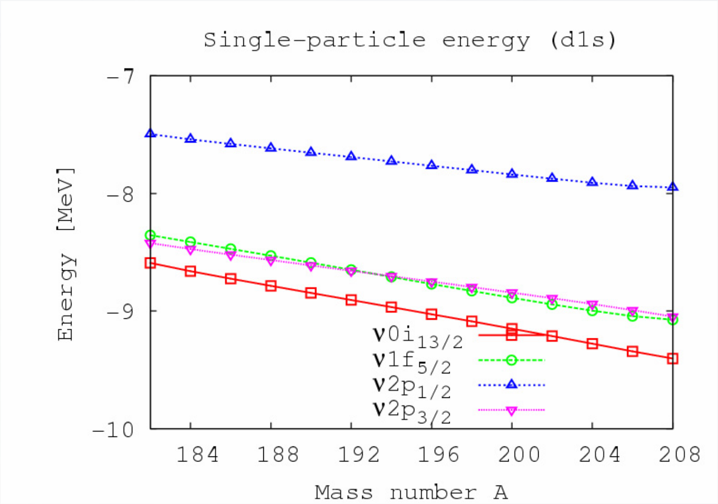
Neutron single-particle energy, D1S, Z=82

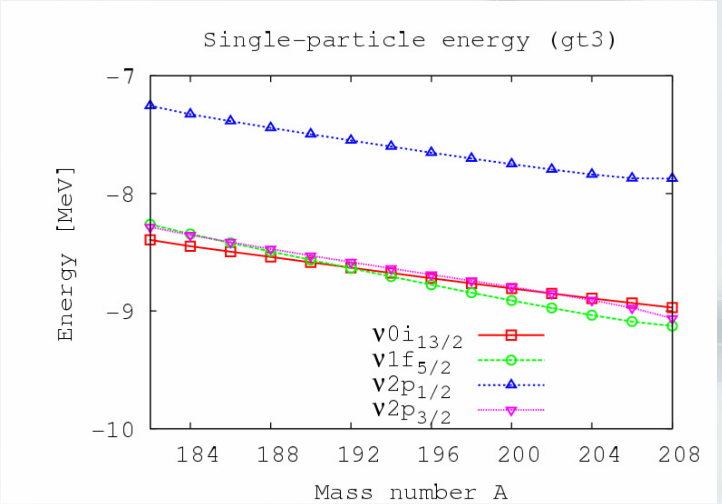


Neutron single-particle energy, GT3, Z=82



Single-particle energy, Z=82

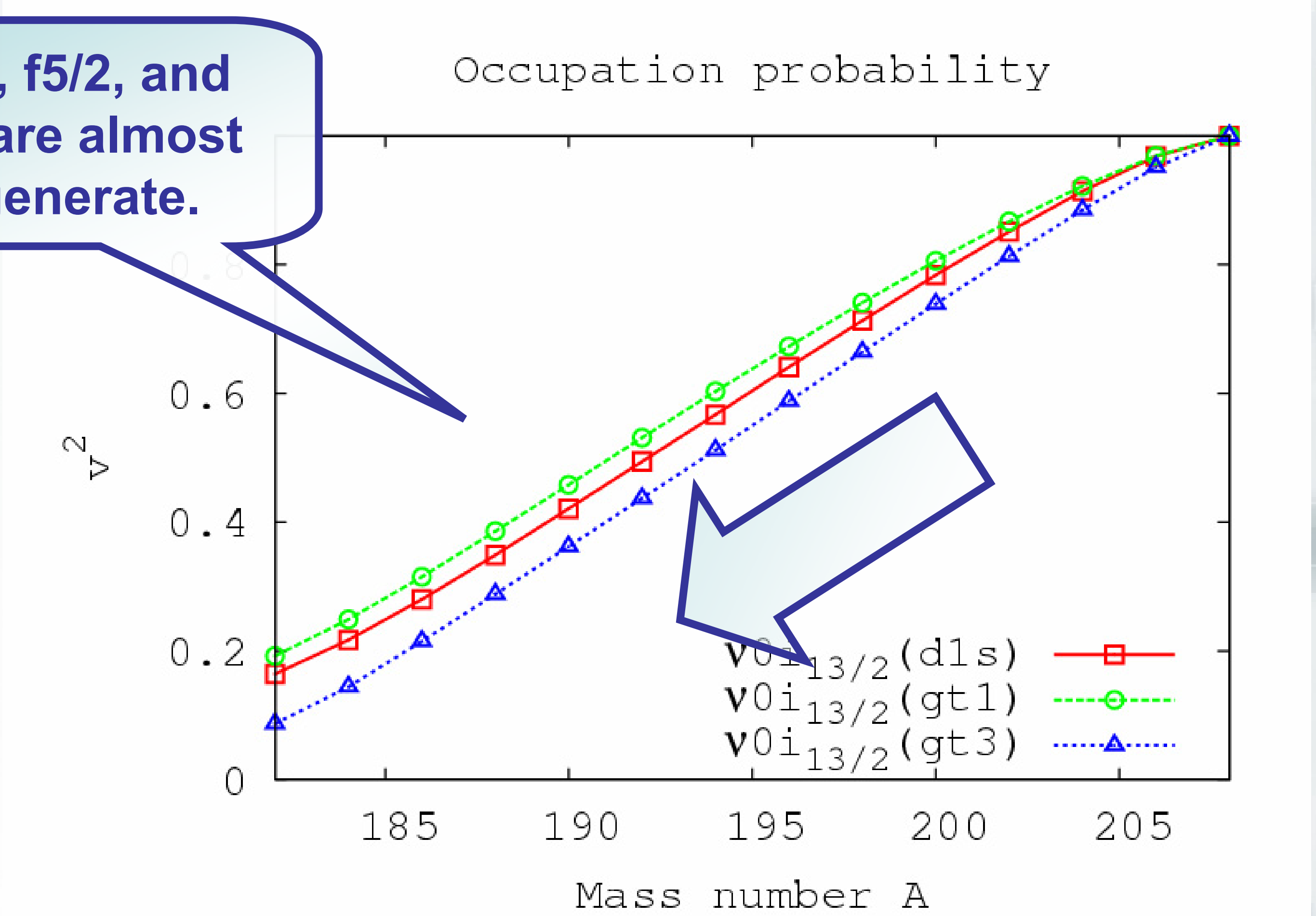




- i13/2, 1f5/2, and 2p3/2 are almost degenerate.
- This degeneracy produces inappropriate results of pairing property

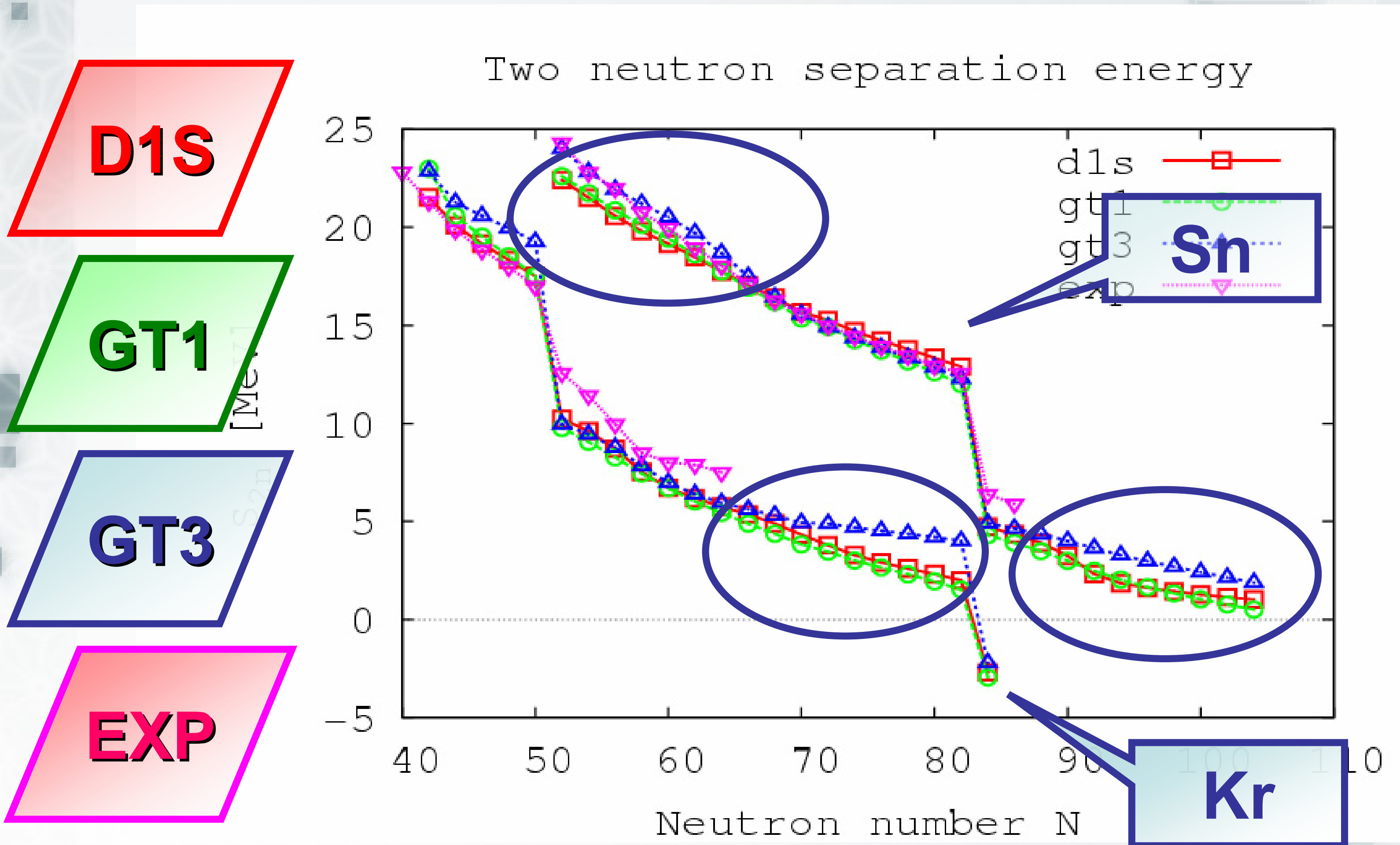
Occupation probability, Z=82

i13/2, f5/2, and p3/2 are almost degenerate.

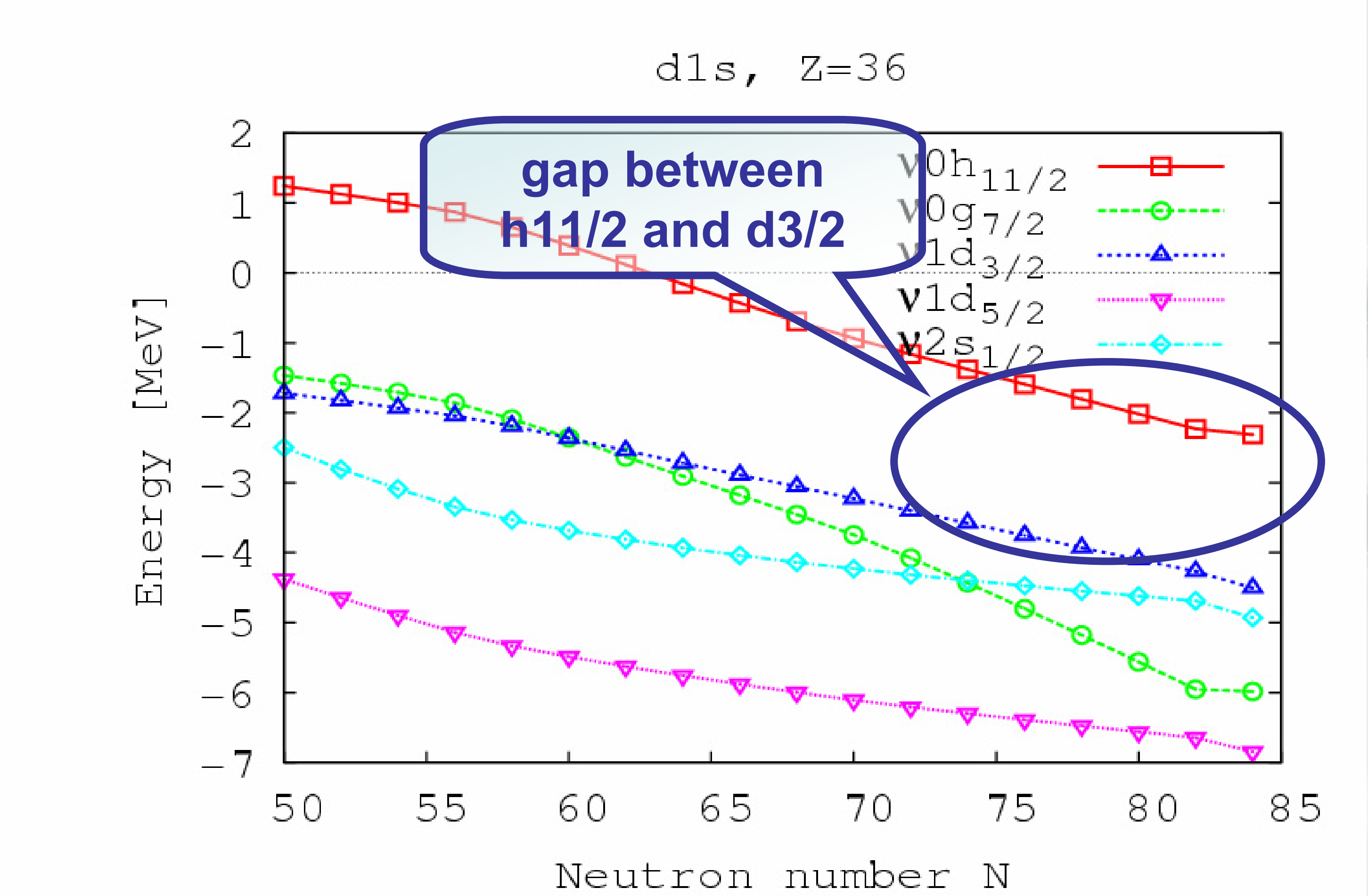


Two neutron separation energy

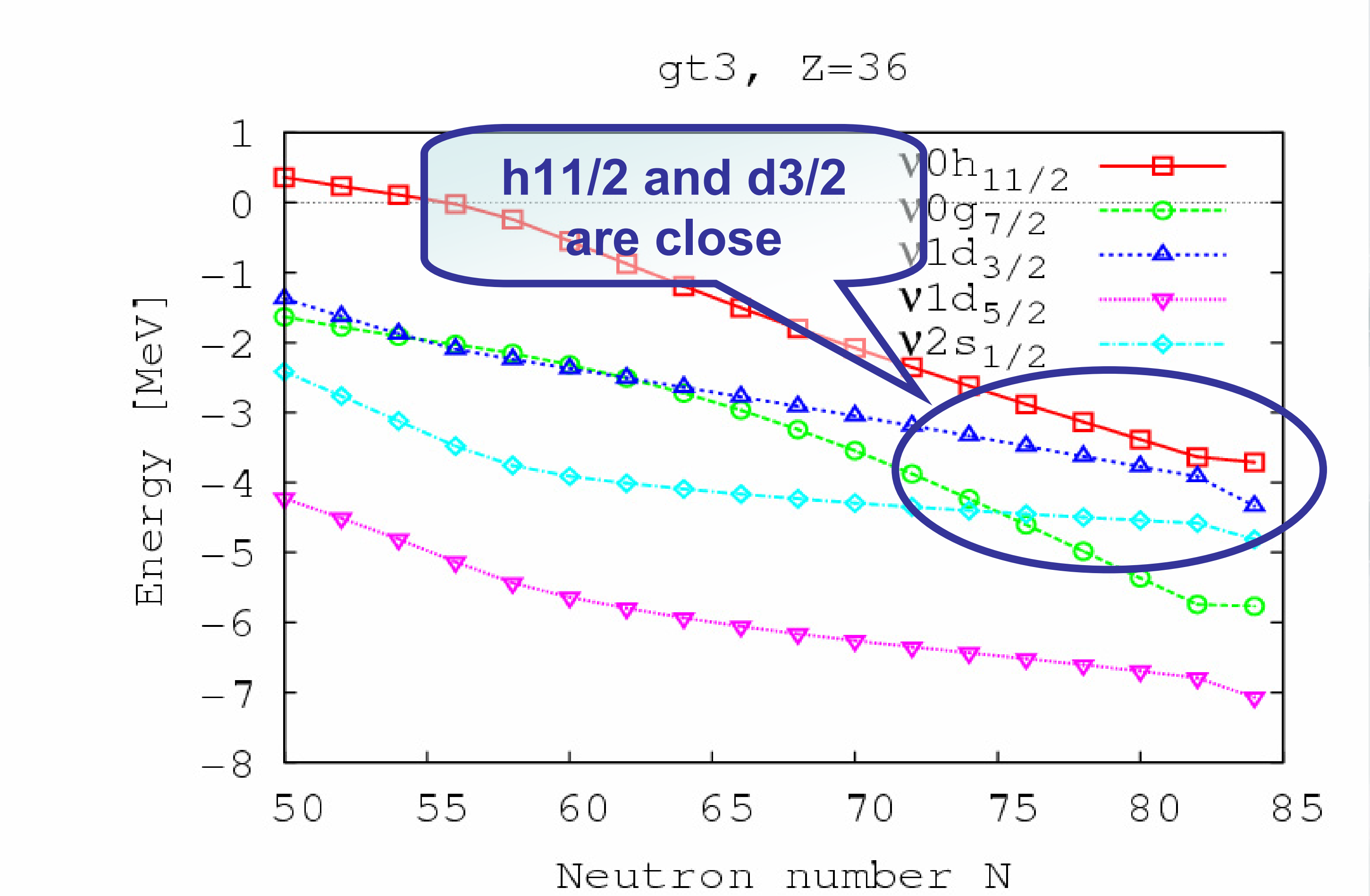
Exp: Audi et al., NPA 595, 409 (1995)



D1S, Kr isotopes



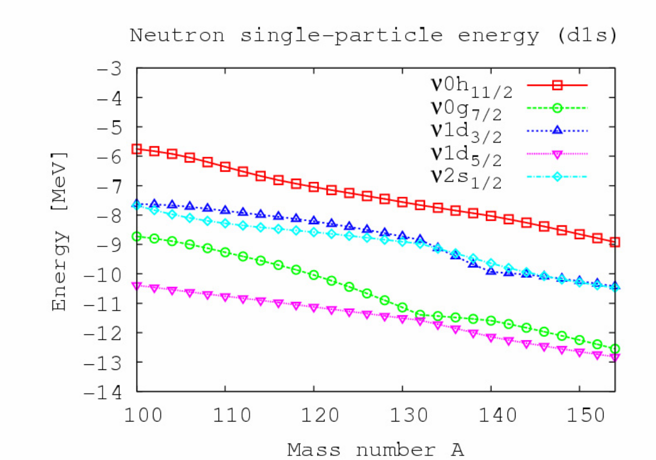
GT3, Kr isotopes

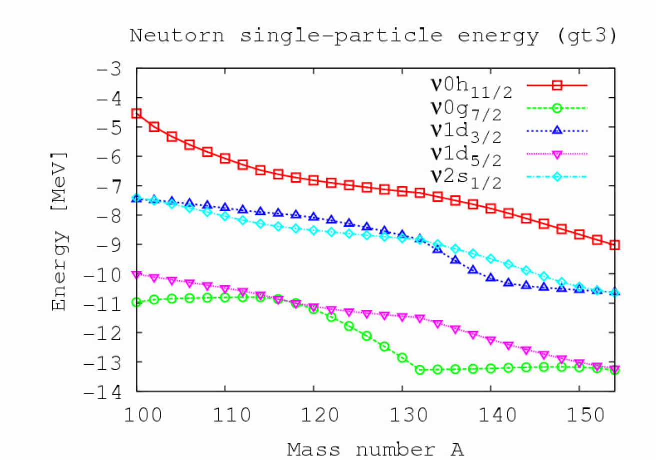


Summary

- We modified our new parameters including tensor force, considering appropriate pairing property of Sn isotopes.
- We can see influence of the tensor force on the pairing property of Sn isotopes.
- We re-examined the gap behavior of Ni and Sb isotopes using new parameters, GT3.
- In Bi isotopes, we can obtain similar trend as the experimental data, but we found some problems on single-particle levels.

Single-particle energies, Z=50





- Changing shell gaps.
- GT3 produces larger gap than D1S.
- Tensor-force effect can be seen.
  - Gap between $h_{11/2}$ and $g_{7/2}$