UNIVERSIDAD
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Tensor force in Gogny interactions

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ECT* Trento

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Work in colaboration with

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Outline

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1. Introduction

2. The method

3. Results

4. Summary and Conclusions

Introduction

- Tensor force is usually neglected in mean-field calculations.
- Otsuka *et al.* showed that shell evolution cannot be studied without tensor force
  Phys. Rev. Lett. **95**, 232502 (2005)
- They proposed a new parametrization for the Gogny force including a tensor-isospin term $\rightarrow$ GT2
  Phys. Rev. Lett. **97**, 162501 (2006)

μ (fm)	W (MeV)	B (MeV)	H (MeV)	M (MeV)
0.7	2311	-3480	2962	-2800
1.2	-339	388	-370	260
W_0=160 MeV fm^5		$x_0 = 1$		$\alpha = 1/3$

Introduction

In addition, GT2 interaction includes a tensor-isospin term

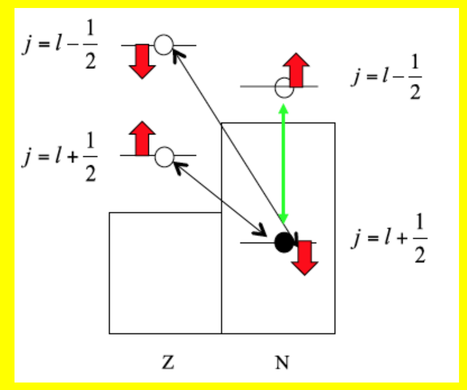
$$v_{\mathrm{T}} = F_{\mathrm{T}}\ \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\, 3 \left(\frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{r}_{12})(\boldsymbol{\sigma}_2 \cdot \mathbf{r}_{12})}{(\mathbf{r}_{12})^2} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \right) f_{\mathrm{G}}(r)$$

$f_{\mathrm{G}}(r) \Rightarrow$ a gaussian function with a range of 1.2 fm.

$F_{\mathrm{T}} = 50.795$ MeV $\Rightarrow$ to reproduce the volume integral of the AV8'

"Regarding the pairing interaction, a new aspect of GT2 is the contribution from the tensor force. Including this, we should refine the central part of GT2, examining pairing properties in addition to single-particle properties. The present work is focused on Hartree-Fock (HF) calculation, and pairing issues are left open for Hartree-Fock- Bogoliubov calculation to be done. Thus, there may be certain rooms for refinement of the parameters, but the GT2 interaction appears to be good enough for the present purpose,..." (from **Phys. Rev. Lett. 97, 162501 (2006))**

The Otsuka effect



H. Sagawa and G. Colò *et al.*, Prog. Part. Nucl. Phys. 76 (2014) 76

Examples:

- Energy difference between proton spin–orbit partners in ^{22}O
- GAP $Z = 8$ in ^{22}O: $\pi 1p_{1/2} \leftrightarrow \pi 1d_{5/2}$, filling of $\nu 1d_{5/2}$

The tensor interaction

- We have proposed different types of finite range tensor interactions onto D1S and D1M Gogny parametrizations.
- Different fits have been done in order to fix the free parameters in each case:
  1. Adding a tensor-isospin term, and modifying the strength of the spin-orbit term: D1ST
  2. Adding a pure tensor and tensor-isospin terms: D1ST2a, D1ST2b
  3. Adding a pure tensor, tensor-isospin and modifying the spin-orbit term: D1ST2c
- With these interactions, we have studied:

1. Binding and single particle energies in HF approximation.
2. Excitation states with DRPA and CRPA approximations.
3. Pairing properties using a HF+BCS model.

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Our Hartree-Fock (HF) approximation

- We considere as effective nucleon-nucleon interaction a finite-range two-body force of the type:

$$V(\vec{r_1}, \vec{r_2}) = \sum_{p=1}^{6} V_p(\vec{r_1}, \vec{r_2}) O_p(1,2) + V_{\mathrm{SO}}(\vec{r_1}, \vec{r_2}) + V_{\mathrm{DD}}(\vec{r_1}, \vec{r_2}) + V_{\mathrm{Coul}}(\vec{r_1}, \vec{r_2})$$

- $O_p(1,2)$ indicates $\mathbb{1}$, $\vec{\tau_1} \cdot \vec{\tau_2}$, $\vec{\sigma_1} \cdot \vec{\sigma_2}$, $\vec{\sigma_1} \cdot \vec{\sigma_2}\, \vec{\tau_1} \cdot \vec{\tau_2}$, S_{12}, $S_{12}\, \vec{\tau_1} \cdot \vec{\tau_2}$.
- V_{SO} and V_{DD}, terms of zero-range.
- We solve, in coordinate space, a set of equations of the type:

$$-\frac{\hbar^2}{2m_k} \nabla_1^2 \phi_k(\vec{r_1}) + U(\vec{r_1})\phi_k(\vec{r_1}) - \int d^3 r_2 W(\vec{r_1}, \vec{r_2}) \phi_k(\vec{r_2}) = \epsilon_k \phi_k(\vec{r_1})$$

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Our Hartree-Fock (HF) approximation: Numerical procedure

JOURNAL OF COMPUTATIONAL PHYSICS **45**, 374–389 (1982)

On the Numerical Integration of the Schrödinger Equation in the Finite-Difference Schemes

R. GUARDIOLA

Departamento de Física Nuclear,
Universidad de Granada, Granada, Spain

AND

J. ROS

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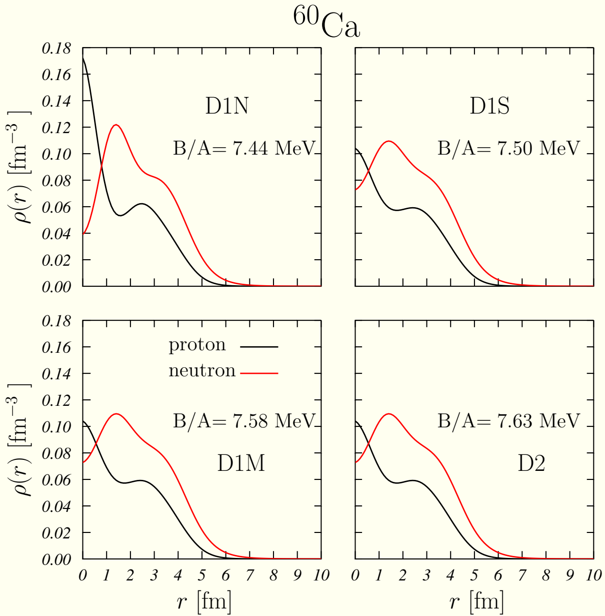
Received August 14, 1981

Formulae for the integration of the Schrödinger equation for bound states based on the scheme of central differences are generated from the Taylor expansion with the help of formal Padé approximants. These methods are studied in matrix form, and a limiting formula—the best for a given discretization—is obtained.

Our Hartree-Fock (HF) approximation: an example



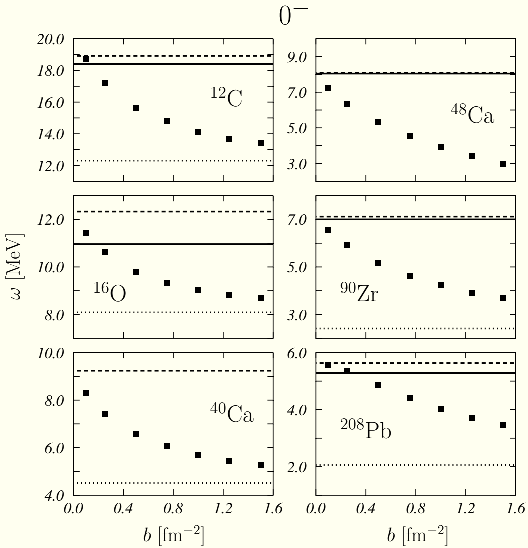
Fit of the D1ST interaction

$$v_{6,b}(r) = v_{6,AV18}(r)\left(1 - e^{-br^2}\right)$$

$$V_6(q)S_{12}(\mathbf{q}) = \int d^3r e^{i\mathbf{q}\cdot\mathbf{r}} v_6(r)S_{12}(\mathbf{r}) = -4\pi \int drr^2 j_2(qr)v_6(r)S_{12}(\mathbf{r})$$

Fit of the tensor force: D1ST

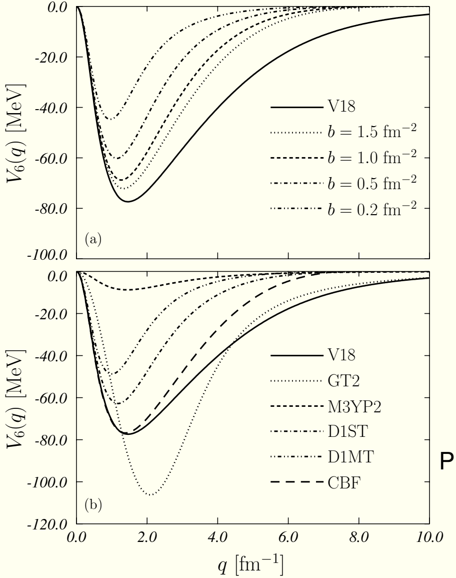
Energies of the first 0^- states



- Fit for ^{16}O: $E(0^-)$=10.96 MeV
- **D1ST** b=0.6 fm^{-2}, W_0=134 MeV
- **D1MT** b=0.25 fm^{-2}, W_0=122.5 MeV

Phenomenological RPA with LM + $v_{6,b}(r)$

Fit of the D1ST interaction



CBF from:

F. Arias de Saavedra, C. Bisconti, G. Co' and A. Fabrocini

Phys. Rep. 450 (2007) 450

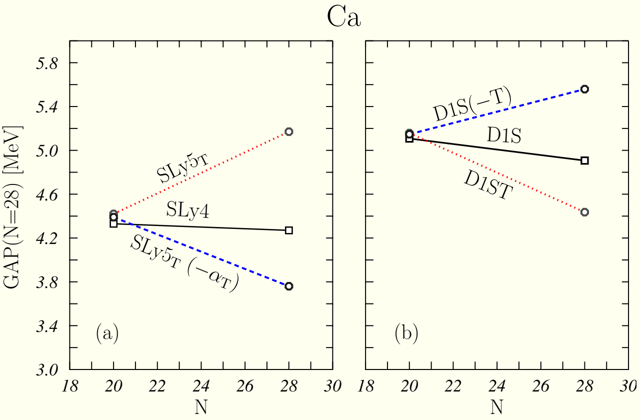
M3YP2 force from:

H. Nakada

Phys. Rev. **C68**, 014316 (2003)

Fit of the tensor force: D1ST2a

- Experimentally, the difference between the energies of the single-particle neutron $2p_{3/2}$, $1f_{7/2}$ states increases from ^{40}Ca to ^{48}Ca (O. Sorlin and M.-G. Pourquet, Prog. Part. Nucl. Phys. **61**, 602 (2008))



M. A, M. Grasso, G. Co', V. De Donno and A.M. Lallena, Phys. Rev. **C86**, 054302 (2012)

Fit of the tensor force D1ST2a

N. Onishi and J.W. Negele, NPA301 (1978), 336

$$V_{\rm tensor}(\vec{r}_1,\vec{r}_2) = (V_{T1} + V_{T2}\,P^{\tau}_{12})\;S_{12}\,e^{-(r_1-r_2)^2/\mu_T^2}$$
$$= \left[\left(V_{T1} + \frac{1}{2}V_{T2}\right) + \frac{1}{2}V_{T2}\,\boldsymbol{\tau}(1)\cdot\boldsymbol{\tau}(2)\right] S_{12}\;e^{-(r_1-r_2)^2/\mu_T^2}$$

D1ST2a $\rightarrow$ neutron $1f$ splitting in ^{48}Ca and 0^- state of ^{16}O:

$V_{T1} = -135$ MeV, $V_{T2} = 115$ MeV, $\mu_{\rm T} = 1.2$ fm

D1MT2a $\rightarrow$ neutron $1f$ splitting in ^{48}Ca and 0^- state of ^{16}O:

$V_{T1} = -310$ MeV, $V_{T2} = 260$ MeV, $\mu_{\rm T} = 1.0$ fm

Fit of the tensor force D1ST2c

Following the strategy of Zalewski *et al.*, Phys. Rev. **C77**, 024316 (2008):

D1ST2c → neutron $1f$ splitting in ^{40}Ca, ^{48}Ca and ^{56}Ni

1. First, we fit the splitting $1f$ in ^{40}Ca by modifying the spin-orbit parameter W_{LS},
2. second, we fit the splitting $1f$ in ^{48}Ca adjusting the like-particle part of the Gogny tensor term, $V_{T1} + V_{T2}$, and
3. finally, we use the ^{56}Ni to fit the neutron-proton contribution of the tensor term, V_{T2} [1].

$$W_{\mathrm{LS}} = 103 \text{ MeV fm}^5, \quad V_{T1} = -135 \text{ MeV}, \quad V_{T2} = 60 \text{ MeV}$$

D1MT2c → following the same procedure, and using D1M as starting point we have fit another interaction

$$W_{\mathrm{LS}} = 95 \text{ MeV fm}^5, \quad V_{T1} = -175 \text{ MeV}, \quad V_{T2} = 40 \text{ MeV}$$

[1] M. Grasso and M. A, Phys. Rev. **C88**, 054328 (2014)

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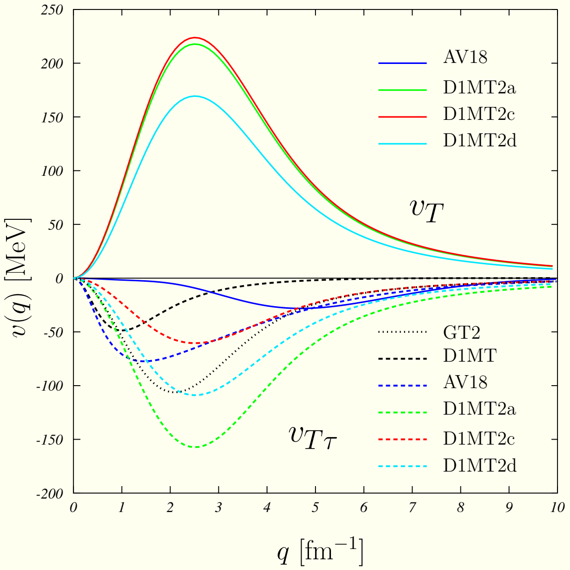
Tensor term in the pure and isospin channels



Discrete RPA: 0^- states

	exp	D1S	D1ST	D1M	D1MT	D1MT2c
^{12}C	18.40	19.63	14.42	18.83	15.27	
^{16}O	10.96	13.95	10.94	13.08	10.96	14.22
^{40}Ca	10.78	12.22	9.57	11.56	9.60	12.81
^{48}Ca	8.05	14.10	11.63	12.85	11.26	12.95
^{208}Pb	5.28	8.27	7.93	8.24	7.92	8.24

M. A, G. Co', V. De Donno and A.M. Lallena, Phys. Rev. **C83** (2011) 064306

Exp. values:

A. Heusler *et al.* Phys. Rev. **C75** (2007) 024312

http://www.nndc.bnl.gov/

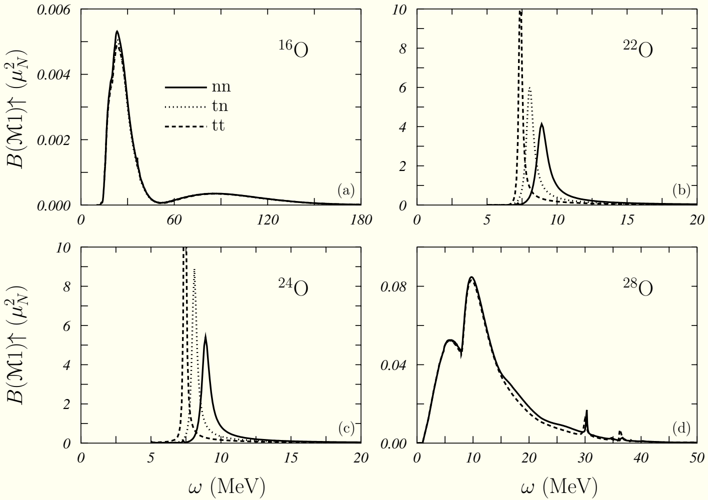
Discrete RPA: 1^+ excitations in $N \neq Z$ nuclei

First 1^+ state in ^{208}Pb

	E(1_1^+) [MeV]	$B(M1)_1$ [μ^2_n]
exp	5.85	2.00
D1S	7.80	5.08
D1ST	4.76	2.41
D1M	6.50	2.33
D1MT	4.82	1.80

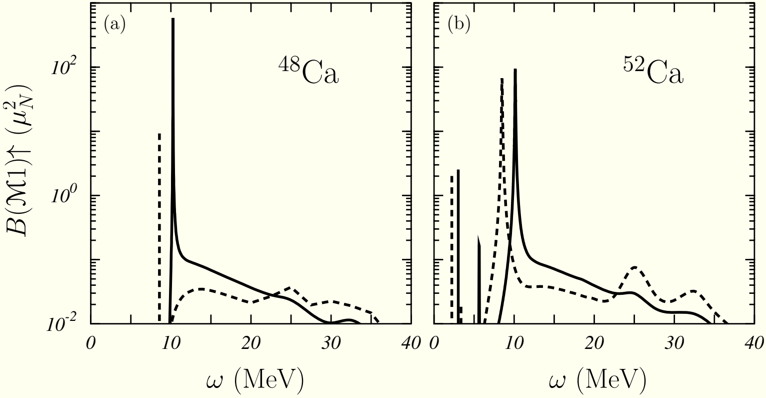
M.A, G. Co', V. De Donno and A.M. Lallena, Phys. Rev. **C83** (2011) 064306

CRPA: Magnetic dipole response in O isotopes



main p-h excitation $\Rightarrow$ $[(\nu 1d_{3/2})(\nu 1d_{5/2})^{-1}]$

CRPA: Magnetic dipole response in Ca isotopes



main p-h excitation $\Rightarrow$ $[(\nu 1f_{5/2})(\nu 1f_{7/2})^{-1}]$

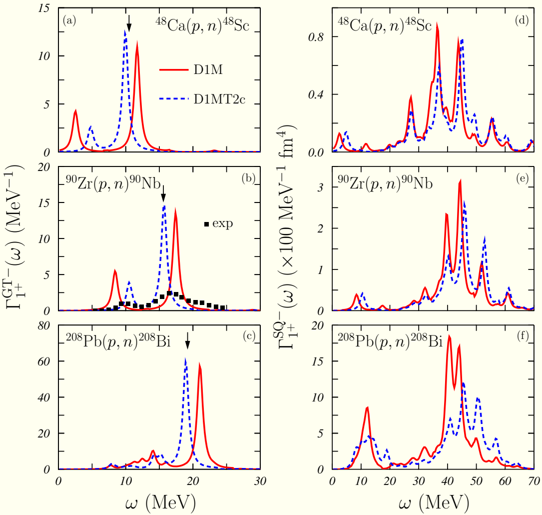
E(1^+): 10.23 MeV (EXP) 10.15 MeV (D1S) 8.56 MeV (D1ST)

Charge exchange (DRPA): 1^+ GT and SQ

$$\mathcal{Q}^{\mathrm{GT}\pm}_{1^+,M} = \sqrt{4\pi} \sum_{i=1}^{A} [Y_0(i) \otimes \boldsymbol{\sigma}(i)]^1_M \, t_\pm(i)$$

$$\mathcal{Q}^{\mathrm{SQ}\pm}_{1^+,M} = \sum_{i=1}^{A} r_i^2 \, [Y_2(i) \otimes \boldsymbol{\sigma}(i)]^1_M \, t_\pm(i)$$

Charge exchange (DRPA): 1^+ GT and SQ



V. De Donno *et al.*, Phys. Rev. **C90**, 024326 (2014)

Charge exchange CRPA: Spin Dipole excitation (SD)

$$\mathcal{Q}^{\mathrm{SD}\pm}_{J^-,M} = \sum_{i=1}^{A} r_i \left[Y_1(i) \otimes \boldsymbol{\sigma}(i)\right]^J_M t_\pm(i)$$

which excites the multipoles 0^-, 1^- and 2^-. We calculate the strength functions corresponding to each individual multipolarity and also

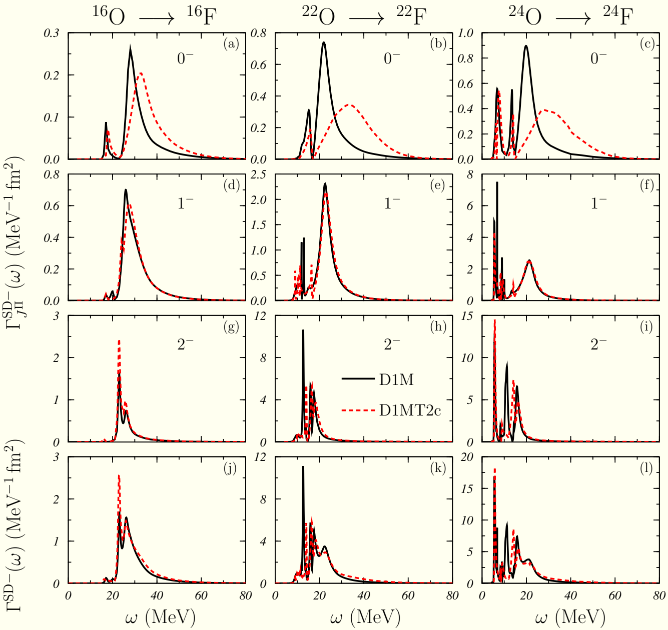
$$\Gamma^{\mathrm{SD}\pm}(\omega) = \sum_{J^\Pi=0^-,1^-,2^-} \Gamma^{\mathrm{SD}\pm}_{J^\Pi}(\omega) .$$

that is the total SD strength.

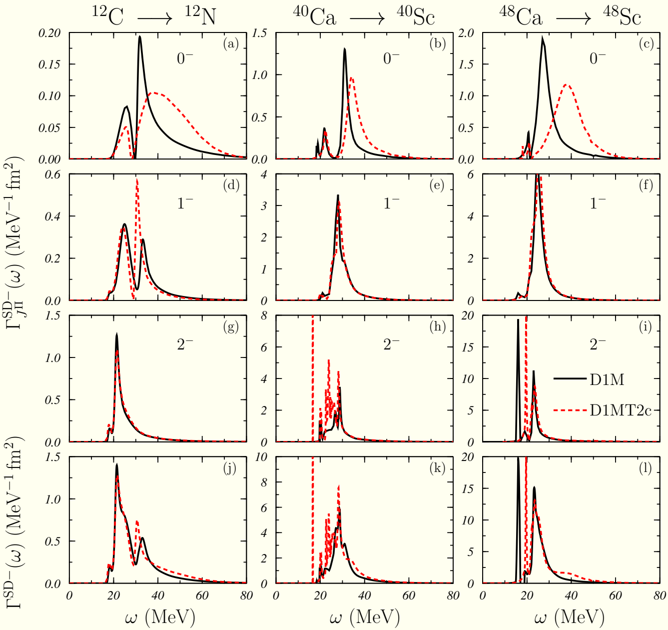
- Tensor force moves the peak of the resonance toward higher energies and a larger spreading of the 0^- width,

V. De Donno *et al.*, Phys. Rev. **C93**, 034320 (2016)

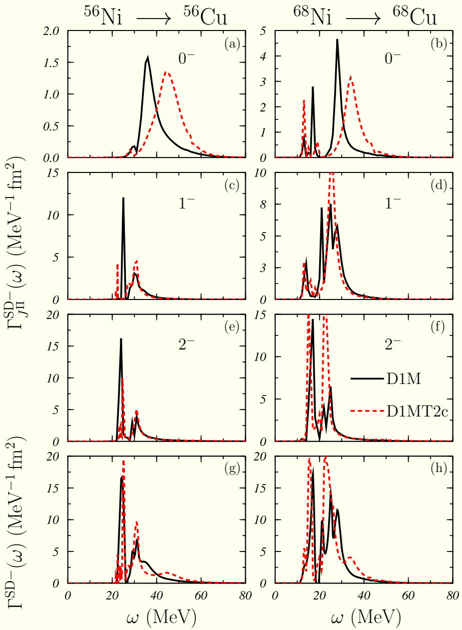
Charge exchange CRPA: Spin Dipole excitation (SD)



Charge exchange CRPA: Spin Dipole excitation (SD)



Charge exchange CRPA: Spin Dipole excitation (SD)



Charge exchange CRPA: Spin Dipole excitation (SD)

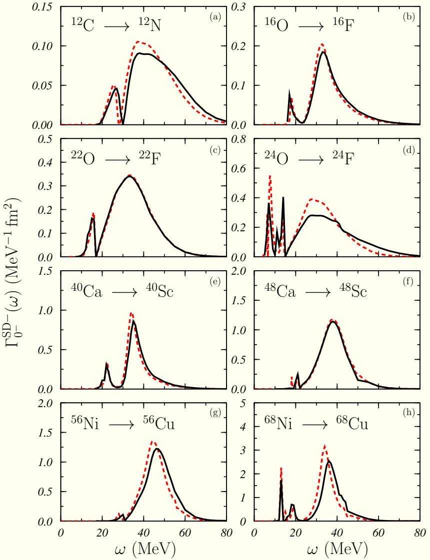


Figure: Dashed red curves correspond to the D1MT2c force. Solid black lines were obtained by using the D1M s.p. wave functions and the D1MT2c interaction in CRPA.

Splitting in ^{40}Ca, ^{36}S and ^{34}Si: $N = 20$

- ^{40}Ca: filled until $1d_{3/2}$
- ^{36}S: filled until $2s_{1/2}$ $\rightarrow$ proton state $1d_{3/2}$ is empty.
- ^{34}Si: filled until $1d_{5/2}$ $\rightarrow$ proton states $1d_{3/2}$ and $2s_{1/2}$ are empty

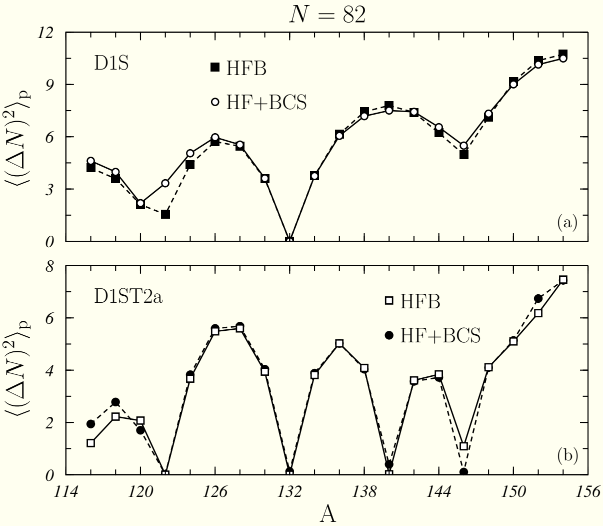
Tensor induced and pure spin-orbit effects

	From ^{40}Ca to ^{36}S (tensor)	From ^{36}S to ^{34}Si (spin orbit)
Splitting	**D1S**	**D1S**
neutron $2p$	13%	43%
	D1ST2a	**D1ST2a**
neutron $2p$	40%	39%
	D1ST2c	**D1ST2c**
neutron $2p$	27%	42%

Reductions of the neutron $2p$ splitting.

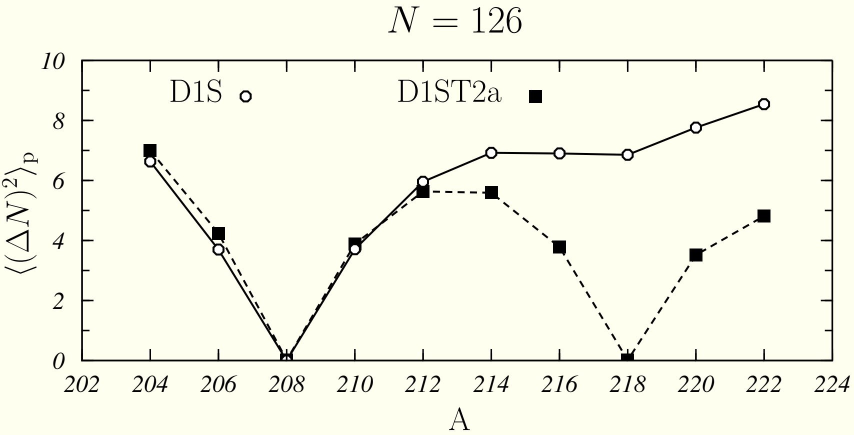
M. Grasso and M. A, Phys. Rev. **C92**, 054216 (2015)

Interplay between tensor force and pairing correlations



M. A, R.N. Bernard, A.M. Lallena, G. Co' and V. De Donno, Nucl. Phys. **A955**, 181 (2016)

Interplay between tensor force and pairing correlations



Interplay between tensor force and pairing correlations

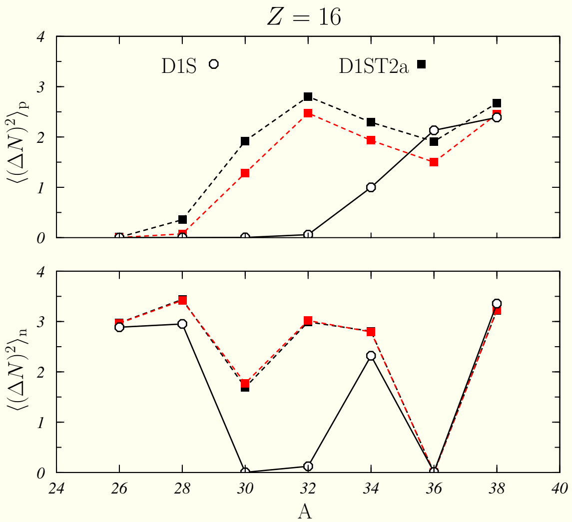


Figure: Red squares: Considering the tensor and Coulomb terms in the pairing interaction.

Interplay between tensor force and deformation

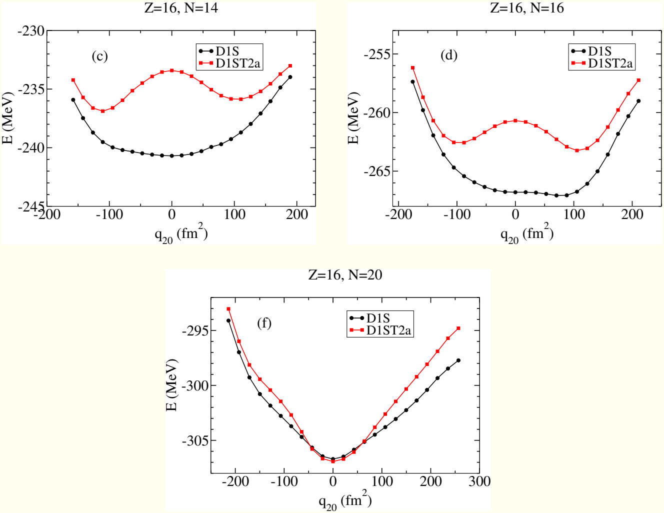


Figure: Potential Energy Curves for ^{30}S, ^{32}S and ^{36}S (from R. Bernard and M. A, Nucl. Phys. **A953**, 32 (2016))

Interplay between tensor force and deformation

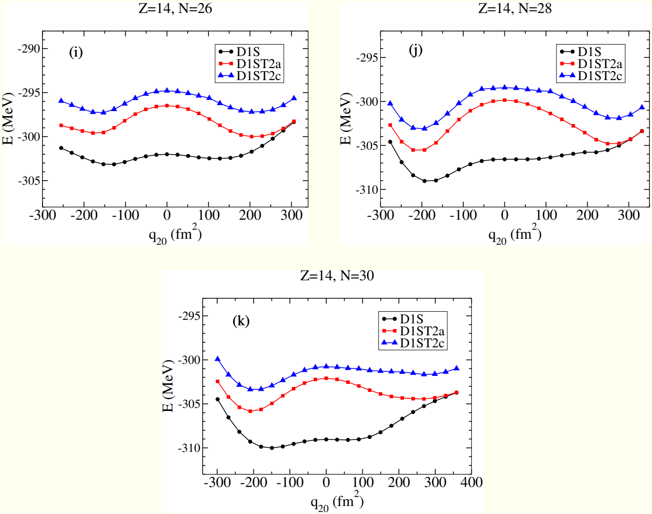


Figure: Potential Energy Curves for ^{40}Si, ^{42}Si and ^{44}Si (from R. Bernard and M. A, Nucl. Phys. **A953**, 32 (2016))

Summary and Conclusions

1. Tensor interaction cannot be neglected in the description of shell evolution
2. A finite range tensor force with two channels (pure and isospin terms) has been proposed to be added in the traditional Gogny interaction (D1S and D1M).
3. We have done different fits for this force, considering some observables very sensitive to this part of the interaction:
   - Neutron splitting $1f_{7/2} - 1f_{5/2}$ for ^{40}Ca, ^{48}Ca and ^{56}Ni nuclei.
   - Energy of the first 0^- state in ^{16}O
4. Using these interactions (D1ST, D1ST2a, D1ST2c) including the tensor force, we have analyzed its contribution to some ground state properties and excitations. Our findings reveal that we could have an important effect in the study of:
   - Neutron $2p$ splitting in ^{36}S
   - 1^+ excitation
   - Charge exchange excitations: 1^+ GT and SD in the continuum
   - Deformation (in particular, ^{30}S and ^{32}S)
5. Next step: to do a global fit for the Gogny force, including the tensor interaction $\rightarrow$ HOW?

Summary and Conclusions

- We have isolated the like-particle contribution ($V_{T1} + V_{T2}$) and the unlike-particle one (V_{T2}).
- For all the interactions we have fitted until now, the sign of $V_{T1} + V_{T2}$ is negative and that of V_{T2} is positive.
- From the fit based in SNM (D. Davesne *et al*, PRC93, 064001 (2016)):

$$V_{T1} + V_{T2} = 82.3\,\mathrm{MeV} \quad V_{T2} = 177.9\,\mathrm{MeV}$$

- Why this discrepancy in the sign of $V_{T1} + V_{T2}$?

D1MT2d

$W_{LS} = 115.36$ MeV fm^5
$V_{T1} = -230$ MeV
$V_{T2} = 180$ MeV

We obtain:

$E(0^-)$ for ^{16}O $\rightarrow 11.5$ MeV (10.96 MeV exp.)
$E(0^-)$ for ^{48}Ca $\rightarrow 7.9$ MeV (8.05 MeV exp.)
$E(0^-)$ for ^{40}Ca $\rightarrow 10.01$ (10.78 MeV exp.)
Neutron splitting $1f_{7/2} - 1f_{5/2}$ for ^{48}Ca $\rightarrow$ 8.8 MeV, like exp.)
Neutron splitting $1f_{7/2} - 1f_{5/2}$ for ^{56}Ni $\rightarrow$ 5.9 MeV, 7.1 MeV exp.).