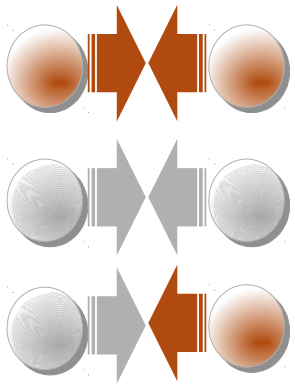
Mirror Energy Difference in sd shell

Dmitry Testov Alberto Boso Silvia Monica Lenzi Francesco Recchia

Charge invariance and isospin

The strong interaction of protons and neutrons is largely independent of their charge

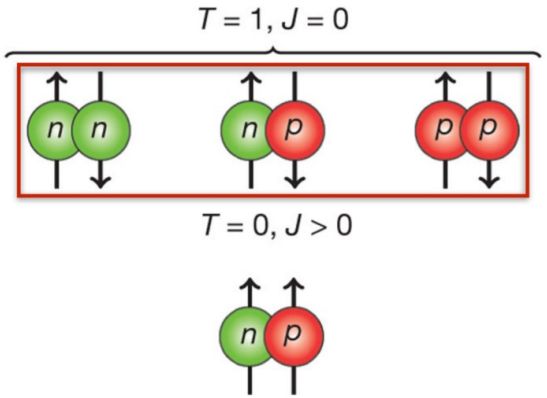


Charge Symmetry: $V_{pp} = V_{nn}$

Charge Independence: $V_{pp} = V_{nn} = V_{pn}$

Proton and neutron can be viewed as two states of the same particle (the **nucleon**) characterized by the isospin quantum Number

Proton: $t_z = -1/2$ Neutron: $t_z = +1/2$

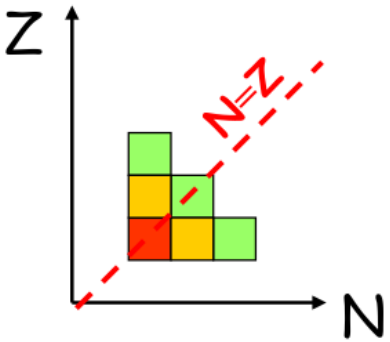


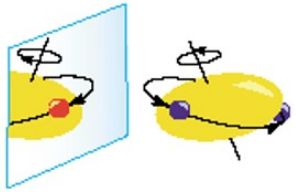
$$T_z = \sum_{i=1}^{A} t_{z,i} = \frac{N-Z}{2}$$

$$\left|\frac{N-Z}{2}\right| \leq T \leq \frac{N+Z}{2}$$

Differences in analogue excited states

Isospin symmetry is based on the fundamental assumptions of charge symmetry and charge independence of the strong force.

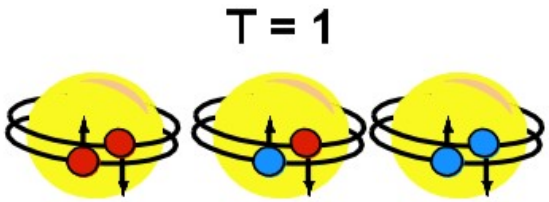




Mirror Energy Differences (MED)

$$\mathrm{MED}_{J,T} = E^*_{J,T,T_z=-T} - E^*_{J,T,T_z=T}$$

Test the charge symmetry of the interaction



Triplet Energy Differences (TED)

Test the charge independency of the interaction

$$TED_{J,T} = E^*_{J,T,T_z=-1} + E^*_{J,T,T_z=+1} - 2E^*_{J,T,T_z=0}$$

The Coulomb-induced breakdown of the isospin symmetry, most evident in mirror nuclei and isobaric triplets, provides a powerful tool to shade light on the nuclear structure properties

Differences in analogue excited states

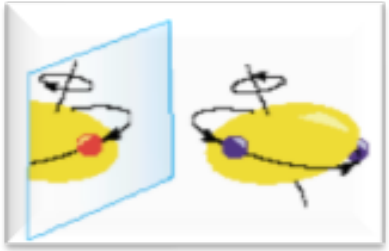
Measuring MED and TED

Can we reproduce such energy differences?
What can we learn from them?

They contain a richness of information about spin-dependent structural phenomena

- How the nucleus generates its angular momentum
- Evolution of radii (deformation) along a rotational band
- Learn about the configuration of the states
- Isospin non-conserving terms of the interaction

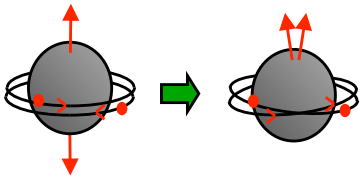
Mirror Energy Differences



$$MED_J = VCM_J + VCm_J + VB_J$$

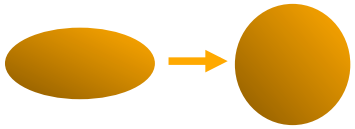
V_{CM}: Multipole Coulomb

Nucleon Alignment

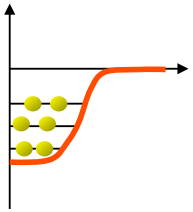


V_{Cm}: Monopole Coulomb

Radius Evolution



State Configurations



Additional Isospin Symmetry Breaking Term of "**nuclear**" origin: $\mathbf{V_B}$

A. P. Zuker et al., PRL 89, 142502 (2002)

M.A. Bentley and S.M. Lenzi, Prog. Part. Nucl. Phys. 59, 497-561 (2007)

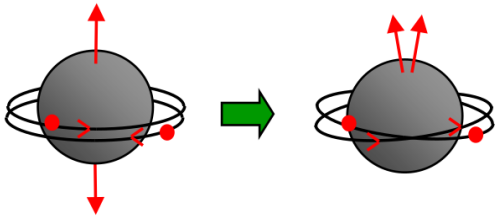
Summary of Coulomb „terms"

M. A. Bentley and S. M. Lenzi, Prog. Part. Nucl. Phys. 59, 497 (2007)

$$MED(J) = \Delta\langle V_{CM}\rangle + \Delta\langle E_{ll}\rangle + \Delta\langle E_{ls}\rangle + \Delta\langle V_R\rangle$$

Multipole part of the Coulomb energy V_{CM} :

Alignment between valence protons only



Interaction with the core

Monopole part of the Coulomb energy V_{cm} :

$$E_C = \frac{3}{5}\frac{Z(Z-1)e^2}{R_C}$$

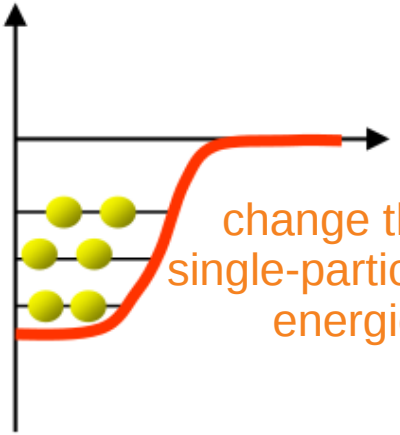
radial effect

radius changes with J

electromagnetic spin-orbit interaction

$$V_{ls} = (g_s - g_l)\frac{1}{2m_N^2c^2}\left(\frac{1}{r}\frac{\mathrm{d}V_c}{\mathrm{d}r}\right)\vec{l}\cdot\vec{s}$$

$$E_{ll} = \frac{-4.5Z_{cs}^{13/12}[2l(l+1) - N(N+3)]}{A^{1/3}\left(N+\frac{3}{2}\right)}\ \mathrm{keV}$$

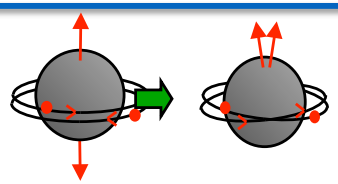


change the single-particle energies

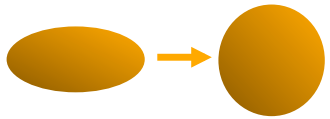
A. P. Zuker et al., Phys. Rev. Lett. 89, 142502 (2002).

Mirror Energy Differences in A=49

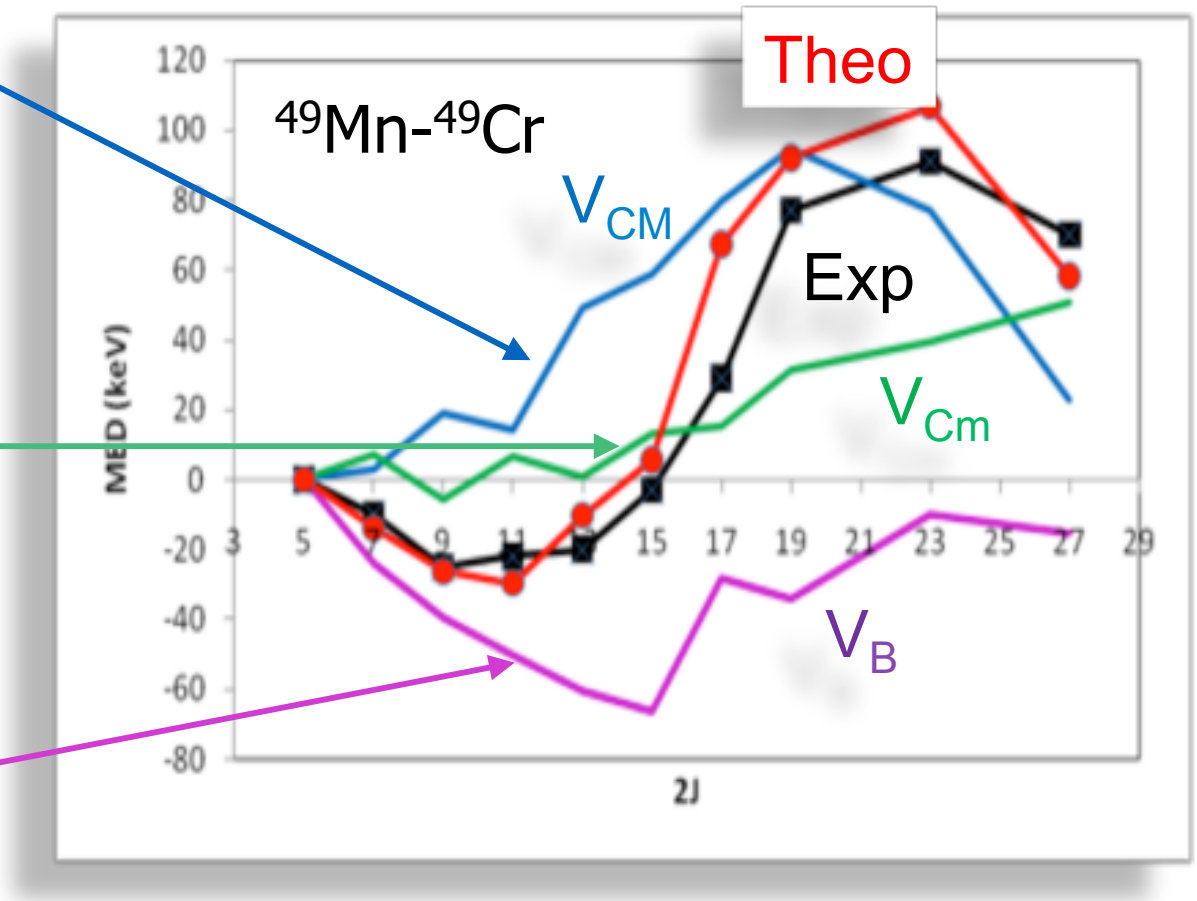
V_{CM}: Multipole Term



V_{Cm}: Monopole Term



V_B: "Nuclear" Term

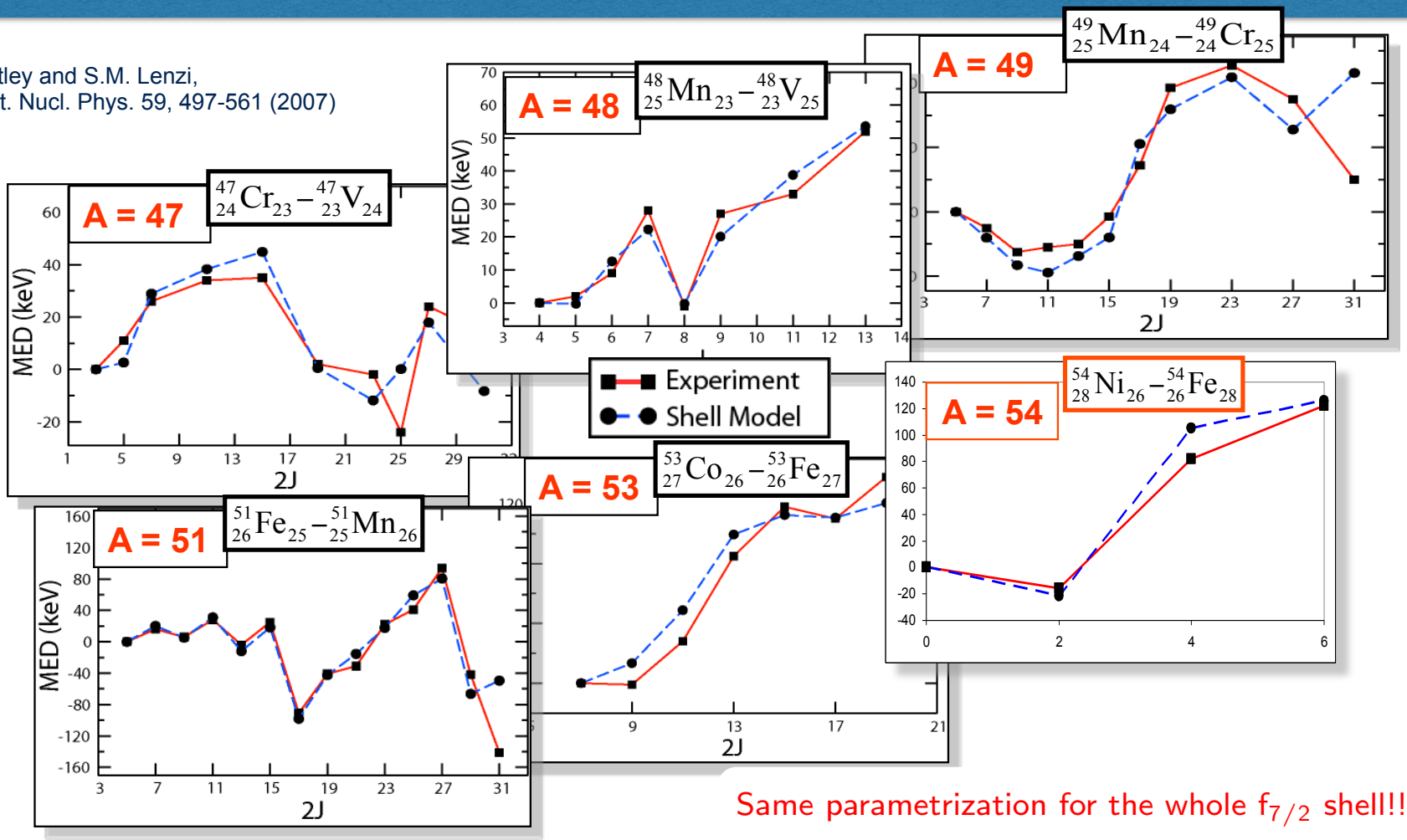


The V_B term is of the **same order** as the Coulomb contributions and it is **crucial** to reproduce the MED

A. P. Zuker et al., PRL 89, 142502 (2002)

Mirror Energy Differences in f7/2 shell

M.A. Bentley and S.M. Lenzi,
Prog. Part. Nucl. Phys. 59, 497-561 (2007)

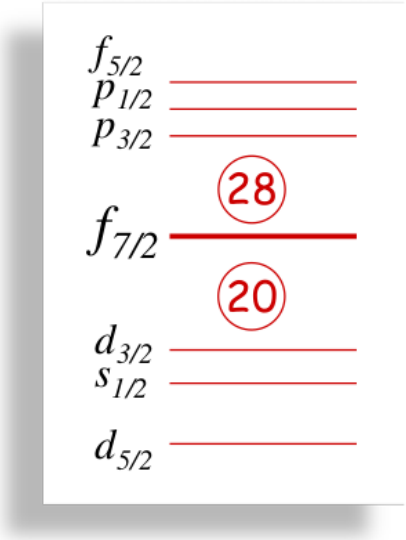


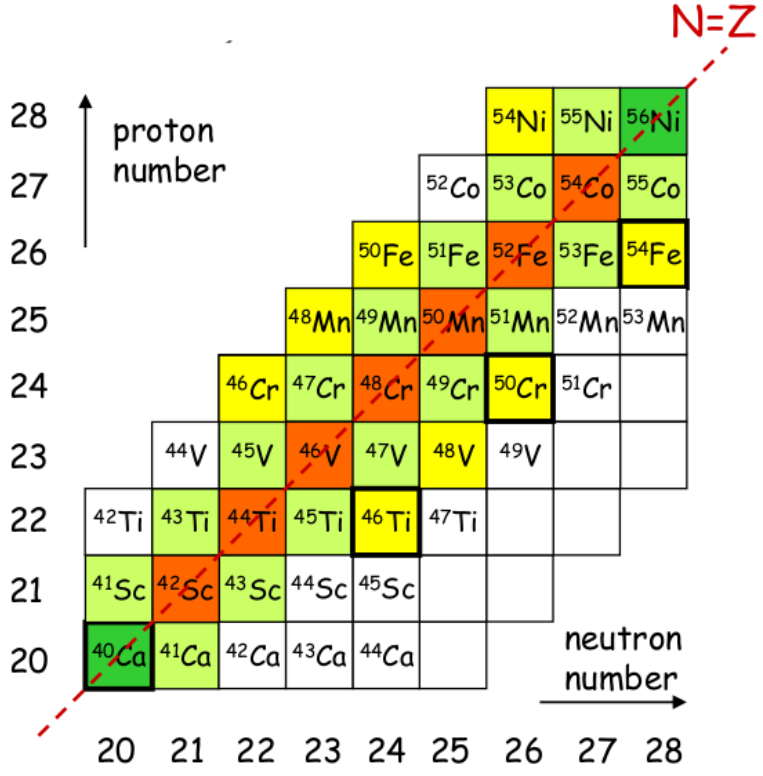
Same parametrization for the whole $f_{7/2}$ shell!!!

This permits to reproduce the MED in the **$f_{7/2}$ shell**

Is the V_B a **general** feature of the effective n-n interaction??

Mirror Energy Differences in f7/2 shell





The $1f_{7/2}$ shell is isolated in energy from the rest of fp orbitals

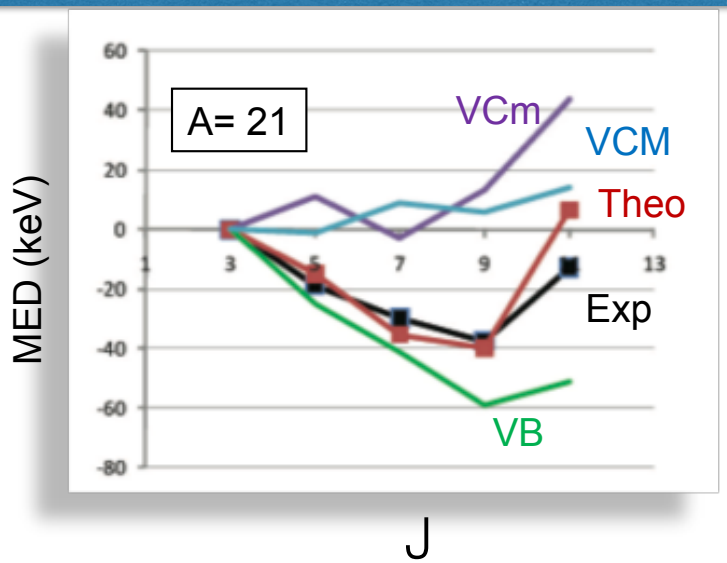
Wave functions are dominated by $(1f_{7/2})^n$ configurations
High-spin states experimentally reachable

Experimental issue 1 : proton-rich T_z =-1/2 isobars are weakly populated

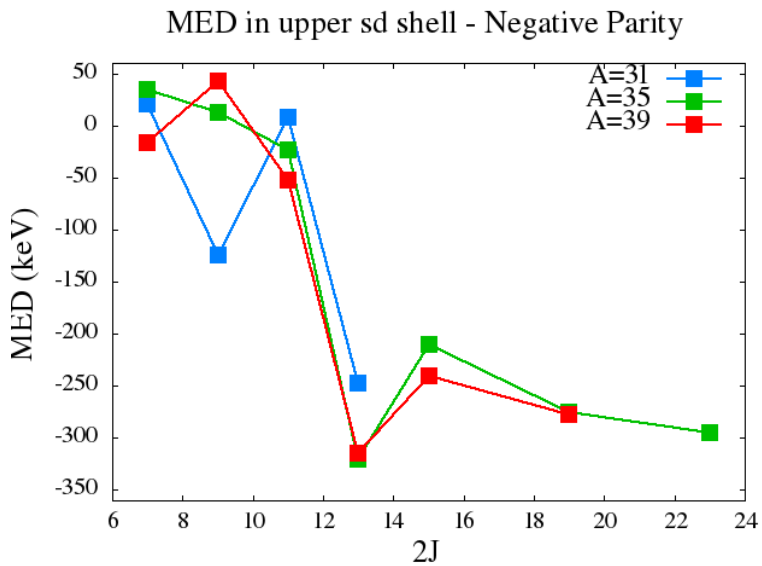
Experimental issue 2 : ,,Mirrored" gamma ray energies almost identical need very clean reaction channel selection...

Mirror Energy Differences is sd-shell

The **same type** of V_B term as in the $f_{7/2}$ shell is needed in the lower sd shell to reproduce MED



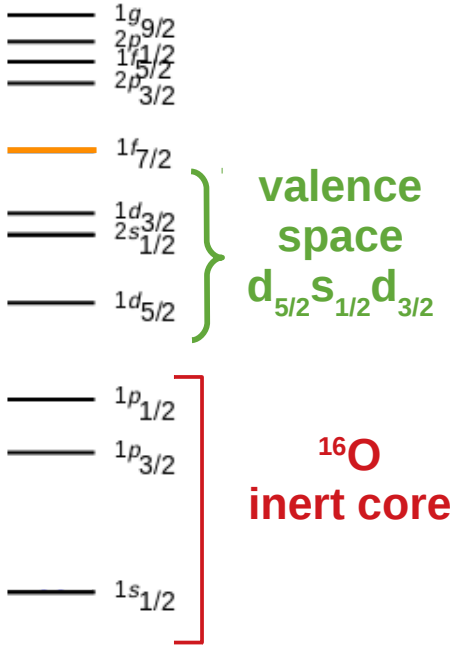
In the **upper sd shell** the excitations to the fp shell are **important:**

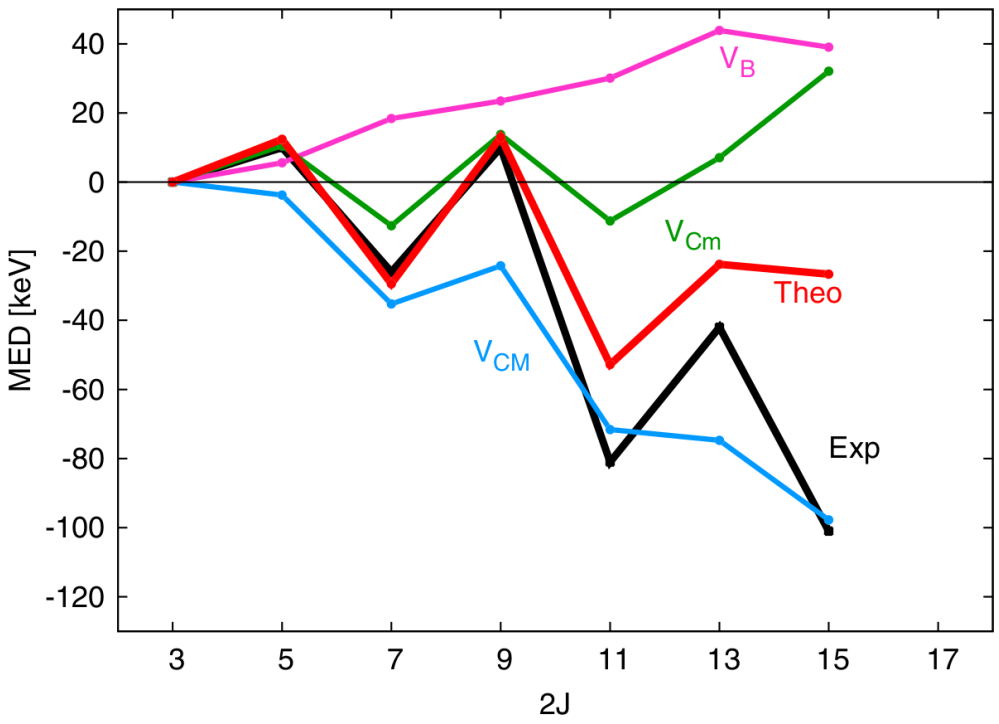


- **Large** MED: **EMSO** term
- **V_B** parameterization ?
- Effective interactions **cross-shell** ?

Systematic studies
in this region are needed

Mirror Energy Difference in sd-shell A=23





sd-orbitals are considered on the same footing

V_b terms includes all the orbitals from the valence space ($d_{5/2}s_{1/2}d_{3/2}$)

USD iteration*

$$\Delta\langle V_B\rangle_J = -100\ \mathrm{keV}(\langle V_{\pi\pi}^{I=0}\rangle_J - \langle V_{\nu\nu}^{I=0}\rangle_J)$$

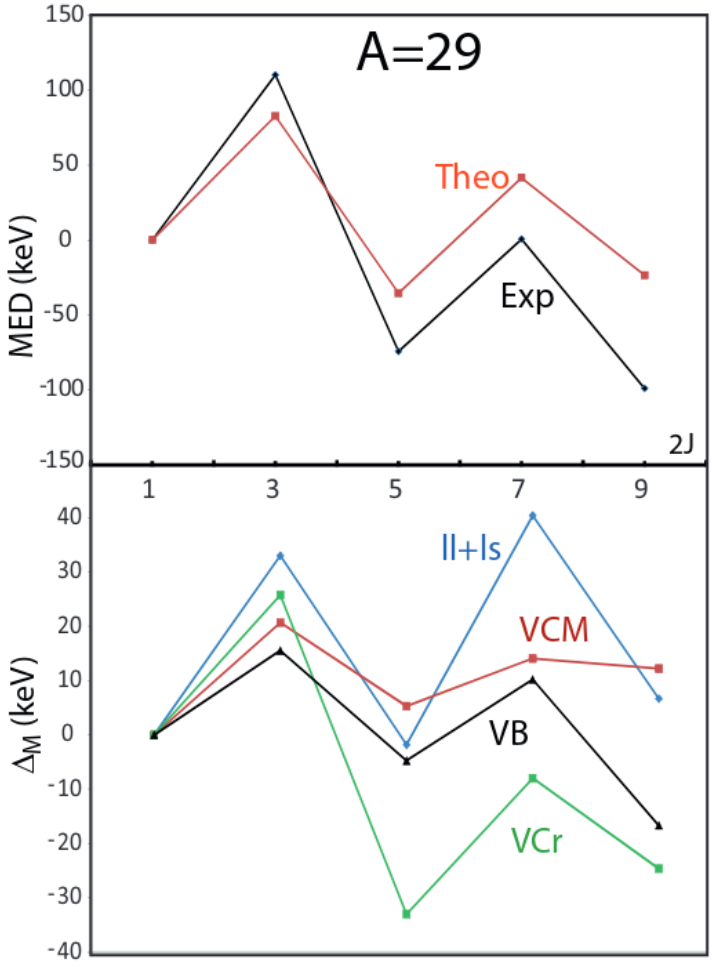
ISB V_B term deduced for the $f_{7/2}$ shell are not confined to this orbital but constitute a more general feature

*J.A. Nolen, J.P. Schiffer, Annu. Rev. Nucl. Sci. 19, 471 (1969)

A. Boso et al., Phys. Rev. Lett. 121, 032502 (2018)

nuclei in sd shell

S.M. Lenzi J. Phys.: Conf. Ser. 580 012028 (2015)



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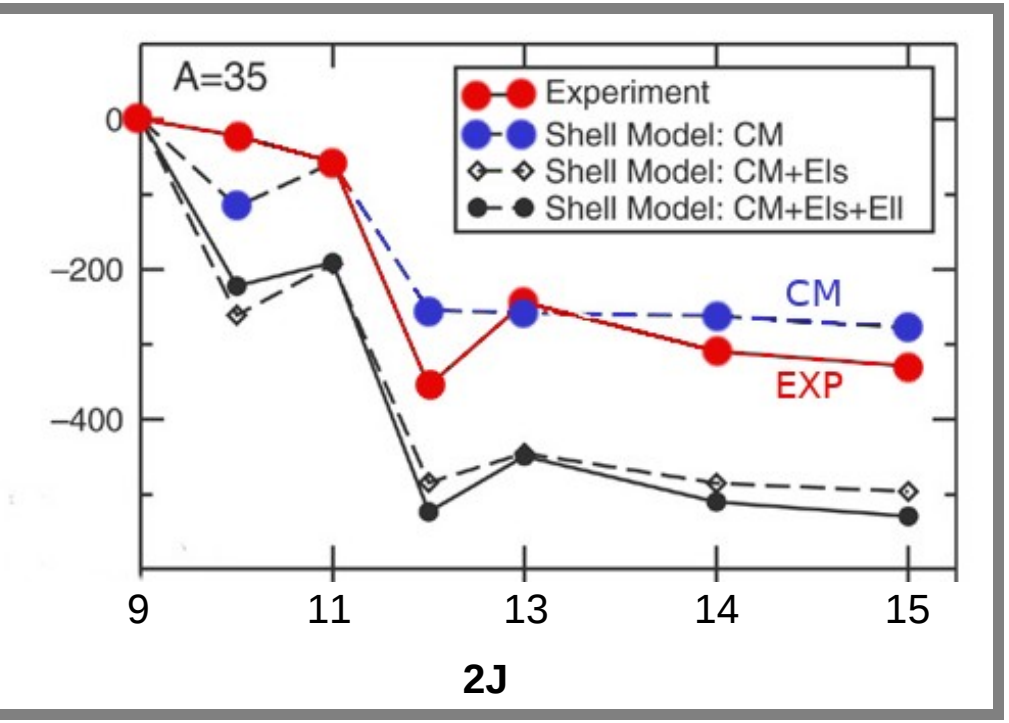

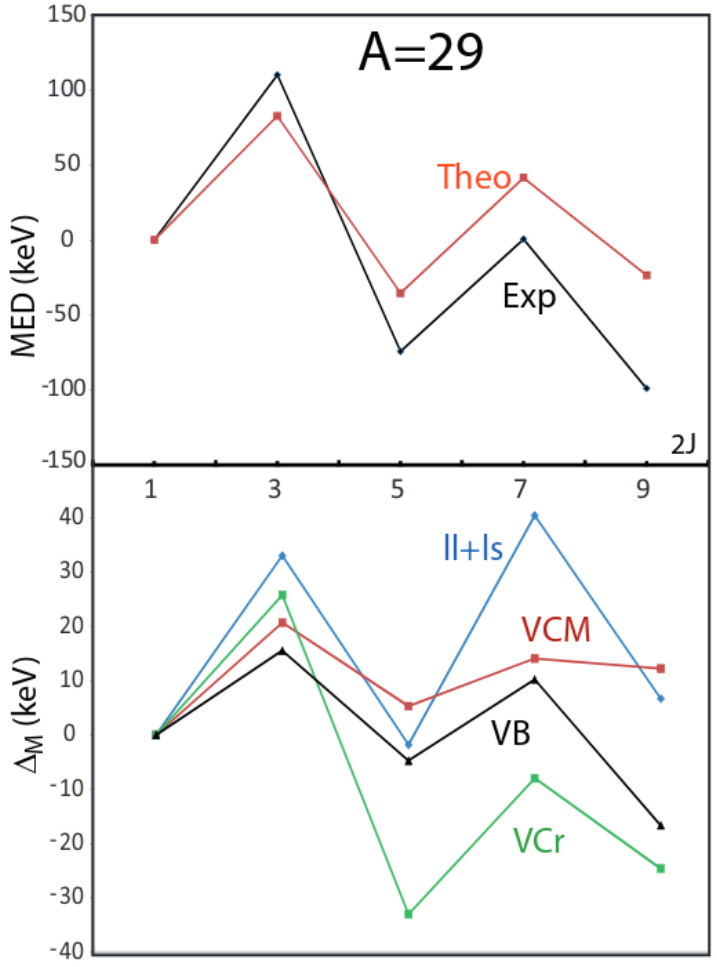

nuclei in sd shell

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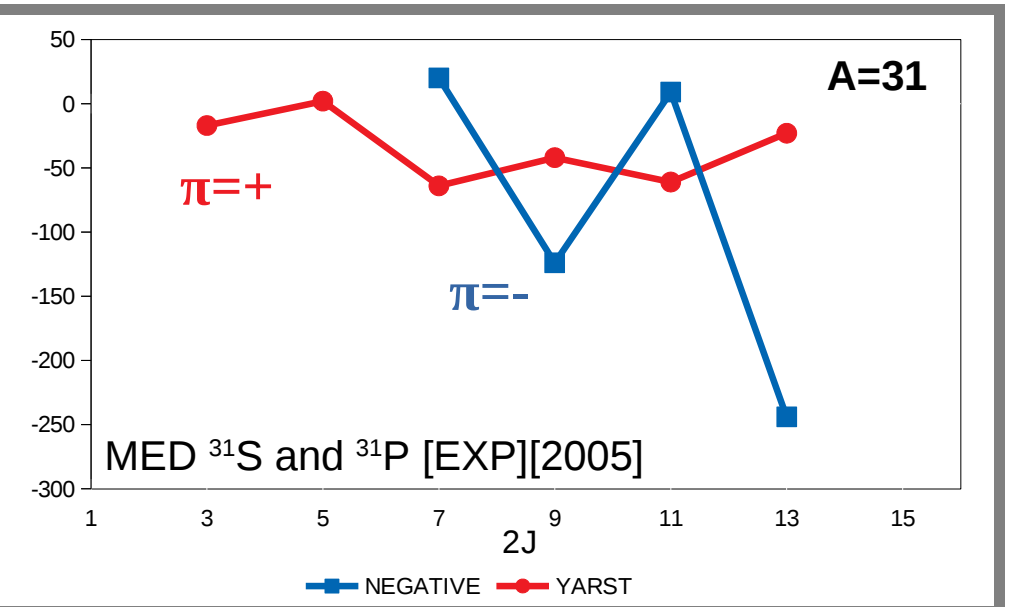
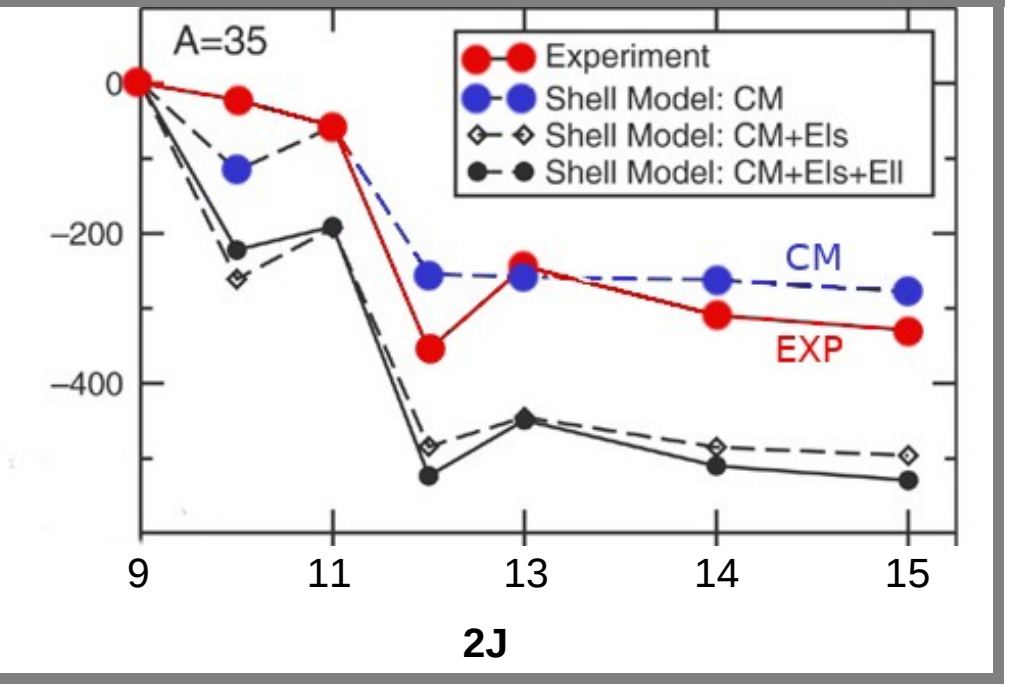
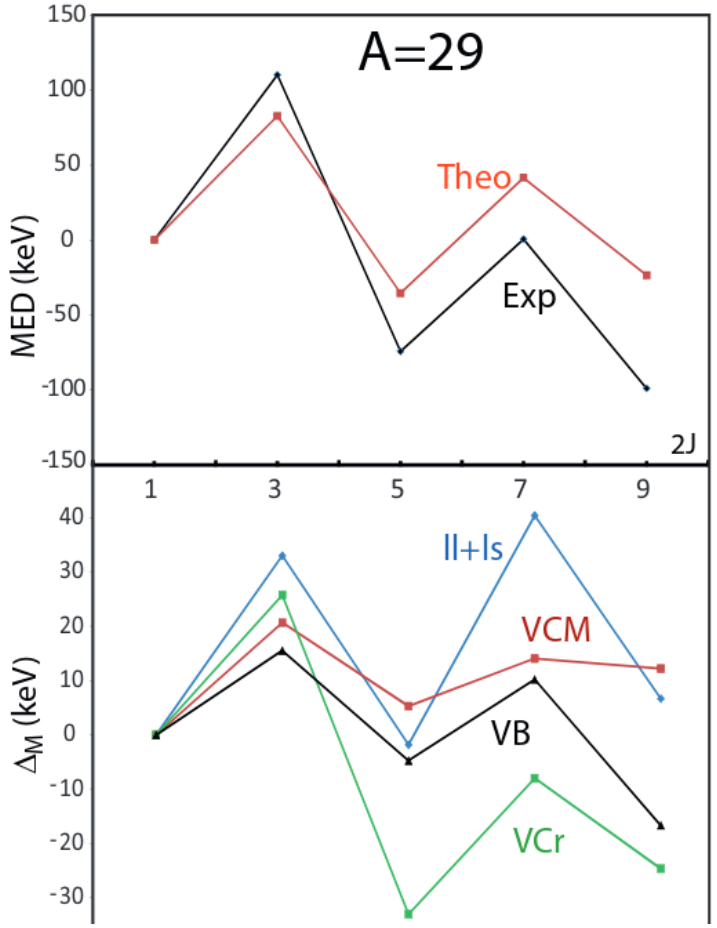






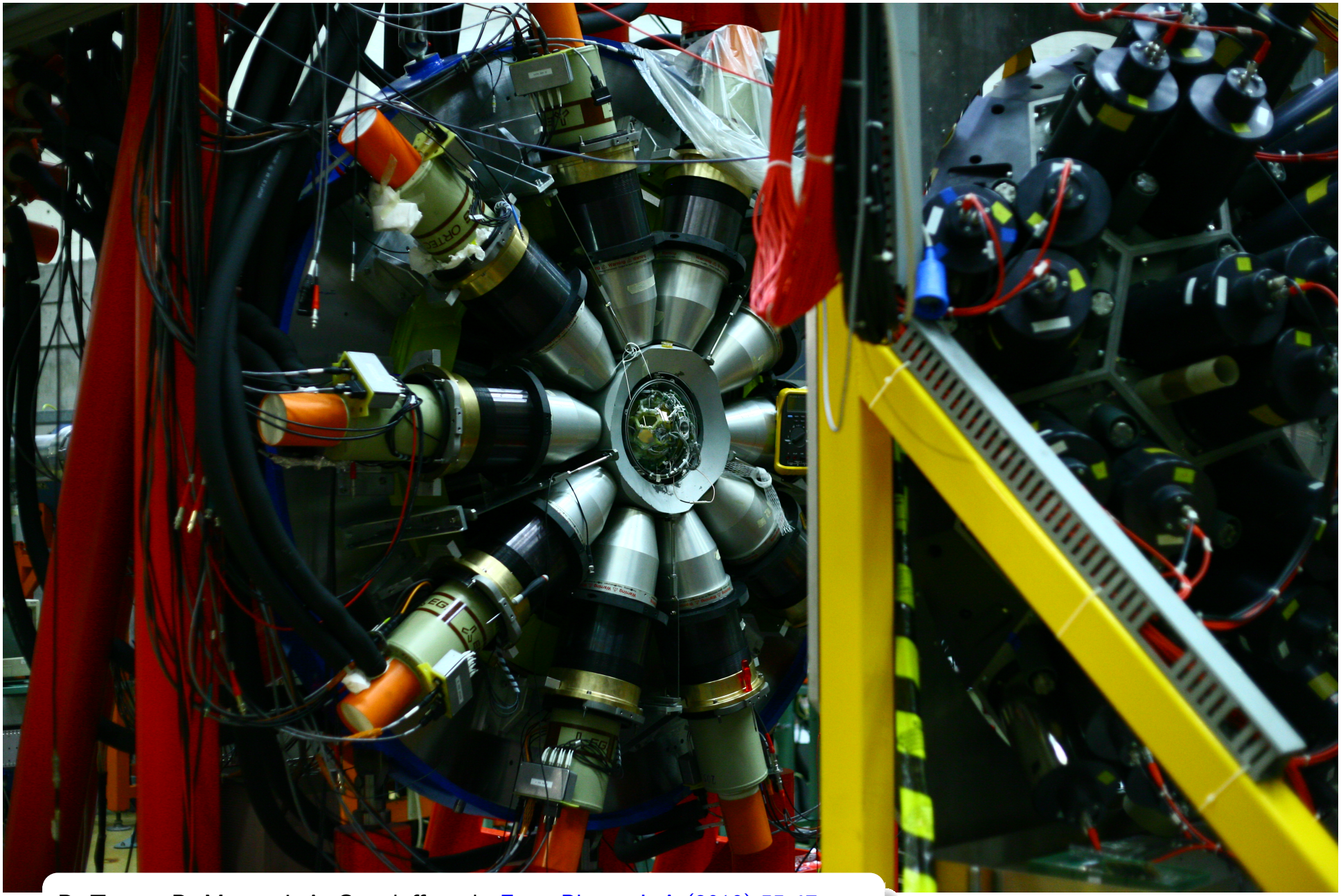
M. Ionescu et al., Phys. Rev,C 73, 024310 (2006)

Jenkins et al., Phys. Rev, C 72, 031303(R) (2005)

Current array: GALILEO

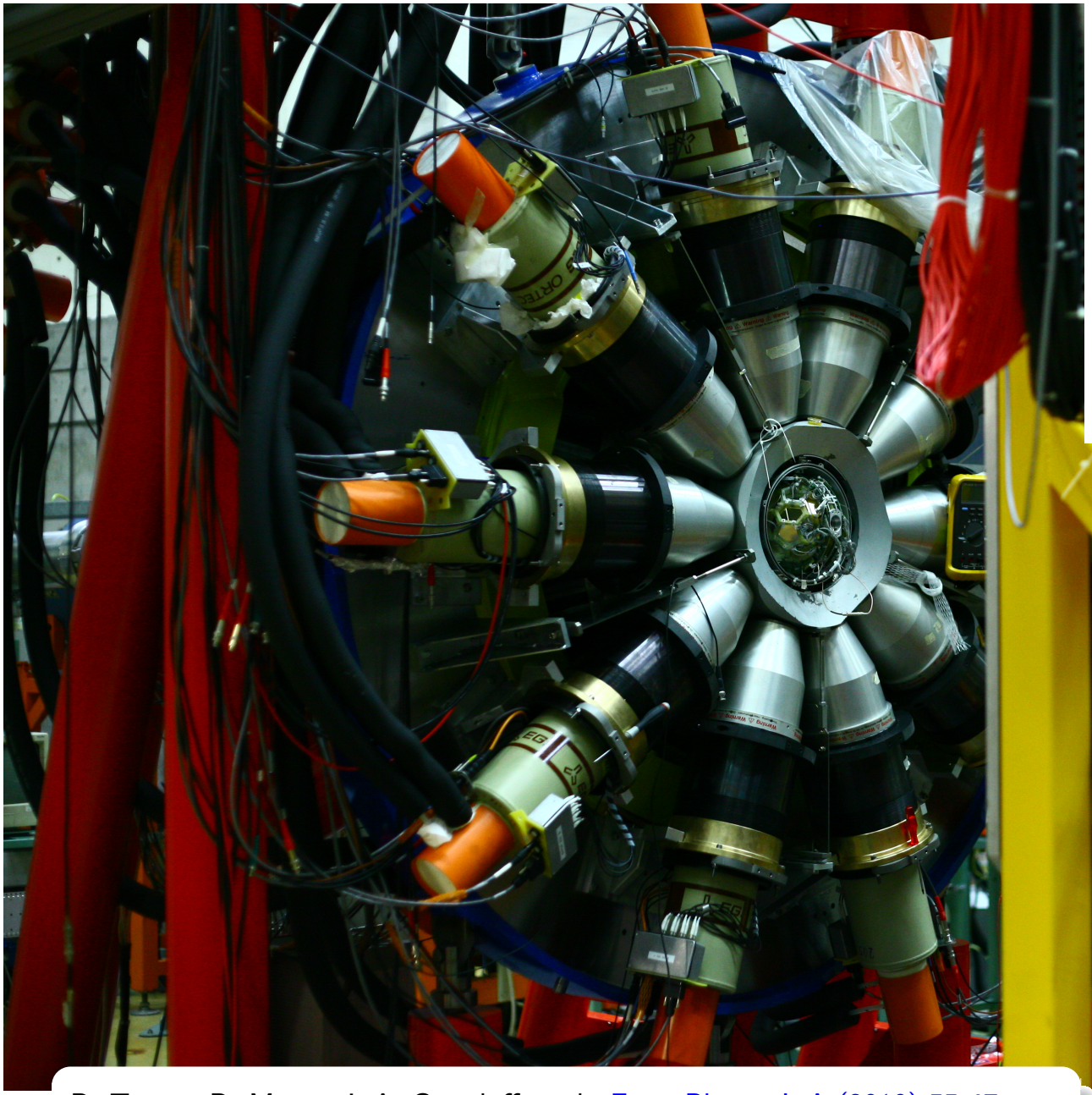
- 25 HPGe CS detectors
- Angles: $90^\circ/60^\circ$, 152°, 129°, 119°
- at 22.5cm; $\epsilon \sim$2.4% at 1332.5 keV
- FWHM at 1332.5 keV $<$ 2.4 keV
- Trigger-less mode
- Typical operational rate $\sim$20 kHz/det
- Common clock synchronization
- Local data processing

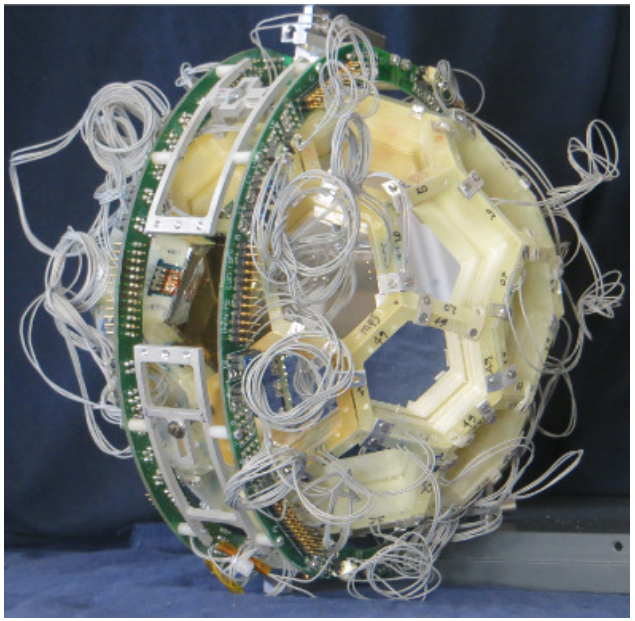
Galileo gamma-ray spectrometer

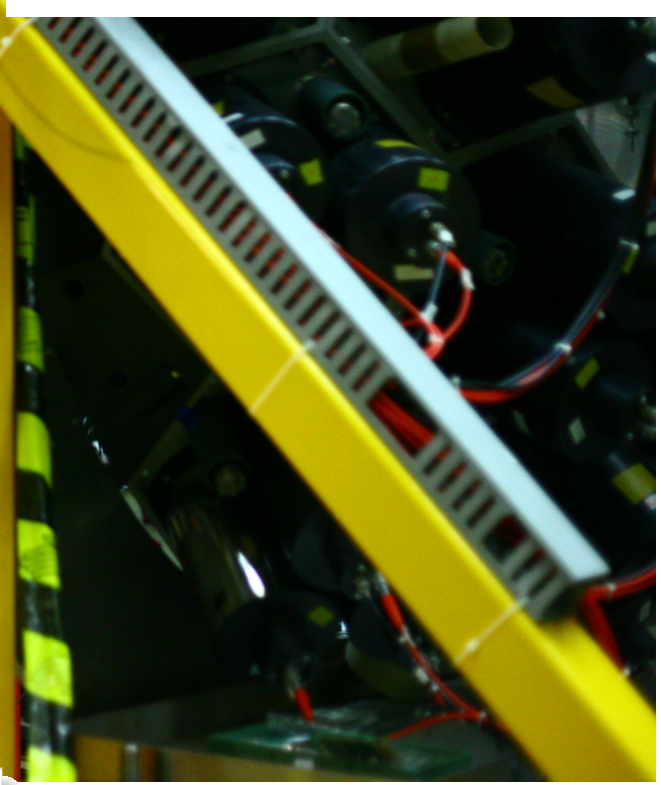


D. Testov, D. Mengoni, A. Goasduff et al., Eur. Phys. J. A (2019) 55 47

Galileo gamma-ray spectrometer

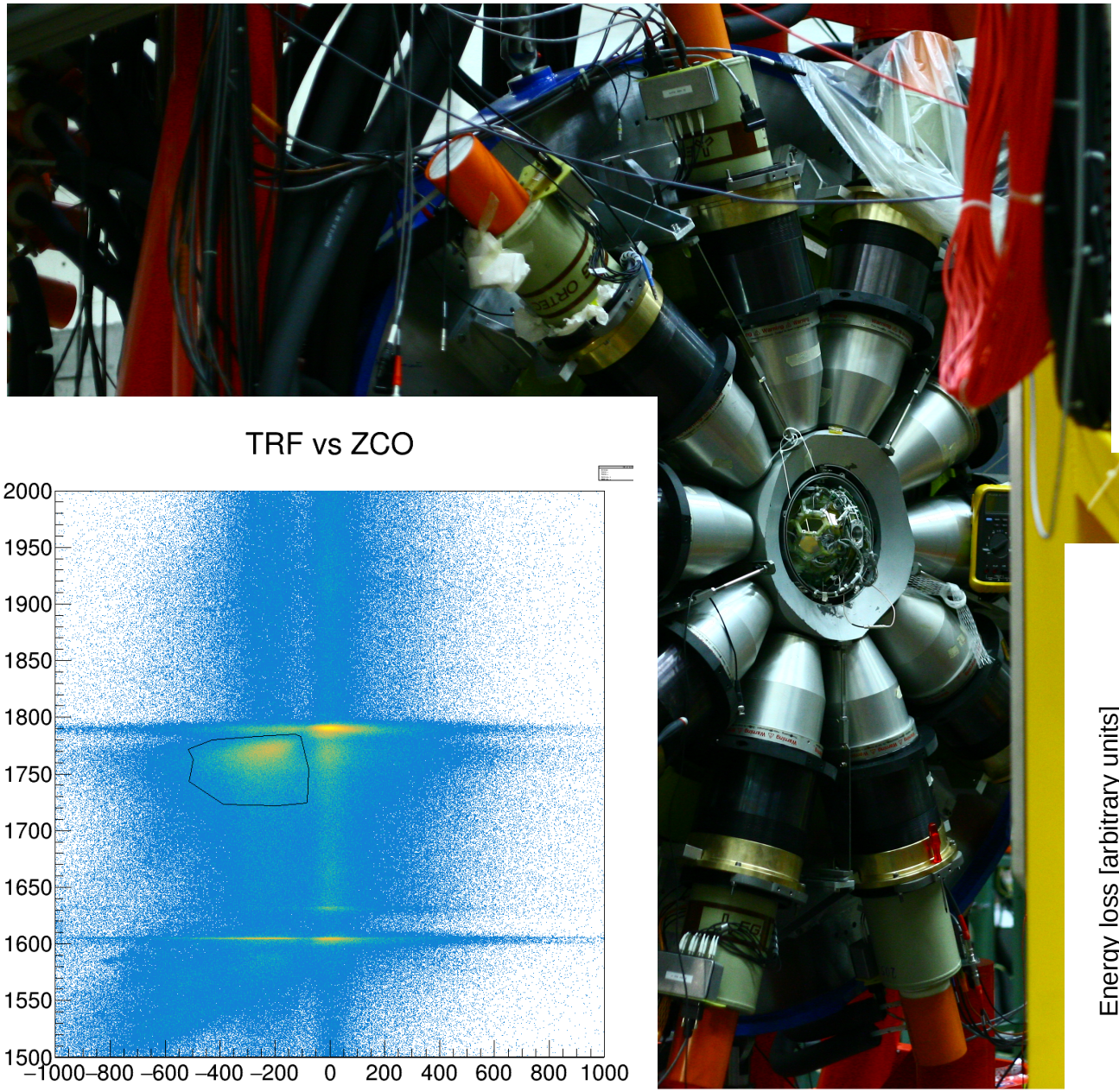


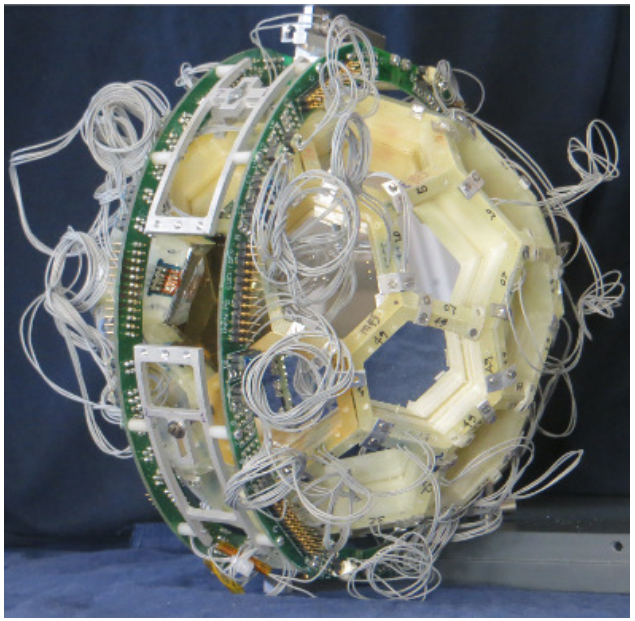


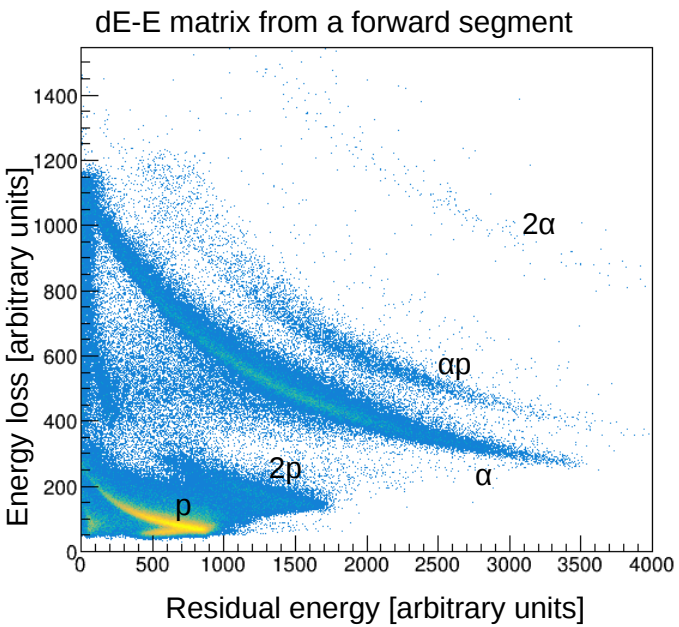


D. Testov, D. Mengoni, A. Goasduff et al., Eur. Phys. J. A (2019) 55 47

Galileo gamma-ray spectrometer



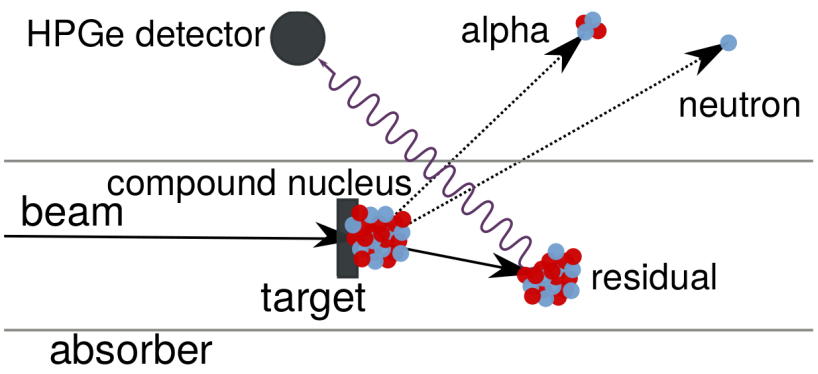


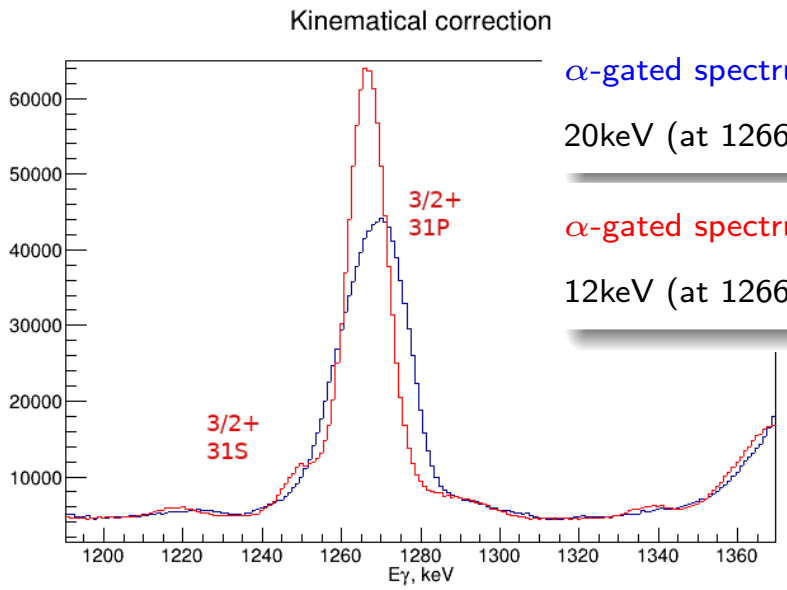


D. Testov, D. Mengoni, A. Goasduff et al., Eur. Phys. J. A (2019) 55 47

Full kinematic reconstruction

^{12}C(at 45 MeV)+^{24}Mg→^{36}Ag* →^{31}P [1α1p]





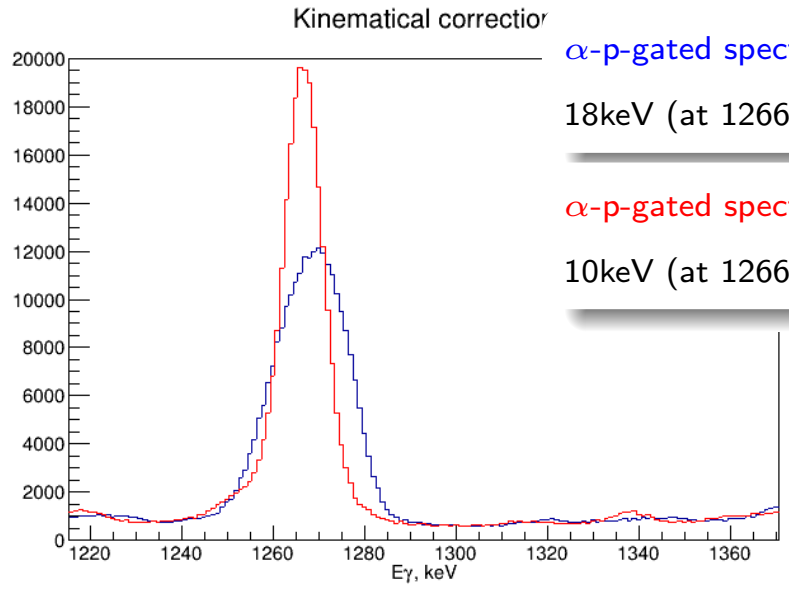
α-gated spectrum

20keV (at 1266 keV)

α-gated spectrum

12keV (at 1266 keV)

$$p_{residual} = p_{compound} + \sum_{particles} p_{particle}$$



α-p-gated spectrum

18keV (at 1266 keV)

α-p-gated spectrum

10keV (at 1266 keV)

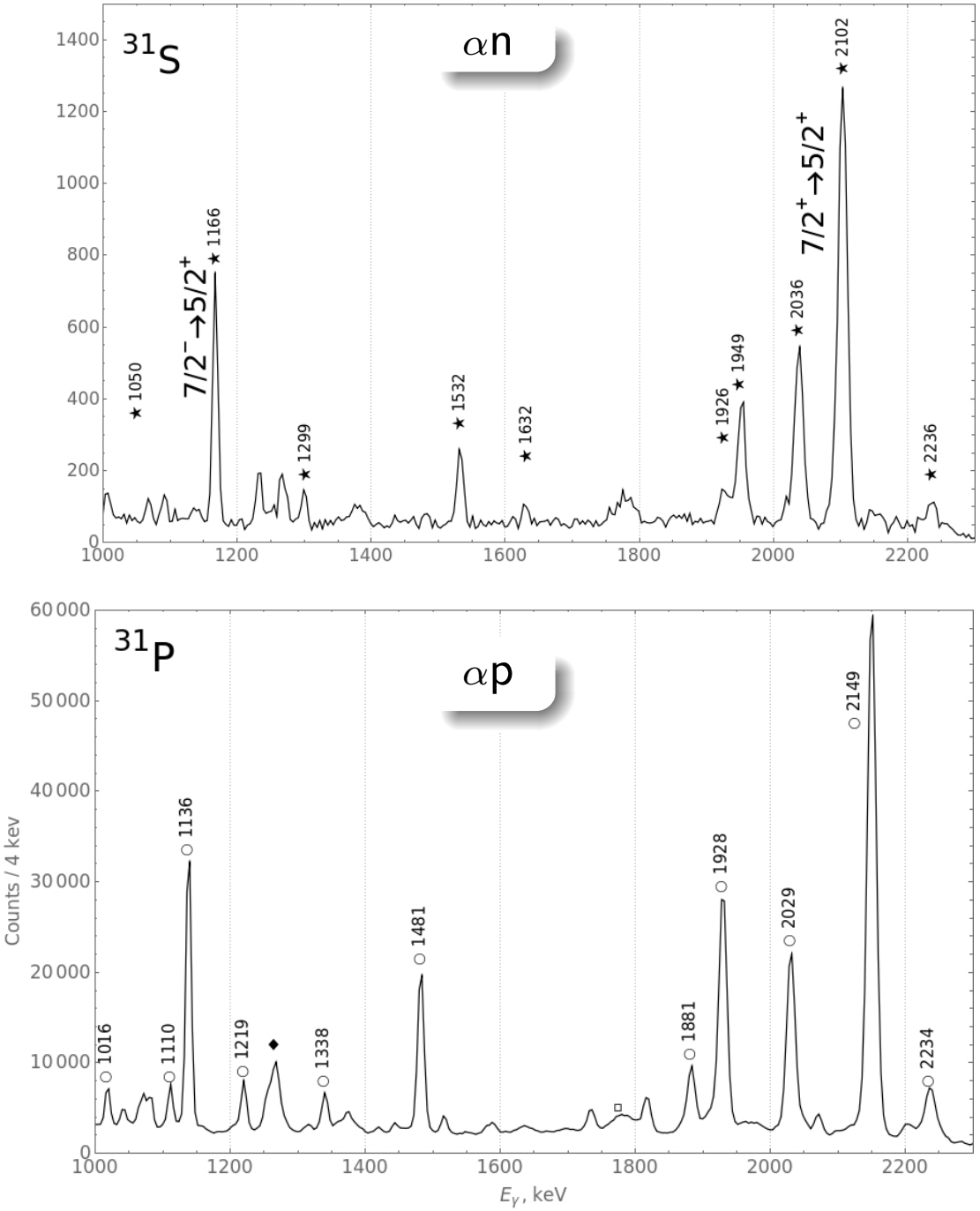
Mean velocity

Euclides Energy Calibration

Energy-loss for each particle in the absorber

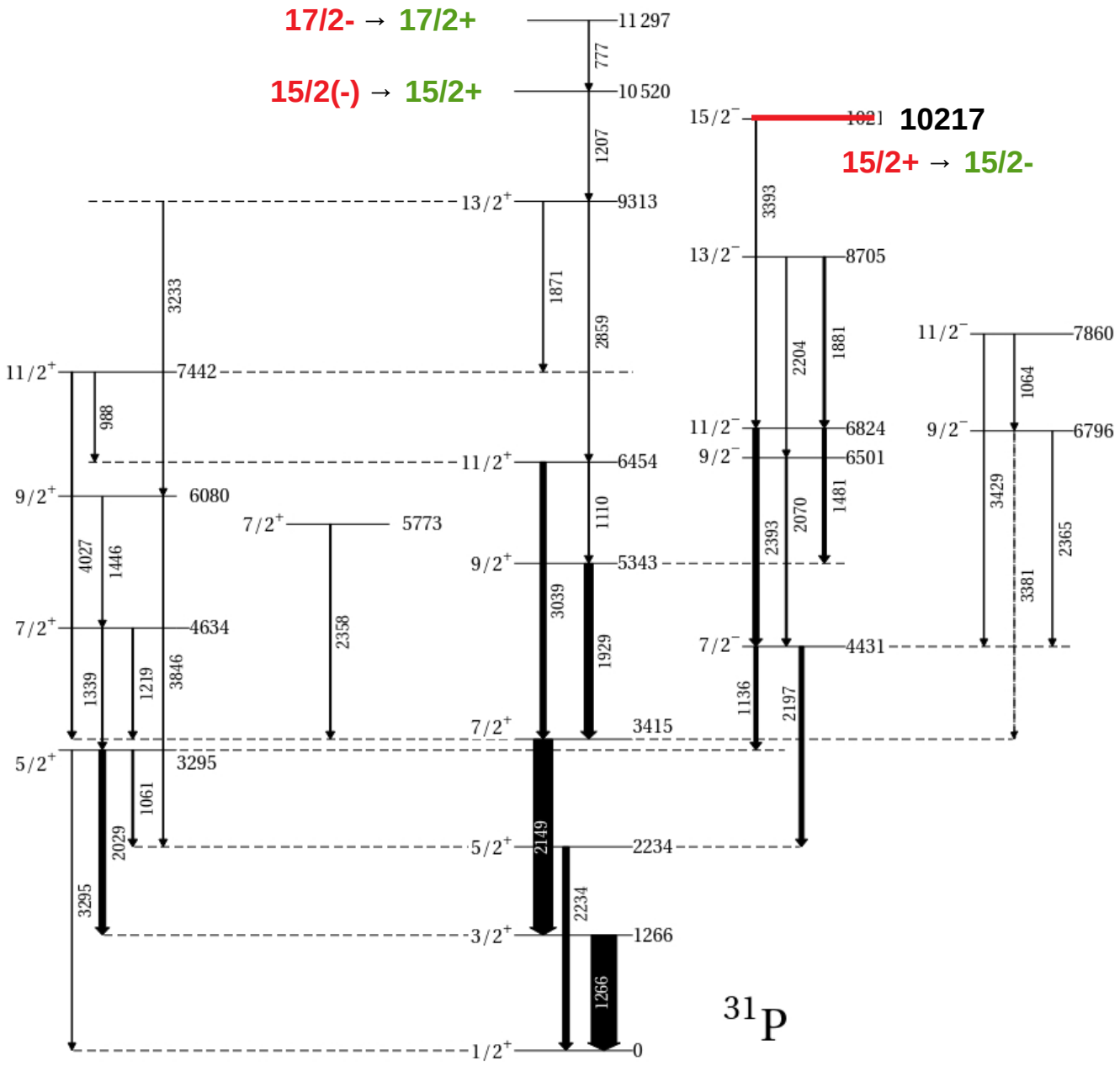
Angles of Euclides telescopes

Mirror symmetry at work: A=31



Projection on $\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$ transition in $\gamma - \gamma$ matrix recorded in coincidence with: 1α and 1 neutron; with 1 proton and 1 neutron

Spectroscopy of ^{31}P



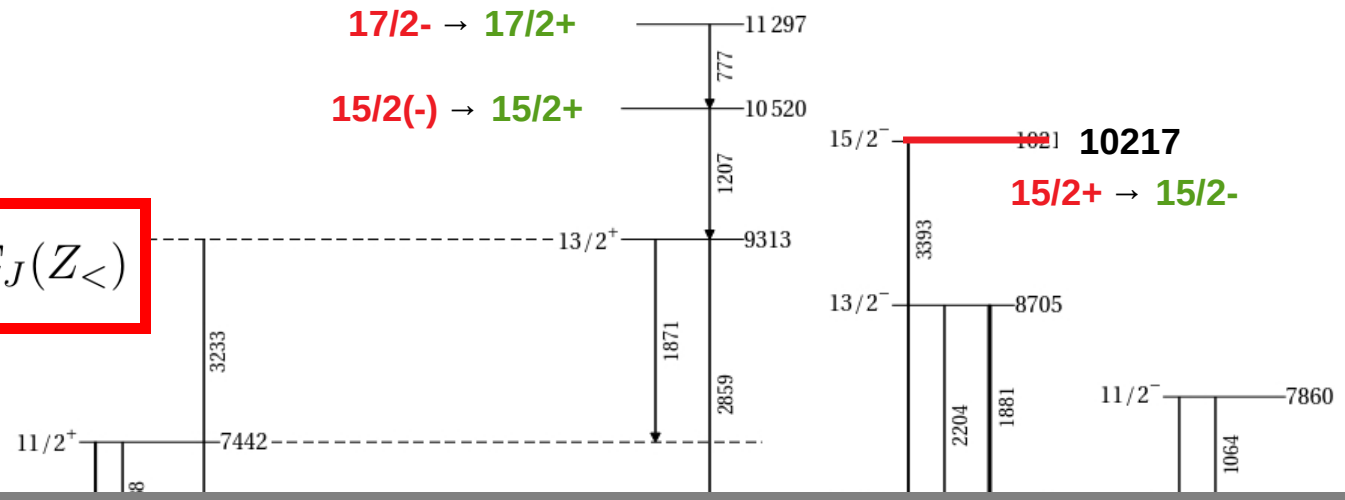
M. Ionescu-Bujor et al.,
Phys. Rev. C 73, 024310 (2006)

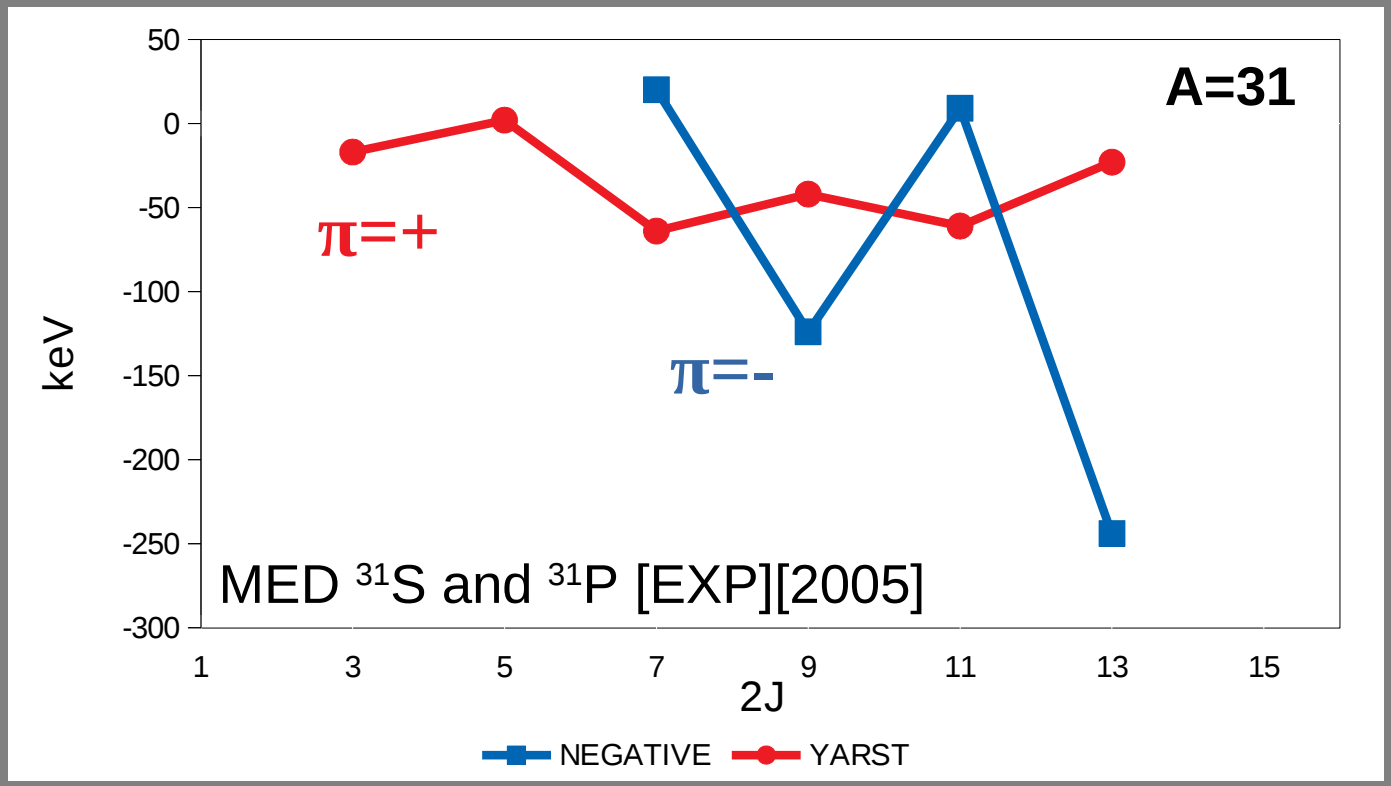
D. Jenkins et al.,
Phys.Rev.C 72 031303(R) (2005)

D. T. Doherty, P. J. Woods, G. Lotay et al.,
Phys. Rev. C 89, 045804 (2014).

Spectroscopy of ^{31}P

$$MED^{J}_{exp} = E_J(Z_>) - E_J(Z_<)$$





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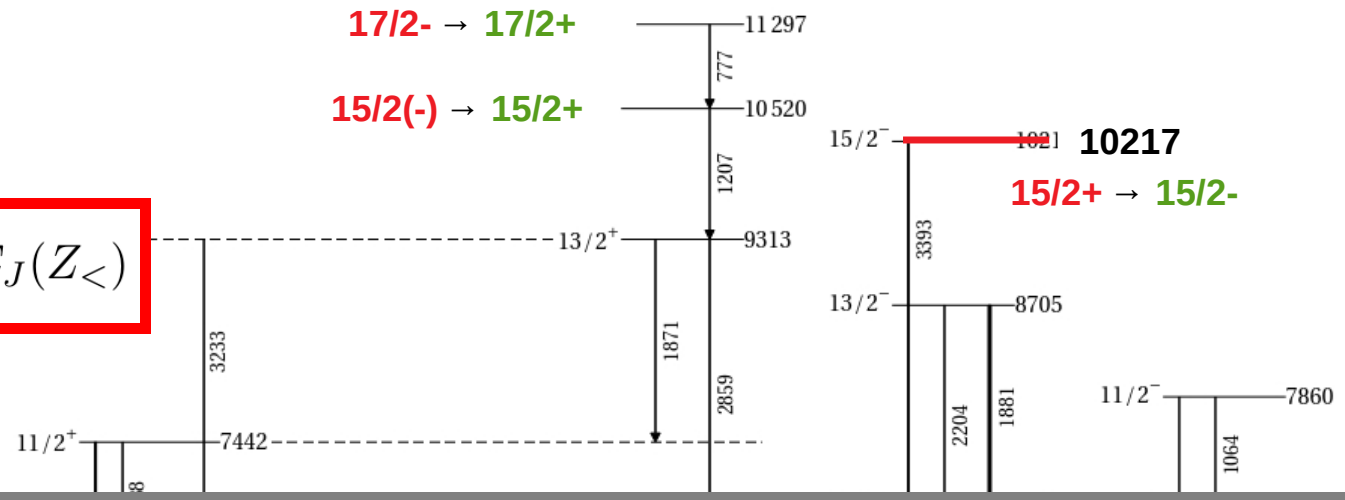

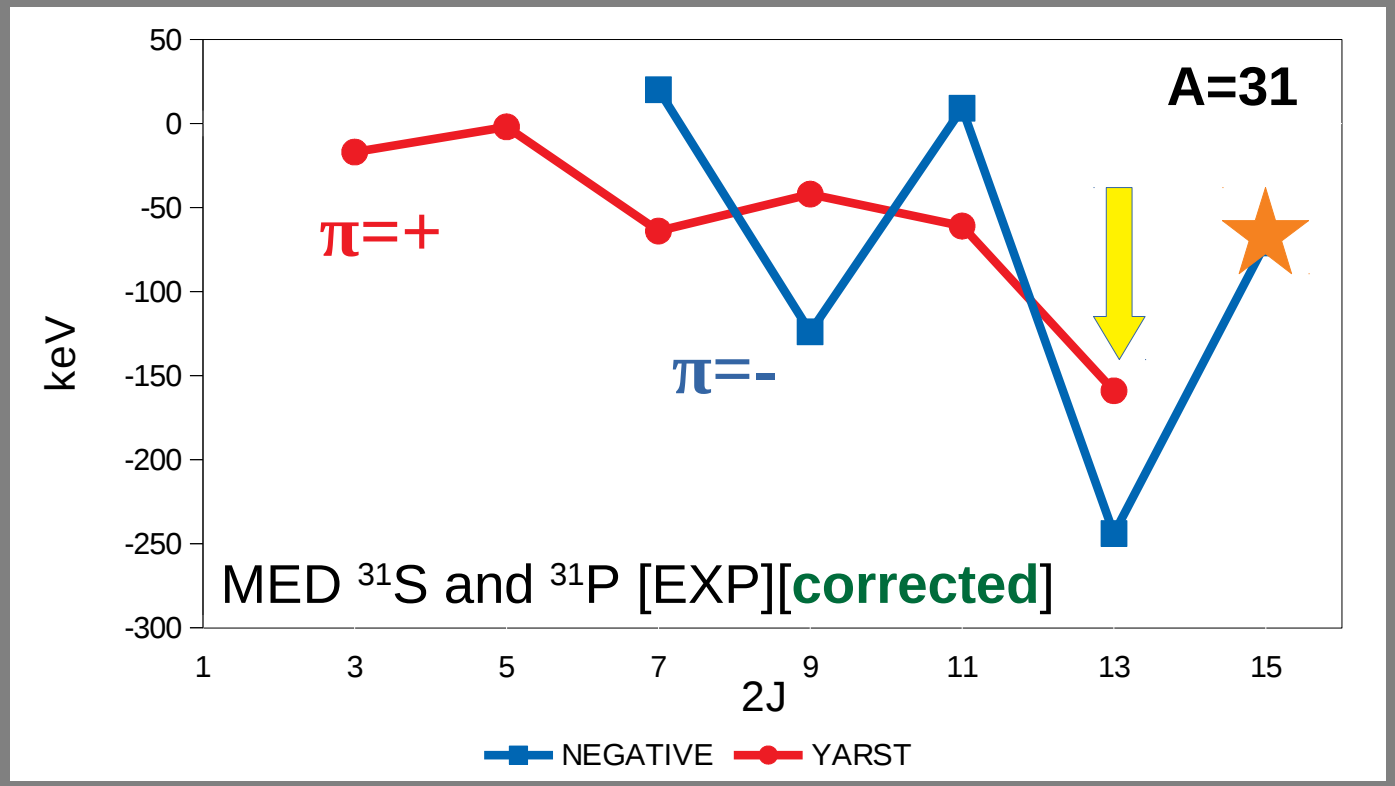

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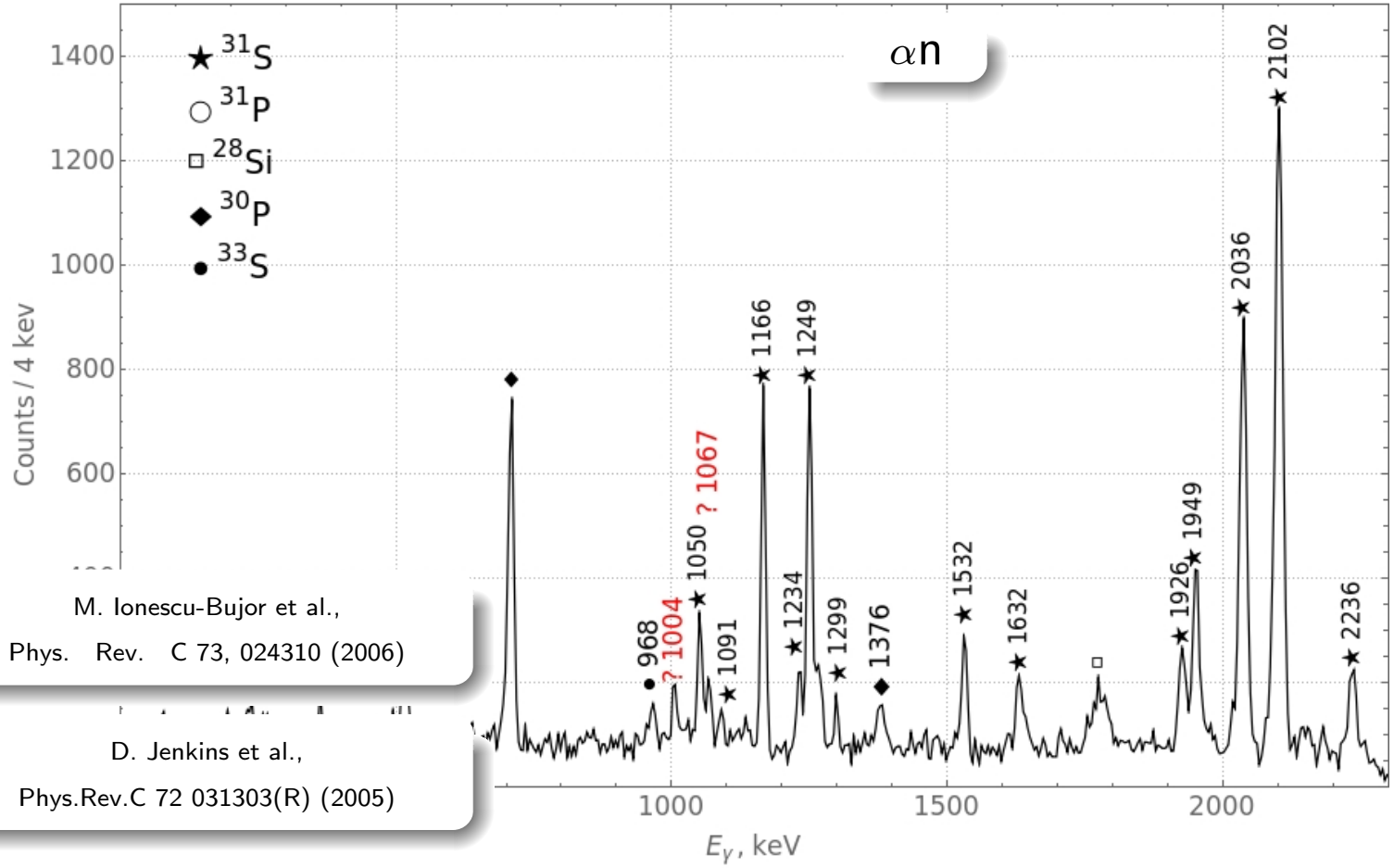
D. Jenkins et al.,
Phys.Rev.C 72 031303(R) (2005)

D. T. Doherty, P. J. Woods, G. Lotay et al.,
Phys. Rev. C 89, 045804 (2014).

Spectroscopy of ^{31}S

Sum of the projections of $\gamma - \gamma$ matrix gated on 1249-keV and 1166-keV transitions in ^{31}S. 1α and 1 neutron conditions was requested.



M. Ionescu-Bujor et al., Phys. Rev. C 73, 024310 (2006)

D. Jenkins et al., Phys.Rev.C 72 031303(R) (2005)

D. T. Doherty, P. J. Woods, G. Lotay et al., Phys. Rev. C 89, 045804 (2014).

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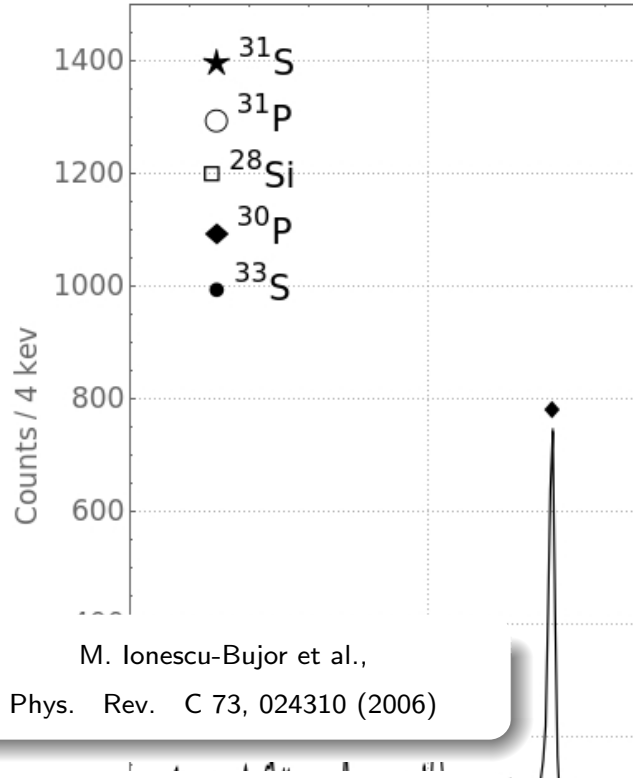

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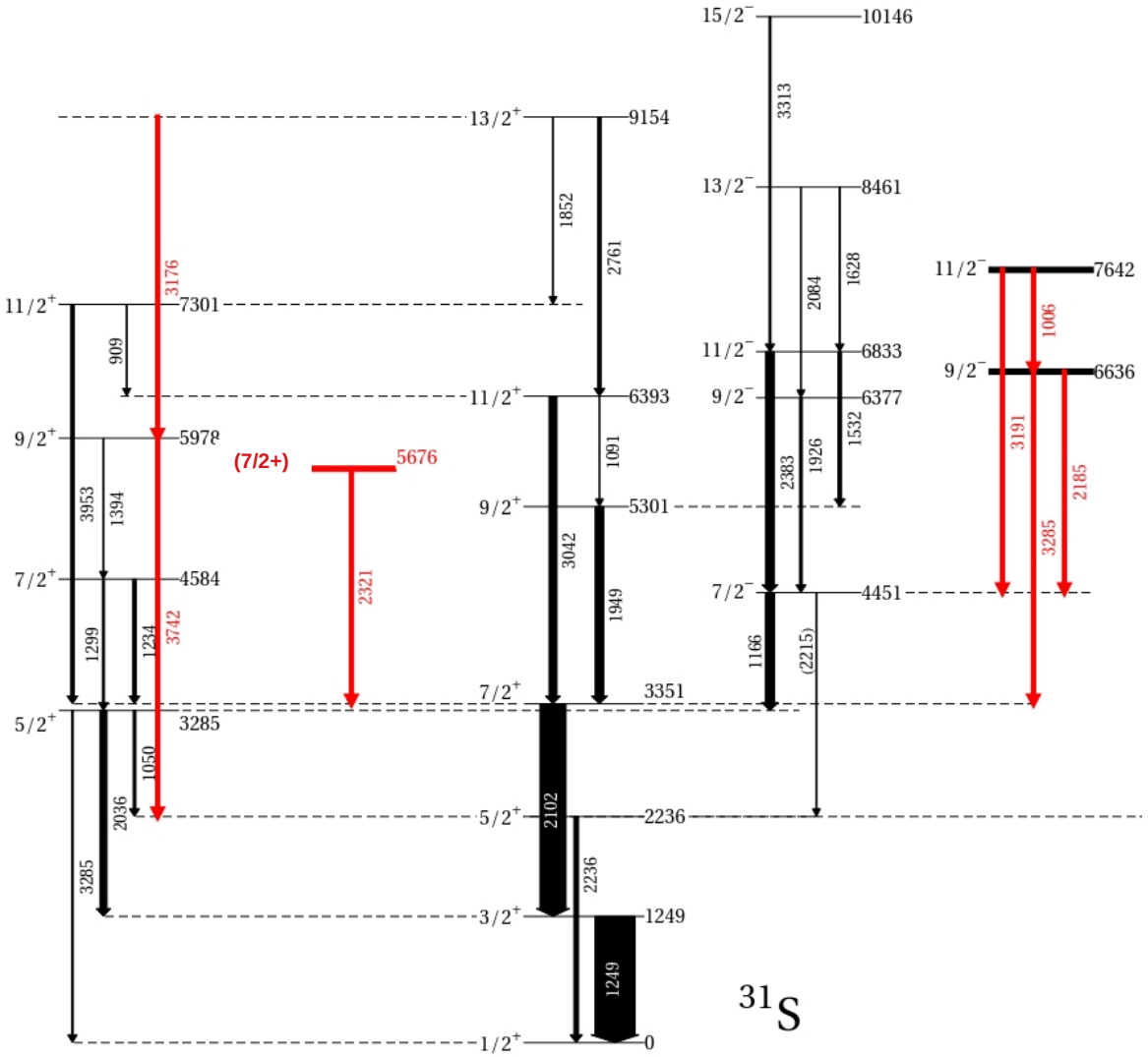
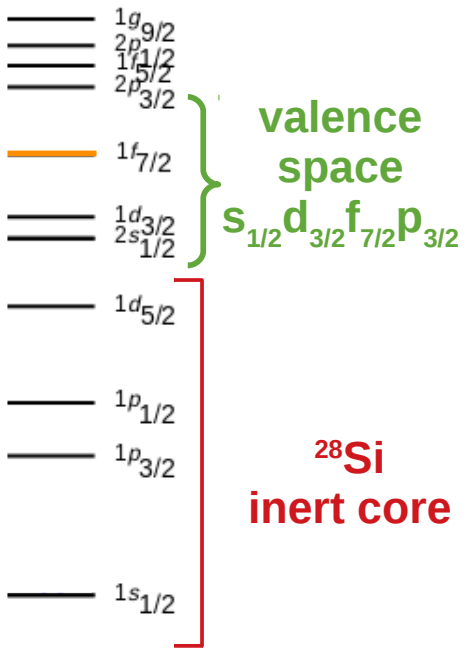
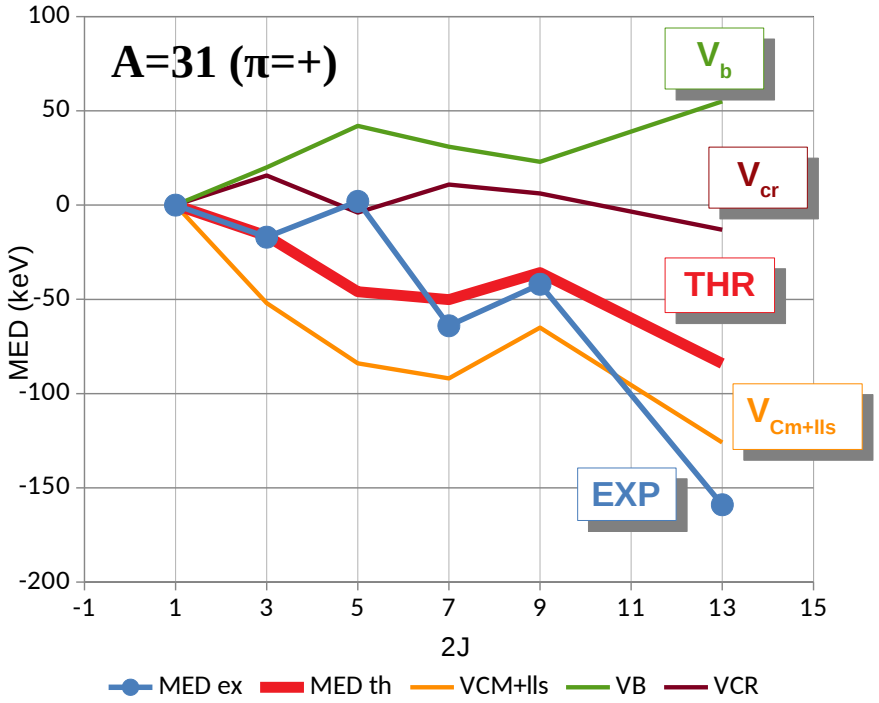


Mirror Energy Difference in sd-shell A=31





sd-orbitals are considered on the same footing

V_b terms includes all the orbitals from the valence space ($s_{1/2}d_{3/2}f_{7/2}p_{3/2}$)

USD iteration*

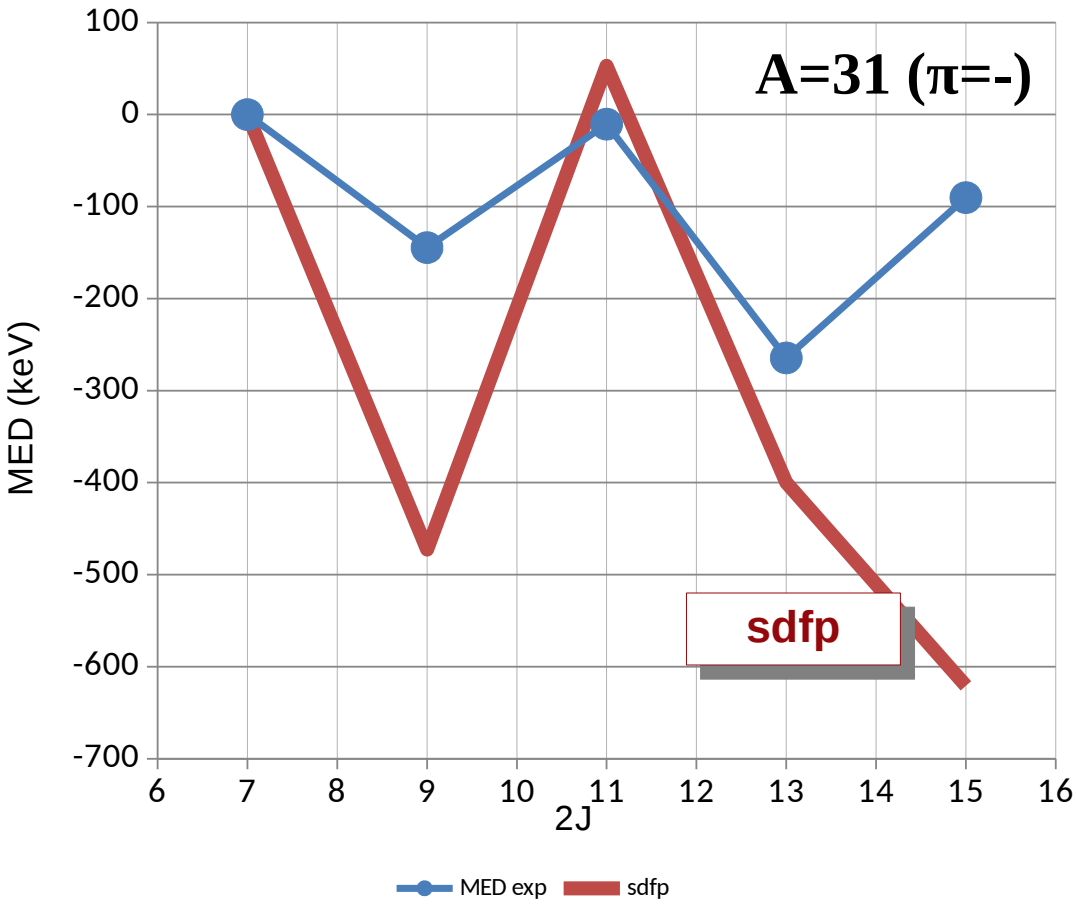
$$\Delta\langle V_B\rangle_J = -100\ \mathrm{keV}(\langle V_{\pi\pi}^{I=0}\rangle_J - \langle V_{\nu\nu}^{I=0}\rangle_J)$$

ISB V_B term deduced for the $f_{7/2}$ shell are not confined to this orbital but constitute a more general feature

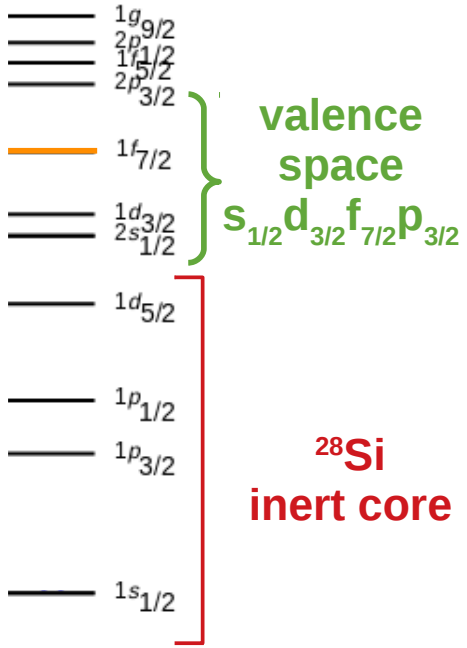
*J.A. Nolen, J.P. Schiffer, Annu. Rev. Nucl. Sci. 19, 471 (1969)

A. Boso et al., Phys. Rev. Lett. 121, 032502 (2018)

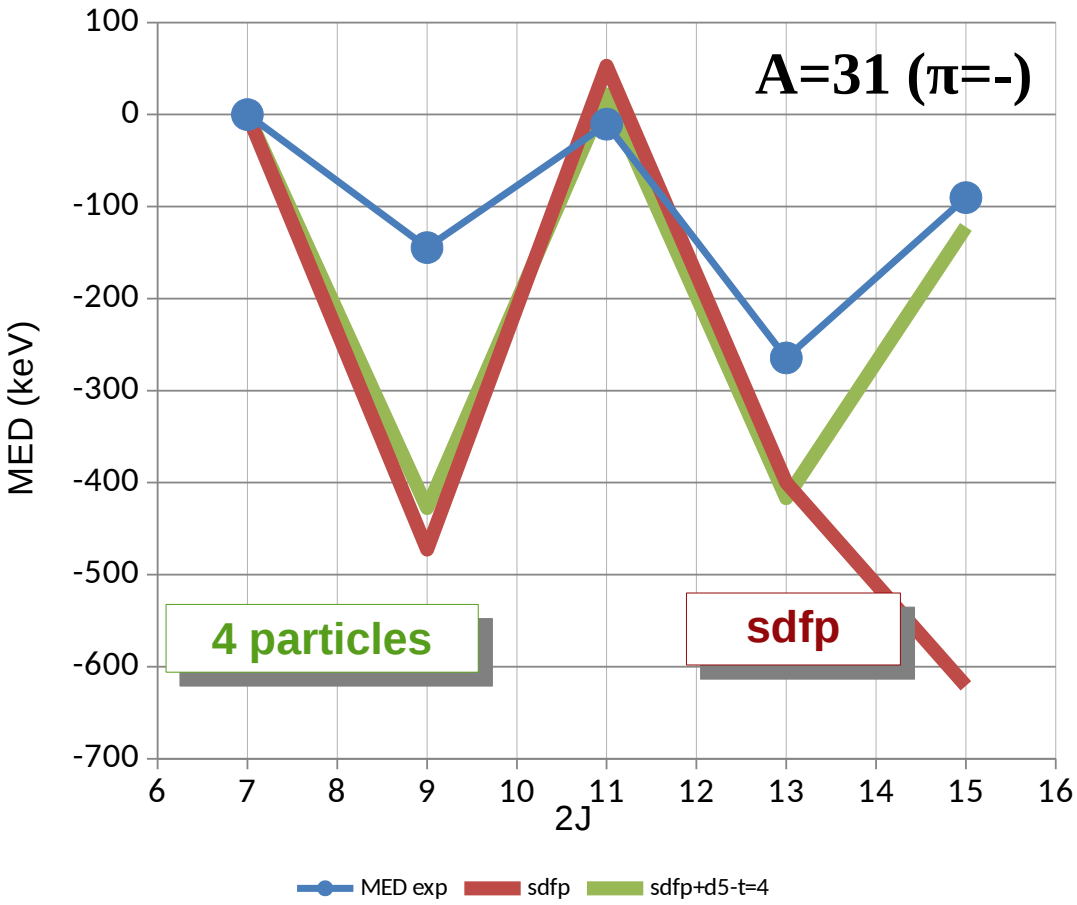
A=31 mirror energy differences, the negative parity states



A	31
$Z_>$	$^{31}_{16}S_{15}$
$Z_<$	$^{31}_{15}P_{16}$



A=31 mirror energy differences, the negative parity states



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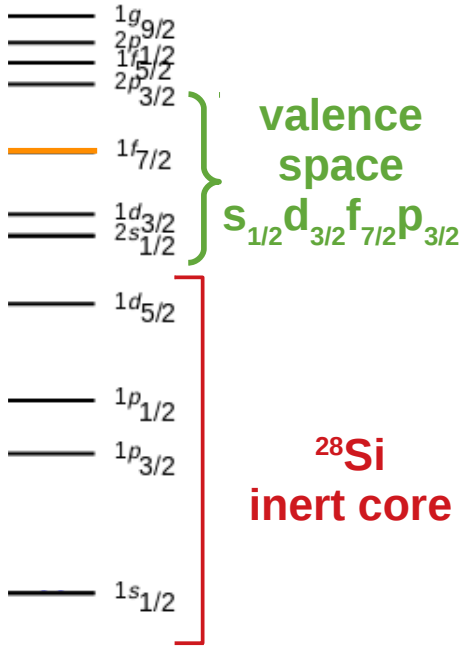

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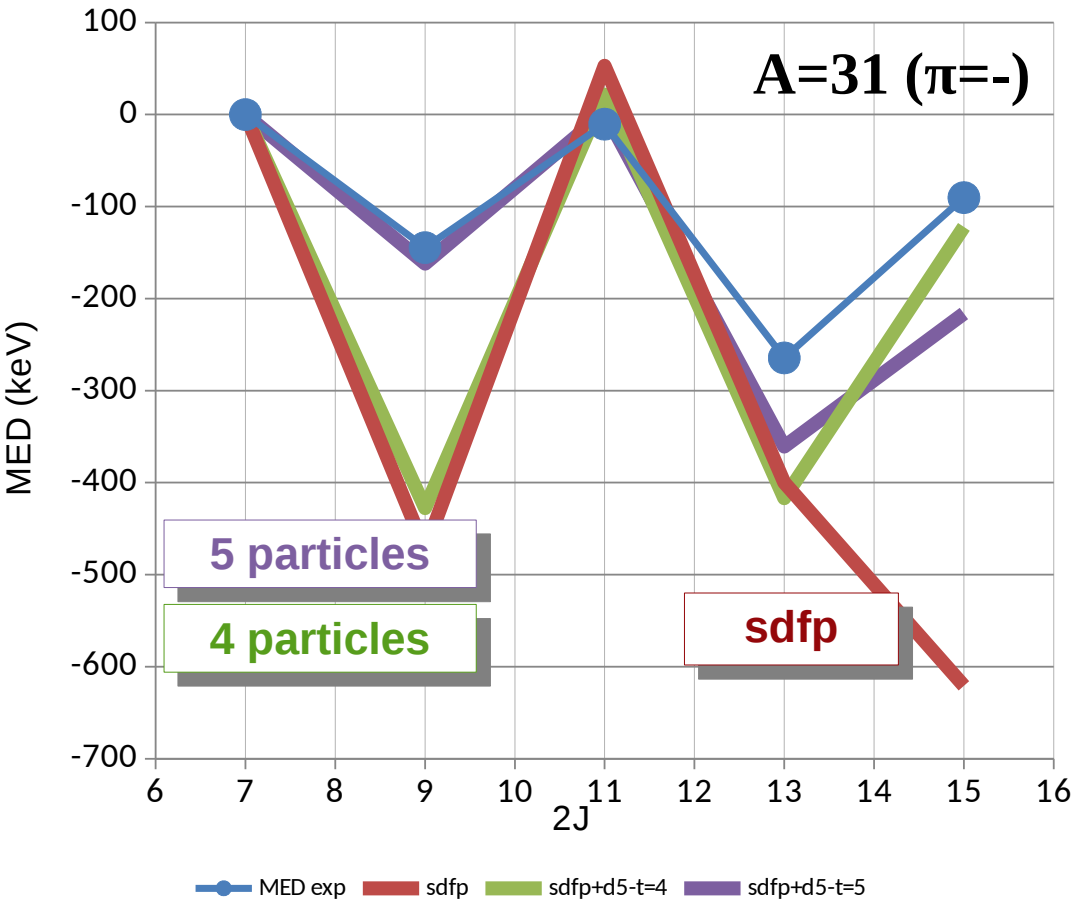

A	31
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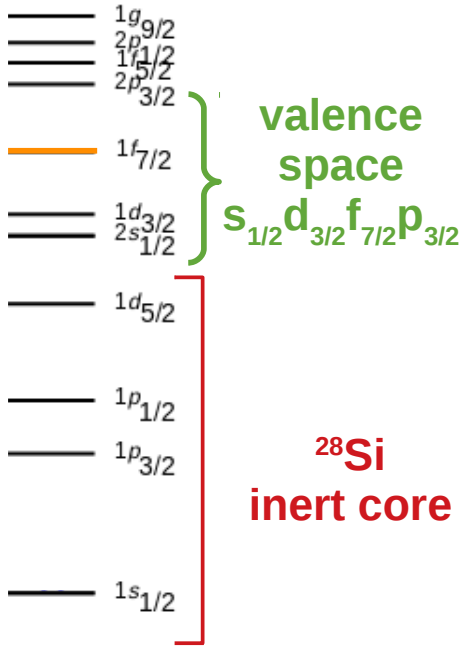
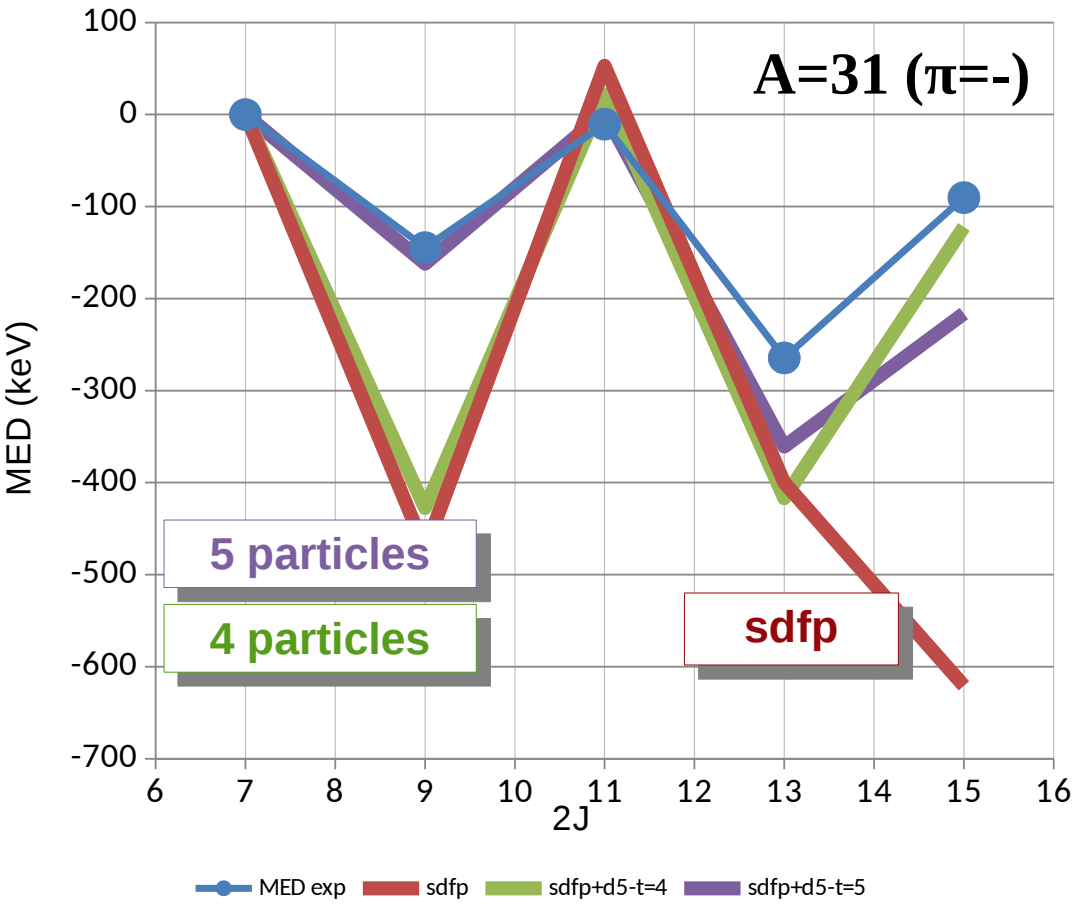
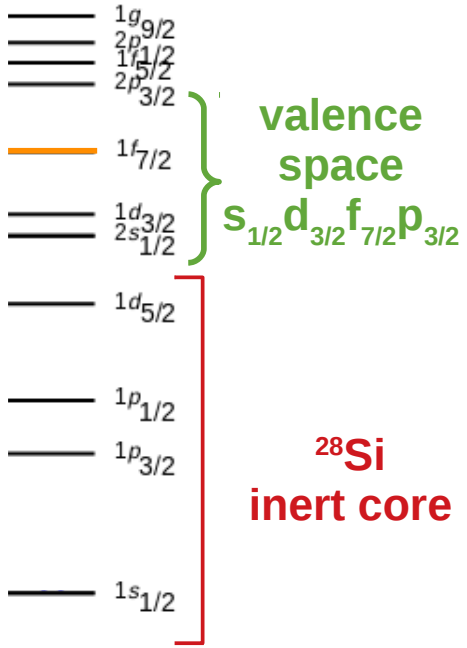


A=35 mirror energy differences, the negative parity states

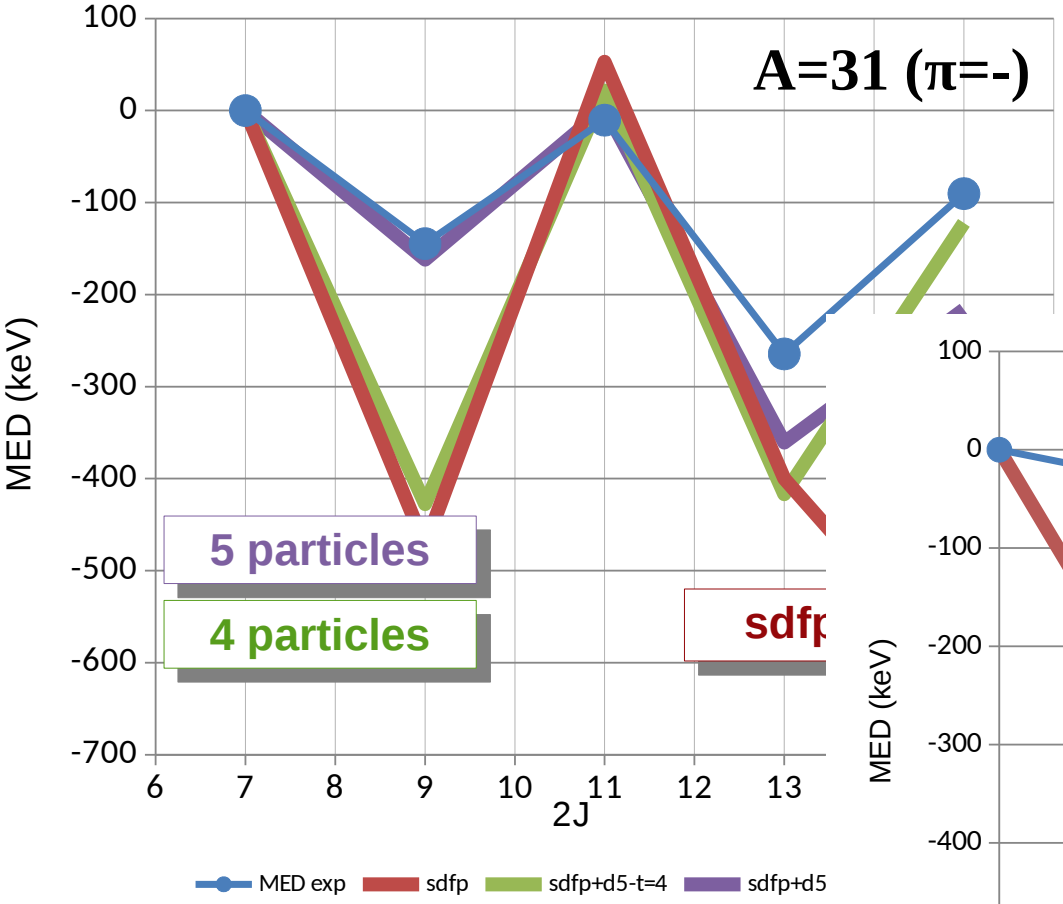


A	31
$Z_>$	$^{31}_{16}S_{15}$
$Z_<$	$^{31}_{15}P_{16}$

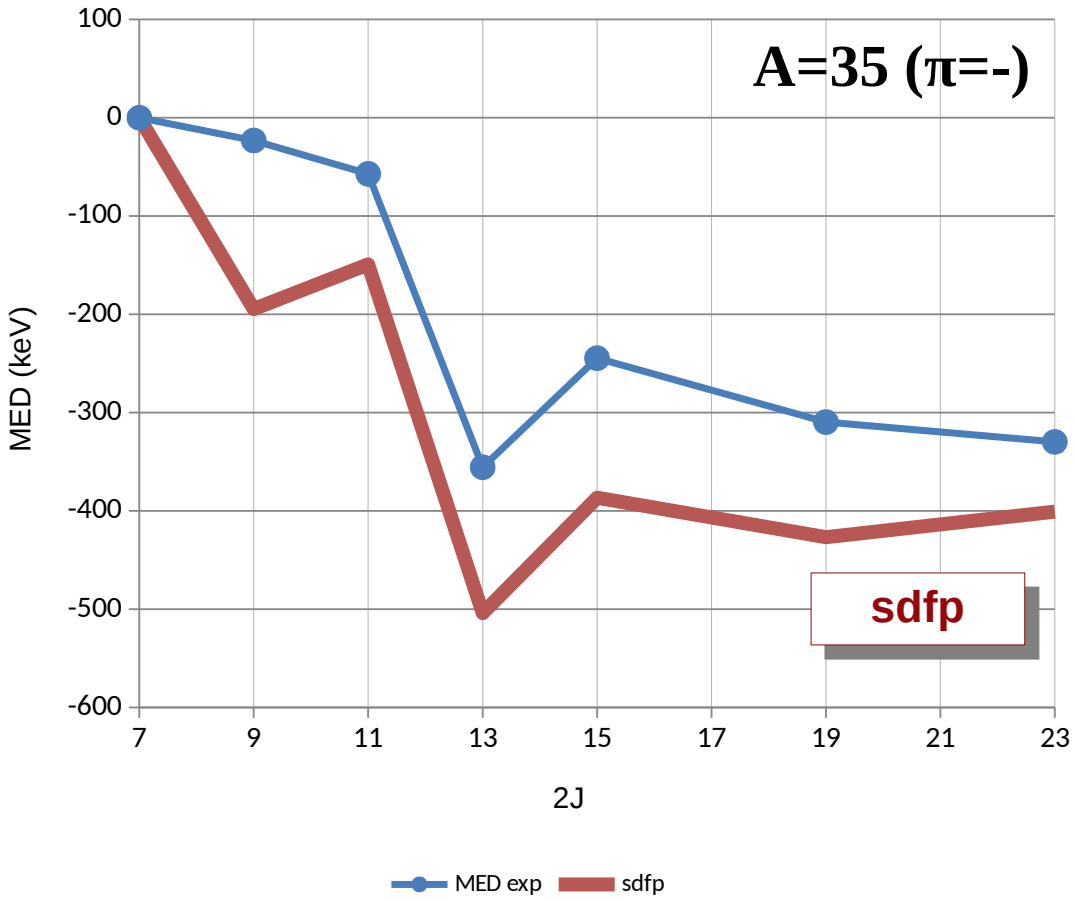


Does the theory work for other nuclei in sd-shell ???

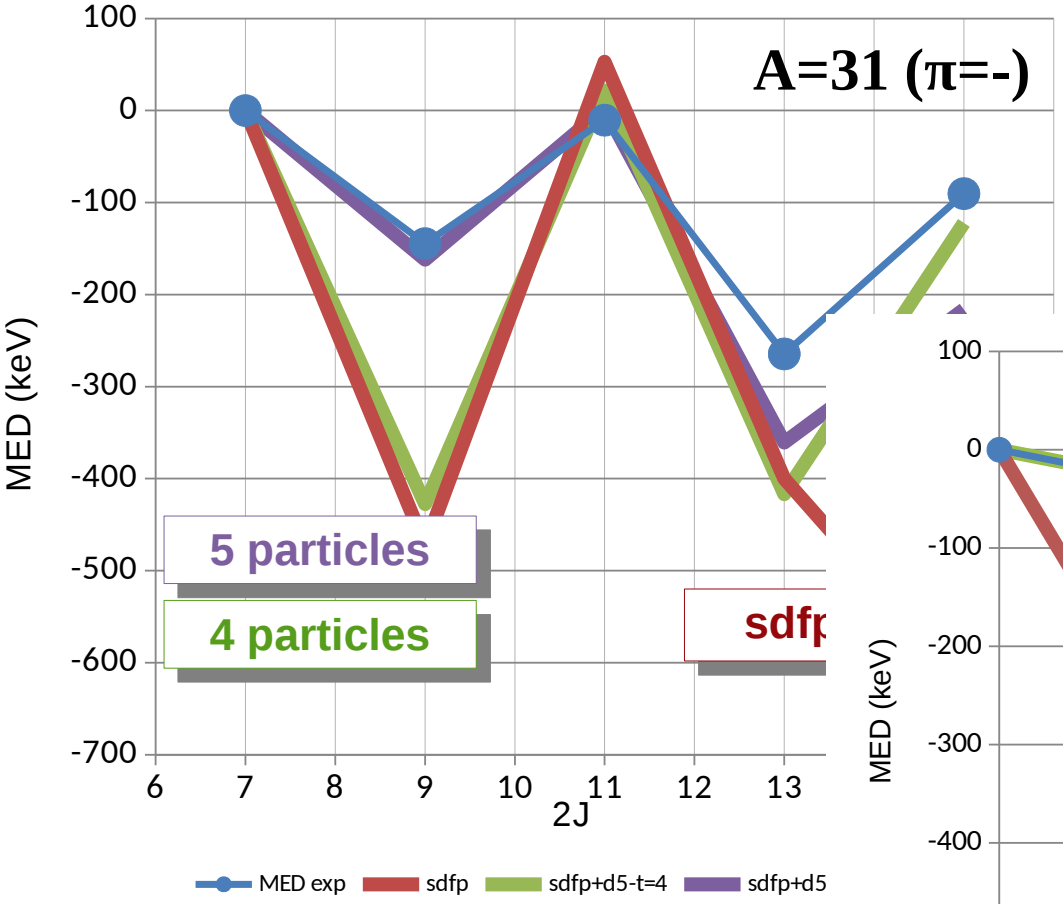
A=35 mirror energy differences, the negative parity states



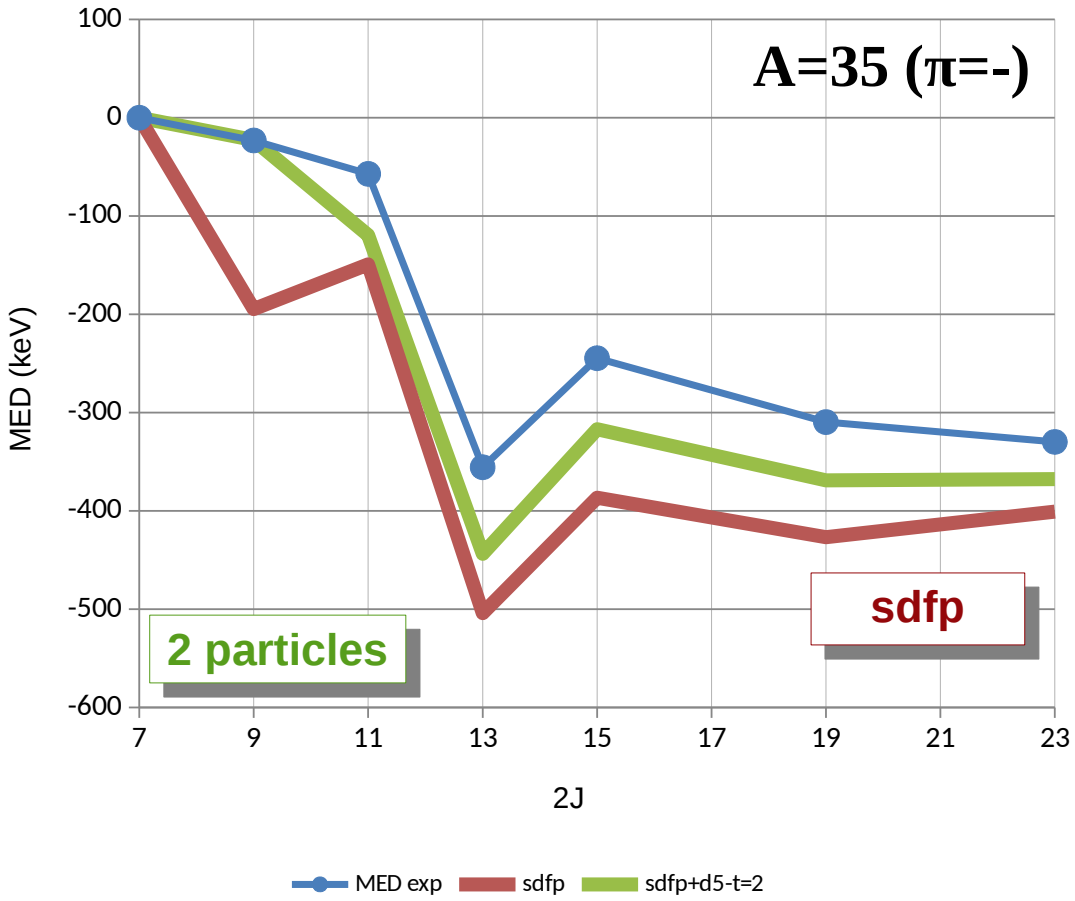
A	31	35
$Z_>$	${}^{31}_{16}S_{15}$	${}^{35}_{18}Ar_{17}$
$Z_<$	${}^{31}_{15}P_{16}$	${}^{35}_{17}Cl_{18}$



A=35 mirror energy differences, the negative parity states



A	31	35
$Z_>$	${}^{31}_{16}S_{15}$	${}^{35}_{18}Ar_{17}$
$Z_<$	${}^{31}_{15}P_{16}$	${}^{35}_{17}Cl_{18}$



A	31	35
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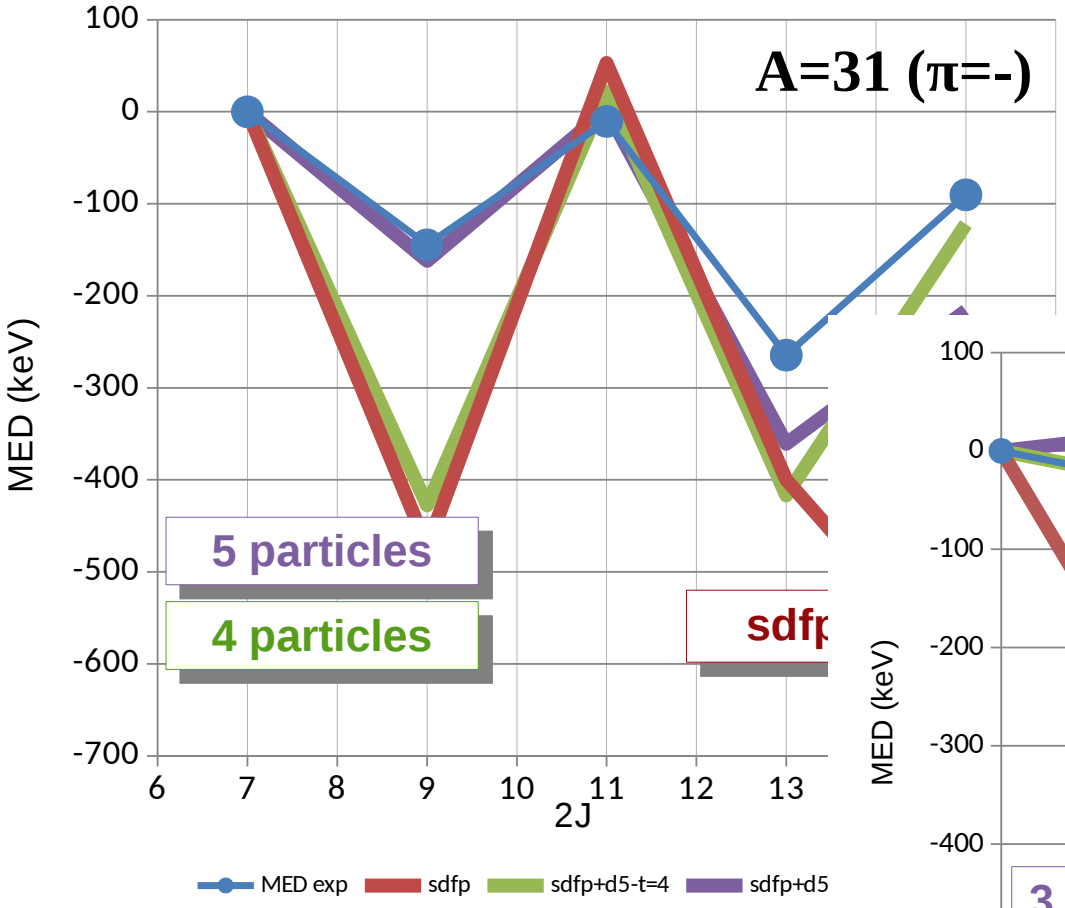

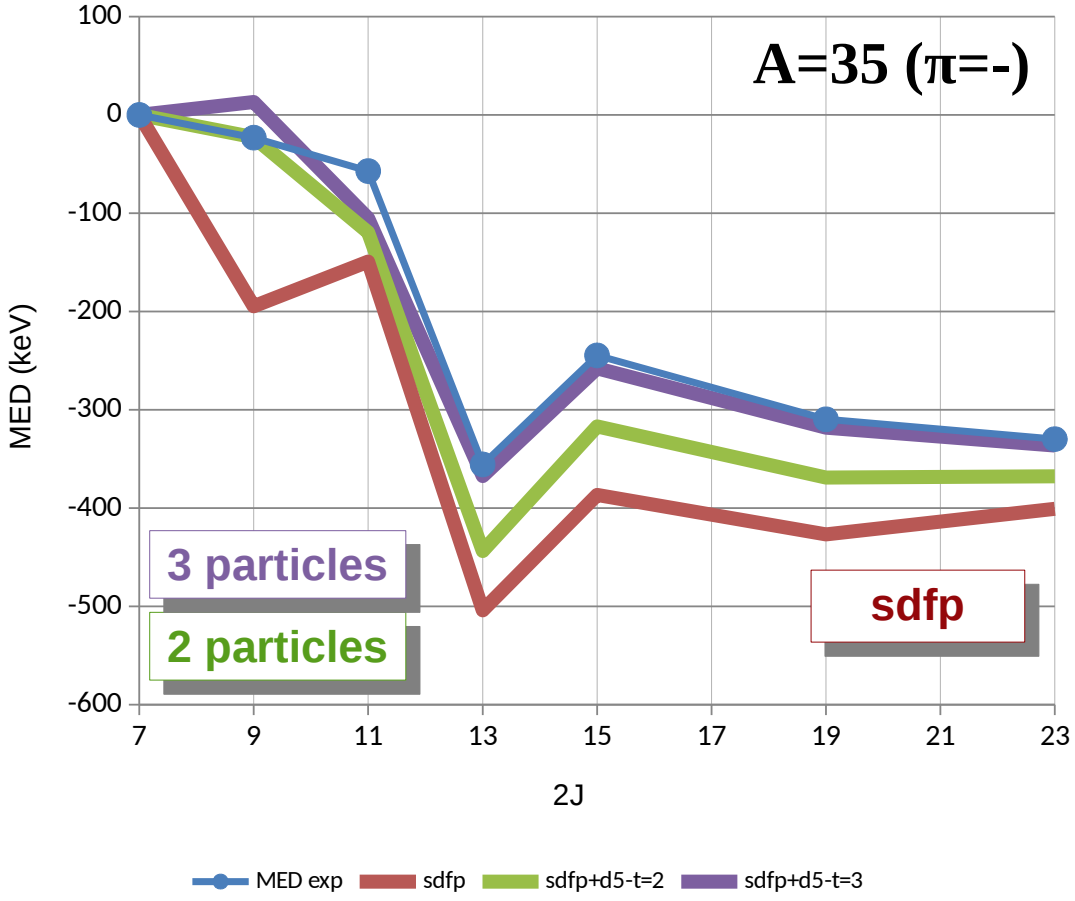

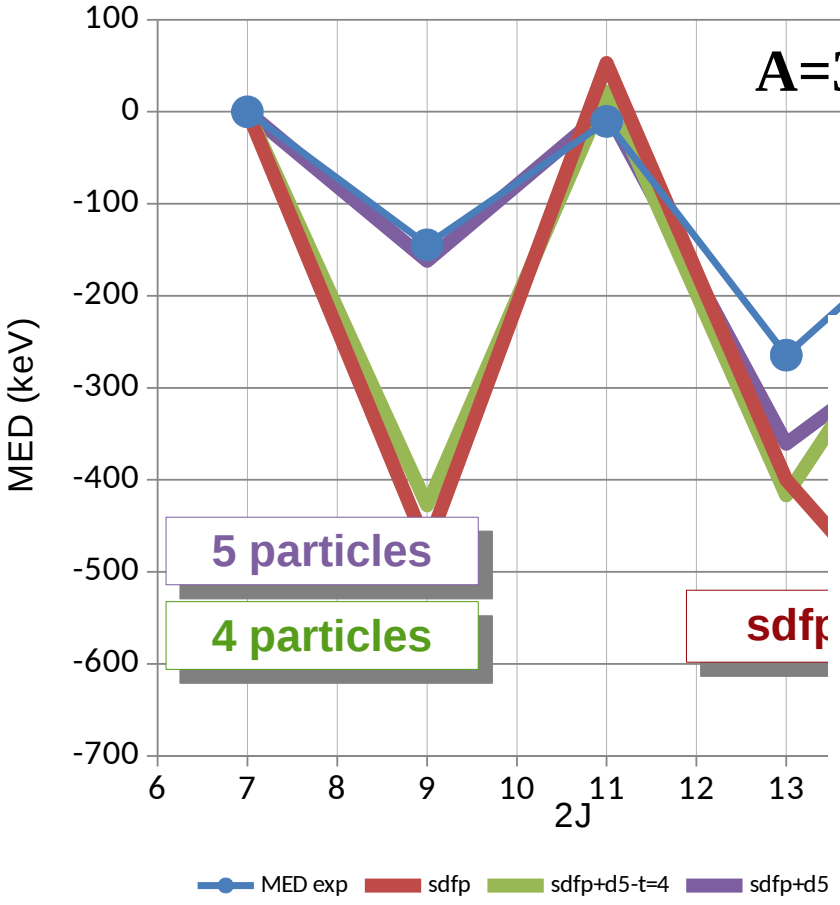

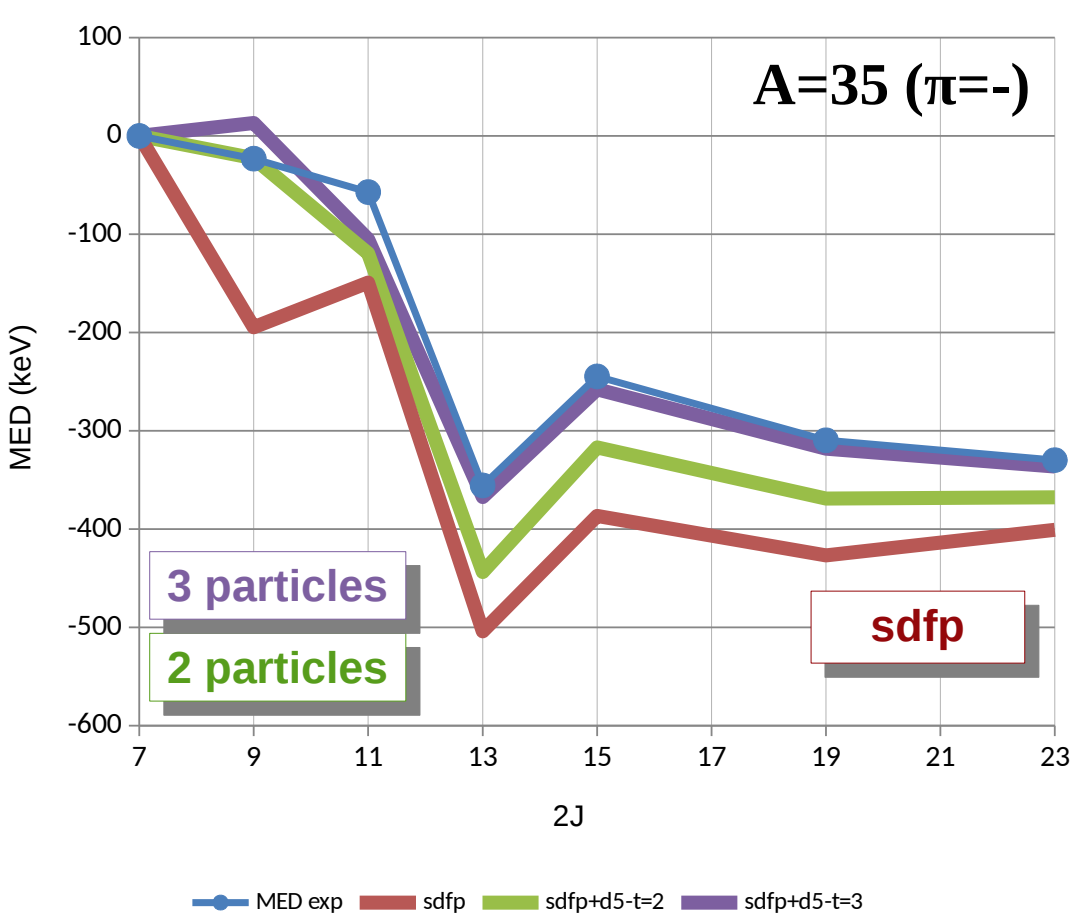

Opening the ^{28}Si core allows reliable description of nuclei on the lower part of sd-shell

To take home:

The first experiment at GALILEO & Co to study A=31 mirror nuclei

- Enhanced resolving power of GALILEO coupled to EUCLIDES+NW
- The full kinematical corrections for Doppler 1.22 MeV γ-line FWHM $\sim$9 keV

Spectroscopy ^{31}S and ^{31}P

- Corrections of spin-parity assignment from previous works
- Systematics of transitions and levels known previously

Shell model calculations

- MED description A=31 for high spin states $\pi+$ and π-
- USD interaction for $\pi+$
- First description of MED in the cross-shell excitation, A=31, 35
- Breaking the ^{28}Si core allows reliable description of A=31, 35 MED values (a few particles in sdfp)
- V_b terms includes all the orbitals from the valence space ($s_{1/2}d_{3/2}f_{7/2}p_{3/2}$)

Thank you for your attention! Credits to collaboration:

D. Testov, A. Boso, S. Lenzi, F. Recchia, G. de Angelis, D. Bazzacco, C. Boiano, G. Colucci, F. Galtarossa, A. Goasduff, A. Gozzelino, K. Hadyńska-Klęk, G. Jaworski, P.R. John, S. Lunardi, R. Menegazzo, D. Mengoni, A. Mentana, V. Modamio, A. Nannini, D.R. Napoli, M. Palacz, M. Rocchini, E. Sahin, M. Siciliano, J.J. Valiente-Dobón