Isospin symmetry breaking in mirror nuclei

Microscopic description of CED

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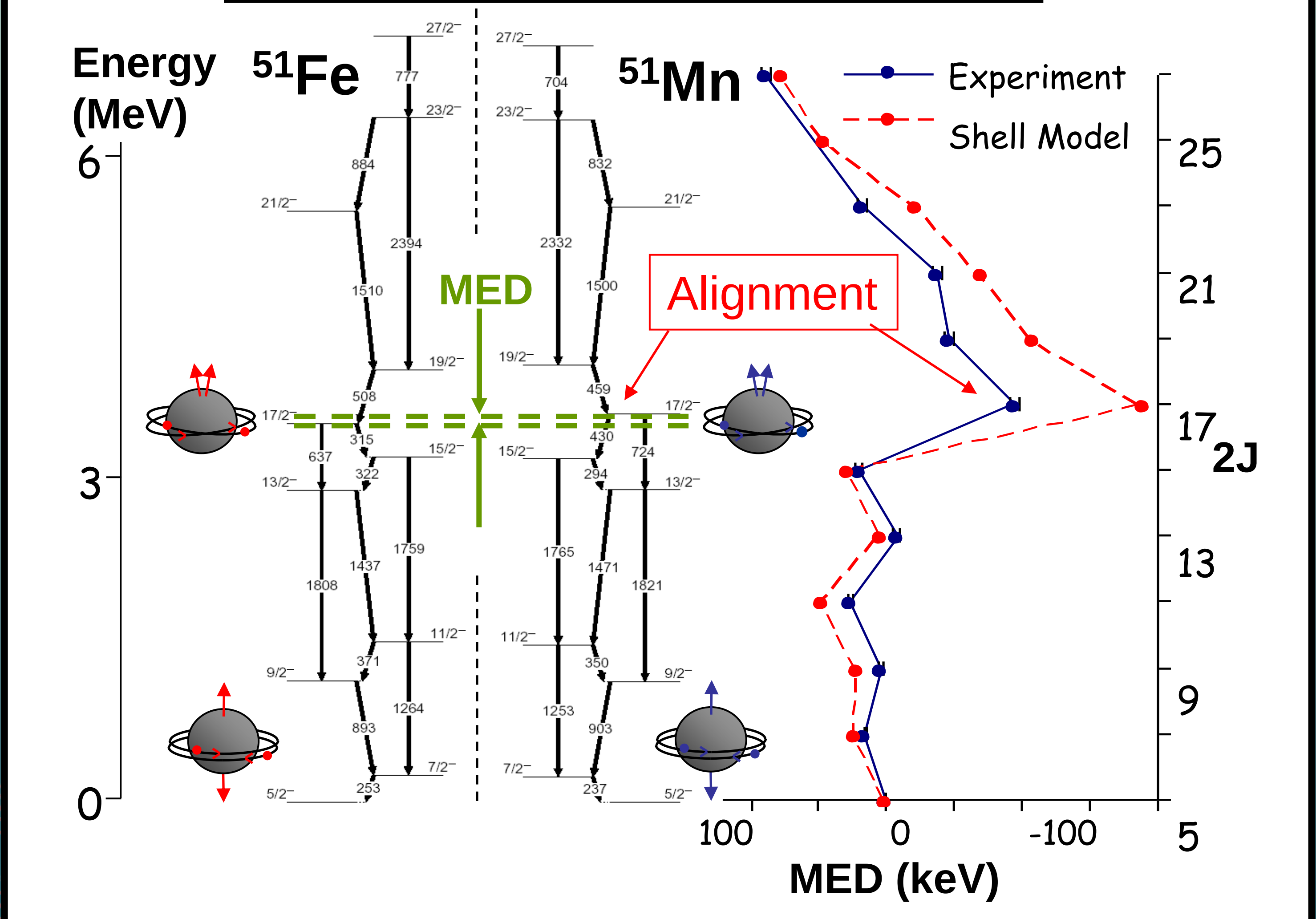
3. Theoretical tools
Second part

Nucleon alignment at the backbending

D.D. Warner, M.A. Bentley and P. Van Isacker., Nature Physics 2 (2006) 311



Alignment and shell model

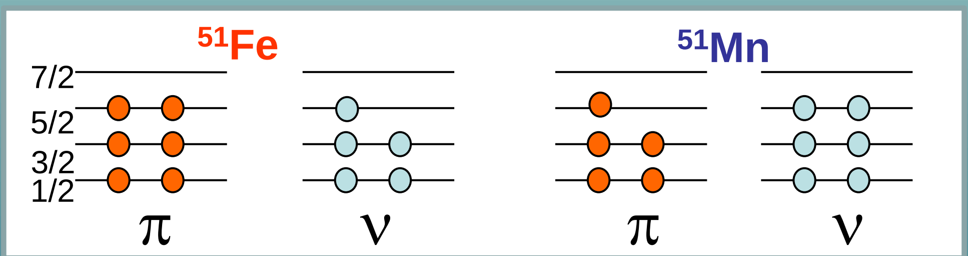
Define the operator

$$\mathbf{A}_\pi = \left[\left(a_\pi^+ a_\pi^+ \right)^{J=6} \left(a_\pi a_\pi \right)^{J=6} \right]^0$$

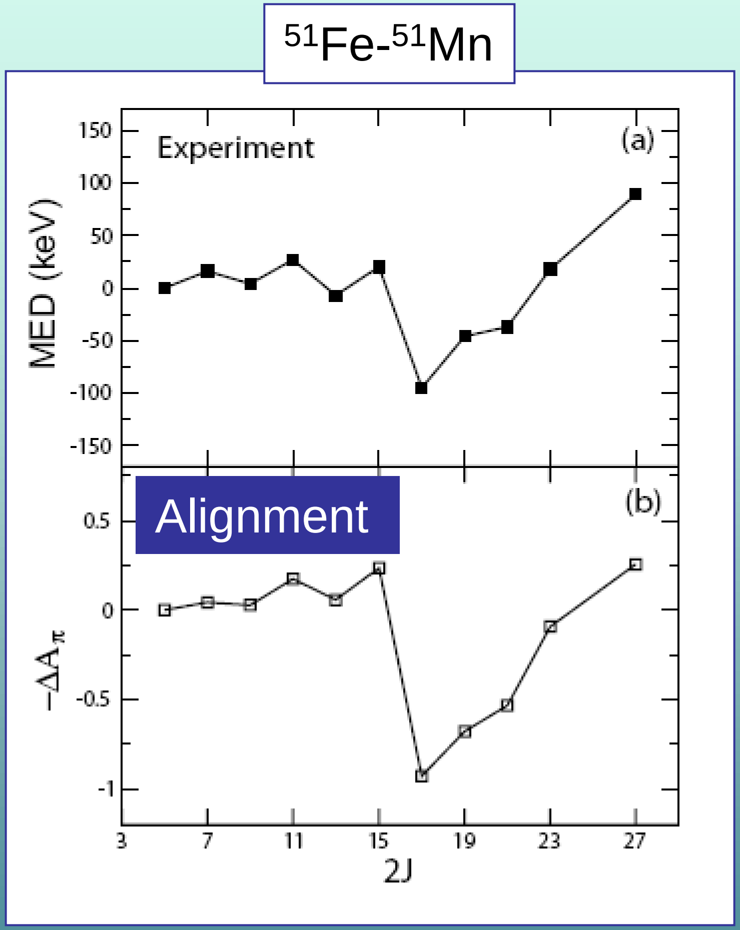
"Counts" the number of protons coupled to J=6

Calculate the difference of the expectation value in both mirror as a function of the angular momentum

$$\Delta \mathbf{A}_{\pi,J} = \langle \Phi_J | \mathbf{A}_\pi (Z_>) | \Phi_J \rangle - \langle \Phi'_J | \mathbf{A}_\pi (Z_<) | \Phi'_J \rangle$$



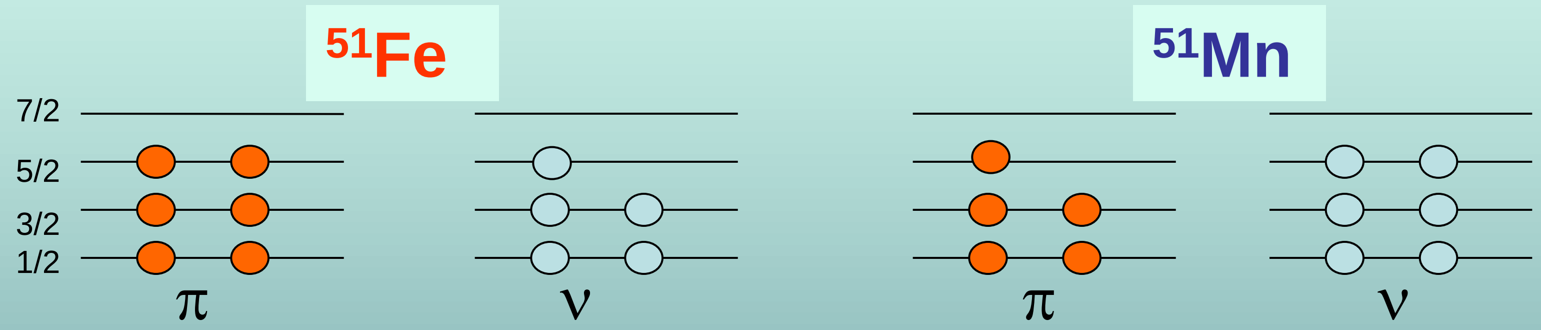
In ^{51}Fe (^{51}Mn) a pair of protons (neutrons) align first and at higher frequency align the neutrons (protons)



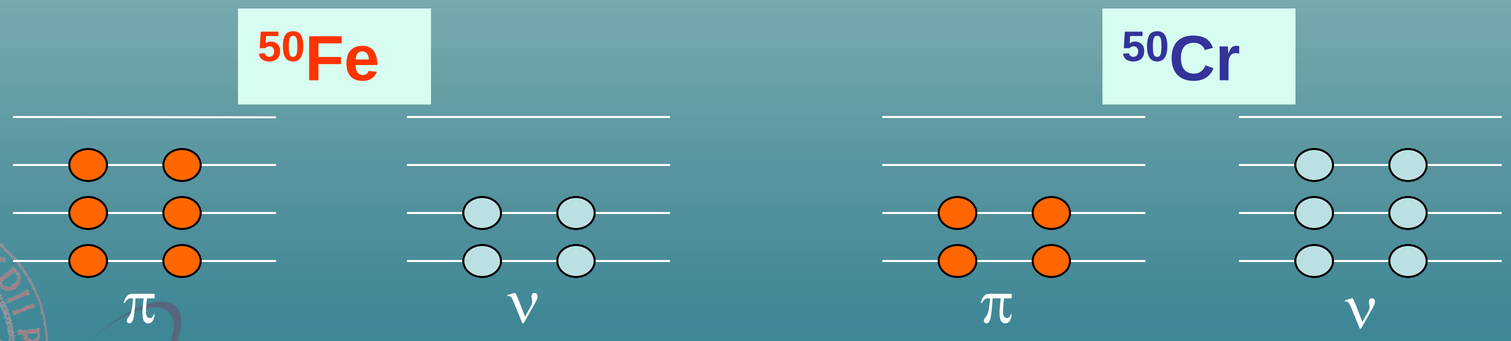
M.A.Bentley et al. Phys Rev. C62 (2000) 051303

Alignment in odd- and even-mass nuclei

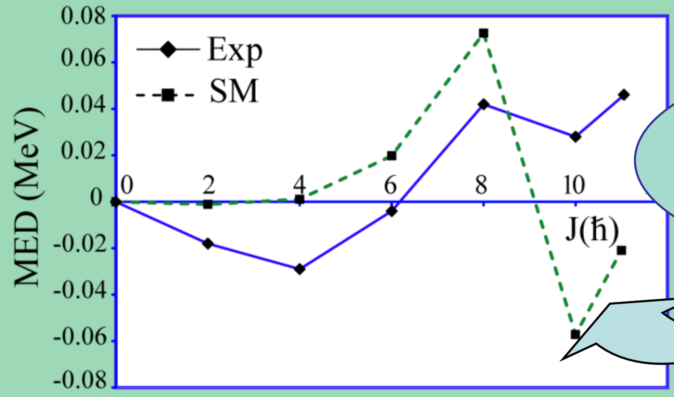
In odd-mass nuclei, the type of nucleons that aligns first is determined by the **blocking effect** → the even fluid will align first



What about even-even rotating nuclei?



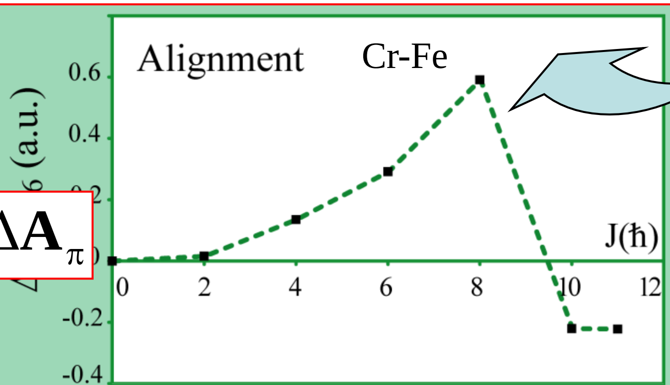
Alignment in even-even rotating nuclei



Renormalization of the Coulomb m.e.? Only a Coulomb effect?

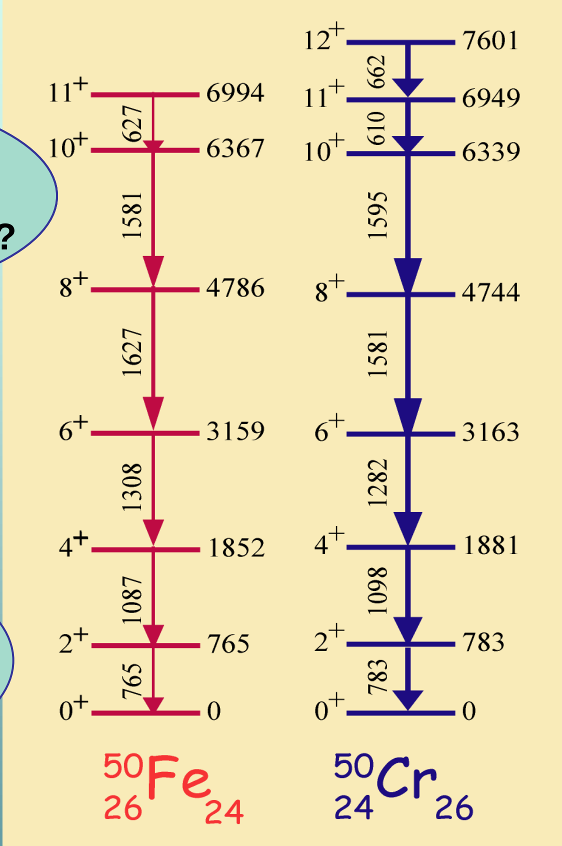
calculate for protons in both mirrors:

$$\Delta \mathbf{A}_\pi = \langle \Phi_J | \mathbf{A}_\pi(Z_>) | \Phi_J \rangle - \langle \Phi'_J | \mathbf{A}_\pi(Z_<) | \Phi'$$



$-\Delta \mathbf{A}_\pi$

counts the number of aligned protons



In ^{50}Cr (^{50}Fe) a pair of protons (neutrons) align first and at higher frequency align the neutrons (protons)

S.M.Lenzi et al., Phys. Rev. Lett. 87, 122501 (2001)

can shell model do better?

Can we do better?

By adding the Coulomb interaction to the effective nuclear hamiltonian in the valence space, we forget the interaction with the core!

This Coulomb interaction between valence protons is just the multipole term V_{CM}. The monopole term is missing.

$$V_C = V_{CM} + V_{Cm}$$

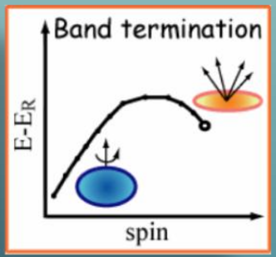
Multipole

monopole

The monopole term gives the bulk properties which contribute largely
→ to the nuclear mass (100's of MeV)
→ to the CDE (10's of MeV)

Monopole Coulomb effects

When we “normalize” to the g.s. energy, these large effects vanish, however…
a small but important effect remains as a function of the angular momentum, and it is related to changes of the nuclear radius, or deformation (10’s of keV), and to single-particle effects.



1) The radial term

Coulomb energy of a charged sphere:

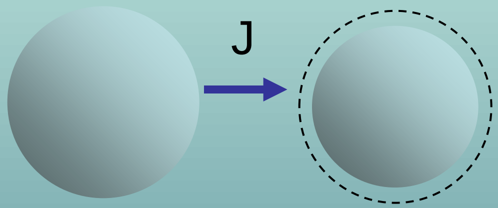
$$E_C = \frac{3Z(Z-1)e^2}{5R_C}$$

The difference between the energy of the ground states (CDE):

$$T_z = \pm\frac{n}{2}$$

$$\Delta E_C(J=0) = E_C(Z_>) - E_C(Z_<) = \frac{3n(2Z_> - n)e^2}{5R_C}$$

If R_C changes as a function of the angular momentum…



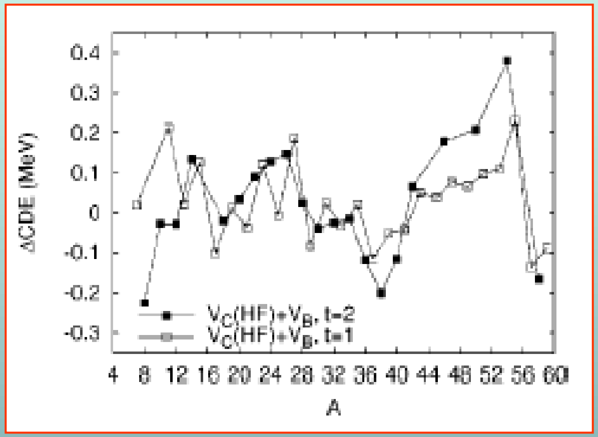
$$\Delta E_{Cr}(J) = \Delta E_C(J) - \Delta E_C(0) = \frac{3}{5}n(2Z_> - n)e^2\left(\frac{R_C(0) - R_C(J)}{R_C^2}\right)$$

$$= -\frac{3}{5}n(2Z_> - n)e^2\,\frac{\Delta R_C(J)}{R_C^2} = \boxed{nC\cdot\Delta R_C(J)}$$

Radial contribution to the MED

2) The orbital term

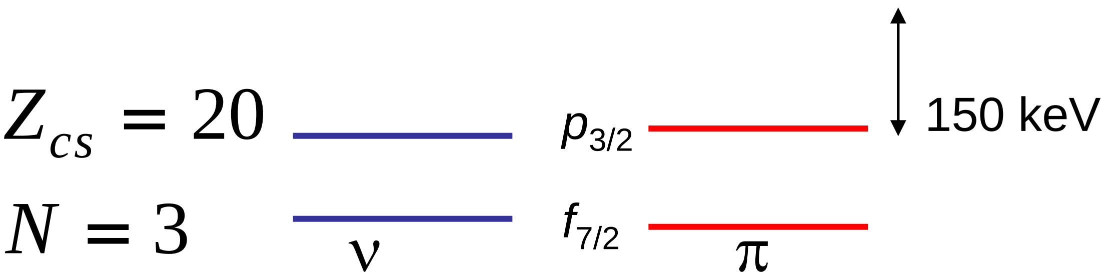
J. Duflo and A.P. Zuker, *Phys. Rev.* C 66 (2002) 051304(R)



The monopole Coulomb term accounts for shell effects.
It changes the single-particle energy of the protons proportionally to the square of the orbital angular momentum.
For a proton in a main shell N above a closed shell Z_{cs} its value is deduced:

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

Eg. in the fp shell:



proton s.p. relative energy is increased by 150 keV

3) The electromagnetic spin-orbit term

Analogous to the atomic case, the nuclear electromagnetic spin-orbit coupling has relativistic origin.

It results from the Larmor precession of the nucleons (protons and neutrons) in the nuclear electric field due to the intrinsic (spin) magnetic moments and the Thomas precession experienced by the protons due to their electric charge (orbital magnetic moment).

$$V_{Cls} = (g_s - g_l)\frac{1}{2m_N^2c^2}\left(\frac{1}{r}\frac{dV_C}{dr}\right)\vec{l}\cdot\vec{s}$$

(50 times smaller than the nuclear spin-orbit term)

$$E_{Cls} = (g_s - g_l)\frac{1}{2m_N^2c^2}\left(-\frac{Ze^2}{R}\right)\langle\vec{l}\cdot\vec{s}\rangle$$

$$\langle\vec{l}\cdot\vec{s}\rangle = -l \Leftrightarrow j = l + s$$

$$\langle\vec{l}\cdot\vec{s}\rangle = l + 1 \Leftrightarrow j = l - s$$

Effect depending on the orbit!!!

Electromagnetic spin-orbit term

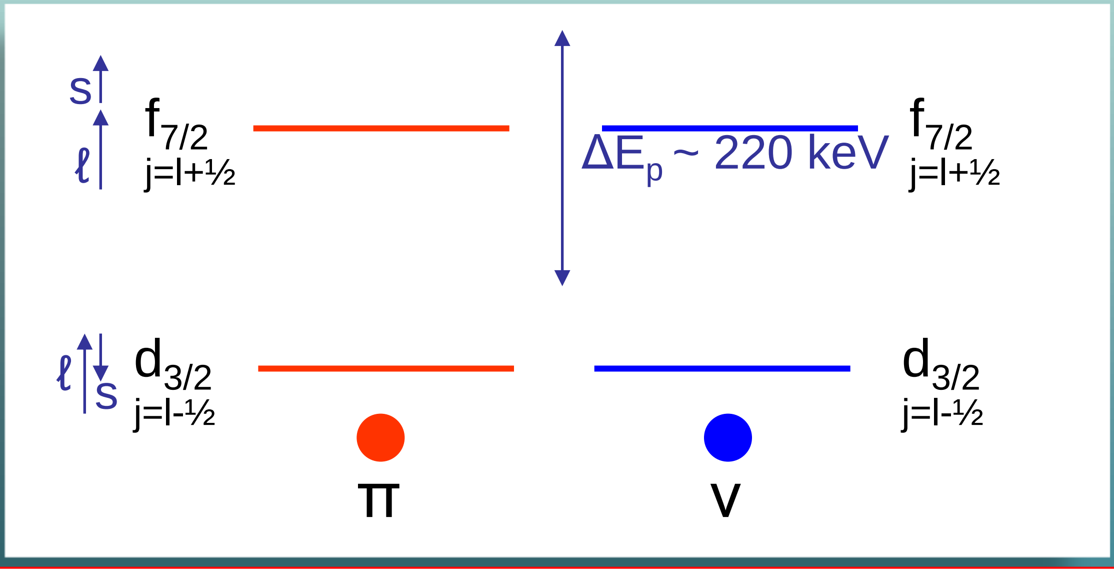
Acts differently on protons and neutrons: using free giromagnetic factors…

$$g_s^{\pi} = +5.586, \quad g_{\ell}^{\pi} = 1$$

$$g_s^{\nu} = -3.828, \quad g_{\ell}^{\nu} = 0$$

The approximate values for the energy shifts result:

	$\pi, j = l + \frac{1}{2}$	$\pi, j = l - \frac{1}{2}$	$\nu, j = l + \frac{1}{2}$	$\nu, j = l - \frac{1}{2}$
E_{ls}	$-42(Z/A)l$	$+42(Z/A)(l+1)$	$+35(Z/A)l$	$-35(Z/A)(l+1)$



Its contribution to the MED becomes significant for configurations with a ***pure*** single-nucleon excitation to the $f_{7/2}$ shell: a proton excitation in one nucleus and a neutron excitation in its mirror

First result in *sd* shell: *A*=35

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Unusual Isospin-Breaking and Isospin-Mixing Effects in the $A = 35$ Mirror Nuclei

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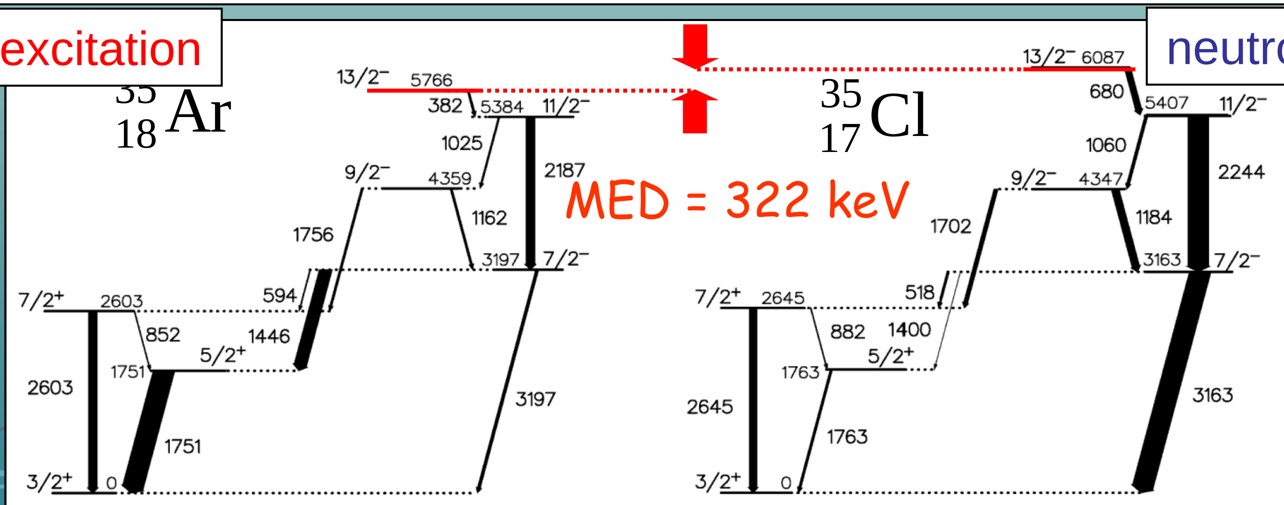
Excited states have been studied in ^{35}Ar following the ^{16}O(^{24}Mg, $1\alpha 1n$)^{35}Ar fusion-evaporation reaction at 60 MeV using the Ge-detector array GASP. A comparison with the mirror nucleus ^{35}Cl shows two remarkable features: (i) A surprisingly large energy difference for the $13/2^-$ states, in which the hitherto overlooked electromagnetic spin-orbit term is shown to play a major role, and (ii) a very different decay pattern for the $7/2^-$ states, which provides direct evidence of isospin mixing.

proton excitation

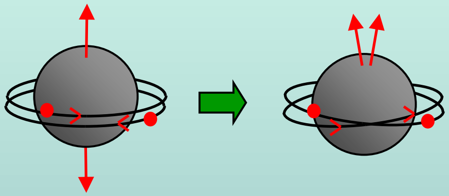
neutron excitation



Summary of Coulomb effects

$$V_C = V_{CM} + V_{Cm}$$

Multipole part of the Coulomb energy V_{CM}: → Between valence protons only

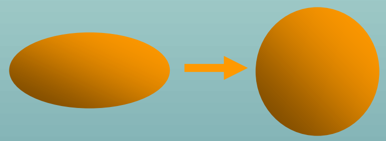


Monopole part of the Coulomb energy V_{cm}:

interaction with the core

$$E_{Cr} = \frac{3}{5}\frac{e^2 Z(Z-1)}{R}$$

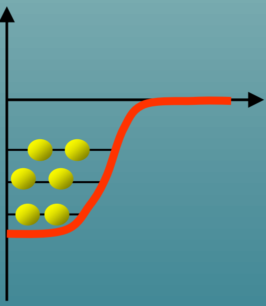
radial effect: radius changes with J



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

$$E_{Cls} = (g_s - g_l)\frac{1}{4m_N^2 c^2}\left(\frac{1}{r}\frac{dV_C}{dr}\right)\mathbf{l.s}$$

change the single-particle energies



A.P. Zuker

How to calculate MED with the shell model

1) Effective Coulomb interaction: Multipole Coulomb V_{CM}
The matrix elements are obtained in the harmonic oscillator basis with standard parameters.

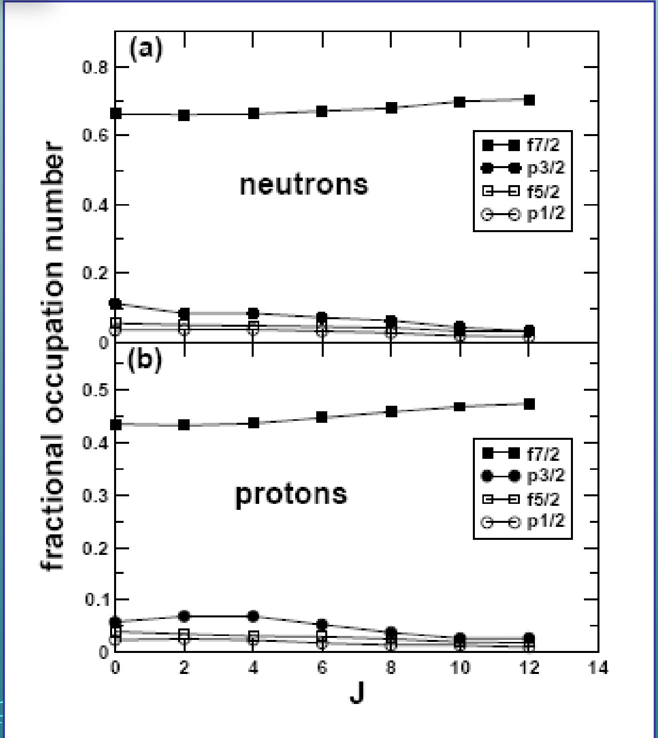
2) Monopole Coulomb effects:
i. Single-particle energies for protons and neutrons are changed following $E_{C\ell\ell}$ and $E_{C\ell s}$.
ii. Radial term:

The radial term

The total radius depends on those of the single orbits. Orbital radii depend on ℓ . In the *fp* shell, *p* orbits have larger radius than *f* orbits and therefore are less affected by Coulomb repulsion.

Wave functions are dominated by the $f_{7/2}$ shell.
Deformed low-spin states have larger $p_{3/2}$ admixtures than aligned high-spin states

fractional occupations for ^{50}Cr



The radial effect with the shell model

The radial contribution can be calculated from the relative $p_{3/2}$ occupation number along the yrast band in the shell model framework:

$$\Delta\langle V_{Cr}\rangle_J = n a_m \langle m_{p_{3/2}}\rangle_J = n a_m \left\langle \frac{z_{p_{3/2}} + n_{p_{3/2}}}{2} \right\rangle_J$$

z and n are the number of protons and neutrons in the $p_{3/2}$ orbit, relative to the g.s. (J=0)

$$n = |N - Z| = 2T_z$$

a_m is not a free parameter but can be estimated experimental data:

The radial parameter amounts to $a_m \sim 200$ keV
the same for all MED studied so far (not only fp shell).

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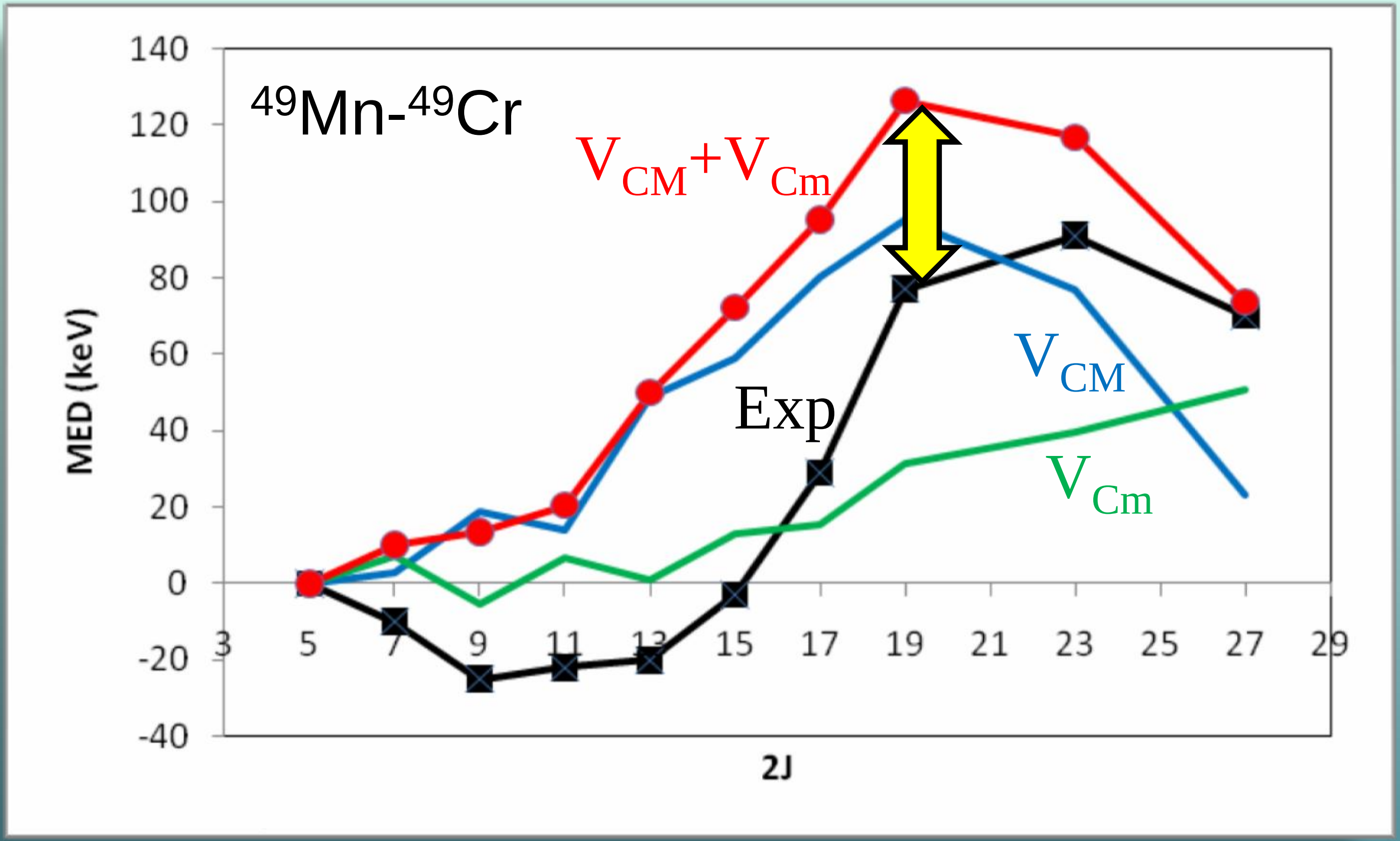
Are Coulomb corrections enough?



Still a large discrepancy is observed between data and theory

Another term of <u>non-Coulomb nature</u> is needed, but it has to be big!

Looking for an empirical interaction

In the single $f_{7/2}$ shell, an interaction V can be defined by two-body matrix elements written in the proton-neutron formalism :

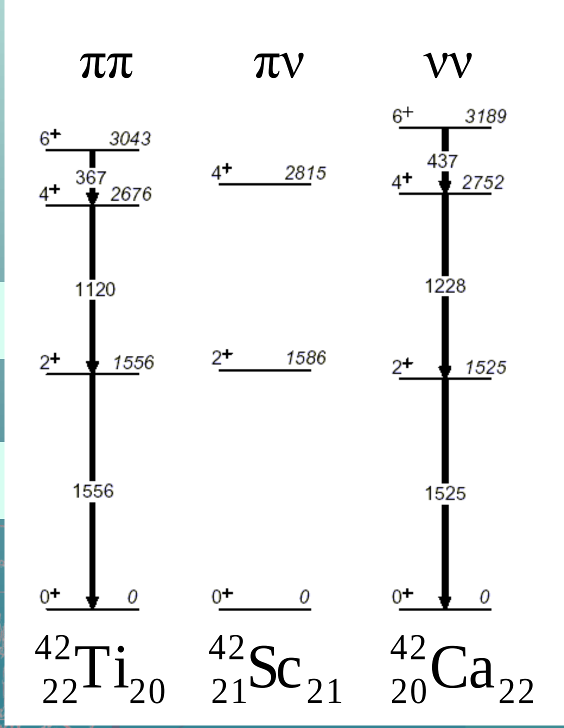
$$V^{\pi\pi}, V^{\pi\nu}, V^{\nu\nu}$$

We assume that the configurations of these states are pure $(f_{7/2})^2$

We can recast them in terms of isoscalar, isovector and isotensor contributions

$$U^{(0)} = V^{\pi\pi} + V^{\pi\nu} + V^{\nu\nu}$$
$$U^{(1)} = V^{\pi\pi} - V^{\nu\nu}$$
$$U^{(2)} = V^{\pi\pi} + V^{\nu\nu} - 2V^{\pi\nu}$$

V_B is an ISB term of non-Coulomb origin



^{42}Ti-^{42}Ca$) = U^{(1)}_{f_{7/2},J} = V^{(1)}_{C,J} + V^{(1)}_{B,J}$ — Isovector

^{42}Ca - 2·^{42}Sc$) = U^{(2)}_{f_{7/2},J} = V^{(2)}_{C,J} + V^{(2)}_{B,J}$ — Isotensor

differences are due only to V_C one expects
small numbers for all J values for V_B

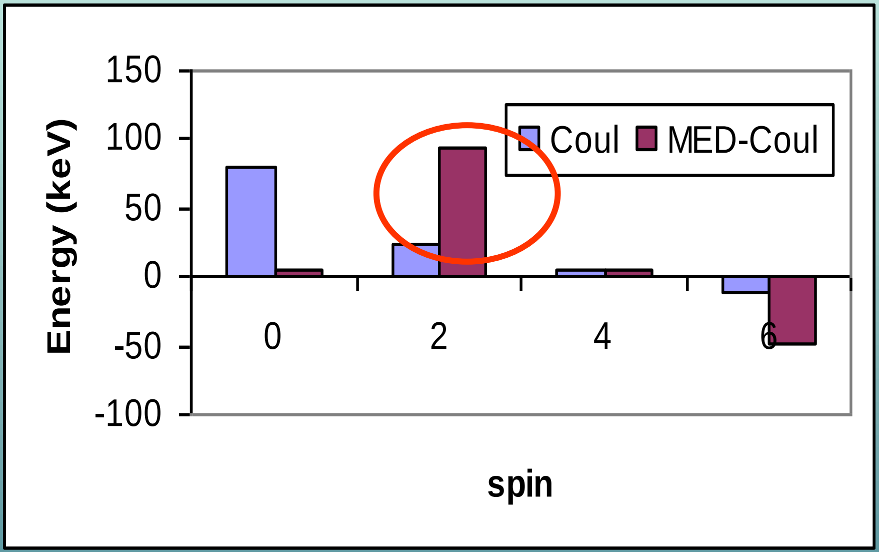
A. P. Zuker et al., Phys. Rev. Lett. 89, 142502 (2002)

Looking for an empirical interaction

V_C is calculated for every J state in the $f_{7/2}$ shell
and then subtracted to MED and TED to estimate V_B

$$MED_J\,(^{42}\text{Ti-}^{42}\text{Ca}) - V^{(1)}_{C,J} = V^{(1)}_{B,J}$$

	J=0	J=2	J=4	J=6
V_C	81	24	6	-11
MED-V_C= $V^{(1)}_B$	5	**93**	5	-48
TED-V_C=$V^{(2)}_B$	**117**	81	3	-42



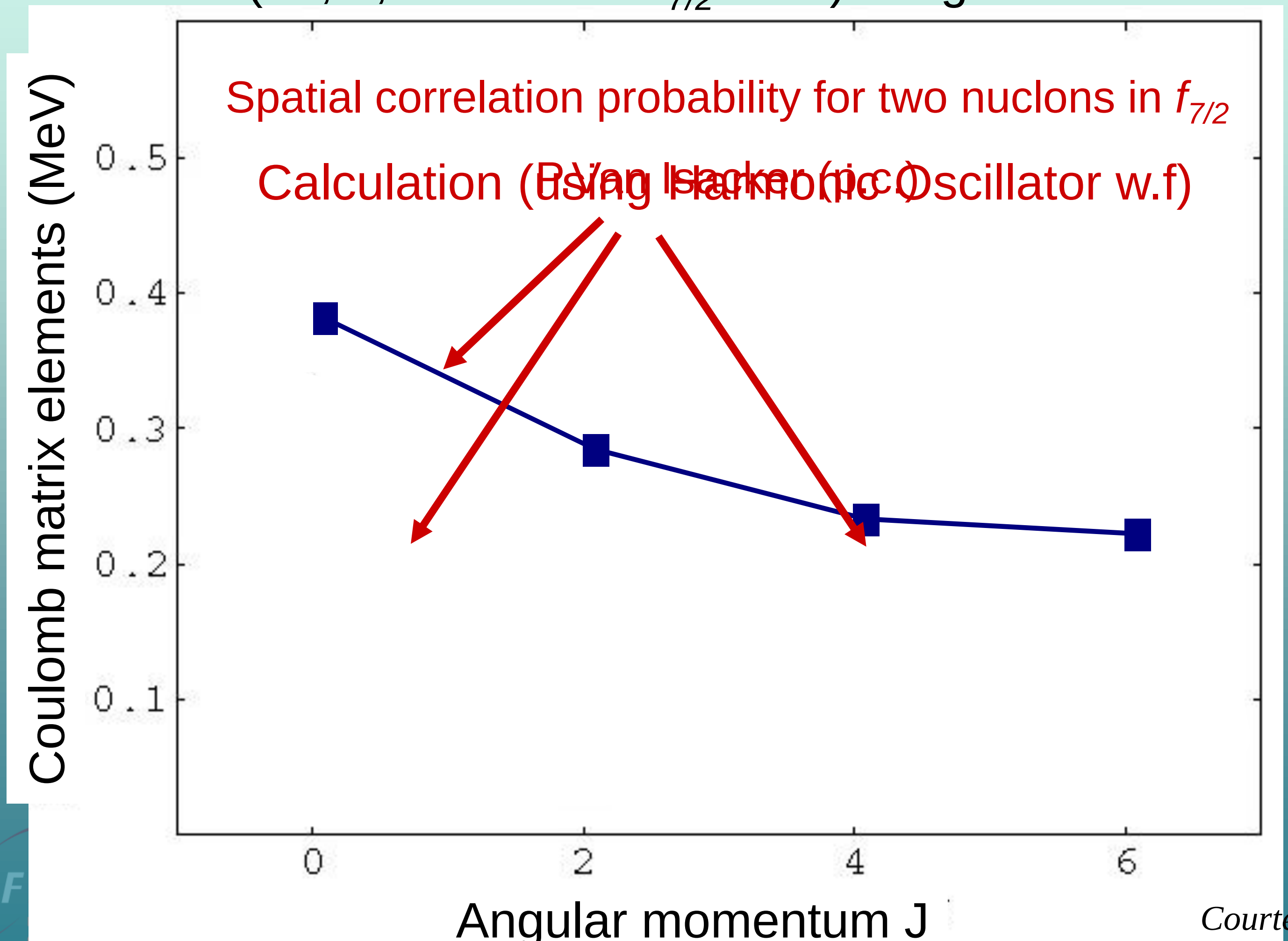
This suggests that the role of the isospin non conserving nuclear force is at least as important as the Coulomb potential in the observed MED

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

The "J=2 anomaly"

Clearly not just Coulomb two-body effects:

Coulomb Matrix Elements: Coulomb energy of proton pair as a function of J (=0, 2, 4 and 6 for $f_{7/2}$ *shell*) – ingredient for SM



Courtesy M. Bentley

Learning from MED and TED in A=42

From the yrast spectra of the T=1 triplet ^{42}Ti, ^{42}Sc, ^{42}Ca we deduce:

$$V_C = V_C^{h.o.}(f_{7/2})$$

	J=0	J=2	J=4	J=6	
V_C	81	24	6	-11	Calculated
MED-V_C	5	**93**	5	-48	estimate $V_{Bf7/2}^{(1)}$
TED-V_C	**117**	81	3	-42	estimate $V_{Bf7/2}^{(2)}$

How to include this effect in the shell model framework and in the full pf calculation?

Simple ansatz
for the application to
nuclei in the pf shell:

$$V_{Bpf}^{(1)} = 100\,\text{keV}\ (J=2)$$

$$V_{Bpf}^{(2)} = 100\,\text{keV}\ (J=0)$$

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

Calculating MED and TED

We rely on isospin-conserving shell model wave functions and obtain the energy differences in first order perturbation theory as sum of expectation values of the Coulomb (V_C) and isospin-breaking (V_B) interactions

$$MED_J^{\exp} = E_J^*(Z_>) - E_J^*(Z_>)$$

$$MED_J^{theo} = \Delta_M \langle V_{Cm} \rangle_J + \Delta_M \langle V_{CM} \rangle_J + \Delta_M \langle V_B \rangle_J$$

$$TED_J^{\exp} = E_J^*(Z_>) + E_J^*(Z_>) - 2E_J^*(N=Z)$$

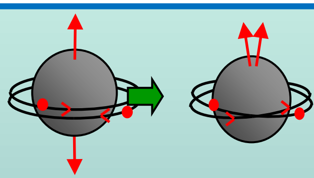
$$TED_J^{Theo} = \Delta_T \langle V_{CM} \rangle_J + \Delta_T \langle V_B \rangle_J$$

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

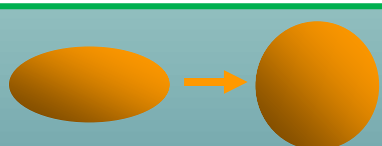
Evidence of ISB of the nuclear interaction?

Very good quantitative agreement between theory and data

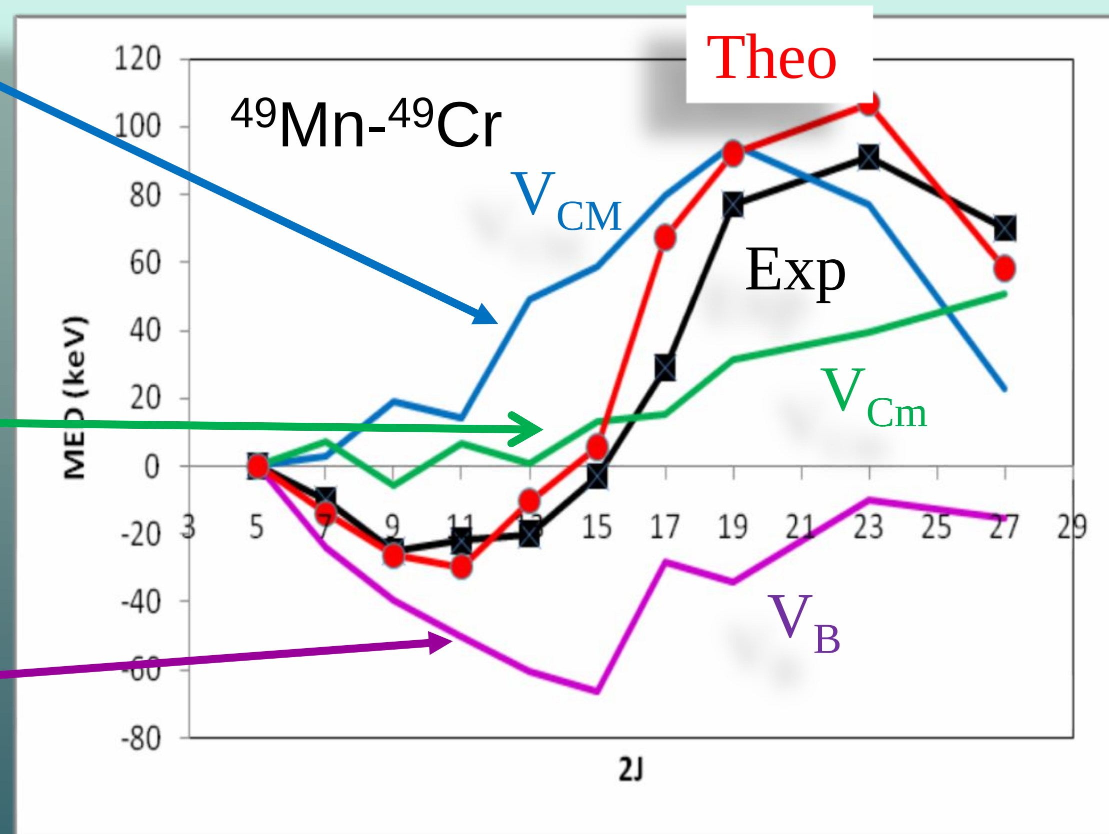
The multipole Coulomb V_{CM} gives information on the nucleon alignment



The monopole Coulomb V_{Cm} gives information on changes in the nuclear radius (deformation)



The "nuclear" ISB term V_B, is of the same order as the Coulomb contributions!!!!!

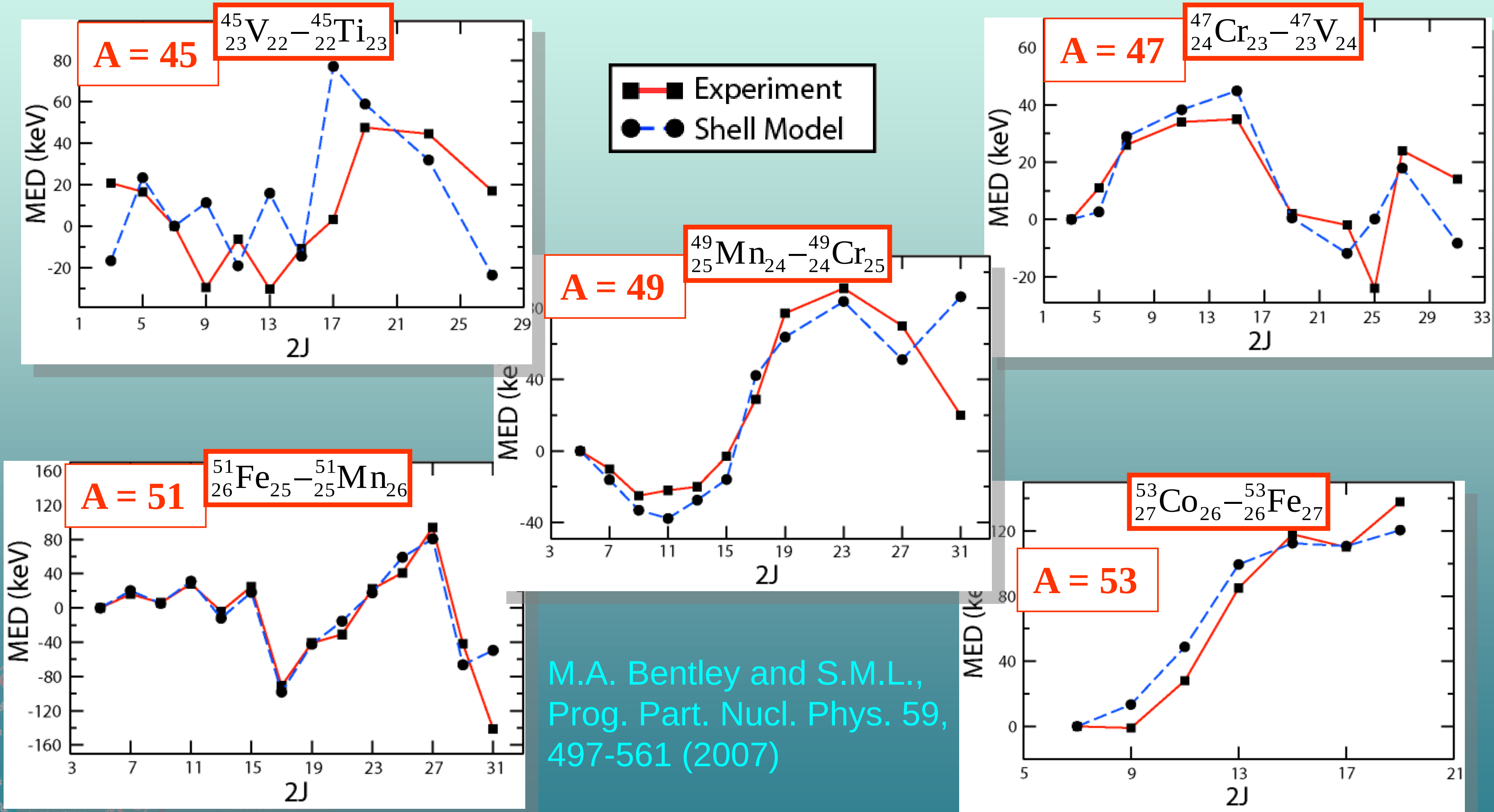


Now, without changing the parametrization, see how the rest of the MED for nuclei along the f7/2 shell are described by the calculations…

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

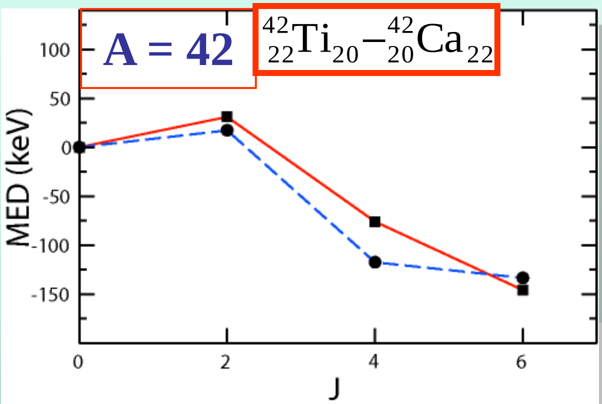
MED in T=1/2 states

Very good quantitative description of data without free parameters

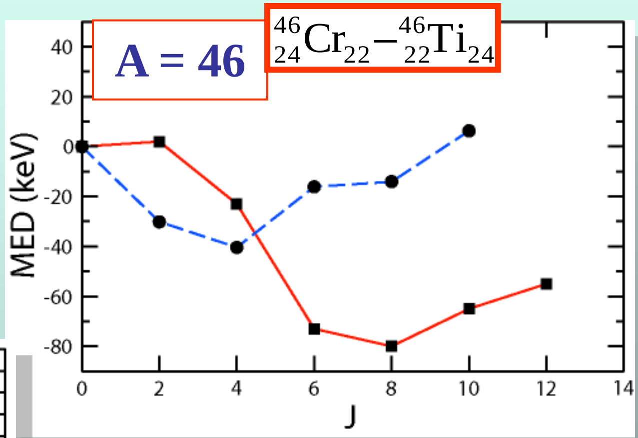


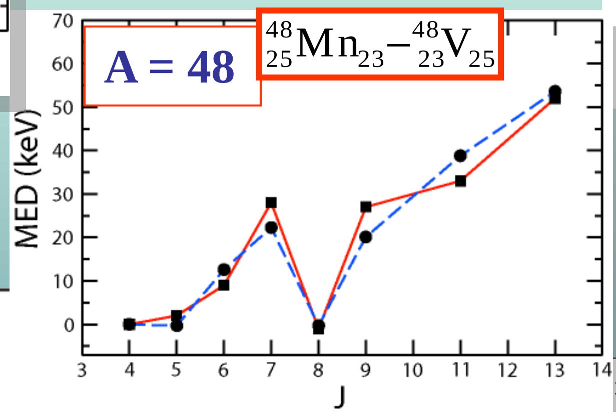
M.A. Bentley and S.M.L., Prog. Part. Nucl. Phys. 59, 497-561 (2007)

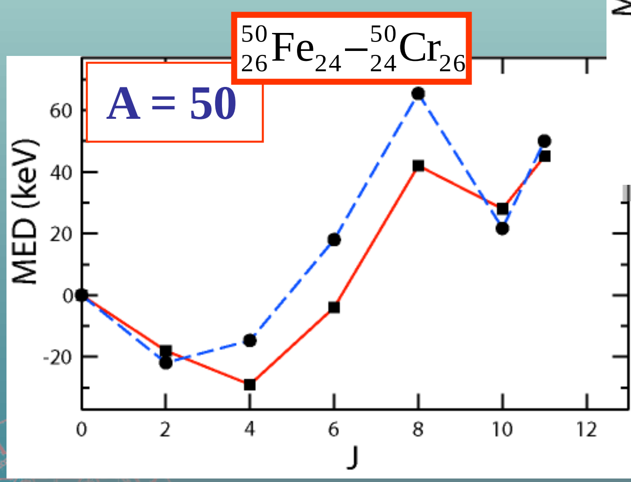
Mirror Energy Differences in T=1 states



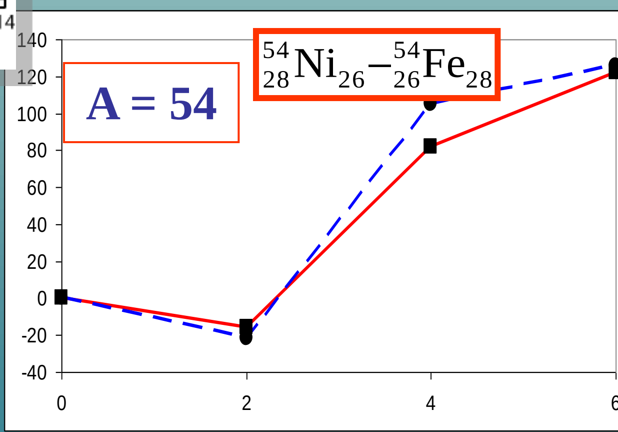
Experiment
Shell Model







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

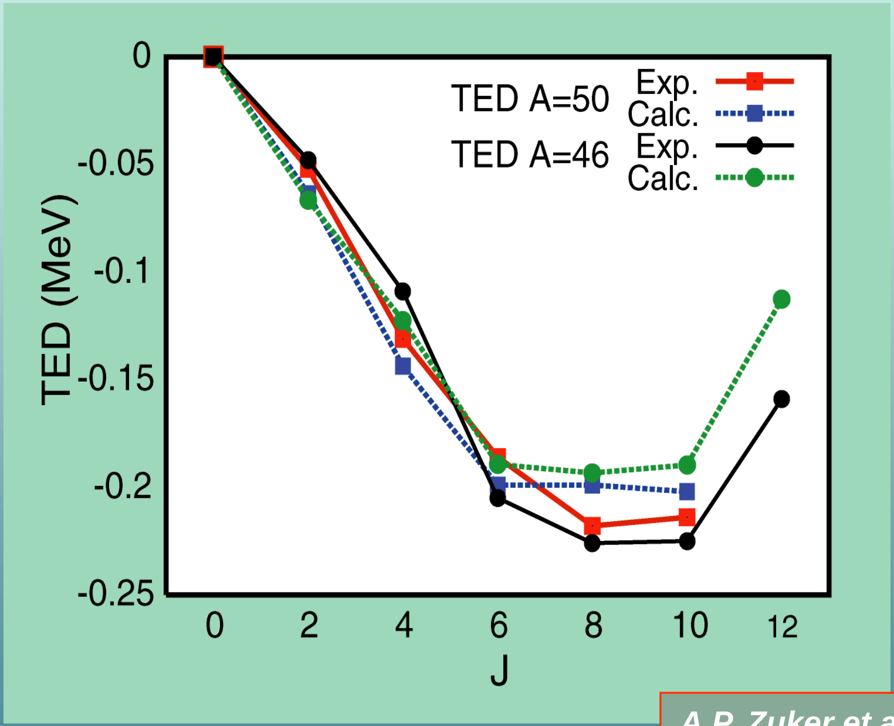


Same parametrization for the whole $f_{7/2}$ shell!

Triplet Energy Differences (TED)

With the same parametrization the energy differences (TED) in the T=1 triplets A=46, 50 can be reproduced

$$TED_J = E_J(T_z = 1) + E_J(T_z = -1) - 2E_J(T_z = 0)$$



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

Experimental data

P.E. Garrett et al., Phys. Rev. Lett. 87, 132502 (2001)
C.D. O'Leary et at., Phys. Lett. B 525, 49 (2002)
S.M. Lenzi et al., Phys. Rev. Lett. 87, 122501 (2001)

4. What do we learn from the data? Some illustrative examples

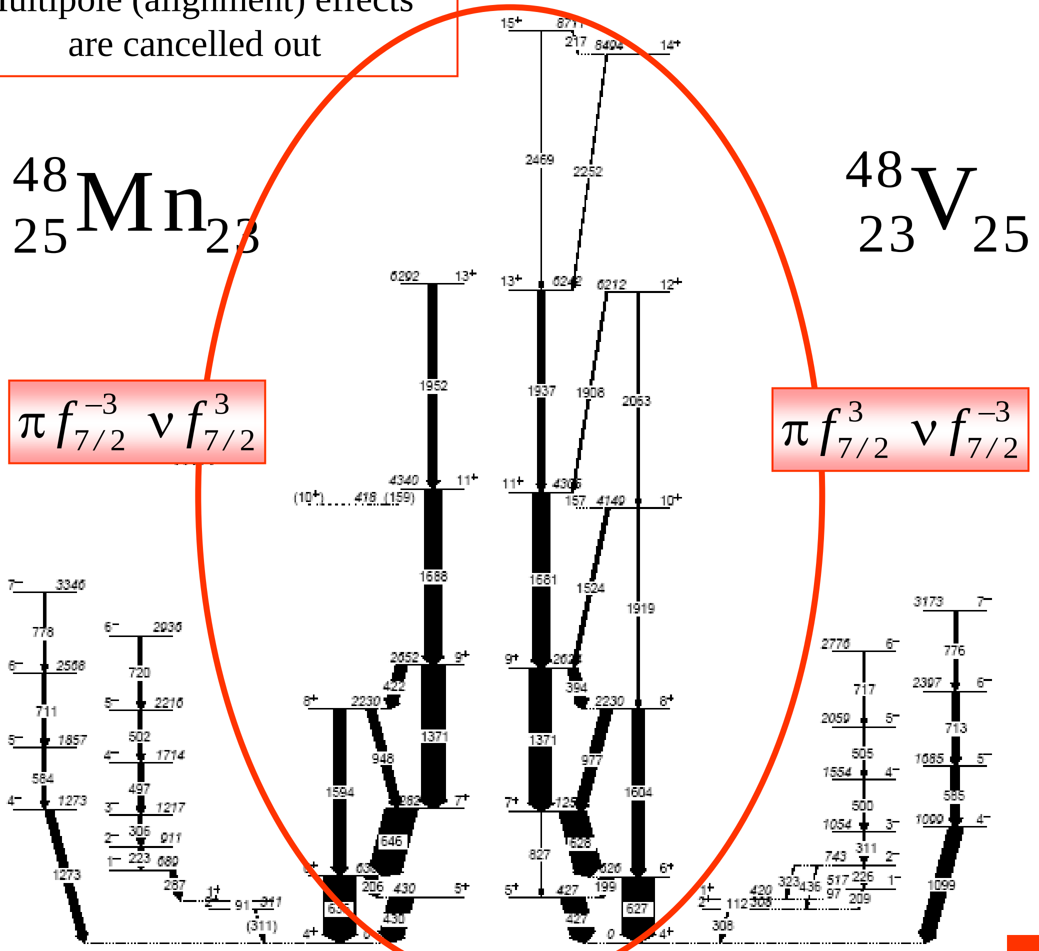
The radial term

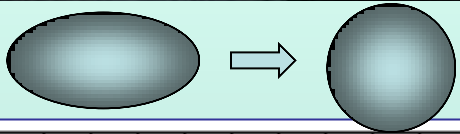
Evidence of the monopole radial effect

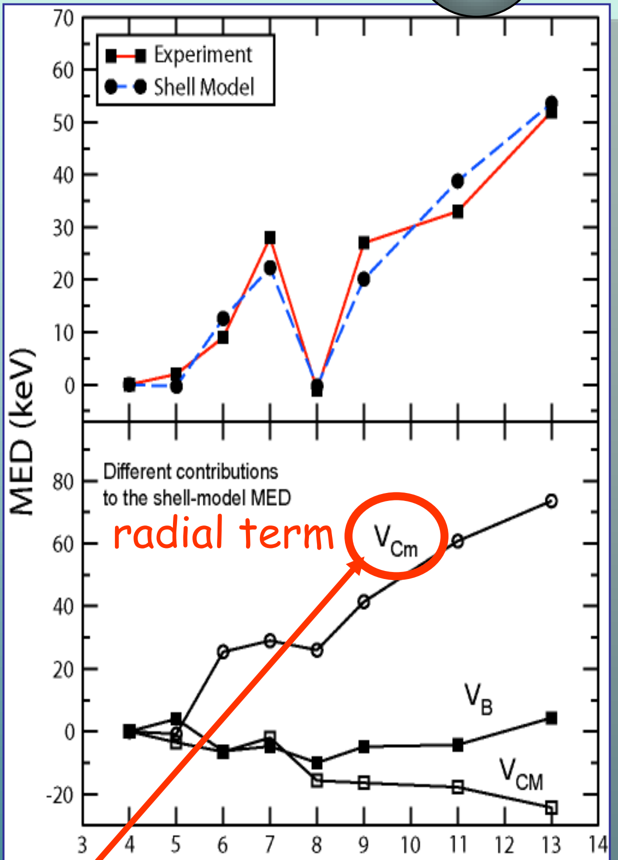
Multipole (alignment) effects are cancelled out

$^{48}_{25}\mathrm{Mn}_{23}$ $\qquad$ $^{48}_{23}\mathrm{V}_{25}$

$\pi f_{7/2}^{-3}\ \nu f_{7/2}^{3}$ $\qquad$ $\pi f_{7/2}^{3}\ \nu f_{7/2}^{-3}$







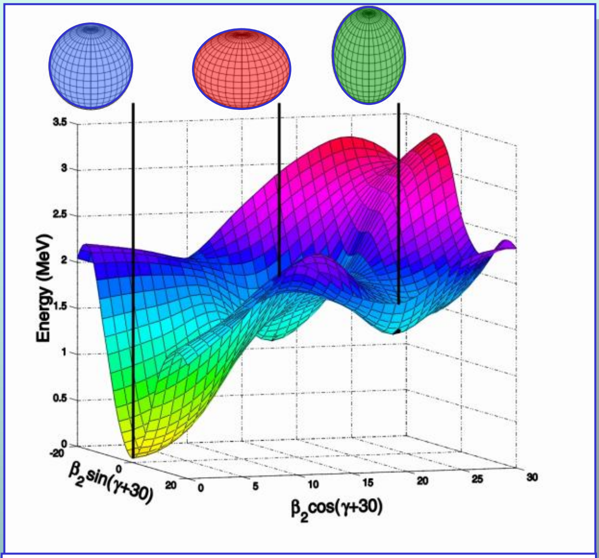
Most important contribution

The nucleus changes shape towards band termination

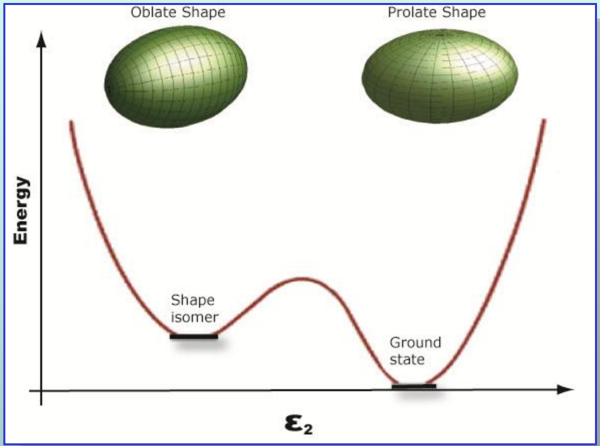
M.A. Bentley et al.,
PRL 97, 132501 (2006)

INFN Istituto Nazionale di Fisica Nucleare

Isospin symmetry and shape coexistence



186Pb: A. N. Andreyev *et al.*, Nature (London) **405**, 430 (2000).



Large shell gaps exist at both oblate *and* prolate shape for *N* = *Z* = 34 and 36

Shape coexistence → long lived isomers → bypass routes for the *rp*-process waiting-points → consequences on astrophysics

The case of ^{70}Se

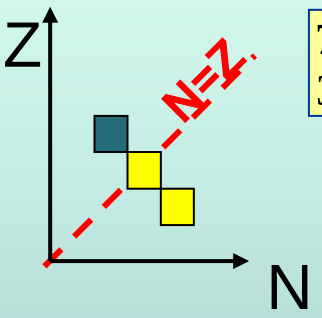
A. M. Hurst et al., PRL**98,** 072501 (2007)

REX-ISOLDE MINIBALL Coulomb excitation experiment: prolate shape up to the 2^+ state

J. Ljungvall et al., PRL 100, 102502 (2008)

LNL GASP RDDS experiment: oblate shape up to the 4^+ state

The case of the non-identical twins

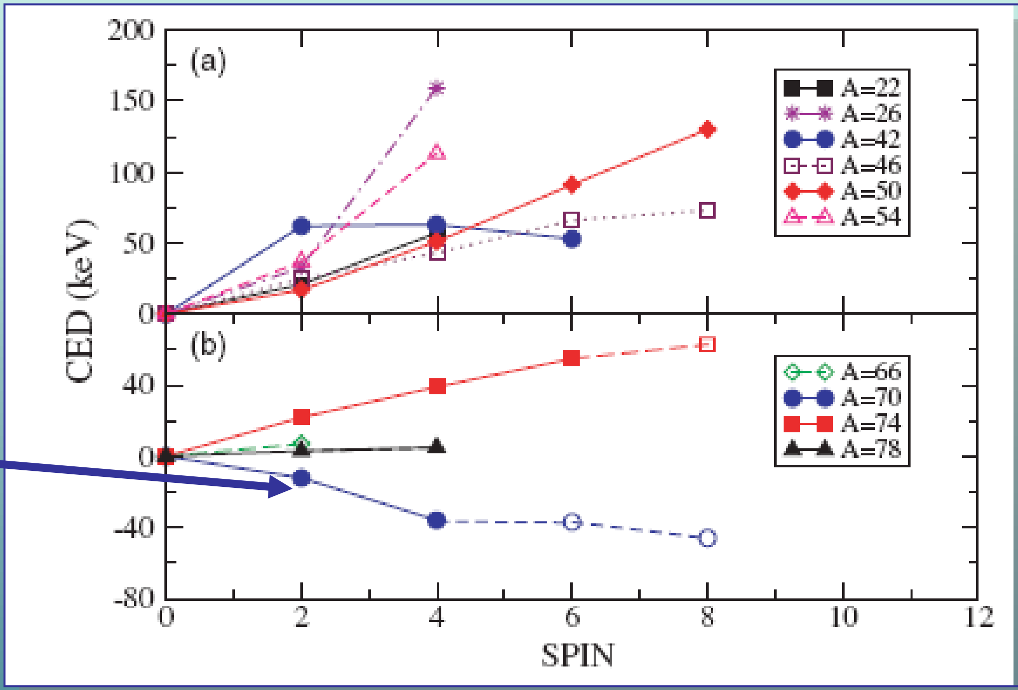


$$^{70}_{35}\mathrm{Br}_{35} - ^{70}_{34}\mathrm{Se}_{36}, T = 1$$

^{70}Br: G.de Angelis et al., EPJ. A **12**, 51 (2001)
D.G.Jenkins *et al.*, PRC **65**, 064307 (2002)

CED very sensitive to structural changes

Negative values of the CED are associated to changes in the Coulomb energy due to shape changes as a function of J



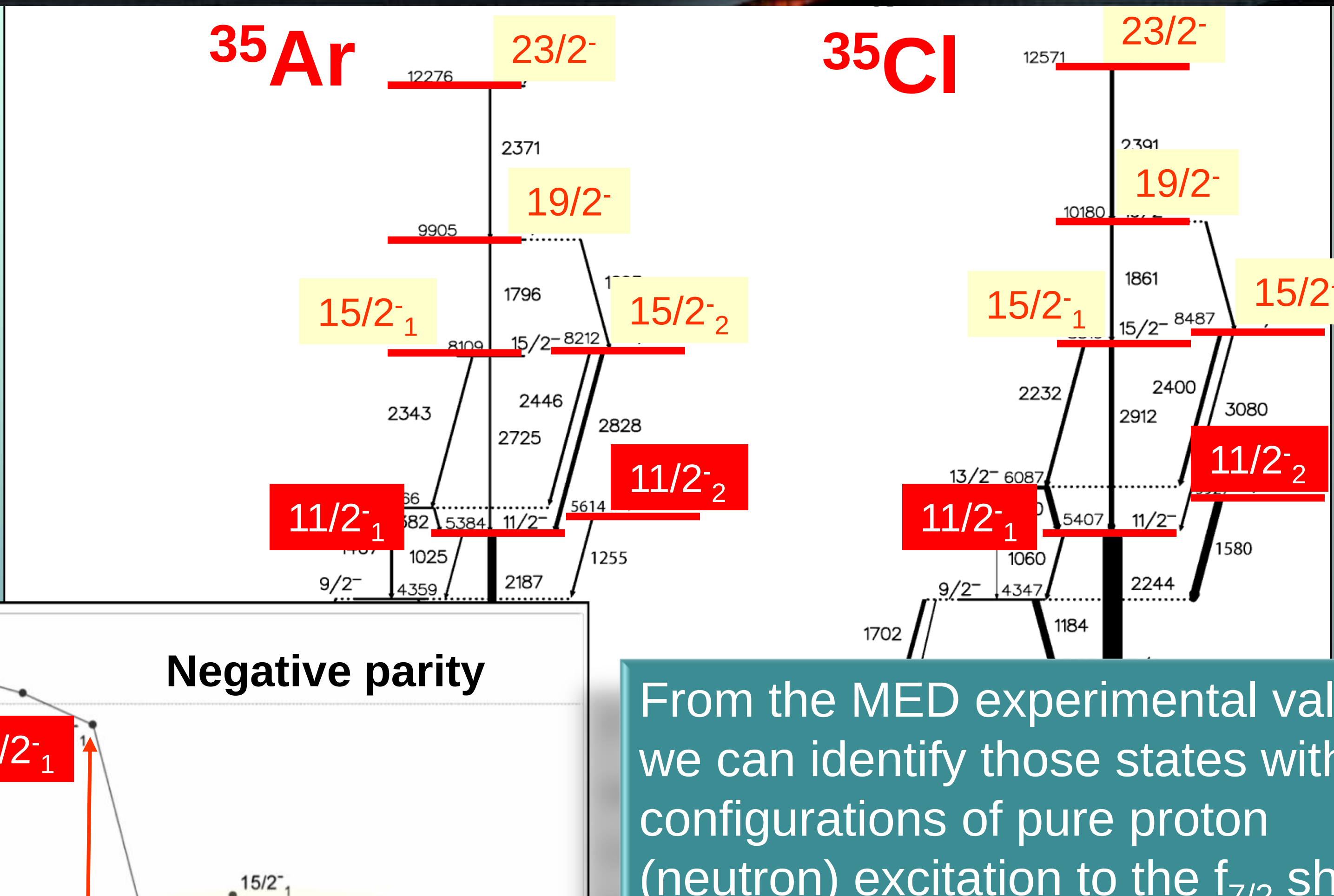
Need to measure the $T_z = -1$ member of the isobaric triplet to verify this interpretation

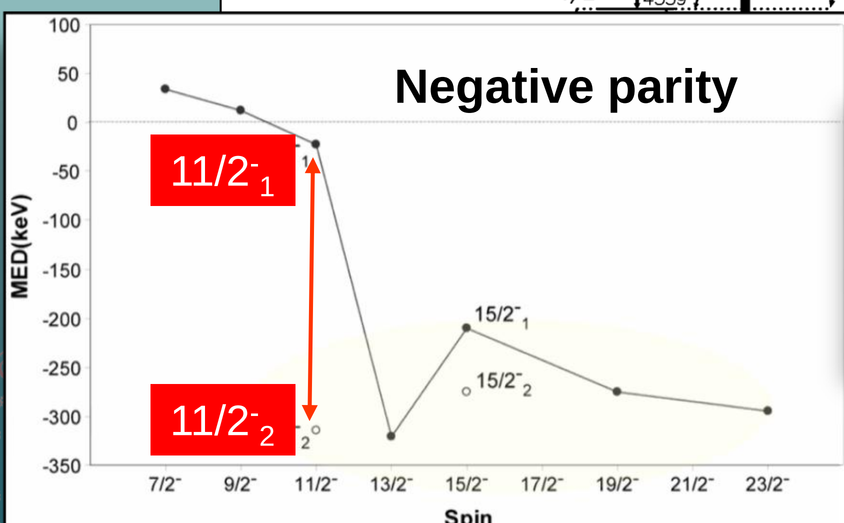
B. S. Nara Singh et al.,
PRC**75**, 061301(R) (2007)

^{74}Rb, ^{78}Y: Recoil β – tagging: prompt gamma + correlated electrons from the short-lived β decay

The electromagnetic spin-orbit effect

The electromagnetic spin-orbit effect: disentangling configurations



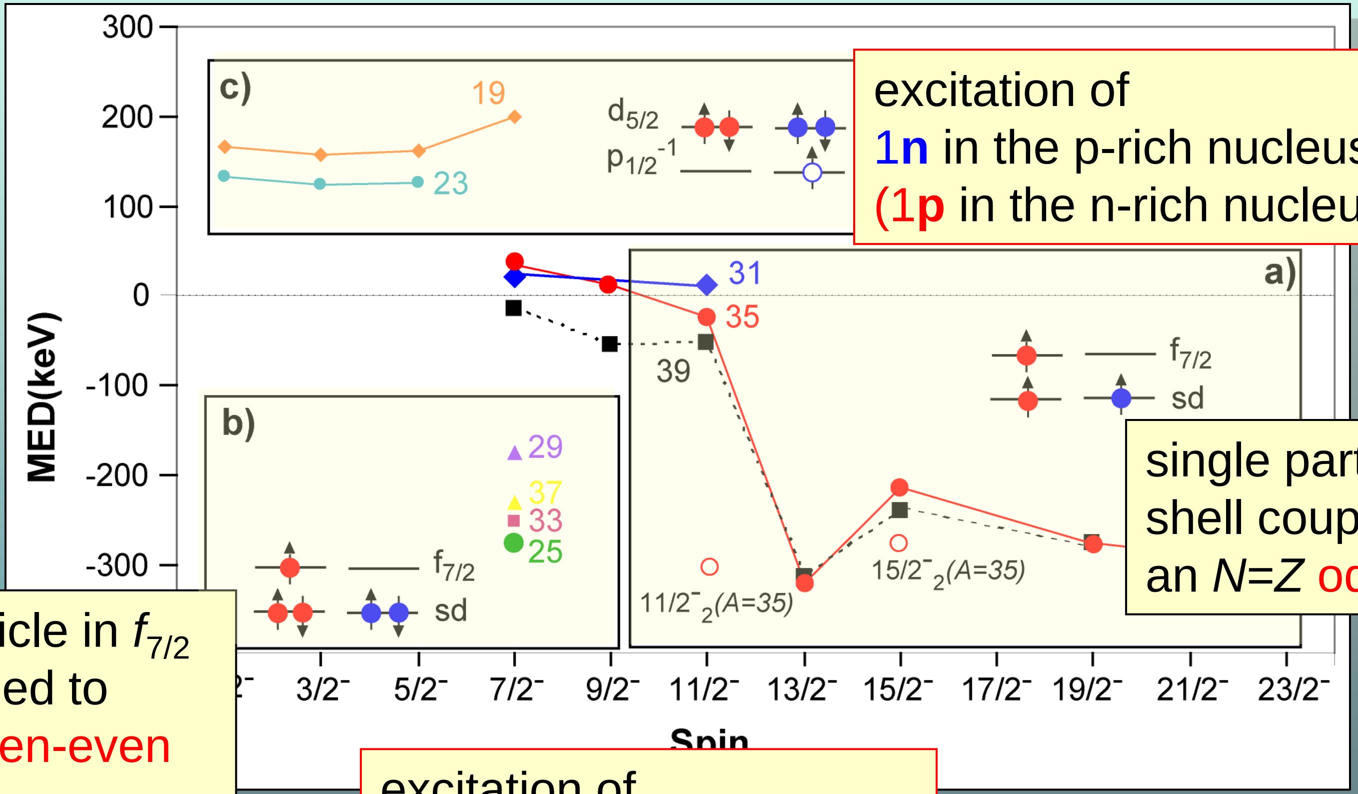


From the MED experimental values, we can identify those states with configurations of pure proton (neutron) excitation to the $f_{7/2}$ shell.

F. Della Vedova et al., Phys.Rev. C 75, 034317 (2007)

Systematics of MED of negative parity states in the *sd* shell

The electromagnetic spin-orbit effect explains the systematics of negative parity MED in the sd shell, thus giving information on the configuration of the states!



excitation of
1**n** in the p-rich nucleus
(1**p** in the n-rich nucleus)

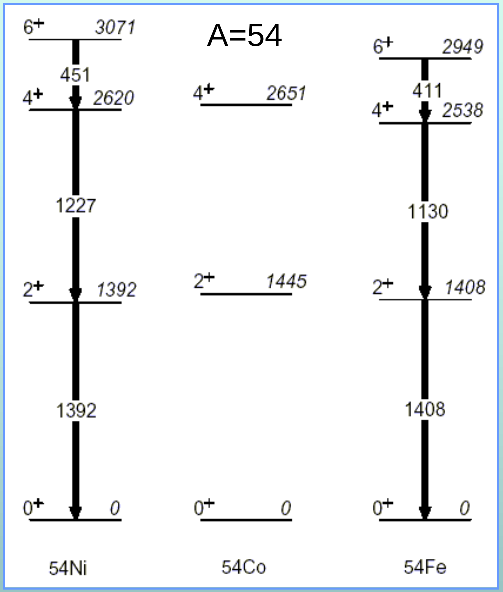
single particle in $f_{7/2}$ shell coupled to an *N*=*Z* odd-odd core

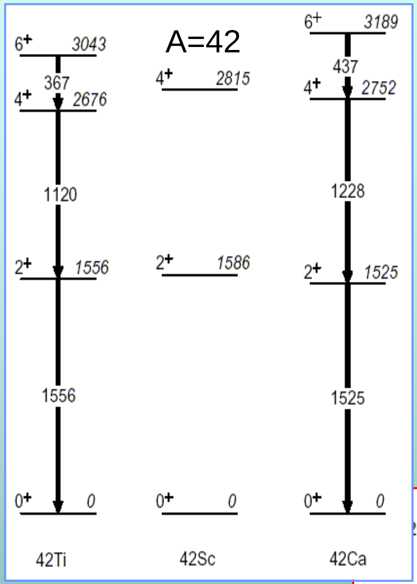
single particle in $f_{7/2}$ shell coupled to an *N*=*Z* even-even core

excitation of
1**n** in the n-rich nucleus
(1**p** in the p-rich nucleus)

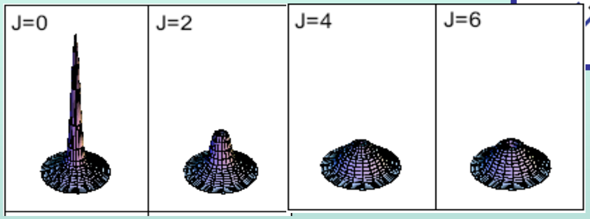
The ISB VB term

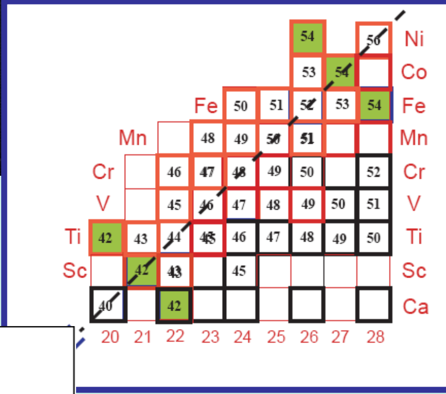
T=1 A=54/42 MED: the VB term





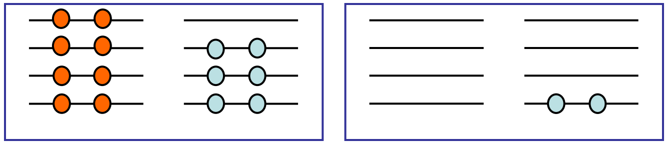
J=2 anomaly

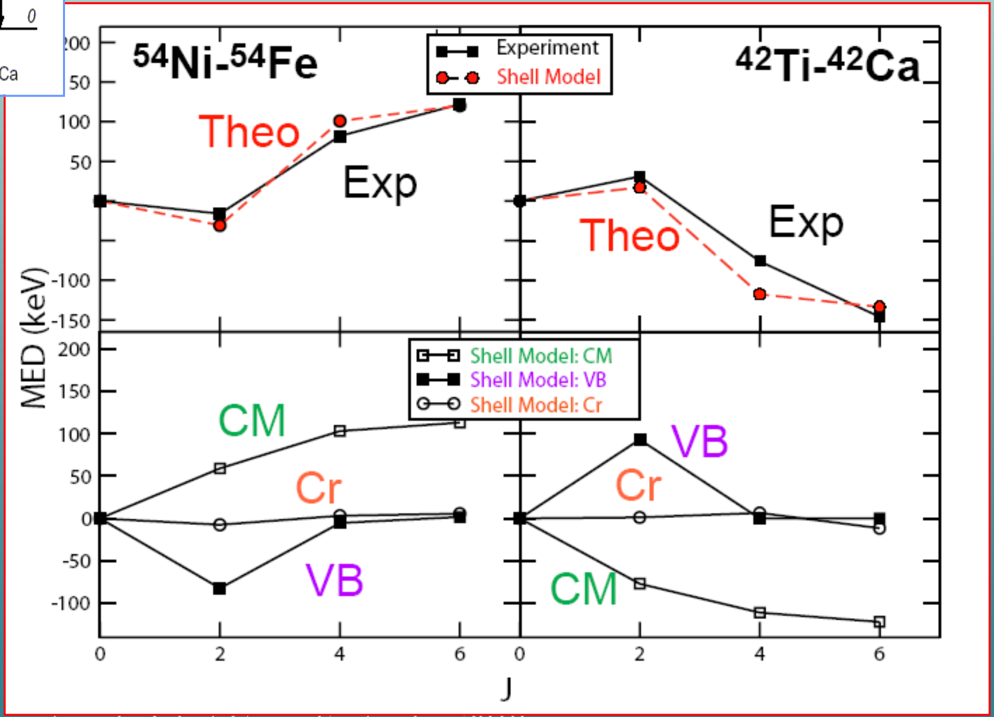




no collectivity: only multipole effects: smooth recoupling and J=2 anomaly

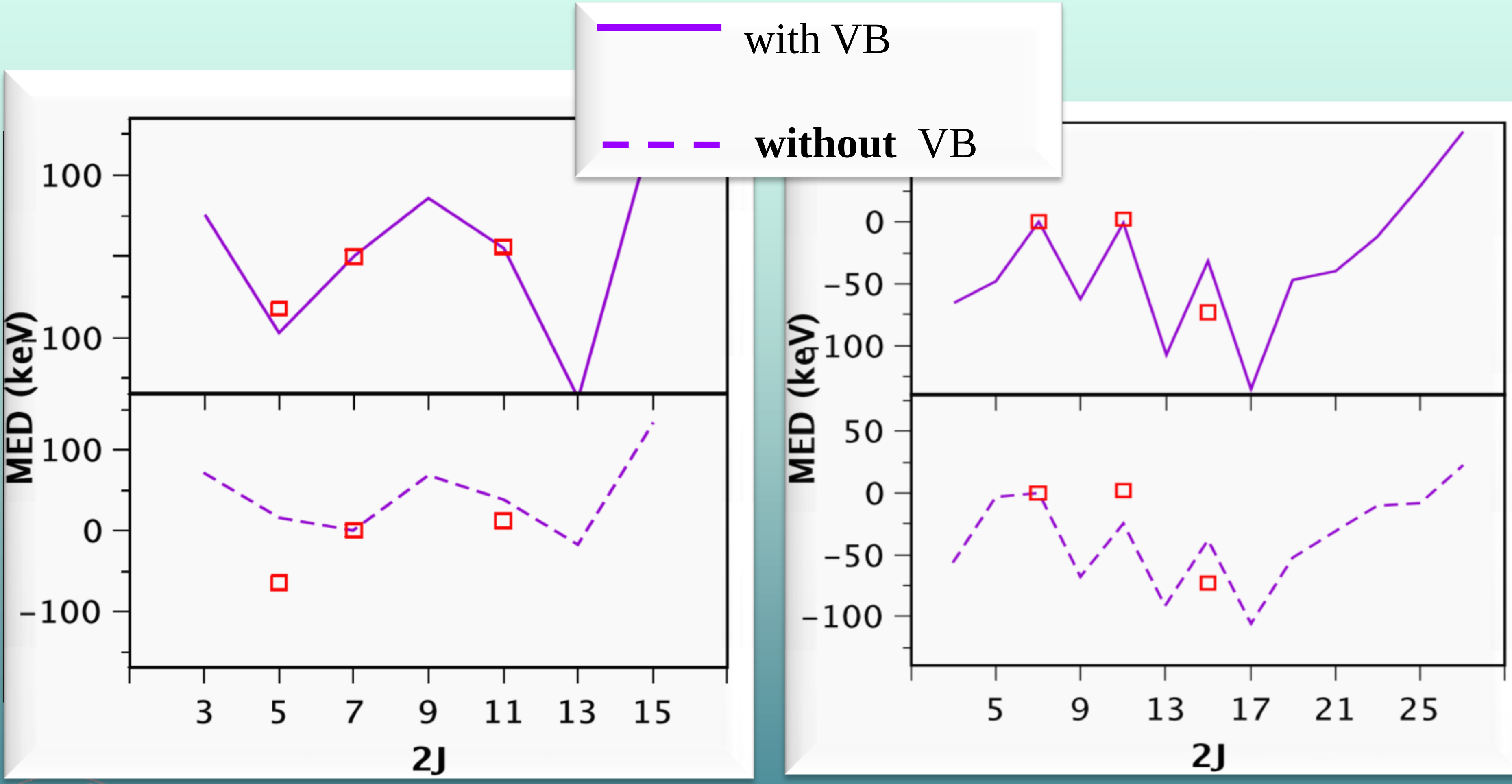
2 particles / holes





A.Gadea et al., PRL 97, 152501 (2006)

V_B in MED between T=3/2 states (A=49,53)



MSU experiment, double (mirrored) fragmentation of the N=Z nucleus 56Ni
J5.R. Brown *et al*. PRC80, 011306(R) 2009

Extension to other main shells

Understanding the ISB term VB

Can we understand the origin of this term from the N-N interaction?

Is the ISB term a general feature?
or is it just confined to the $f_{7/2}$ shell?

Necessary conditions for such studies:
- good and enough available data
- good shell model description of the structure

Ideal case: the sd shell
In particular the deformed region at A~20-26

But…few data and no indications of J=2 anomaly in A=18

MED in the sd shell and the ISB VB term

INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. 29 (2003) 509–519 — PII: S0954-3899(03)56487-8

Gamma-decay study of ^{21}Na and ^{21}Ne, octupole bands in ^{21}Ne

S Thummerer[1], W von Oertzen[1,2], Tz Kokalova[1,2], H G Bohlen[1], B Gebauer[1], A Tumino[1], T N Massey[3], G de Angelis[1,4], M Axiotis[4], A Gadea[4], Th Kröll[4], N Marginean[4], D R Napoli[4], M De Poli[4], C Ur[4], D Bazzacco[5], S M Lenzi[5], C Rossi Alvarez[5], S Lunardi[5], R Menegazzo[5], P G Bizzeti[6] and A M Bizzeti-Sona[6]

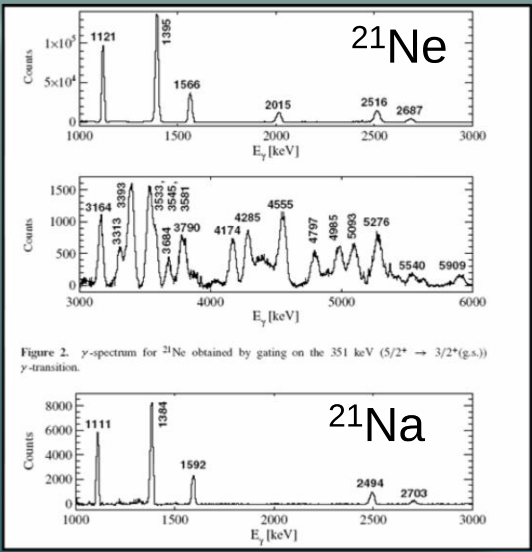
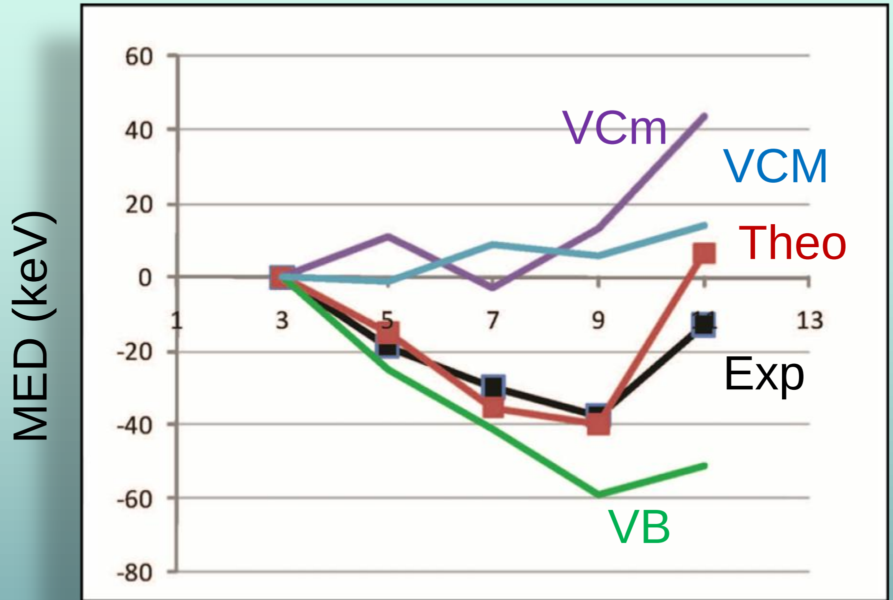


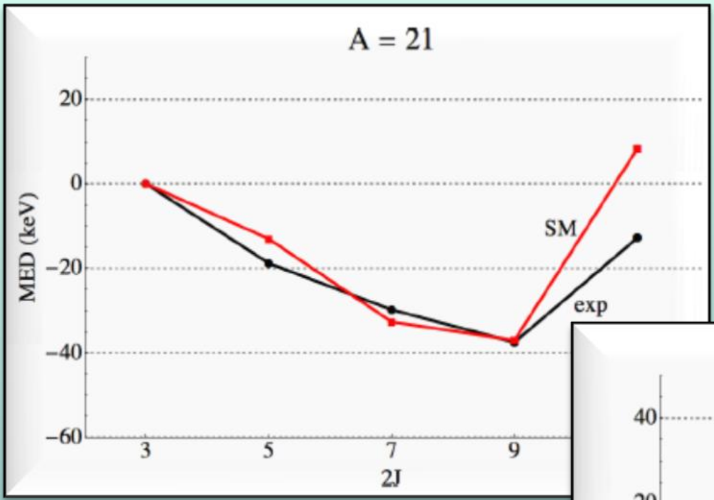
Figure 2. γ-spectrum for ^{21}Ne obtained by gating on the 351 keV ($5/2^+ \rightarrow 3/2^+$(g.s.)) γ-transition.



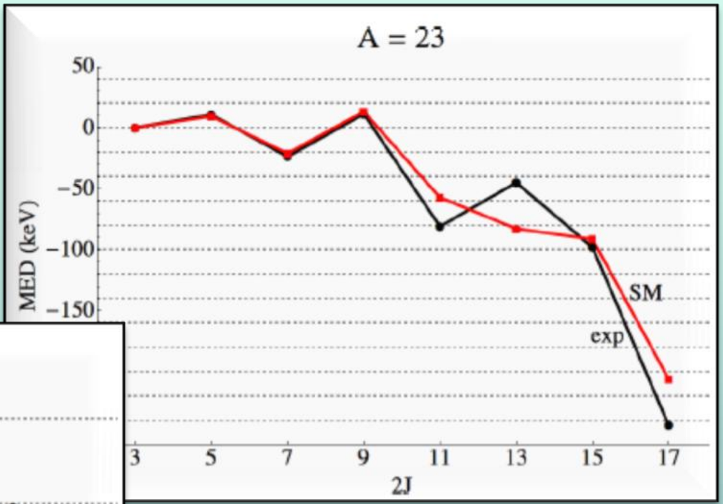
The same VB term as in the $f_{7/2}$ shell is needed to reproduce these data!

This suggests that the ISB term has a general character

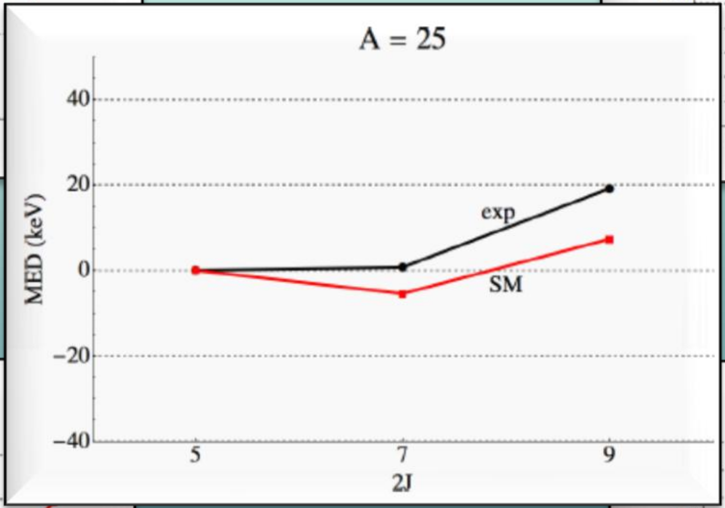
MED in the sd shell



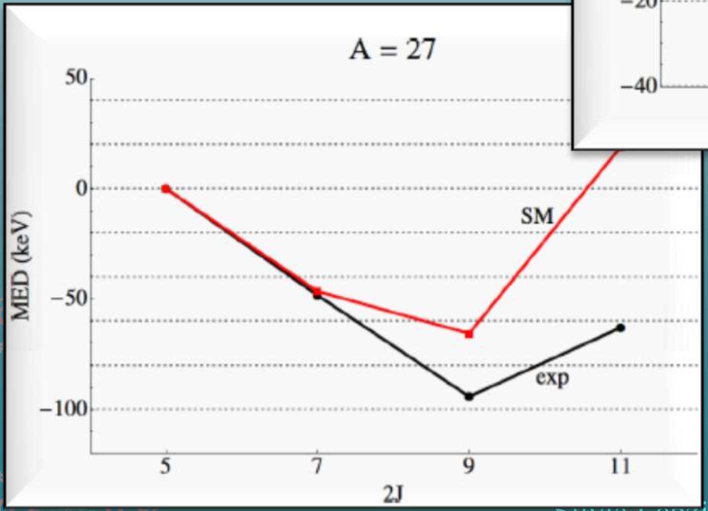
No free parameters



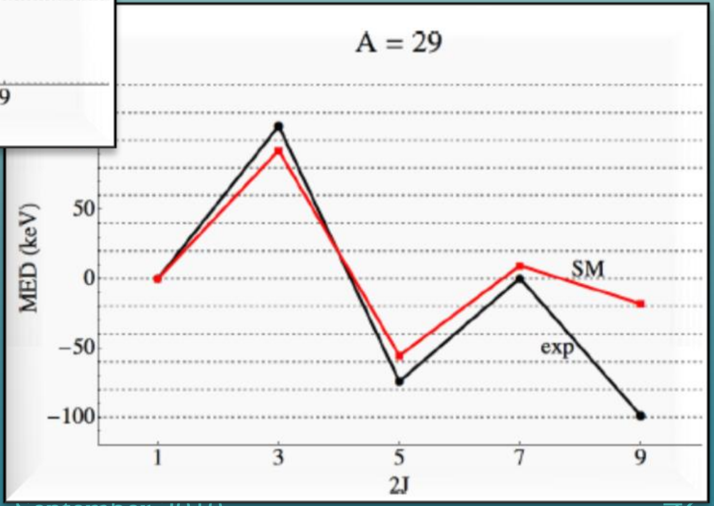
sd calculations



sdfp calculations



SML and A.P.Zuker in preparation

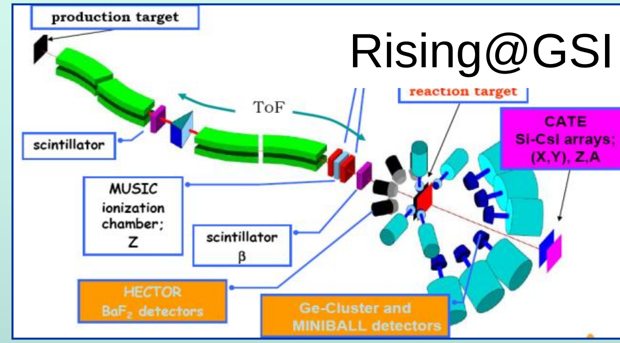


MED in the sd shell: another approach

$$^{36}_{20}\mathrm{Ca}_{16} - ^{36}_{16}\mathrm{S}_{20}$$

$$T = 2, J^{\pi} = 2^{+}$$

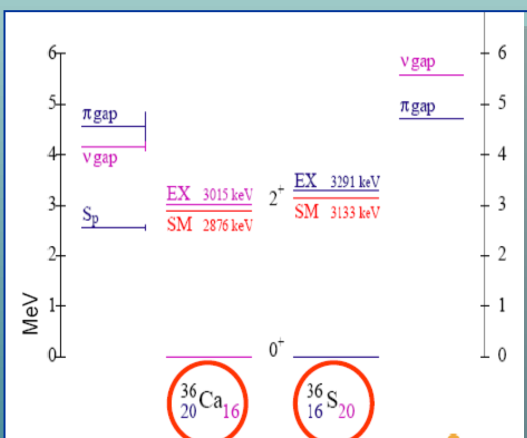
$$\mathrm{MED}(2^{+}) = -276\ \mathrm{keV}$$

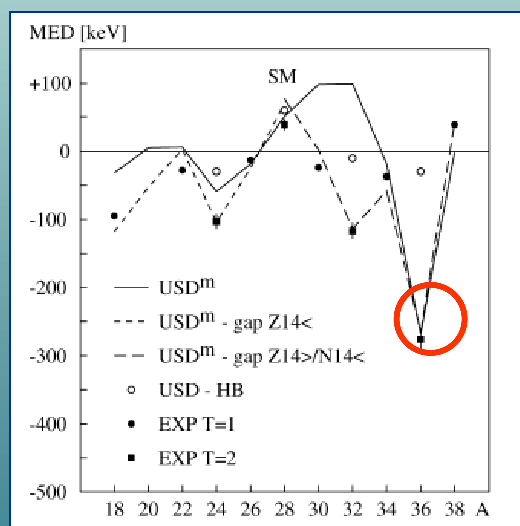


P. Doornebal et al., PLB 647 (2007) 237

Shell model calculations (H. Grawe):
- USD interaction
- empirical s.p. energies (^{17}F, ^{17}O)
- ad hoc corrections to the gaps

results consistent with shell evolution and the development of a “mirror” island of inversion starting in ^{34}Ca





More data needed for larger values of T towards the drip lines to understand this mechanism

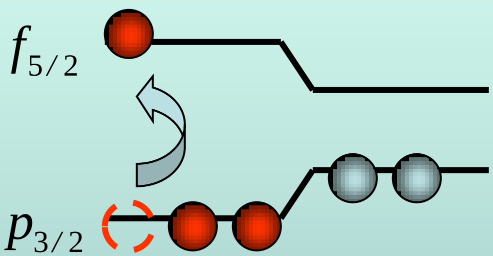
Astrophysics: Important information for the calculation of proton capture rates in rp-path network calculations

GANIL: A. Burger et al., EPJ S. Top. 150, (2007) 89

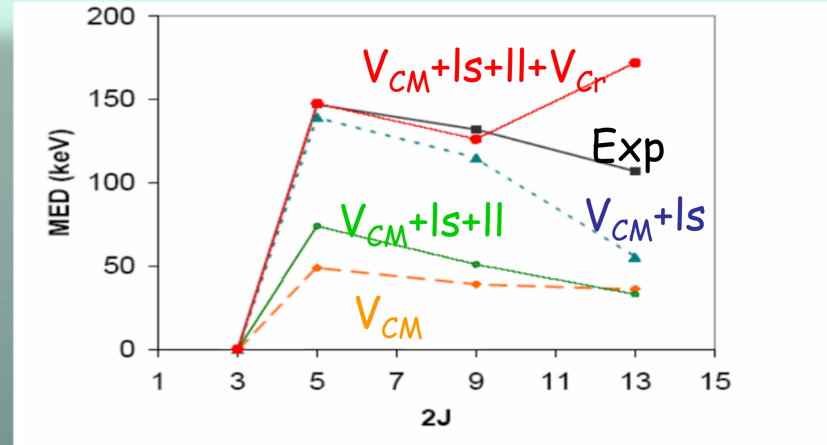
MED in the upper fp shell

The mirror pair ^{61}Ga – ^{61}Zn

$^{61}_{31}\mathrm{Ga}_{30}$

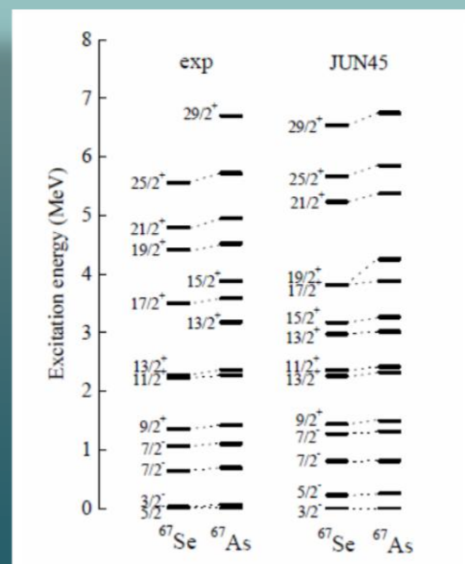


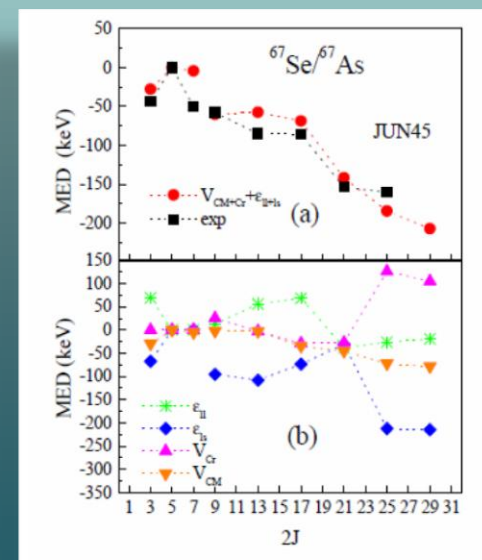
Data: L-L. Andersson et al., PRC (2005)



The mirror pair ^{67}Se – ^{67}As

Data: R. Orlandi et al.,
PRL 103, 052501 (2009)
Calc. K. Kaneko et al.,
submitted to PRC

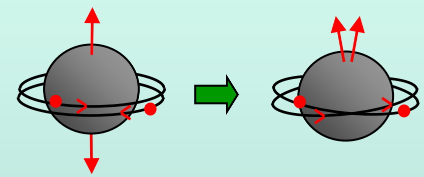




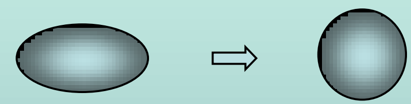
Summary

These studies allow to learn about:

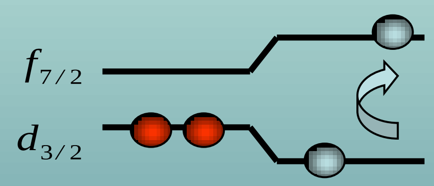
- Mechanism of nucleon alignment at the backbending



- Evolution of the radii along a rotational band



- Importance of the single-particle effects:
  - test interactions and basis
  - information on the configurations



- Evidence of isospin-non-conserving terms in the nuclear interaction

J=2 anomaly

The same parametrization seems to hold in other shells which indicate a general character of this model

Istituto Nazionale di Fisica Nucleare

Outlook

MED and TED in T > 1 isobaric multiplets in medium-light nuclei

- Coulomb effects proportional to T_z

Lifetimes, effective charges, isospin mixing…

New reaction methods (RIB, two-step fragmentation)

Improvement of shell model calculations needed to understand the origin of the Isospin symmetry braking term VB

In all cases the proton-rich mirror partners become weakly bound or unbound. Difficult to measure the analogue states and calculations would include the coupling to the continuum, a common problem when dealing with nuclei far from the stability line.

Moving the frontier

We continue the research from both the experimental and the theoretical side to study the MED at the limits of stability and to understand some interesting but not yet clear issues such as the J=2 anomaly…

Special thanks to:

Mike Bentley (York)
Andres Zuker (Strasbourg)

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4) N. Auerbach, Phys. Rep. 98 (1983) 273

5) Theory on CDE: J. Duflo and A.P. Zuker, Phys. Rev. C 66 (2002) 051304(R)

6) Theory on CED: A.P. Zuker, S.M. Lenzi, G. Martinez-Pinedo and A. Poves, Phys. Rev. Lett. 89 (2002) 142502;

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8) Shell model reviews: B.A. Brown, Prog. Part. Nucl. Phys 47 (2001) 517; T. Otsuka, M. Honma, T. Mizusaki and N. Shimitzu, Prog. Part. Nucl. Phys 47 (2001) 319; E. Caurier, G. Martinez-Pinedo, F. Nowacki, A.Poves, and A.P. Zuker, Rev. Mod. Phys. 77 (2005) 427

9) Review article on N~Z: D. D. Warner, M. A. Bentley, P. Van Isacker, Nature Physics 2, (2006) 311 - 318

Lecture 3
The end