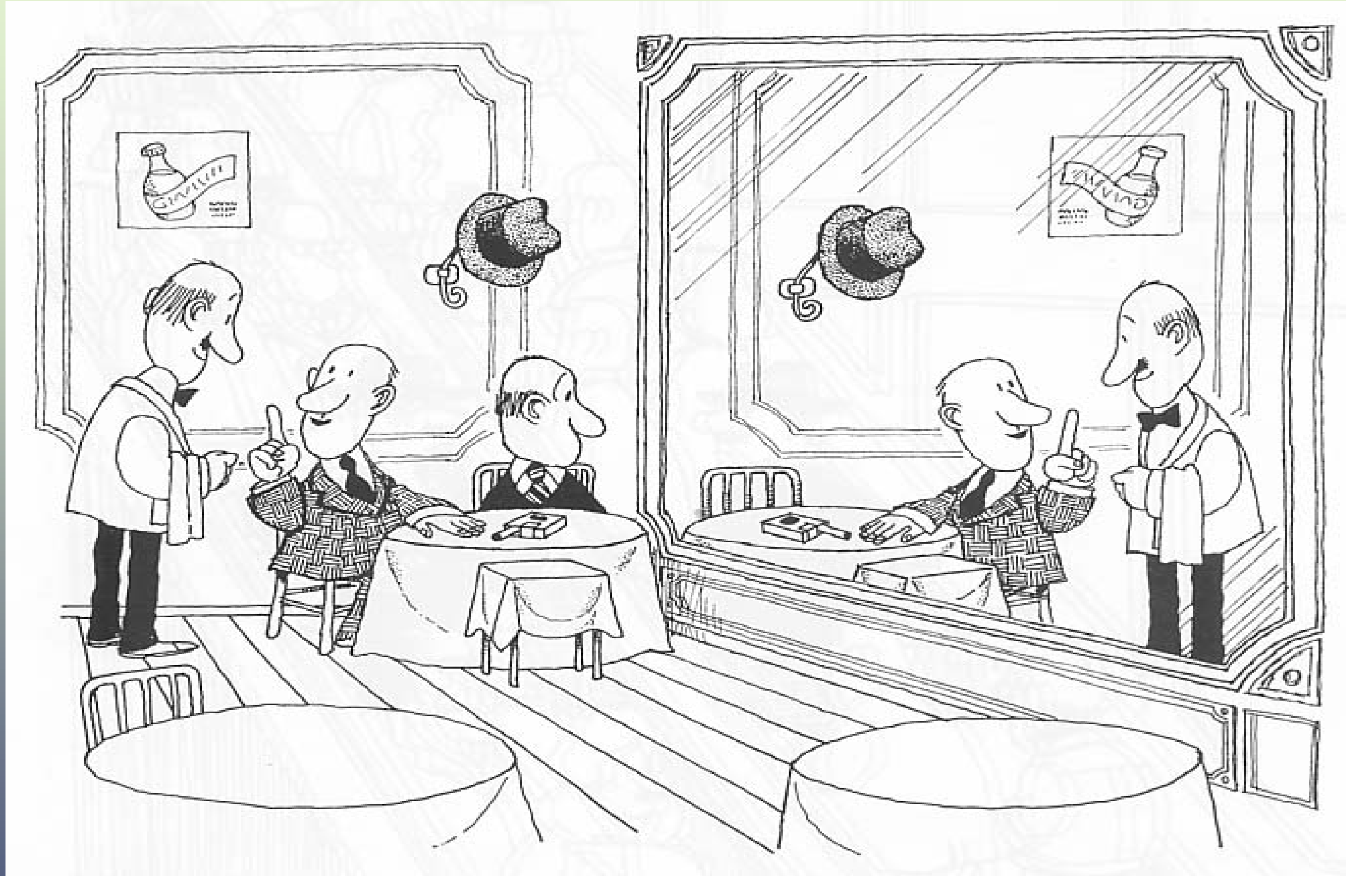
Symmetries along the N≈Z line

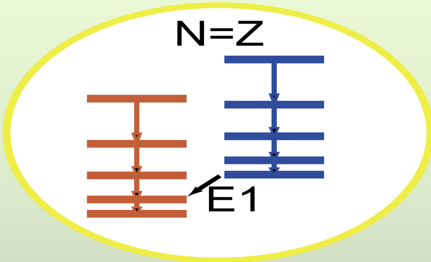
Silvia M. Lenzi - *Università di Padova and INFN*

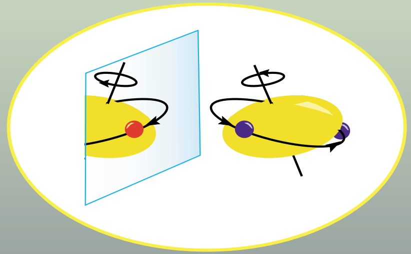


Isospin symmetry is a fundamental topic in nuclear physics.
Its slight breakdown, mainly due to the Coulomb field, manifests when comparing mirror nuclei.
This constitutes an efficient observatory for a direct insight into nuclear structure properties.

Possible Signatures of Isospin Symmetry Breaking

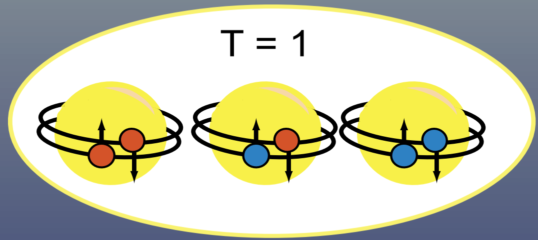
Observation of forbidden
E1 transitions in N = Z nuclei



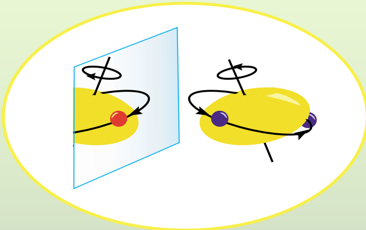
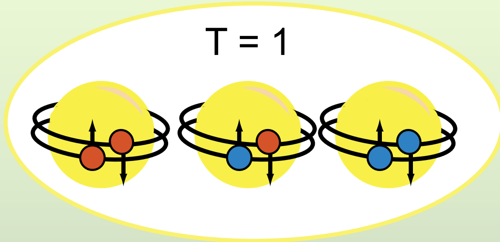


Different strength of E1
transitions in mirror nuclei

Mirror Energy Differences (MED)
Triplet Energy Differences (TED)



Energy differences in the $f_{7/2}$ shell: MED and TED

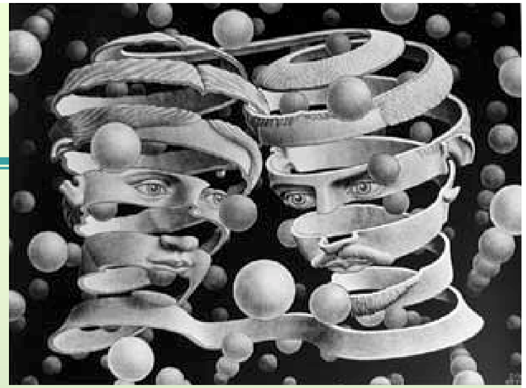
MED  

TED

We "measure":

- Nucleon alignment at the backbending
- Evolution of the radii along a band
- Isospin-non-conserving terms in the nuclear interaction

Excitation energy differences: MED and TED



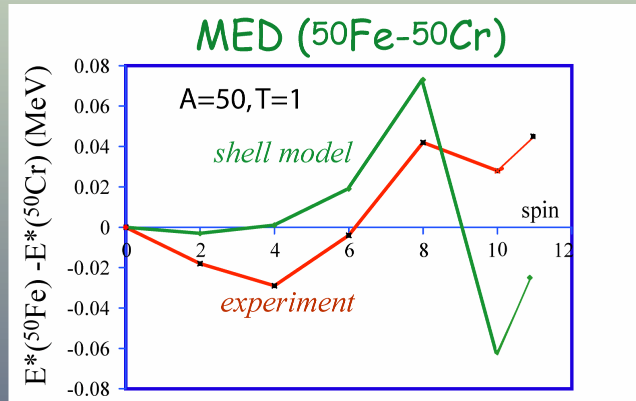
Coulomb effects in isobaric multiplets:

- **bulk energy (100's of MeV)**
- **displacement energy (g.s.) CDE (10's of MeV)**
- **differences between excited states MED and TED (10's of keV)**

The energy differences at each yrast state J for mirror nuclei (MED) and isobaric triplets (TED) are defined as:

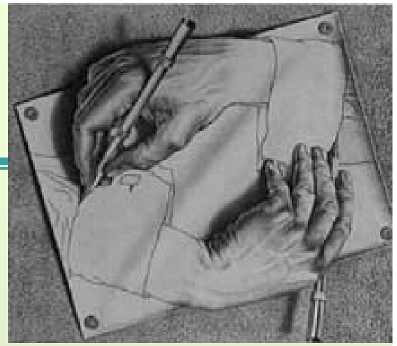
$$MED_J = E_J(Z>N) - E_J(Z<N)$$

$$TED_J = E_J(Z>N) + E_J(Z<N) - 2E_J(N=Z)$$



Both MED and TED are needed to achieve a clear understanding of the interplay between the Coulomb potential V_C and the isospin-breaking nuclear interaction V_B

MED and TED in the shell model framework



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 nuclear (V_B) interactions

The Coulomb interaction is separated in a monopole (m) and a Multipole (M) component

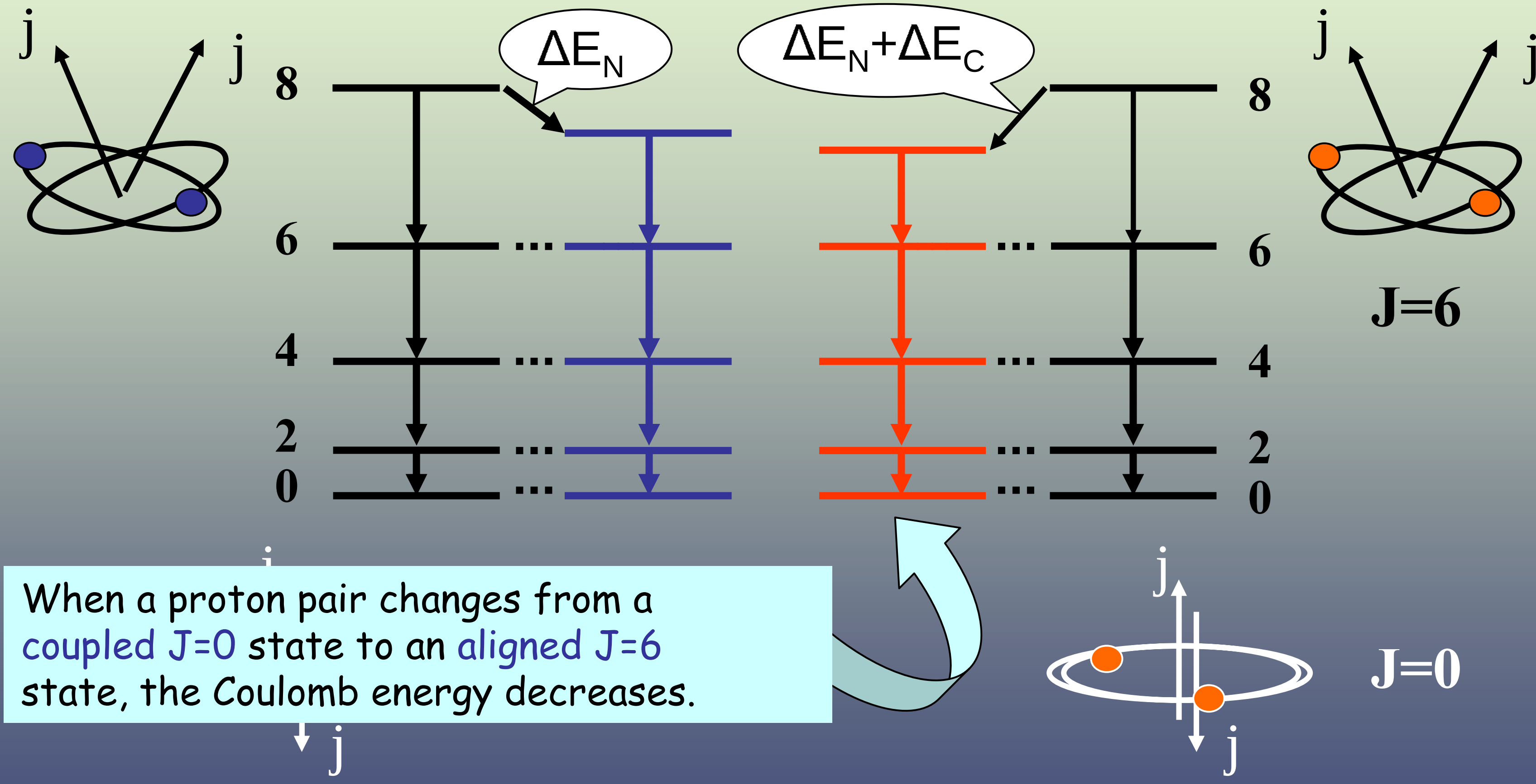
$$MED_J = \Delta_M \langle V_{CM} \rangle_J + \Delta_M \langle V_{Cm} \rangle_J + \Delta_M \langle V_B \rangle_J$$

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

Coulomb effects in rotational bands: The Multipole Coulomb (CM) contribution

The Multipole Coulomb (CM) contributions to MED and TED are obtained using harmonic oscillator Coulomb matrix elements in the *fp* shell

Its contribution is significant in rotational nuclei. CM "sees" to the alignment of nucleons.



When a proton pair changes from a coupled J=0 state to an aligned J=6 state, the Coulomb energy decreases.

J.A. Cameron et al., Phys. Lett. B 235, 239 (1990)
M.A. Bentley et al., Phys. Lett. B 437, 243 (1998)
J.A. Sheikh et al., Phys. Lett. B 443, 16 (1998)

Monopole Coulomb and the drift in radii

Produces large bulk and displacement energies that cancel approximately in MED
However, small but significant contributions remain:

Monopole part of the Coulomb field:

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

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

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

single-particle

The single-particle contributions are proportional to the difference in proton orbital occupation numbers of both mirrors. In A = 46-51 they result ~10 times smaller than the radial effect. Therefore they are neglected in MED calculations for $f_{7/2}$-shell nuclei.

J. Duflo and A.P. Zuker, Phys. Rev. C 66, 051304 (2002)
A.P. Zuker et al.,, Phys. Rev. Lett. 89, 142502 (2002)
J. Ekman et al., Phys. Rev. Lett. in press

Change of radii along the yrast bands

Its effect in MED is proportional to the difference $$\frac{1}{R(J)} - \frac{1}{R(0)} \approx \frac{R(0)-R(J)}{R^2}$$

The total radius depends on those of the single orbits. Orbital radii depend on ℓ.

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 → larger radius and less Coulomb energy

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

$$\Delta\langle V_{Cr}\rangle_J = a_r \left\langle \frac{z_{p_{3/2}}(Z_>) + z_{p_{3/2}}(Z_<)}{2} \right\rangle_J$$

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

The value of a_r is obtained from the experimental data of A=41

A.P. Zuker et al.,, Phys. Rev. Lett. 89, 142502 (2002)
S.M. Lenzi et al., Phys. Rev. Lett. 87, 122501 (2001)
LDM: M.A. Bentley et al., Phys. Lett B 437, 243 (1998)

ISB component of the nuclear interaction in A=42

$$^{42}_{22}\mathrm{Ti}_{20},\ ^{42}_{21}\mathrm{Sc}_{21},\ ^{42}_{20}\mathrm{Ca}_{22}$$

Mirrors $\quad MED(A=42, T=1) \approx V^{(1)}_{Bf_{7/2}} + V^{(1)}_{Cf_{7/2}} \quad$ Isovector

Isobaric triplets $\quad TED(A=42, T=1) \approx V^{(2)}_{Bf_{7/2}} + V^{(2)}_{Cf_{7/2}} \quad$ Isotensor

From the yrast spectra of the T=1 triplet in A = 42 we deduce:

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

$MED_J = E_J(^{42}Ti) - E_J(^{42}Ca)$

$TED_J = E_J(^{42}Ti) + E_J(^{42}Ca) - 2E_J(^{42}Sc)$

	J=0	J=2	J=4	J=6
V_C	81	24	6	-11
MED-V_C	5	**93**	5	-48
TED-V_C	**117**	81	3	-42

estimate $V_{Bf7/2}^{(1)}$ (Isovector)

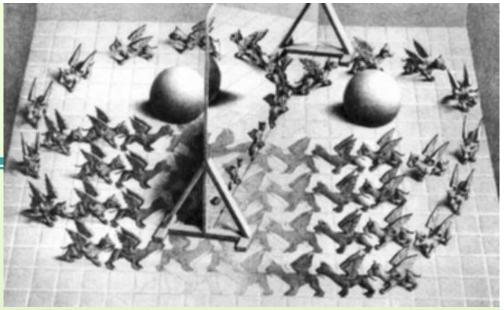
estimate $V_{Bf7/2}^{(2)}$ (Isotensor)

If the effect is due only to V_C one expects the same and small numbers for $V_B^{(1)}$ and $V_B^{(2)}$

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

A. P. Zuker

MED and TED in the full fp shell model calculation



The isospin non-conserving nuclear contributions are deduced from the MED and TED in the T = 1, A = 42 triplet data.

To construct an interaction in the whole pf shell we use a multiplicative prescription:

$$\Delta\langle V_{Bpf}\rangle_J = \beta\,\Delta\langle V_{Bf_{7/2}}^{J'}\rangle_J$$

$$\beta_1 = \beta_2 = 100\,\mathrm{keV}$$

$$\mathrm{MED}_J = a_r\langle\frac{z_{p_{3/2}}(Z_>) + z_{p_{3/2}}(Z_<)}{2}\rangle_J + \Delta_M\langle V_{Cpf}^{ho}\rangle_J + \beta_1\Delta_M\langle V_{f_{7/2}}^{J=2}\rangle_J$$

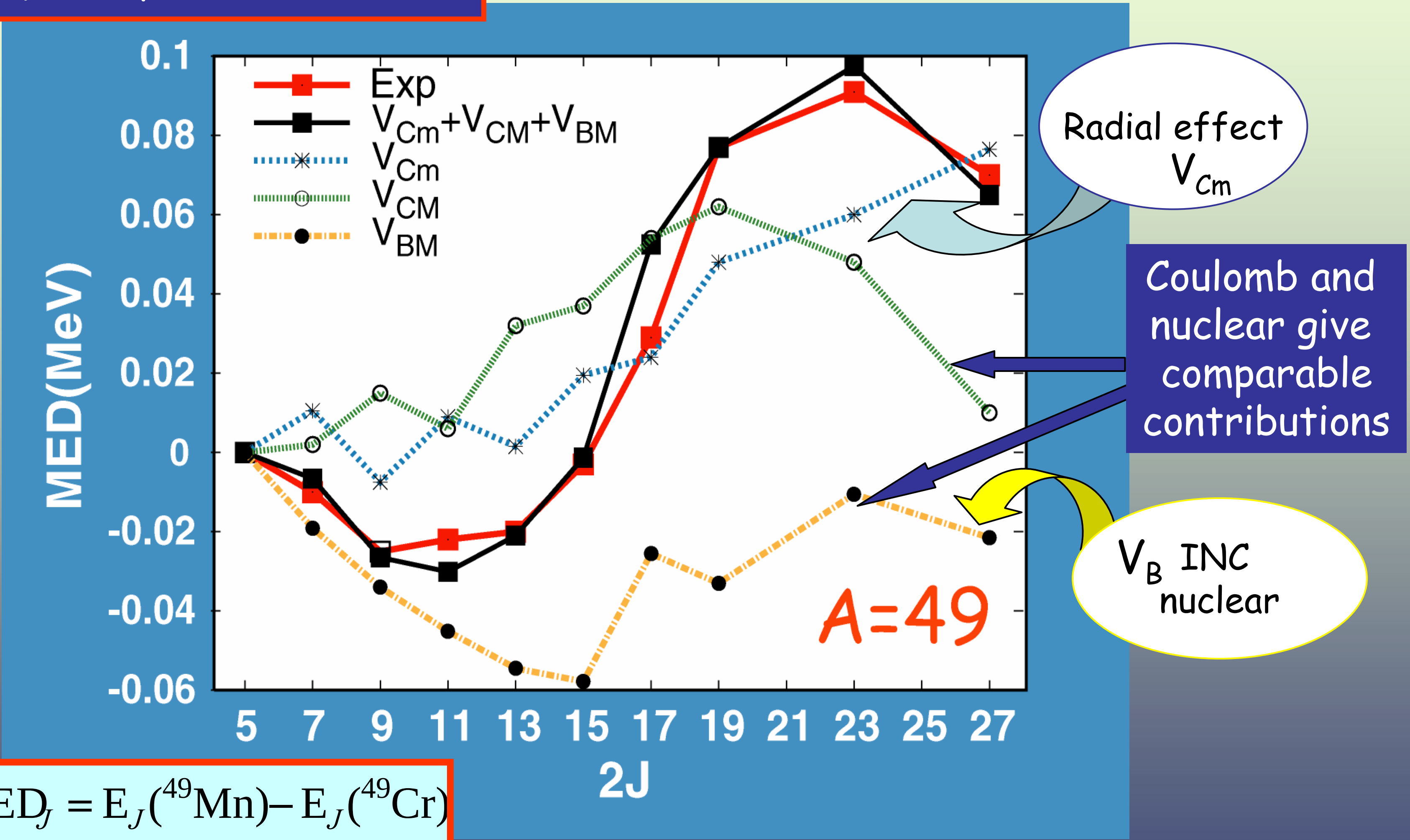
$$\mathrm{TED}_J = \Delta_T\langle V_{Cpf}^{ho}\rangle_J + \beta_2\Delta_T\langle V_{f_{7/2}}^{J=0}\rangle_J$$

In this way we can calculate (without free parameters) the MED and TED along the yrast rotational bands for all the isobaric multiplets measured so far in the $f_{7/2}$ shell

A.P. Zuker

Mirror Energy Differences in A=49

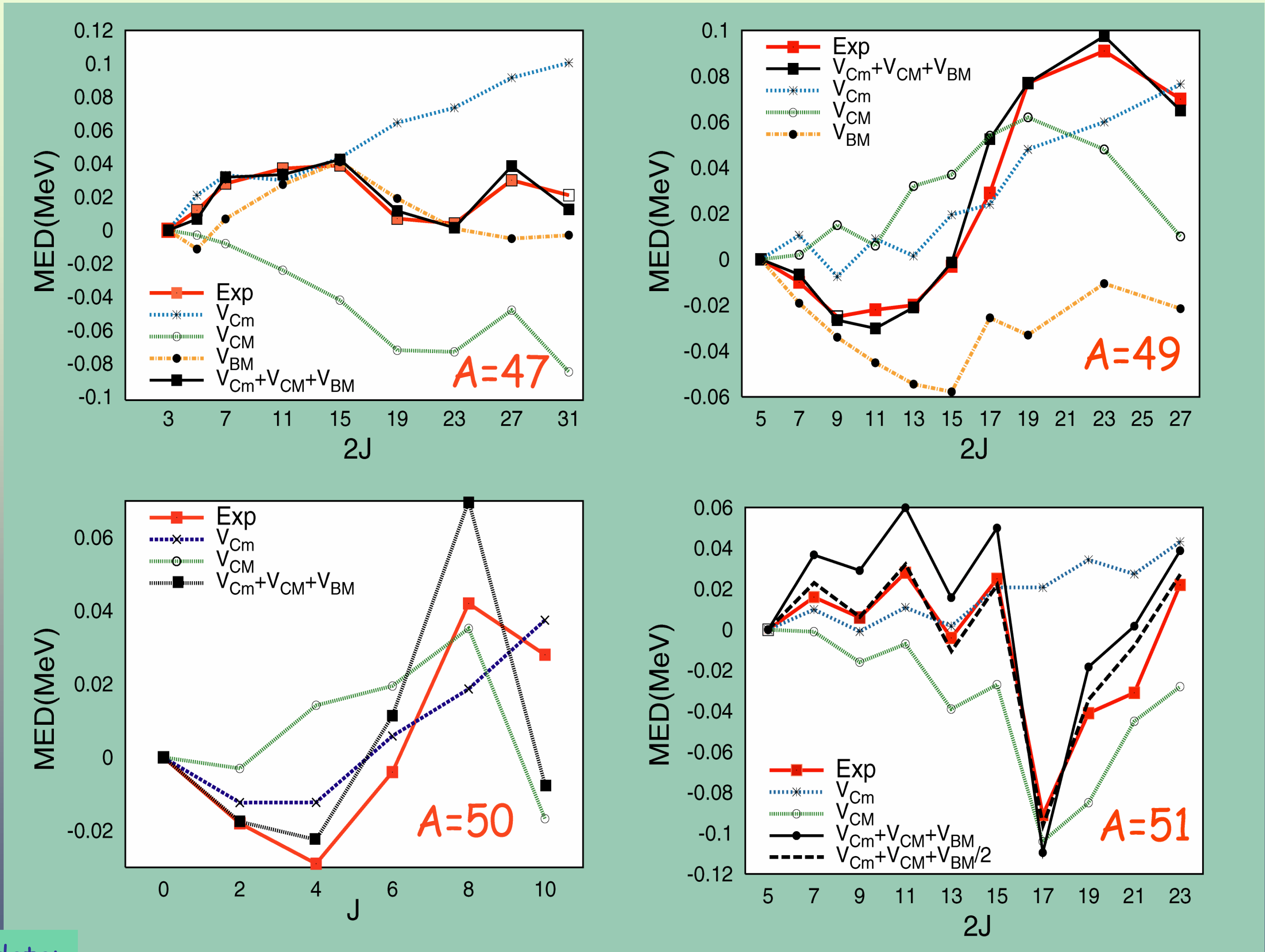
Parameter free calculations



$$MED_J = E_J(^{49}\mathrm{Mn}) - E_J(^{49}\mathrm{Cr})$$

Theo: *A.P. Zuker, S.M. Lenzi, G. Martinez-Pinedo and A. Poves, Phys. Rev. Lett. 89, 142502 (2002)*
Data: *M.A. Bentley et al., Phys. Lett. B 437, 243 (1998)*

MED along rotational bands in $f_{7/2}$-shell nuclei



Experimental data:

C.D. O'Leary et al.,, Phys. Rev. Lett. 79, 4349 (1997)
M.A. Bentley et al., Phys. Lett. B 437, 243 (1998)
J. Ekman et al., Eur. Phys. J A9, 13 (2000)
S.M. Lenzi et al., Phys. Rev. Lett. 87, 122501 (2001)

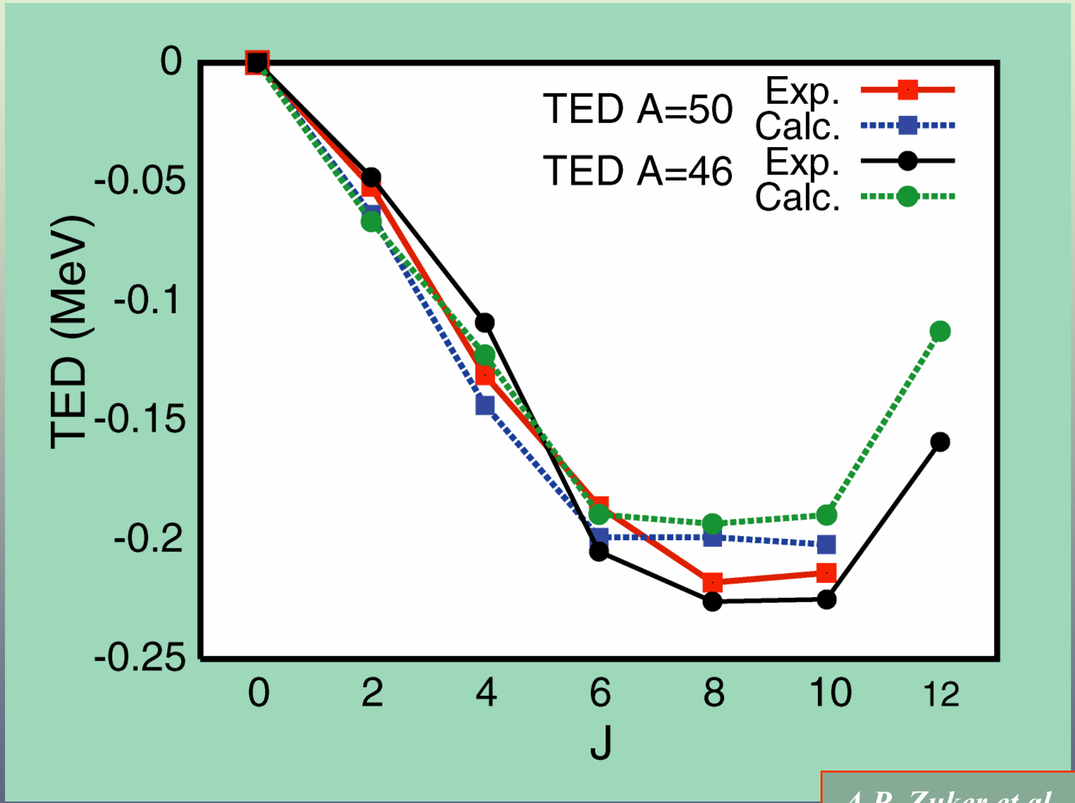
A.P. Zuker et al., Phys. Rev. Lett. 89, 142502 (2002)

TED along rotational bands in $f_{7/2}$-shell nuclei

T=1 triplets A=46, 50 in the $f_{7/2}$ shell have been recently observed at high spin

$$\mathbf{TED}_J^{(exp)} = E_J(T_z = 1) + E_J(T_z = -1) - 2E_J(T_z = 0)$$

$$\mathbf{TED}_J^{(theo)} = \Delta_T \langle V_{Cpf}^{ho} \rangle_J + \beta_2 \Delta_T \langle V_{f_{7/2}}^{J=0} \rangle_J$$

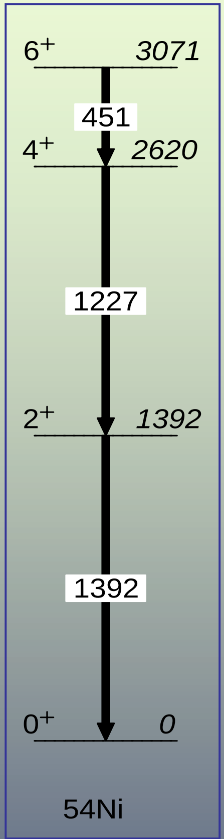


A.P. Zuker et al., Phys. Rev. Lett. 89, 142502 (2002)

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)

Mirror Energy Differences in the cross-conjugate A=42 and A=54 $f_{7/2}$-shell nuclei

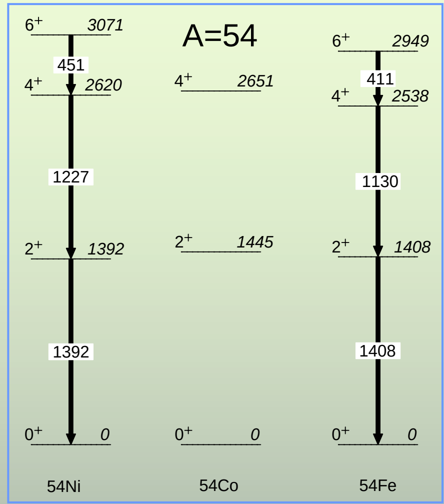


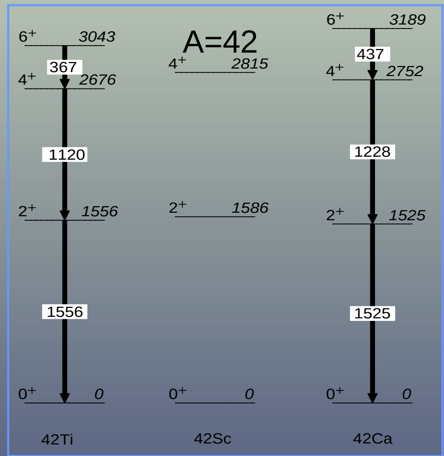
First observation of excited states in ^{54}Ni

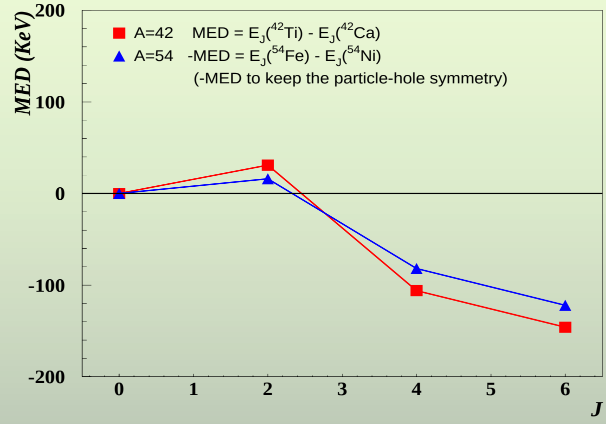
EUROBALL + EUCLIDES + N-wall

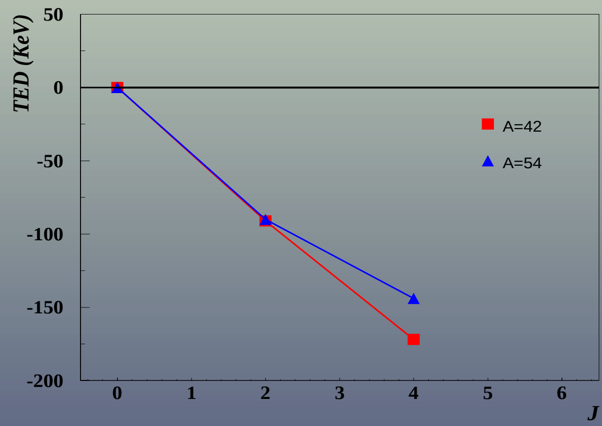
^{24}Mg (^{32}S , 2n) @75 MeV

A. Gadea, N. Mărginean et al.



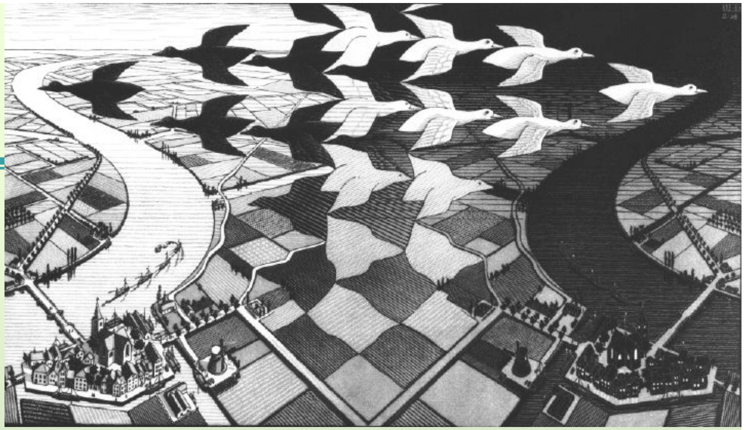






A rigorous treatment, calling upon state-of-the-art CSB potentials, is necessary to confirm these phenomenological findings.

Extending these investigations to other regions



- ✓ To check the limit of validity of the isospin symmetry for increasing A
- ✓ To look for the INC terms of the nuclear interaction
- ✓ To identify the origins of the symmetry breaking
- ✓ To look for new Coulomb effects

For a quantitative understanding we need:

1) to perform precise measurements of the different observables
2) to perform shell-model calculations on a large basis (more than one major shell) and with reliable effective interactions

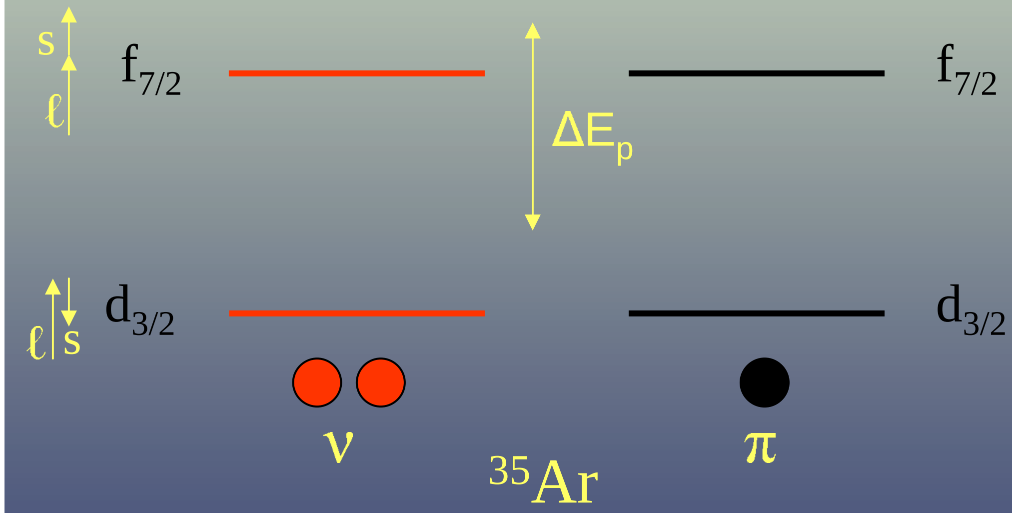
We can apply our experience in the $f_{7/2}$ shell to other mass regions

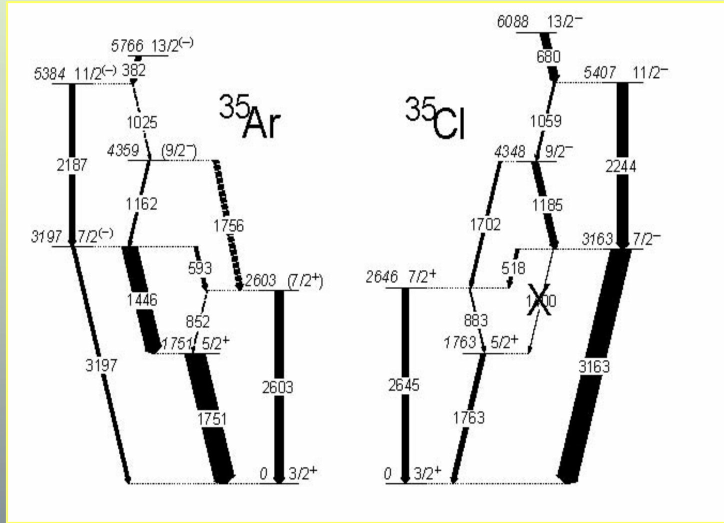
Large MED in the sd shell: the electromagnetic spin-orbit term

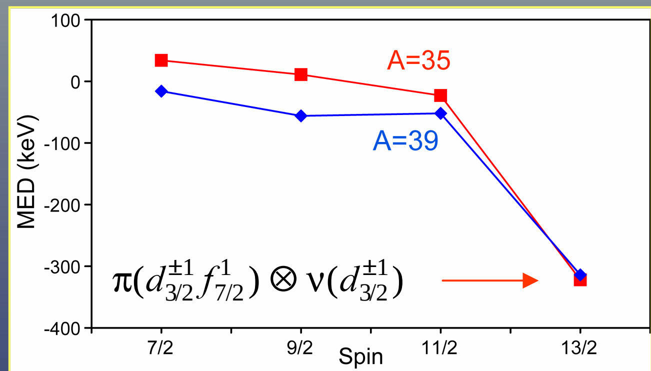
The electromagnetic spin-orbit coupling results from the Larmor precession of the nucleons in the nuclear electric field due to their intrinsic magnetic moments and to the Thomas precession experienced by a proton because of its charge.

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

It is important when a nucleon is promoted from a j=l-s level to a j=l+s level. The effect on a proton is opposite to the effect on a neutron orbit





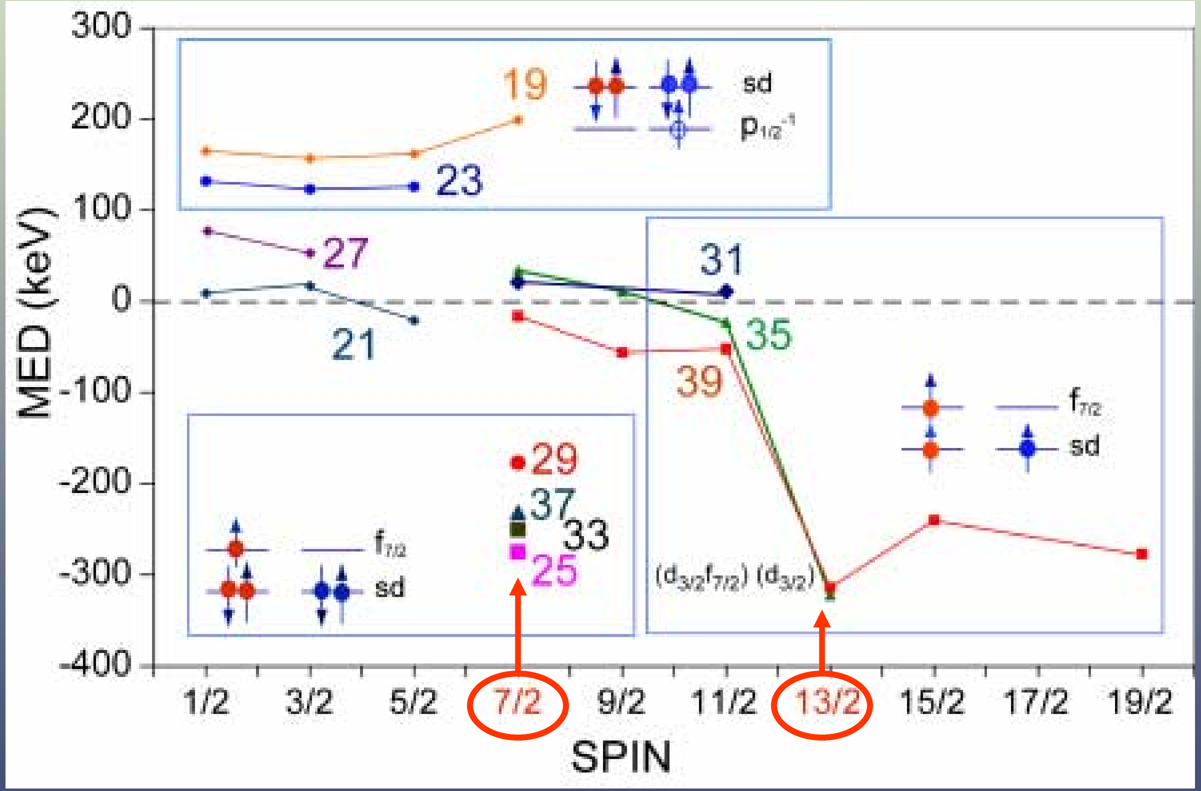


J. Ekman et al., Phys. Rev. Lett. in press

MED between negative parity states in T_Z=1/2 sd-shell nuclei

The effect of the electromagnetic spin-orbit term is proportional to the difference of proton and neutron occupation numbers.

Its contribution to MED becomes significant for configurations with *pure* single-nucleon excitations: a proton excitation in one nucleus and a neutron excitation in its mirror

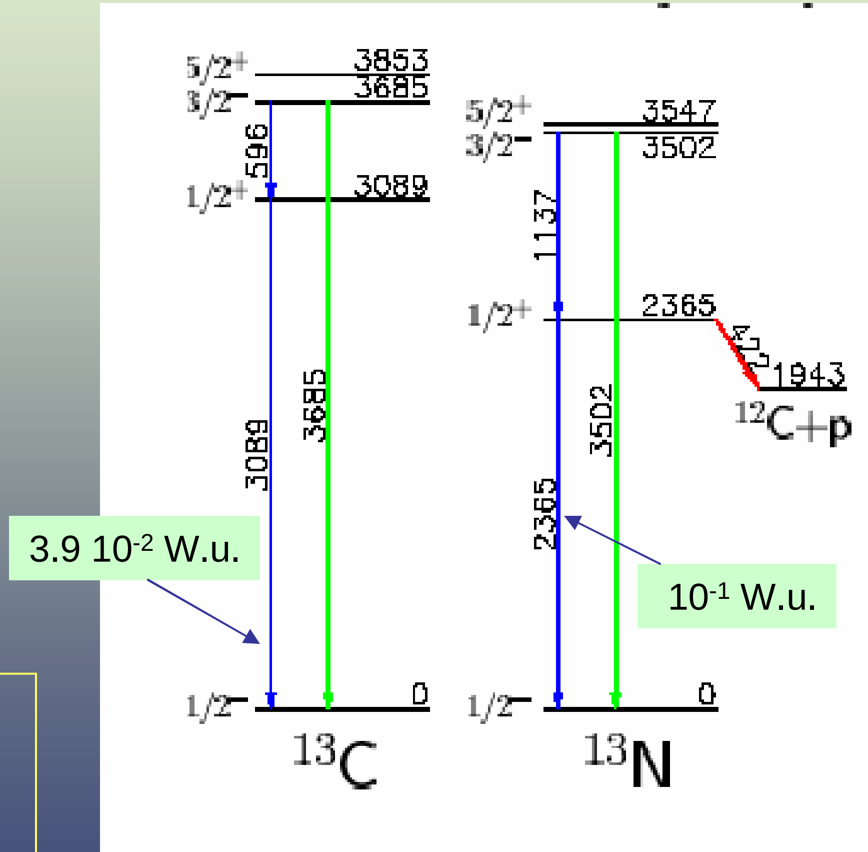


Loosely-bound nuclei: The Thomas-Ehrman shift
(Coulomb and nuclear effect in mirror nuclei)

The Thomas-Ehrman shift has conventionally been regarded as a Coulomb effect but…

Even under the assumption of charge symmetry of the nuclear interaction, TBME can be sizably affected due to the broad radial distribution of proton s.p. wave functions.

The effect is large for small-ℓ orbits and light nuclei



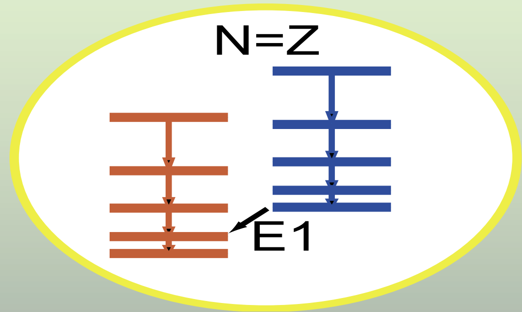
TES → large MED

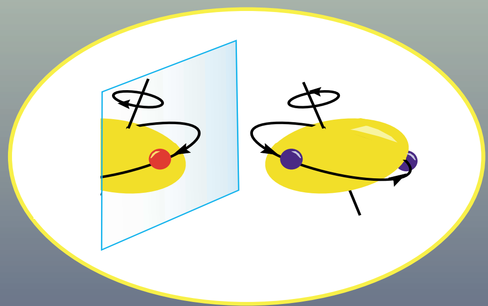
TES → Different E1 strengths: isospin mixing due to coupling with the continuum for weakly-bound or unbound states

P.G. Bizzeti and A.M. Bizzeti-Sona

Forbidden and Irregular E1 transitions

Observation of forbidden E1 in N = Z nuclei





Different strengths of E1 transitions in mirror nuclei

Isospin symmetry and E1 transitions along the N~Z line

In the validity of isospin symmetry

→ E1 ($\Delta T=0$) transitions are forbidden in N=Z nuclei

→ E1 transitions in mirror nuclei have identical strength

⇕

1) *Charge invariance* of the *nuclear interaction*

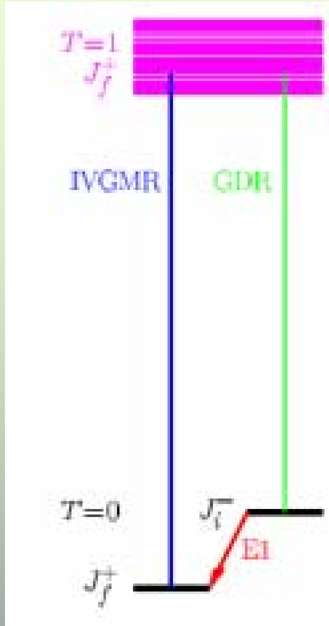
2) *Long-wavelength approximation* (first term in $j_1(kr)$) in the expansion of the E1 operator)

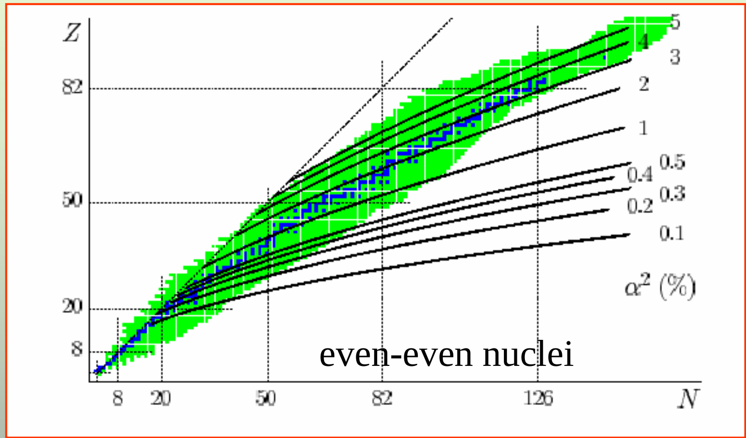
Signatures of symmetry breaking:
forbidden E1's in N=Z nuclei,
irregular E1 transitions in mirror nuclei

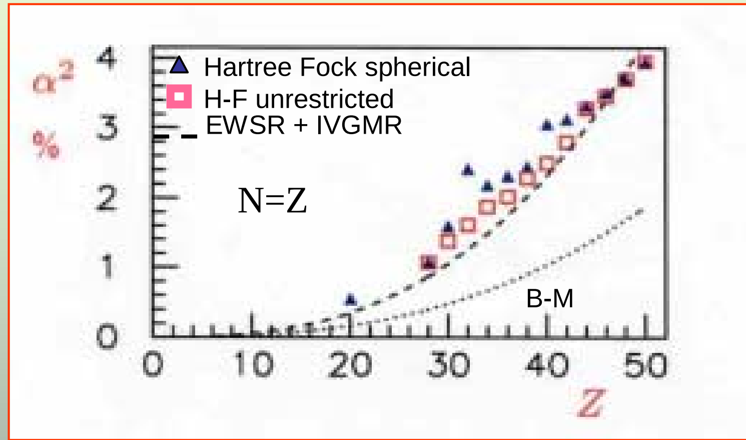
Possible origin:

- isospin breaking of the *nuclear interaction*
- *higher order terms* in the series expansion in $j_1(kr)$
- Isospin mixing due to the coupling to the continuum for nuclei close to the proton drip line
- Isospin mixing of quasi degenerate levels of equal J^π and different T
- Isospin mixing with the IVGMR

Isospin mixing due to the coupling to the IVGMR







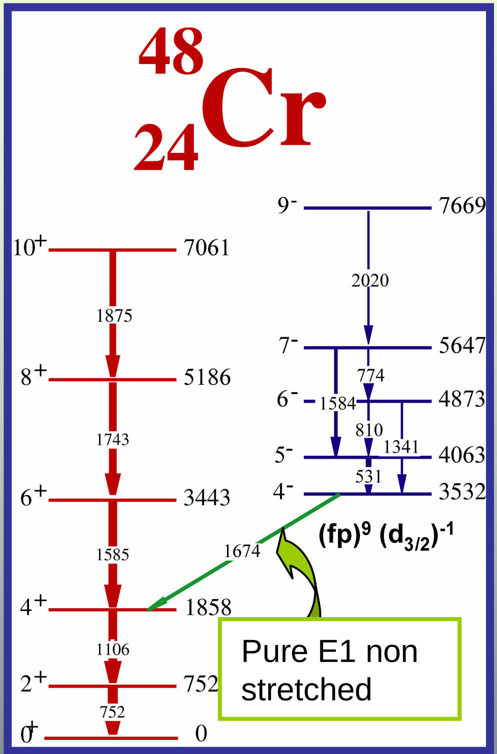
Isospin impurity of the g.s. due to mixing with the Isovector Giant Monopole Resonance.

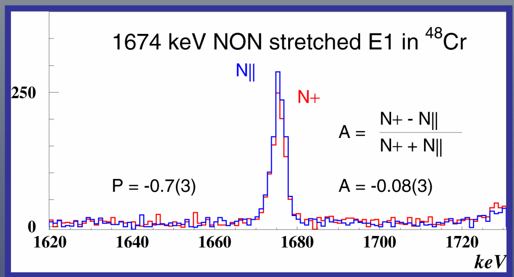
The calculated mixing increases significantly with A and, for a given A, is maximum for N=Z

In the fp and $g_{9/2}$ region it is possible to find qualitatively new aspects, as those related to the onset of deformation

G. Colò et al., Phys. Rev. C 52, R1175 (1995)
J. Dobaczewski and I. Hamamoto, PLB 345, 181 (1995)
I. Hamamoto and H. Sagawa, PRC 48, R960 (1993

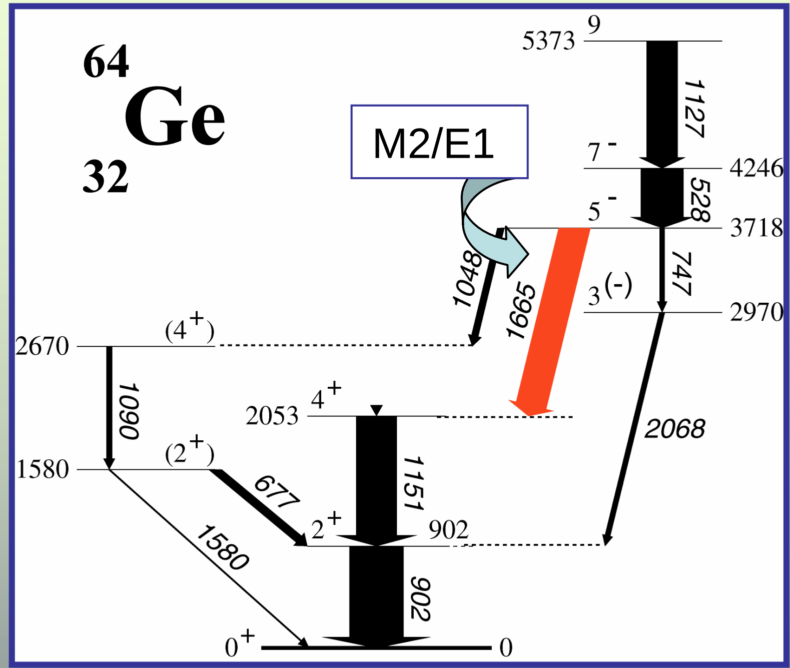
Forbidden E1 transition in N=Z nuclei





The minimum isospin mixing is $\alpha^2 \approx 0.15\%$

E. Farnea, A. Gadea, N. Mărginean et al.



Measured: lifetime, ang. distr. and polarization

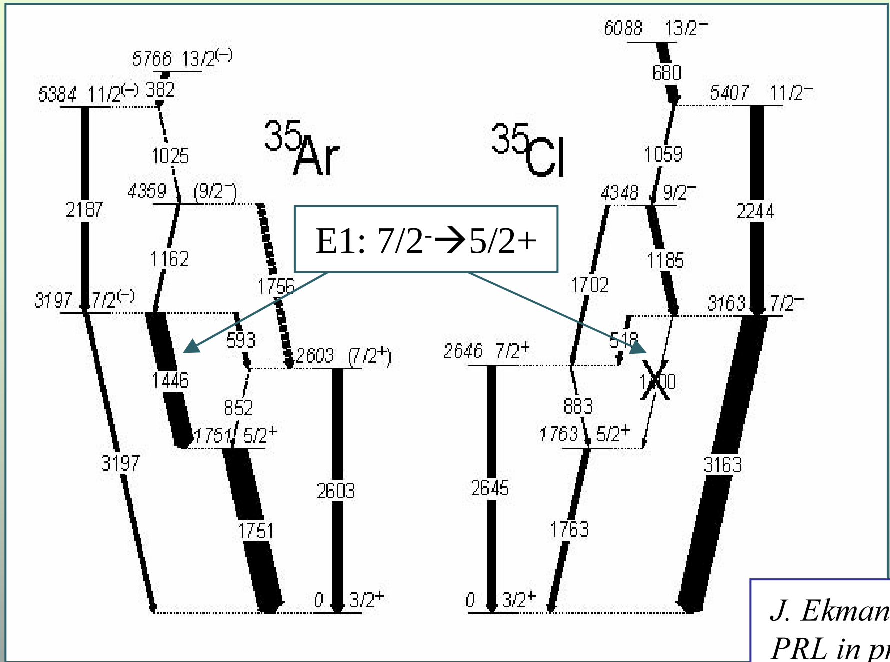
The *minimum* isospin mixing results

$\alpha^2 = 2.3(1.4)\%$

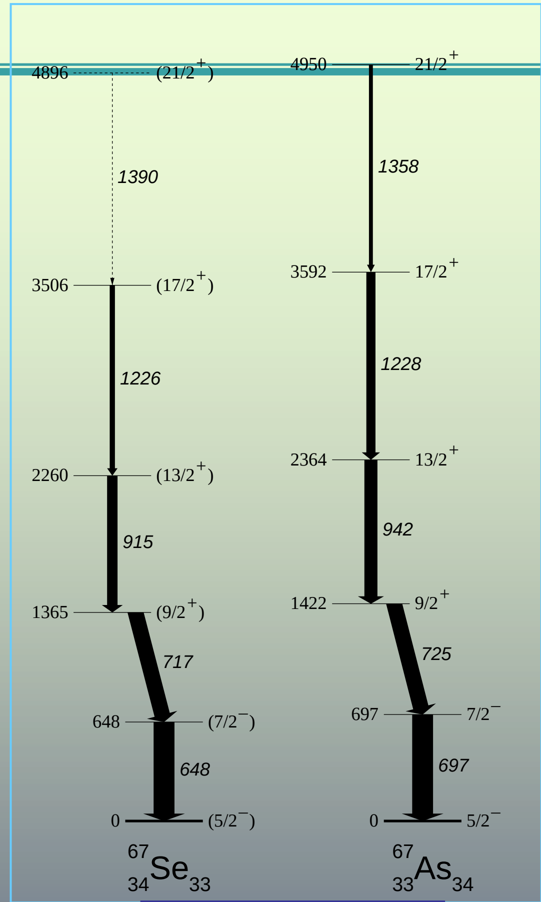
E. Farnea et al., PLB 551, 56 (2003)

Euroball data

Irregular E1 transitions in mirror nuclei



J. Ekman et al., PRL in press



G. de Angelis et al., analysis in progress

The electromagnetic transition operator can be expressed in terms of:
1) isoscalar (IS): it does not depend on Tz
2) isovector (IV): is linear in Tz (changes sign in each mirror)

E1 amplitudes in mirror nuclei: the IS component vanishes (kR >>1), therefore E1 transitions (IV) in mirror nuclei must have the same strength.

Induced Isoscalar amplitude
First order effect
in mirror nuclei

Higher-order IS amplitudes and isospin mixing are responsible of asymmetries: interference of regular (IV) and irregular amplitudes.

They can be measured!

Lifetime measurements are needed.

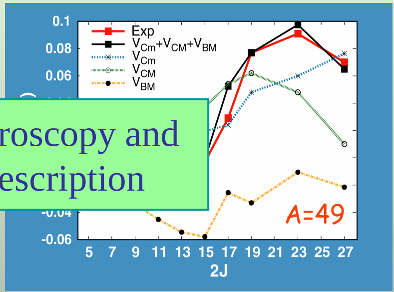
Conclusions

The isospin symmetry is slightly broken in isobaric multiplets due (mainly) to the Coulomb interaction.

We can use MED as an efficient observatory for a direct insight into **nuclear structure properties**

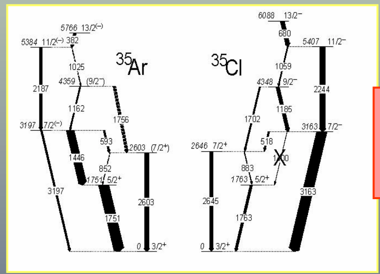
Energy differences

- Studying MED and TED along rotational bands we can learn about:
  - ➢ Mechanism of nucleon alignment at the backbending
  - ➢ Evolution of the radii along a rotational band
  - ➢ Isospin non-conserving terms in the nuclear interaction

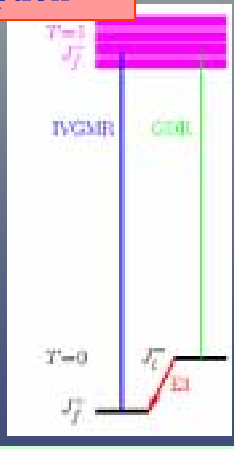


with: good spectroscopy and good SM description

- Extending these studies to cross-shell excitations we can learn about:
  - ➢ Further Coulomb effects
  - ➢ Configuration of states



need: good spectroscopy and good SM description



E1 transitions

- Studying E1 transitions in N=Z nuclei and mirrors we can learn about:
  - ➢ Isospin mixing
  - ➢ Coupling to GR
  - ➢ Induced IS terms
  - ➢ Coupling to the continuum

Perspectives with AGATA

These investigations are at the beginning.

High intensity stable beams

We need to know the limits of validity of the isospin symmetry

- get a deeper understanding of nuclear INC term
- identify the different Coulomb effects
- identify the origin of isospin mixing

Radioactive beams

Ancillary detectors to select the channels of interest

High granularity and sensitivity

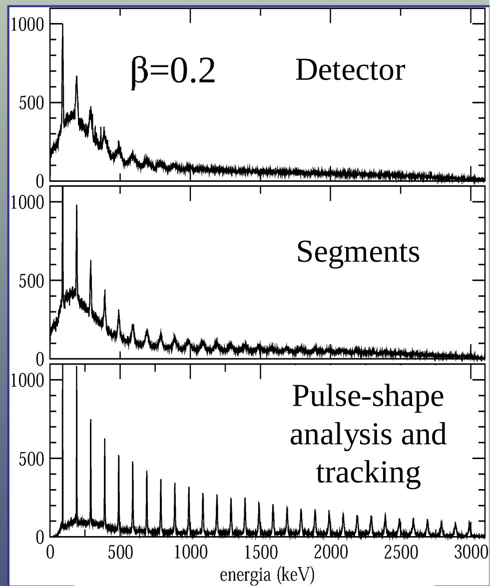
Light and medium-light nuclei:

- N=Z nuclei up to high spin
- MED for positive and negative parity states
- MED for T > 1
- TED measurements

High efficiency for h.e. γ-rays

Deal with high rates

Kinematical reconstruction for Doppler correction



F. Recchia, E. Farnea

Some effects are larger for heavier nuclei:

- higher-order terms in the series expansion of $j_1(kr)$
- isospin mixing
- *Heaviest particle-stable nucleus with Z=N is expected to be ^{100}Sn*
- *Heaviest particle-stable nuclei with T_z=1/2 and T_z=3/2 are ^{95}Ag and ^{74}Se*

Powerful shell model codes

Reliable effective interactions


AGATA