Theoretical and experimental challenges in isospin symmetry breaking studies

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Outline

Isospin symmetry breaking in

Energy differences between mirror nuclei (MED)

- How we calculate them within the shell model
- The role of the Coulomb force
- Other isospin symmetry breaking terms
- Systematic study of MED
- Application to nuclei in the pf+gds shells: The A=73 case

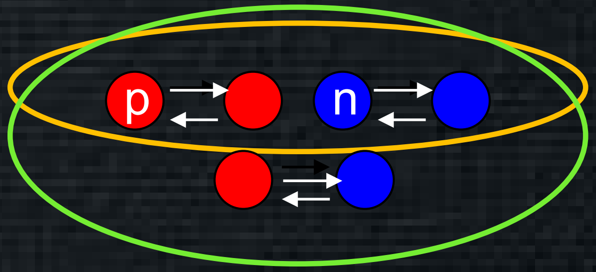
Isospin symmetry breaking in

Electromagnetic transition probabilities

- Recent results with stable and radioactive beams
- Application to nuclei in the pf+gd shells: The A=70 case

Neutron-proton exchange symmetry

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

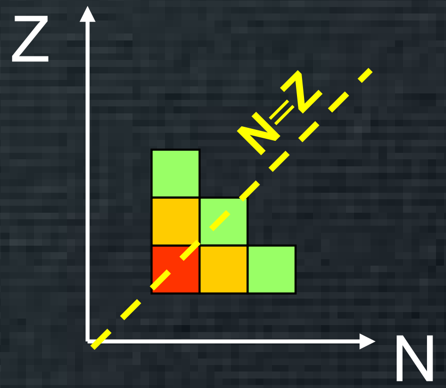


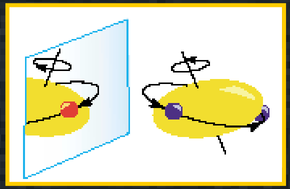
Charge independence: $(V_{pp} + V_{nn})/2 = V_{np}$

Deviations are small

The electromagnetic interaction lifts the degeneracy of the analogue states but does not, in general, affect the underlying symmetry

Differences in analogue excited states

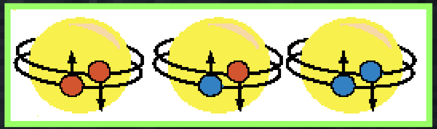




Mirror Energy Differences (MED)

$$\mathrm{MED}_J = \mathrm{E}x_{J,T_z=-T} - \mathrm{E}x_{J,T_z=+T}$$

Test the charge symmetry of the interaction

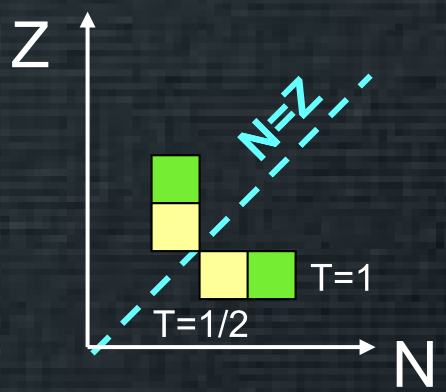


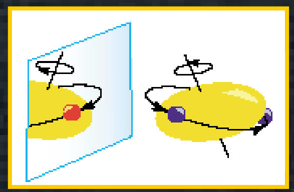
Triplet Energy Differences (TED)

$$\mathrm{TED}_J = \mathrm{E}x_{J,T_z=-T} + \mathrm{E}x_{J,T_z=+T} - 2\mathrm{E}x_{J,T_z=0}$$

Test the charge independency of the interaction

Mirror energy differences

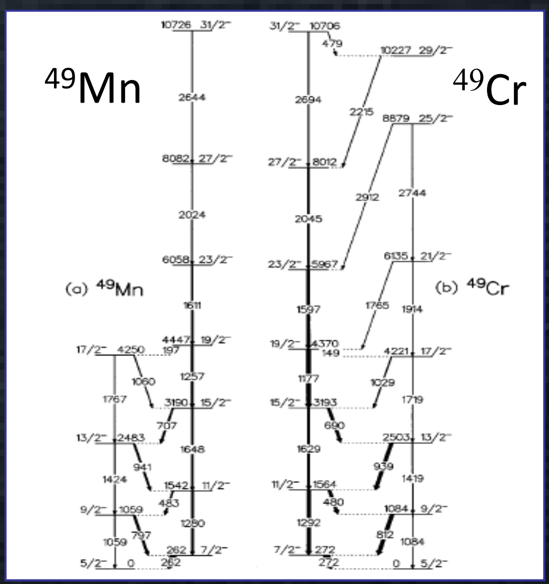


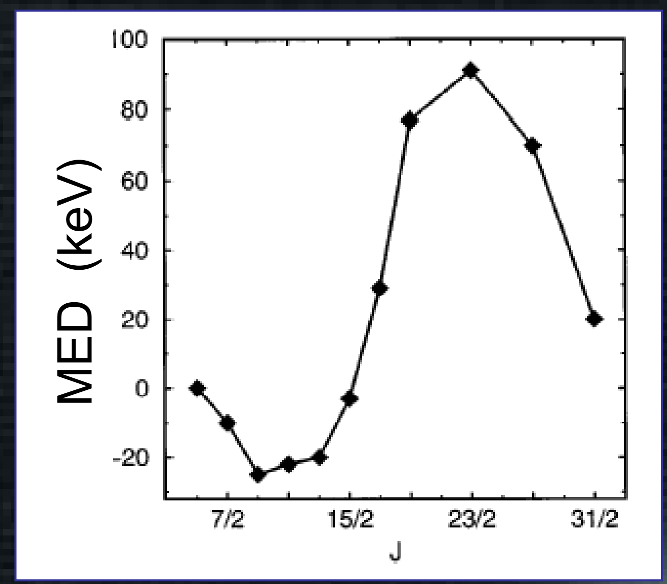


difference in excitation energies

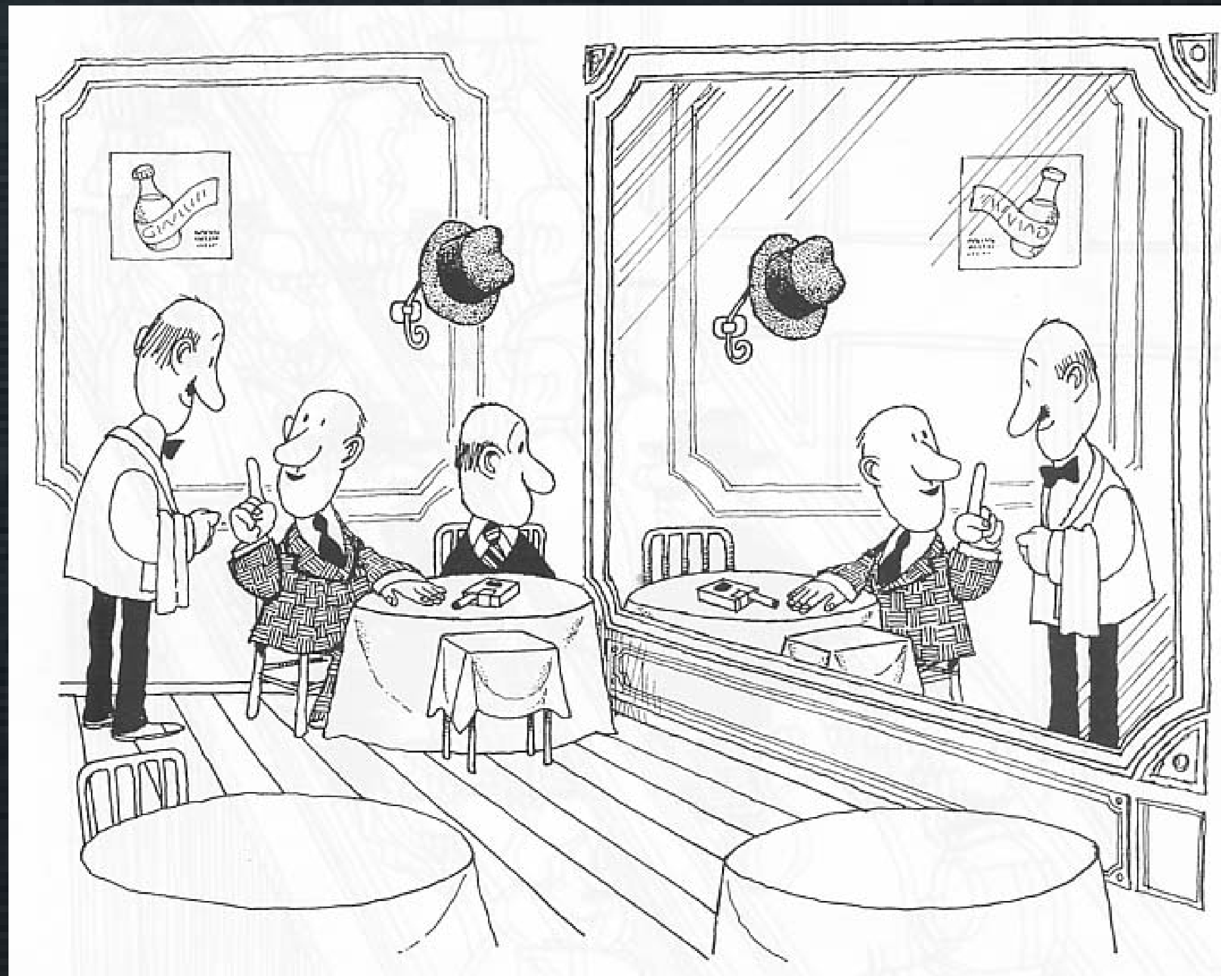
$$MED_J = E^*_{J,-|T_z|} - E^*_{J,|T_z|}$$

Test the charge symmetry of the interaction





Mirror symmetry is (slightly) broken



Isospin symmetry breakdown manifests in the MED.
An efficient observatory for a direct insight into nuclear structure properties.

Measuring MED

What can we learn from them?

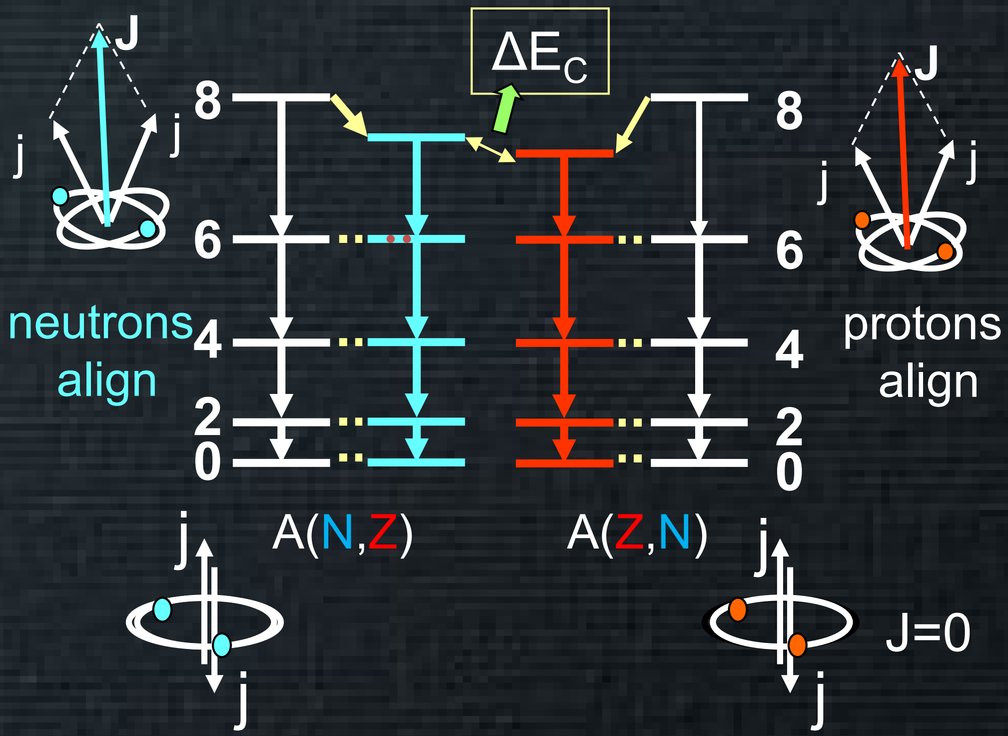
They contain a richness of information
about spin-dependent structural phenomena

We measure **nuclear** structure features:

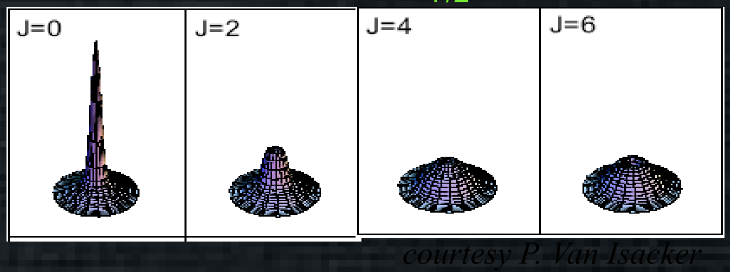
- How the nucleus generates its angular momentum
- Evolution of radii (deformation) along a rotational band
- Learn about the configuration of the states
- Isospin non-conserving terms of the interaction
- Estimate the neutron skin

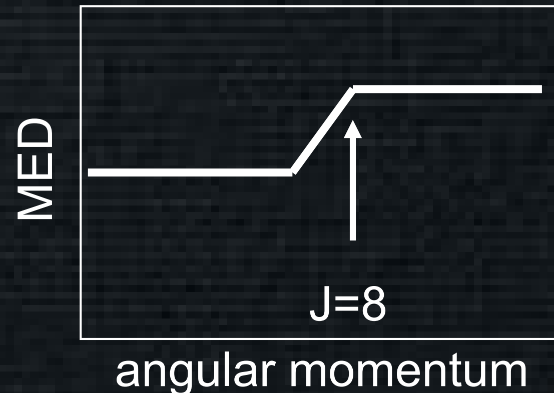
Can we reproduce theoretically such small energy differences?

MED and nucleon spatial correlations



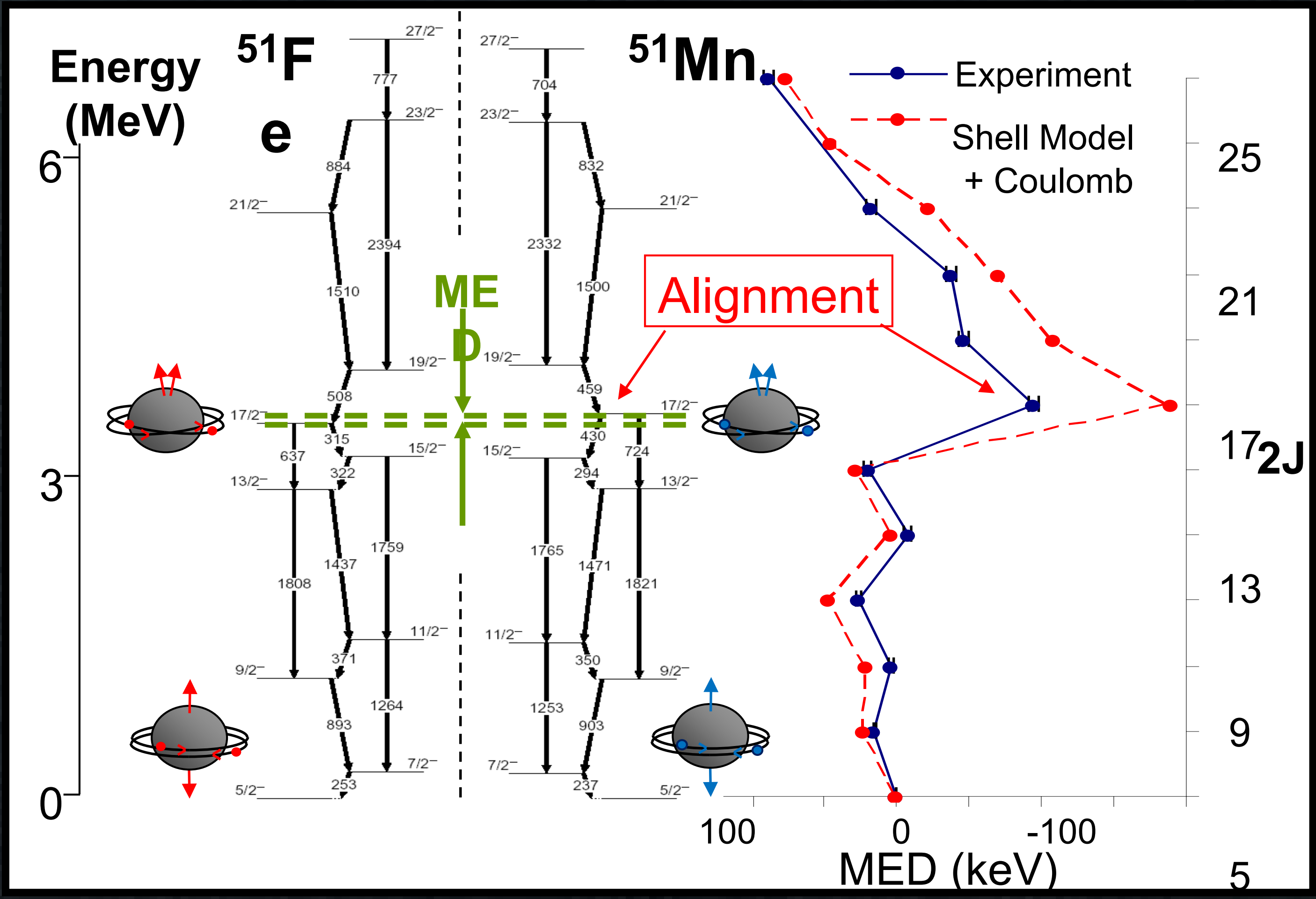
probability distribution for the relative distance of two like particles in the $f_{7/2}$ shell





Shifts between the excitation energies of the mirror pair indicate the type of nucleons that are aligning

MED and nucleon alignment



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

MED and Shell model

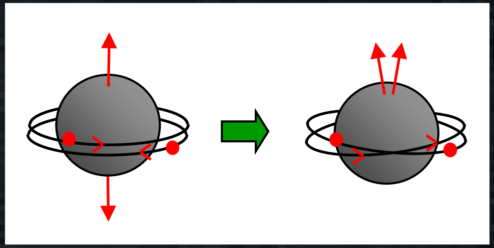
We start from diagonalizing a nuclear hamiltonian that conserves isospin and treat Coulomb and other eventual isospin symmetry breaking (ISB) contributions perturbatively

A.P. Zuker et al., PRL 89, 142502 (2002)
M.A. Bentley and S.M. Lenzi, PPNP 59, 497 (2007)

The Coulomb effects

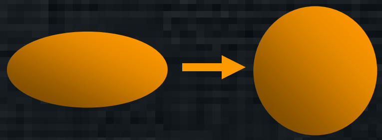
$$V_C = V_{CM} + V_{Cm}$$

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



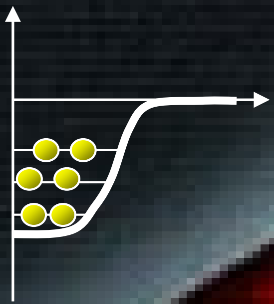
V_{Cm} monopole part of the Coulomb energy

- radial effect: radius changes with J



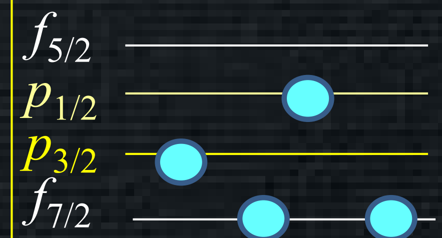
- $\ell \cdot \ell$ term to account for shell effects
- $\ell \cdot s$ electromagnetic spin-orbit term

change the single-particle energies



The radial effect with the shell model

The radius of a nucleus depends on the occupation of the different orbitals and in the fp shell *p* orbits have larger radius than *f* orbits.
The radial term will depend on the change of occupation of the *p* orbitals as a function of *J*



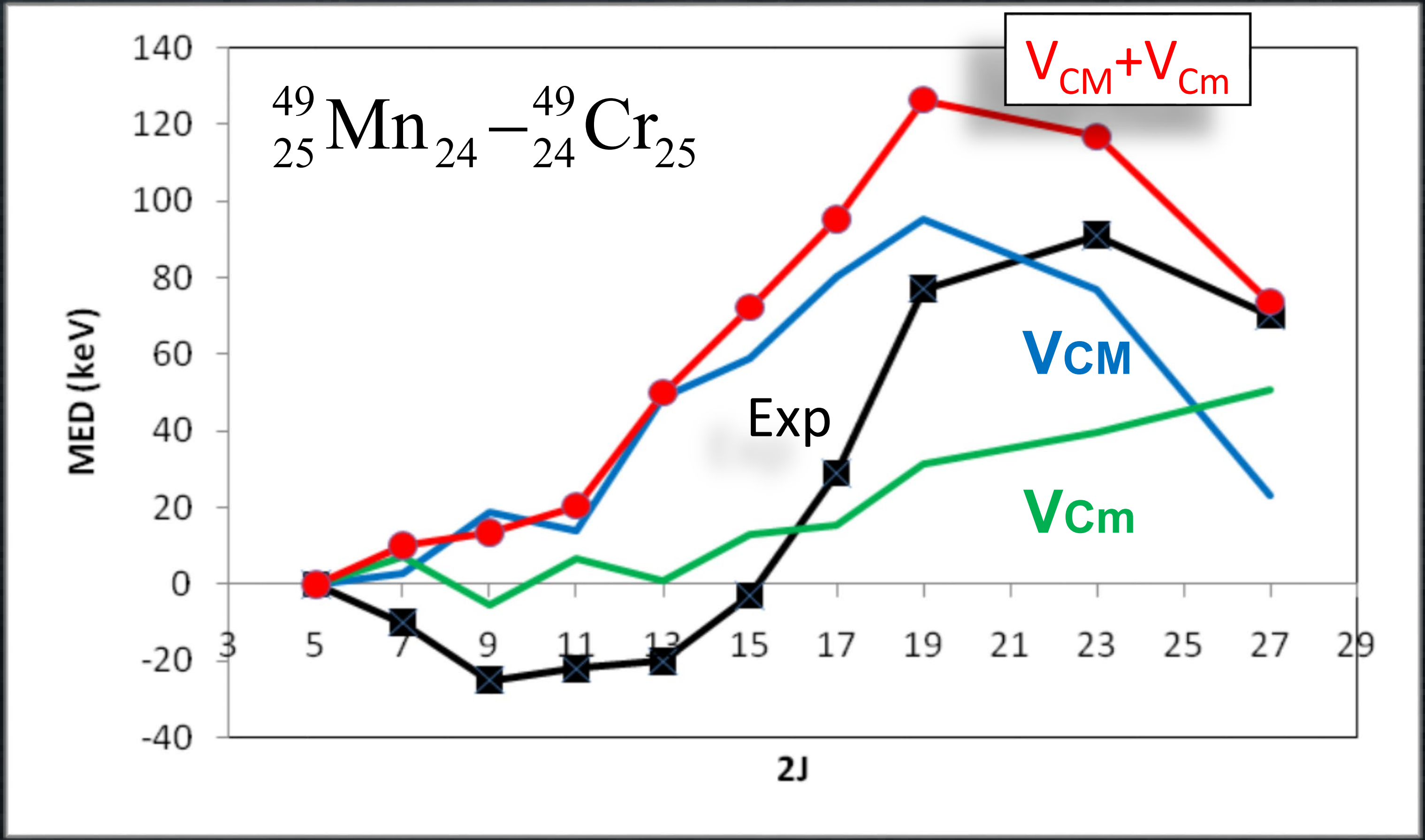
$$V_{Cm}(J) = 2|T_z| a_m \left\langle \frac{\Delta z_p + \Delta n_p}{2} \right\rangle_J$$

Δz and Δn are the number of protons and neutrons in the p orbits, relative to the g.s. (J=0)

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

The radial parameter amounts to $a_m \sim 200$ keV for nuclei in the $f_{7/2}$ shell

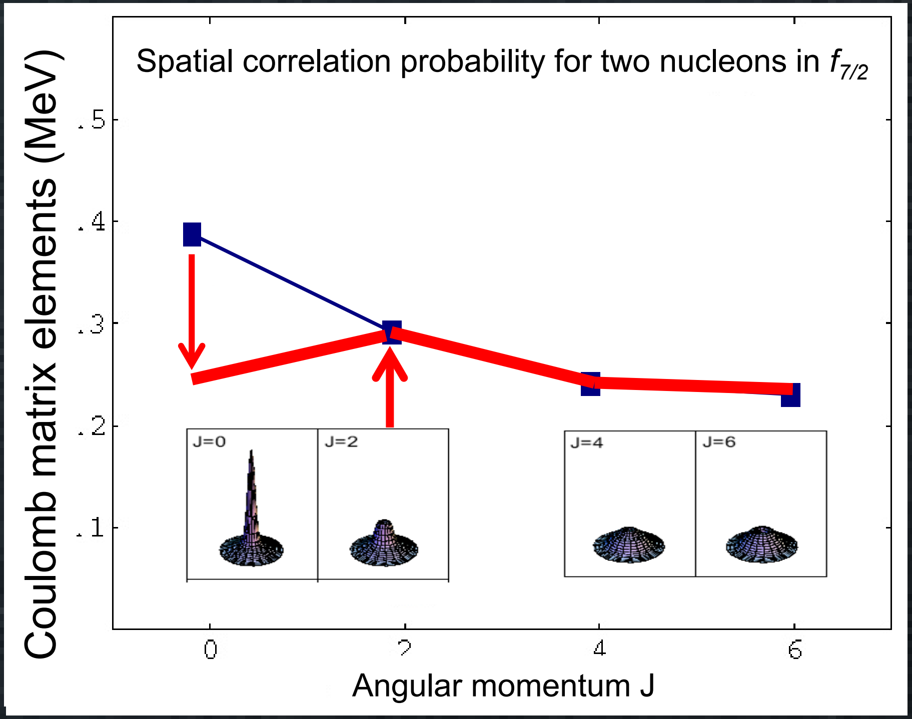
Are Coulomb corrections enough?



Another term of “nuclear” nature is needed, but it has to be big!

An empirical ISB interaction

Based on the experimental MED of A=42, Zuker et al.(PRL 89,142502 (2002)) suggested an empirical isovector correction of «nuclear» origin to account for the MED's in nuclei of the $f_{7/2}$ shell



$$V_B = \left[\pi f_{7/2}^{\,2}\right]^{J=2} - \left[\nu f_{7/2}^{\,2}\right]^{J=2} = +100\,\mathrm{keV}$$

$$V_B = \left[\pi f_{7/2}^{\,2}\right]^{J=0} - \left[\nu f_{7/2}^{\,2}\right]^{J=0} = -100\,\mathrm{keV}$$

The ansatz has been further developed and generalized to all shells

M.A. Bentley, S.M. Lenzi, S.A. Simpson, and C.Aa. Diget, Phys.Rev. C92, 024310 (2015).

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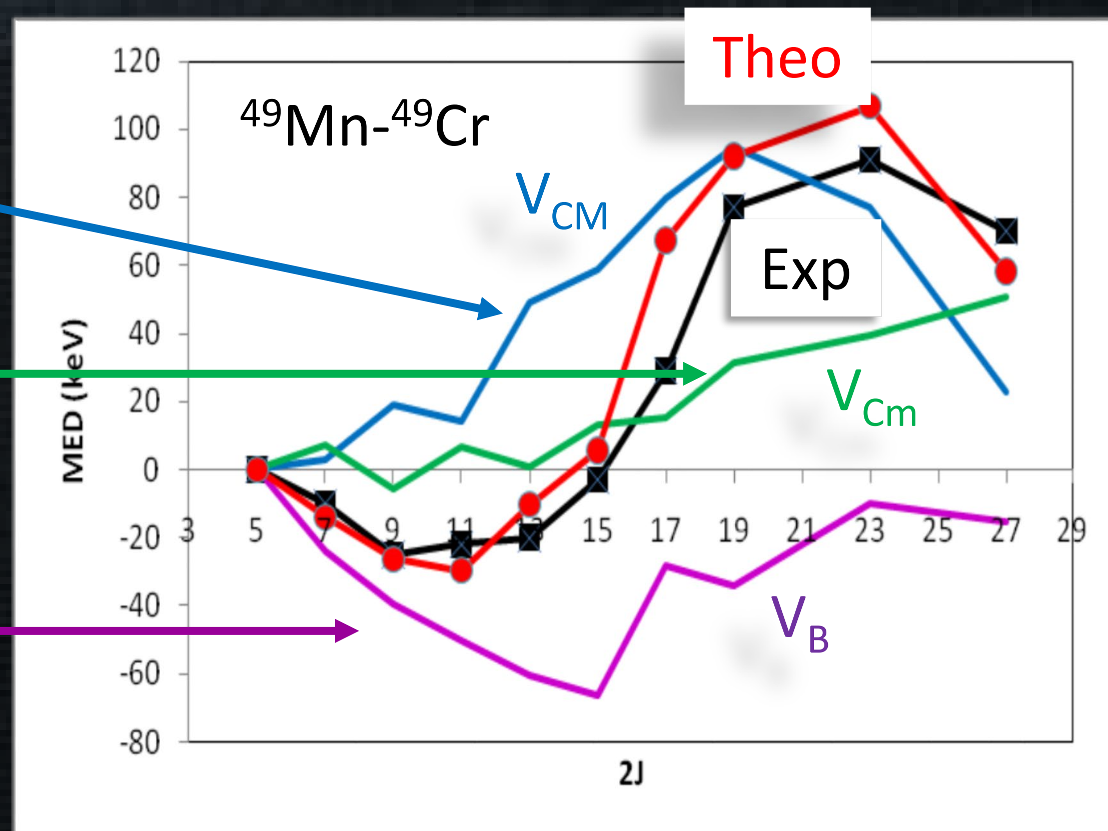
Calculating the MED with SM

$$MED_J^{theo} = \Delta\langle V_{CM}\rangle_J + \Delta\langle V_{ls} + V_{ll}\rangle_J + \Delta\langle V_{Cm}\rangle_J + \Delta\langle V_B\rangle_J$$

V_{CM}: gives information on the nucleon alignment or recoupling

V_{Cm}: gives information on changes in the nuclear radius

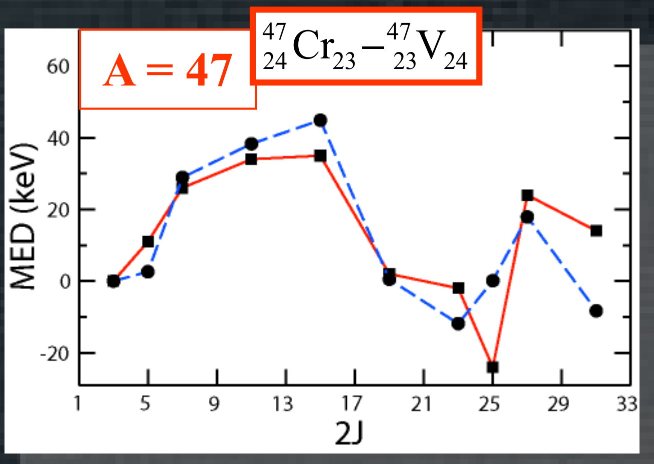
Important contribution from the ISB V_B term:
of the same order as the Coulomb contributions

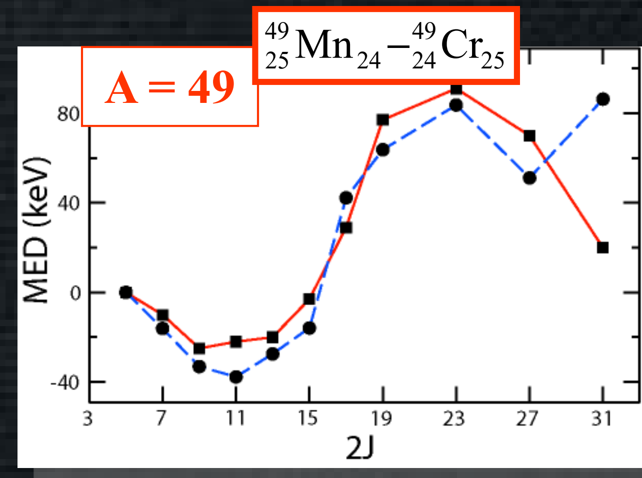


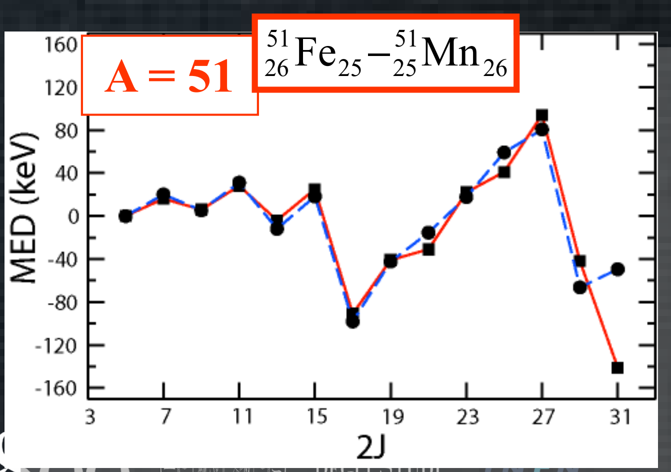
A. P. Zuker et al., PRL 89, 142502 (2002)

MED in T=1/2 states

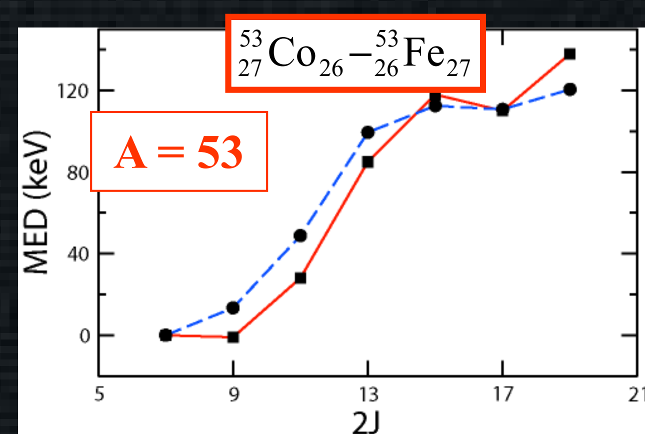
Very good quantitative description of data without free parameters



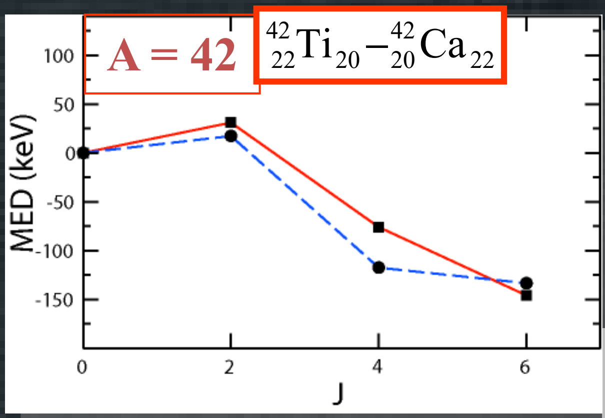




M.A. Bentley and S.M. Lenzi, Prog. Part. Nucl. Phys. 59, 497-561 (2007)

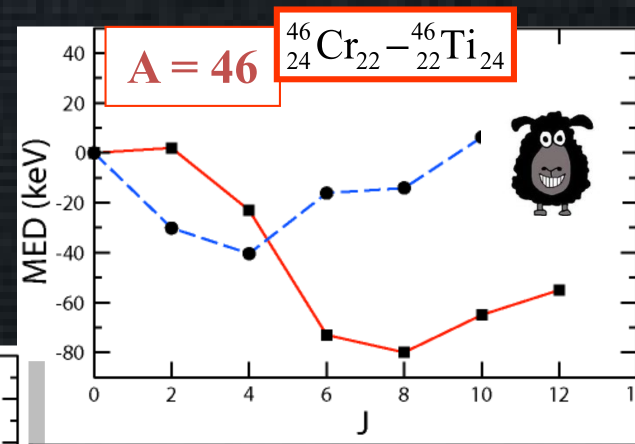


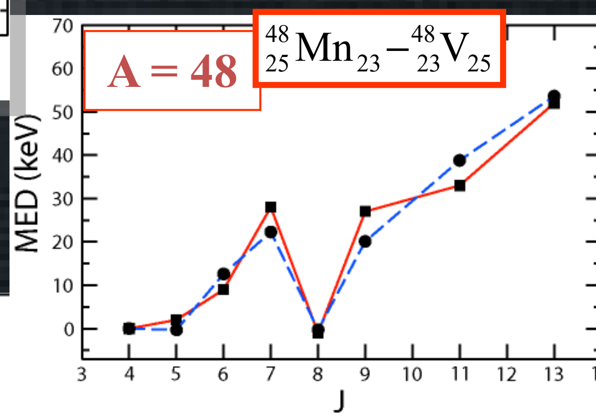
MED in T=1 states

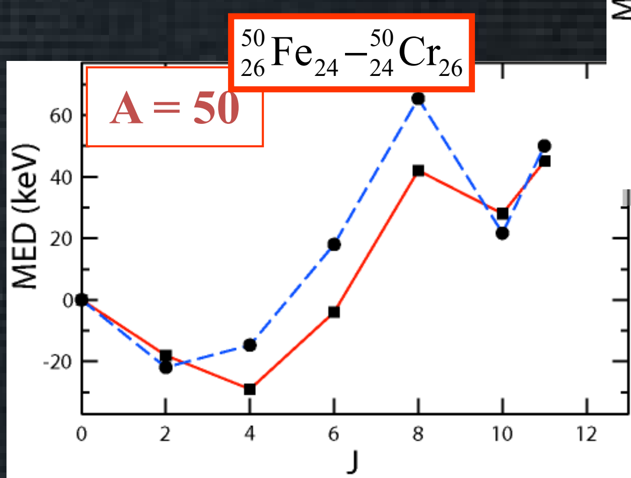


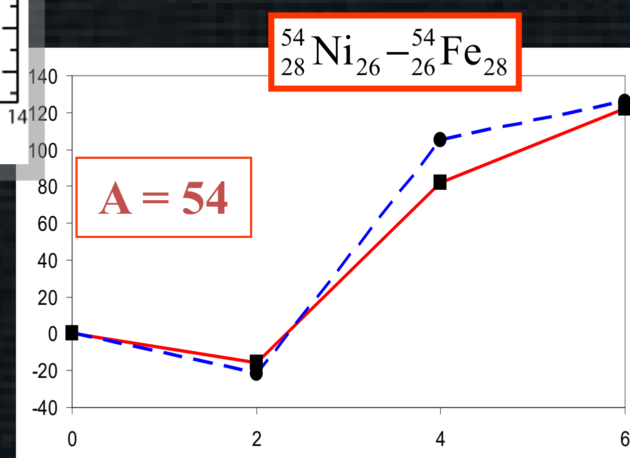
Experiment
Shell Model

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







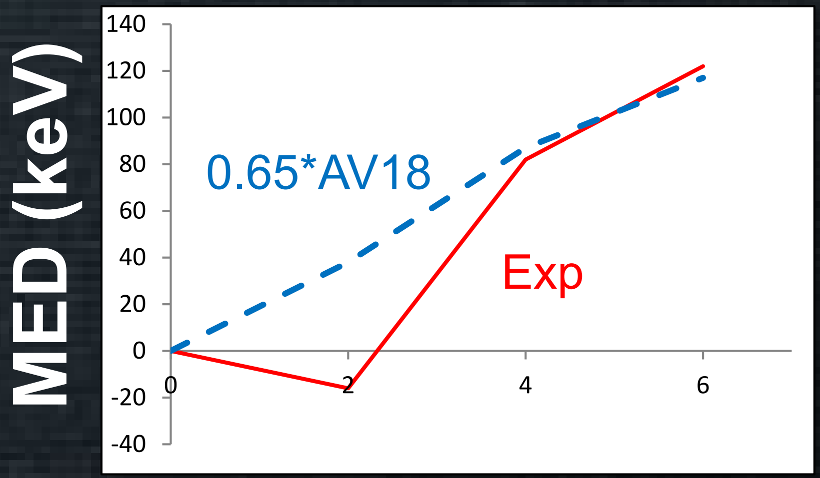


M.A. Bentley and S.M. Lenzi, Prog. Part. Nucl. Phys. 59, 497-561 (2007)

ISB from realistic interactions

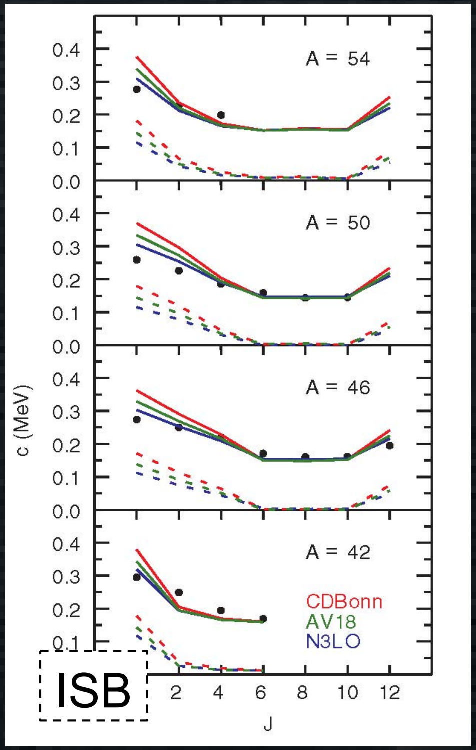
Charge-dependent realistic interactions do not reproduce the MED and TED

$$^{54}_{28}\mathrm{Ni}_{26} - ^{54}_{26}\mathrm{Fe}_{28}$$



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

TED



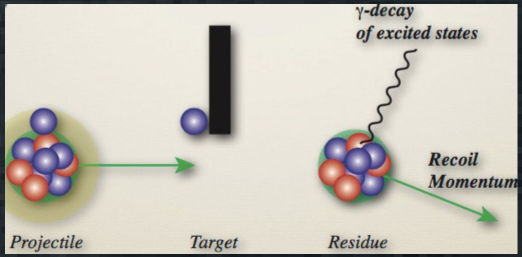
W.E. Ormand *et al*., PRC 96, 024323 (2017)

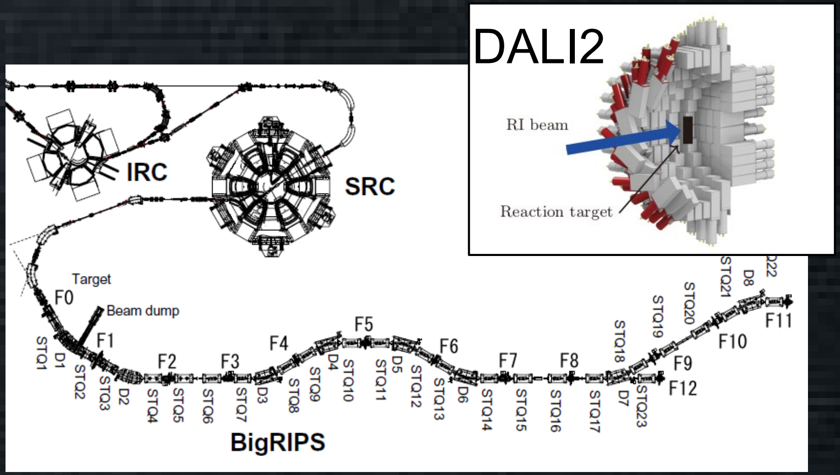
The charge-symmetry breaking in the nucleon-nucleon interaction is poorly known

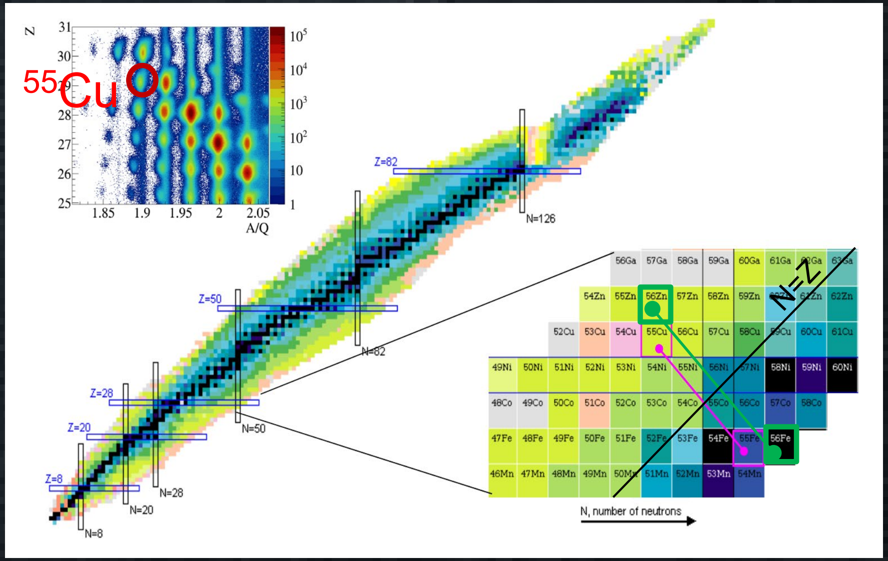
MED in T=3/2 and T=2

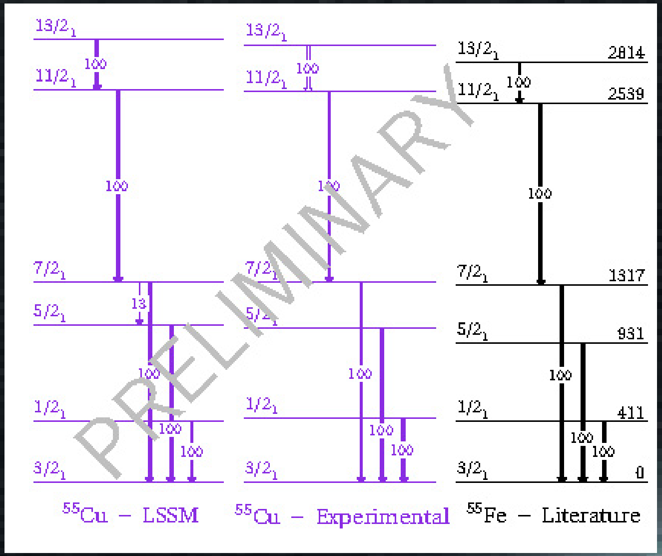
Knockout reactions at relativistic energy

Need high efficiency of gamma detection for large T mirror pairs



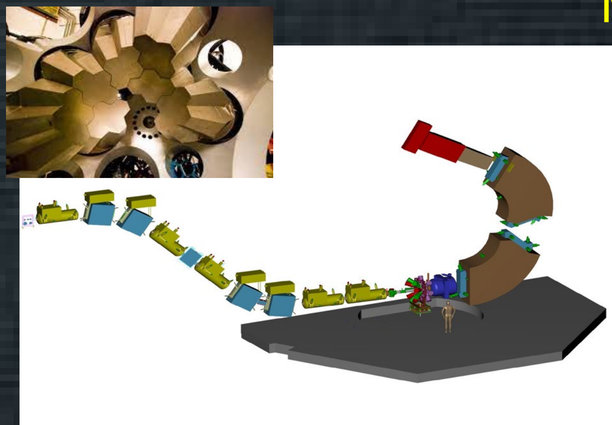




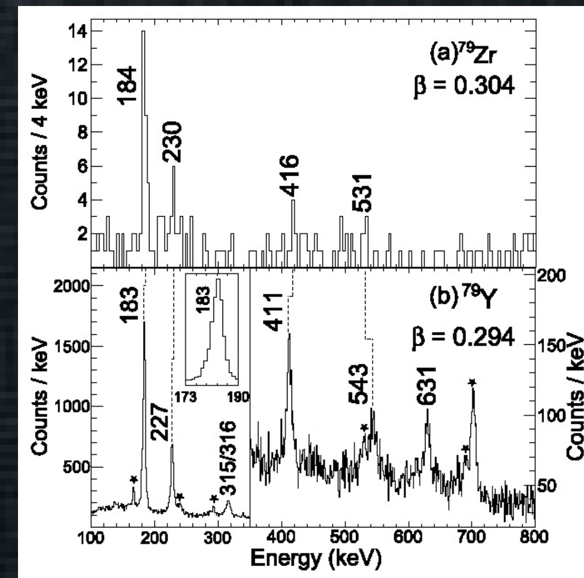


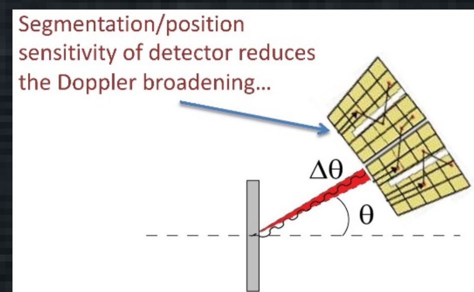
S. Pigliapoco *et al.*, to be published

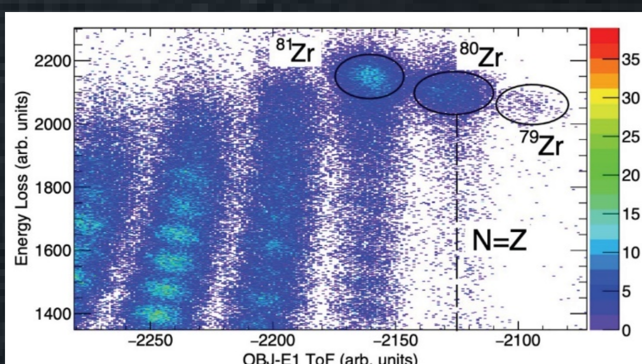
A=79: the highest T=1/2 MED observed

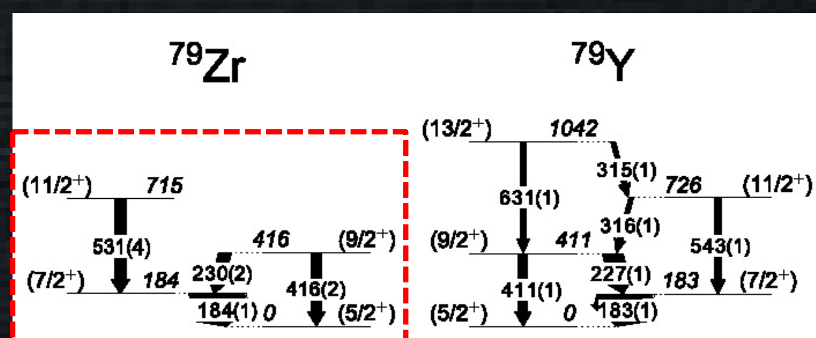


Measures at NSCL (MSU) using GRETINA
High-resolution measurements





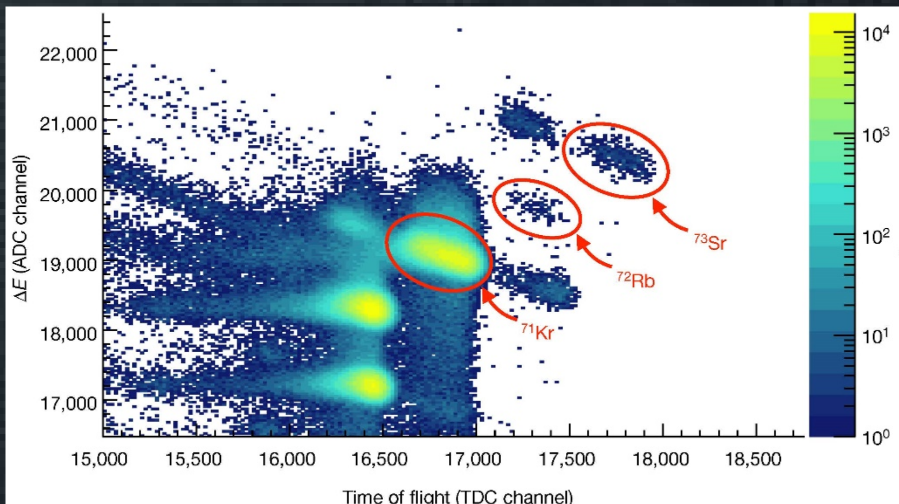




R.D.O. Llewellyn *et al.*, Phys Lett B 811(2020)135873

From M. Bentley lectures at Euroschool 2021

The case of ^{73}Sr-^{73}Br

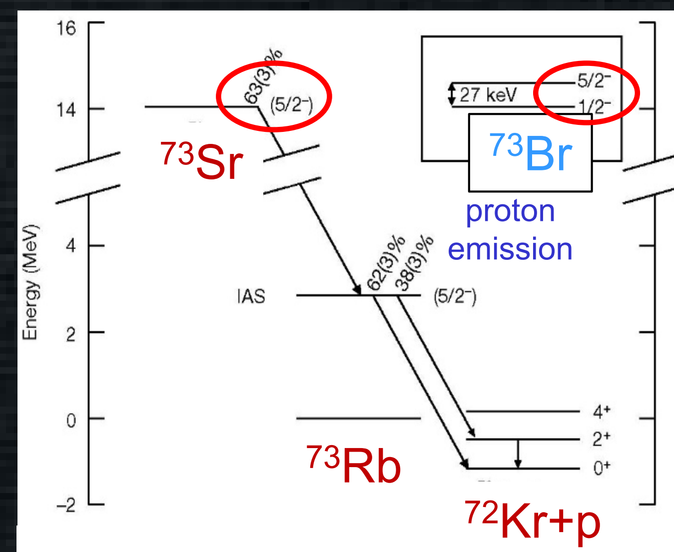


Study the decay of the $T = 3/2$, $T_z=-3/2$, ^{73}Sr

$^{73}_{38}\mathrm{Sr}$ $^{73}_{37}\mathrm{Rb}$ $^{73}_{36}\mathrm{Kr}$ $^{73}_{35}\mathrm{Br}$

Isobaric multiplet

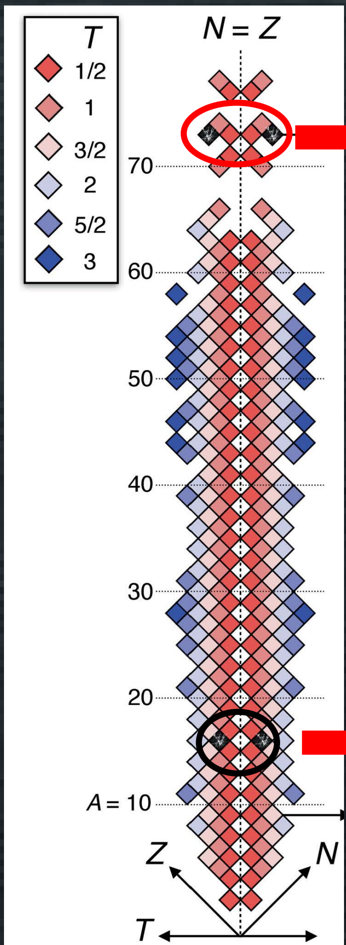
A $J^{\pi} = 5/2^{-}$ spin assignment to the g.s. of ^{73}Sr is needed to explain the proton-emission pattern observed from the $T = 3/2$ IAS in ^{73}Rb



➡ the ground state of ^{73}Sr differs from that of its mirror ^{73}Br

E. M. Ho, A. M. Rogers *et al.*, Nature 580 52 (2020)

Interpretation of the data



E. M. Ho, A. M. Rogers *et al.*, Nature 580 52 (2020)

- *"Need of charge-symmetry-breaking forces"*
- *"Small changes in the two competing shapes"*

Thomas-Ehrman shift

$^{16}_{9}$F $^{16}_{7}$N

The data are interpreted by means of the Gamow coupled-channel calculations, considering prolate and oblate deformations.

Conclusion: g.s. $J^{\pi} = 5/2^{-}$ in ^{73}Sr, but the inversion of the states in ^{73}Br is not reproduced

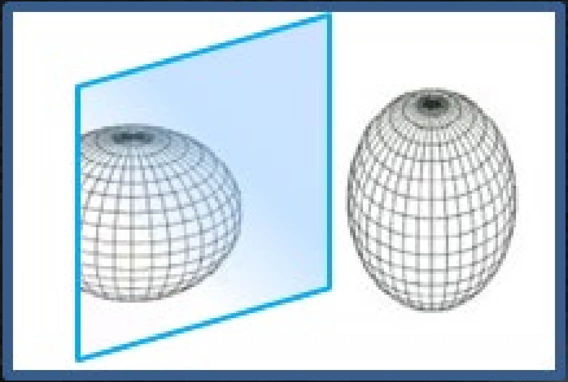
N~Z nuclei in the A~70-80 region

Around the N=Z line quadrupole correlations are dominant

The onset of the different modes of quadrupole collectivity depends on the structure of the spherical mean field

Prolate and oblate shapes coexist

Experimentally it may happen that ISB effects exchange the order of nearby states of different intrinsic structure in mirror nuclei

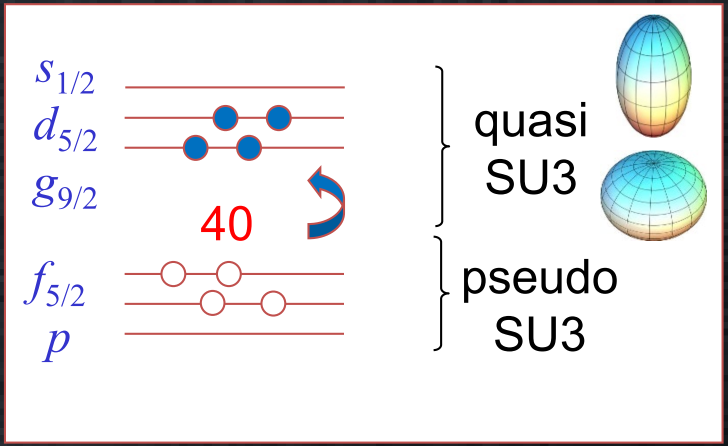


Quadrupole collectivity and Shell model

Deformed structures can be reproduced by shell model provided a suitable (symmetry-based) model space is considered

Lowest
Δj=Δl=2

Full shell
except the
larger j-orbit



In this mass region the model space that contains the relevant degrees of freedom for the development of quadupole correlations is the *fpgds*

A.P. Zuker *et al*., PRC 92, 024320 (2015)

The effective interaction is PFSDG-U: F. Nowacki, A. Poves, E. Caurier, and B. Bounthong, Phys. Rev. Lett 117, 272501 (2016)

These calculations are not restricted to axially symmetric shapes

The full MED for A=73, T=3/2

$$MED_J = E_J^*(^{73}_{38}\mathrm{Sr}) - E_J^*(^{73}_{35}\mathrm{Br})$$
$$= \Delta\langle V_{CM}\rangle_J + \Delta\langle V_{\ell s+\ell\ell}\rangle_J + \langle V_{cm}\rangle_J + \langle V_B\rangle_J$$

J^π	V_{CM}	V_{ls+ll}	V_{Cm}	V_B	MED
$1/2^-$	11 keV	23 keV	-16 keV	25 keV	43 keV

Since the excitation energy of the $1/2^-$ state in ^{73}Sr is not yet known we have just a lower experimental limit for the MED of this state: MED ≥ 27 keV.

MED and the ISB in ^{73}Sr-^{73}Br

Experimental data

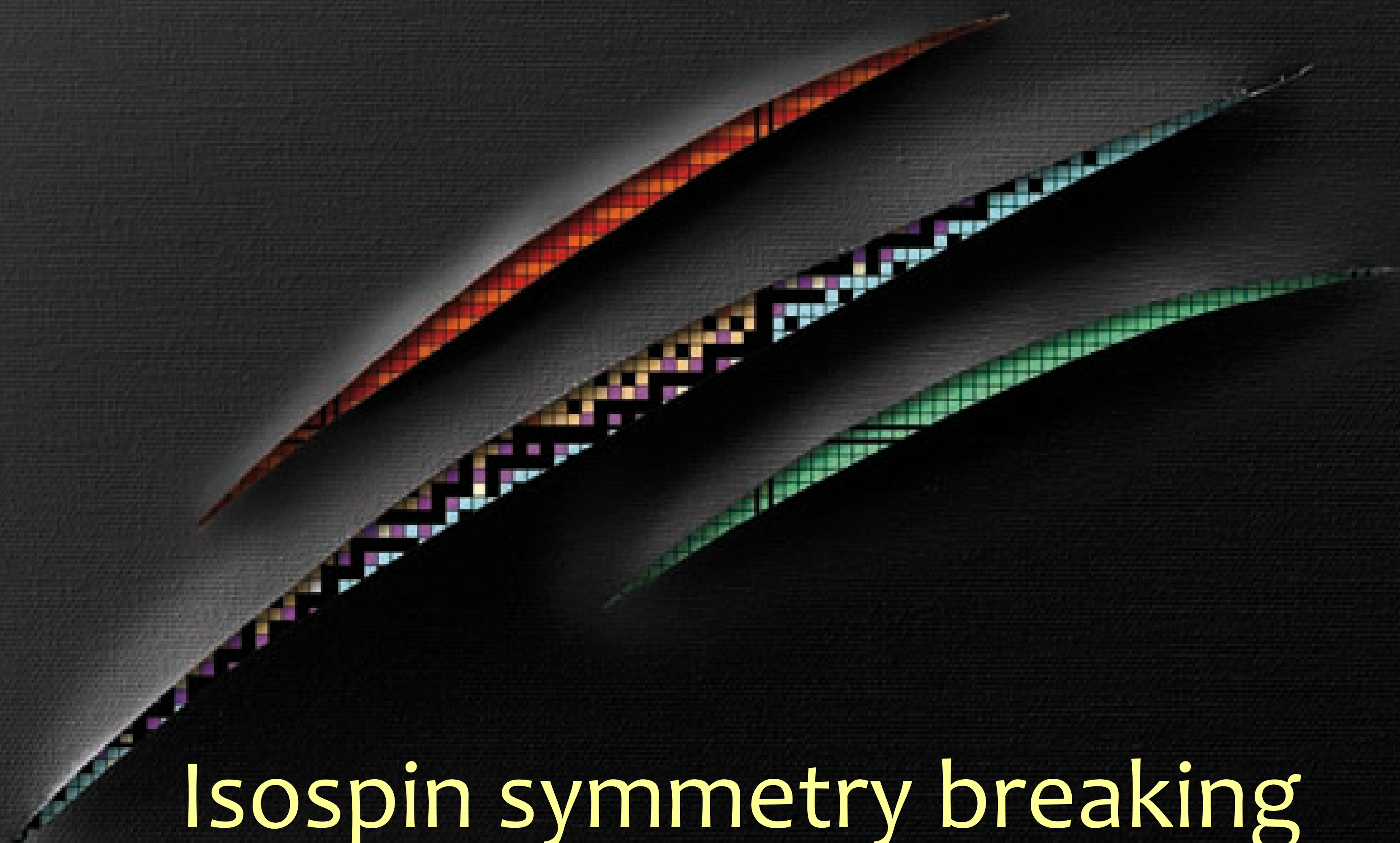
E. M. Ho, A. M. Rogers *et al*.,
Nature 580 52 (2020)

Putting together the calculated MED and the data in ^{73}Br, the inversion of the states in ^{73}Sr is obtained

We predict the $1/2^-$ state in ^{73}Sr at ~16 keV

To account for the experimental MED lower limit, an ISB contribution of $V_B \geq 10$ keV is needed

S.M. Lenzi, A. Poves and A. O. Macchiavelli, PRC 031302(R) (2020)



Isospin symmetry breaking from electromagnetic transitions

Isospin mixing

Electromagnetic transitions between analogue states in i
sospin multiplets follow some selection rules:

For E1 transitions:

- Analogue E1 transitions in mirror nuclei must have the same strength
  D. Tonev *et al.*, Physics Letters B 821 (2021) 136603
- ΔT = 0 E1 transitions in self-conjugate nuclei are forbidden
  E. Farnea *et al,* Physics Letters B 551 (2003) 56

For E2 transitions:

- Electric quadrupole matrix elements between ΔT = 0 states are linear in T_z within an isobaric multiplet

These selections rules assume isospin symmetry.
The Coulomb field, however, introduces (perturbatively) an asymmetry

The small isospin impurity admixtures that it causes can allow transitions otherwise forbidden or induce violations to these rules.

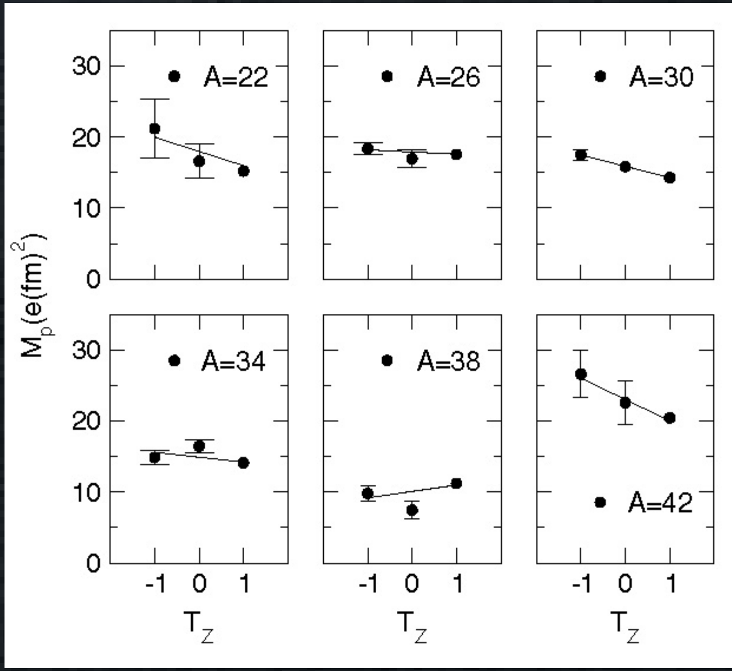
Isospin symmetry in T=1 triplets

The selection rule for E2 transitions implies that in an isobaric triplet, the proton matrix element between two states of the same isospin has to be linear in T_z

$$M_p = \sqrt[2]{(2J_i+1)B(E2, J_i \rightarrow J_f)}$$

$$M_p(T_z) = \frac{1}{2}(M_0 - M_1 T_z)$$

This can be tested for the case of the B(E2, $2^+ \rightarrow 0^+$)



F. M. Prados Estevez, Phys. Rev. C 75 (2007) 014309

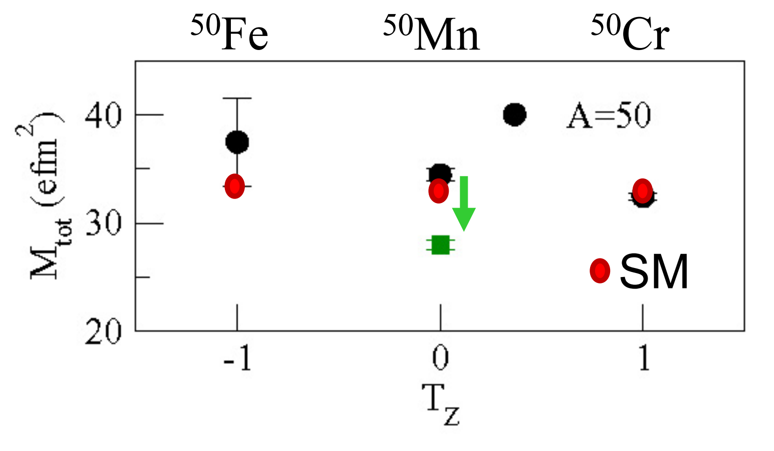
Test of isospin symmetry in T=1 triplets

Deviations from the linear dependence of M_p may arise from isospin mixing

This may occur in the T_z=0 odd-odd isobar where T=0 and T=1 states coexist at low excitation energy

These measurements are challenging and systematic errors are usually large (~10%)

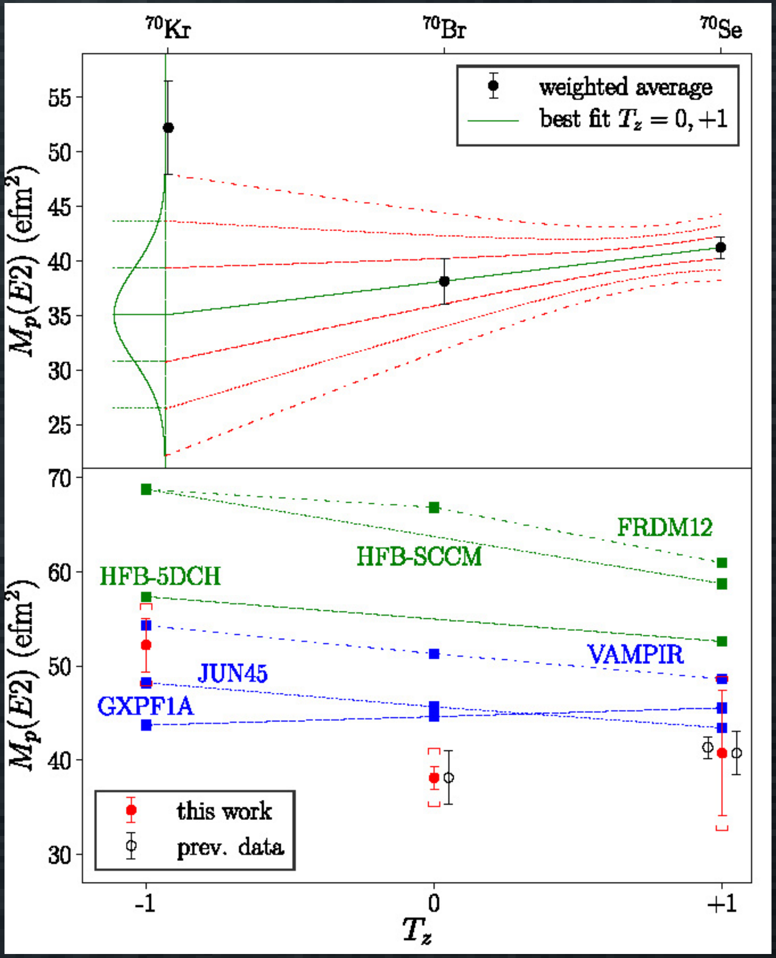
The B(E2) may be determined by lifetime measurements or by Coulomb excitation and this, in general, requires radioactive beams



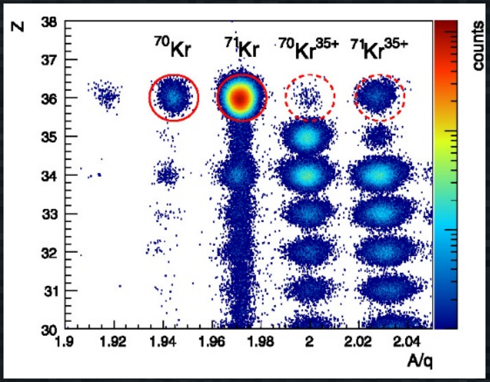
^{50}Mn, ^{50}Cr: M.M. Giles et al., Phys Rev C99, 044317 (2019)
Phys. Rev. C104 029901(E) (2021)

^{50}Fe: K. Yamada *et al*., Eur. Phys. J. A 25, 409 (2005)

The case of the A=70 triplet



Relativistic Coulomb excitation of ^{70}Kr (15 pps) produced by projectile fragmentation at RIBF (RIKEN)



The >3σ deviation from the linear behaviour is explained in terms of: shape of ^{70}Kr different from the other isobars (shape coexistence is expected near the ground state)

K. Wimmer et al, Phys Rev Lett 126, 072501 (2021)

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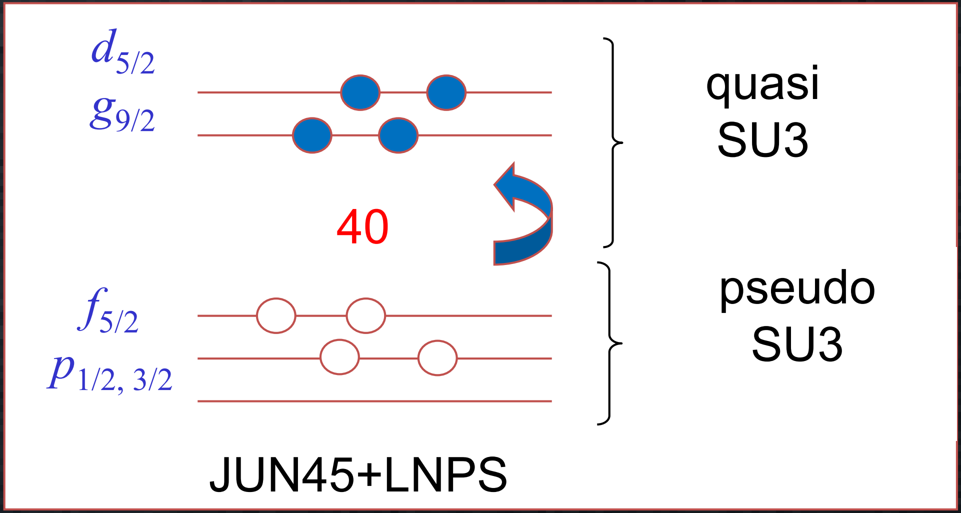
Shell model analysis for A=70

We calculate the excitation energy and the B(E2) values using two different valence spaces and incorporate the Coulomb interaction



JUN45: M. Honma, T. Otsuka, T. Mizusaki, M. Hjorth-Jensen, PRC 80, 064323 (2009)
LNPS: S. M. Lenzi, F. Nowacki, A. Poves, and K. Sieja, PRC 82, 054301 (2010)

JUN45
$1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$, $0g_{9/2}$

JUN45+LNPS
$1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$, $0g_{9/2}$, $1d_{5/2}$

JUN45+LNPS gives better spectroscopy than JUN45

S.M. Lenzi, A. Poves, A. O. Macchiavelli, in press PRC Lett.

The results for A=70

The triplet does not show a well defined shape

A Kumar* analysis gives for the intrinsic deformation parameters: $\beta = 0.22 \pm 0.05$

$$\gamma = 32°(+28° - 24°)$$

Our results do not support a change of shape between ^{70}Kr and ^{70}Se

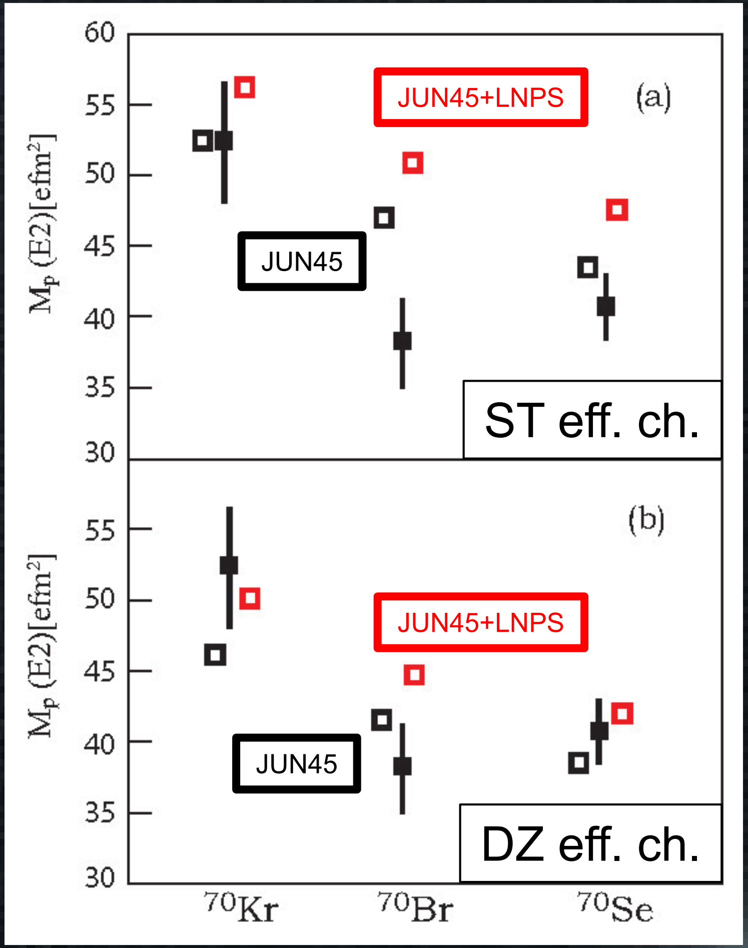
We calculate the M_p matrix elements using two sets of effective charges:

Standard values (ST): $e_p = 1.5e, e_n = 0.5e$

Dufour-Zuker (DZ): $e_p = 1.31e, e_n = 0.46e$

M. Dufour and A. P. Zuker, Phys. Rev. C **54**, 1641 (1996)

*A. Poves, F. Nowacki, Y. Alhassid, Phys. Rev. C **101**, 054307 (2020)



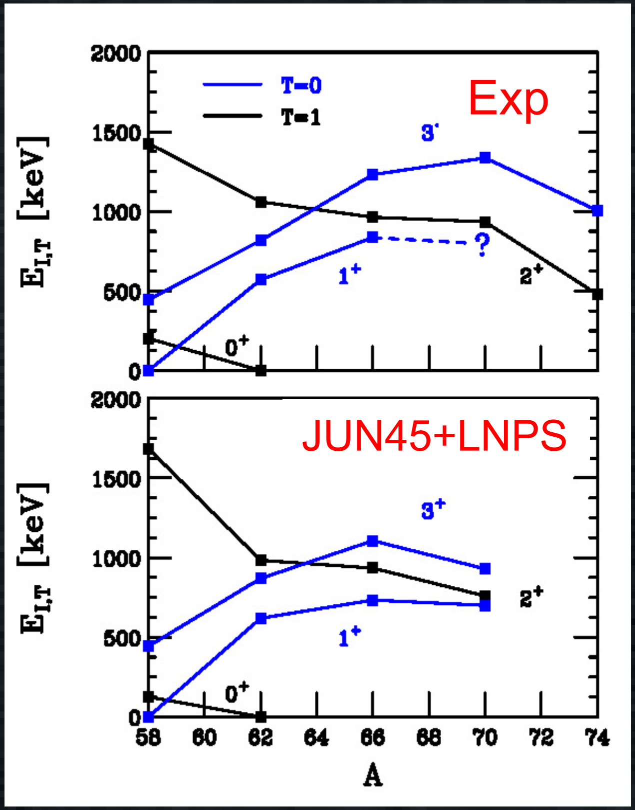
S.M. Lenzi, A. Poves, A. O. Macchiavelli, in press PRC Lett.

The ^{70}Br scenario

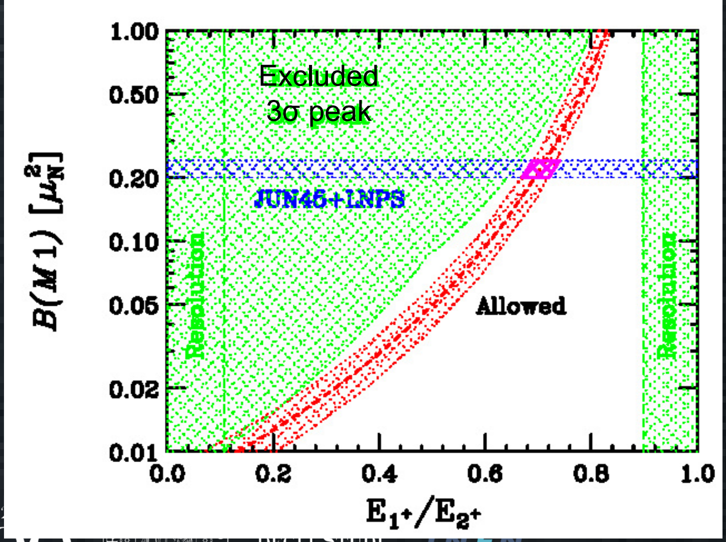
The deviation of the B(E2) in ^{70}Br from the straight line determined by the even-even isobars could be due to:

- isospin mixing
- an unobserved 1^+ T=0 state below the 2^+ T=1

N=Z odd-odd nuclei



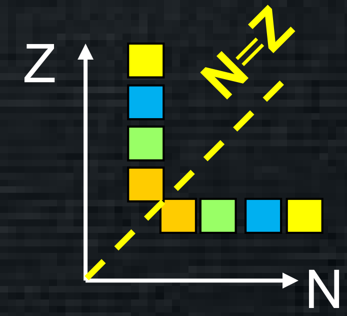
Exclusion plot to determine the excitation energy of an hypothetical 1+ state that could explain this anomaly

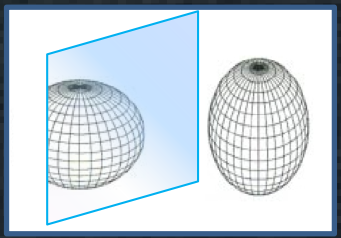


S.M. Lenzi, A. Poves, A. O. Macchiavelli, in press PRC Lett.

Conclusions

MED put in evidence the isospin symmetry-breaking of the nuclear interaction that is not well reproduced by realistic interactions





$^{73}_{38}Sr$ $^{73}_{35}Br$

They are sensitive to the nuclear structure and therefore constitute a very powerful tool to understand several nuclear properties

Several experiments are being performed at different facilities using stable and radioactive beams to study mirror nuclei far from stability and to characterize the ISB interaction

To come to solid conclusions it important to have a reliable theoretical description, including the relevant degrees of freedom of the system

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Sara Pigliapoco
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Peter Doornenbal

Thank you for your attention!