Coulomb Energies in Isobaric Multiplets

M.A.Bentley, Keele University

- Isospin symmetry and Coulomb energies
- Spin-dependent Coulomb phenomena

  proton alignments

  Coulomb matrix elements

  Bulk effects
- Shell model developments - large-scale *pf*
- New results - from *sd* to high-*pf*
- Conclusion

Energy Differences in Isobaric Multiplets

$T_z = \pm 1/2$ Mirror Nuclei

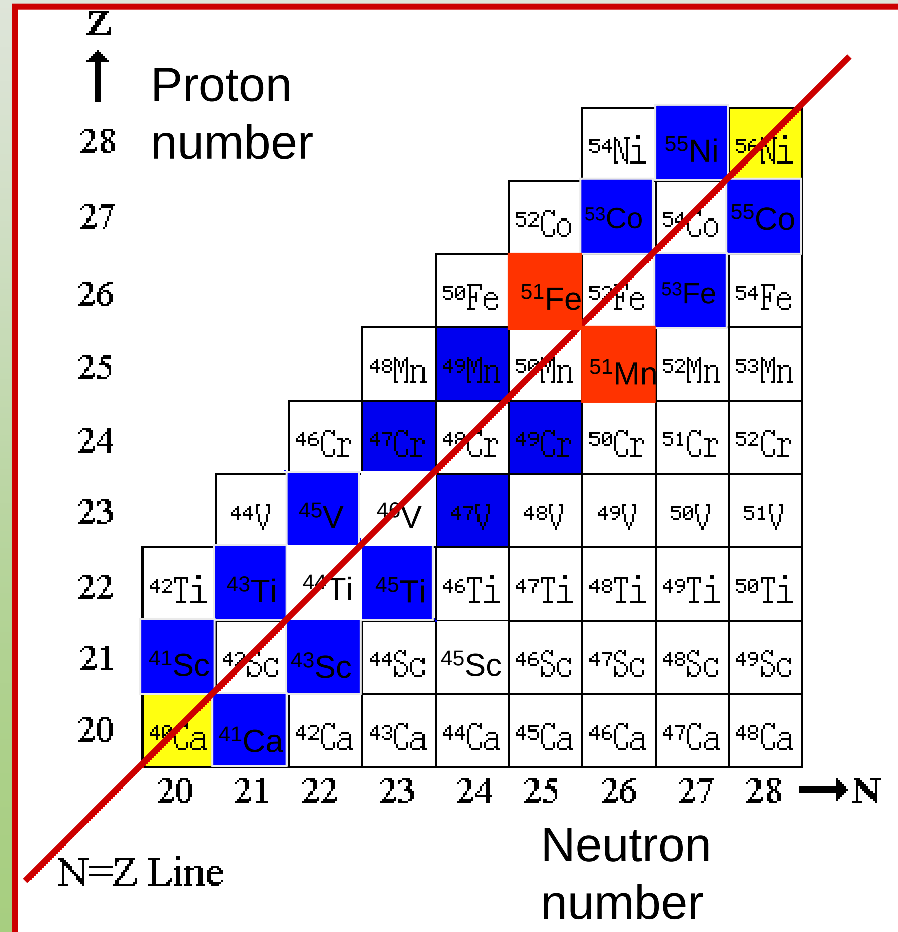
^{51}Fe (Z=26,N=25)

^{51}Mn (Z=25,N=26)

- Study energy displacement of excited states (*CED or MED*)
- States of the same (α,*J*,*T*) are isobaric analogue states (α=state 'label')

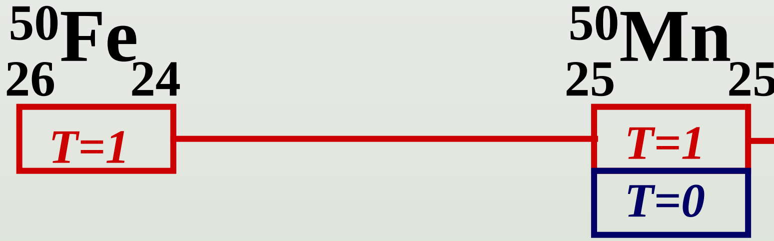
$$CED = \left(E_x^J\right)_{T_z=-1/2} - \left(E_x^J\right)_{T_z=1/2}$$

- Yields Coulomb energies if charge-symmetry is assumed
- Isovector energy differences



Energy Differences in Isobaric Multiplets

T=1 Isobaric Triplets



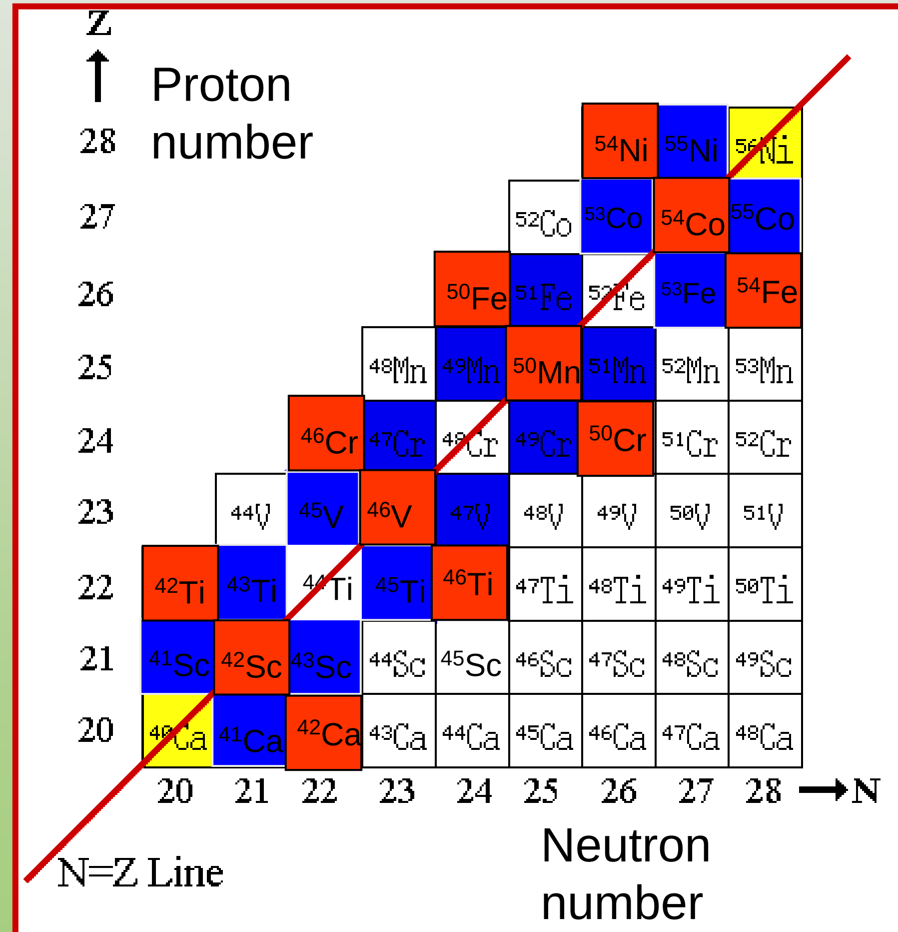
- States of the same (α,J,T) are isobaric analogue states (α=state 'label')

- Triplet energy differences…

$$TED = \left(E_x^J\right)_{T_z=-1} + \left(E_x^J\right)_{T_z=+1} - 2\left(E_x^J\right)_{T_z=0}$$

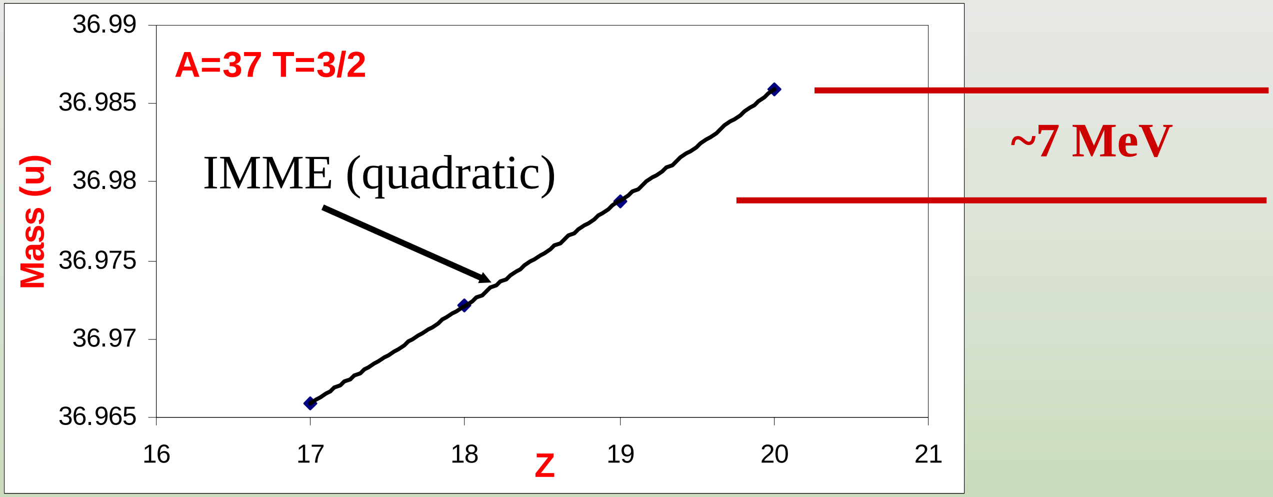
- Yields Coulomb energies if charge-independence is assumed

- Isotensor energy differences



Nolen Schiffer Anomaly

Coulomb Displacement Energy (CDE)



Understanding the absolute energy difference (mass)

- CDE = Difference in mass:

$$(CDE)_{J,T,T_z} = M_{J,T,T_z+1} - M_{J,T,T_z} + \Delta M_{np}$$

- e.g. Difference in g.s. mass of mirror pair ~ 9 MeV
- Models only accounted for ~95% of this - ~500keV discrepancy.
  Nolen-Schiffer Anomaly (Ann. Rev. Nuc. Sci. 1969)
- Differences in excitation energy typically 10's keV !

A=51 Mirror Nuclei

Data from Gammasphere + FMA (Argonne, USA)

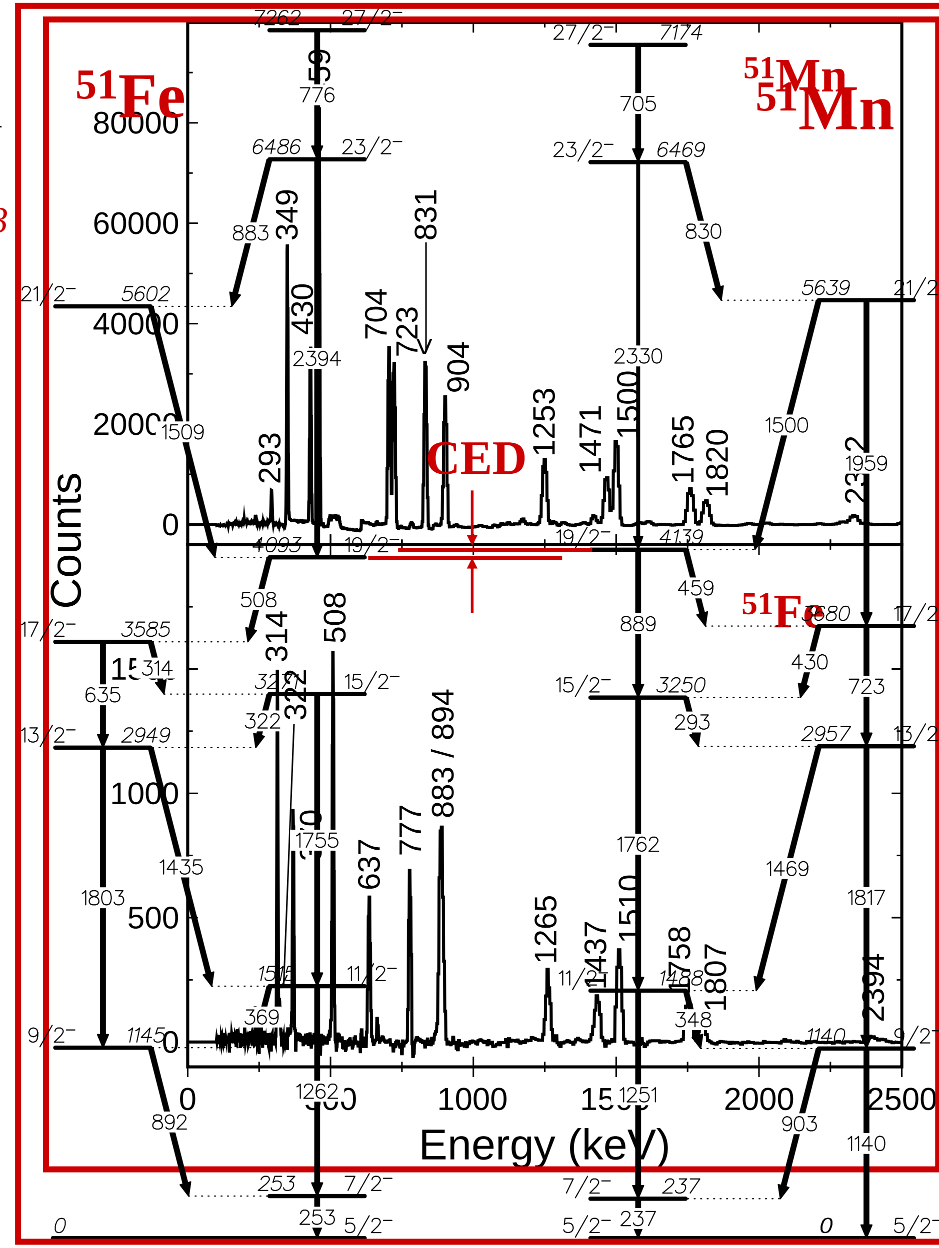
*M.A.B. et al. Phys Rev. **C62** (2000) 051303*

- Observed up to $\pi(f_{7/2})^{-2}\nu(f_{7/2})^{-3}$ band termination

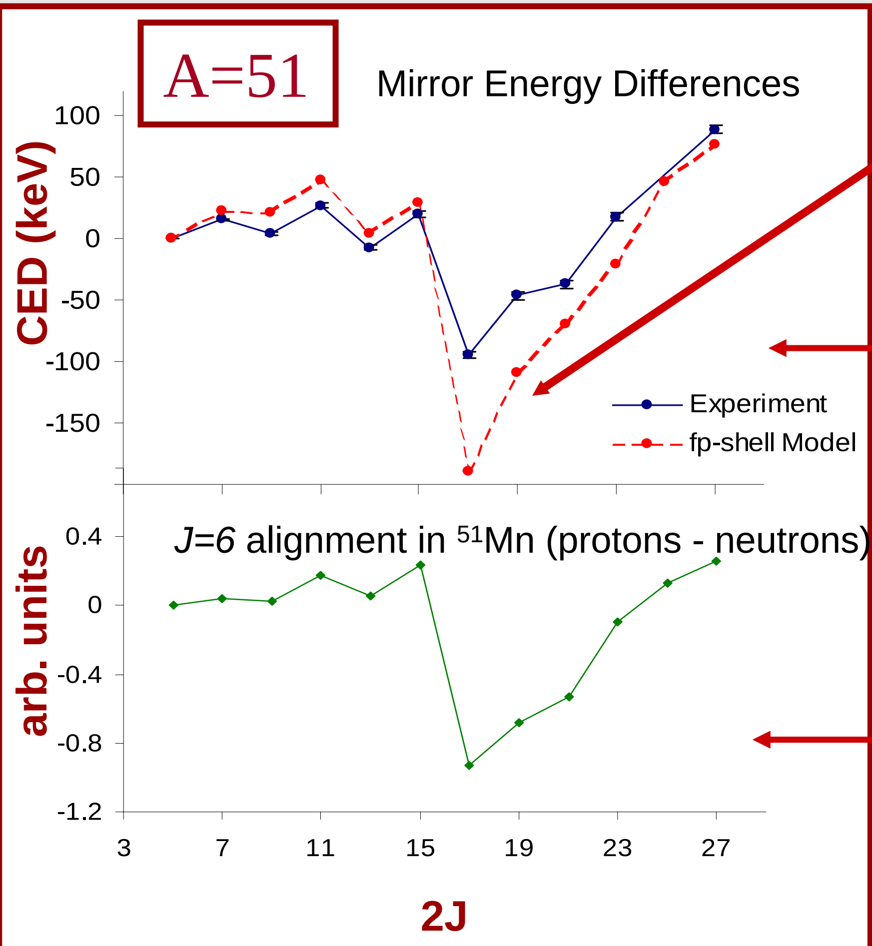
- Assume **charge-symmetry**

- Small differences in excitation energy → Coulomb effects

Coulomb Energy Differences (CED) vary with angular momentum…



Proton alignments



- Aligned pp-pair (J=6) ^{51}Fe
- Aligned nn-pair (J=6) ^{51}Mn

- Empirical $f_{7/2}$-shell two-body Coulomb energies taken directly from A=42 mirror pair

- shell-model modified to 'count' pairs of aligned *J=6* particles

$$H_{Align} = \left[\left(a^{+}_{7/2} a^{+}_{7/2} \right)^{6,1}_{\pi\pi} \left(a_{7/2} a_{7/2} \right)^{6,1}_{\pi\pi} \right]$$

Large-scale fp-shell model work…

A.Poves, E.Caurier, A.Zuker, G.Martinez-Pinedo et al. (Madrid, Basel, Strasbourg)

A=53 Mirror Nuclei

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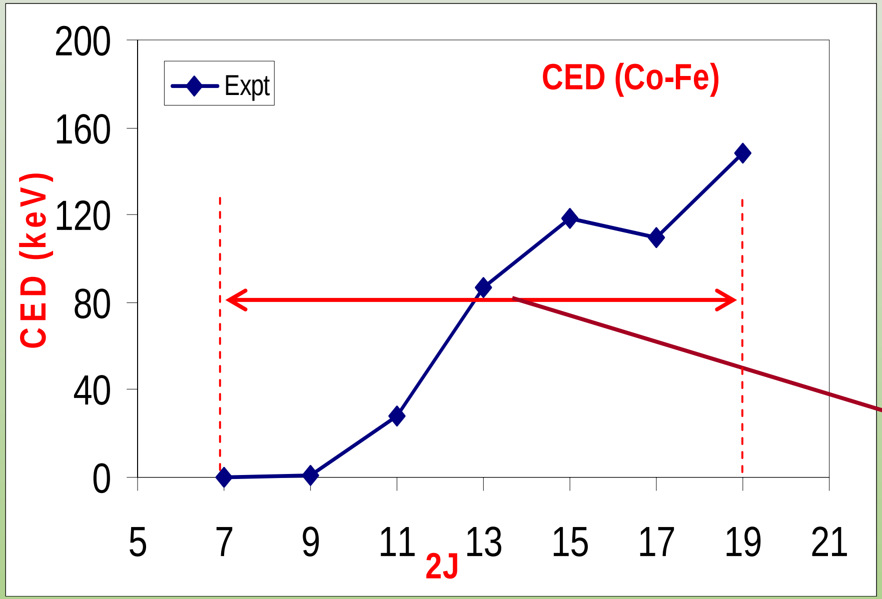
Simple yrast structure, $J^{\pi}=7/2^{-}$ *to* $19/2^{-}$, well described by 3 $f_{7/2}$ holes in ^{56}Ni

^{53}Fe: $(\nu f_{7/2})^{-1}{}_{J=7/2} \otimes (\pi f_{7/2})^{-2}{}_{J=0}$ re-couple one proton pair $(\nu f_{7/2})^{-1}{}_{J=7/2} \otimes (\pi f_{7/2})^{-2}{}_{J=6}$

Ground state, *J=7/2* → Band termination, *J=19/2*

^{53}Co: $(\pi f_{7/2})^{-1}{}_{J=7/2} \otimes (\nu f_{7/2})^{-2}{}_{J=0}$ re-couple one neutron pair $(\pi f_{7/2})^{-1}{}_{J=7/2} \otimes (\nu f_{7/2})^{-2}{}_{J=6}$



- Alignment of a single $f_{7/2}$ pair of protons in ^{53}Fe and neutrons in ^{53}Co
- Smooth alignment of ~ 100 keV

S.J.Williams et al. Phys. Rev. C. ***68*** *(2003) 011301R*

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J=2 Anomaly?

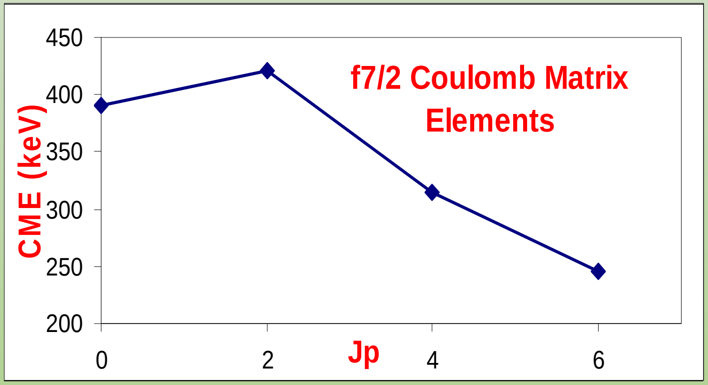
Single-j shell model picture, the wave functions in ^{53}Fe can be written…

$$|J\rangle = \sum_{J_p} a^J_{J_p} \left| j_n = \frac{7}{2}, {j_p}^2 = J_p ; J \right\rangle$$

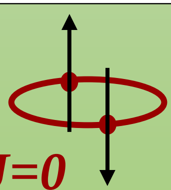
…where J_p= 0, 2, 4, and 6.

Thus - can fit the CED to predictions of $(f_{7/2})^n$ model →

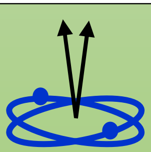
Extract Coulomb Matrix Elements (CME)



A=42 - Empirical CME



J=0



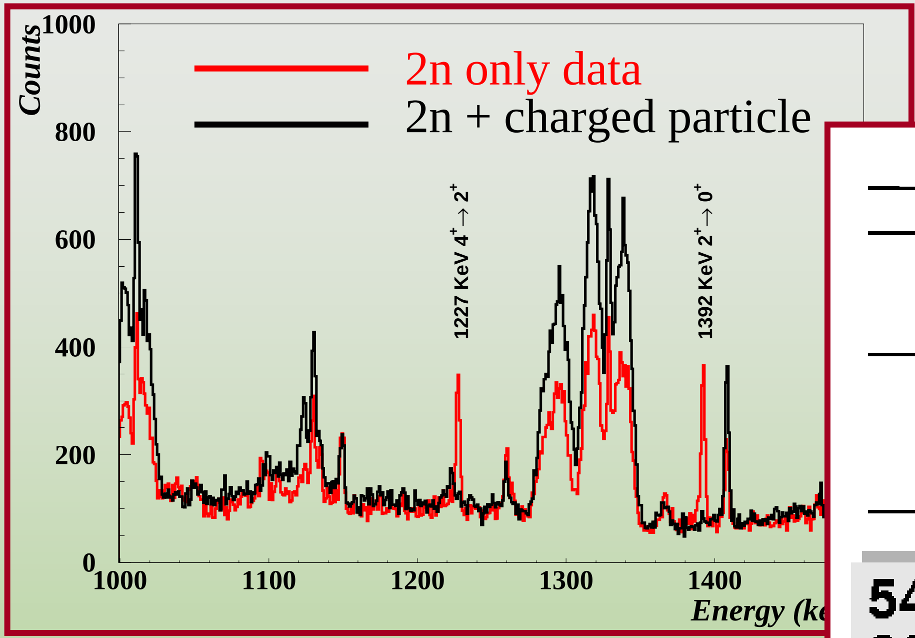
J=6

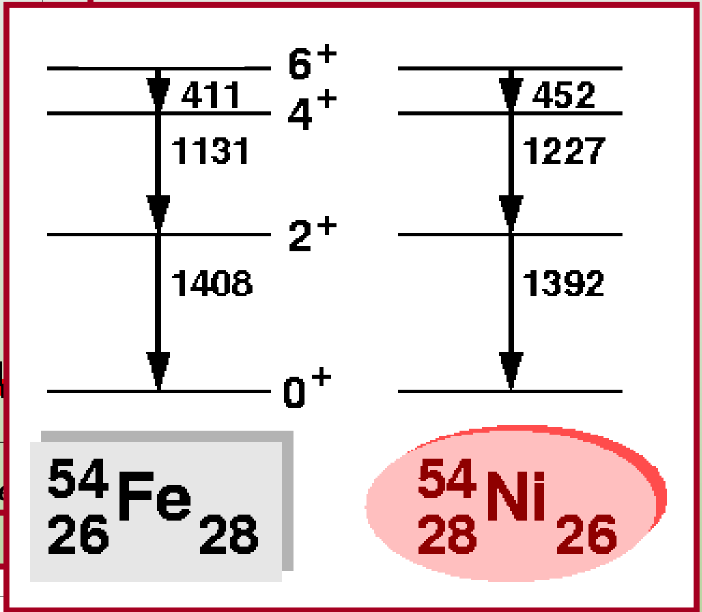
J=2 Anomaly appears across whole shell….

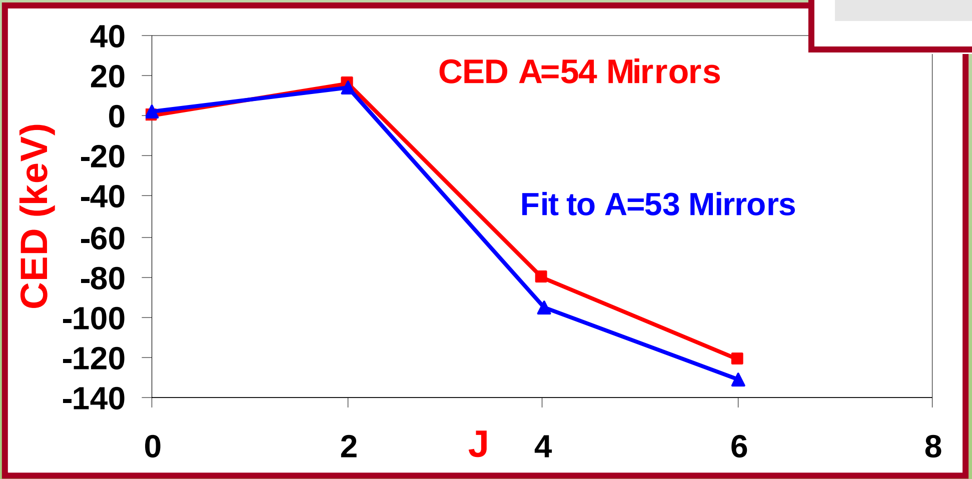
A=54 T=1 Mirror Nuclei

Euroball + Euclides + n-wall 2003

A.Gadea et al, Priv. Comm.







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Shell Model Developments

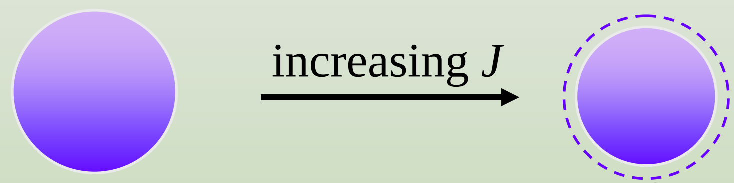
Refinements to Large-scale pf-shell Model

e.g. **A.P. Zuker** *et al* PRL **89**(2002)142502, **S.M.Lenzi** *et al* PRL **87**(2001)122501

Three effects considered:

1. **Multipole Coulomb effects** - calculated using HO Coulomb matrix elements

2. **Radial Effects** -



- Yields an increase in the Coulomb energy, influences CED
- Taken to be vary with occupation of non-$f_{7/2}$ orbits $\rightarrow \alpha <m_{p3/2}>$

3. **Isospin non-conserving** nuclear interaction

- Not Coulomb
- For CED, $J=2$ component needed

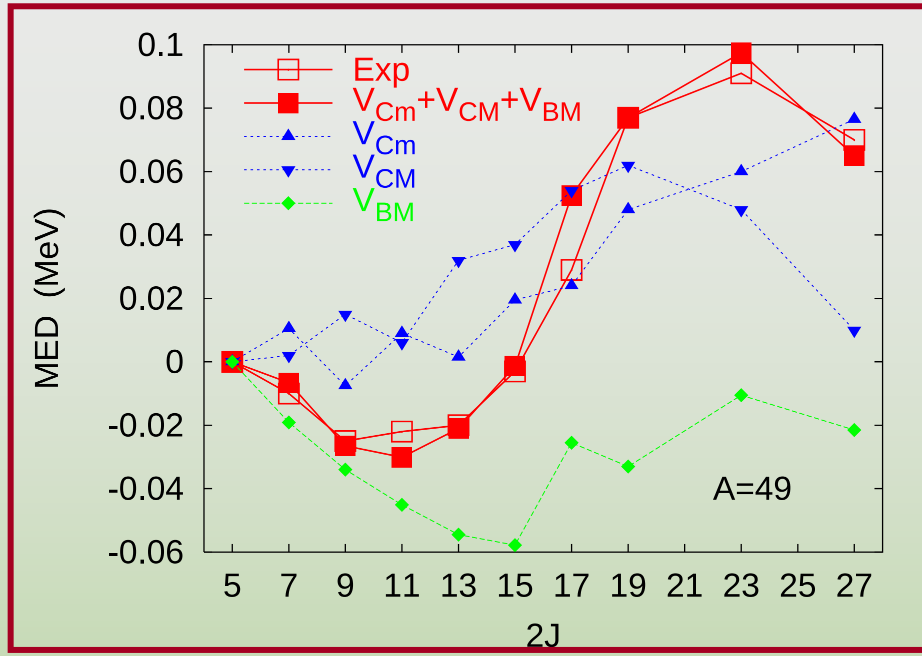
Shell Model Developments

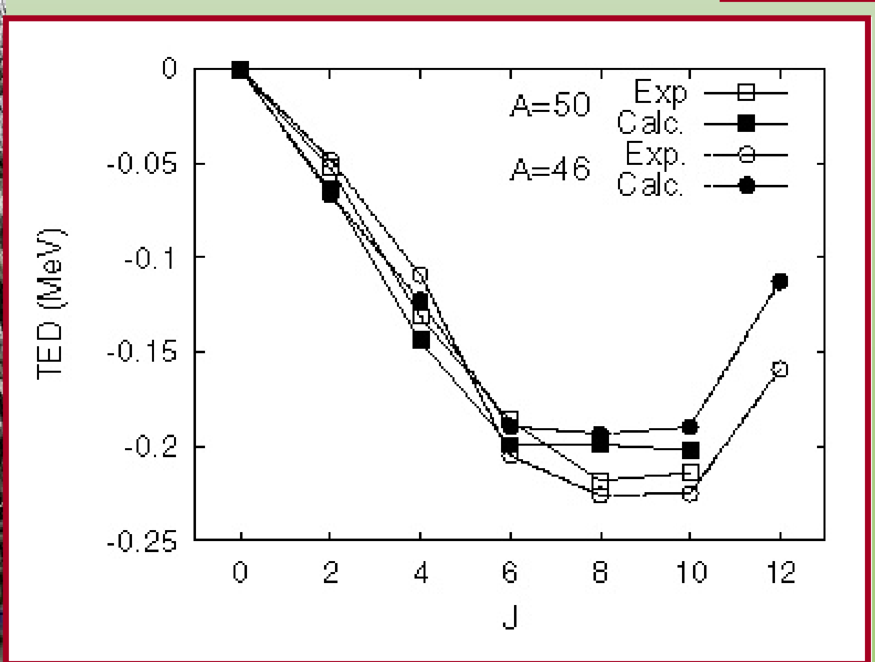
A=49 Mirror pair

Full *pf*-calculations

CED(J) - A.P.Zuker (p.c.)

Isovector energy differences





A=46 and 50 T=1 triplets

TED(J) - Isotensor Energy Differences

A=45 Mirror Nuclei

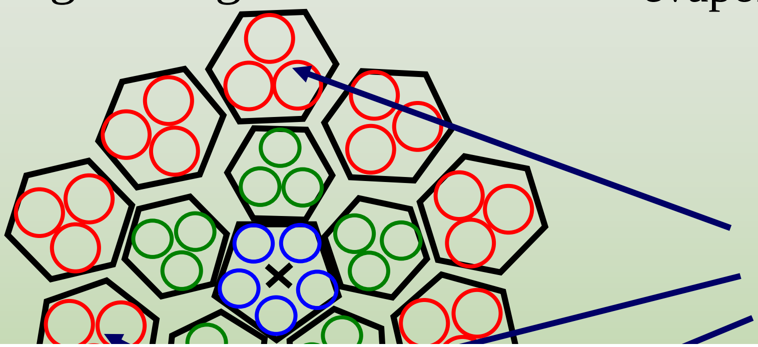
Experiment IReS Strasbourg

EUROBALL + Euclides + Neutron Wall

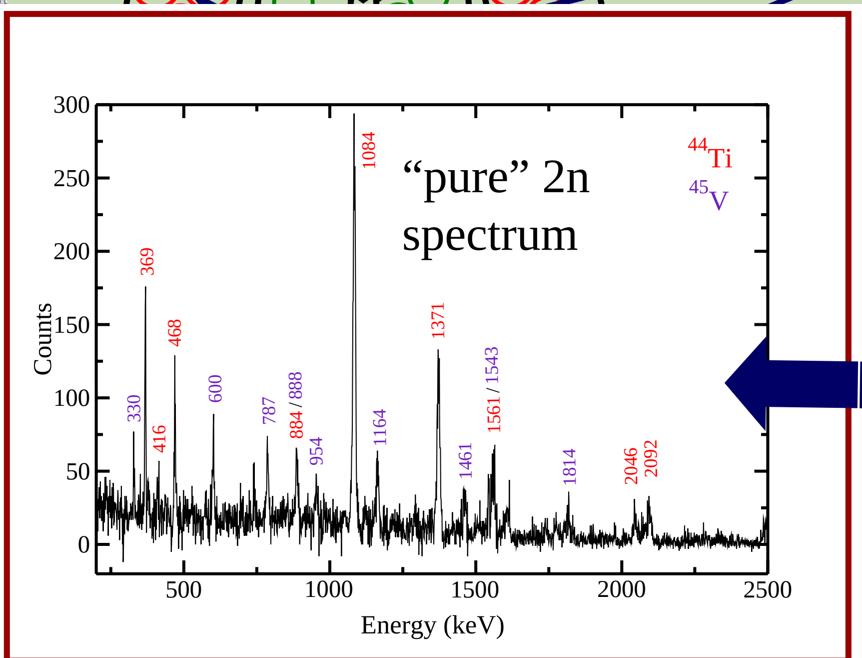
^{24}Mg + ^{24}Mg at 83 MeV

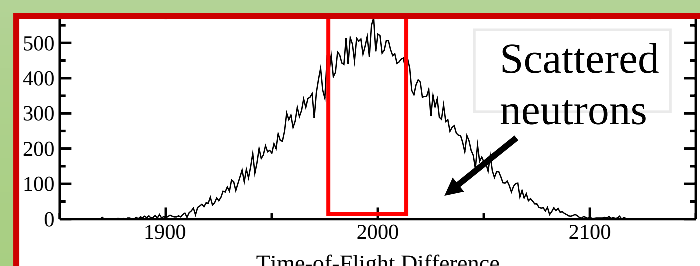
- ^{45}V from p,2n evaporation
- ^{45}Ti from 2p,n evaporation

Need to select “pure” 2-neutron evaporated events



1. Require 2n detected in n-wall
2. Reject nearest neighbour coincidences
3. Require similar time of flight recorded





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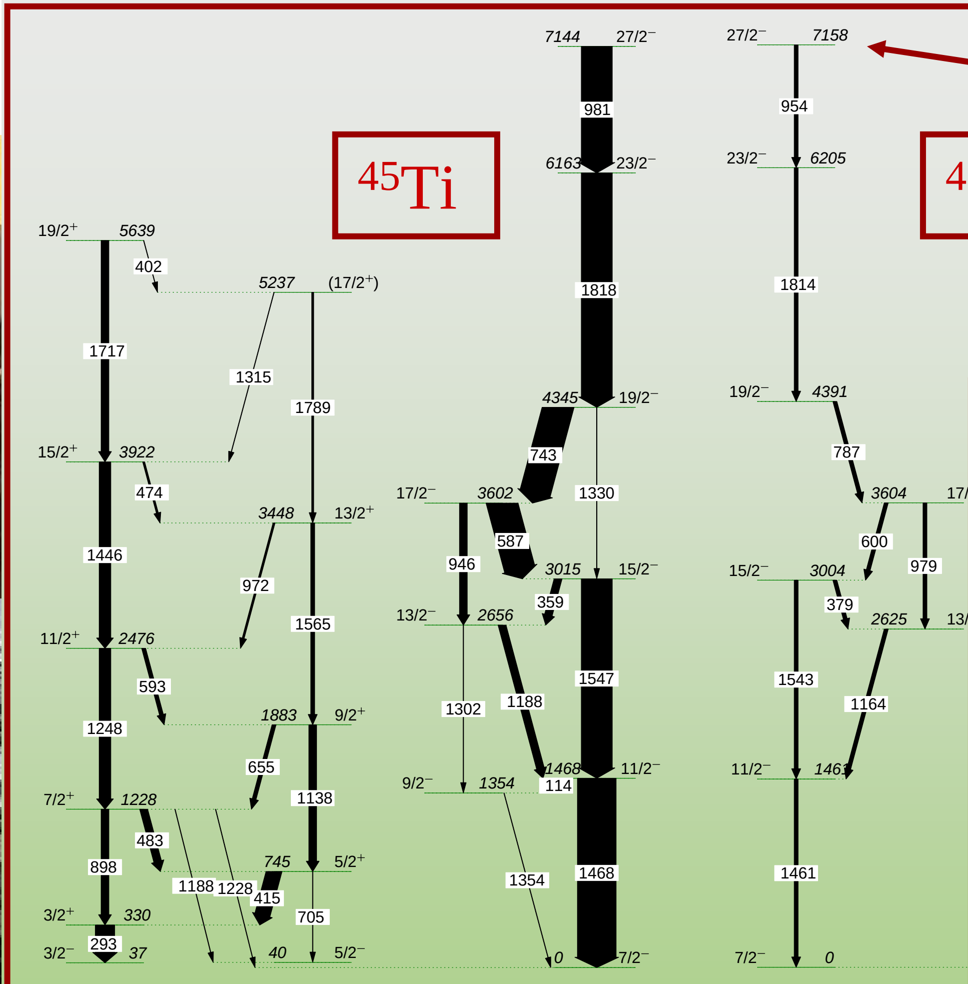
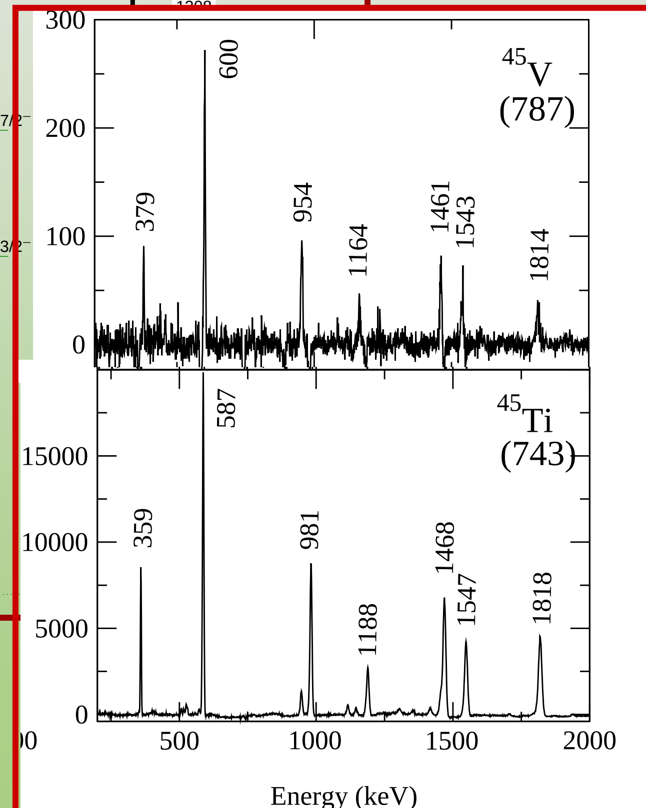
A=45 Mirror Nuclei



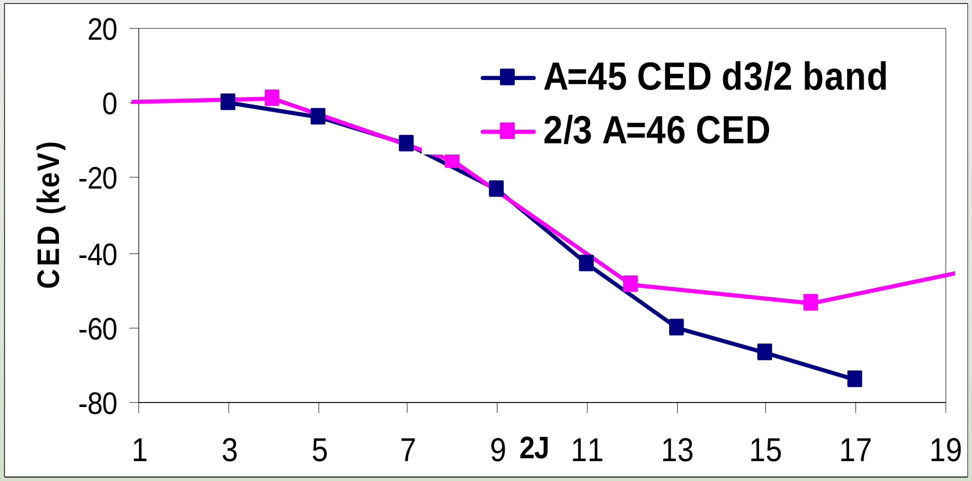


Well-deformed $(d_{3/2})^{-1}(f_{7/2})^6$ structure

Non-collective $(f_{7/2})^5$ structure

C.Chandler et al, to be published 2004

A=45 Mirror Nuclei



^{45}V: $\nu(f_{7/2})^2 \pi(f_{7/2})^4 \otimes \pi(d_{3/2})^{-1}$

4 $f_{7/2}$ protons aligning

^{46}Cr + $d_{3/2}$ *p-hole*

^{45}Ti: $\pi(f_{7/2})^2 \nu(f_{7/2})^4 \otimes \nu(d_{3/2})^{-1}$

2 $f_{7/2}$ protons aligning

^{46}Ti + $d_{3/2}$ *n-hole*

→ Reducing *CED(J)*

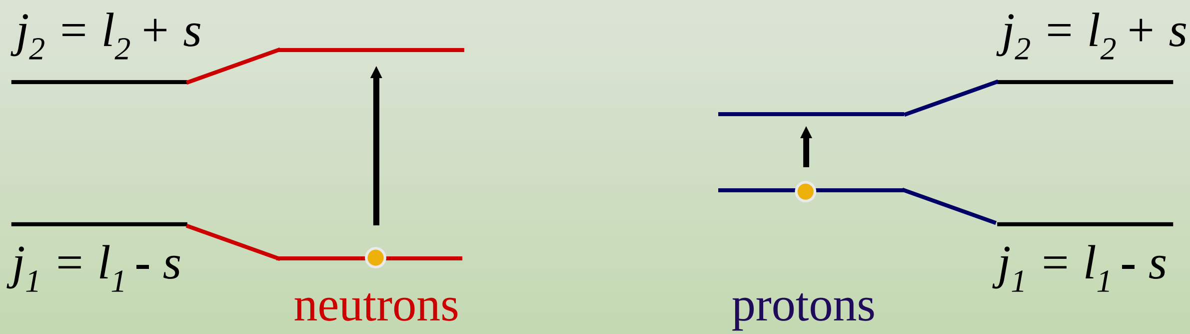
*Shell-model predicts this accounts for **2/3** of the configuration*

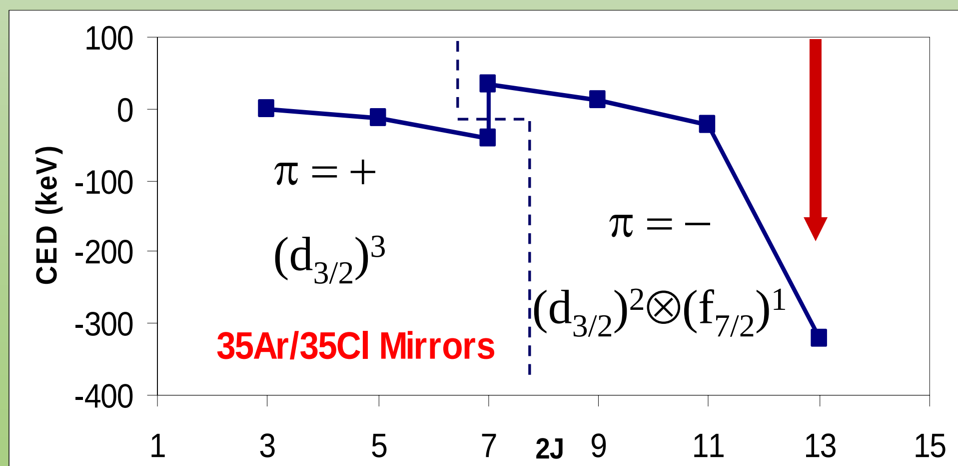
Compare with 2/3 of the A=46 CED !

C.Chandler et al, to be published 2004

EM Spin-Orbit Effect?

- Must be an electromagnetic spin-orbit effect - analogous to atomic SO splitting.
- ~50 times weaker than nuclear SO effect
- BUT acts in opposite directions for protons and neutrons

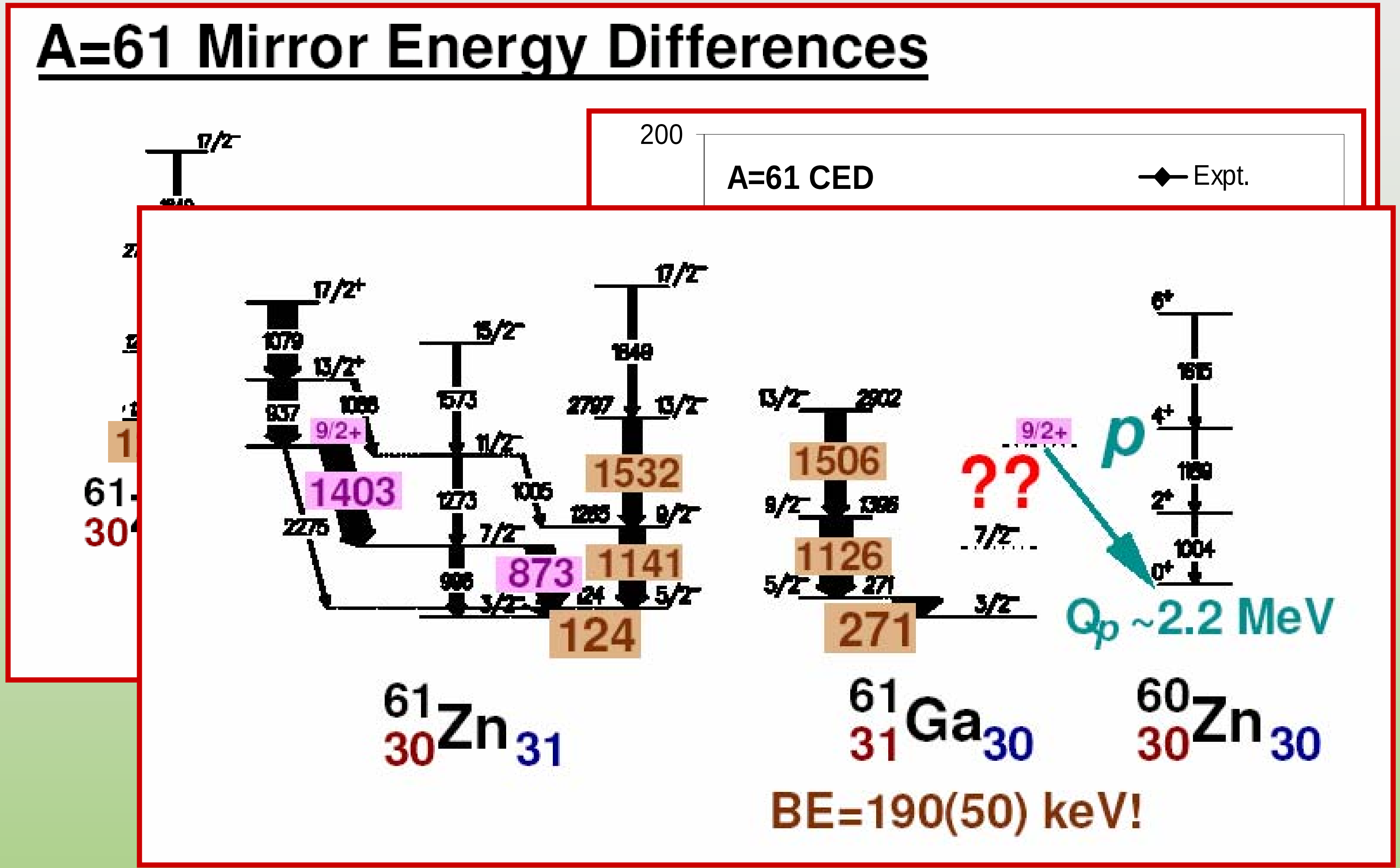




$J^{\pi}=13/2^-$ requires "pure" sp excitation from $d_{3/2}$ to $f_{7/2}$ (proton in Ar, neutron in Cl)

J.Ekman et al PRL 92(2004)132502

A=61 Mirror Nuclei



L.-L. Andersson and E.K.Johansson et al,

Lund University, ORNL data

Summary

Coulomb Energies in Isobaric Multiplets

- Coulomb energies sensitive probe of structure
- Consistent picture emerging…

  spatial correlations, band-termination, radial/deformation effects, spin-orbit, $J=2$ anomaly…

- Driven refinements to large-scale SM

OUTLOOK

- Lifetimes, effective charges, isospin mixing…
- Push to larger isospin ($T=3/2$, $T=2$)
- New reaction methods (RIB, two-step fragmentation)

Thanks to…

- Analysis…

    C. Chandler (Keele), S.J. Williams (Surrey), J. Ekman (Lund), S.M. Lenzi (Padova), A. Gadea (Legnaro) L-L. Andersson & E.K. Johansson (Lund)

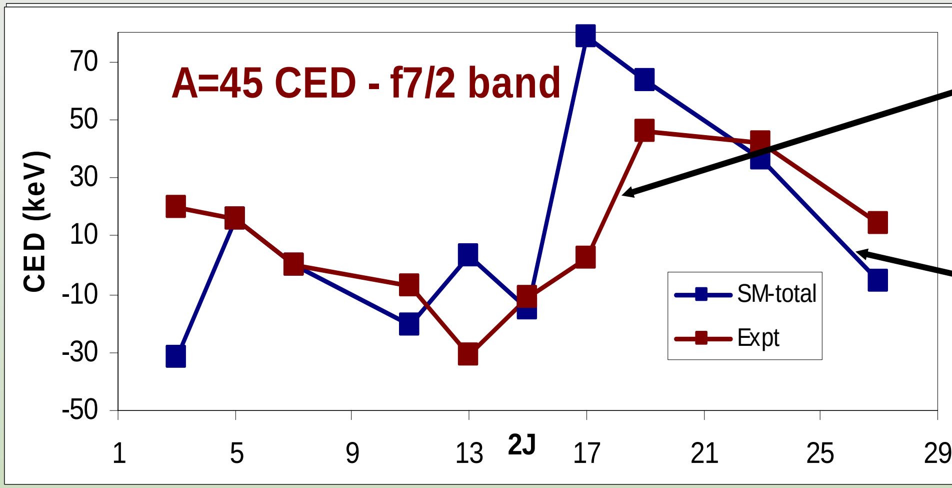
- Calculations

    A.Poves (Madrid), A.P. Zuker (Strasbourg), S.M. Lenzi (Padova), J.Ekman (Lund)

- Experimental Teams:

    Argonne, Strasbourg, Legnaro, ORNL

A=45 Mirror Nuclei



Alignment of protons in ^{45}Ti, and neutrons in ^{45}V

Full *pf* space works less well for lighter systems (A<46)

Alignment of neutrons in ^{45}Ti, and protons in ^{45}V

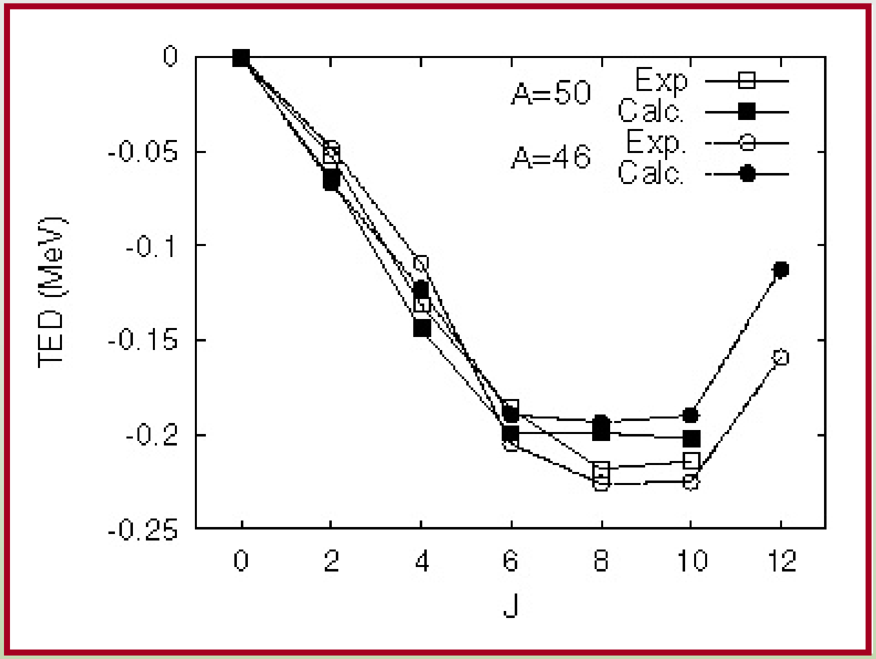
Evidence for *J=2* anomaly

Full *pf*-shell model - J.Ekman, A.P.Zuker (pc)

Shell Model Developments

A=46 and 50 T=1 triplets

TED(J) - Isotensor Energy Differences



*A.P.Zuker et al PRL **89**(2002)142502*
*S.M.Lenzi et al PRL **87**(2001)122501*
*P.E.Garrett et al PRL **87**(2001)132502*