Study of the N=34 subshell closure via beta decay.

Jose Javier Valiente Dobón, Daniele Mengoni,
Dora Sohler, Alexandre Obertelli, Alejandro Algora, …
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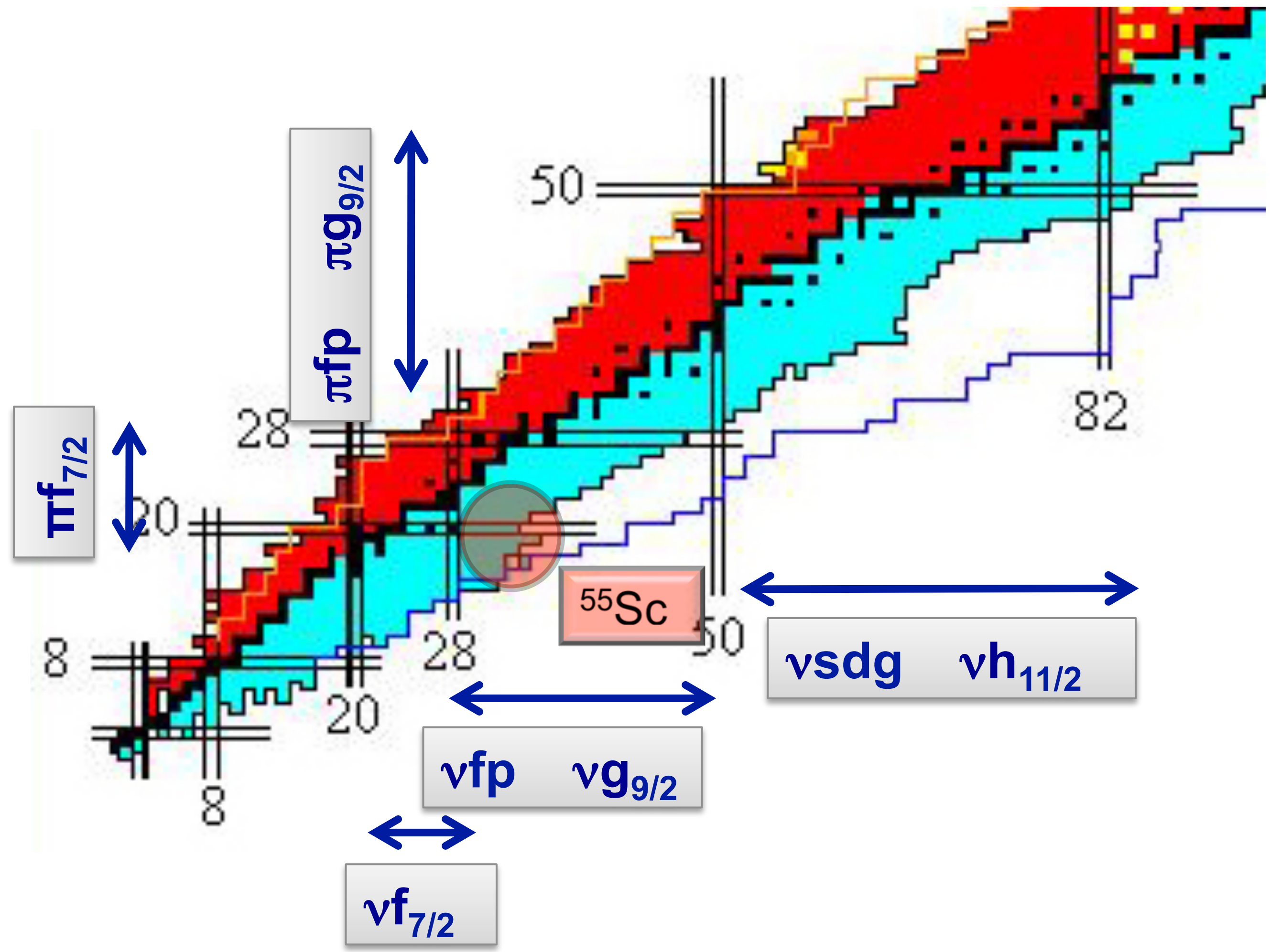
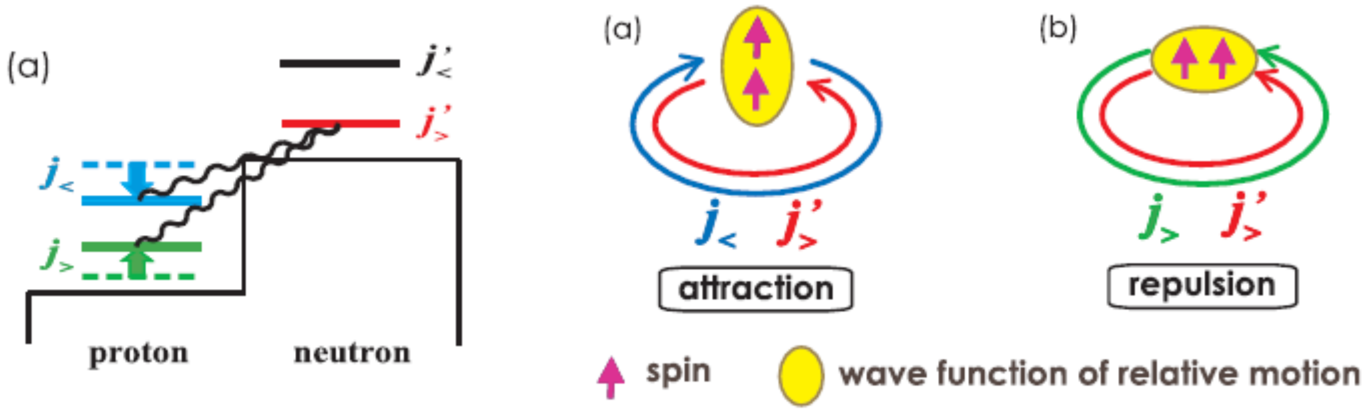
Ductu naturae

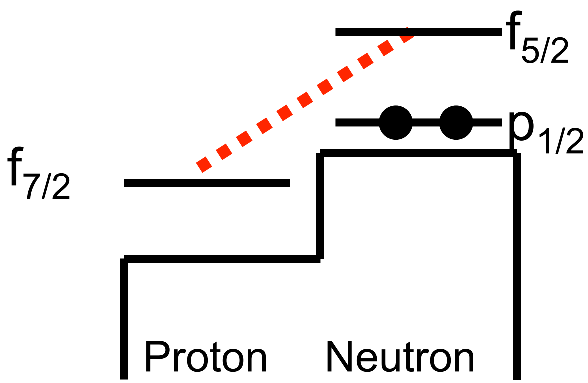


N=34 subshell gap

Monopole effect of the tensor interaction in shell evolution



T. Otsuka et al., PRL95 232502 (2005)

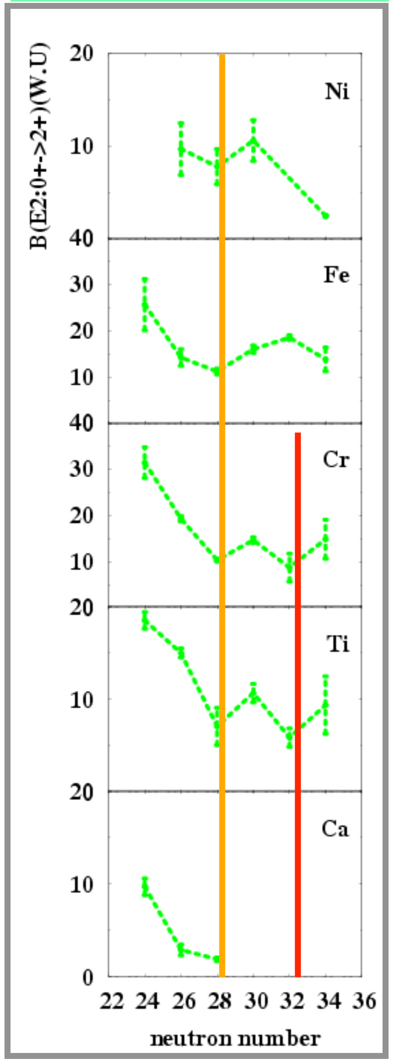


- Posible subshell closure between $p_{3/2}$-$p_{1/2}$ and $f_{5/2}$
- Atraction between the $f_{7/2}$ and $f_{5/2}$
- Does ^{54}Ca present N=34 subshell?

Energies and B(E2) values

Indication of shell gaps

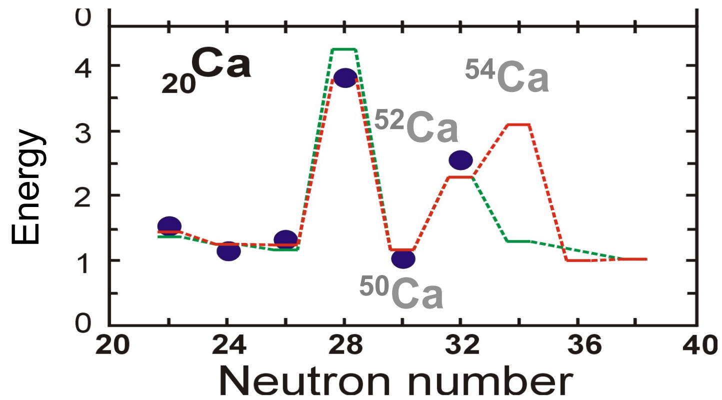
B(E2) values



Energies and B(E2) values are complementary to study in detail shell evolution.

N=28

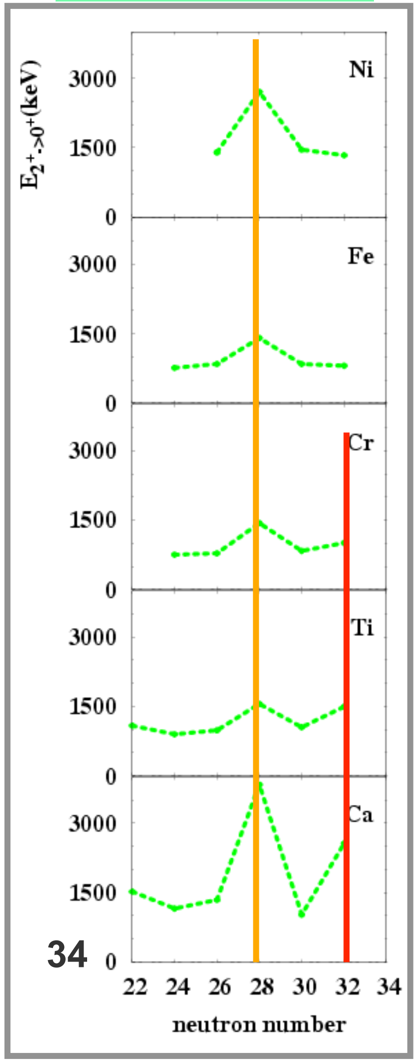
N=32



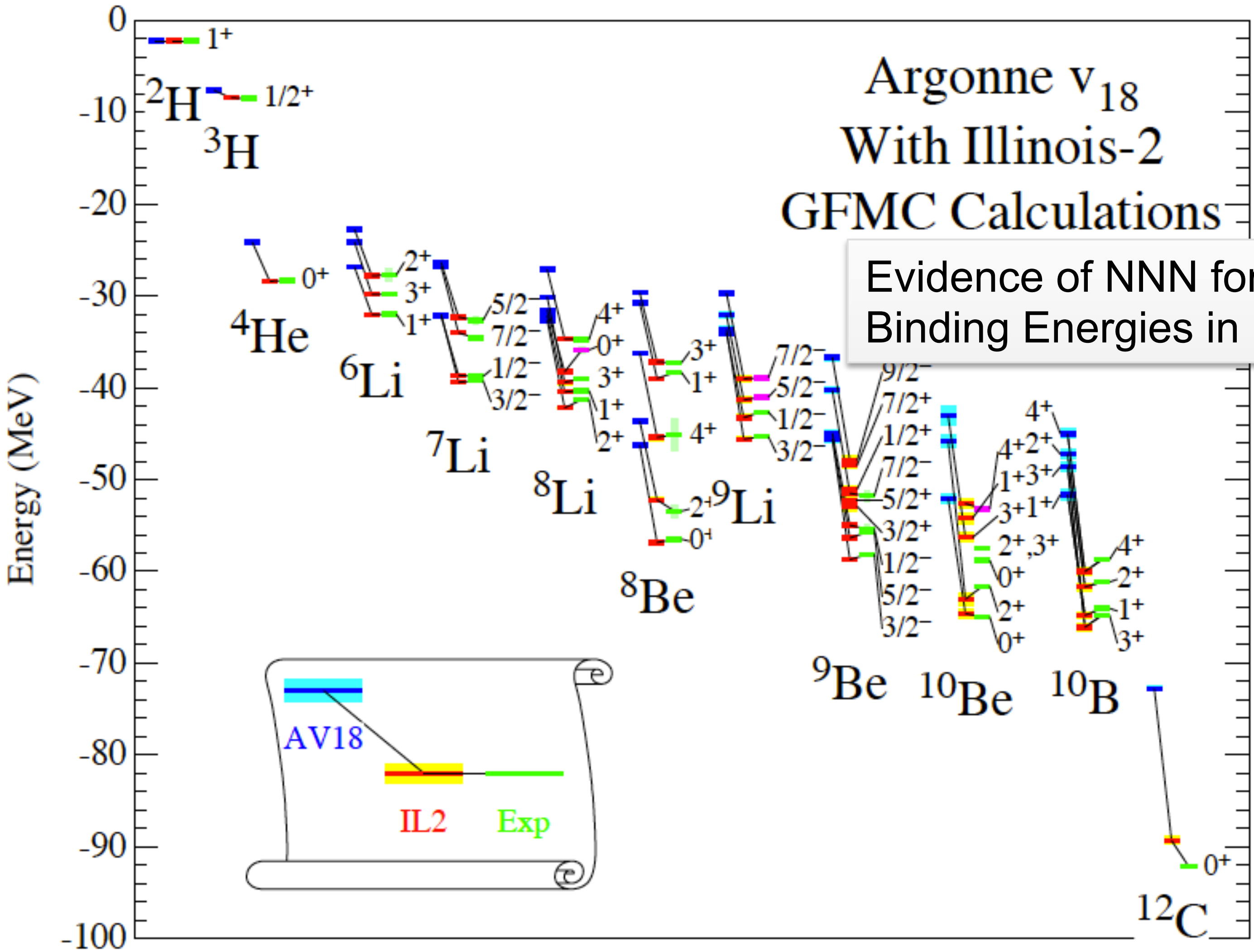
KB3G: A. Poves, et al., Nucl. Phys. A (2001).

GXPF1A: M. Honma et al., *Phys. Rev. C (2002); Eur. Phys. J. A (2004).*

Energy



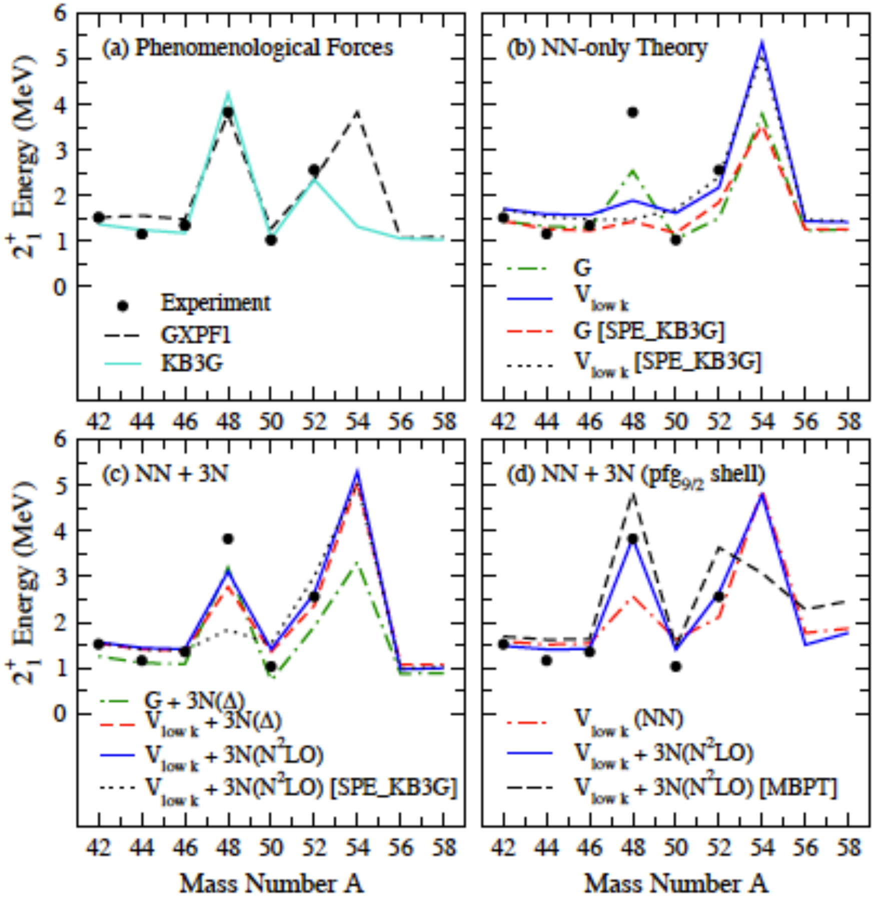
Indication of three body forces NNN



Evidence of NNN forces in the Binding Energies in light nuclei

Courtesy of C. Pipier, Argonne National lab.

NNN in the Ca region



Microscopic calculations with well-established two-nucleon NN, do not reproduce N=28.

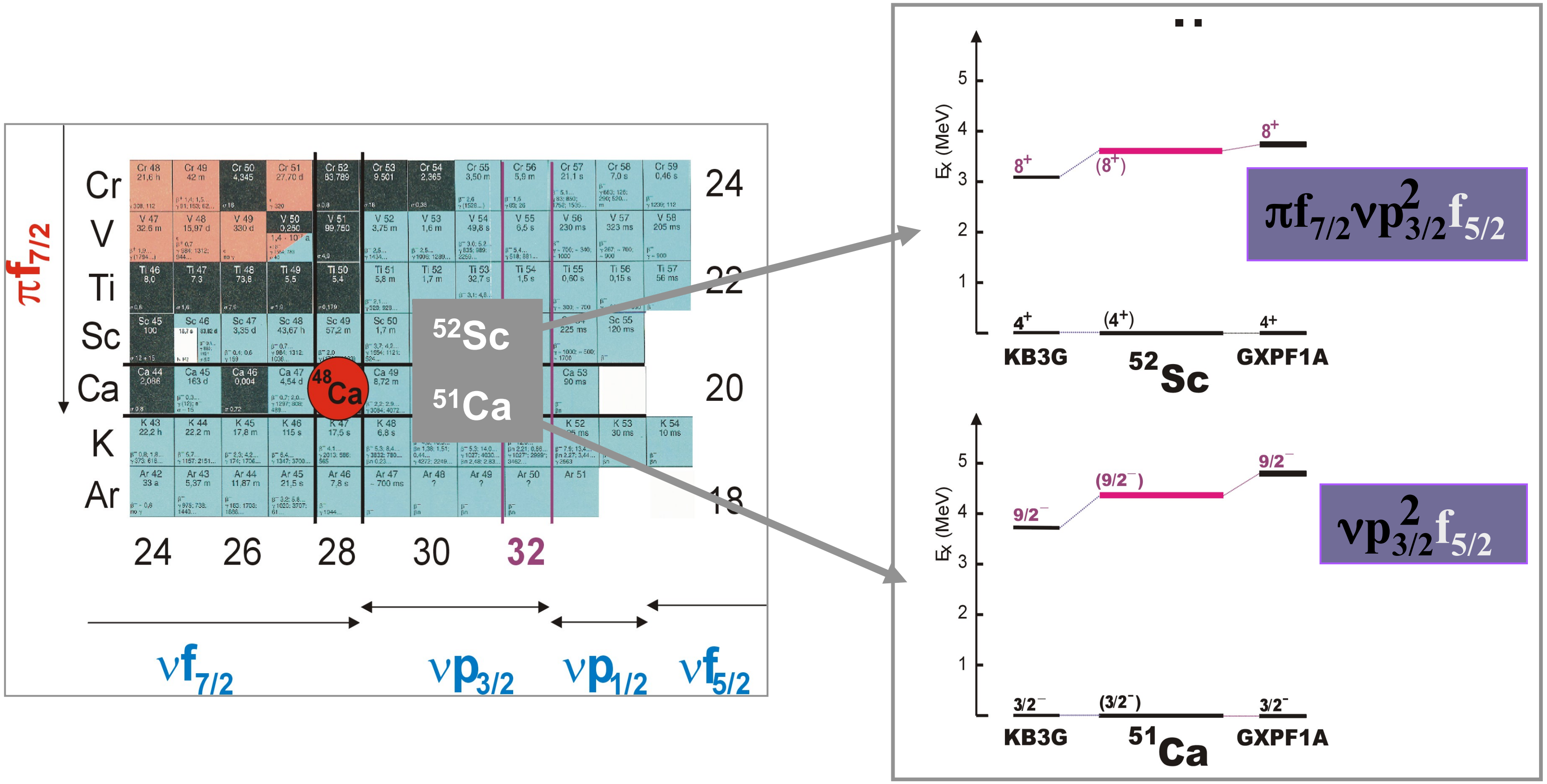
However NN and NN+3N forces predict a hight 2^+ energy in ^{54}Ca, but with quantitative differences.

The changes due to 3N forces are amplified in neutron-rich nuclei and will play a crucial role for matter at the extremes

T. Otsuka et al., PRL105, 032501 (2010)
J.D. Holt et al., arXiv:1009.5984v1 (2010)

What is known in the region?

Scandium, calcium isotopes

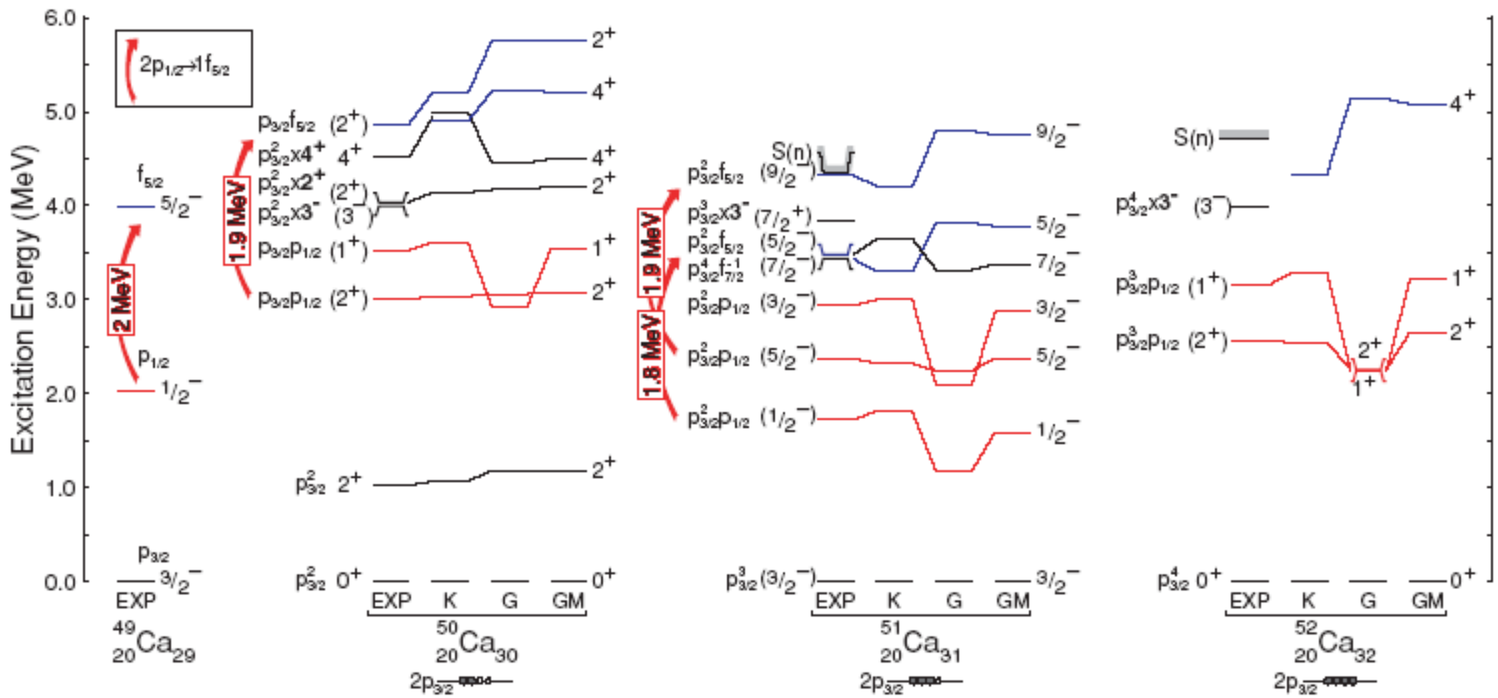


States with predominant $\nu f_{5/2}$ predict that the $p_{1/2}$-$f_{5/2}$ energy difference might be smaller that the one predicted by GXPF1A. Nevertheless this does not rule out the possible N=34 shell gap, since the change in the gap still gives good description of ^{54}Ca.

B.Fornal et al., PRC77, 014304 (2008)

What is known in the region?

Calcium isotopes



A SM interpretation of the experimental levels shows that the energy spacing between the $p_{1/2}$ and $f_{5/2}$ is almost constant up to ^{52}Ca, and when extrapolated to ^{53,54}Ca shows that N=34 might not be a magic number.

M. Rejmund et al., PRC76 021304(R) (2007)

Investigating the N=34 with β decay

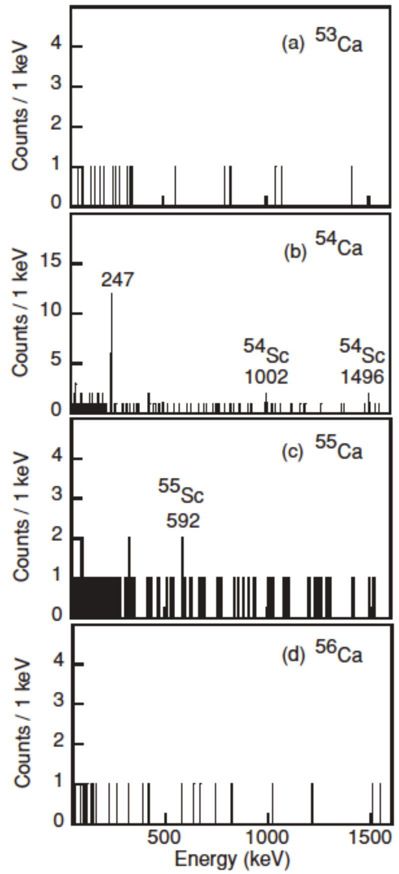
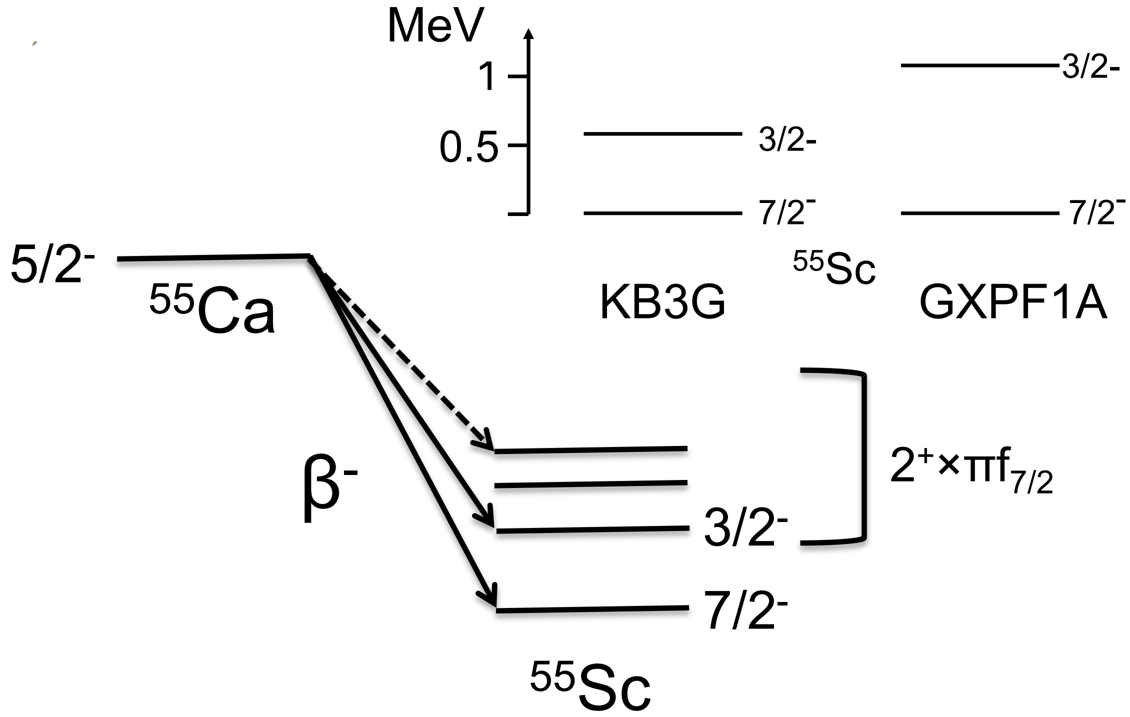


FIG. 3. The γ-ray spectrum in the range 50 to 1600 keV correlated with β-decay events for (a) ^{53}Ca, (b) ^{54}Ca, (c) ^{55}Ca, and (d) ^{56}Ca. Observed transitions are marked by their energy in keV.



We propose the study of the β decay ^{55}Ca ➔^{55}Sc in order to disentangle the evolution of $\pi f_{7/2}$ –$\nu f_{5/2}$ monopole tensor interaction and NNN forces, that might give rise to the subshell closure N=34.

P.F. Mantica et al., PRC77, 014313 (2008)

Possible beam time request

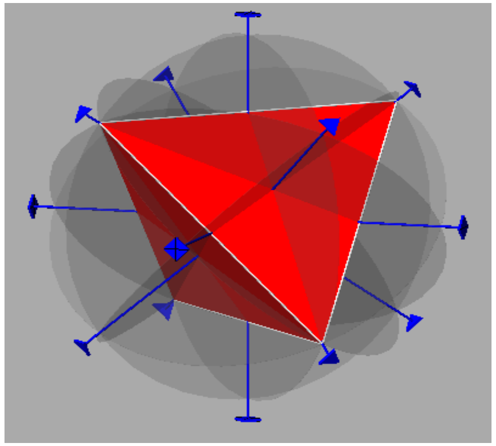
- Beam ^{86}Kr - 30pnA - 345MeV/nucleon
- Setting ^{55}Ca
- Be primary target ~2.5 g/cm^2
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- Production ~0.5pps ^{55}Ca
- 8 days → 34000 gamma if β has a ~ 100% efficiency
- Complementary measurement to the GSI AGATA in beam experiment with knockout reactions.

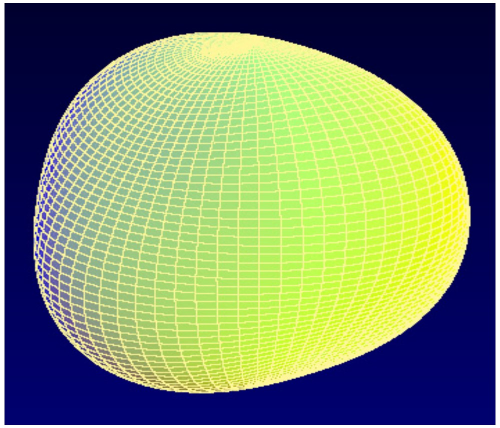
Isomer spectroscopy: ^{110}Zr

Spokeperson: G. de Angelis, J. Dudek, D. Curien, A. Gadea, F. Haas, …

Tetrahedral symmetry

New nuclear deformation never observed: **tetrahedral** shape





The tetrahedron is a Platonic solid with 24 symmetries

The corresponding symmetry group for nuclei (fermionic hamiltonian) has 48 symmetries

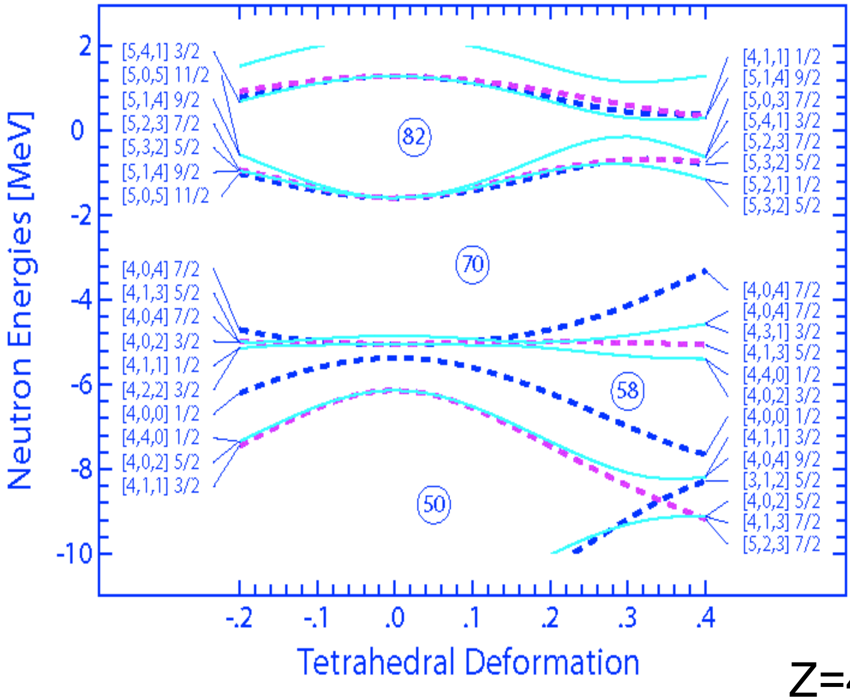
$$R(\theta,\varphi) = \sum_{\lambda,\mu} \alpha_{\lambda\mu} Y_{\lambda\mu}$$

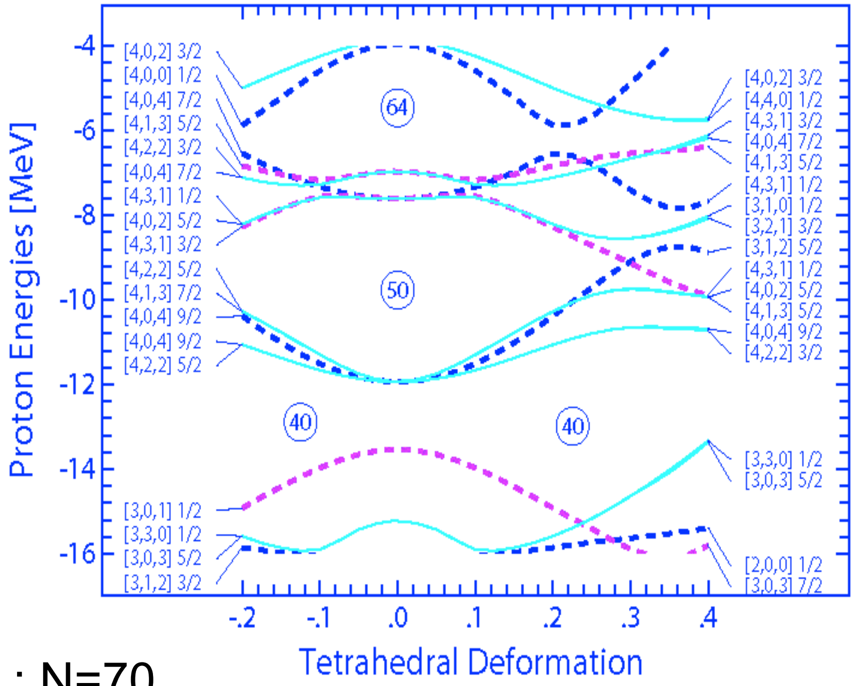
A tetrahedral deformation is a kind of non-axial octupole shape: $\boldsymbol{\alpha_{32}}$

J. Dudek *et al.*, Phys. Rev. Lett. 88 (2002), 252502

Symmetry and nuclear stability

The presence of a symmetry in the hamiltonian leads to the appearance of new magic numbers





Z=40 ; N=70

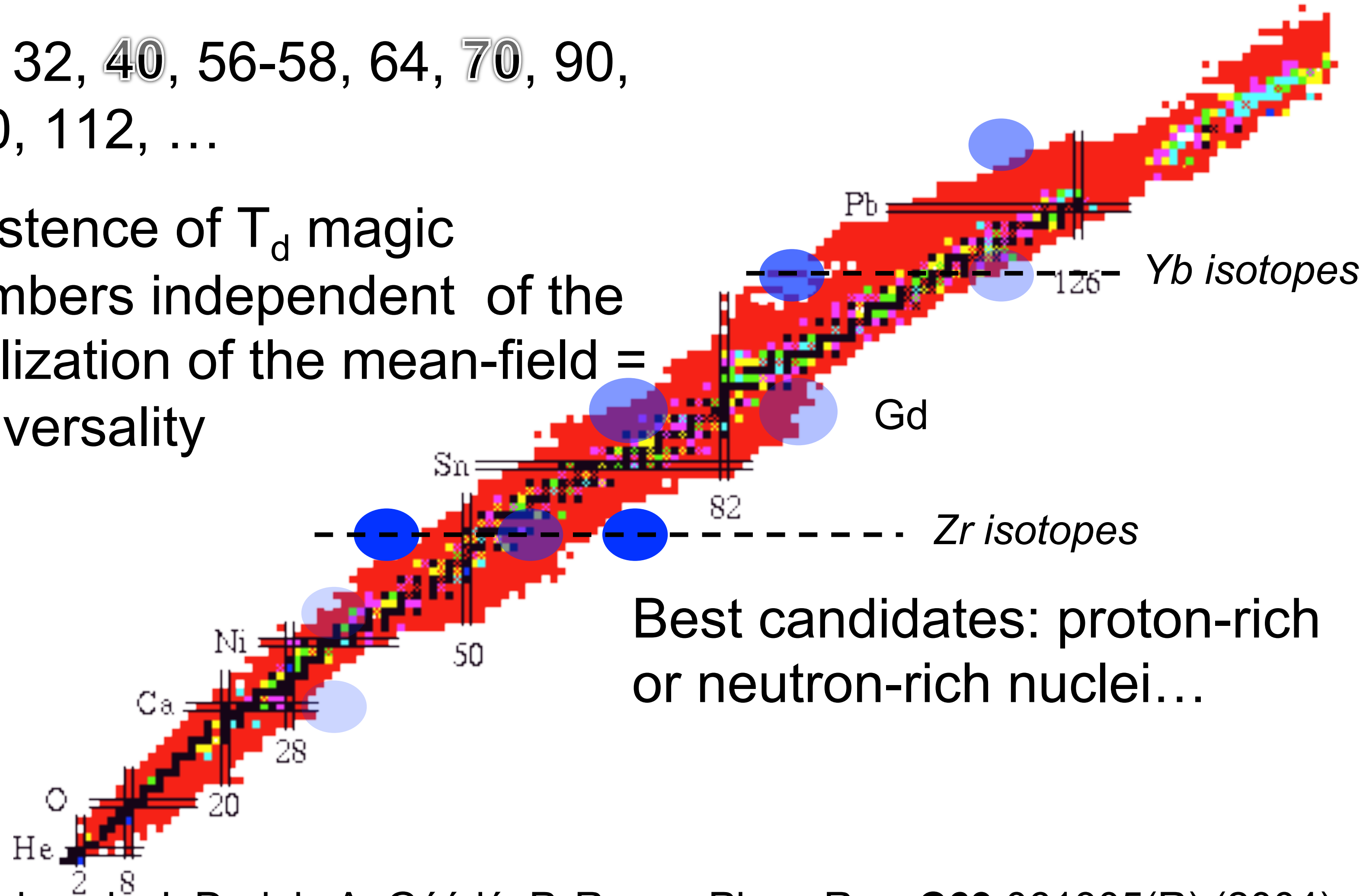
N. Schunck et al., PRC69 061305(R) 2004

Tetrahedral magic numbers

- From a WS potential:

  20, 32, **40**, 56-58, 64, **70**, 90, 100, 112, …

- Existence of T_d magic numbers independent of the realization of the mean-field = Universality



Best candidates: proton-rich or neutron-rich nuclei…

N. Schunck, J. Dudek, A. Góźdź, P. Regan Phys. Rev. **C69** 061305(R) (2004)

^{156}Gd, a test of tetrahedral symmetry

PRL **104**, 222502 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

Ultrahigh-Resolution γ-Ray Spectroscopy of ^{156}Gd: A Test of Tetrahedral Symmetry

M. Jentschel,[1] W. Urban,[1,2] J. Krempel,[1] D. Tonev,[3] J. Dudek,[4] D. Curien,[4] B. Lauss,[5] G. de Angelis,[6] and P. Petkov[3]
[1]*Institut Laue-Langevin, 6 rue Jules Horowitz, BP 156, F-38042 Grenoble, France*
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[3]*Institute for Nuclear Research and Nuclear Energy, BAS, BG-1784 Sofia, Bulgaria*
[4]*Departement de Recherches Subatomiques, Institut Pluridisciplinaire Hubert Curien, DRS-IPHC, 23 rue du Loess, BP 28, F-67037 Strasbourg, France*
[5]*Paul Scherrer Institut, CH-5232 Villigen-PSI, Switzerland*
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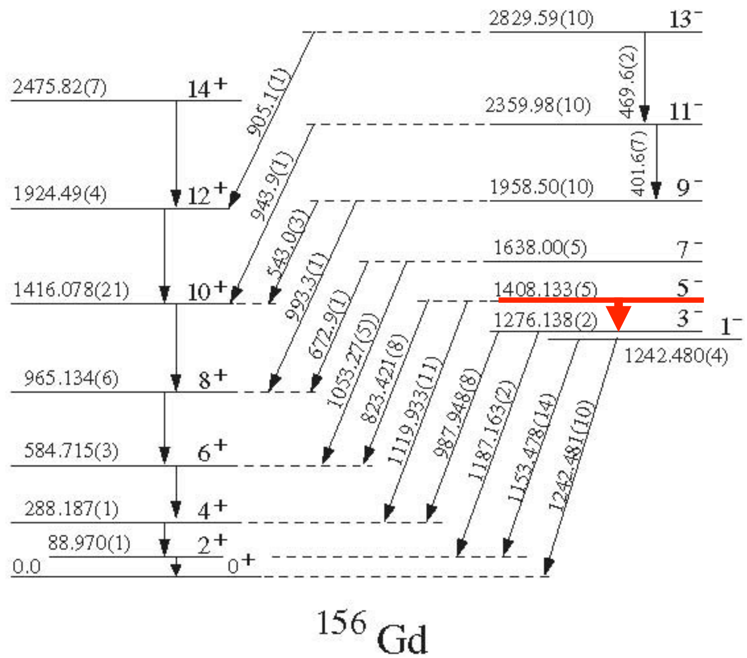
(Received 26 February 2010; published 4 June 2010)

PRL **104**, 222502 (2010) PHYSICAL

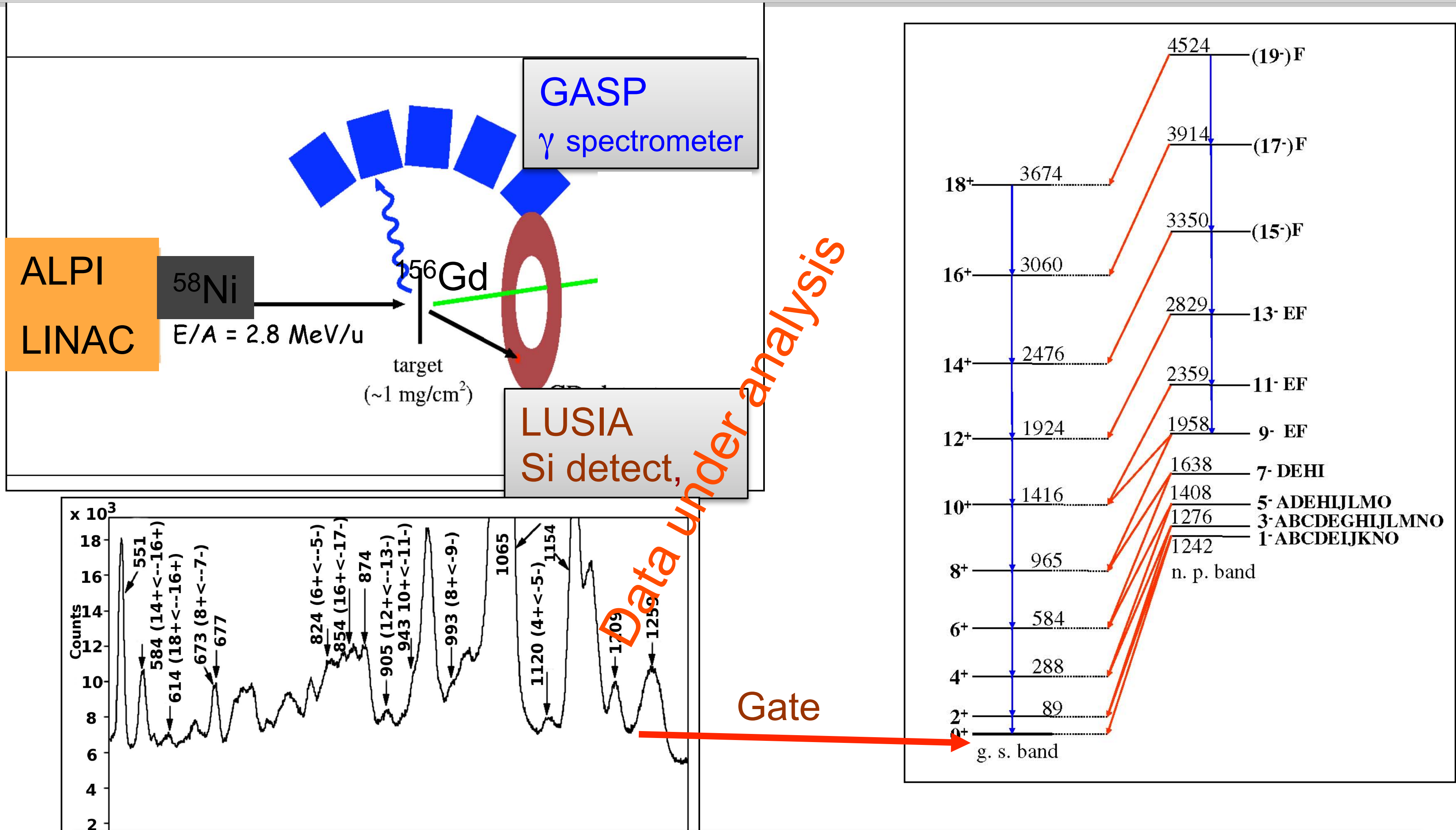


Highly accurate measurement with a Bragg spectrometer and the GRID technique.

- Lifetime of the 5^- level at 1.408 MeV
- Intensity of the 132 keV $5^- \rightarrow 3^-$ γ ray

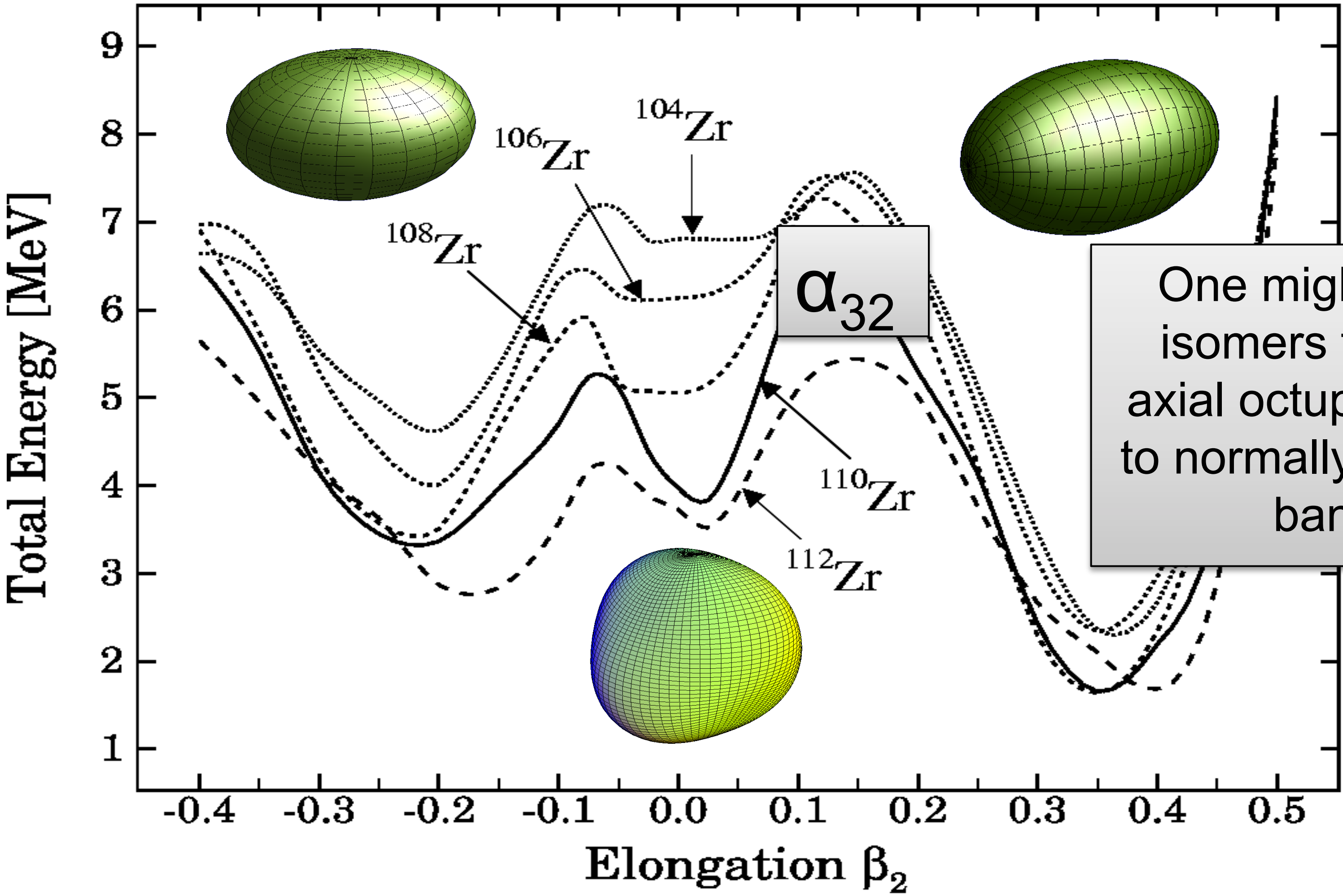
The measurend lifetime gives an intrinsic Q_0=7.104(35)b is obtained → Large quadrupole collectivity. Therefore the negative parity band incompatible with a tetrahedral symmetry

Coulex to access Tetahedral shapes



Electromagnetic transition matrix elements and quadrupole moment (with sign) accessible by low energy Coulomb excitation

^{110}Zr, shape isomers



One might expect isomers from non axial octupole bands to normally deformed bands.

N. Schunck, J. Dudek, A. Góźdź, P. Regan Phys. Rev. **C69** 061305(R) (2004)

^{106,108}Zr at RIKEN

Structural evolution in the neutron-rich nuclei ^{106}Zr and ^{108}Zr

T. Sumikama,[1,*] K. Yoshinaga,[1] H. Watanabe,[2] S. Nishimura,[2] Y. Miyashita,[1] K. Yamaguchi,[3] K. Sugimoto,[1] J. Chiba,[1] Z. Li,[2] H. Baba,[2] J. S. Berryman,[4,5] N. Blasi,[6] A. Bracco,[6,7] F. Camera,[6,7] P. Doornenbal,[2] S. Go,[8] T. Hashimoto,[8] S. Hayakawa,[8] C. Hinke,[9] E. Ideguchi,[8] T. Isobe,[2] Y. Ito,[10] D. G. Jenkins,[11] Y. Kawada,[12] N. Kobayashi,[12] Y. Kondo,[12] R. Krücken,[9] S. Kubono,[8] G. Lorusso,[2,5] T. Nakano,[1] M. Kurata-Nishimura,[2] A. Odahara,[10] H. J. Ong,[13] S. Ota,[8] Zs. Podolyák,[14] H. Sakurai,[2] H. Scheit,[2] K. Steiger,[9] D. Steppenbeck,[2] S. Takano,[1] A. Takashima,[10] K. Tajiri,[10] T. Teranishi,[15] Y. Wakabayashi,[16] P. M. Walker,[14] O. Wieland,[6] and H. Yamaguchi[8]

The spherical N=70 sub-shell gap is not having a large effect at N=68 ^{108}Zr

The isomeric state of ^{108}Zr is proposed to be the candidate for a tetrahedral shape

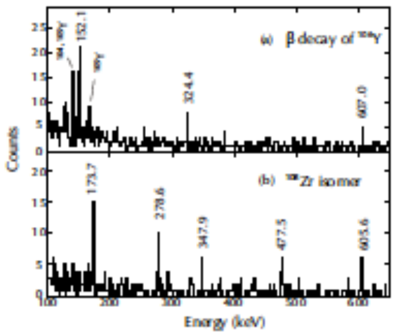


FIG. 1. Gamma-ray spectra measured (a) in coincidence with β rays detected within 200 ms after implantation of ^{106}Y and (b) with a particle gate on ^{108}Zr within 4 μs. Peaks marked with the nucleus name indicate ones measured also in coincidence with the β decay of its nucleus.

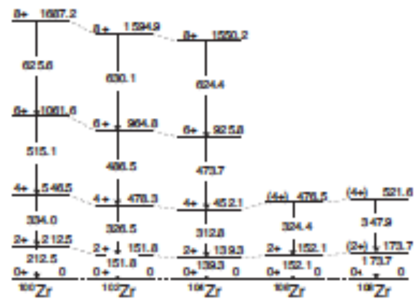


FIG. 2. Ground-state bands of neutron-rich even-even Zr isotopes with $N \geq 60$. The energies of $^{100-104}$Zr are taken from the ENSDF database [23].

T. Sumikama et al., arXiv:1104.2958v1 [nucl-ex] 15 Apr 2011

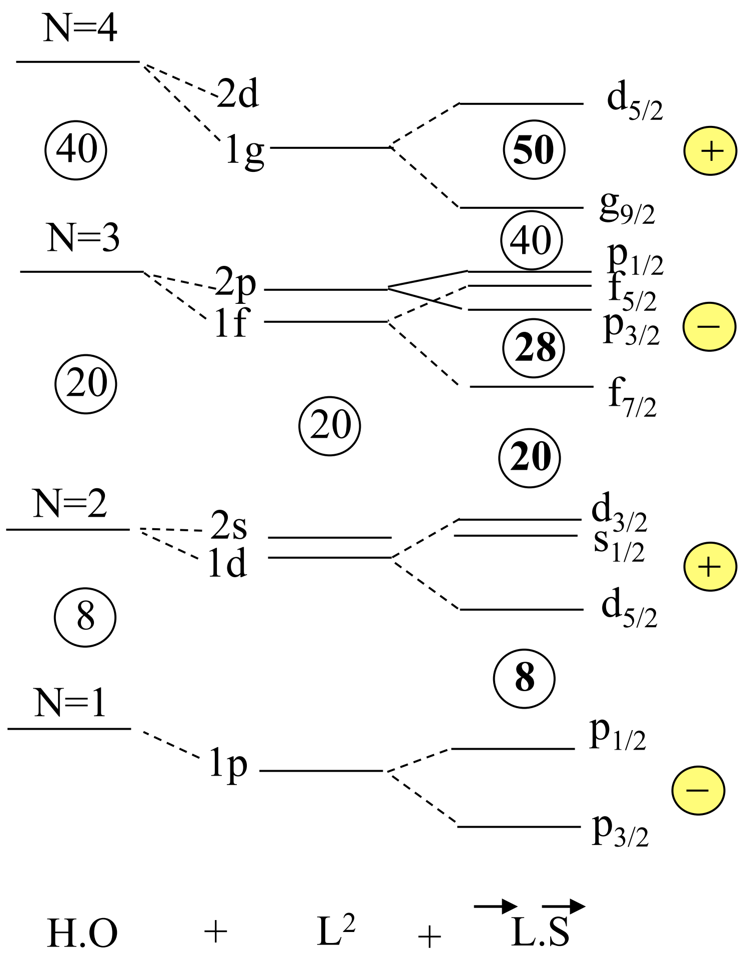
Possible beam time request

- Beam ^{238}U – 5pnA - 345MeV/nucleon
- Setting ^{110}Zr
- Be primary target ~1 g/cm^2
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- Production ~7pps ^{110}Zr
- Isomeric ratio ~10%
- 8 days → 5 10^4 gamma

Summary

- Proposals to study neutron-rich nuclei
  - Address the N=34 subshell gap via β delayed γ-ray spectroscopy: $^{55}Ca \rightarrow {}^{55}Sc$
  - Address shell evolution Z=28 nearby N=50 via β delayed γ-ray spectroscopy: $^{75,77}Ni \rightarrow {}^{75,77}Cu$
  - Doubly magic tetrahedral nucleus ^{110}Zr via isomer spectroscopy
- Proposal to study proton-rich nuclei
  - Address IS/IV component and CED via isomer spectroscopy of ^{71}Kr
- GALILEO project at LNL for gamma spectroscopy using Triple Clusters from EUROBALL 7-clusters

The "spin-orbit" magic numbers



Reduction of N=50 gap by tensor force $\pi f_{5/2}$-νg
Behaviour of ^{78}Ni ?

Reduction of N=28 gap by tensor force $\pi d_{3/2}$-νf
strongly deformed ^{42}Si

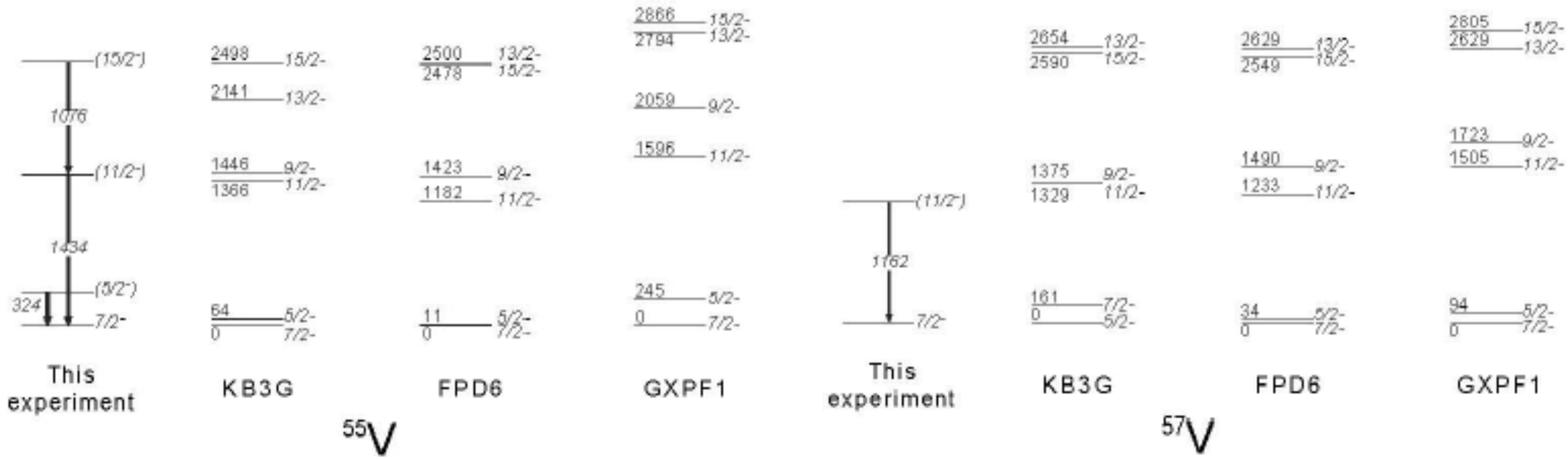
Reduction of N=20 triggered by $\pi d_{5/2}$-$\nu d_{3/2}$
Island of inversion, large collectivity

N=8 collapses at ^{12}Be
Triggered by the $\pi p_{3/2}$-$\nu p_{1/2}$ interaction

What is know in the region?

Vanadium isotopes

N=32 N=34

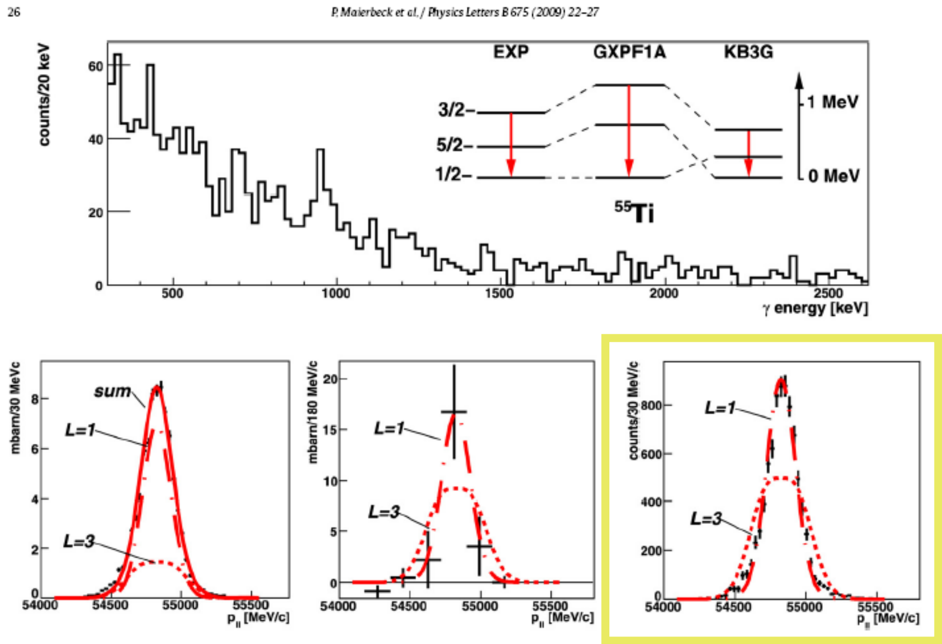


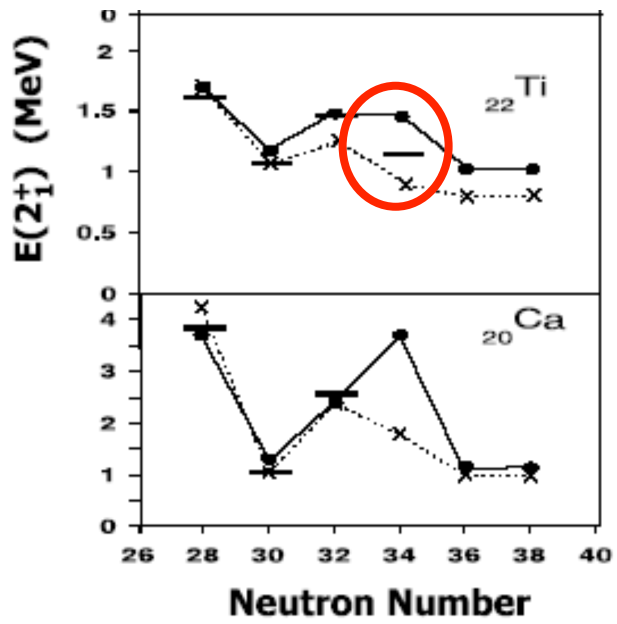
The experimental data in comparison with the Shell Model calculations suggest the N=32 subshell gap for ^{55}V but there is no evidence for N=34 for the ^{57}V (N=34)

D. Napoli et al., Journal of Physics: Conference Series 49 (2006) 91.

What is known in the region?

Titanium isotopes





- Semi-inclusive momentum distribution to the gs of ^{55}Ti
- The data established the ground state of ^{55}Ti is 1/2$^-$ in agreement with GXPF1A.

- Beta decay of ^{56}Sc populate ^{56}Ti.
- Beta –delayed γ ray at 1127 keV assigned 2+ → 0+ in ^{56}Ti
- Midway between GXPF1 and KB3G predictions.

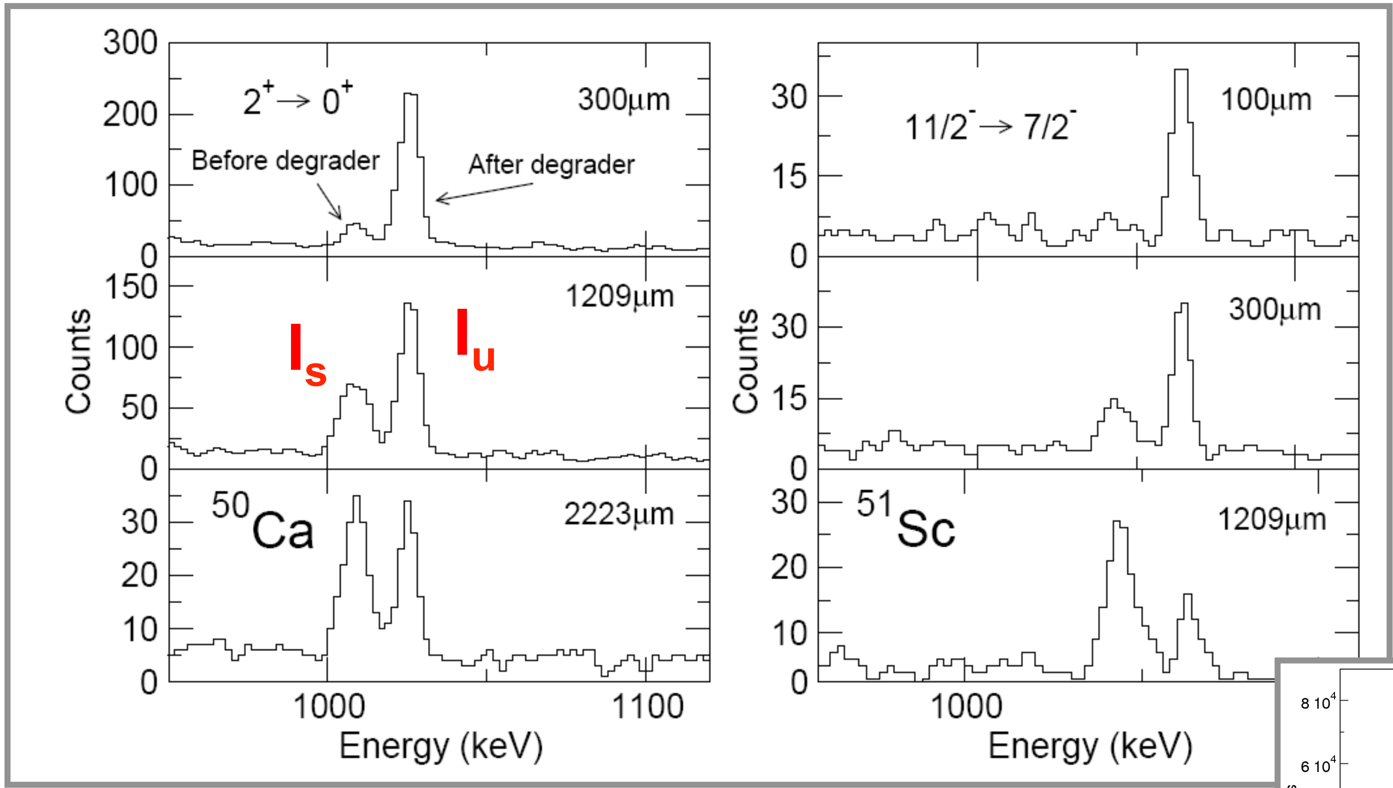
P. Maierbeck et al., Phys. Lett. B 675 (2009) 22.

S.N. Liddick et al., PRL92, 072502 (2004)

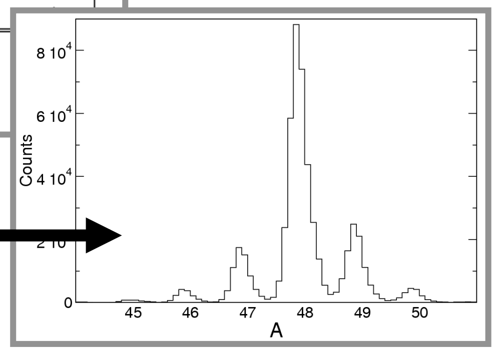
Experimental RDDS spectra

Rection: ^{48}Ca onto ^{208}Pb at 310 MeV

Gamma spectra of the 2^+ and $11/2^-$ in ^{50}Ca and ^{51}Sc (mass gate in PRISMA)



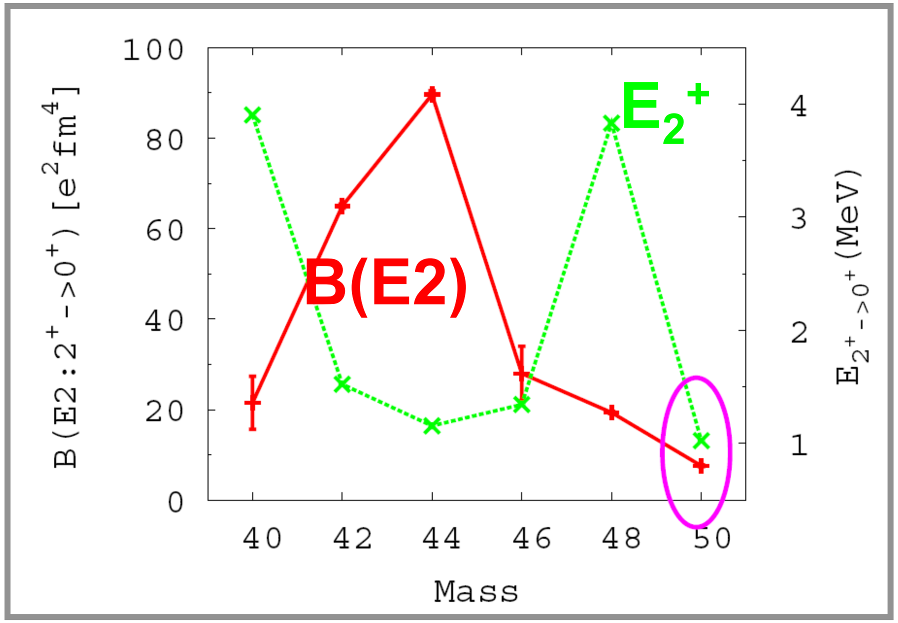
Mass spectrum from PRISMA



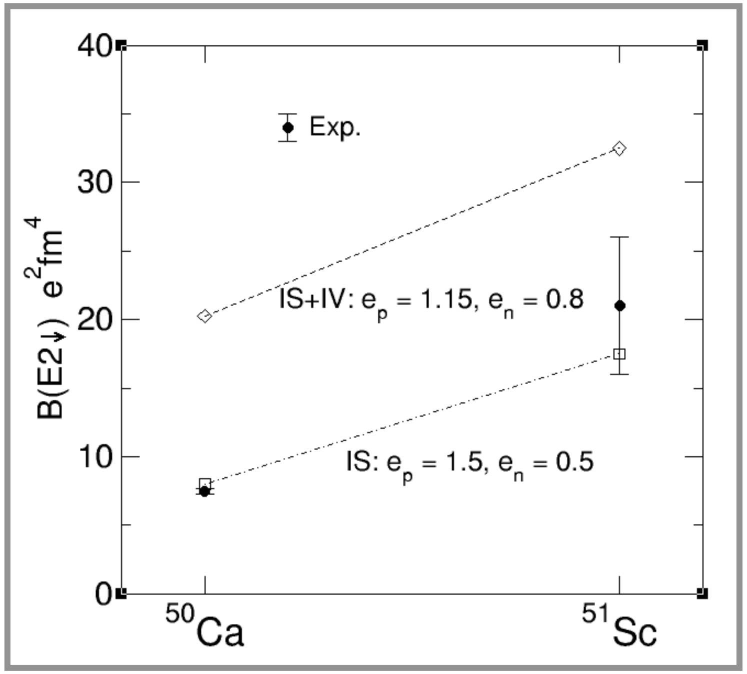
B(E2) and Eff. charges of N=30

Shell-model calculations in the full *fp* shell ^{40}Ca core (KB3G & GXPF1A):

- ^{50}Ca wave function of the $2^+ \rightarrow \nu p^2_{3/2}$
- ^{51}Sc wave function of the $11/2^- \rightarrow \nu p^2_{3/2}, \pi f_{7/2}$



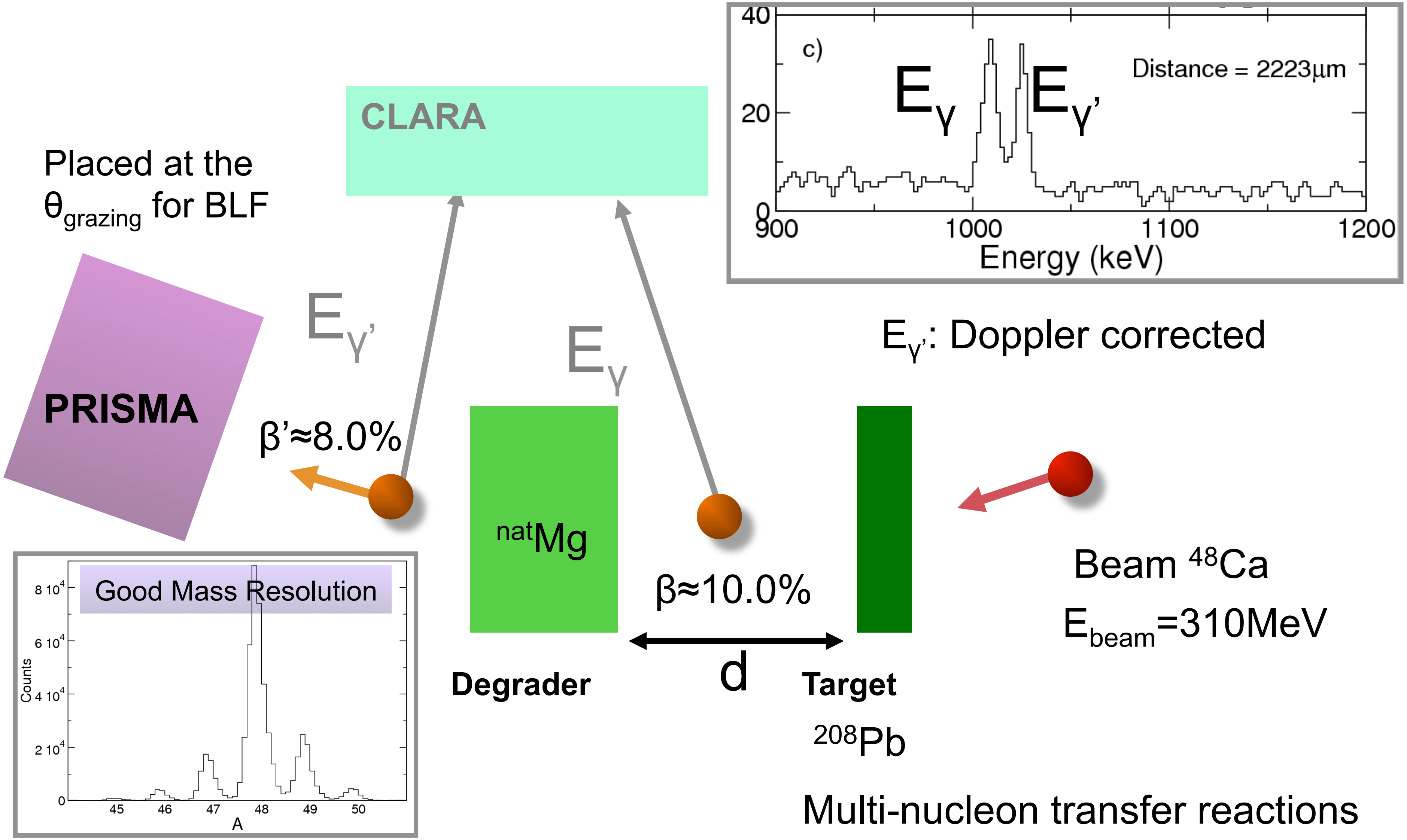
Calcium systematics E and B(E2)



Experimental and theoretical effective charges.

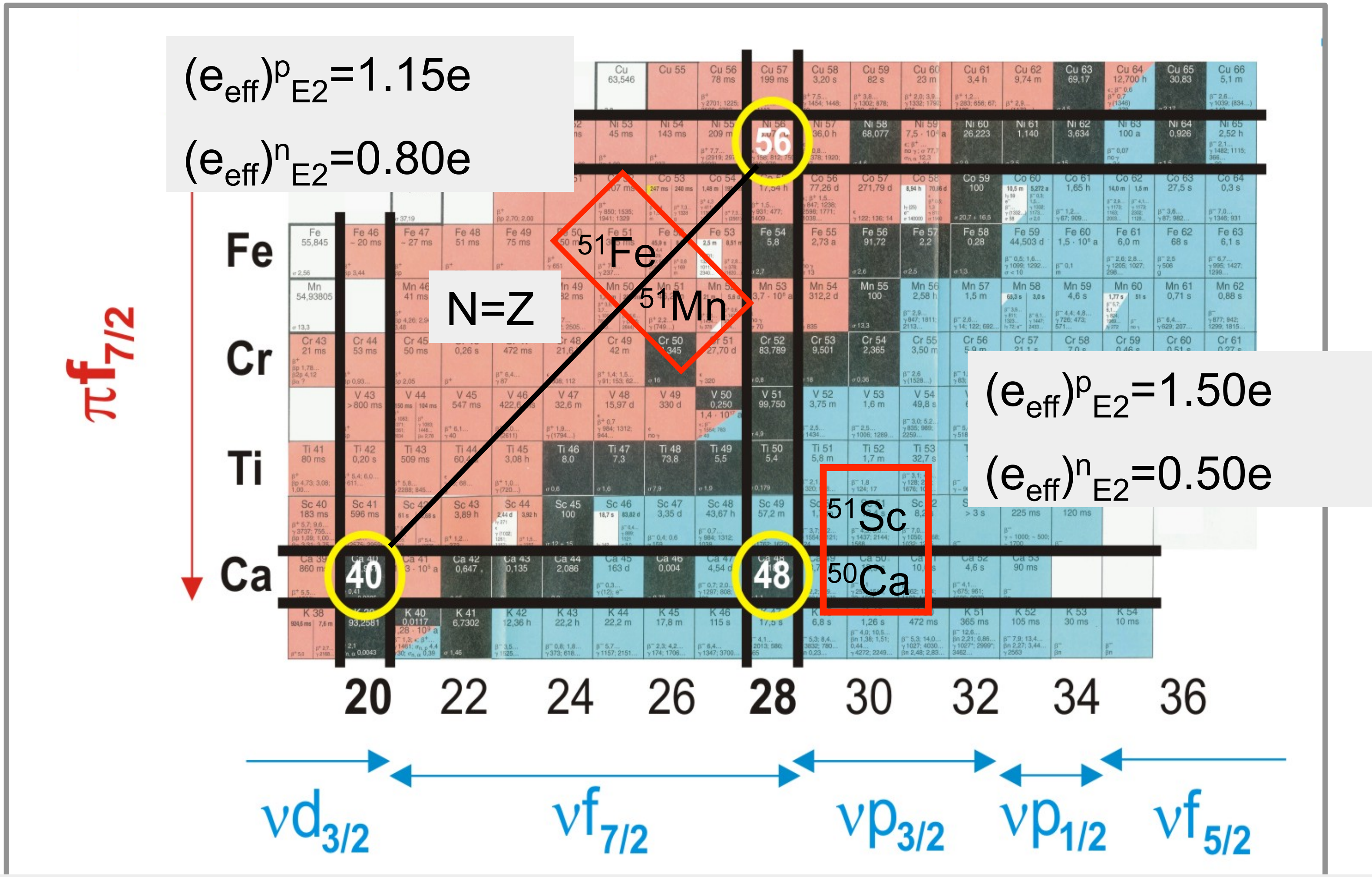
Experimental setup

Recoil Distance Doppler Shift method (RDDS)



Ductu Naturae

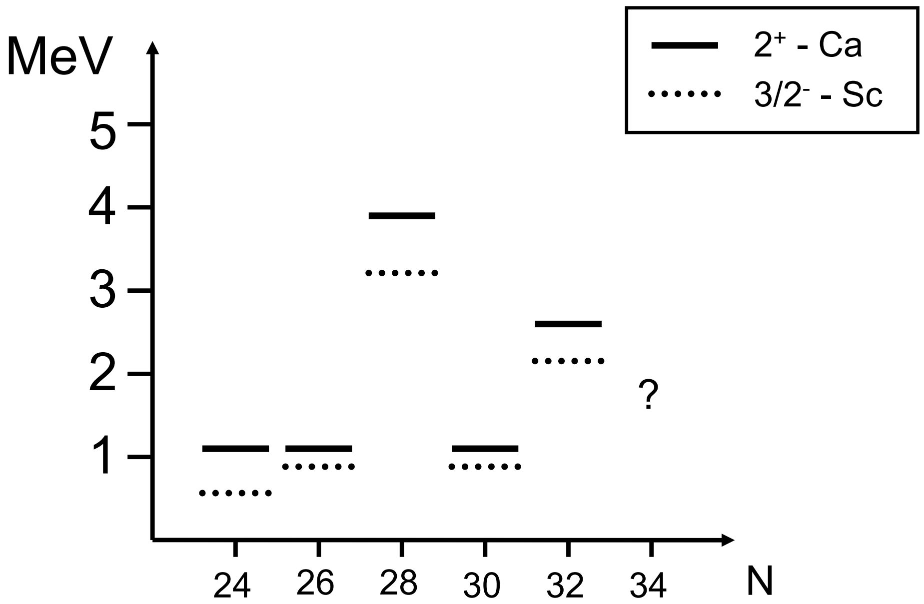
Full *fp* shell with a ^{40}Ca core.

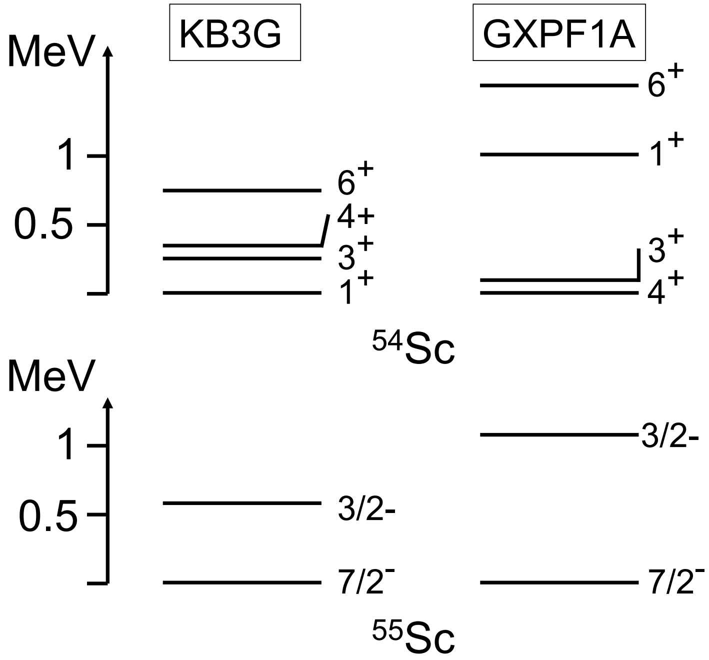


A HO potential and separable (IS and IV) QQ interactions →
Effective charges are constant for a given core and valence space.

Investigating the N=34 with knockout

We propose the study of the neutron-rich Z=21 isotopes $^{54,55}Sc$ in order to disentangle the evolution of $\pi f_{7/2} - \nu f_{5/2}$ monopole tensor interaction and NNN forces, that might give rise to the subshell closure N=34.

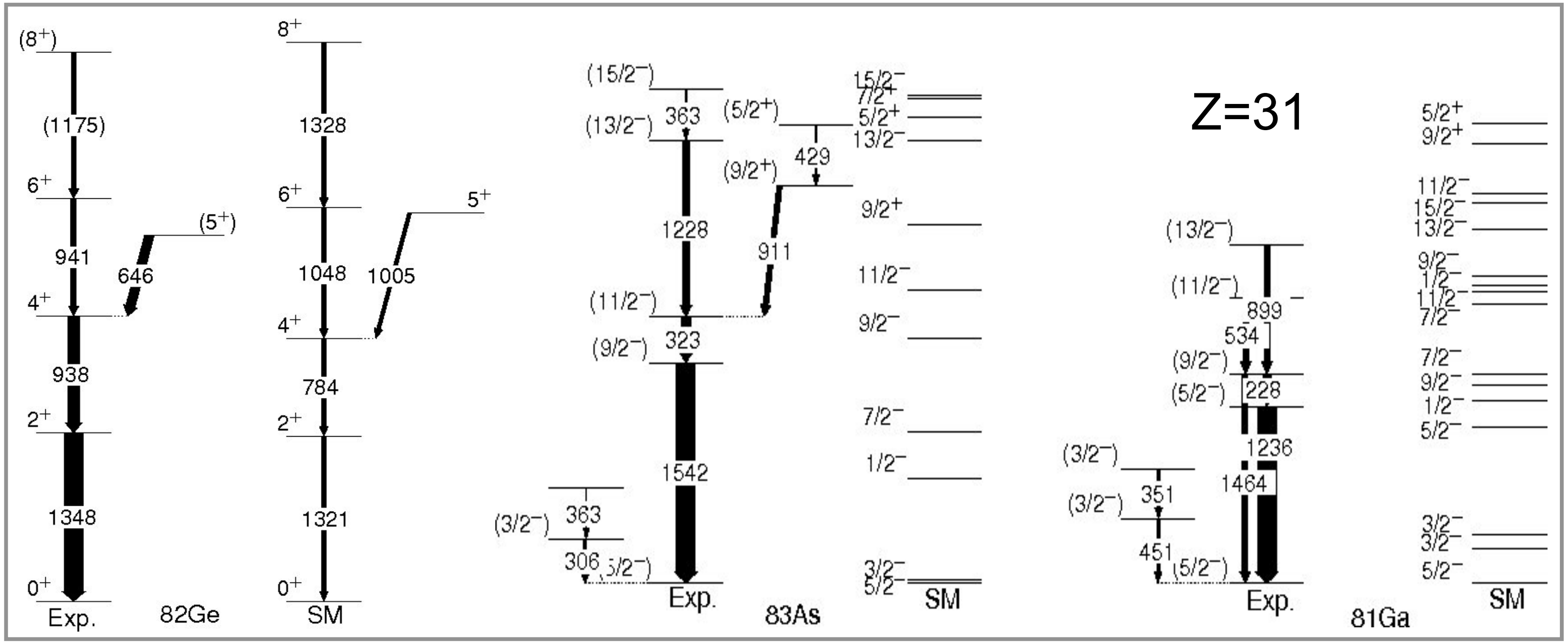




^{54}Sc are known two states: 110 keV (7 ± 5μs) and 247 keV (β decay)

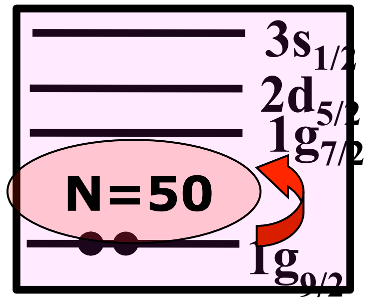
^{55}Sc no excited states known

The N=50 isotones



E. Sahin and G. De Angelis PLB (to be published)
Y.H. Zhang PRC70, 024301 (2004)

Shell Model calcuations: 2p-2h excitations across the N=50 shell to $2d_{5/2}$-$1g_{7/2}$-$3s_{1/2}$ (Lisetsky) for **4.7 MeV** of the shell gap value→No reduction of the shell gap



Coulomb effects

The description of the Coulomb interaction, taken into parts

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

E. Caurier et al., Rev. Mod. Phys. 77 427 (2005)
A.P. Zuker et al., PRL89 142502 (2002)

V_{CM} Multipole term accounts for the interaction between protons in the valence space
V_{cm} monopole term accounts for the single-particle and bulk effects due to the spherical field

- Radial effect $$E_{Cr} = \frac{3}{5}\frac{e^2 Z(Z-1)}{R}$$
- Shell energy $$E_{Cll} = \frac{-4.5 Z_{cs}^{13/12}[2l(l+1) - N(N+3)]}{A^{1/3}(N+3/2)} keV$$

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

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

A=51 mirror nuclei

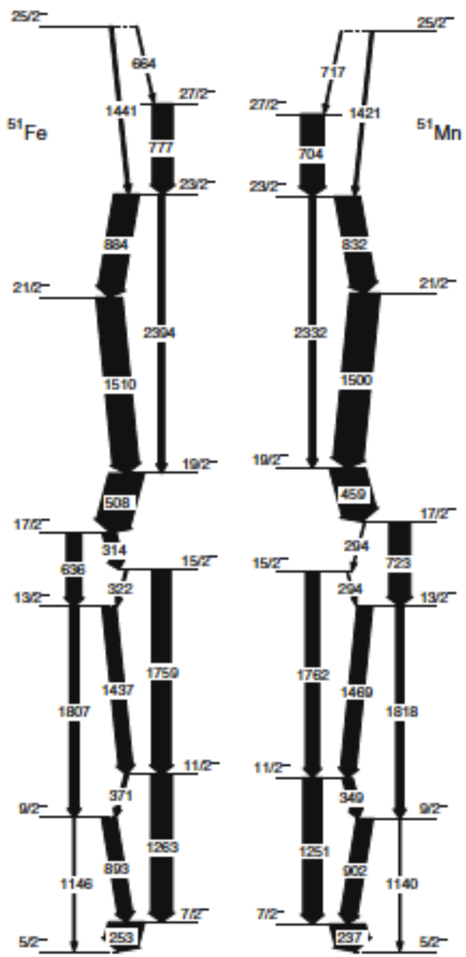
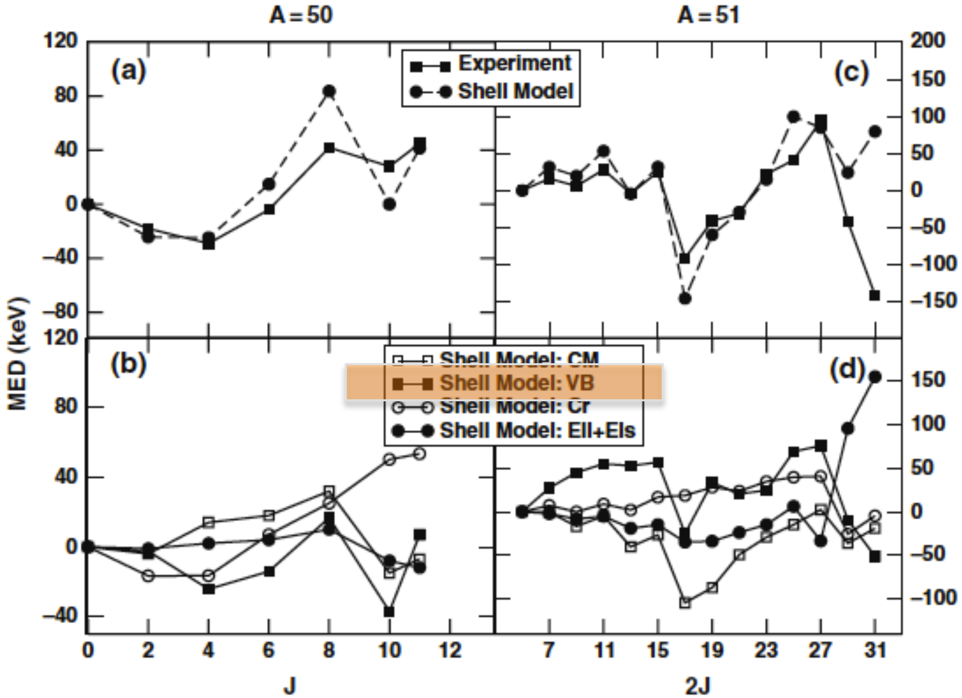


Fig. 11. Partial level schemes of the yrast negative-parity states of ^{51}Fe (data taken from [70]) and of ^{51}Mn (data taken from [72])



The isospin-nonconserving NN interaction –*VB*- is suggested to be as important as the Coulomb part (A.P. Zuker et al., PRL89, 142502(2002).

J. Ekman et al., Eur. Phys. J. A9 13 (2000)
J. Ekman et al., PRC70 0014306 (2004)

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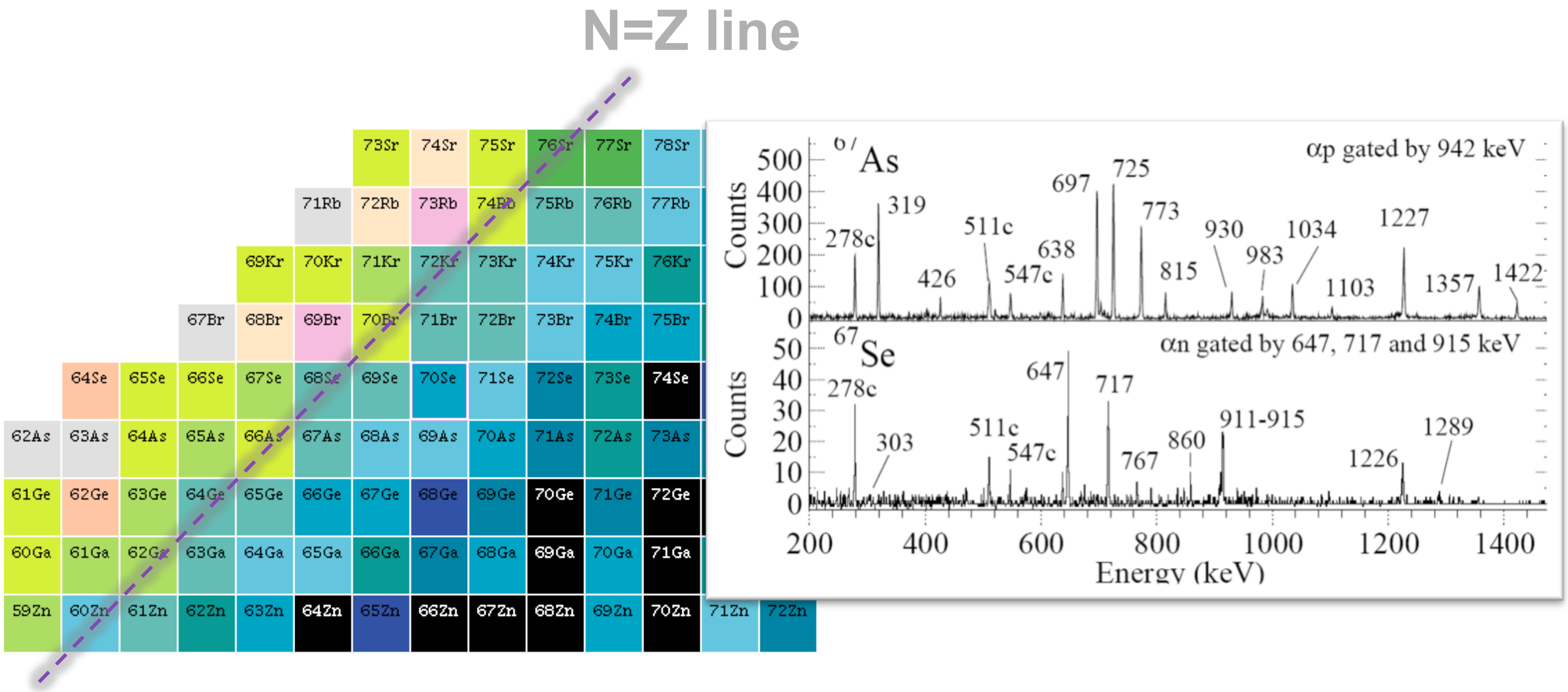
Mirror nuclei in A=70

Existence of E1 transitions fp-$g_{9/2}$



$^{40}Ca(^{32}S,\alpha p)^{67}As$ and $^{40}Ca(^{32}S,\alpha n)^{67}Se$

MED in ^{67}Se and ^{67}As

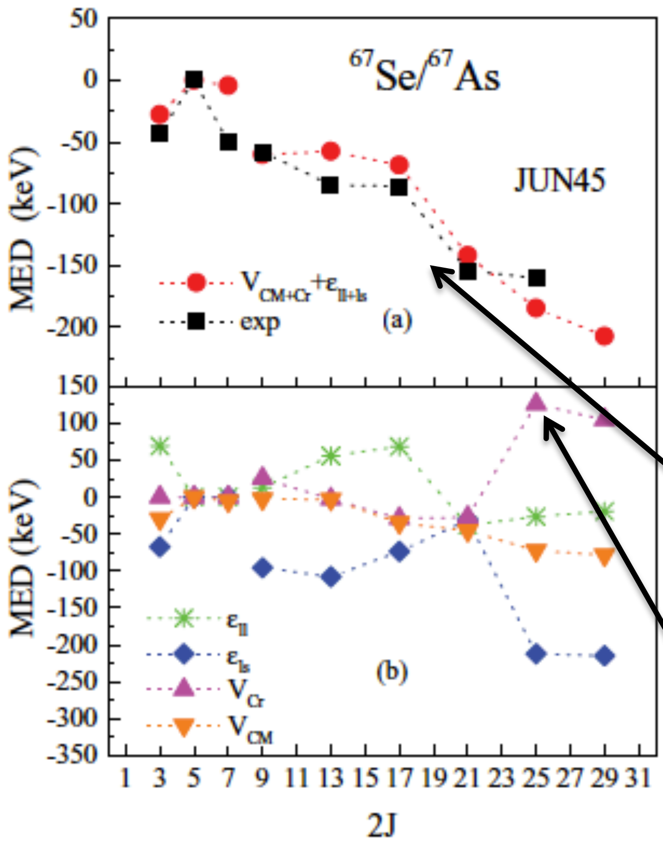


FIG. 2. (Color online) The MED for states shown in Fig. 1. Upper graph: Comparison of calculated MED with available data. Lower graph: Decomposition of theoretical MED into four terms (see text for explanation).

- Need of the $g_{9/2}$ to properly describe the results – Interaction JUN45 ($p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$) ^{56}Ni core - M. Honma et al., PRC80, 064323 (2009)

The experimental MED are well described without including an explicit isospin-breaking NN term

However, the the strength of the V_{Cr} was fitted from data and not determined independently

K. Kaneko et al., PRC82 061301R (2001)