Nuclear structure studies with the EUROBALL cluster detectors: EURICA and GALILEO

Jose Javier Valiente Dobón
Laboratori Nazionali di Legnaro (INFN), Italia

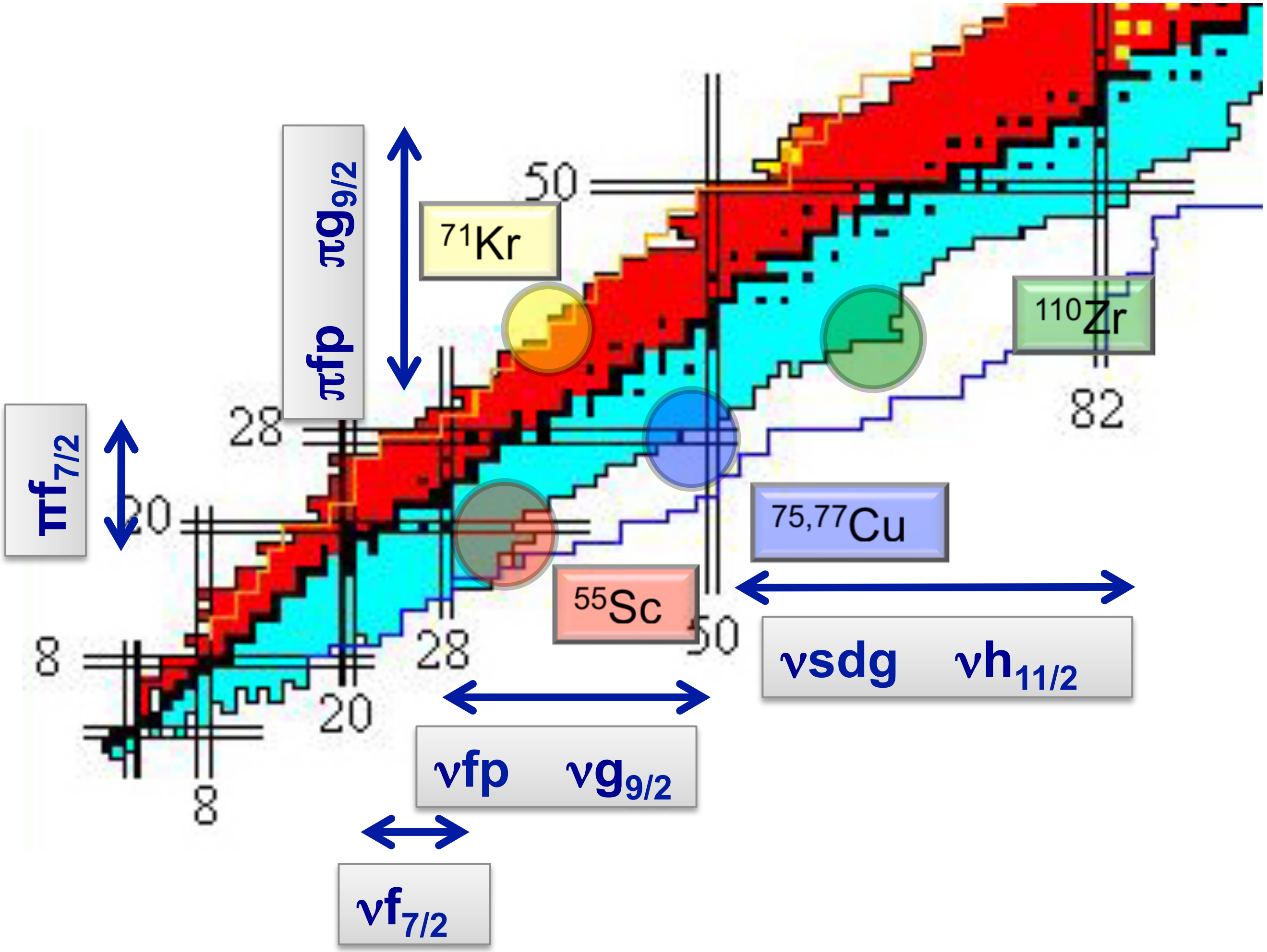
Overview

- Neutron-rich
  - β delayed γ-ray spectroscopy: ^{55}Ca → ^{55}Sc
  - β delayed γ-ray spectroscopy: ^{75,77}Ni→^{75,77}Cu
  - Isomer spectroscopy: ^{110}Zr

- Proton-rich
  - Isomer spectroscopy: ^{71}Kr

- The GALILEO project at LNL

Ductu naturae

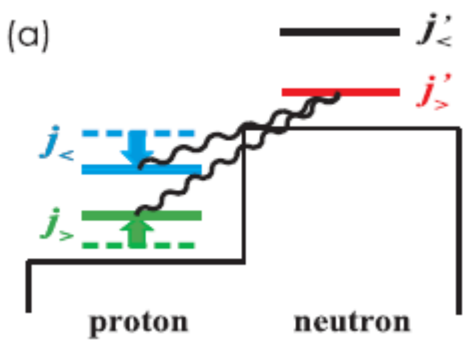


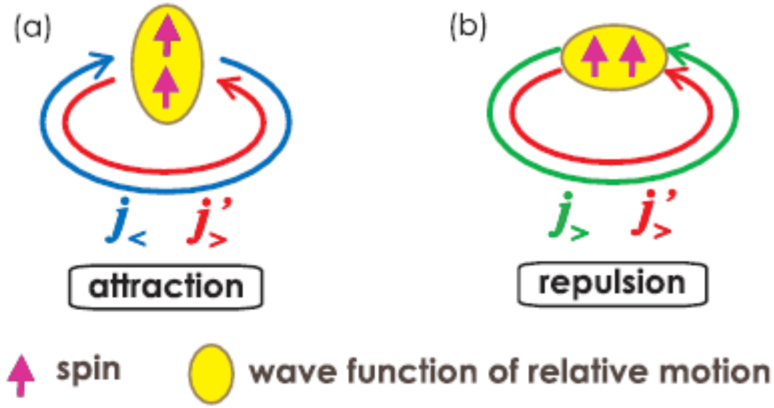
β delayed γ-ray spectroscopy: $^{55}Ca \rightarrow ^{55}Sc$

Spokepersons: J.J. Valiente-Dobón, D. Mengoni, …

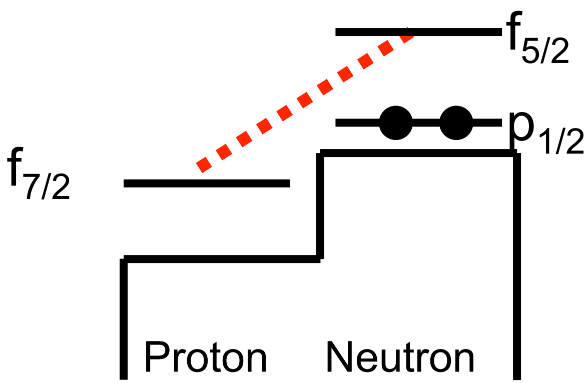
N=34 subshell gap

Monopole effect of the tensor interaction in shell evolution





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

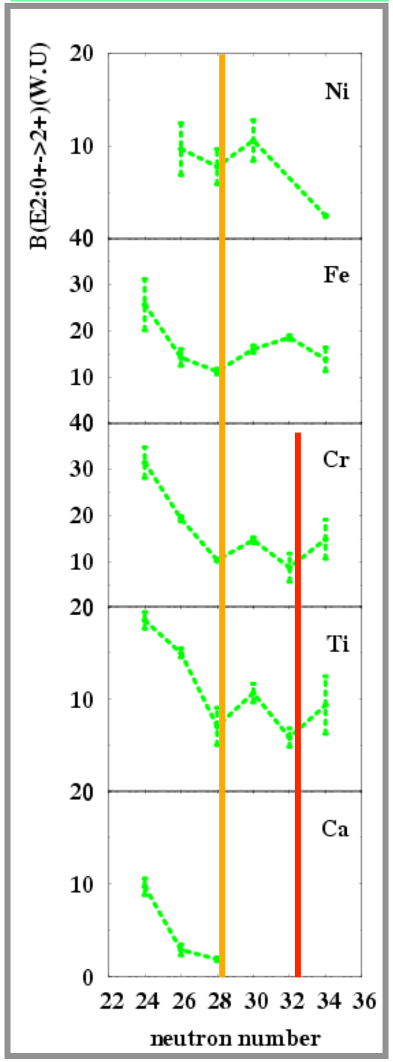


- •Posible subshell closure between $p_{3/2}$-$p_{1/2}$ and $f_{5/2}$
- •Atraction between the $f_{7/2}$ and $f_{5/2}$
- •Does ^{54}Ca present N=34 subshell?

Energies and B(E2) values

Indication of shell gaps

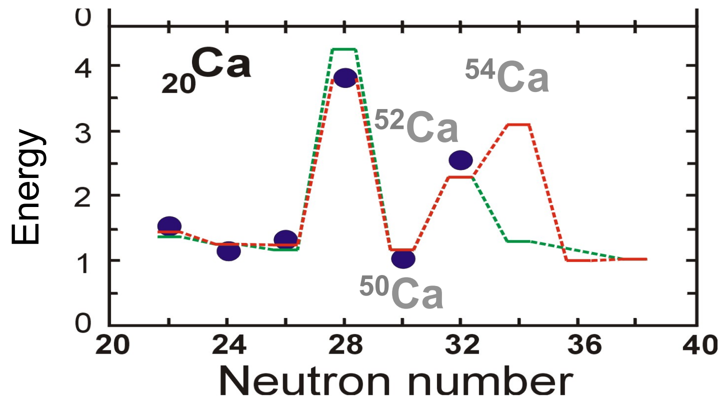
B(E2) values



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

N=28

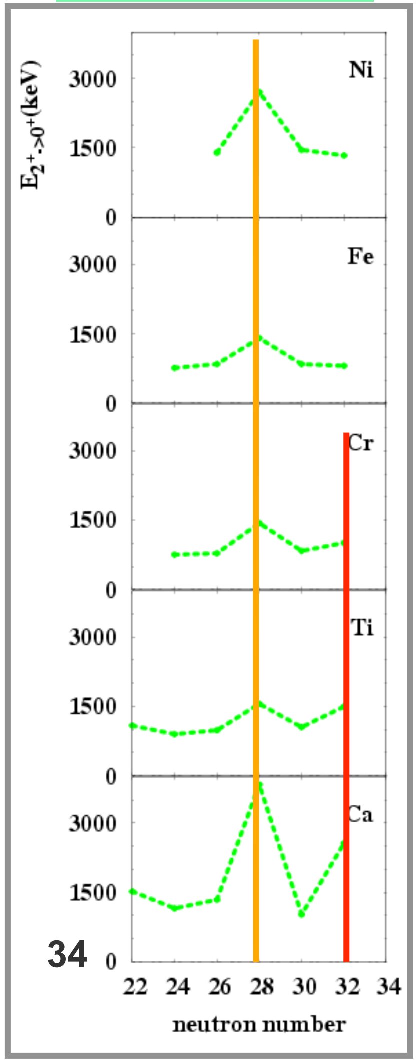
N=32



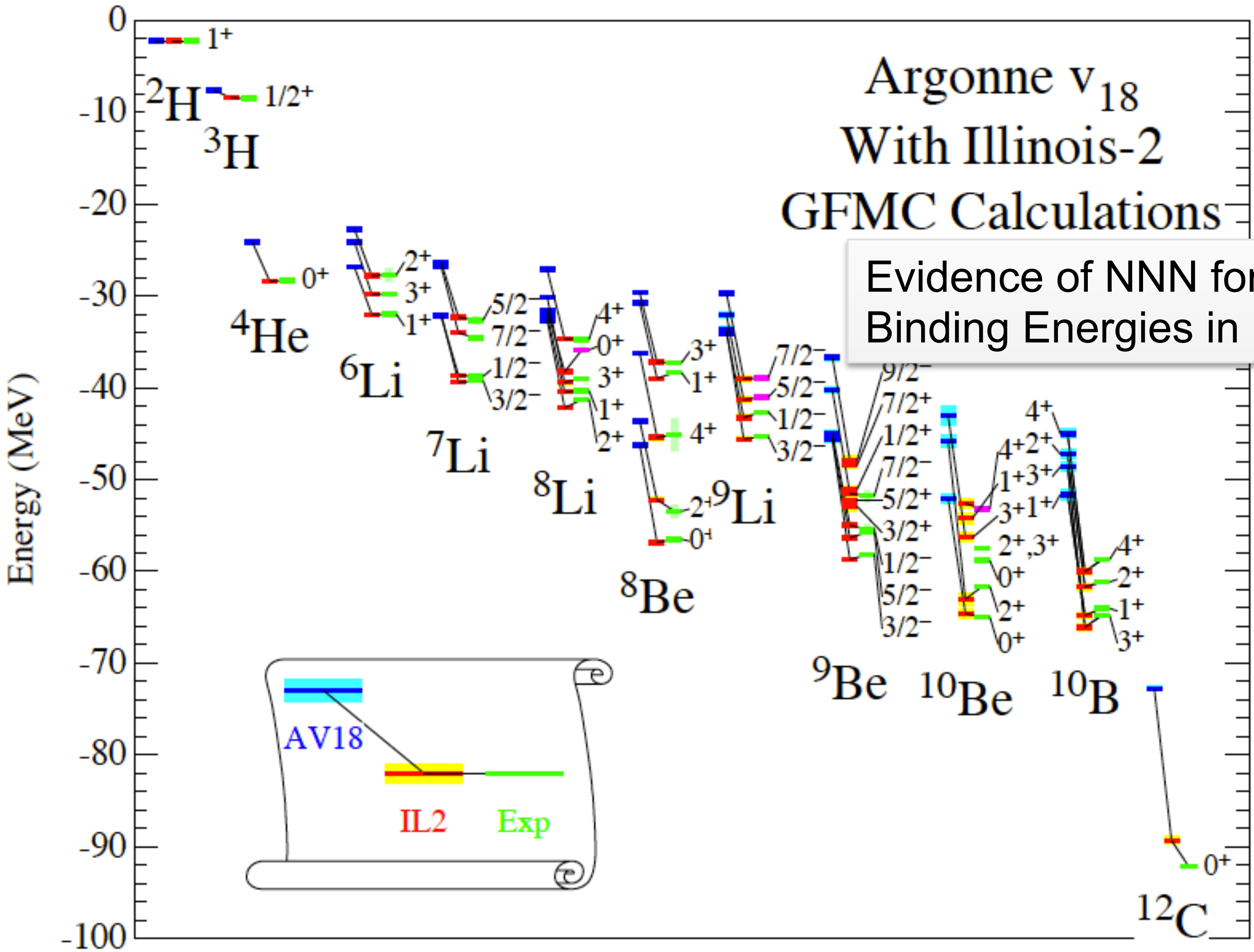
KB3G: A. Poves, et al., Nucl. Phys. A (2001).

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

Energy



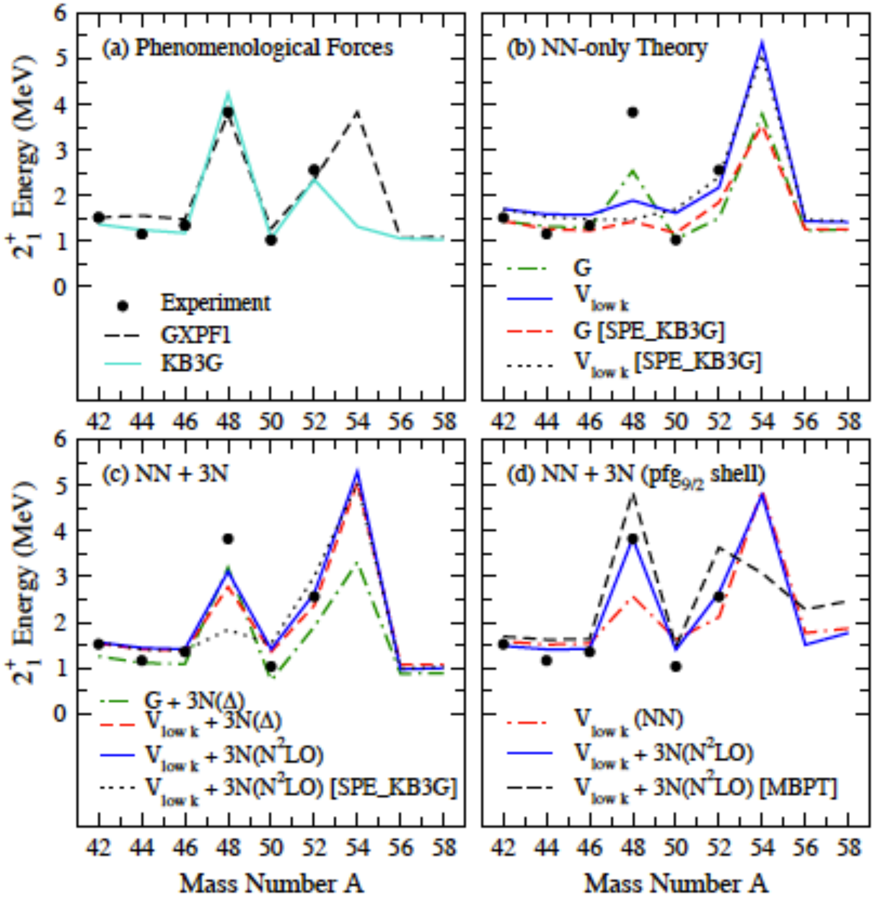
Indication of three body forces NNN



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.

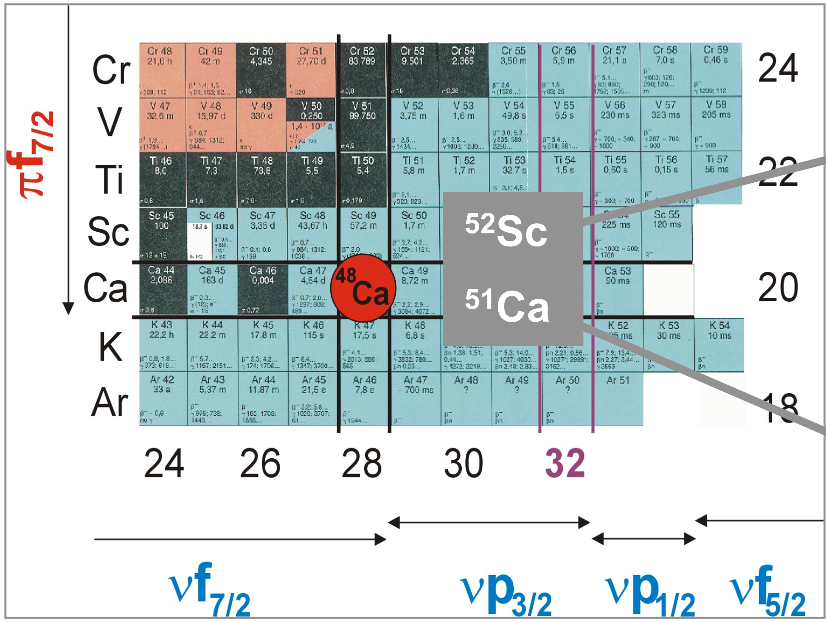
However NN and NN+3N forces predict a hight 2^+ energy in ^{54}Ca, but with quantitative differences.

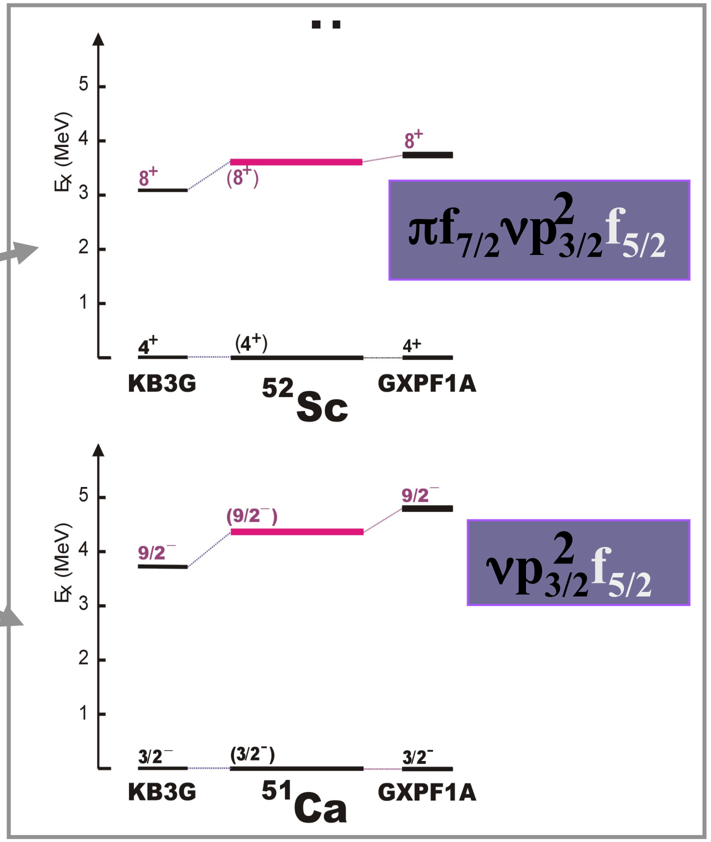
The changes die to 3N forces are amplified in neutron-rich nuclei and will play a crucial role for matter at the extremes

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



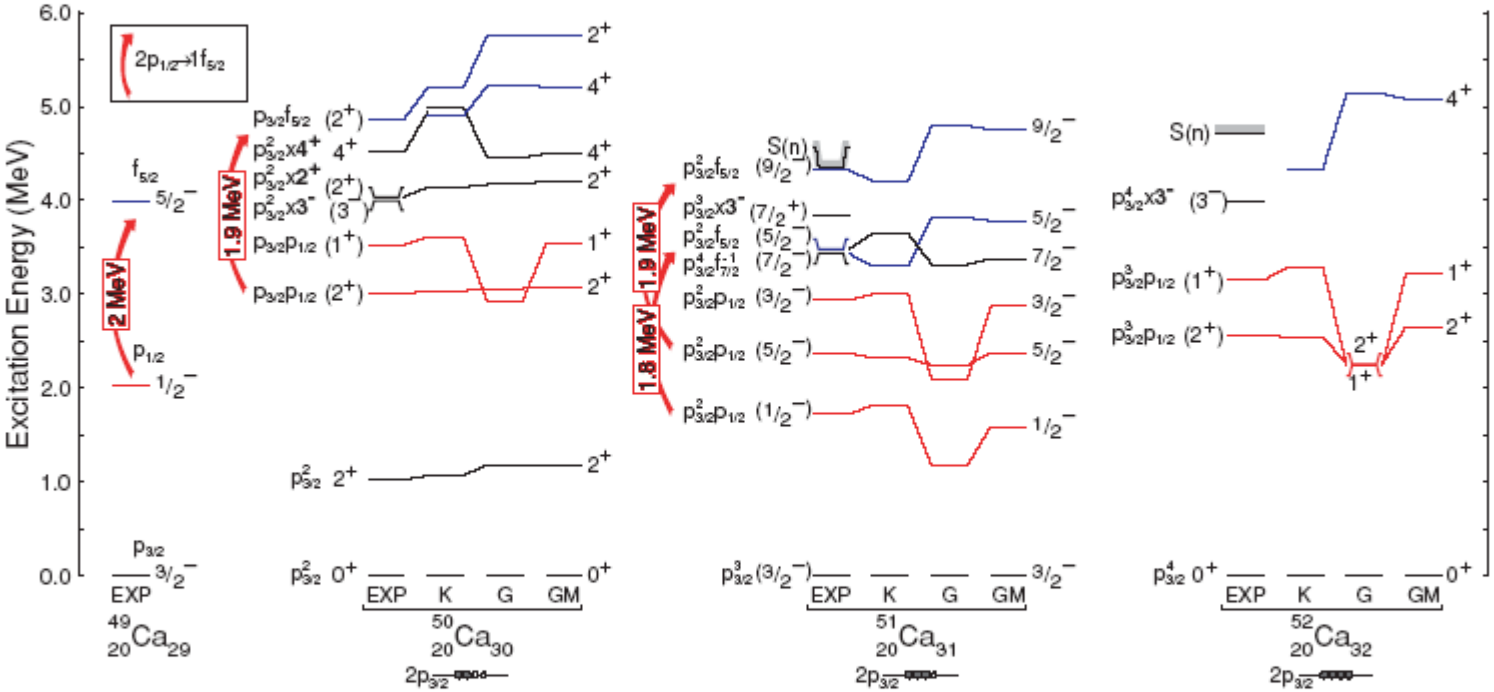


States with predominant $\nu f_{5/2}$ predict that the $p_{1/2}$-$f_{5/2}$ energy difference might be smaller that the one predicted by GXPF1A. Nevertheless this does not rule out the possible N=34 shell gap, since the change in the gap still gives good description of ^{54}Ca.

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

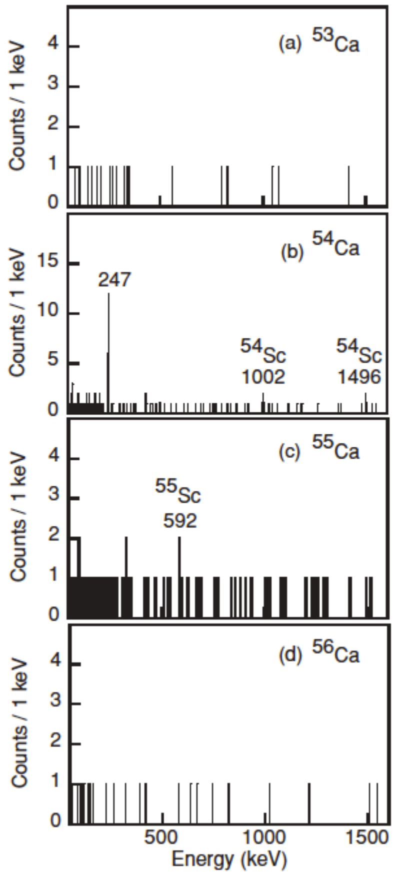
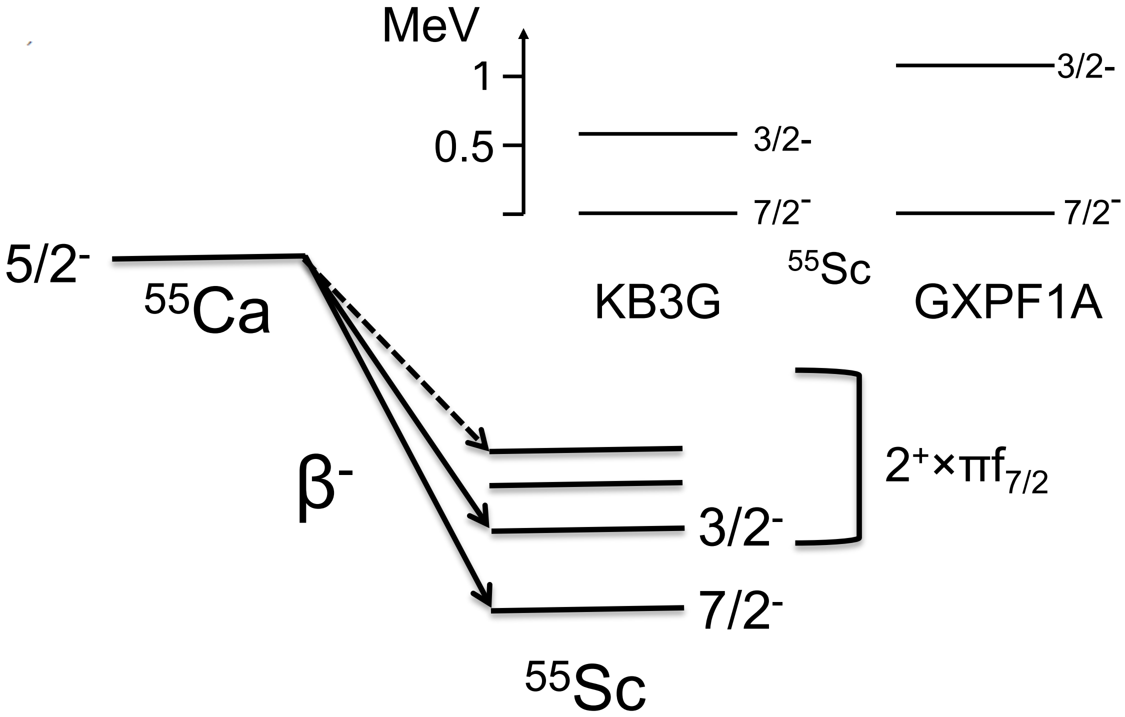


FIG. 3. The γ-ray spectrum in the range 50 to 1600 keV correlated with β-decay events for (a) ^{53}Ca, (b) ^{54}Ca, (c) ^{55}Ca, and (d) ^{56}Ca. Observed transitions are marked by their energy in keV.



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

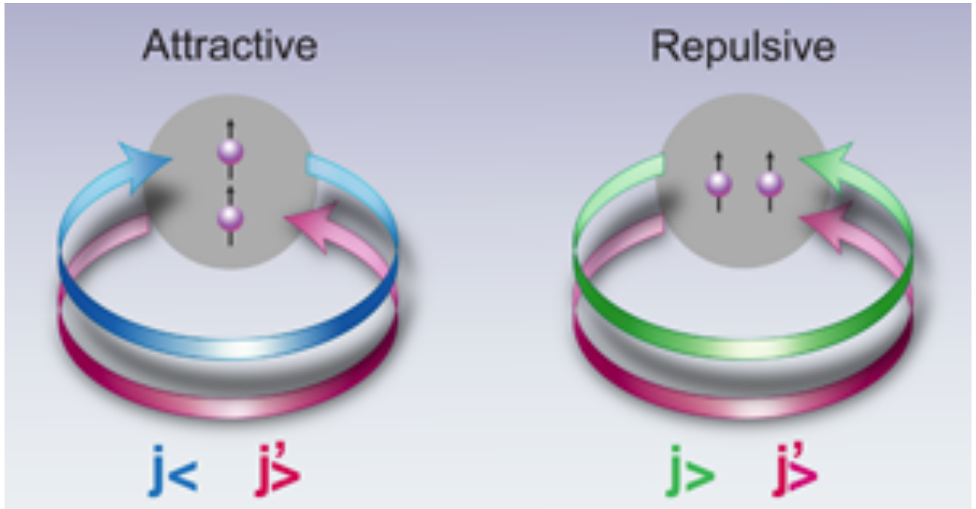
- Beam ^{86}Kr - 30pnA - 345MeV/nucleon
- Setting ^{55}Ca
- Be primary target ~2.5 g/cm^2
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- Production ~0.5pps ^{55}Ca
- 8 days → 34000 gamma if β has a ~ 100% efficiency
- Complementary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

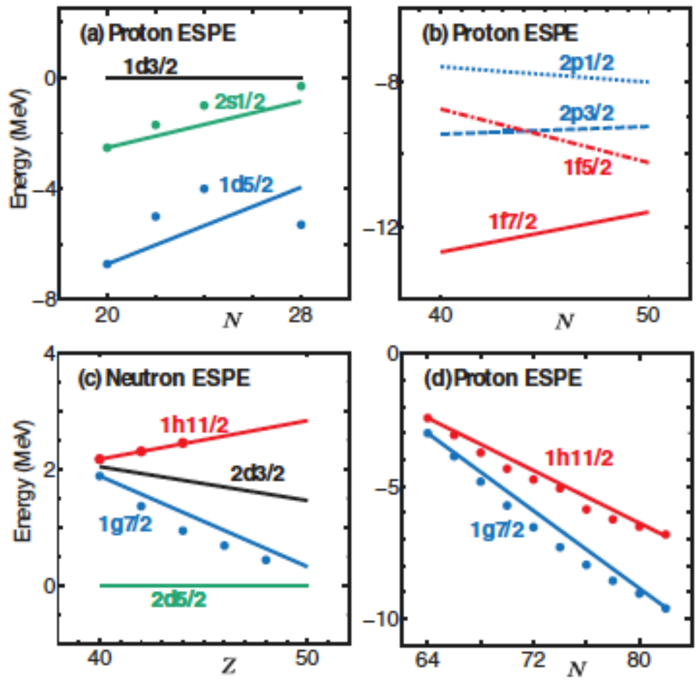
β delayed γ-ray spectroscopy: $^{75,77}Ni \rightarrow ^{75,77}Cu$

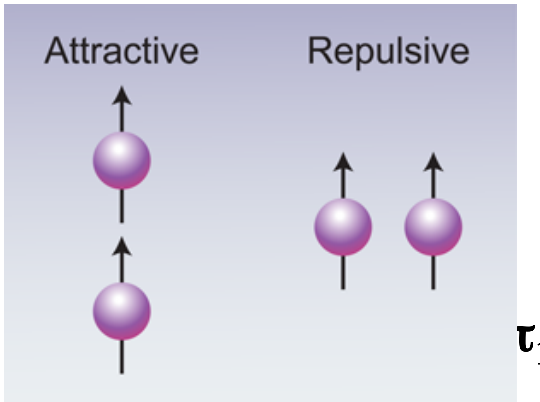
Spokepersons: E. Sahin, V. Modamio, …

Tensor interaction

Systematic variation of effective single-particle energies due to the tensor interaction





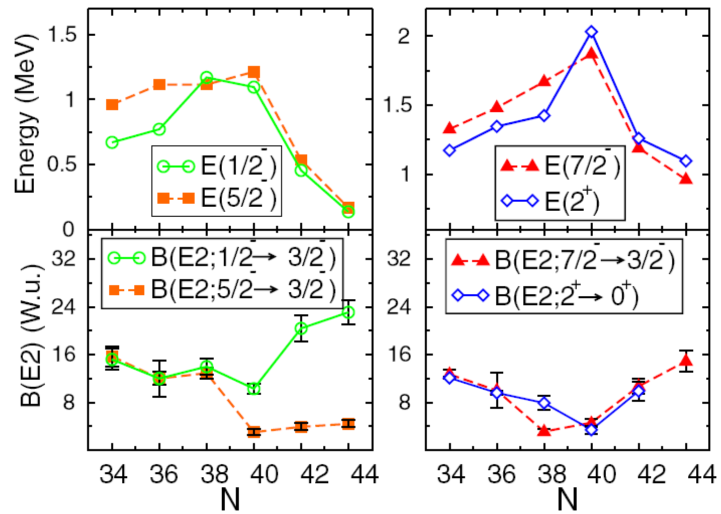


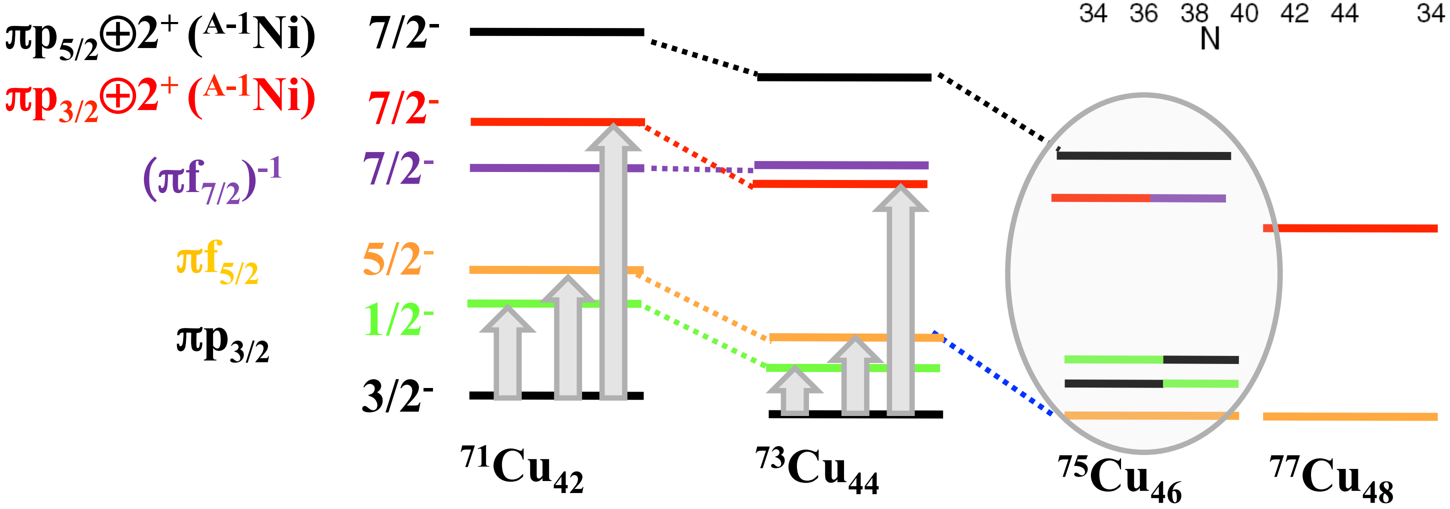
$\tau_1\tau_2)$ $([\sigma_1\sigma_2]^{(2)}\, Y^{(2)}(\Omega))\, Z(r)$

T. Otsuka et al. PRL 95, 232502 (2005)

Cu isotopes, Z=29

Magnetic moment measurement confirmed the inversion of the $f_{5/2}$ with the $p_{3/2}$ in ^{75}Cu

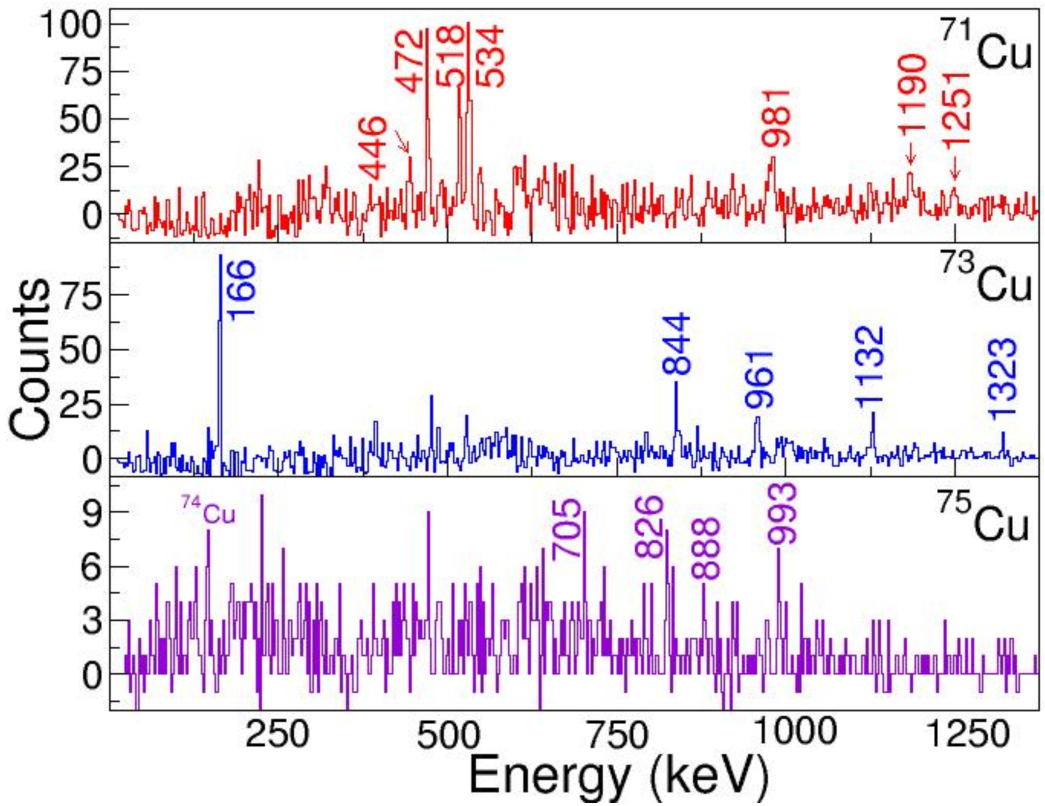


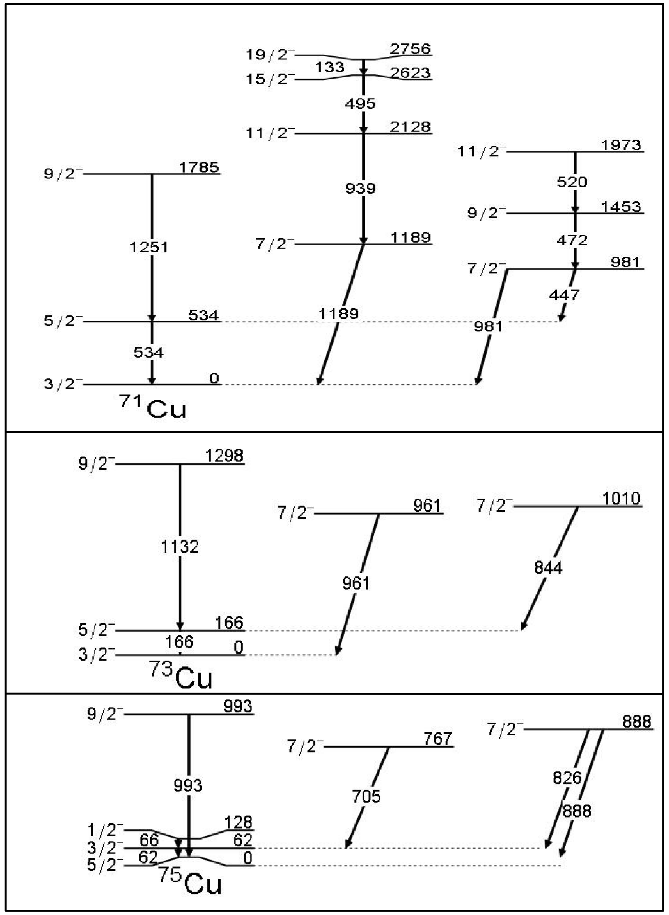


S. Franchoo et al., PRL 81, 3100(1998), I. Stefanescu *et al.,* PRL 100, 112502 (2008) , K. Flanagan PRL, 103, 142501 (2009), J. M. Daugas PRC 81, 034304 (2010)

Study of $^{71,73,75}Cu$ at CLARA+PRISMA

$^{82}Se + ^{238}U$ @ 515 MeV CLARA-PRISMA $\Theta_{PRISMA}=64^{\circ}$

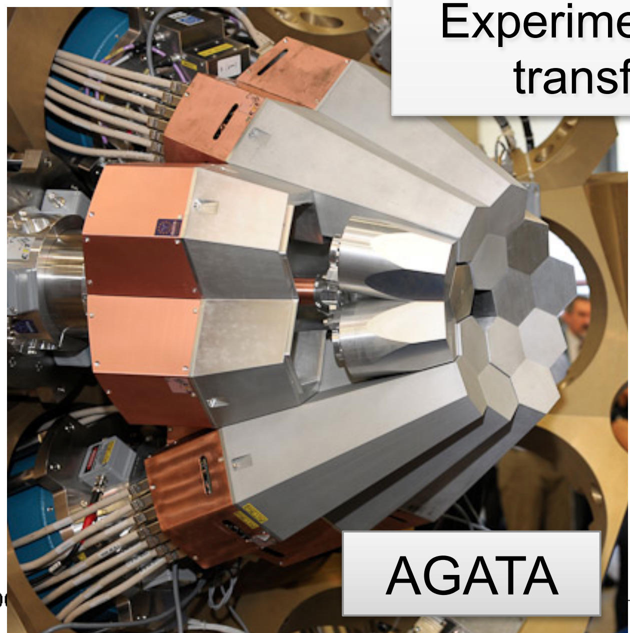




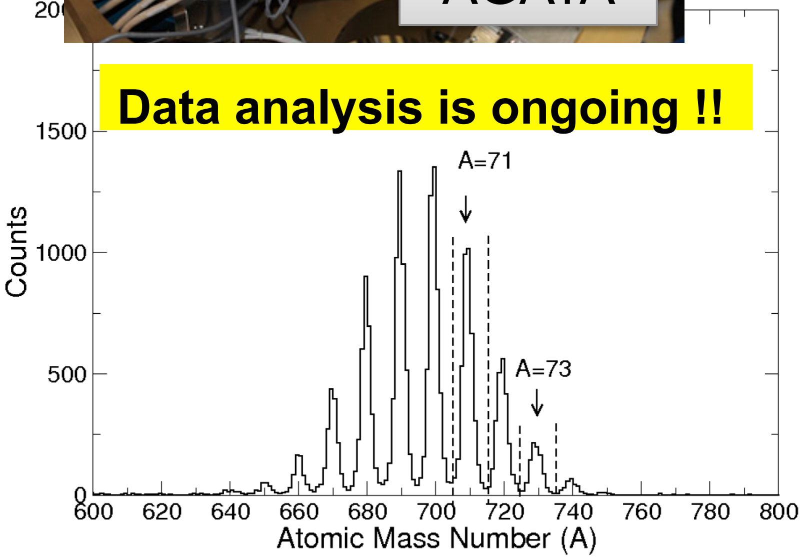
States involving the $\pi f_{7/2}^{-1}$ might allow to have a hint on the Z=28 shell gap.

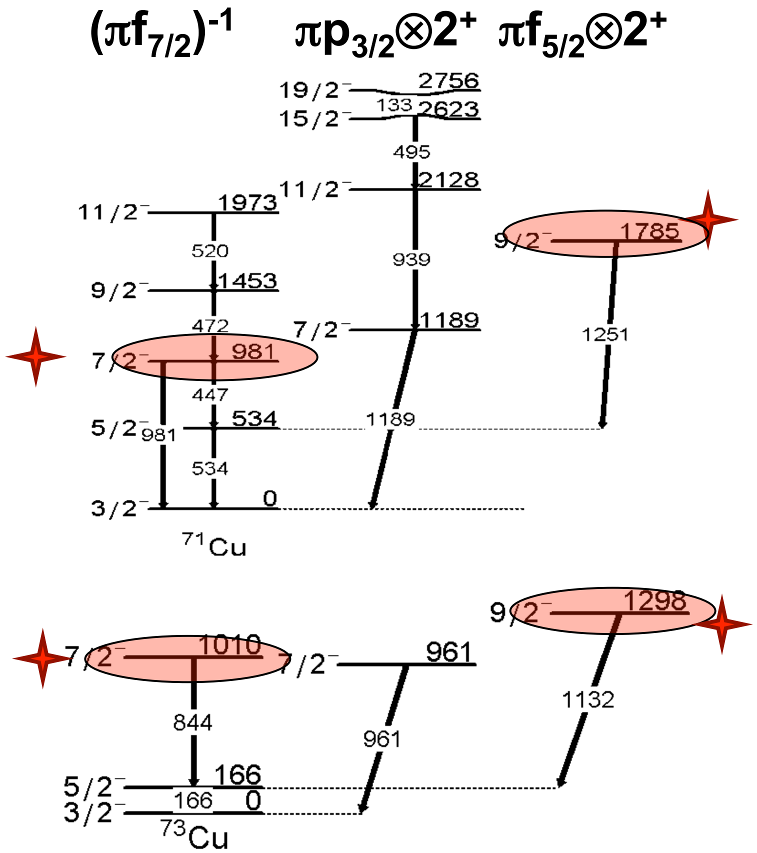
AGATA demonstrator + PRISMA

Experiment Performed in middle June 2010 Multi-nucleon transfer reaction: $^{76}Ge + ^{238}U$ @ $E(^{76}Ge)=577$ MeV



Data analysis is ongoing !!

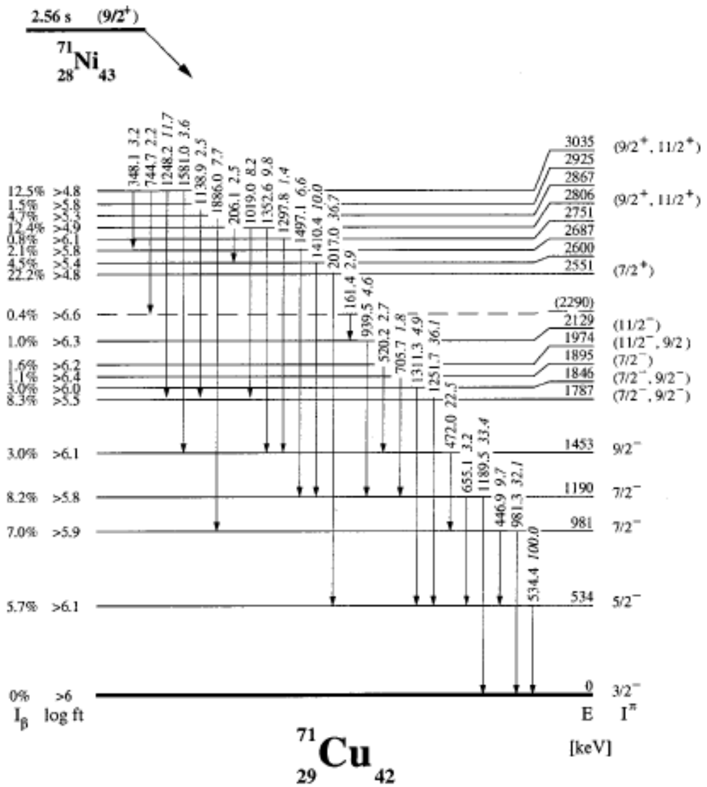




: **Levels to measure lifetimes!**

Beyond ^{73}Cu - ^{75,77}Cu with β decay

Proton induced fission ^{238}U Louvain-la-Neuve



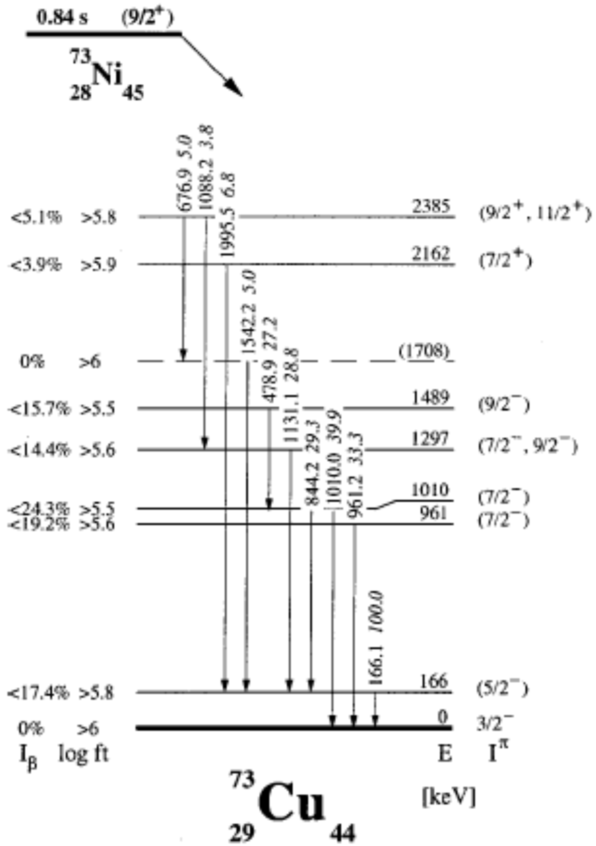


FIG. 8. Decay scheme of ^{73}Ni. For discussion, see text.

S. Franchoo et al PRC64, 054308 (2001)

Possible beam time request

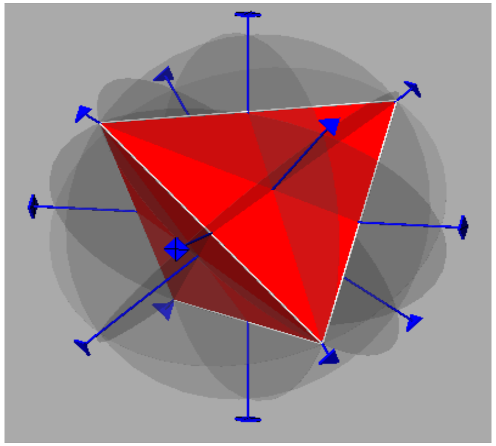
- Beam ^{86}Kr - 30pnA - 345MeV/nucleon
- Setting ^{77}Ni
- Be primary target ~2 g/cm^2
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- N(^{75}Ni)= 1.0 pps
- N(^{77}Ni)= 0.5 pps
- 8 days ^{75}Ni → 68000 gamma if β has a ~ 100% efficiency
- 8 days ^{77}Ni → 34000 gamma if β has a ~ 100% efficiency

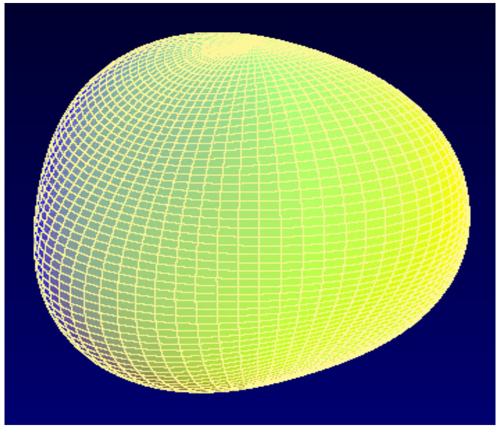
Isomer spectroscopy: ^{110}Zr

Spokeperson: G. de Angelis, J. Dudek, D. Curien, 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

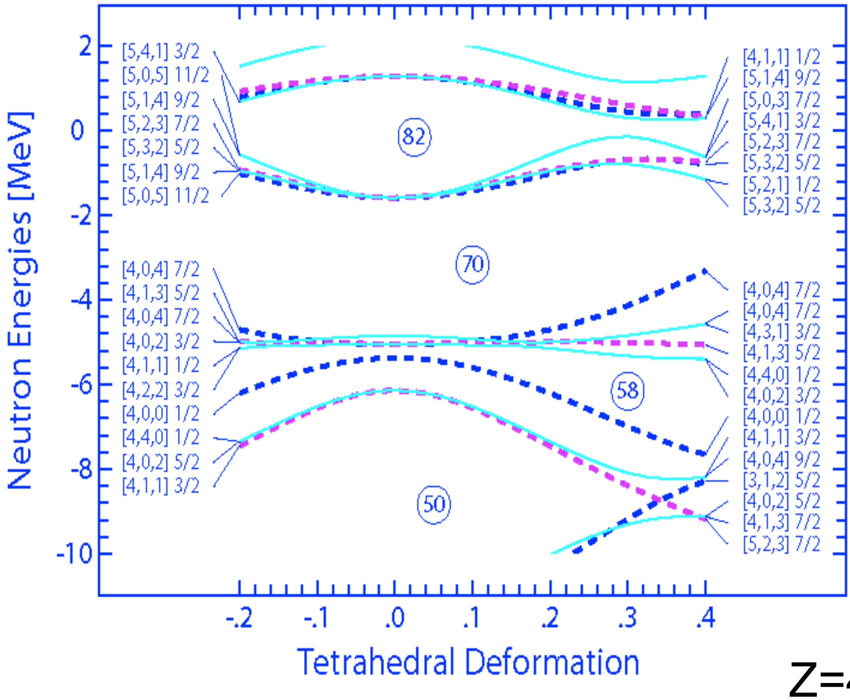
$$R(\theta,\varphi) = \sum_{\lambda,\mu} \alpha_{\lambda\mu} Y_{\lambda\mu}$$

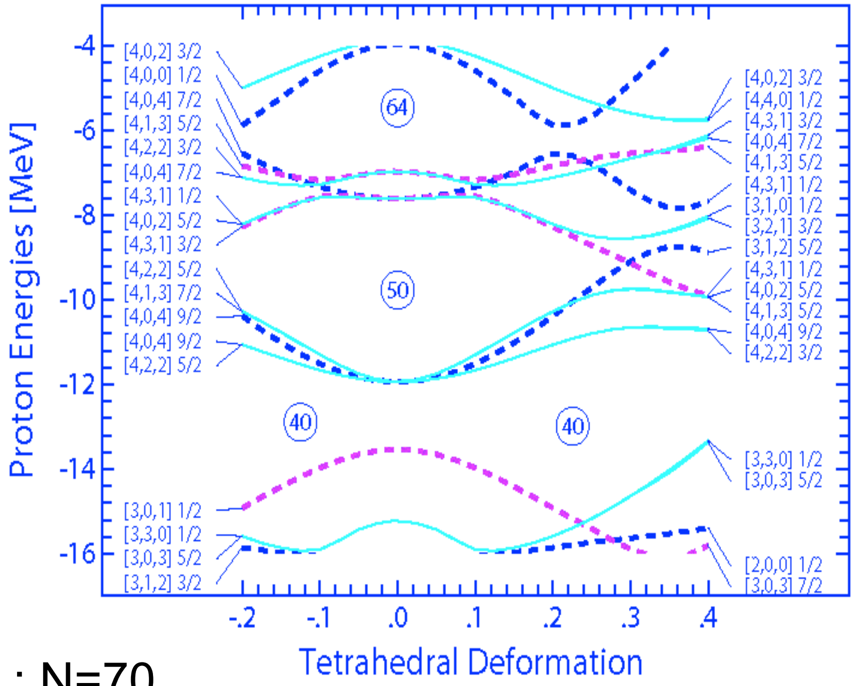
A tetrahedral deformation is a kind of non-axial octupole shape: $\boldsymbol{\alpha_{32}}$

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

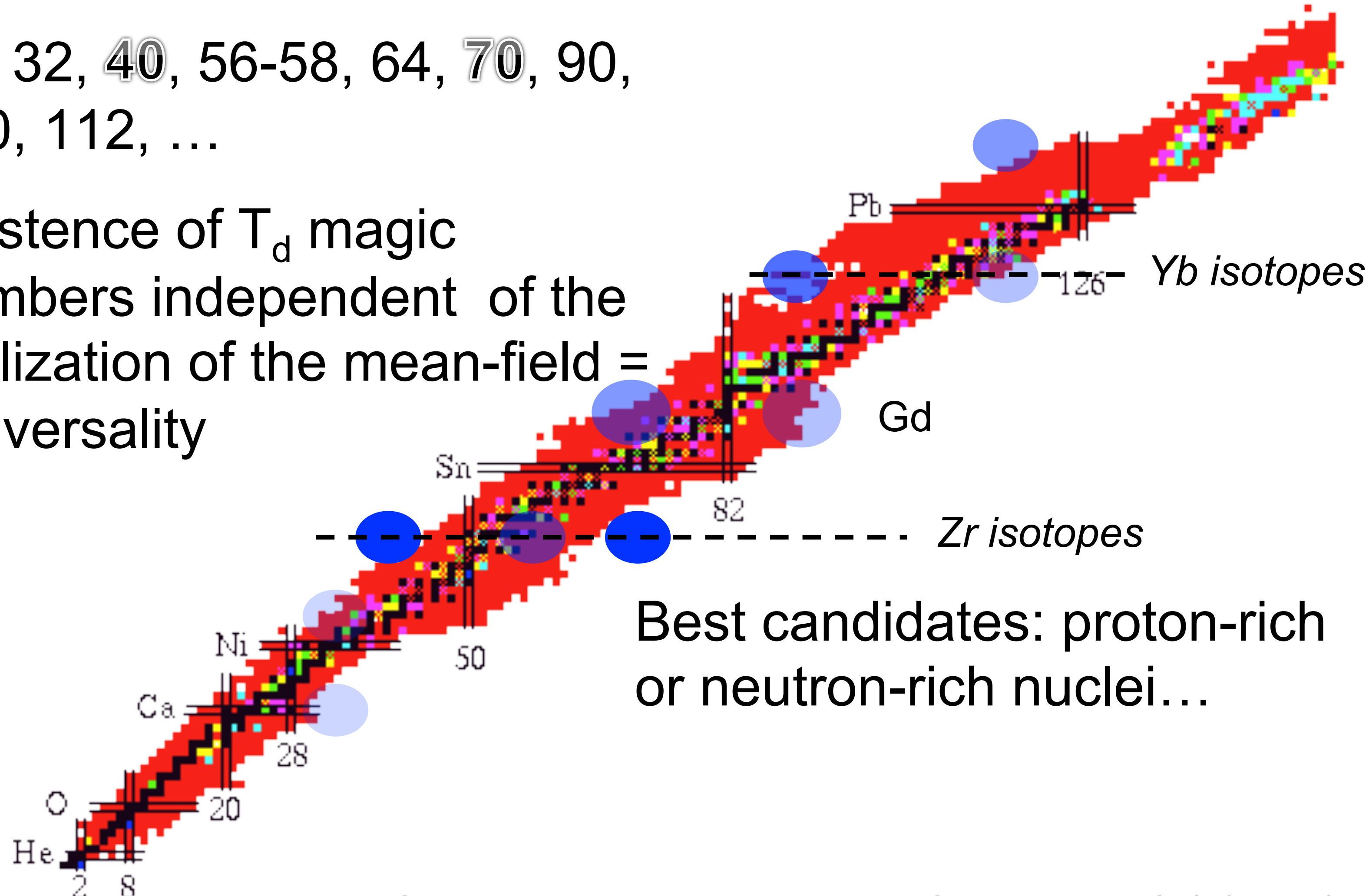
N. Schunck et al., PRC69 061305(R) 2004

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

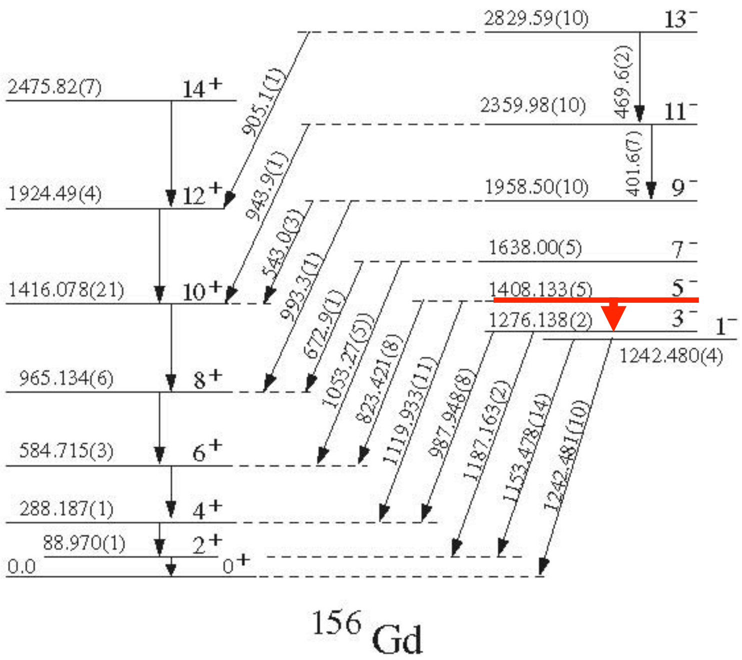
Ultrahigh-Resolution γ-Ray Spectroscopy of ^{156}Gd: A Test of Tetrahedral Symmetry

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*
[2]*Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland*
[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*
[6]*Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*

(Received 26 February 2010; published 4 June 2010)

PRL 104, 222502 (2010) PHYSICAL

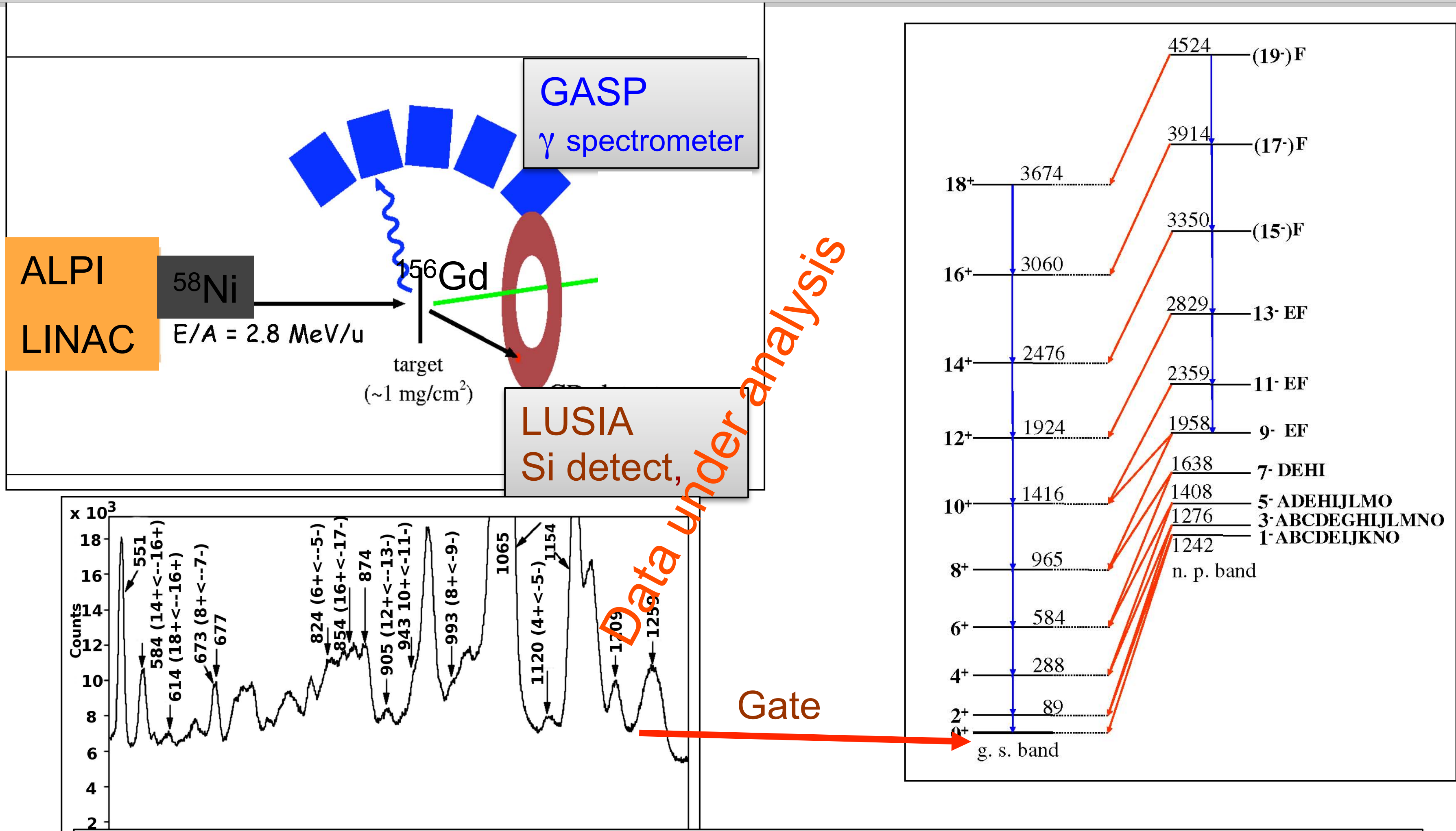


Highly accurate measurement with a Bragg spectrometer and the GRID technique.

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

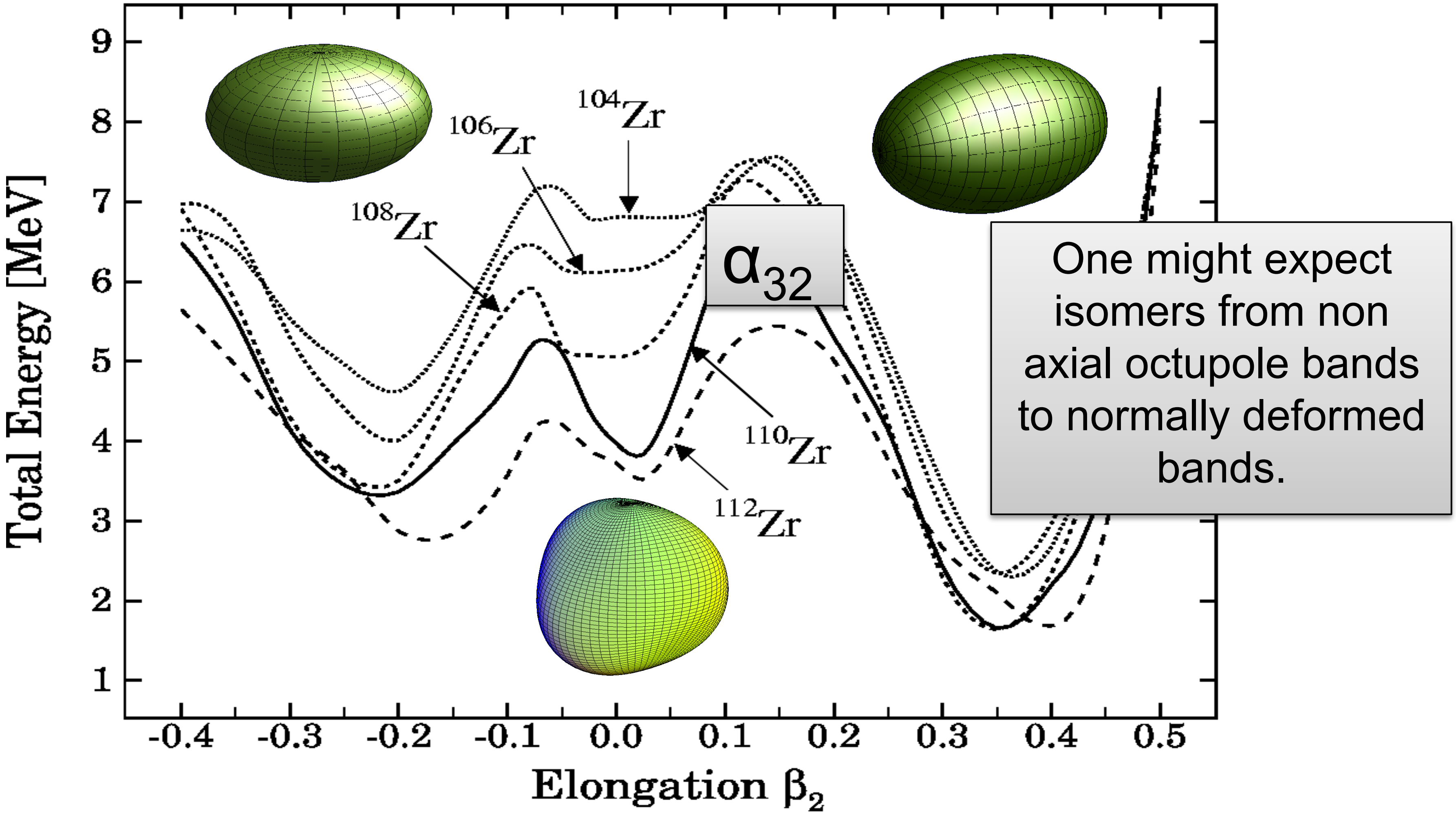
The measurend lifetime gives an intrinsic Q_0=7.104(35)b is obtained → Large quadrupole collectivity. Therefore the negative parity band incompatible with a tetrahedral symmetry

Coulex to access Tetahedral shapes



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

^{110}Zr, shape isomers



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

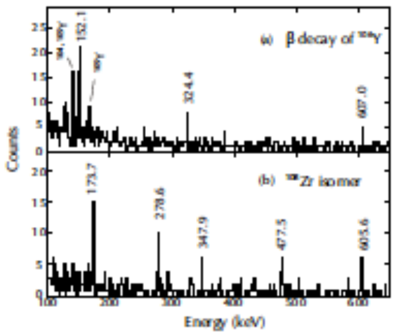


FIG. 1. Gamma-ray spectra measured (a) in coincidence with β rays detected within 200 ms after implantation of ^{106}Y and (b) with a particle gate on ^{108}Zr within 4 μs. Peaks marked with the nucleus name indicate ones measured also in coincidence with the β decay of its nucleus.

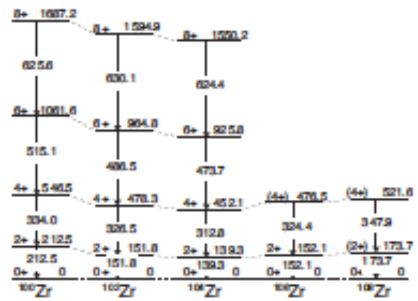


FIG. 2. Ground-state bands of neutron-rich even-even Zr isotopes with $N \geq 60$. The energies of $^{100-104}$Zr are taken from the ENSDF database [23].

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

Possible beam time request

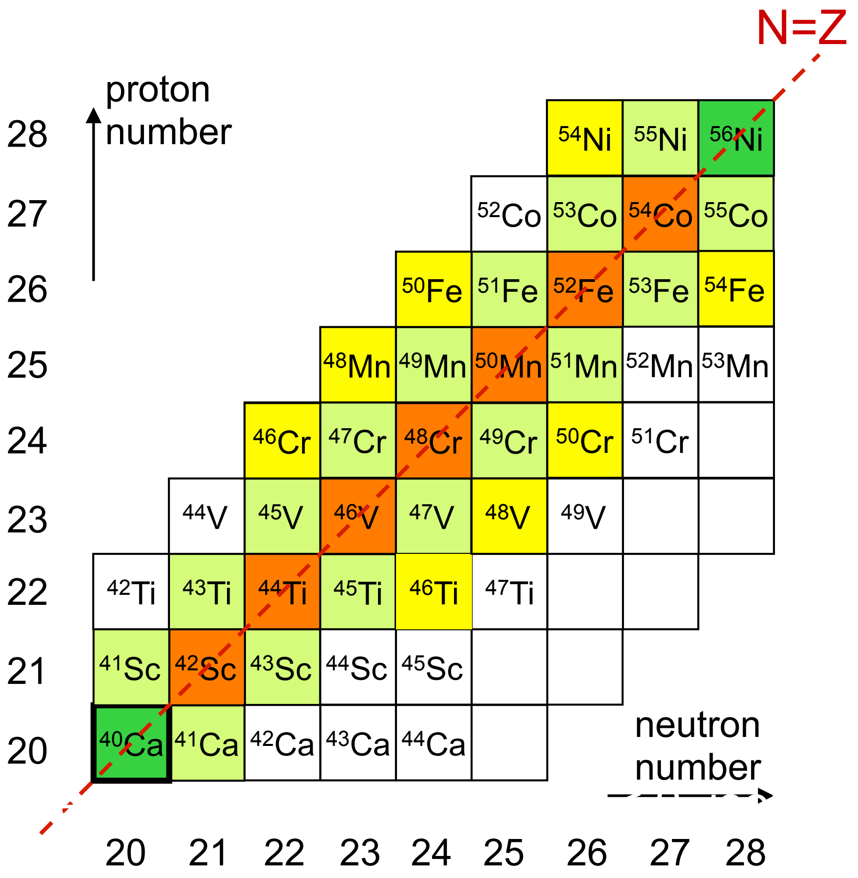
- Beam ^{238}U – 5pnA - 345MeV/nucleon
- Setting ^{110}Zr
- Be primary target ~1 g/cm^2
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- Production ~7pps ^{110}Zr
- Isomeric ratio ~10%
- 8 days → 5 10^4 gamma

Isomer spectroscopy: ^{71}Kr

Spokepersons: F. Recchia, G. de Angelis, …

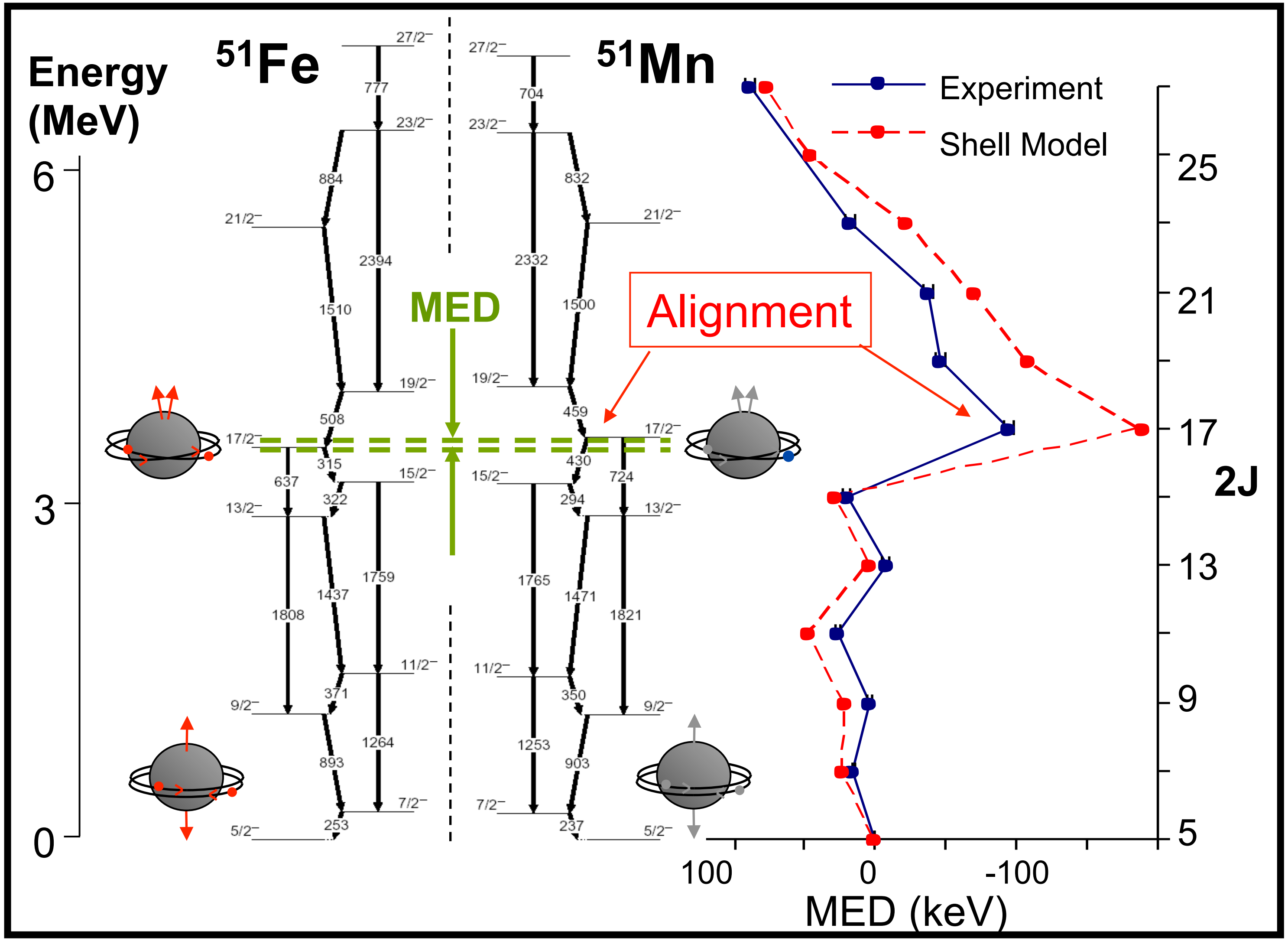
The isospin symmetry in the $f_{7/2}$

- Isospin symmetry manifest better along the N=Z nuclei
- Coulomb Energy Differences CED, difference in excitation energies between isobaric analog states.



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

Isospin symmetry in collective structures



D.D. Warner et al., Nature Physics 2 (2006) 311

Beyond the $f_{7/2}$ shell: ^{67}As – ^{67}Se

PRL 103, 052501 (2009) PHYSICAL REVIEW LETTERS week ending 31 JULY 2009

Coherent Contributions to Isospin Mixing in the Mirror Pair ^{67}As and ^{67}Se

R. Orlandi,[1,*] G. de Angelis,[1] P. G. Bizzeti,[2] S. Lunardi,[3] A. Gadea,[1,†] A. M. Bizzeti-Sona,[2] A. Bracco,[4] F. Brandolini,[3] M. P. Carpenter,[5] C.J. Chiara,[6,∥] F. Della Vedova,[1] E. Farnea,[3] J.P. Greene,[5] S.M. Lenzi,[3] S. Leoni,[4] C.J. Lister,[5] N. Mărginean,[3,‡] D. Mengoni,[3] D.R. Napoli,[1] B. S. Nara Singh,[7] O.L. Pechenaya,[6,§] F. Recchia,[1] W. Reviol,[6] E. Sahin,[1] D.G. Sarantites,[6] D. Seweryniak,[5] D. Tonev,[8] C. A. Ur,[3] J.J. Valiente-Dobón,[1] R. Wadsworth,[7] . Wiedemann,[9] and S. Zhu[5]

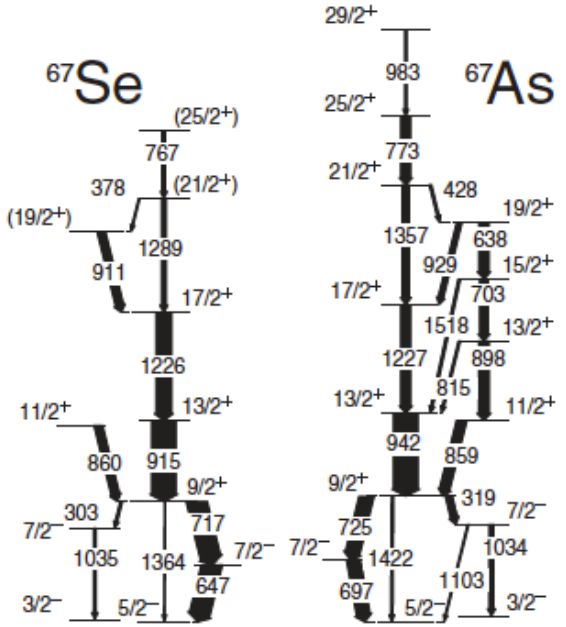


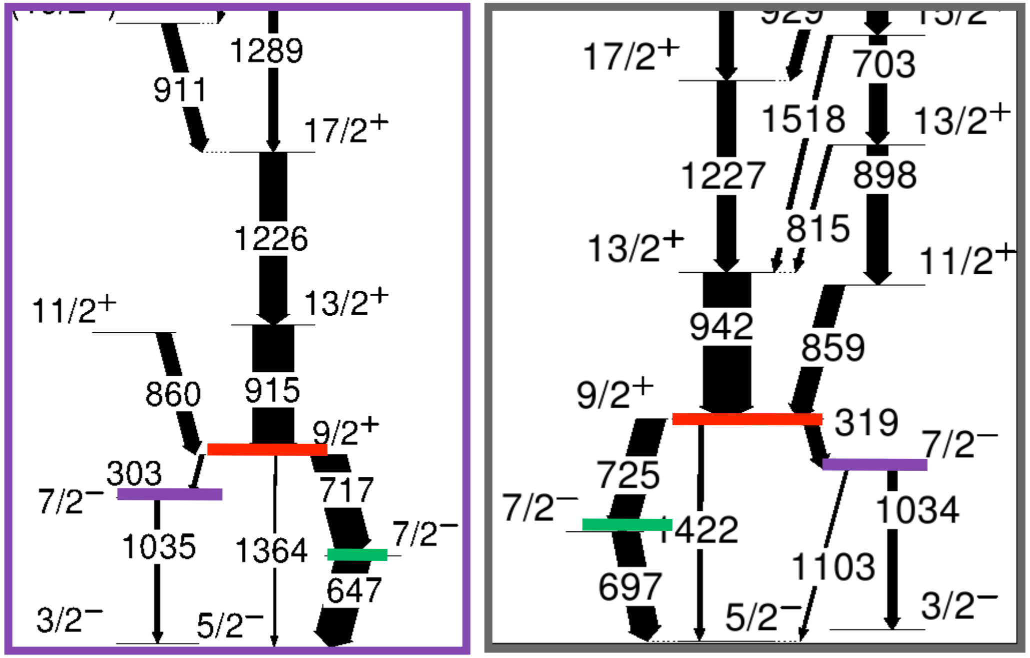
FIG. 1. Proposed partial level schemes for (left) ^{67}Se [16] and (right) ^{67}As determined from the present data. The energy labels are given in keV and the widths of the arrows are proportional to the relative intensities of the γ rays. Spin and parity assignments in ^{67}Se are based on symmetry considerations and on the measured ADO ratios (see text).

If isospin is conserved, the E1 transitions in mirror nuclei should have the same strength.

R. Orlandi et al., PRL103, 052501 (2009)

Measured B(E1)

^{67}Se ^{67}As



- Two pairs of $9/2^+ \rightarrow 7/2^-$ analogue transitions
- To determine B(E1)
  - branching ratios
  - lifetime of 9/2+ state
  - multipolarities and mixing ratios

Energy (KeV)	B(E1) (10^{-6} wu)	B(E1) (10^{-6} wu)	Energy (KeV)
717	0.4(4)	1.4(4)	725
303	<1.4(9)	8.3(2.4)	319

The B(E1) isoscalar/isovector

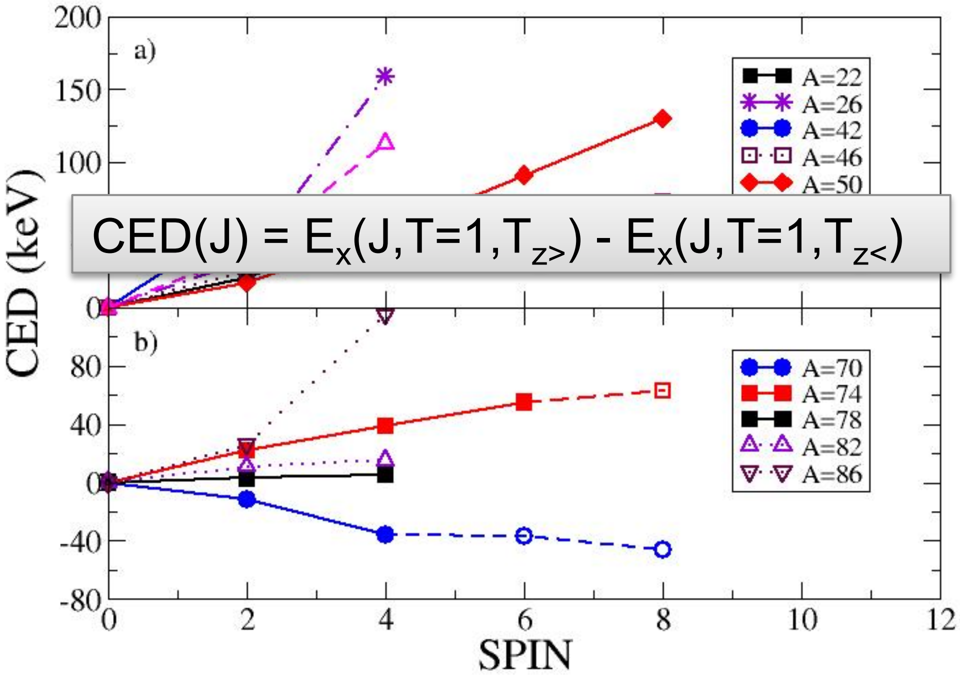
Both transitions consistent with large isoscalar/isovector ratio: IS/IV~ 0.35(20)

$$B(E1)\left(T_z = \pm \tfrac{1}{2}\right) \approx \left\langle J_f; T_f\, T_z \left\| \mathrm{M}(E1)_{IS} \pm \mathrm{M}(E1)_{IV} \right\| J_i; T_i\, T_z \right\rangle^2$$

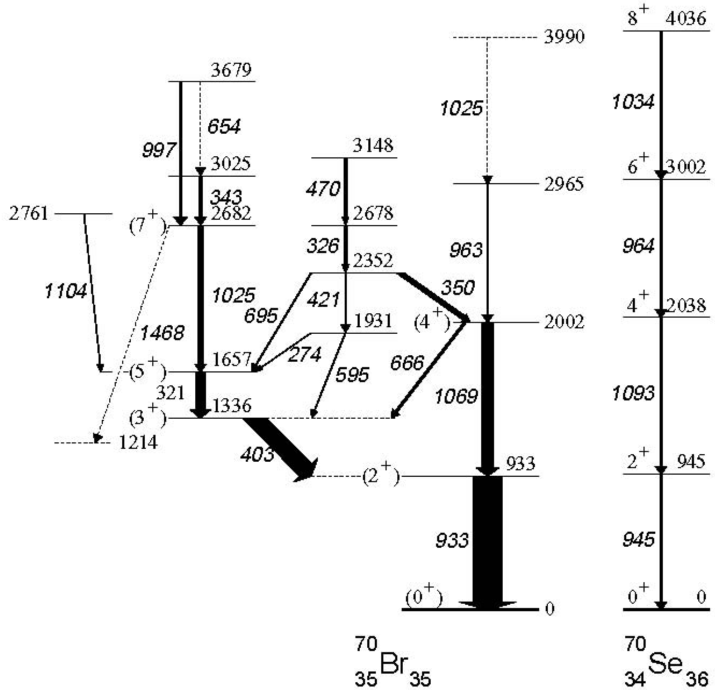
- Selection Rules for charge-symmetric nuclear interaction
  - E1 pure isovector (but different sign in mirror nuclei)
  - E1 transitions in $T_z = ½$ nuclei should exhibit same strength
- If differences, may arise from interference between IV and non-zero IS term
  - 10^{-4} in IS/IV for the neglected terms in the long-wave approximation
  - Coulomb mixing with close lying $7/2^-$ levels
  - Mixing via Isovector Giant Monopole Resonance (IVGMR)

Detailed calculations in a forthcoming publication P.G Bizzeti

Shape effects in the A=70 mass



$CED(J) = E_x(J,T=1,T_{z>}) - E_x(J,T=1,T_{z<})$

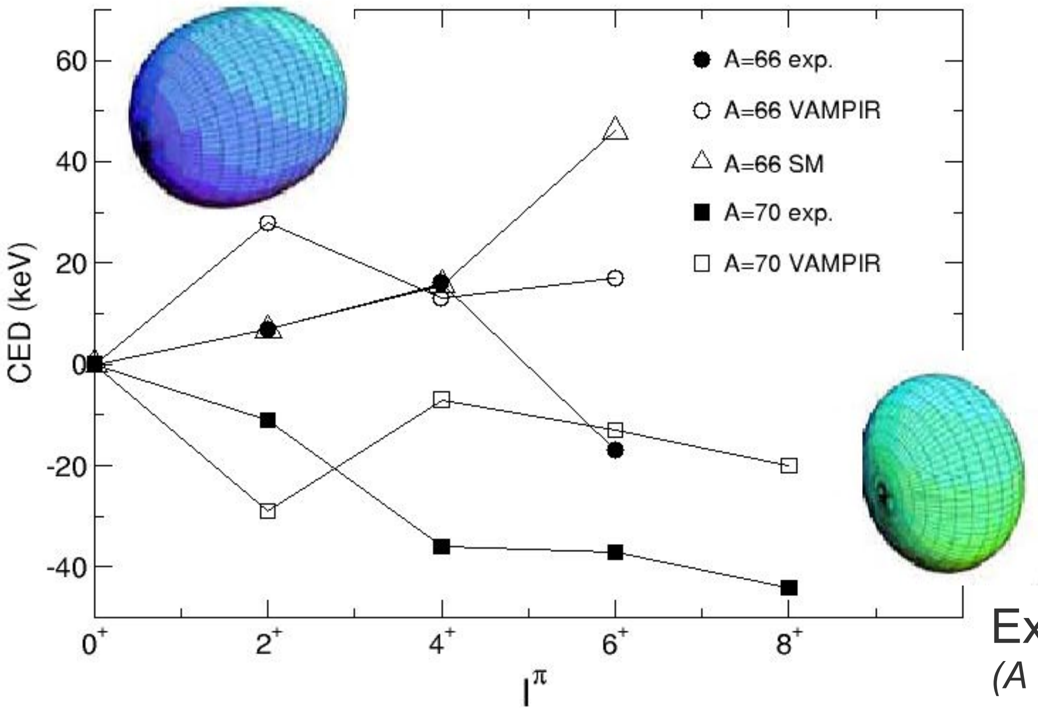


•A=70(^{70}Br/^{70}Se) – large negative CED has been explained as resulting from:

- •Prolate stretching in both nuclei (B S Nara Singh et al., PRC 75,061301(R) (2007))
- •Also speculated that it may be due to diff (obl/ prol) shapes for the two nuclei (R. Wadsworth et al., Act. Pol. B40, 611 (2009), G. de Angelis et al. PRC (R) (to be published))

G. de Angelis et al., EPJ A12, 51 (2001)
D.G. Jenkins et al., PRC 65, 064307 (2002)

Shape effects in CED



•^{70}Se is predominantly oblate GS *(J. Ljungvall et al., PRL100 102502 (2008)*

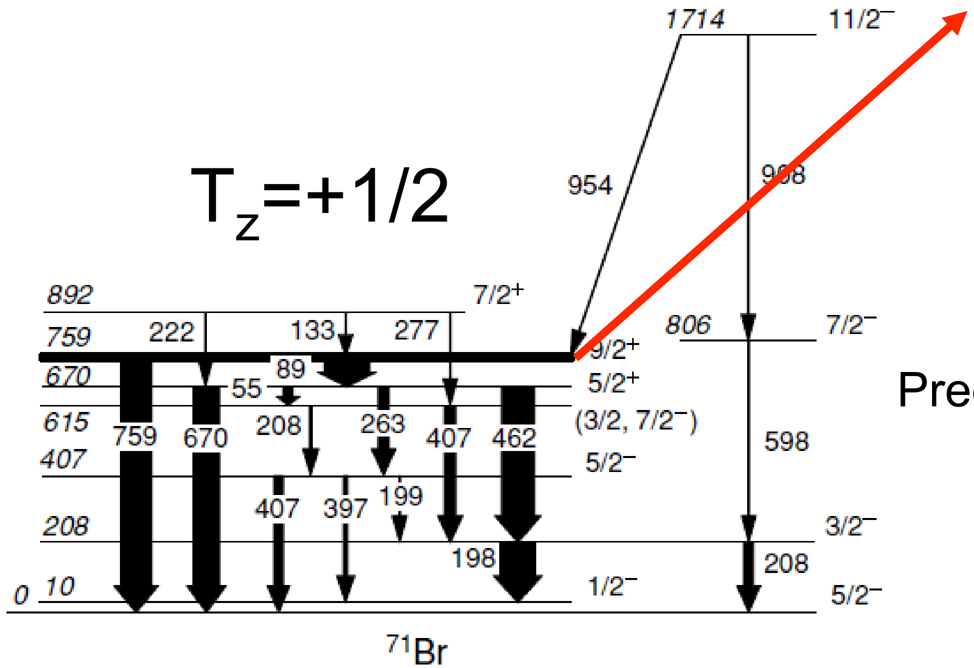
•^{70}Br is predominantly prolate GS

Excited VAMPIR Model
(A Petrovici et al NPA483, 317 (1988))

•Beyond mean-field approach with symmetry projection
•Successfully used to describe analogue states in mass 70 region, Petrovici et al., Nucl Phys A728, 396 (2003)
•Takes into account: Oblate/ prolate shape co-existence and n-p pairing correlations in both the T=0 and T=1 channels
•Calculations performed using the isospin symmetric G matrix based on Bonn A potential and Coulomb interaction between the valence protons.

Character 9/2$^+$ transition in ^{71}Kr

τ = 33ns isomer in ^{71}Br



Predicted τ ~ 100ns isomer in ^{71}Kr

• measurement of the decay branches in ^{71}Br and ^{71}Kr

S.M. Fischer et al., PRC72, 024321 (2005)

Possible beam time request

- Beam ^{78}Kr - 30pnA - 345MeV/nucleon (not in the list)
- Setting ^{71}Kr
- Be primary target 2g/cm^2
- BigRIPS fragment separator
- EURICA eff ~10%
- Nine-layer double-sided silicon-strip detector (DSSSD) PRL106, 052502 (2011)
- Production ~1500pps ^{71}Kr
- Isomeric ratio 10%
- 5 days → 3 10^5 gamma

The GALILEO project at LNL

Project manager: C.A. Ur

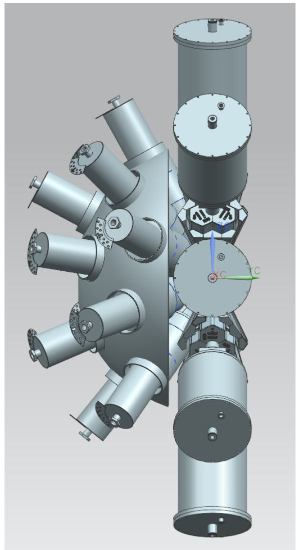
The GALILEO project

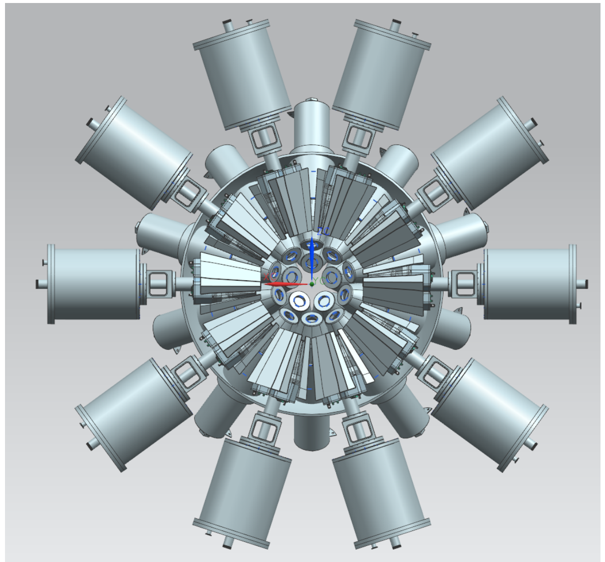
2012 after AGATA

GALILEO – a new gamma–ray array spectroscopy

- takes advantage of the developments made for AGATA
  - preamplifiers
  - digital sampling
  - preprocessing
  - DAQ

- uses the EUROBALL cluster detectors capsules
  - improved efficiency
  - development of a new cluster detector with 3 capsules





e_{ph}~8% P/T~50%

Detector configuration

- 30 GASP detectors @ 22.5cm

5	5	5	5	5	5
29^{o}	51^{o}	59^{o}	121^{o}	129^{o}	131°

- 10 triple cluster detectors @ 24 cm
  90^{o}

GALILEO physics case

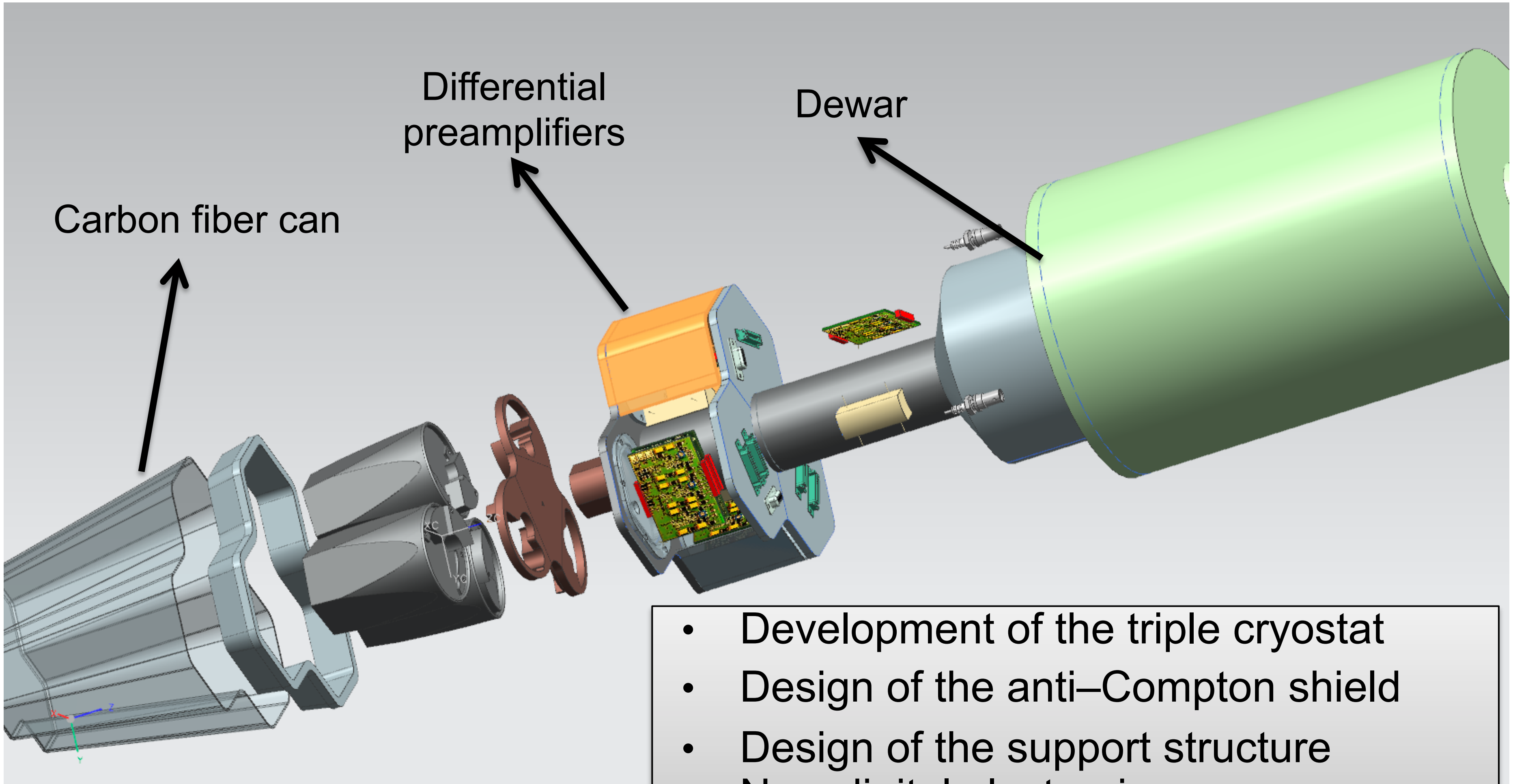
2009 – call for Letters of Intent

15 LoIs (30 institutes, 11 countries)

The proposed physics cases can be grouped in the following categories

- structure of N~Z nuclei
- isospin symmetry
- study of neutron–rich nuclei
- exotic decay of high–spin states
- nuclear structure close to ^{100}Sn
- cluster and highly deformed states in sd–shell nuclei
- giant resonances and warm rotations
- symmetries and shape–phase transitions in nuclei
- shape coexistence in neutron–deficient nuclei
- magnetic moments measurement

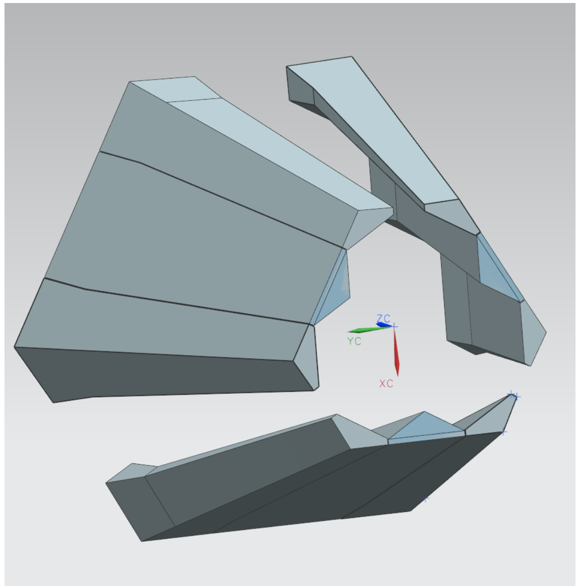
GALILEO Triple Cluster

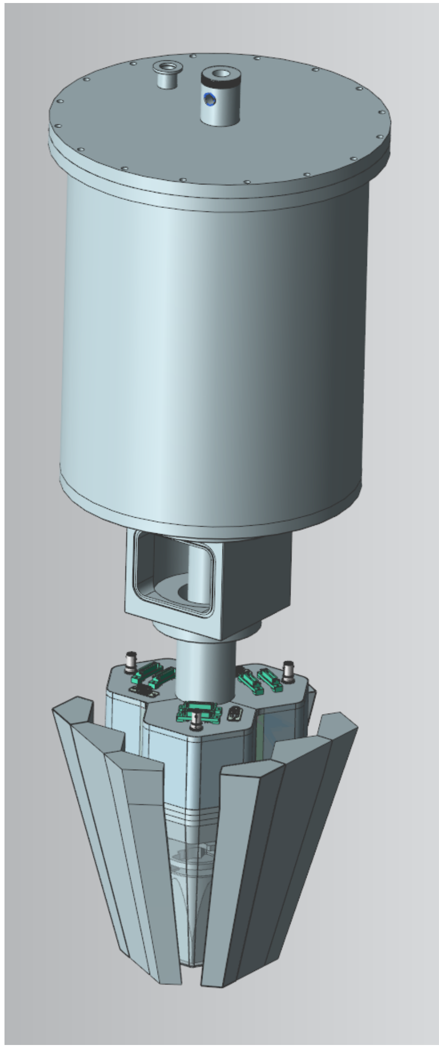


- Development of the triple cryostat
- Design of the anti–Compton shield
- Design of the support structure
- New digital electronics

R&D anti-Compton shields

Recovery from EUROBALL Anti Compton





Ancillary detectors for GALILEO

- Light charged particle detectors
  - EUCLIDES, LUSIA, TRACE
- Neutron detector
  - n–Ring, N–Wall, NEDA
- Binary reaction products detection
  - DANTE, MW-PPAC
- Recoil detectors
  - RFD
- High–energy gamma–rays detector
  - HECTOR
- Fast timing
  - LaBr3 detectors
- Mass spectrometer
  - PRISMA

Study of weak reaction channels stable beams & SPES beams

- High efficiency
- High resolving power

Summary

- Proposals to study neutron-rich nuclei
  - Address the N=34 subshell gap via β delayed γ-ray spectroscopy: ^{55}Ca → ^{55}Sc
  - Address shell evolution Z=28 nearby N=50 via β delayed γ-ray spectroscopy: ^{75,77}Ni→^{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