Nuclear Structure in the fpg Shell

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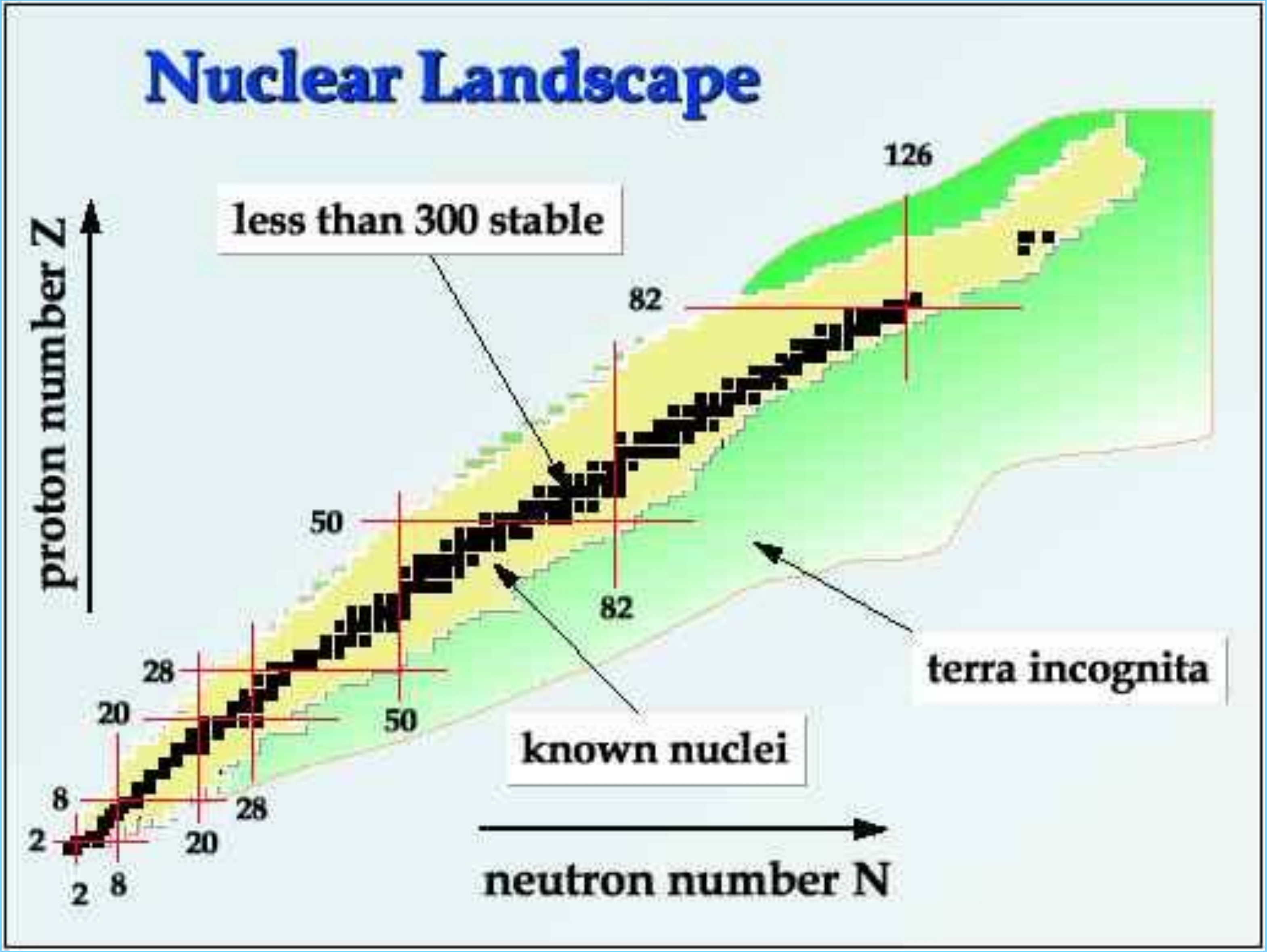


http://www.physics.fsu.edu/users/roberts/roberts_weak.html

OUTLINE

In-beam γ-ray spectroscopy

High spin states

pf shell nuclei

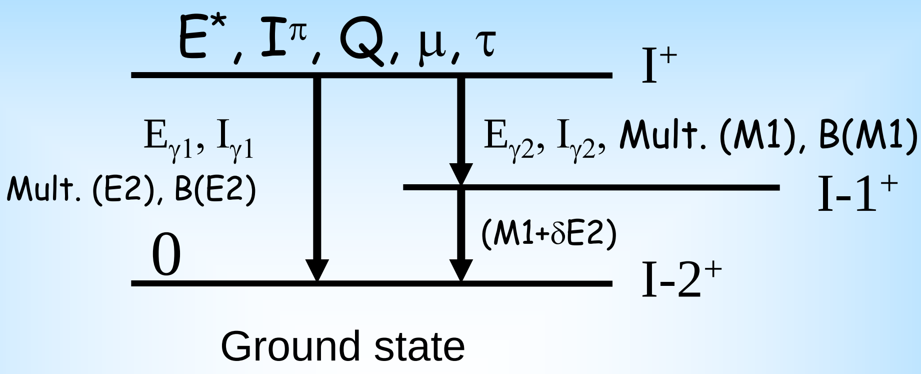
$^{46,48}V$, ^{48}Cr

fpg shell nuclei

$^{64,66,68,70}Ga$

Conclusion

In-beam γ-ray spectroscopy



Excited state properties

E^*, I^π, Q, μ, τ

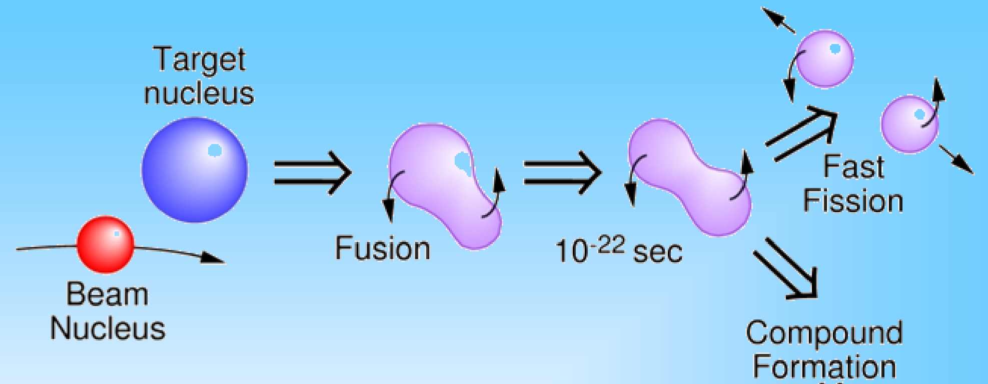
γ-ray transition properties

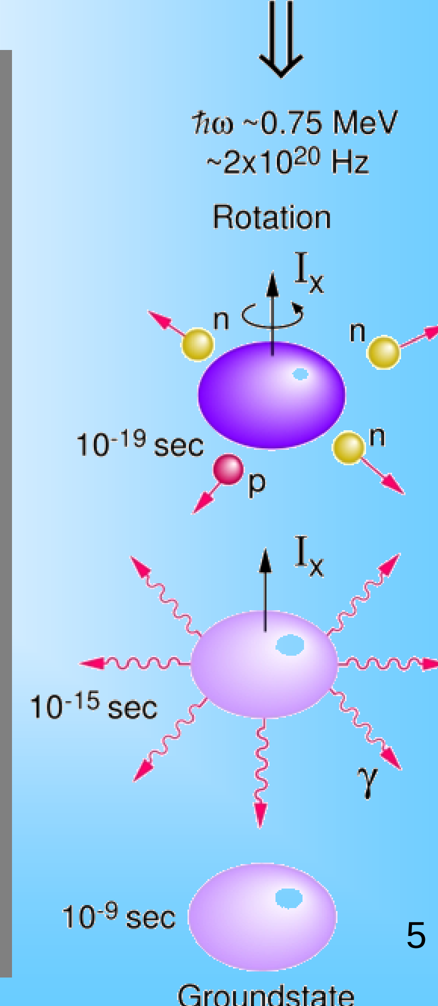
$E\gamma$, $I\gamma$, multipolarity, mixing ratios (δ)

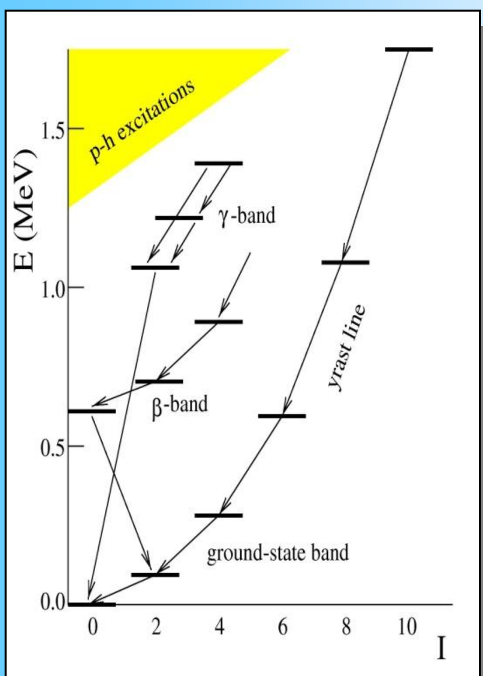
Construction of level schemes

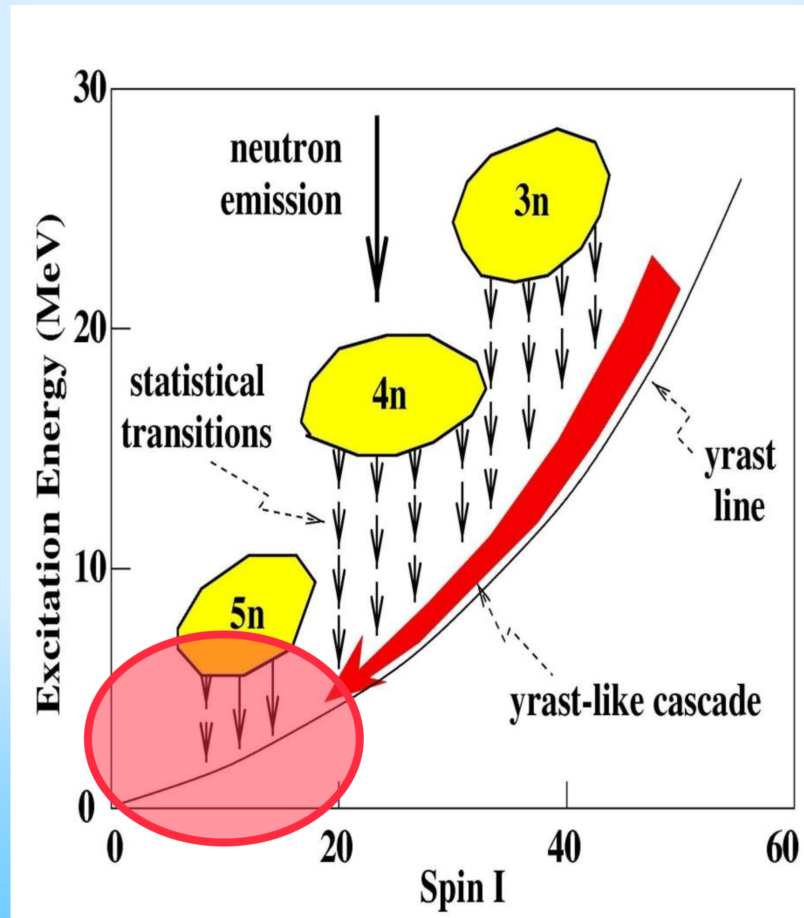
Electromagnetic properties of the excited states

Fusion-evaporation reactions





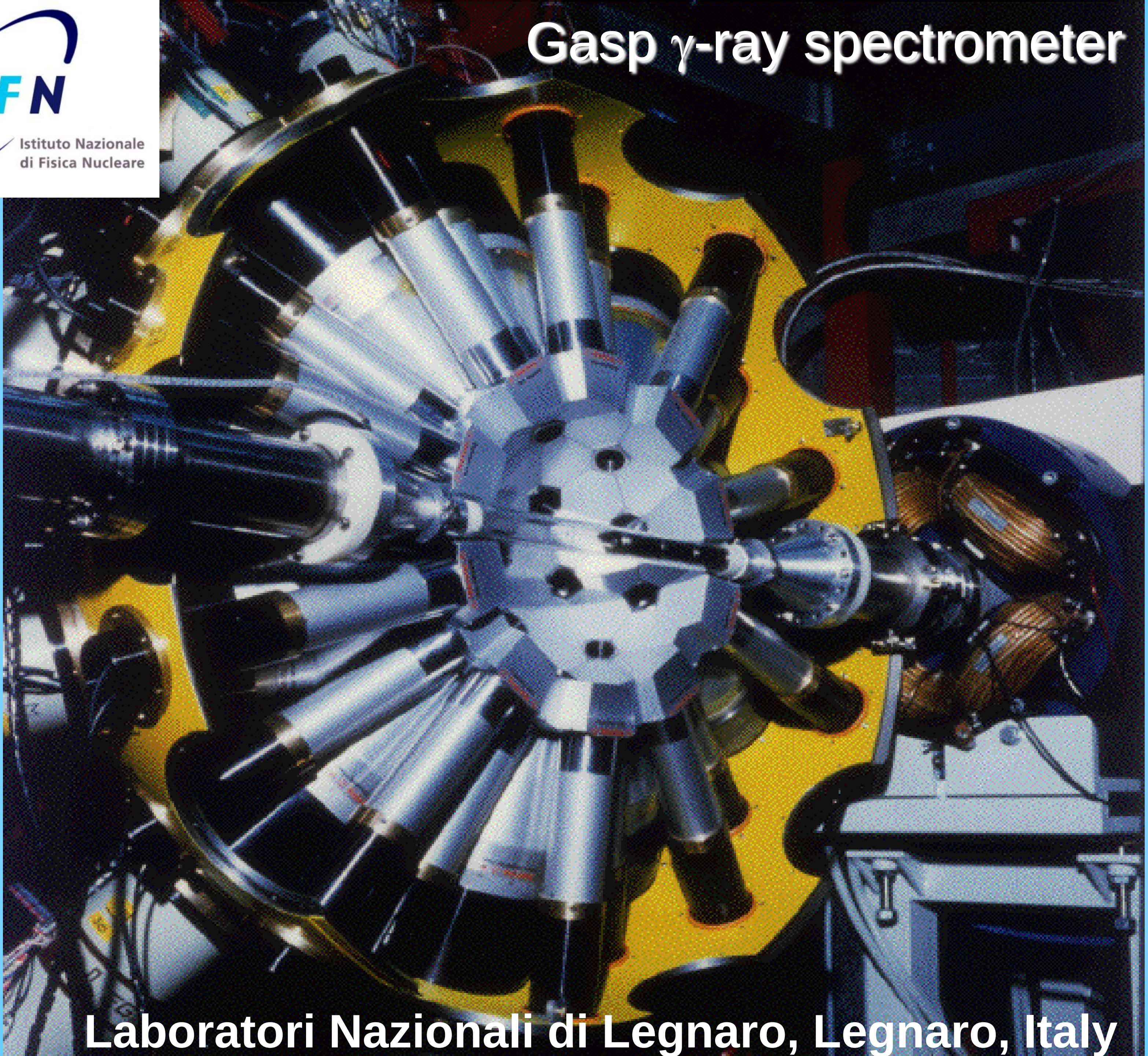




www.lbl.gov

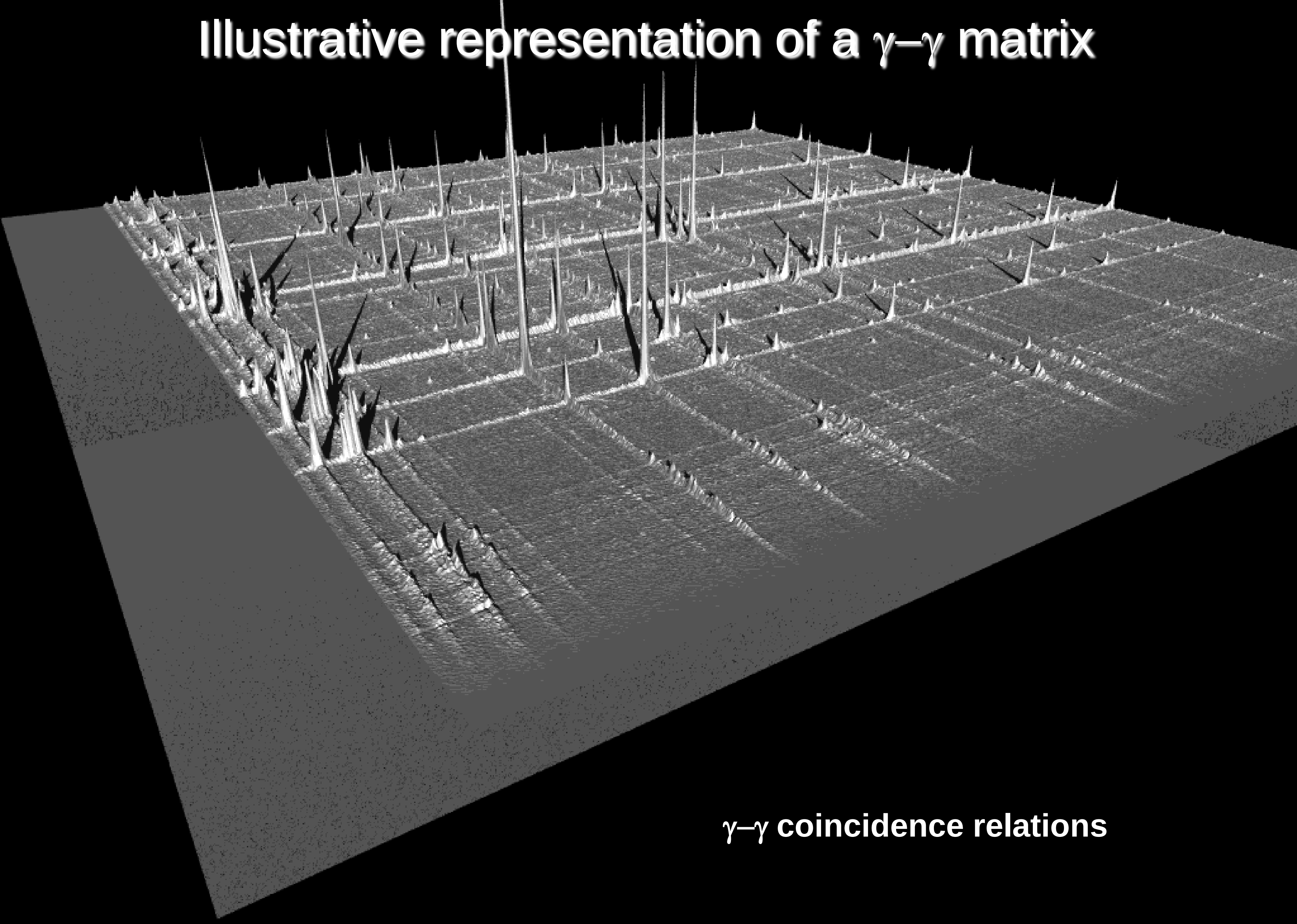
http://nucalf.physics.fsu.edu/~riley/gamma/

Gasp γ-ray spectrometer



Laboratori Nazionali di Legnaro, Legnaro, Italy

Illustrative representation of a γ–γ matrix

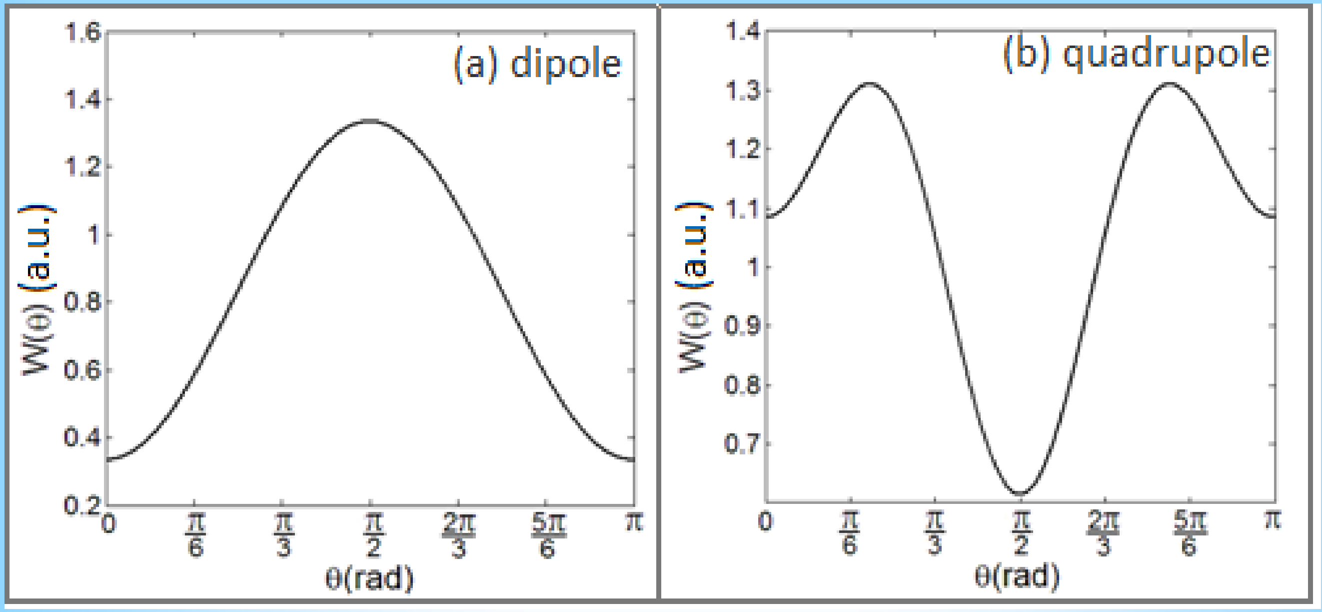


γ–γ coincidence relations

Symmetric γ–γ matrices or cubes allow level scheme construction

Excited State Angular Momentum

Assigned from γ-ray multipolarities



R_{ADO} : γ ray Angular Distribution from Oriented States

Excited states $\rightarrow$ oriented in accordance with the beam direction

Transition between 2 levels

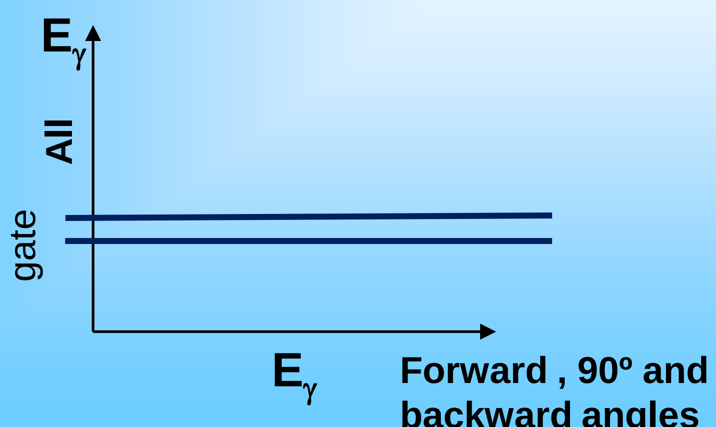
- Quadrupole $\rightarrow$ L=2
- Dipole $\rightarrow$ L=1
- Mixed multipolarities: δ values.

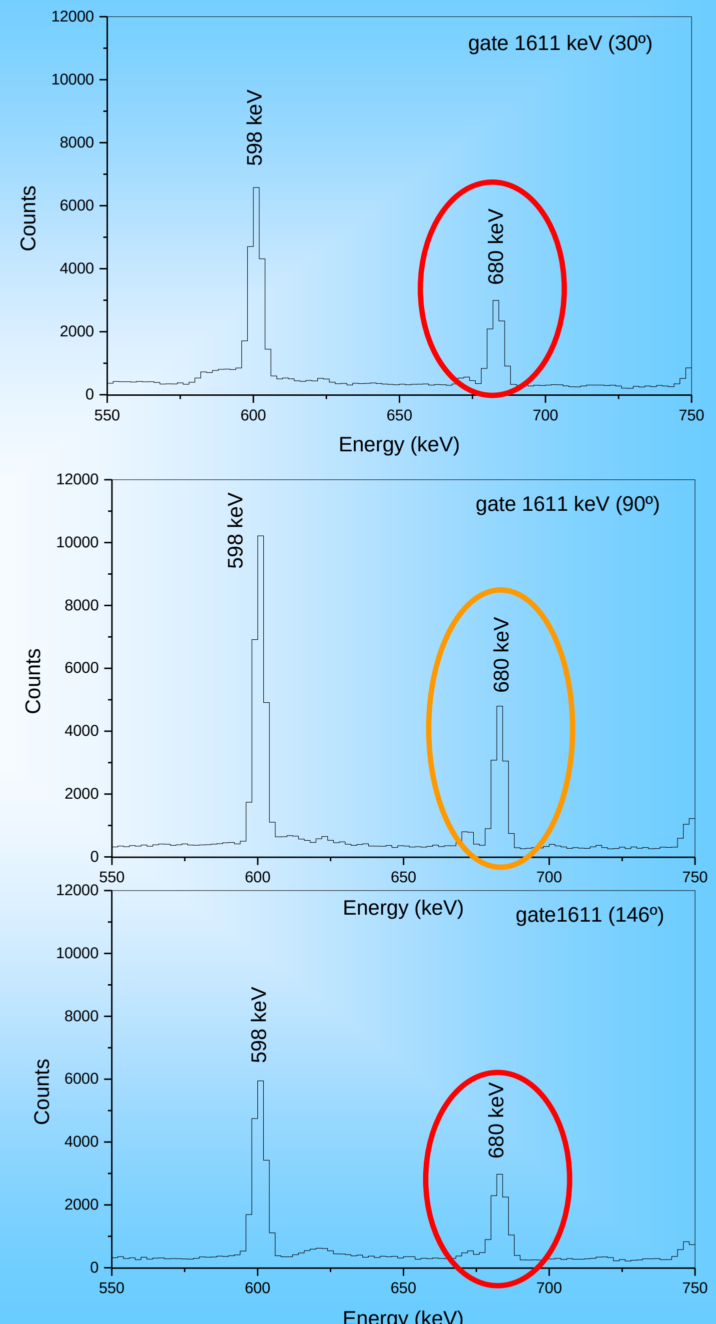
M. Ionescu-Bujor et al., Phys. Rev C, 73 (2006) 024310

R_{ADO} (angular distribution ratios), used to extract information about the γ transition multipolarities.

$$R_{ADO} = \frac{I_\gamma(34^o) \times I_\gamma(146^o)}{2.I_\gamma(90^o)}$$

Three asymmetric matrices having on the first axis the detectors in 34º, 90º and 146º and the second axis all the other detectors.





Doppler Shift Attenuation Method

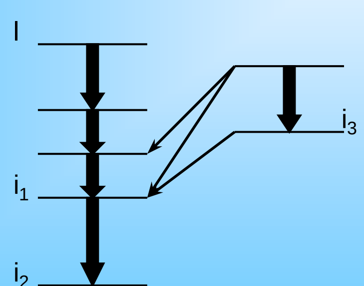
Lifetimes extracted from the lineshape fit of the gamma-rays emitted by nuclei stopping in a backing material (Au or Pb)

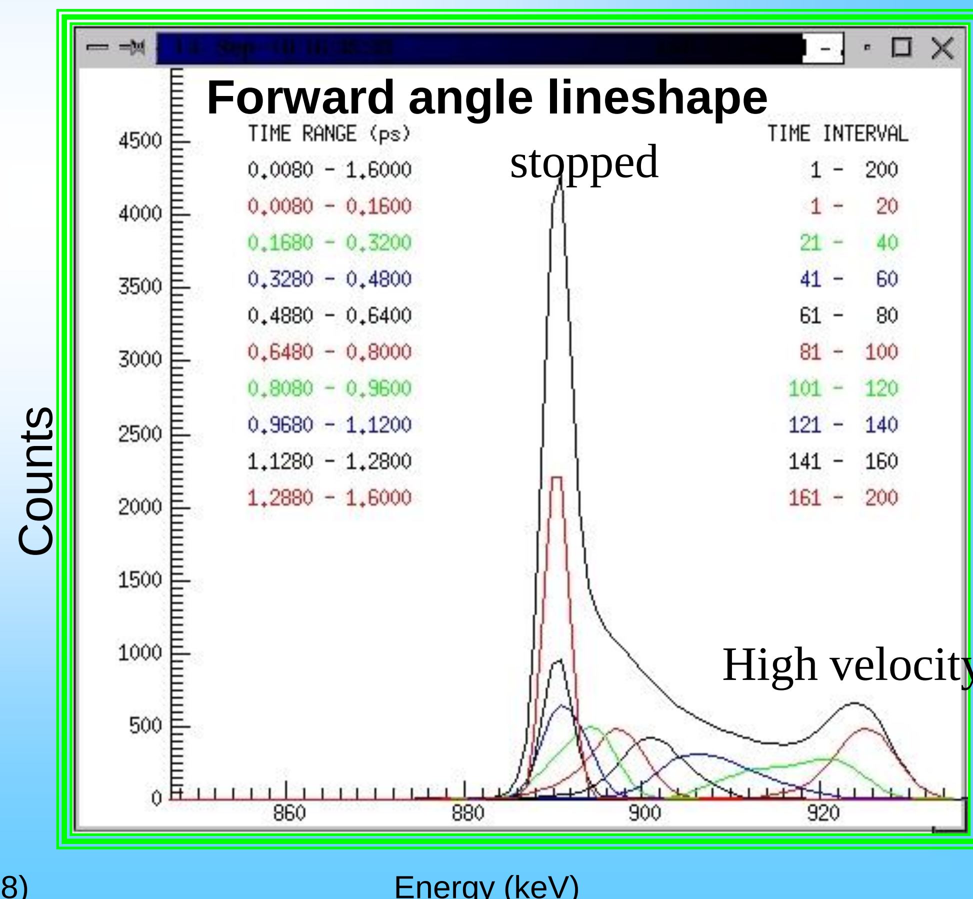
$$E_\gamma \approx E_o \left(1 + (v/c)\cos\theta\right)$$

This method uses Monte Carlo Simulation of the trajectories of the recoiling nuclei in a target using Northcliffe & Schilling stopping power parameterization

L.C. Northcliffe & R.F. Schilling, Nucl. Data Tables A 7, 233 (1970) .

- Velocity components in the direction of the γ-ray detectors
- Free parameters: τ and sidefeeding time

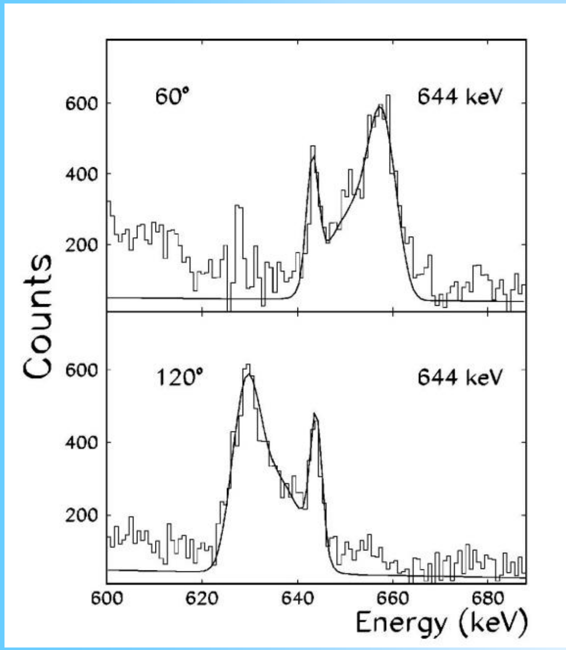




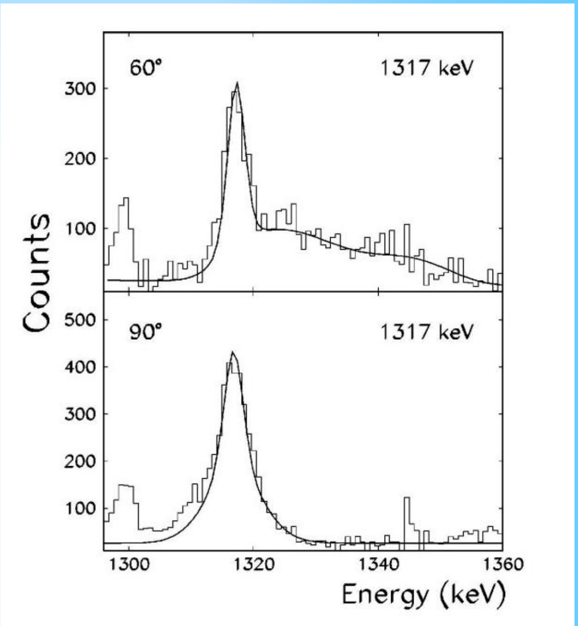
J.C. Wells & N.R. Johnson, Rep. ORNL 6689, 44 (1991)

F. Brandolini and R.V. Ribas, Nucl. Inst. Meth. A 417, 150 (1998)

Examples of γ-ray lineshape observed at 90 degrees, forward and backward angles.



Current and charge distribution are sensitive to the nuclear state wave funcition.



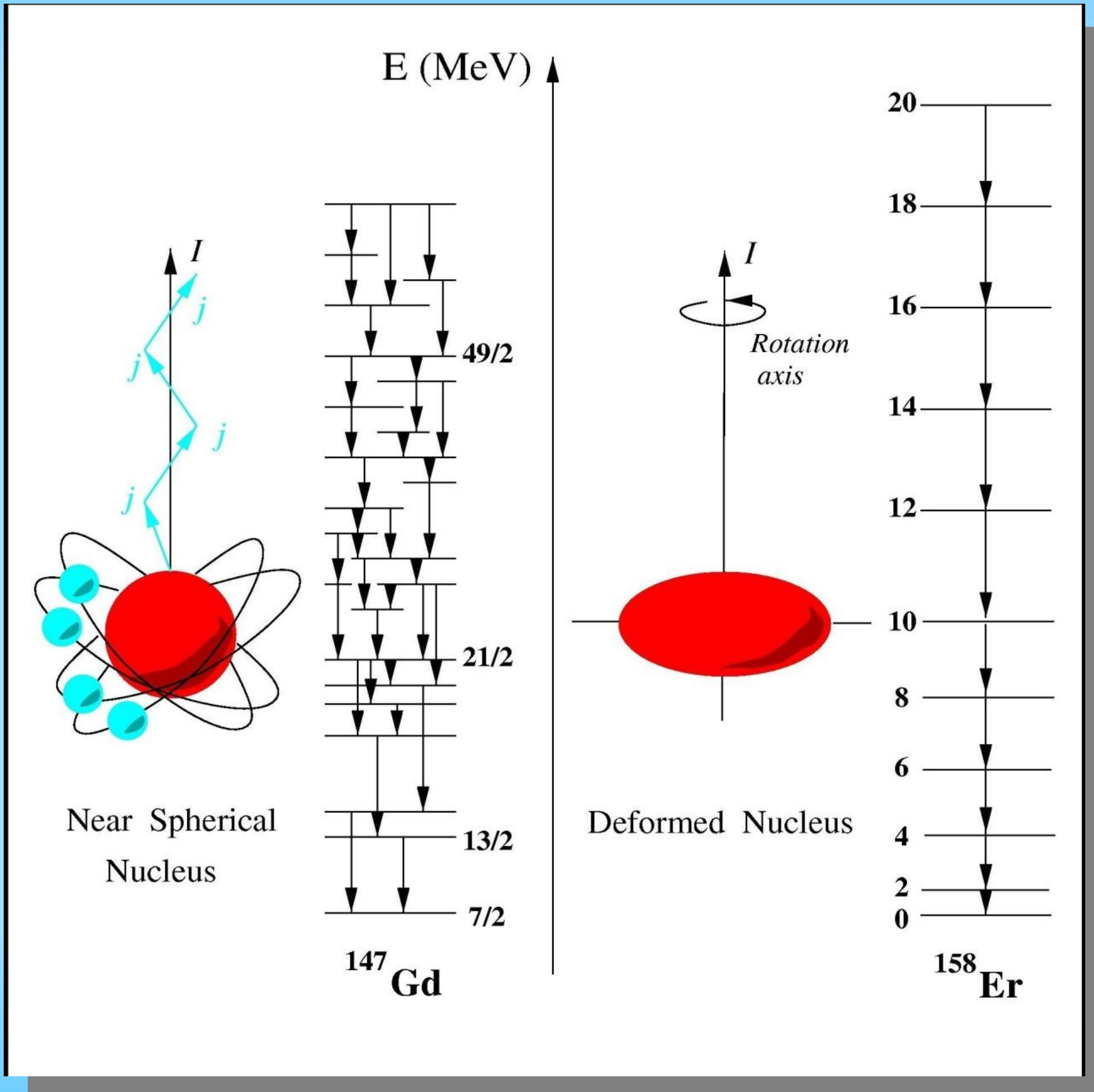
$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L((2L+1)!!)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B\left(\lambda L : I_i \to I_f\right)$$

$$B(E2) = \frac{815.6}{E_\gamma^5 \tau(1+\alpha)} B \quad e^2\, fm^4 \quad ; \quad B(M1) = \frac{0.05697}{E_\gamma^3 \tau(1+\alpha)} B \quad \mu_N^2$$

$$B(E2) = \frac{5}{16\pi} Q_0^2 \left\langle I_i K 20 \middle| I_f K \right\rangle^2$$

$$g = g_R + (g_K - g_R)\frac{K^2}{I(I+1)}$$

High spin states



http://www.phys.utk.edu/expnuclear/gammaspec.html

The Rigid Rotor

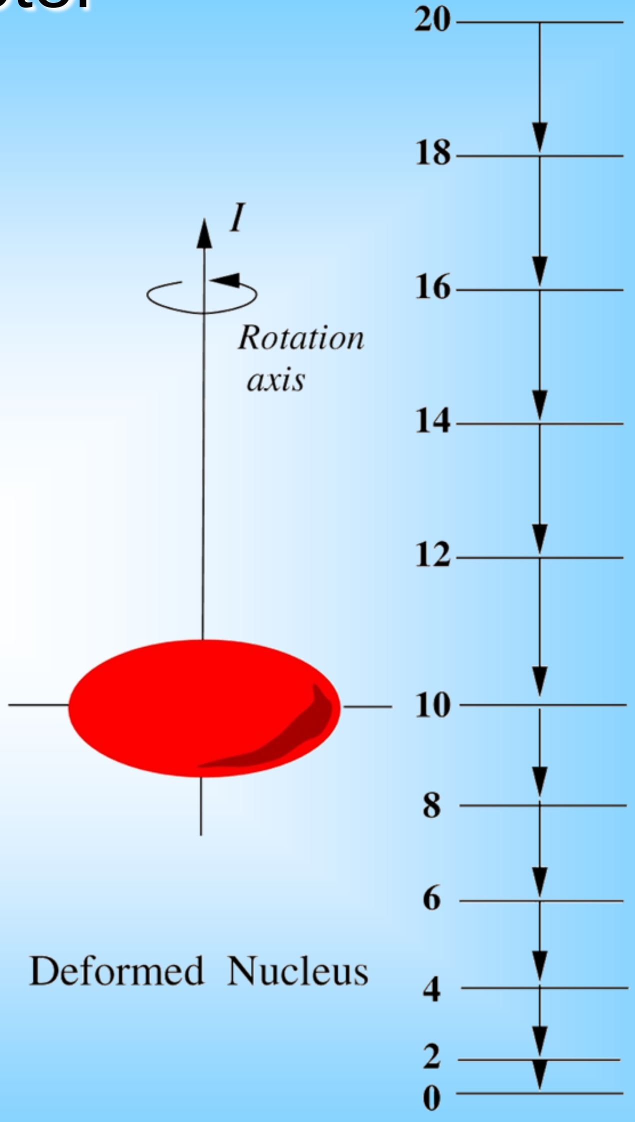
$$E = \frac{1}{2}\Im\varpi^2 \quad ; \quad I = \Im\varpi$$

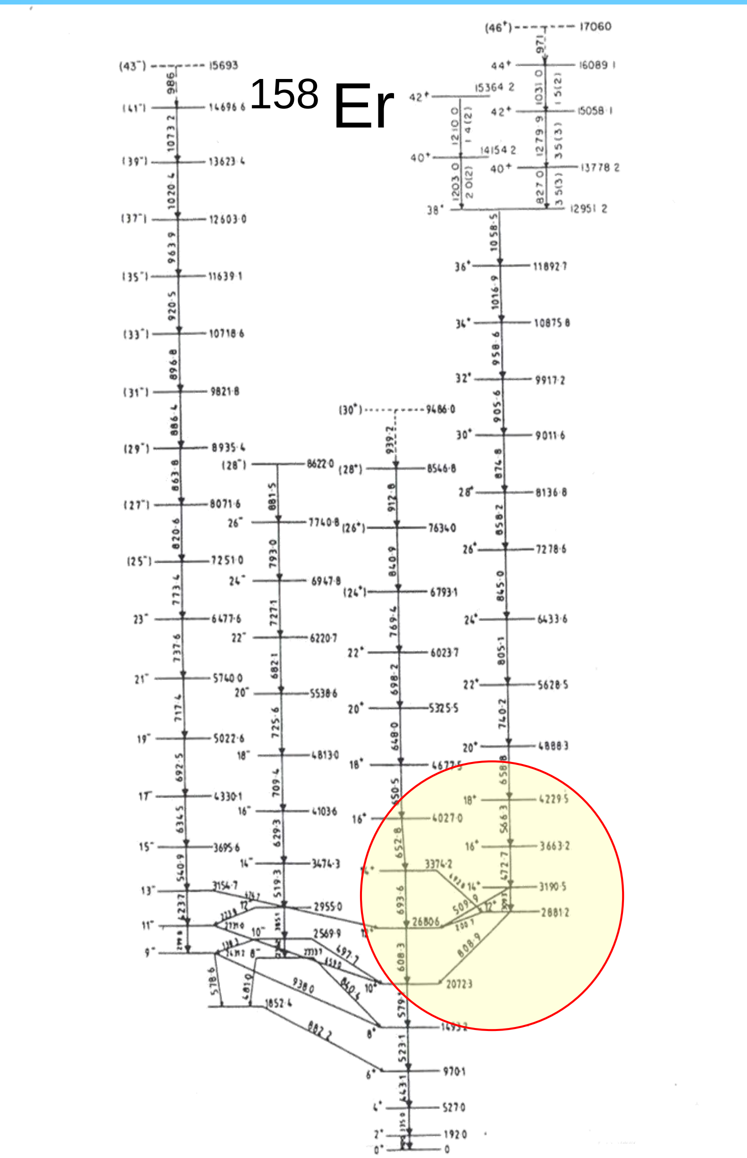
$$E = \frac{\hbar^2}{2\Im} I(I+1)$$

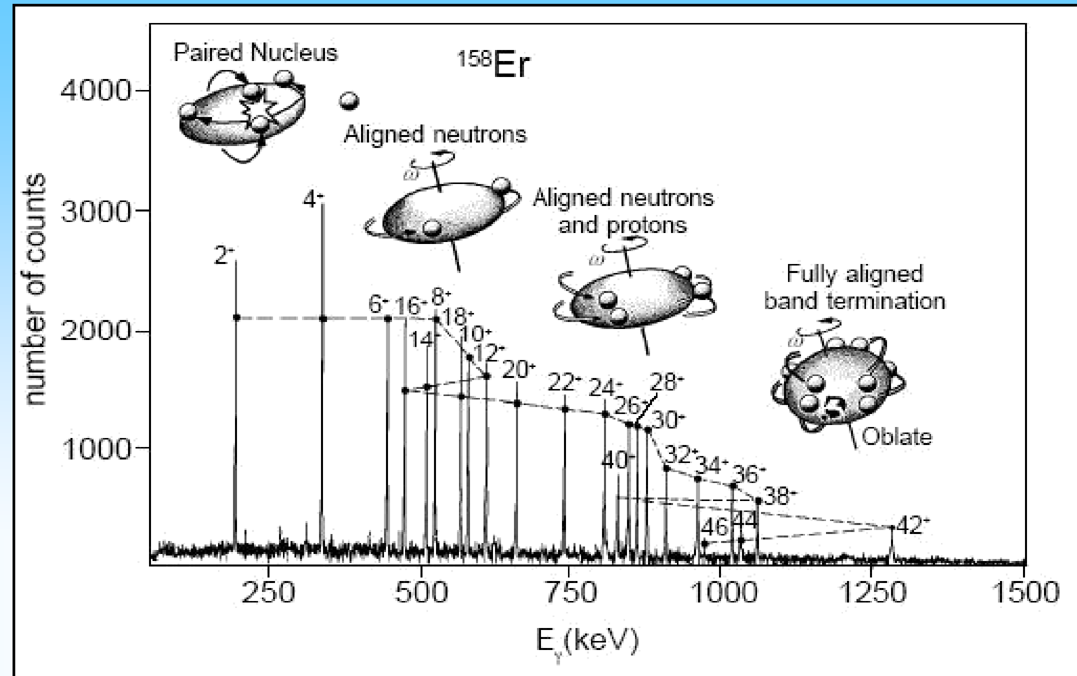
$$Q_s = Q_0 \frac{3K^2 - I(I+1)}{(I+1)(2I+3)}$$

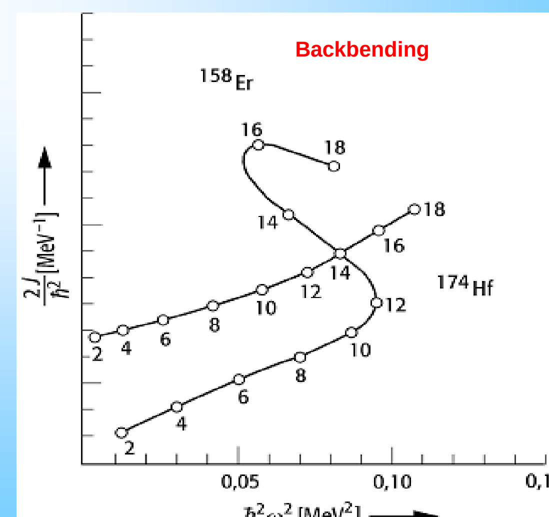
$$B(E2) = \frac{5}{16\pi} Q_0^2 \left\langle I_i K 20 \middle| I_f K \right\rangle^2$$

$$g = g_R + (g_K - g_R)\frac{K^2}{I(I+1)}$$



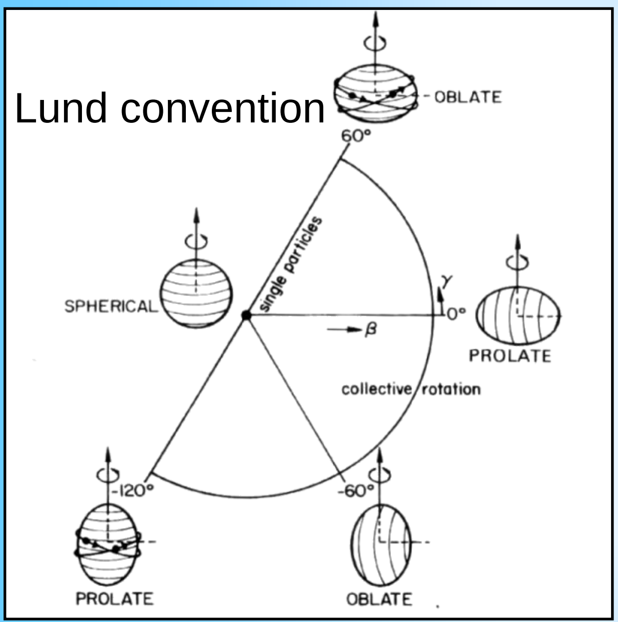


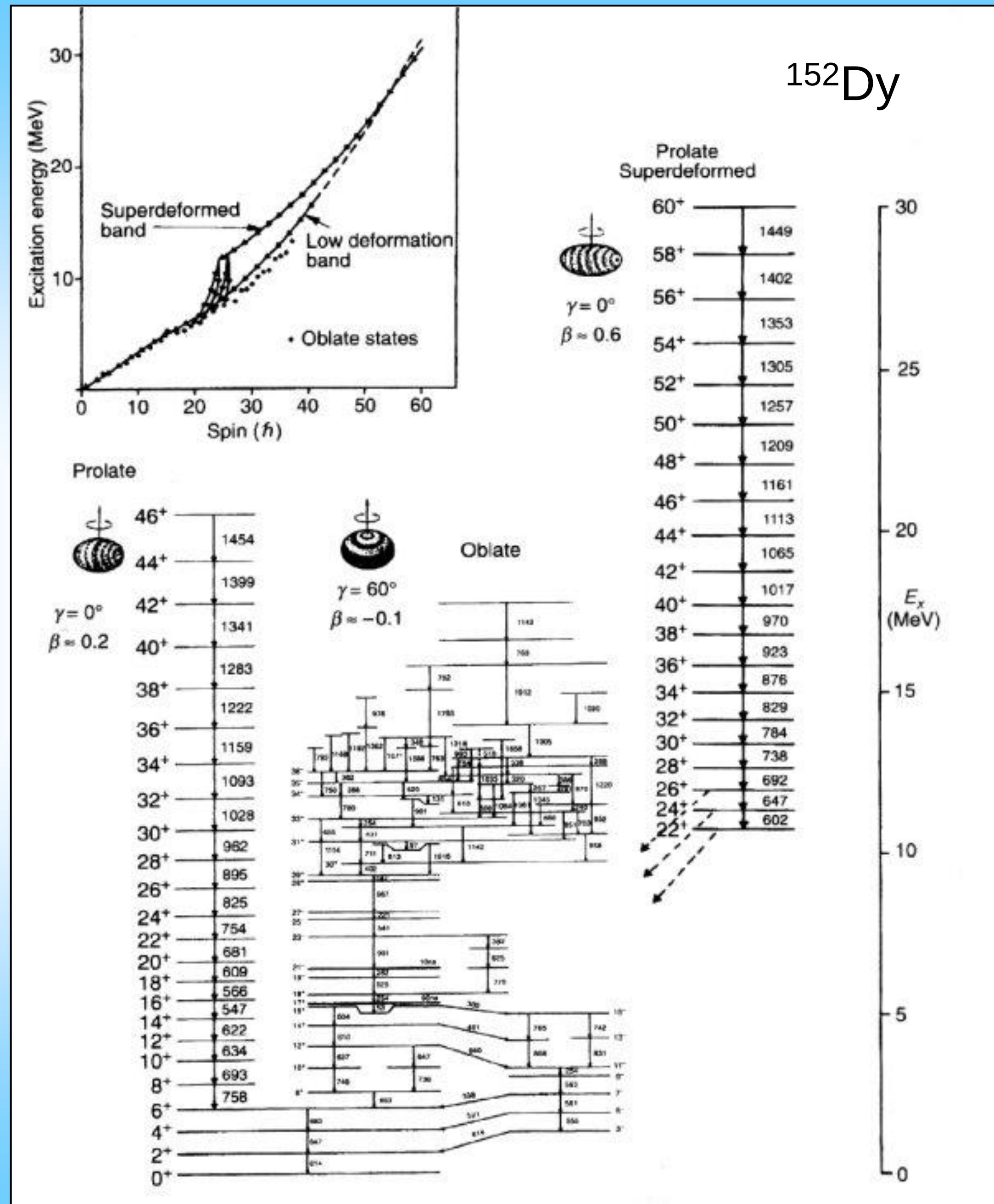




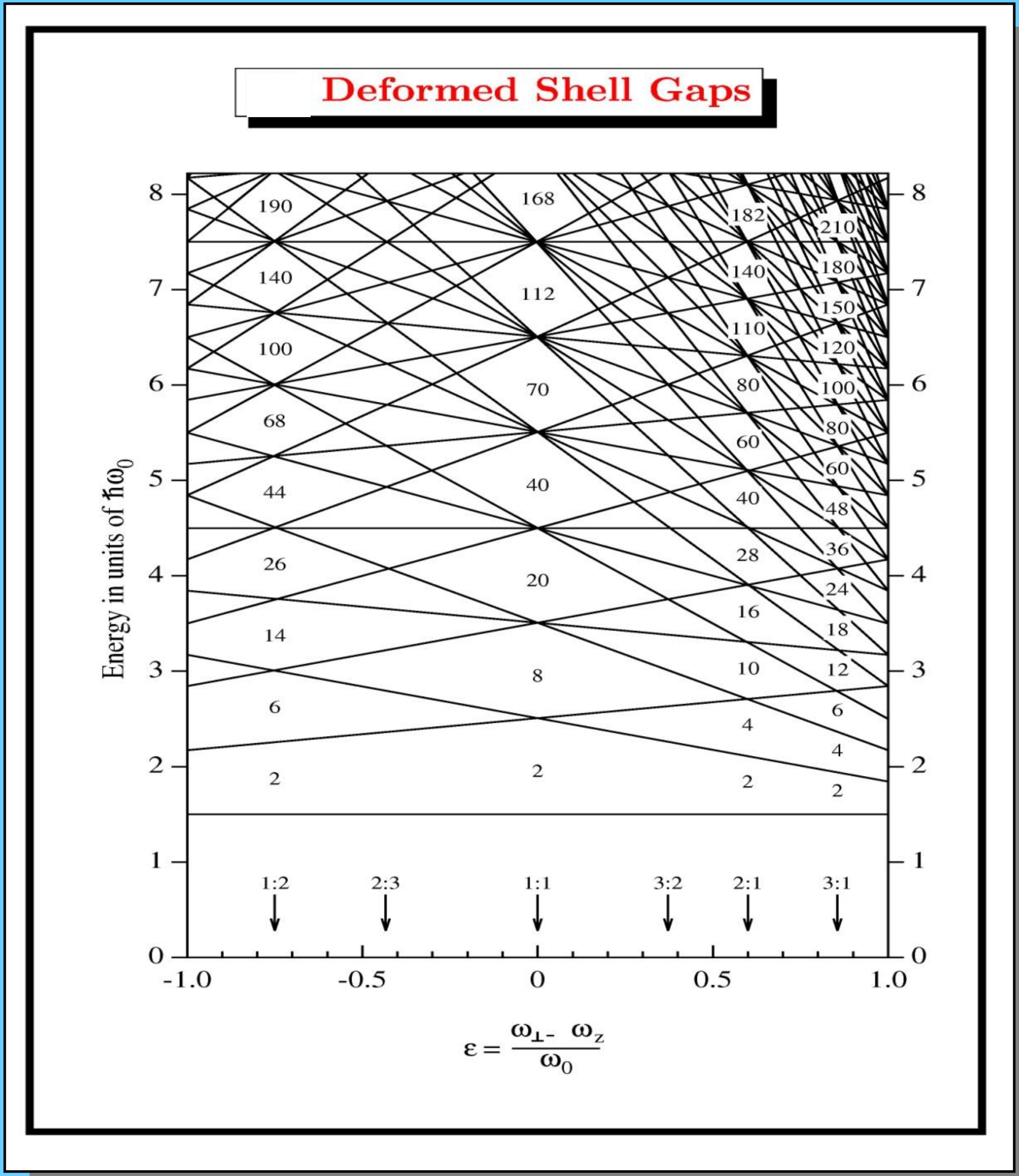
J.D. Garrett, G.B. Hagemann, and B. Hersking, Ann. Rev. Nucl. Part. Sci. 36 (1986) 419

Shape Coexistence





S.G Nilsson and I. Ragnarsson,
Shapes and Shells in Nuclear Structure
Cambridge University Press 1995



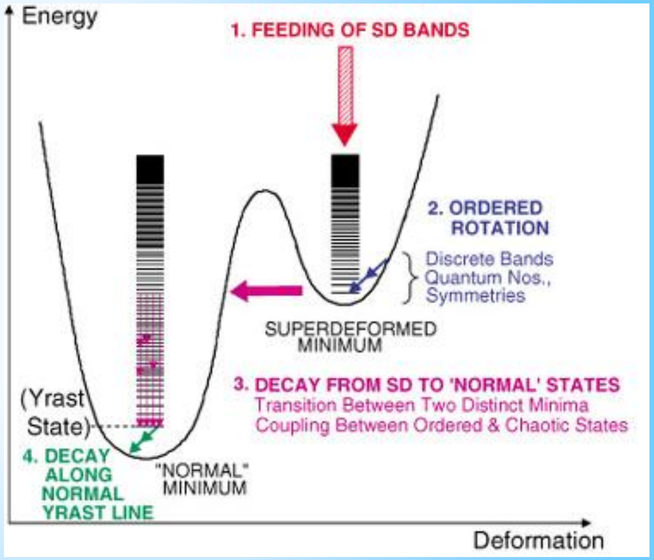
Single-particle level energies calculated for an axially symmetric harmonic oscillator

Second minima $\beta_2 \sim 0.75$

V.M. Strutinski, Nucl. Phys. A 95, 420 (1967)

Observed in the ^{152}Dy nucleus

P.J. Twin et al., Phys. Rev. Lett. 57, 811 (1986)



Third minima $\beta_2 \sim 0.9$

Predicted but not observed

http://nucalf.physics.fsu.edu/~riley/gamma/

Superdeformation

320 superdeformed bands

A= 40, 80,130,150, 160 and 190

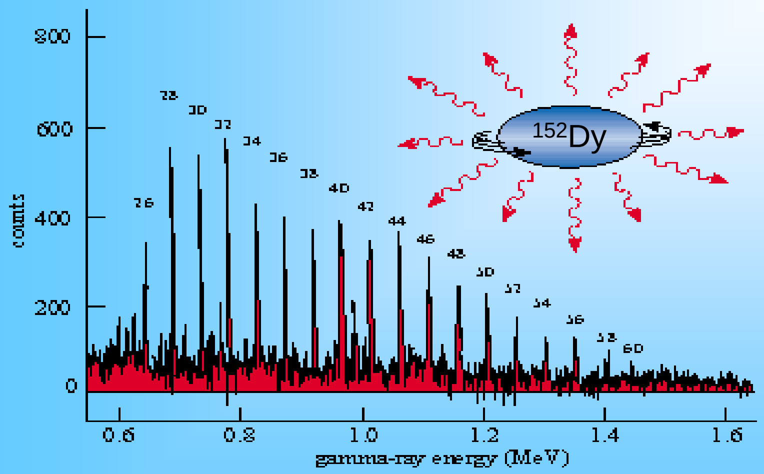
Feeding and Decay modes

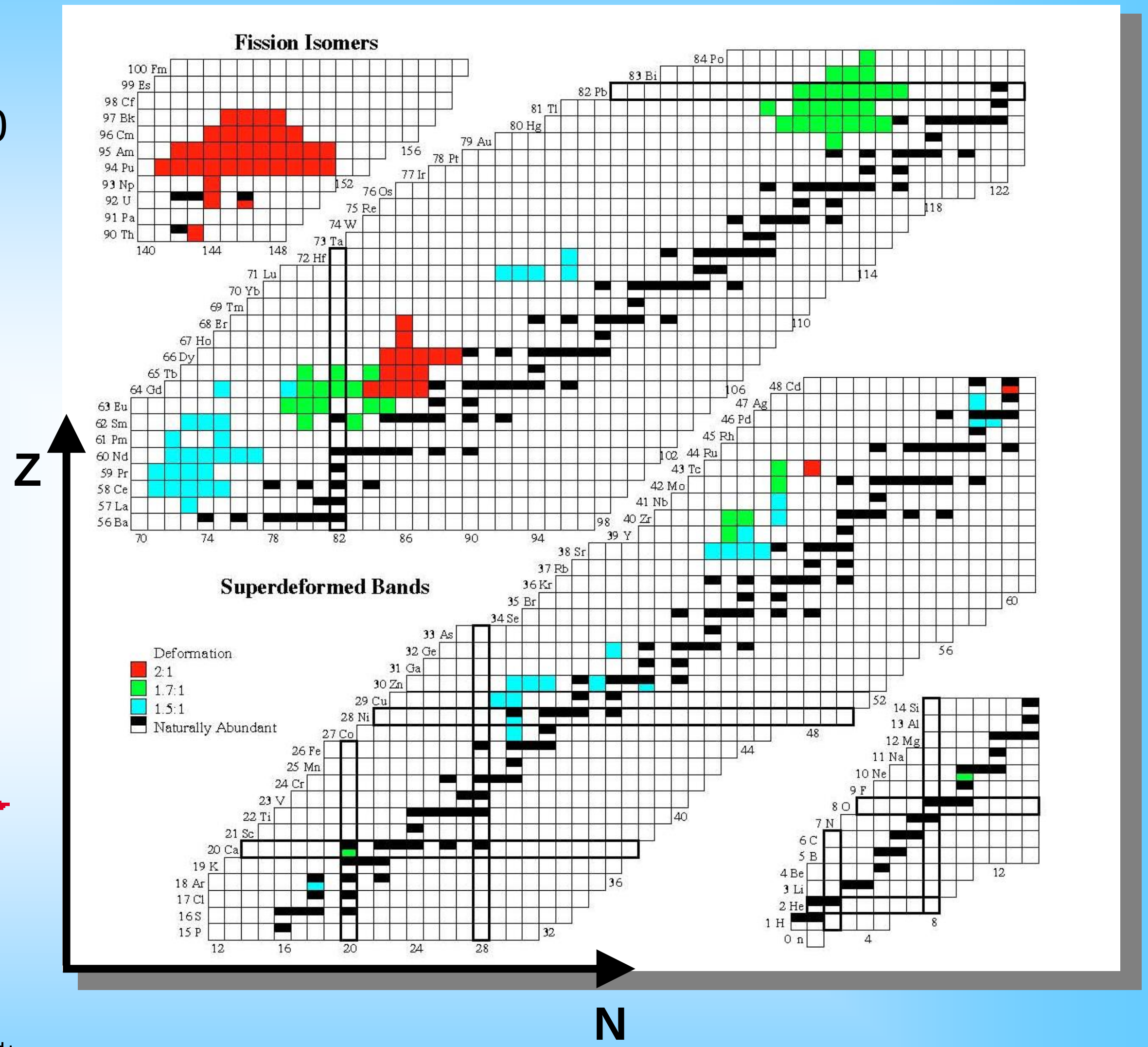
Linking transitions:

^{133,135,137}Nd, ^{194}Hg, ^{194}Pb

^{152}Dy: 6 SD bands

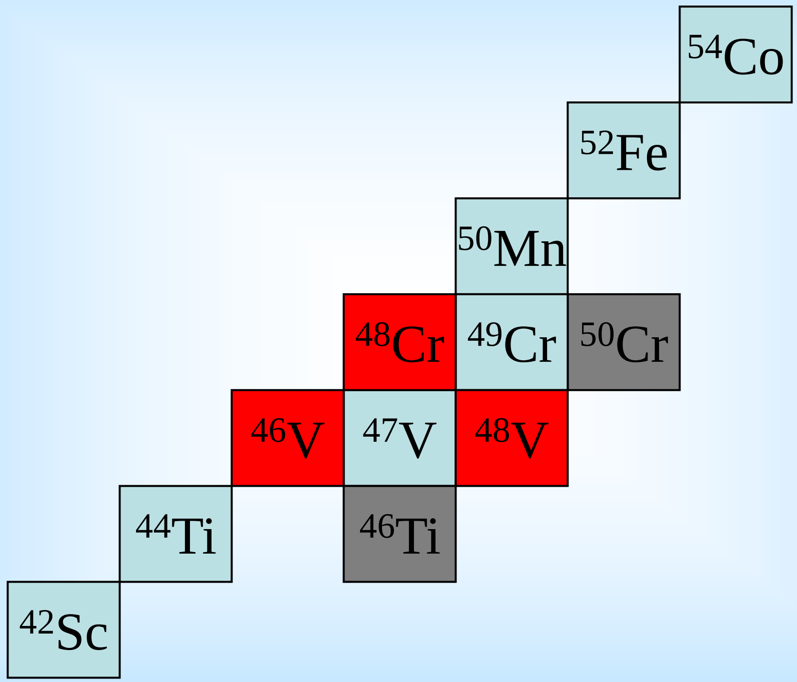
$$\Delta E_{\gamma} \approx const.$$





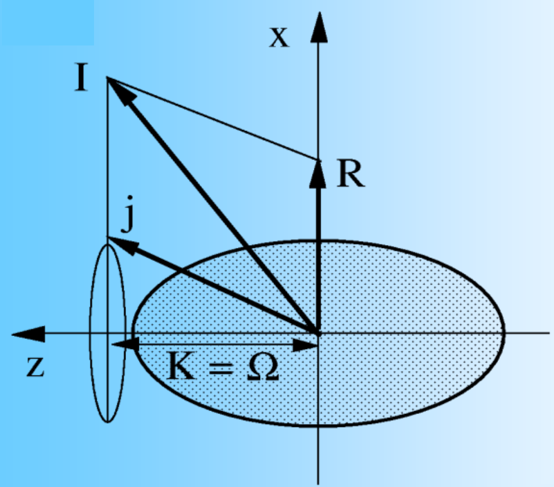
Balraj Singh et al., Nucl. Data Sheets 97, 241 (2002)

pf shell nuclei (A=50)

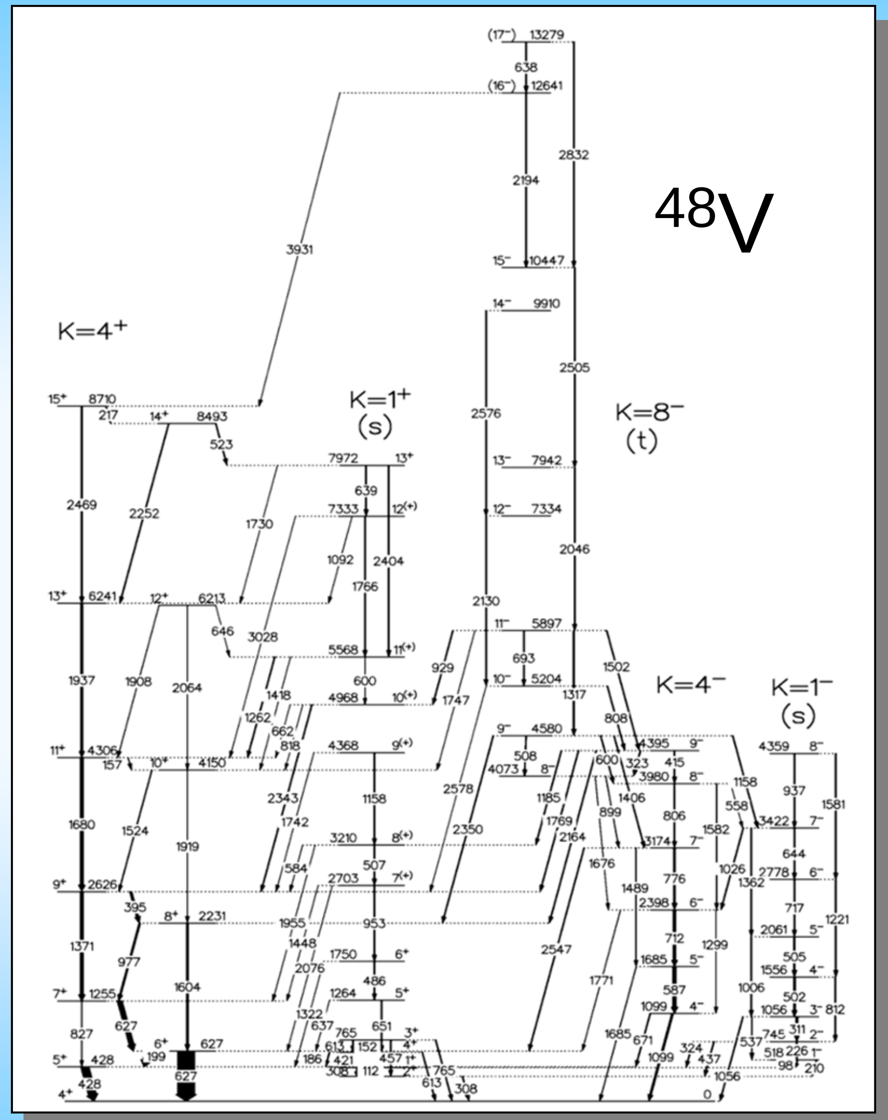


Nuclei with valence nucleons occupying the fp orbitals

The odd-odd ^{48}V nucleus



K is the angular momentum projection in the symmetry axis



Level scheme of the ^{48}V nucleus.

F. Brandolini et al., Phys. Rev. C 66, 024304 (2002)

Experimental Details

Fusion-evaporation reactions:

^{24}Mg (^{28}Si, n3p) ^{48}V

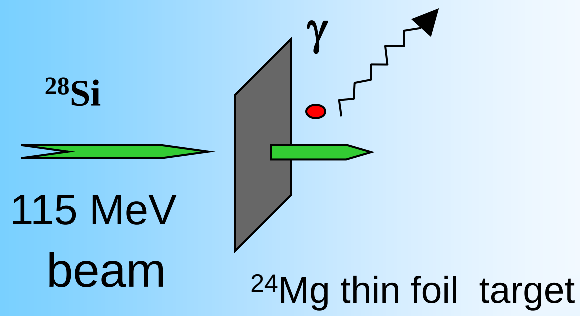
Thin target experiment

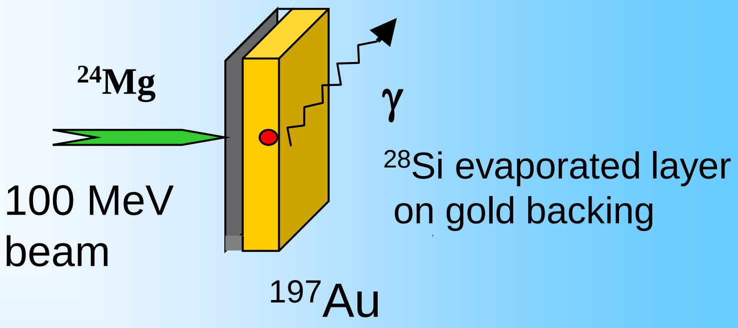
Level scheme investigation.
self-supporting target.

^{28}Si (^{24}Mg, n3p) ^{48}V

Thick target experiment

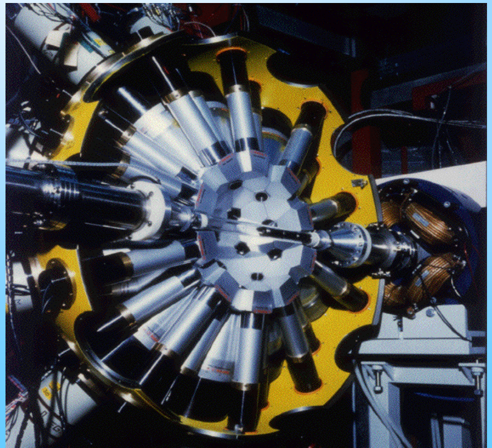
Lifetime measurements.
backed targets



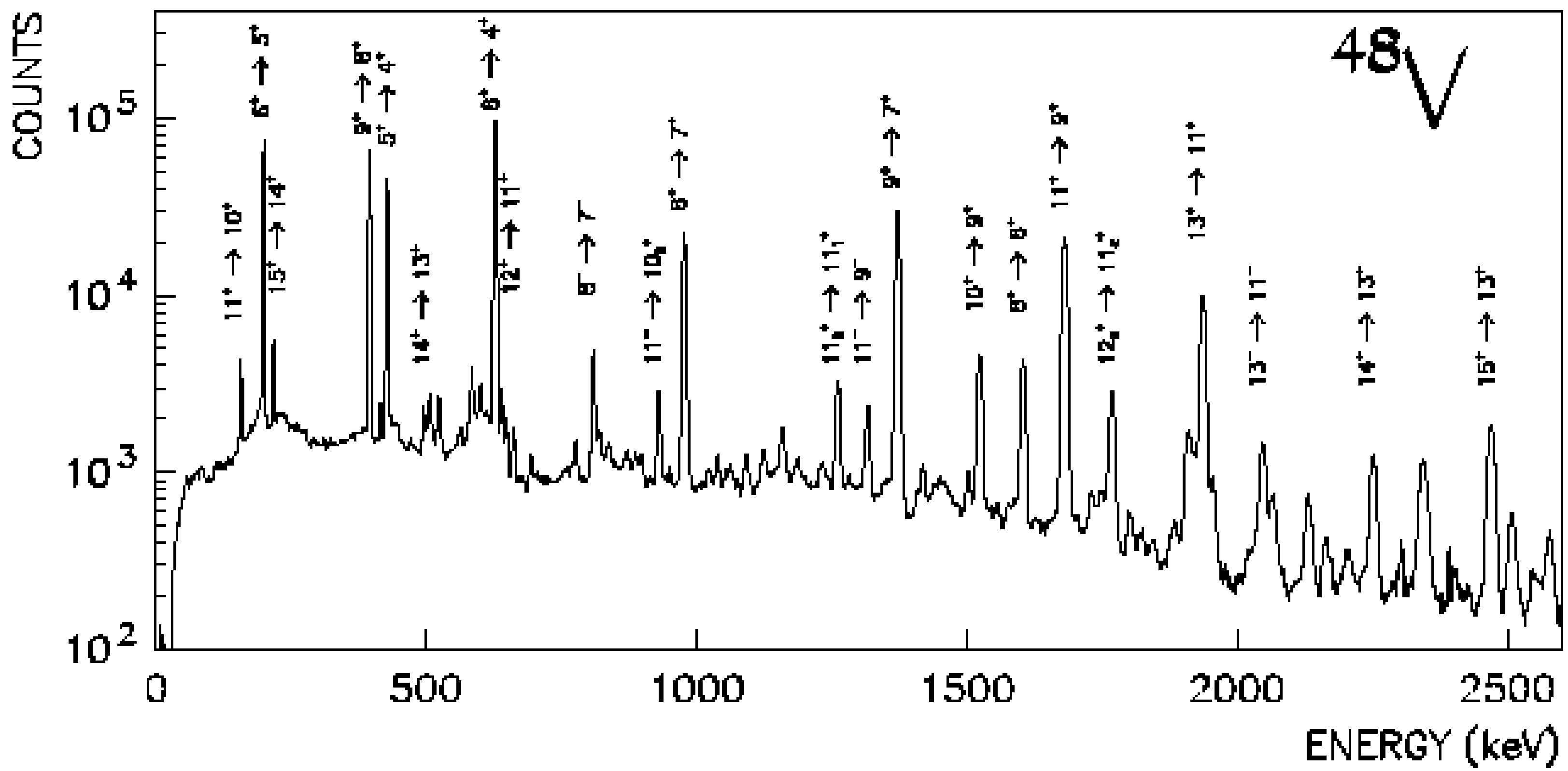


XTU Tandem accelerator
Legnaro National Laboratories, Italy (LNL)

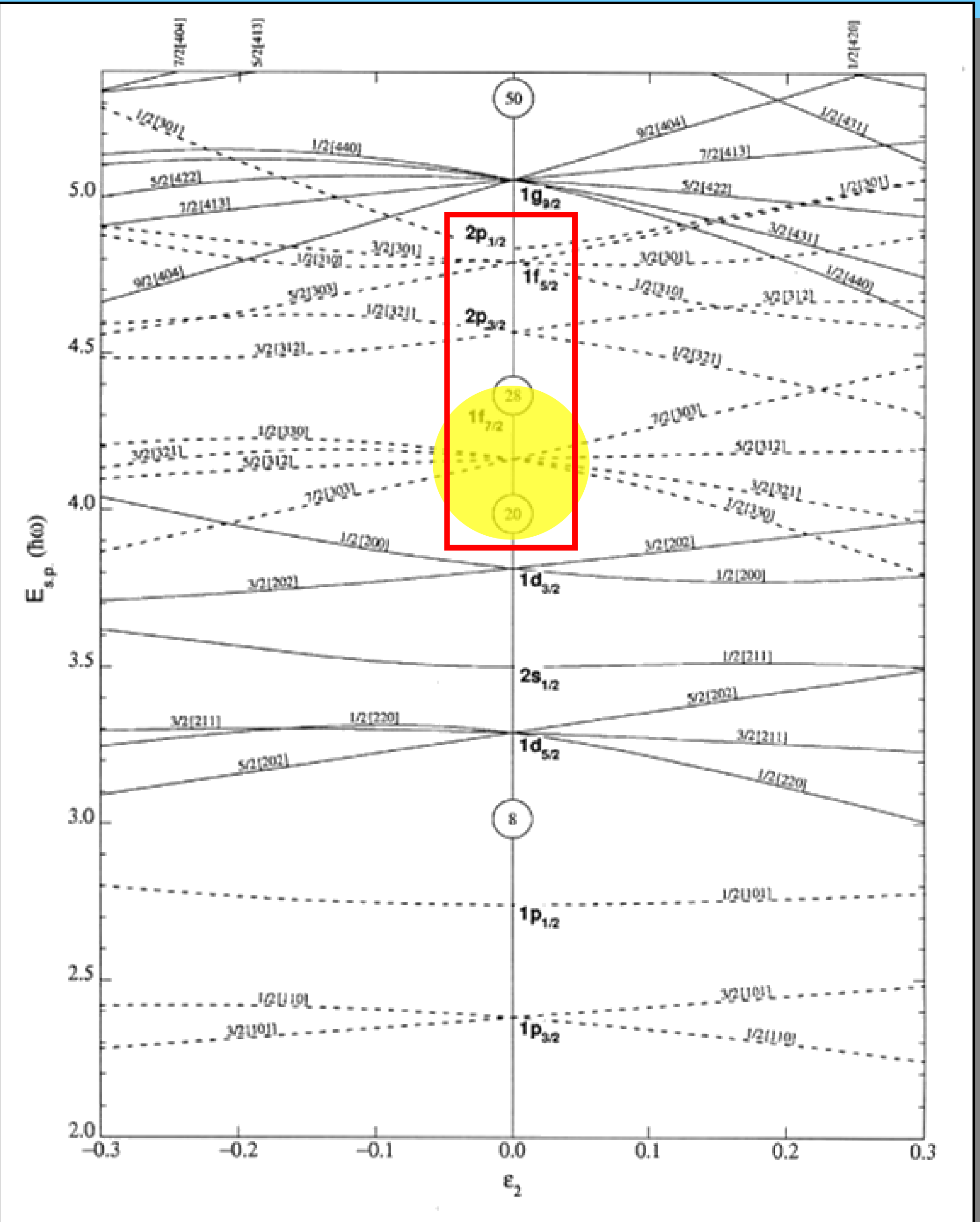
GASP γ-ray spectrometer



γ-ray spectrum



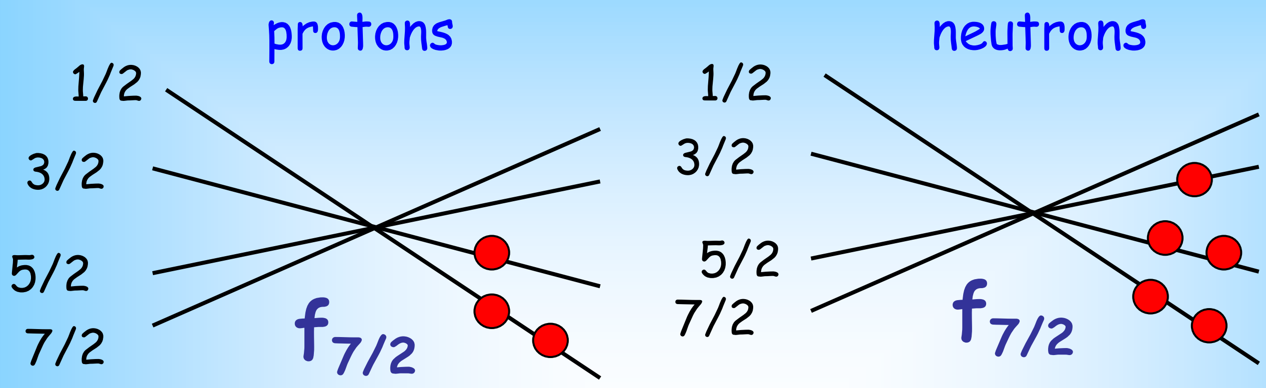
Gamma-ray spectrum from the ^{24}Mg on ^{28}Si fusion reaction (E = 100 MeV) gated on some low-lying transition of the ^{48}V gs band, and on 3 protons detected by the ISIS array



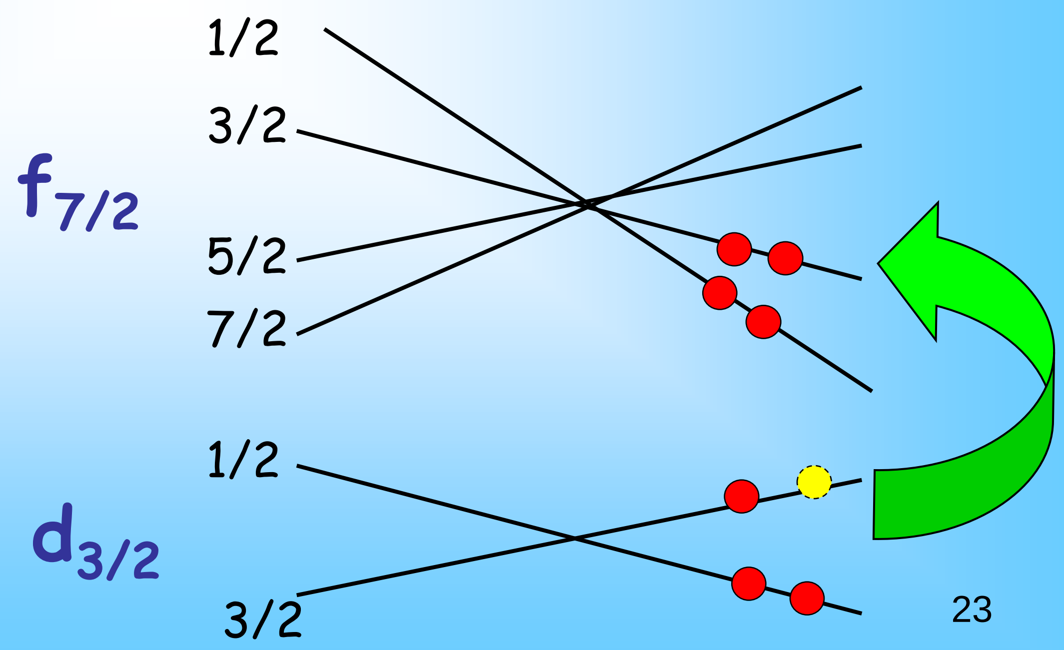
Nilsson diagram for protons and neutrons, Z or N ≤ 50

Natural parity states (positive)

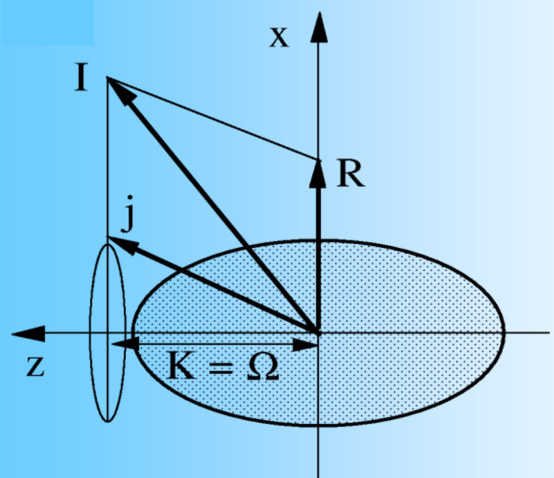
$^{48}_{23}V_{25}$



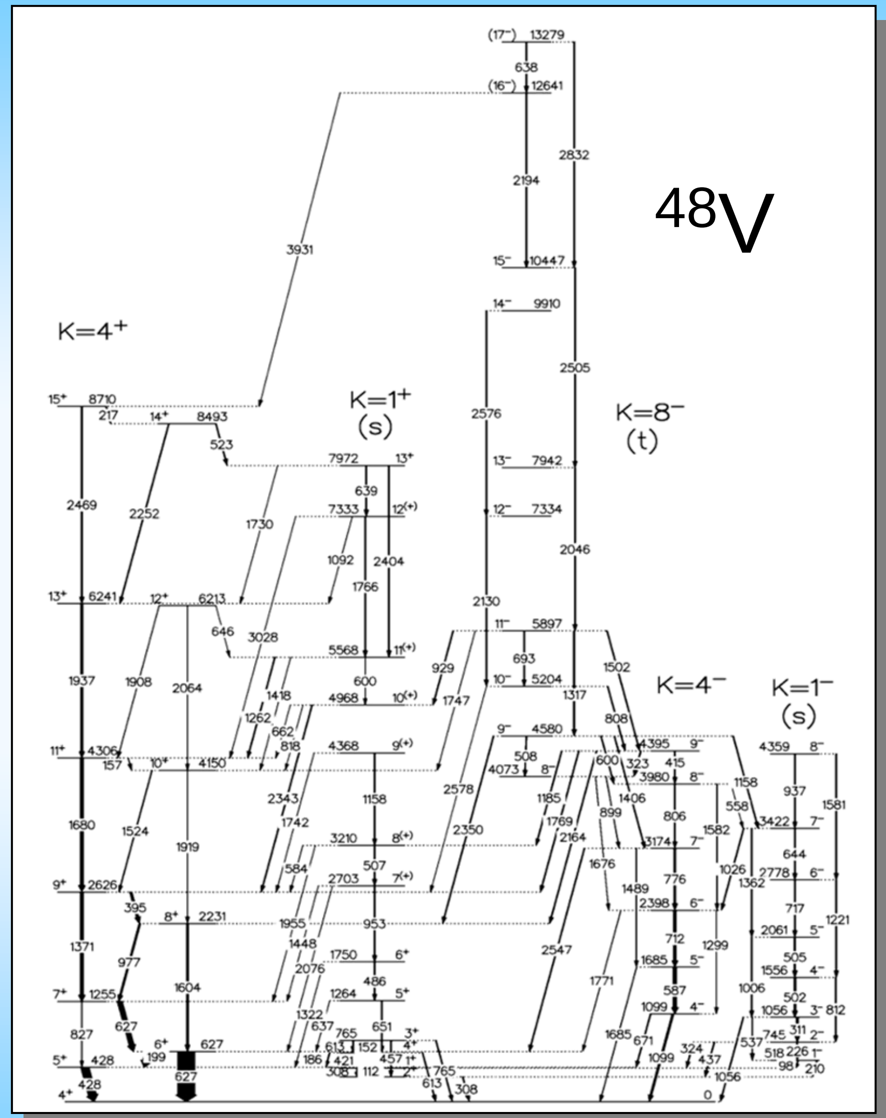
Non-natural parity states (negative)



Odd-odd ^{48}V nucleus



K is the angular momentum projection in the symmetry axis



Level scheme of the ^{48}V nucleus.

F. Brandolini et al., Phys. Rev. C 66, 024304 (2002)

Shell Model

$$\hat{H} = -\sum_{i=1}^{A} \frac{\hbar^2}{2m} \nabla^2 + \frac{1}{2} \sum_{i \neq j} V(x_i, x_j) \qquad \Psi = \Psi(x_1, x_2, x_3, \ldots, x_A)$$

Independent Particles Approximation (mean field)

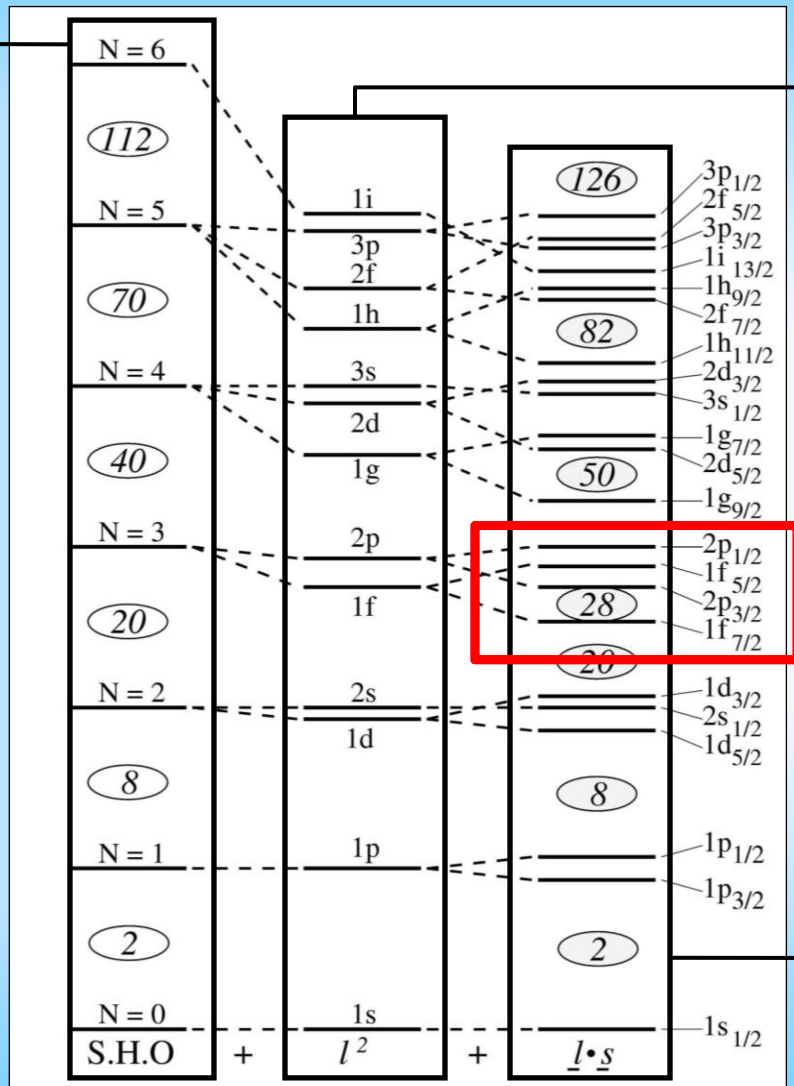
$$\Psi(x_1, x_2, \ldots, x_A) = \phi_1(x_1)\phi_2(x_2)\ldots\phi_A(x_A)$$ (Slater determinant)

$$\left[-\frac{\hbar^2}{2m} \nabla^2 + V_{eff}(x_a) \right] \phi_a = E_a \phi_a$$

$$V_{eff} = \frac{1}{2} m\omega^2 r^2 + Dl^2 - C\mathbf{l}.\mathbf{s}$$

Large Scale Shell Model

Spherical Harmonic Oscillator



Spherical Harmonic Oscillator + Orbital Angular Momentum

Spherical Harmonic Oscillator + Orbital Angular Momentum + Spin-Orbital Interaction

CASTEN, R. F. **Nuclear Structure from a Simple Perspective.** 2° ed. New York: Oxford University Press, 2005, p.66.

Configuration Mixing

Many valence particles

Most of the excited states are formed by mixing particle-hole configurations

$$\Psi = c_0\Psi_{0p0h} + c_1\,\Psi_{1p1h} + c_2\Psi_{2p2h} + \dots$$

Particle-hole configurations are mixed by the two-body **residual interaction:**

$$H = T + V = T + U_{eff} + \underbrace{V - U_{eff}}$$

Mean Field Potential

Residual interaction

Basic idea of the **interacting shell model:**
Diagonalize the Hamiltonian H in the base of independent particle configurations.

Residual Interactions

70´s	sd shell ^{16}O nucleus	(KB)
80´s	*Universal sd (A~30)*	*(USD)*
80's - 2000	*A~50 (fp shell)*	*(KB3, KB3G)*

Collective states described by a coherent superposition of (many) single-particle states.

2004	*Nuclei around* ^{56}Ni	*(GXPF1)*
2009	f_5pg_9 region ($1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$).	(JUN45)
2010	fpg region ($0f_{7/2}$, $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$).	(fpg)
2010	Inclusion of the $2d_{5/2}$ orbital	(LNPS)

KB T.T.S. Kuo and G.E. Brown, Nucl. Phys. **A 114**, 241 (1968)
USD B.H. Wildenthal, Prog. Part. Nucl. **11**, 5 (1984)
KB3 A. Poves and A. P. Zuker, Phys. Rep. **71**, 141 (1981)
KB3G A. Poves et al., Nucl. Phys. **A 694**, 157 (2001)
GXPF1 M. Honma et al., Phys. Rev. C **69**, 034335 (2004)
JUN45 M. Honma et al., Phys. Rev. C **80** 064323 (2009).
fpg K. Sieja and F. Nowacki, Phys. Rev. C **81** 061303 (2010)
LNPS S.Lenzi, K. Sieja and F. Nowacki, Phys. Rev. C **82** 054301 (2010)

Large Scale Shell Model

Large configuration spaces

To have a good description of the nuclear structure with the Shell Model depends on the choice of :

- An adequate configuration space , i.e. defining the inert core and the active orbitals (number of nucleons to be excited).

- An appropriate *residual interaction*. This is the most important ingredient to have a good description of the nuclear structure.

- A code capable to solve the problem .
  To build and diagonalize the Hamiltonian matrix.

E. Caurier et al., Shell Model and Nuclear Structure,
Progress in Particle and Nuclear Physics, v.59, p. 226, 2007.

Large Scale Shell Model

Antoine code

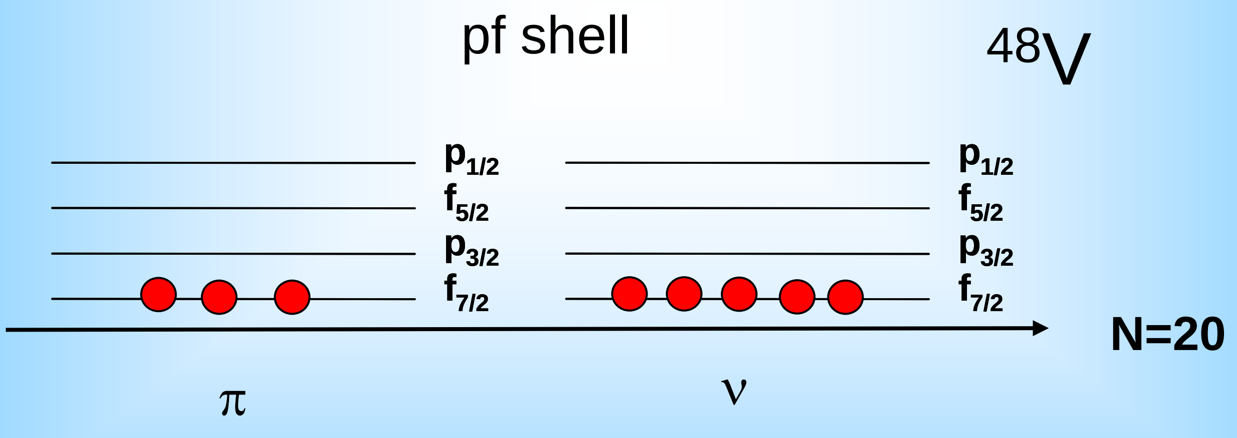
m-scheme and Lanczos method

KB3G residual interaction

Configuration space: 10^7 elements

^{40}Ca inert core

full pf shell



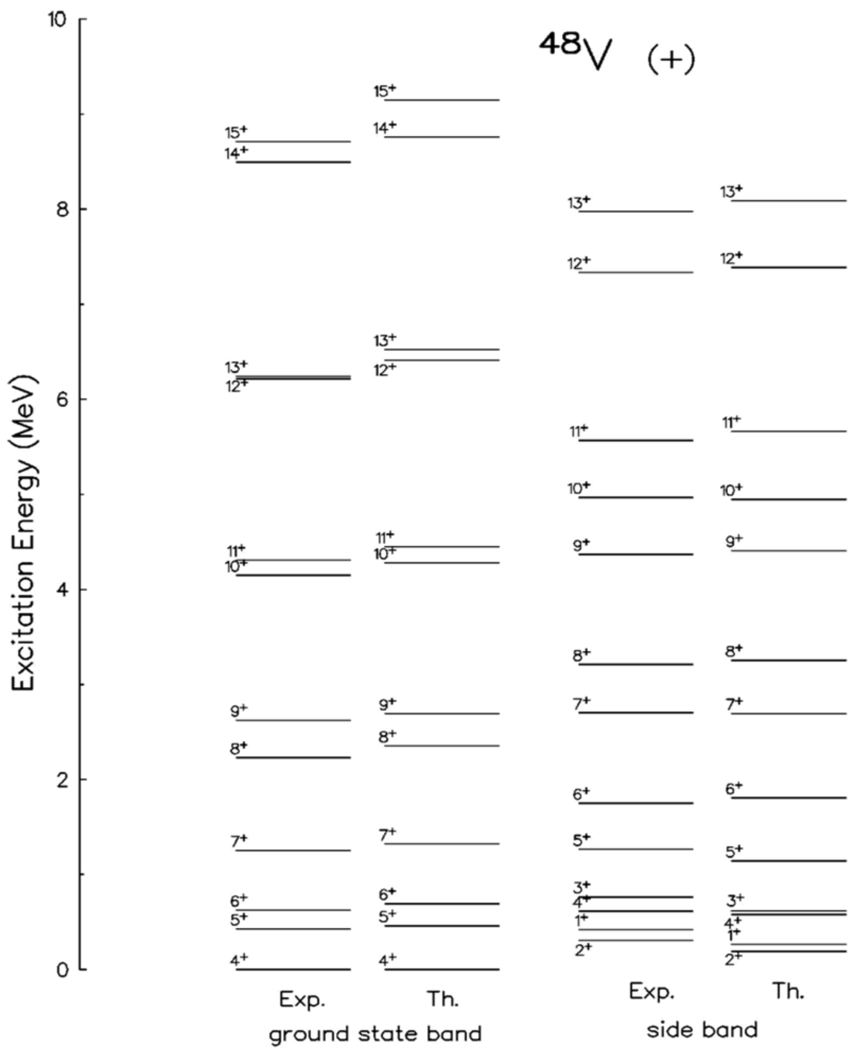
$$q_{ef}^{\pi} = 1{,}5e \quad \text{and} \quad q_{ef}^{\nu} = 0{,}5e$$

$$g_l = \begin{cases} 1 & protons \\ 0 & neutrons \end{cases}$$

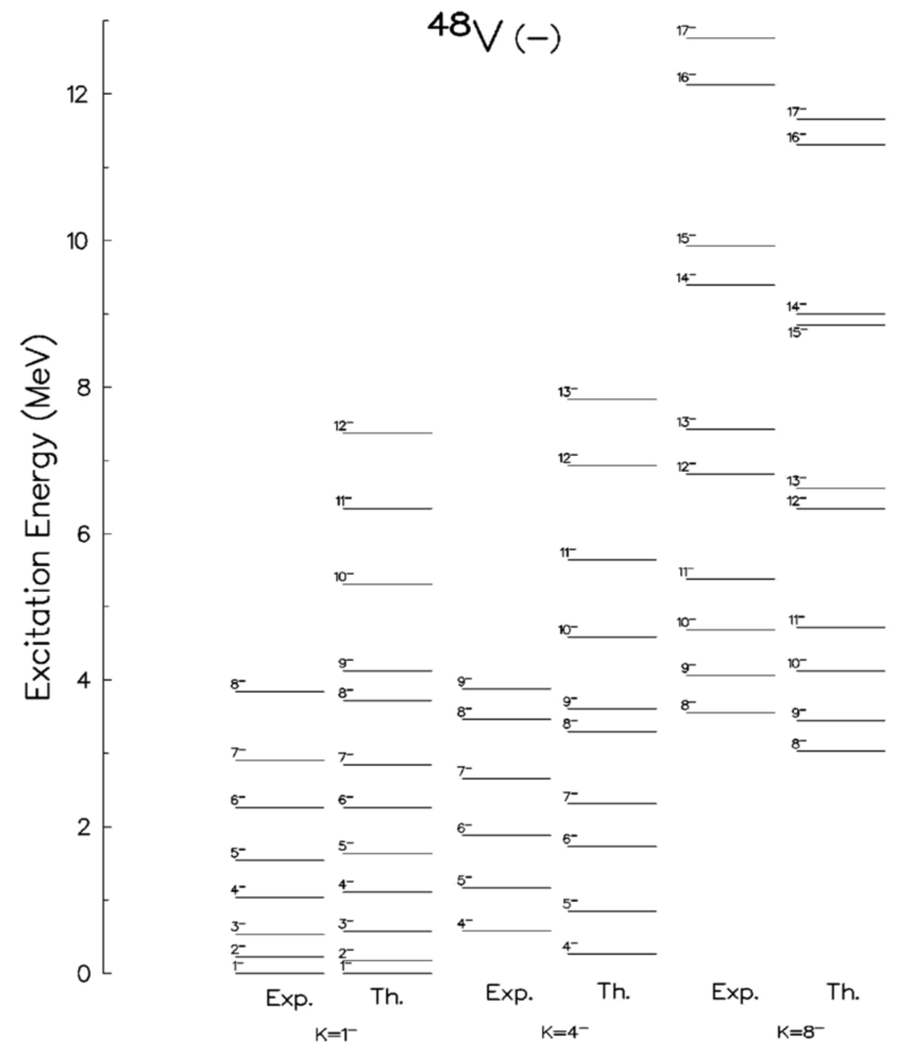
$$g_s = \begin{cases} 5{,}586 & protons \\ -3{,}826 & neutrons \end{cases}$$

E. Caurier, shell model code Antoine, IRES, Strasbourg 1989-2002

E. Caurier and F. Nowacki, Acta Physica Polonica 30, 705 (1999)

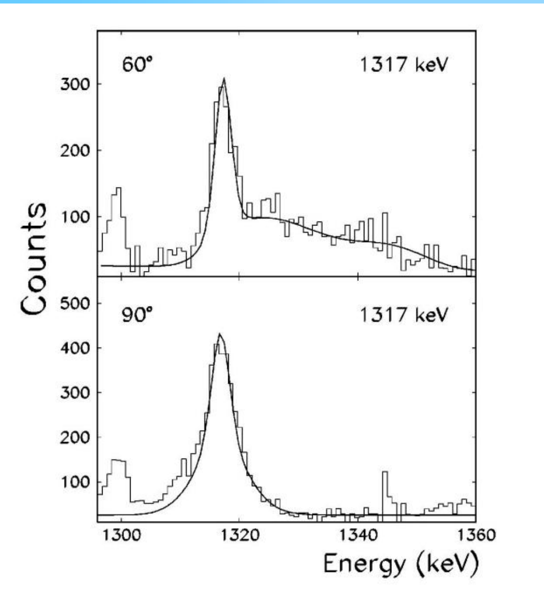


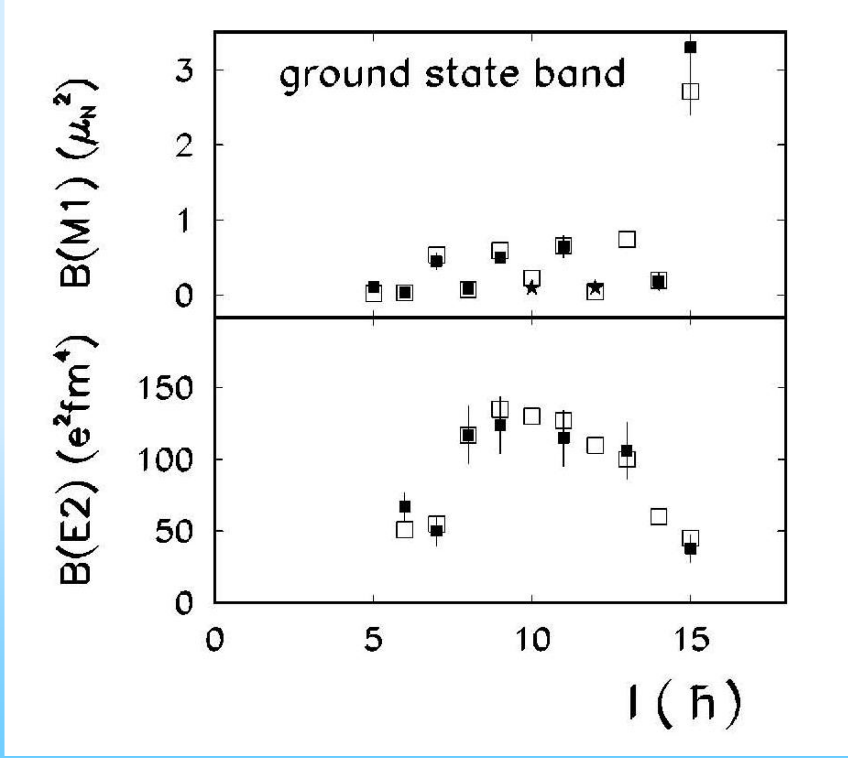
^{48}V (+)
Excitation Energy (MeV)
0
2
4
6
8
10
Exp.
Th.
ground state band
Exp.
Th.
side band

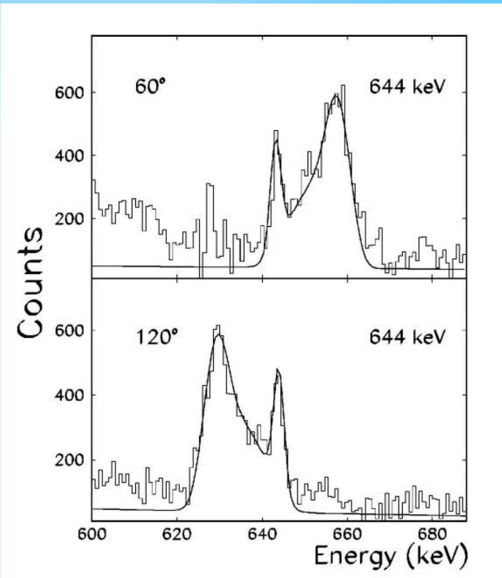


^{48}V (−)
Excitation Energy (MeV)
0
2
4
6
8
10
12
Exp.
Th.
K=1⁻
Exp.
Th.
K=4⁻
Exp.
Th.
K=8⁻

DSAM Lifetime measurements





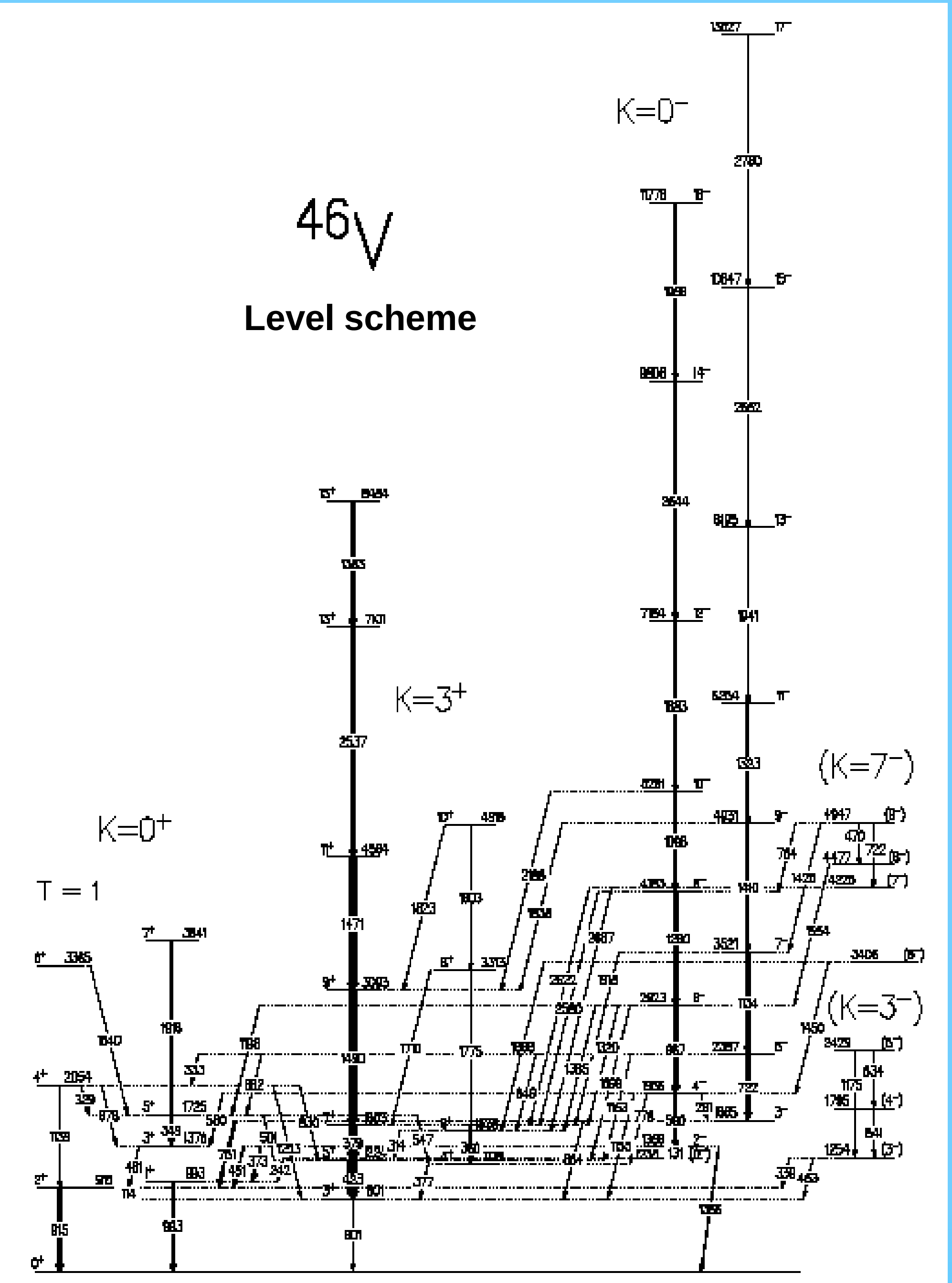


The odd-odd ^{46}V nucleus

XTU Tandem accelerator (LNL)
GASP spectrometer

^{24}Mg + ^{28}Si E = 100 MeV
(lifetime measurements)

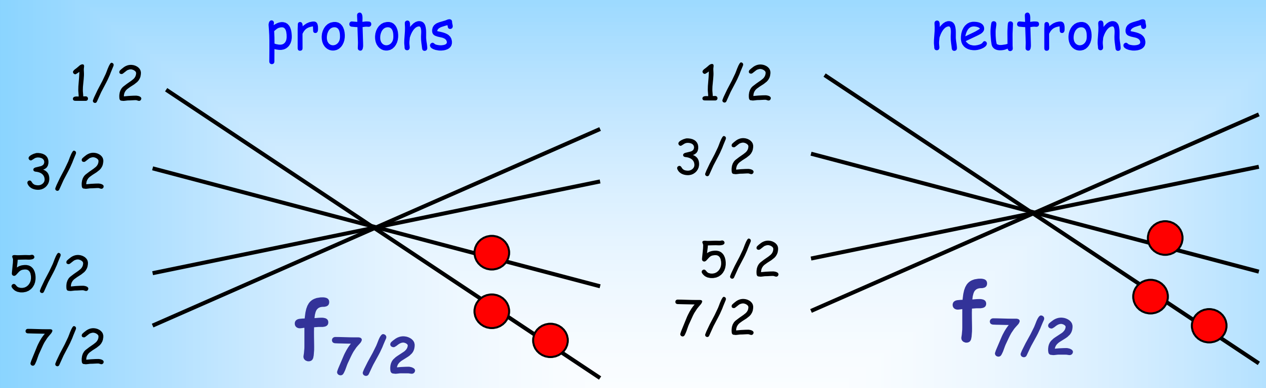
^{28}Si + ^{24}Mg E=115 MeV
(level scheme)



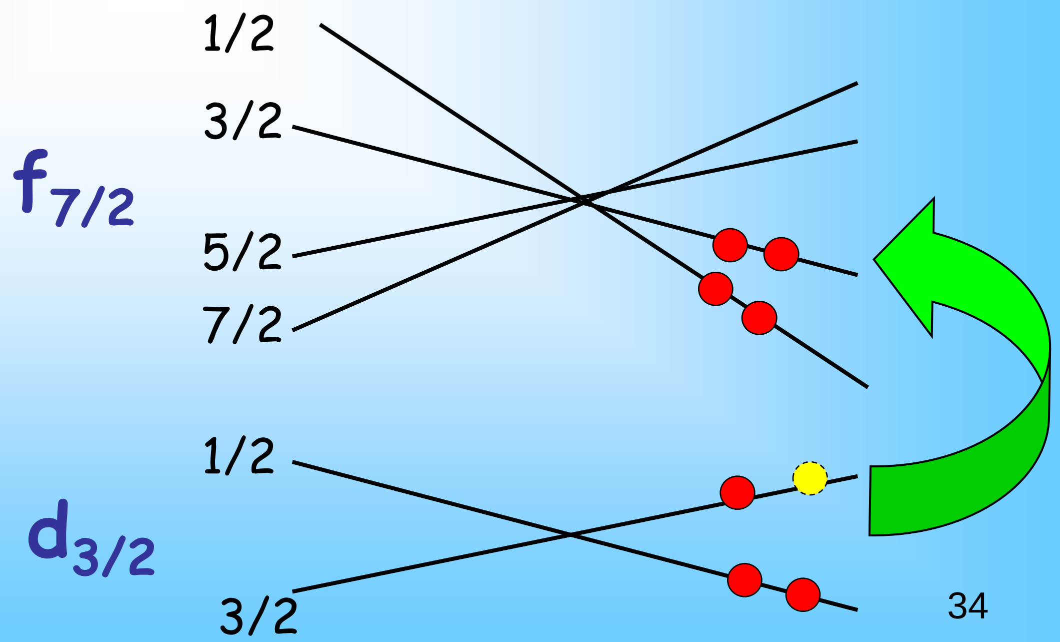
F. Brandolini et al., Phys. Rev. C 64 (2001) 044307

Natural parity states

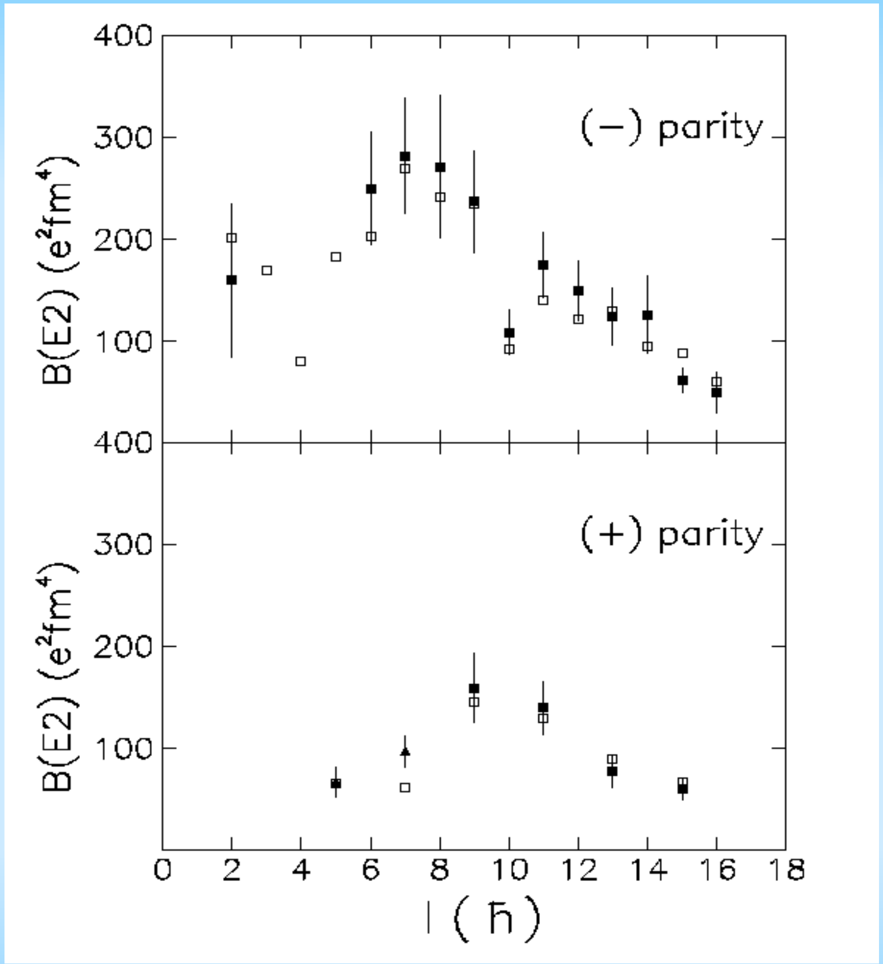
$^{46}_{23}V_{23}$



Non-natural parity states



Lifetime analysis for ^{46}V.



Experimental B(E2) transition rates for positive and negative parity bands in ^{46}V. The drop for the negative parity state at I=10$^-$ is correctly predicted. This is explained by the band crossing of the K=0$^-$ with the K=7$^-$ band.

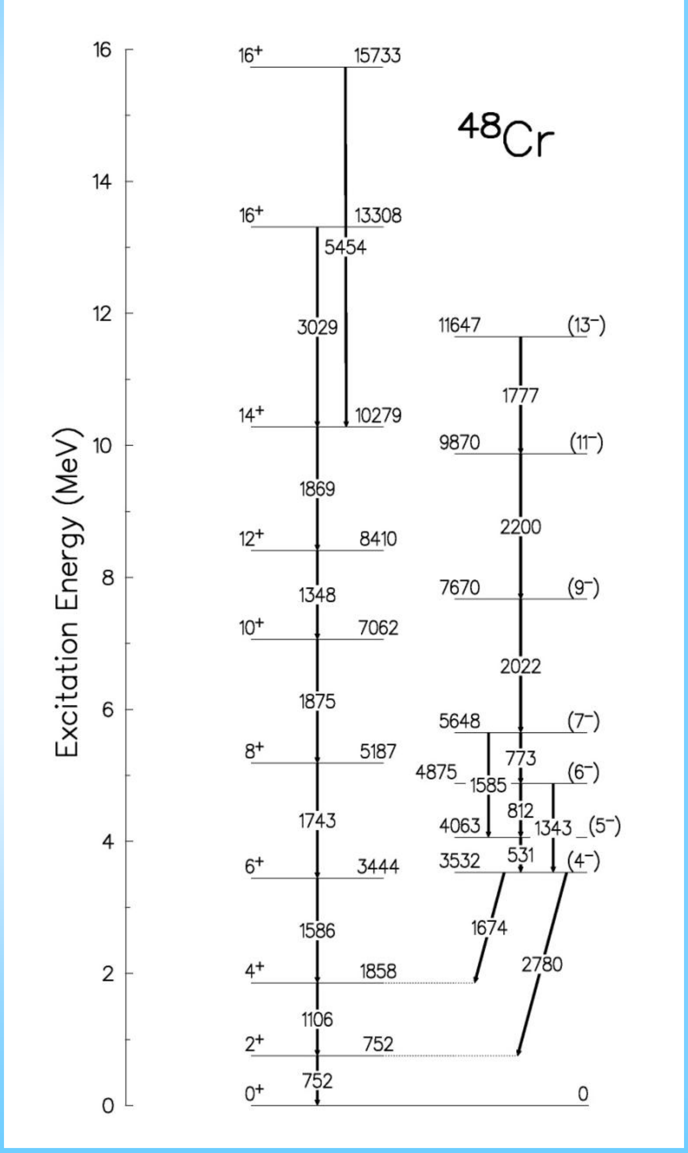
The even-even ^{48}Cr nuclei

XTU Tandem acelerator
Laboratori Nacionali di Legnaro (LNL), Italy
GASP γ-ray spectrometer

Fusion-evaporation reactions:

^{32}S + ^{24}Mg E = 130 MeV
(level scheme construction)

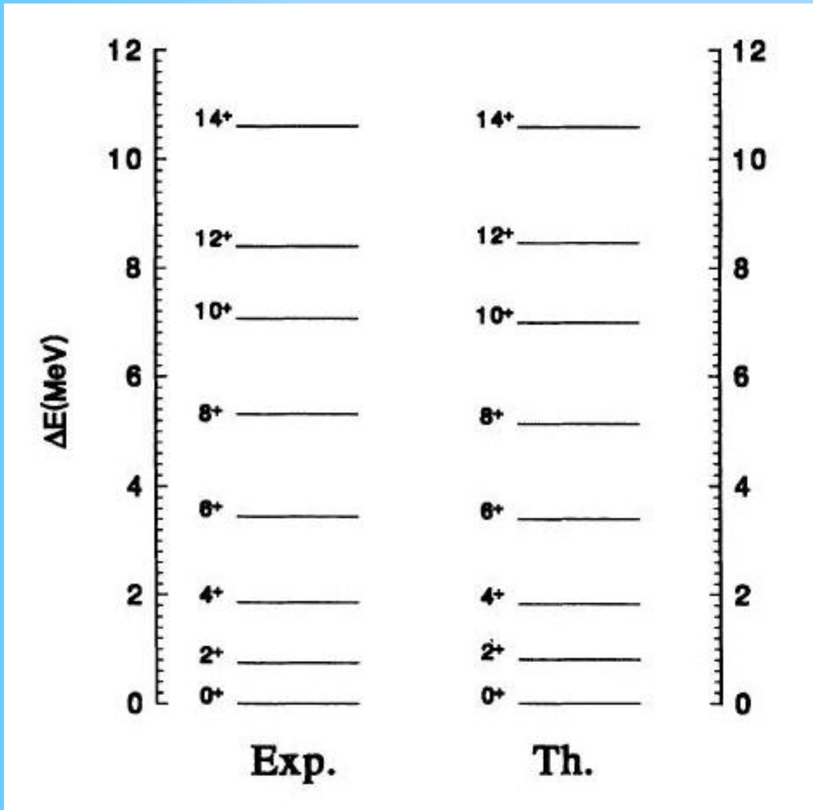
^{28}Si + ^{28}Si E=115 MeV
(lifetime measurements)



^{48}Cr level scheme

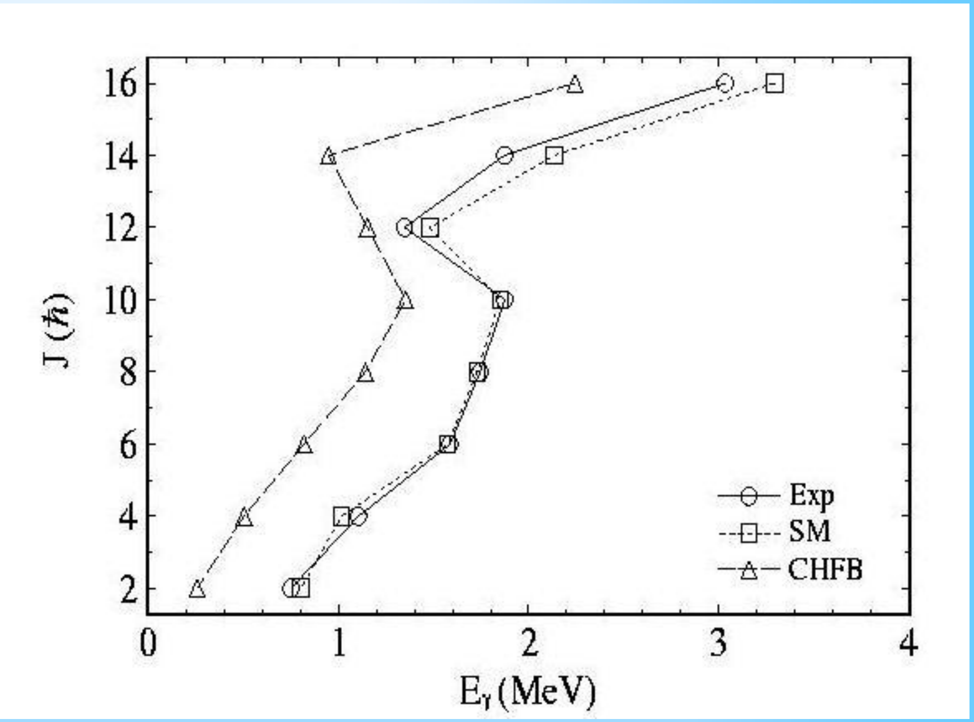
S. Lenzi et al., Z. Phys. A345 (1996) 117
F. Brandolini et al., Nucl. Phys. A 642 (1998) 387

Large Scale Shell Model



Experimental levels compared to those calculated using the LSSM

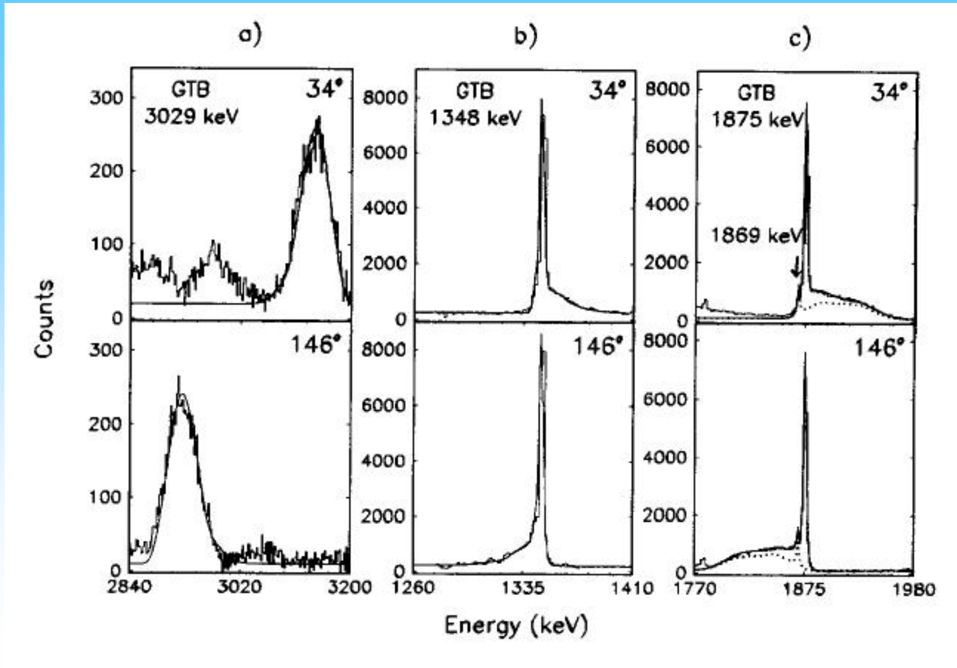
Antoine code
full pf shell
KB3 residual interaction



Experimental levels compared to those calculated using the LSSM and CHFB

E. Caurier et al., Phys. Rev. C 50 (1994) 225.

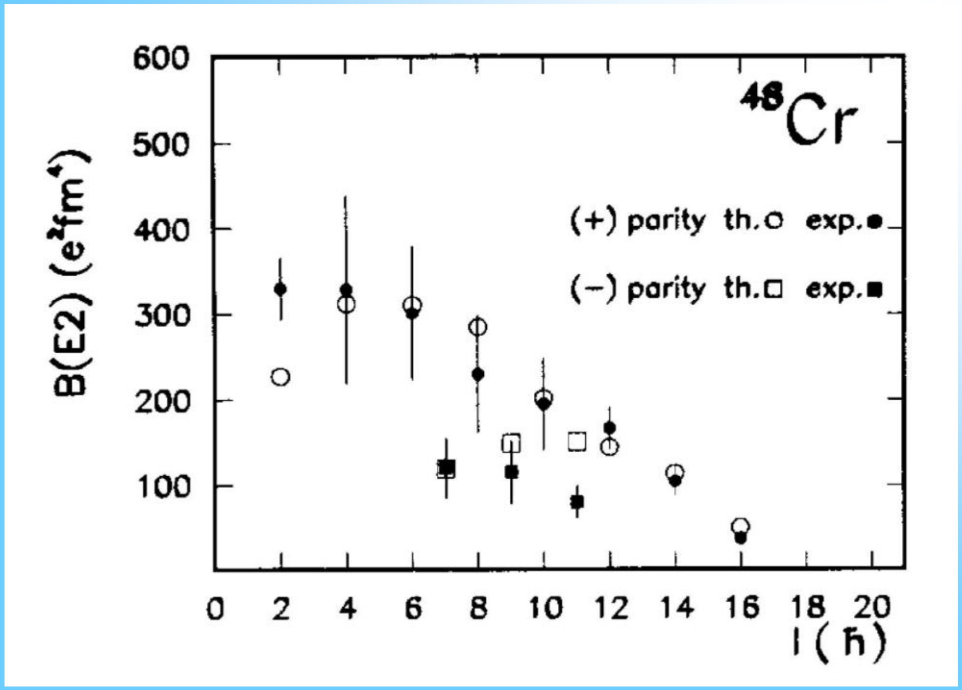
Lineshape examples



^{48}Cr nucleus

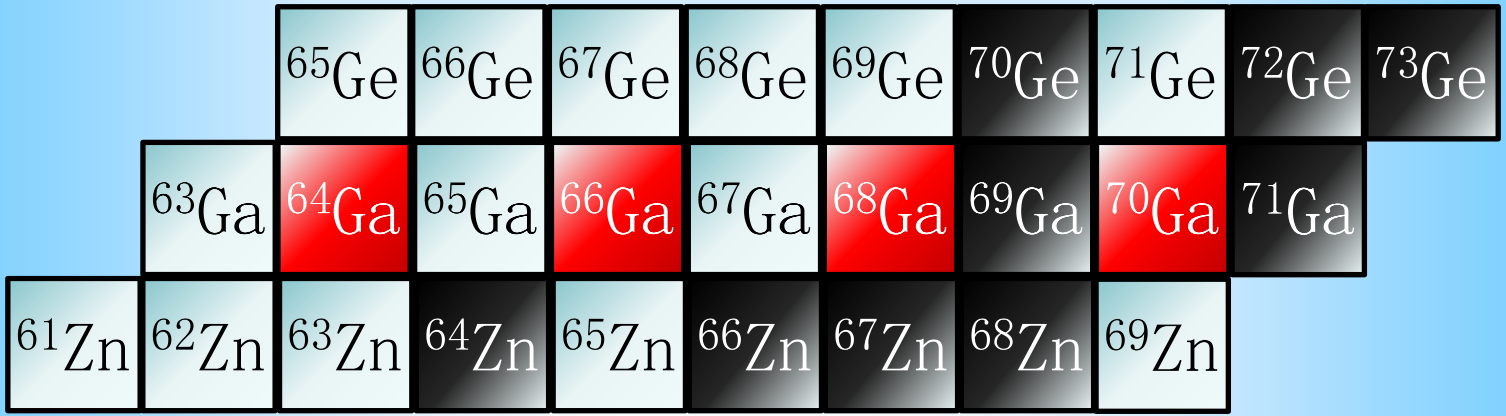
$\beta \sim 0.28$ near the ground state

$\beta \sim 0.1$ at $I^{\pi}=16^{+}$



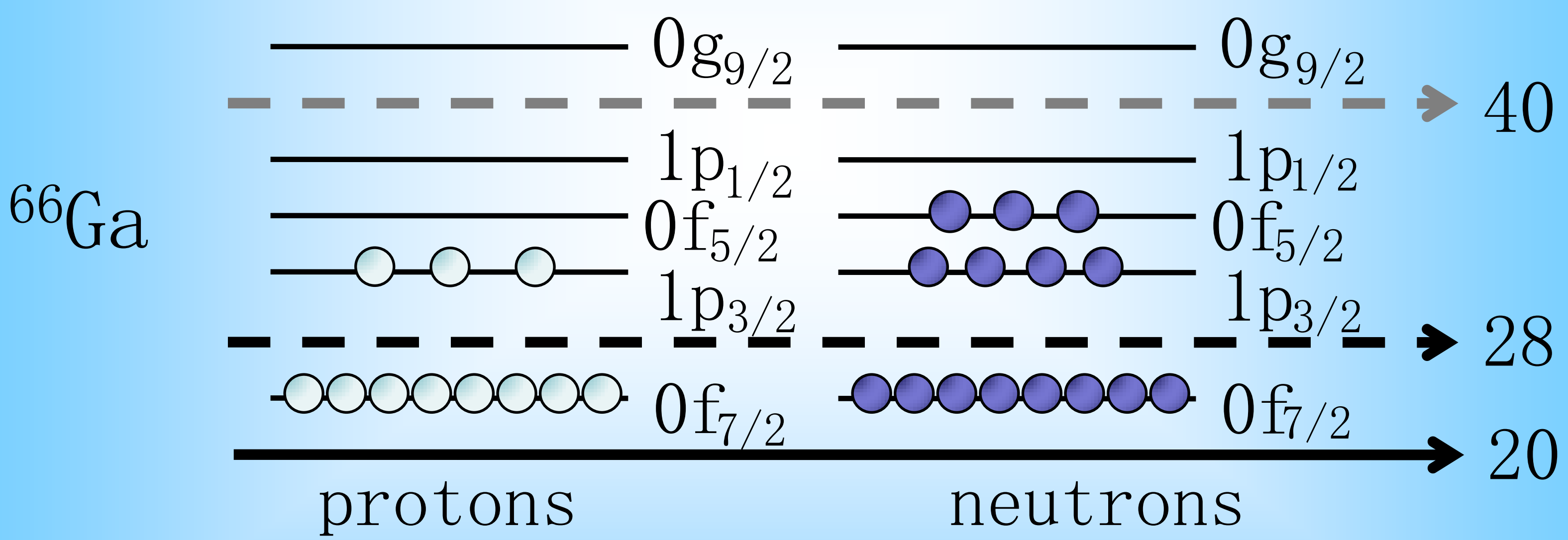
Experimental and calculated B(E2) transition rates of the positive and negative parity states.

A Systematic Study of the odd-odd $^{64,66,68,70}Ga$ nuclei



The goal of this study is to determine the role of the $0g_{9/2}$ orbital in the high spin excited states of the odd-odd $^{64,66,68,70}Ga$ nuclei.

All these Ga nuclei (Z=31) have valence nucleons in the upper part of the *pf* shell.



$$\pi = \prod_{i}^{A} (-1)^{l_i} = (-1)^{\sum_{i=1}^{A} l_i}$$

p orbital: l=1

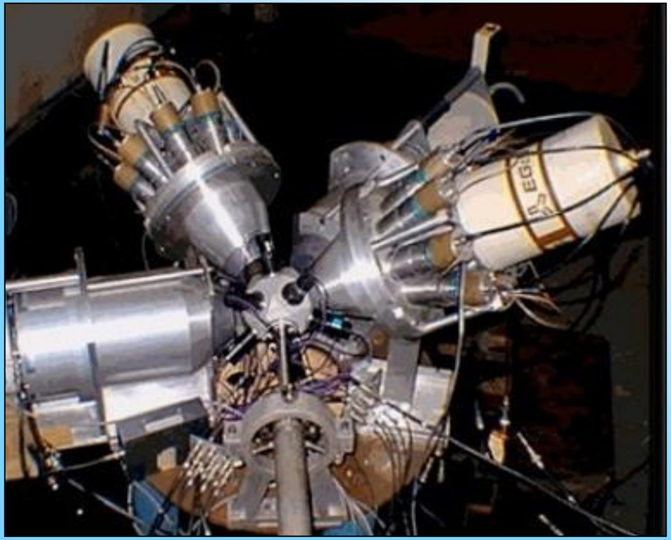
f orbital: l=3

g orbital: l=4

Experiments performed to study the ^{64,66,70}Ga nuclei

- 8 MV tandem Pelletron accelerator
  University of São Paulo, Brazil:
  - $^{58}Ni(^{11}B,2pn)^{66}Ga$, E_{beam}= 44 MeV.
  - $^{51}V(^{19}F,p3n)^{66}Ga$, E_{beam}= 54 MeV.

- SACI-PERERE spectrometer:



4 Compton suppressed HPGe detectors.

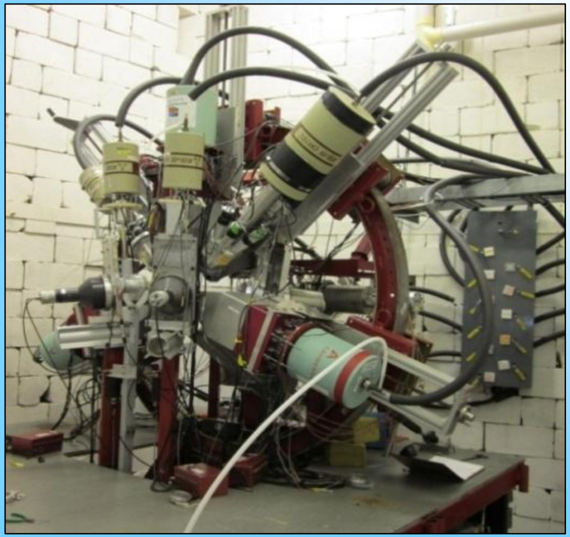
11 ΔE-E plastic scintillator detectors.

J.A. Alcántara-Nuñez et al., Nucl. Inst. Meth. A, 497, 429 (2003)

Experiments performed to study the ^{64,66,70}Ga nuclei

- Super-FN tandem Van de Graaff electrostatic accelerator (9 MV) Florida State University (FSU), USA:
  - ^{58}Ni(^{12}C,αpn)^{64}Ga, E_{beam}= 54 MeV.
  - ^{55}Mn(^{18}O,α3n)^{66}Ga, E_{beam}= 67 MeV.
  - ^{55}Mn(^{18}O,2pn)^{70}Ga, E_{beam}= 50 MeV.

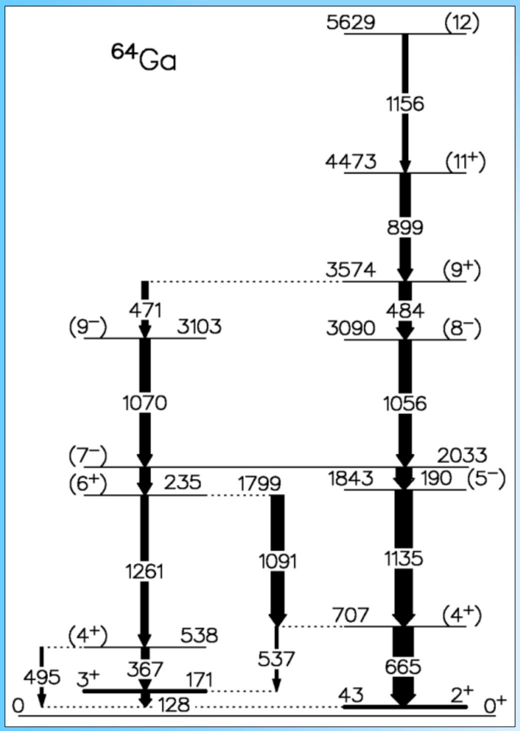
- FSU Clover Array:

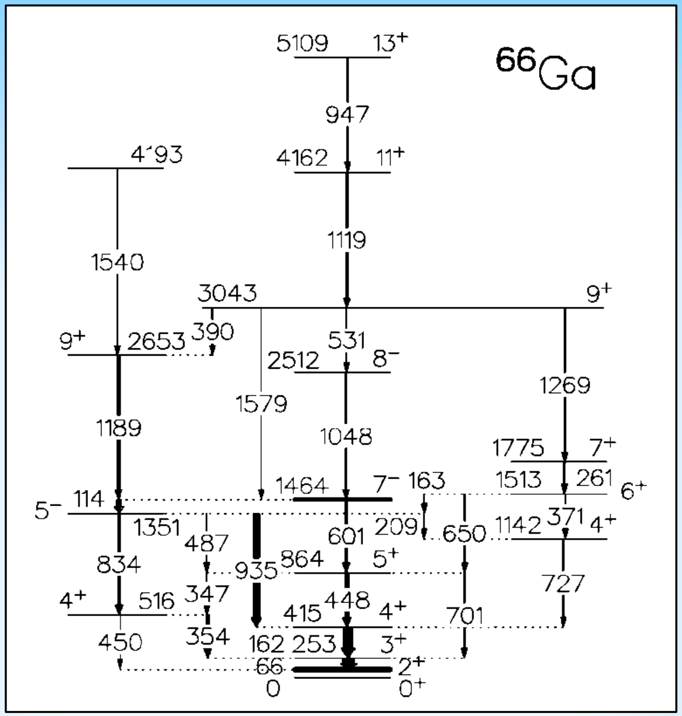


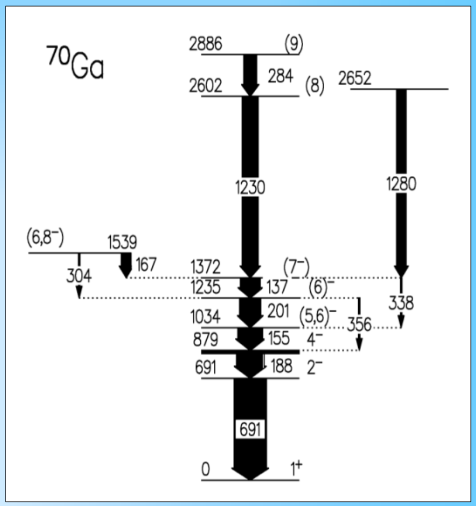
7 Compton suppressed HPGe detectors.
+
3 Compton suppressed Clover detectors (4 detectors each).

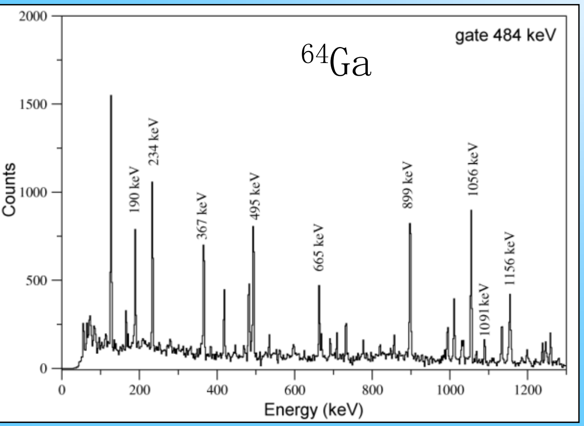
<http://www.physics.fsu.edu/nuclear/foxlab/nuclear-foxlab.html>

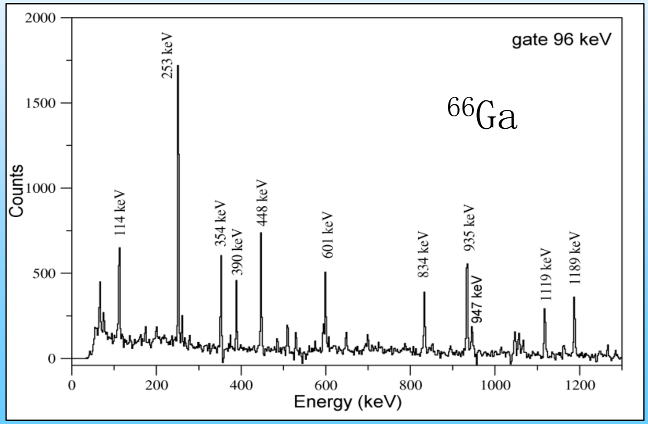
Odd-odd gallium isotope level schemes

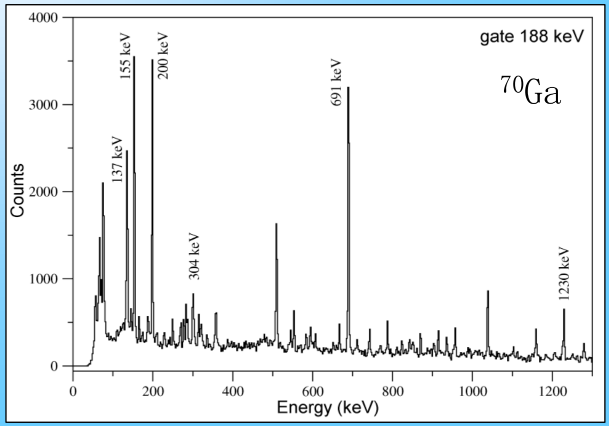




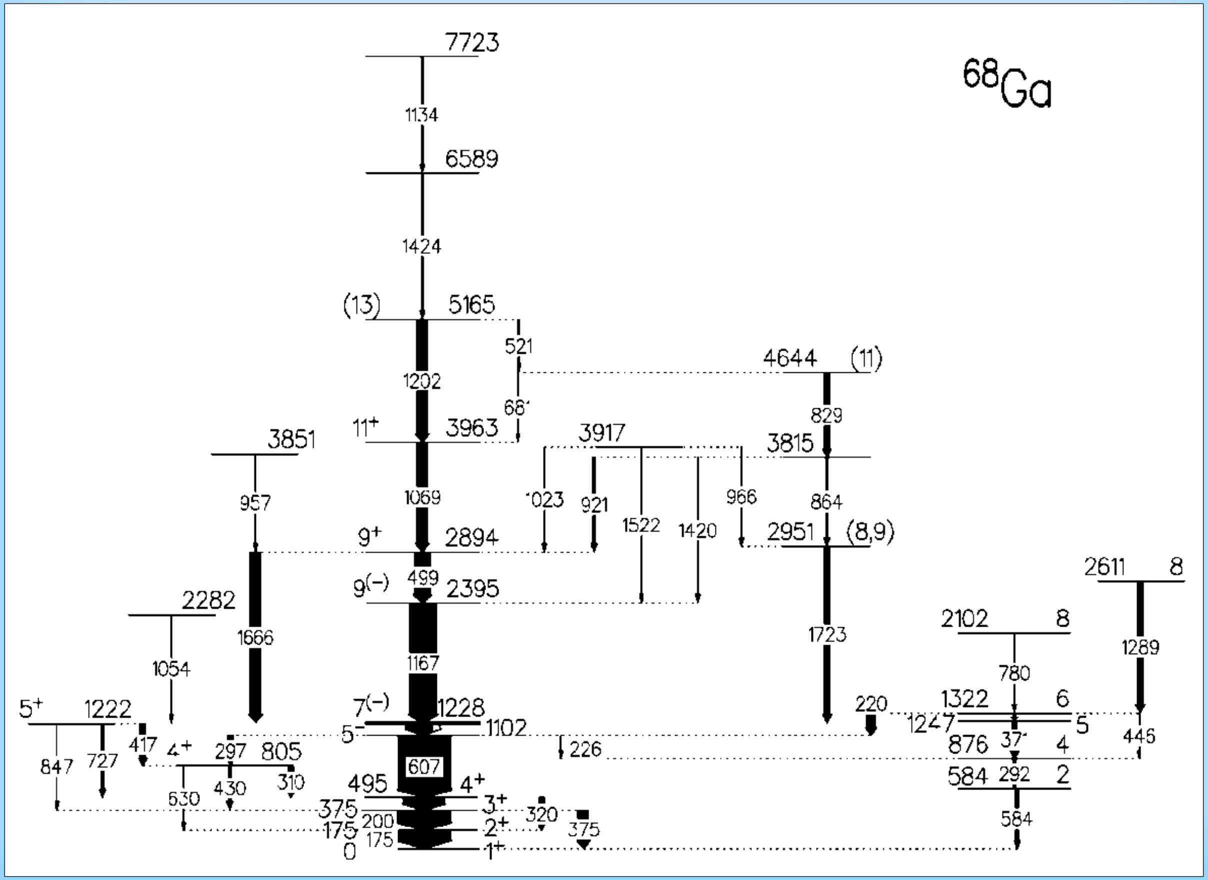








^{68}Ga Level Scheme



A.K. Singh et al., Eur. Phys. J. A 9, p. 197, 2000.

Large Scale Shell Model

- Antoine code.

  CAURIER, E and NOWACKI, F. Acta Physica Polonica B **30**, (1999).

- two different effective interactions:
  - JUN45 -> Developed specially for the f_5pg_9 region ($1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$).

    HONMA, H. et al.,Physical Review C **80**, 064323 (2009).

  - fpg -> Developed for the fpg region (**$0f_{7/2}$**, $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$).

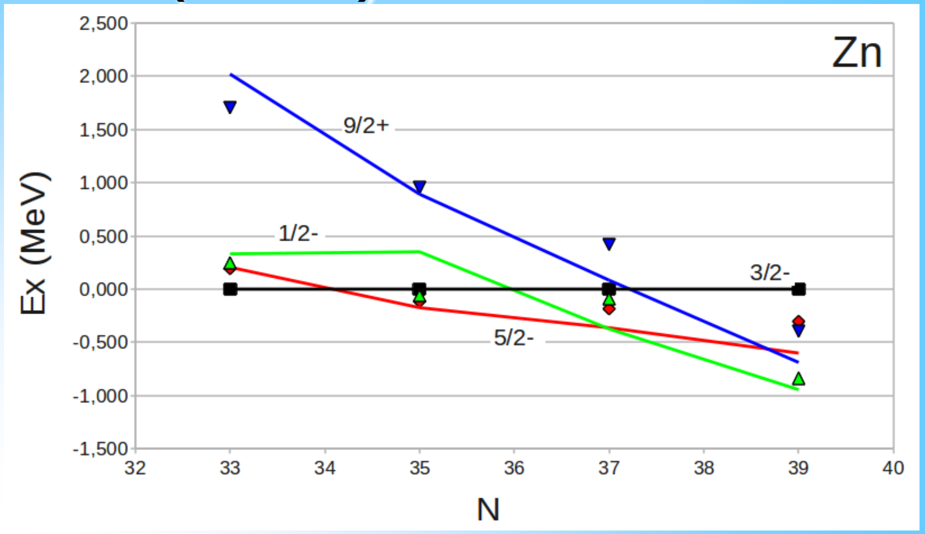
    SIEJA, K. and NOWACKI, F. Physical Review C **81**, 061303(R) (2010).

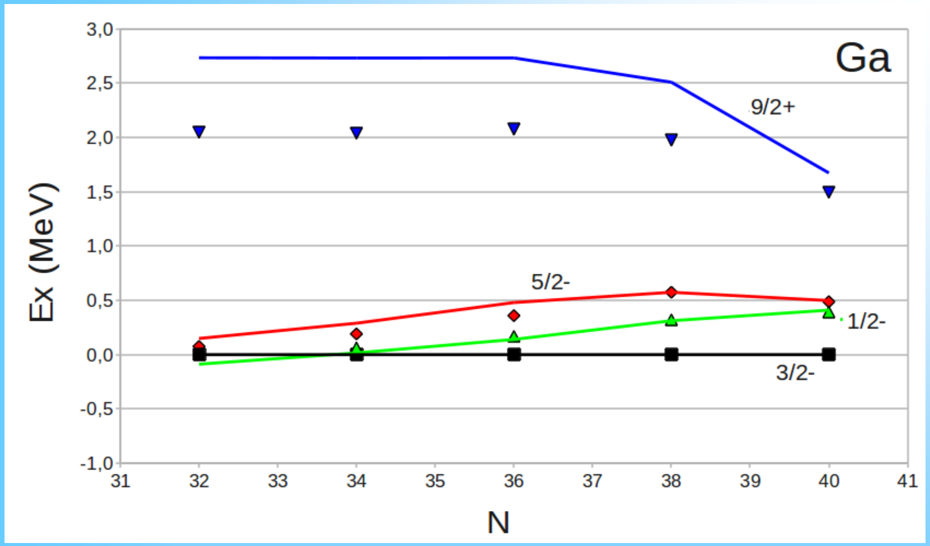
fpg neighbor odd nuclei:
Zn (Z=30), Ga (Z=31) and Ge (Z=32)

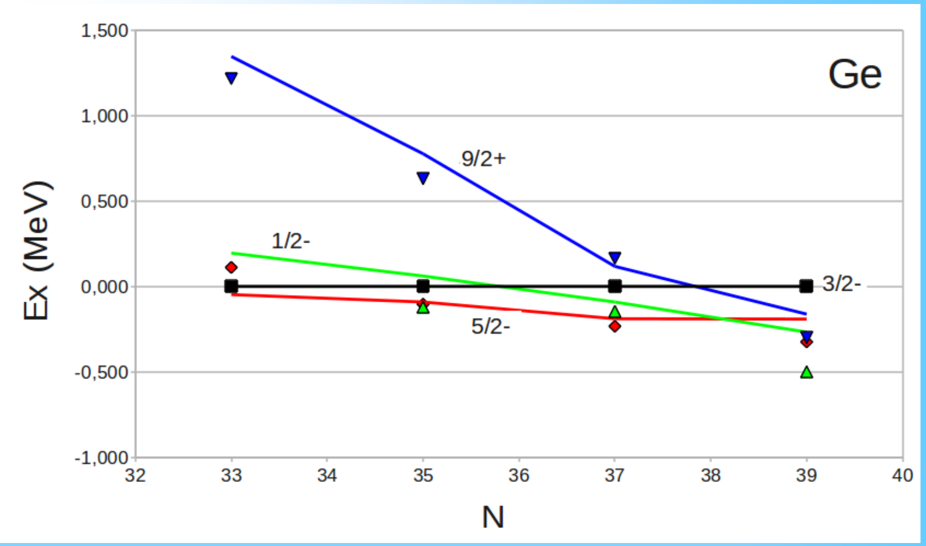
Antoine code

JUN45 residual interaction

$1/2^-$, $3/2^-$, $5/2^-$ and $9/2^+$ excited states



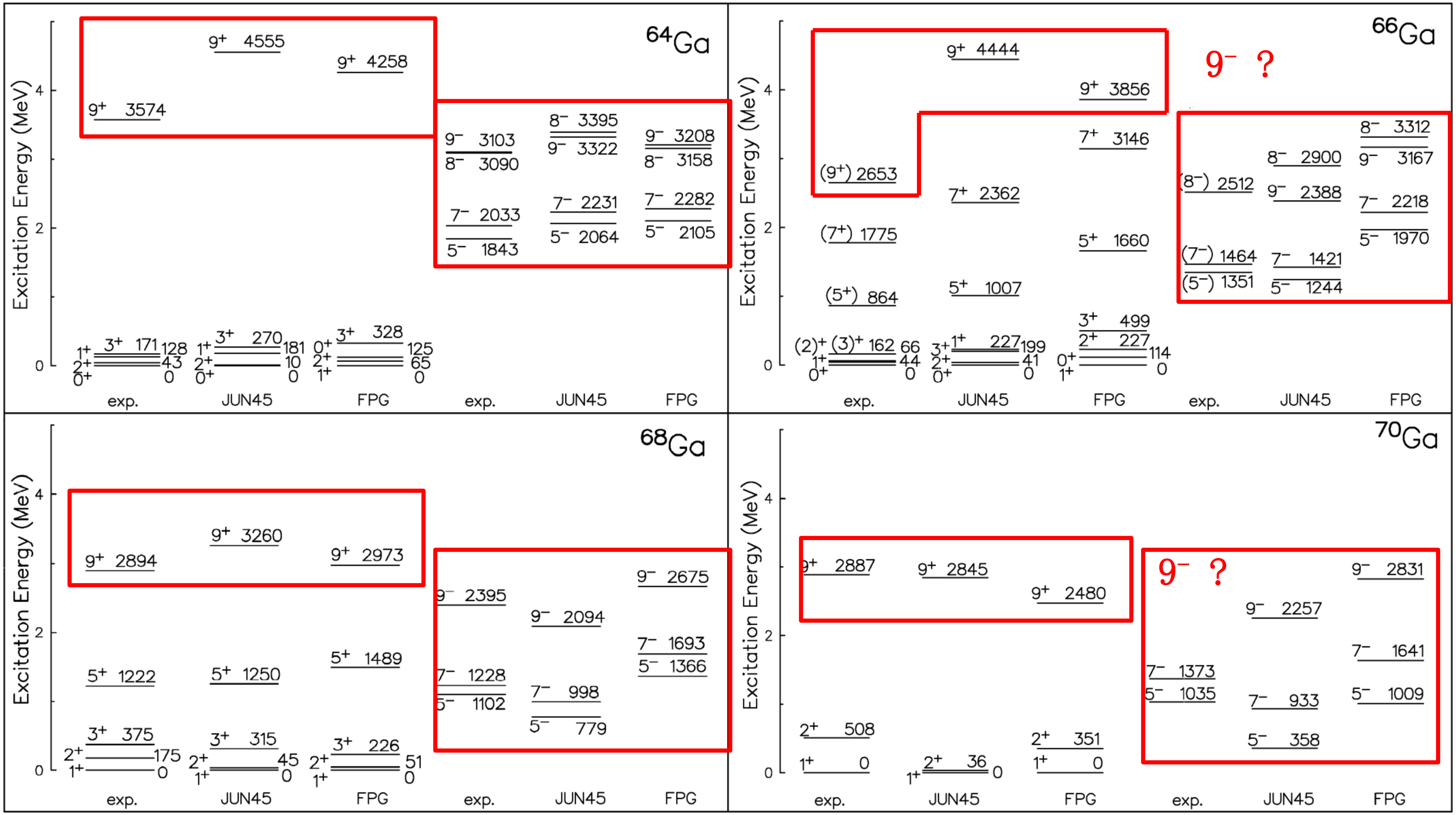




$9/2^+$ excited states are due to nucleon excitation to the $g_{9/2}$ orbital

H. Honma et al. Phys. Rev. C 80 (2009) 064323

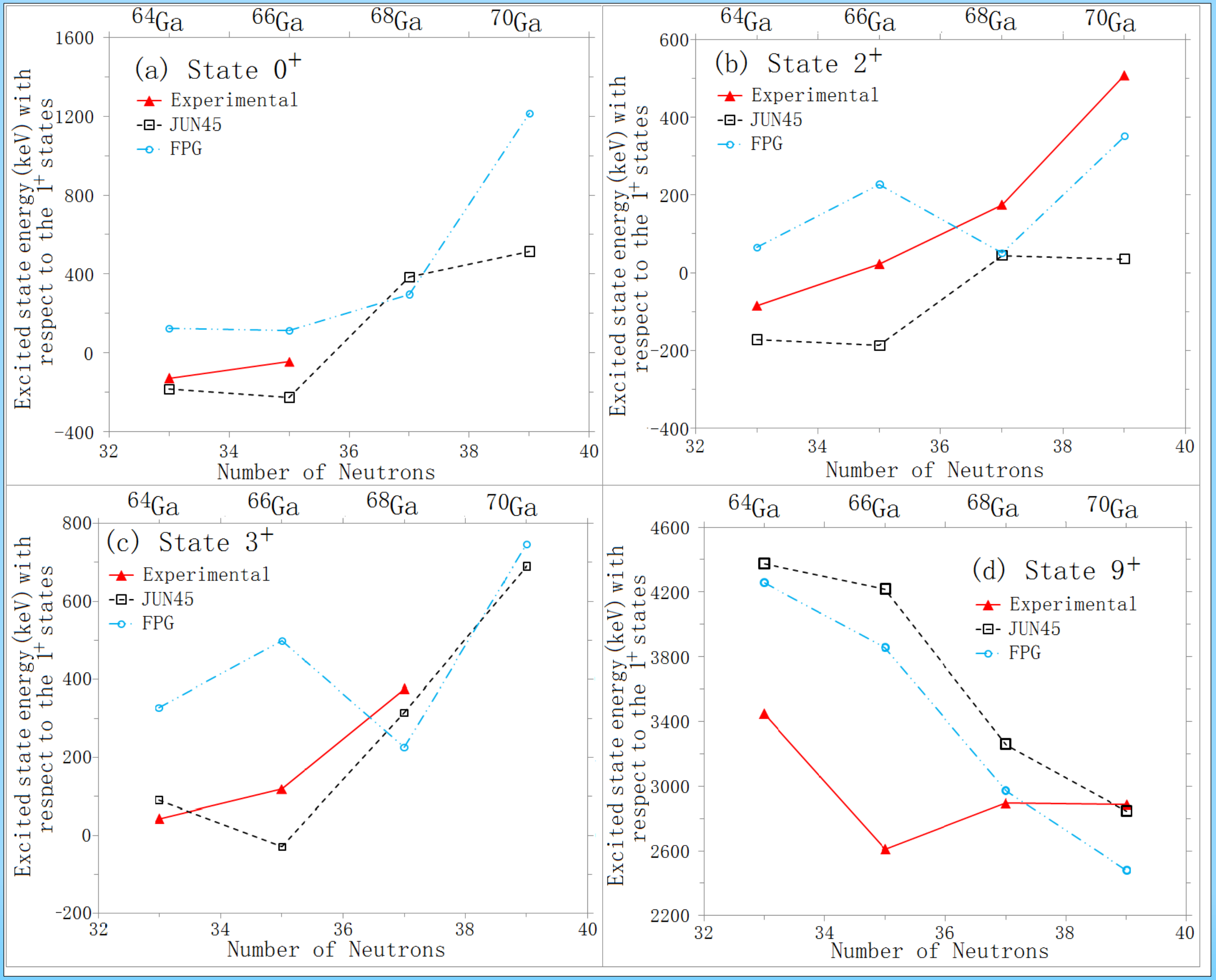
Antoine Results for $^{64,66,68,70}Ga$



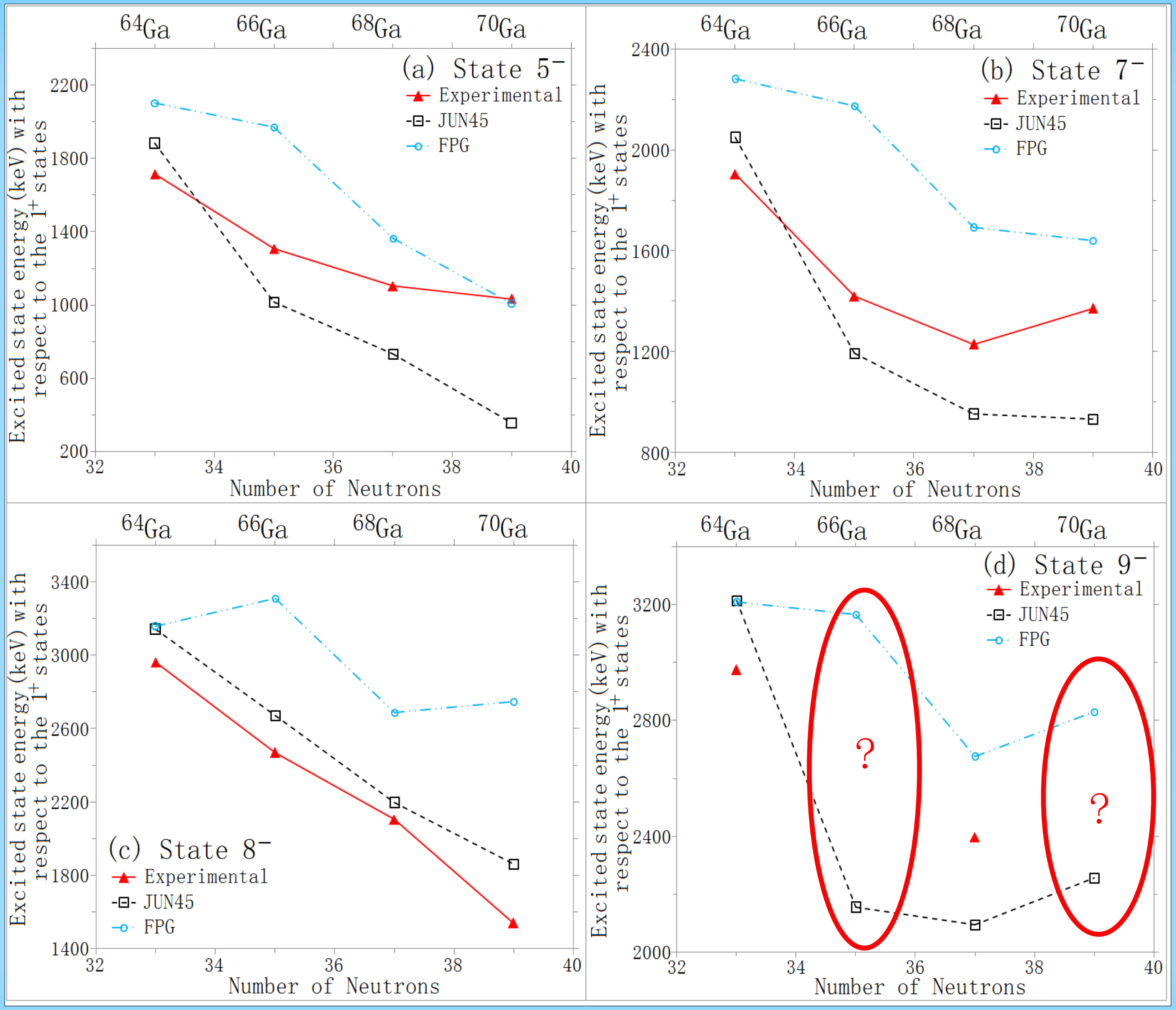
9^{+} state: 1 proton and 1 neutron in the $0g_{9/2}$ orbital

All negative parity states: one neutron in the $0g_{9/2}$ orbital

Systematic Study of $^{64,66,68,70}Ga$ nuclei

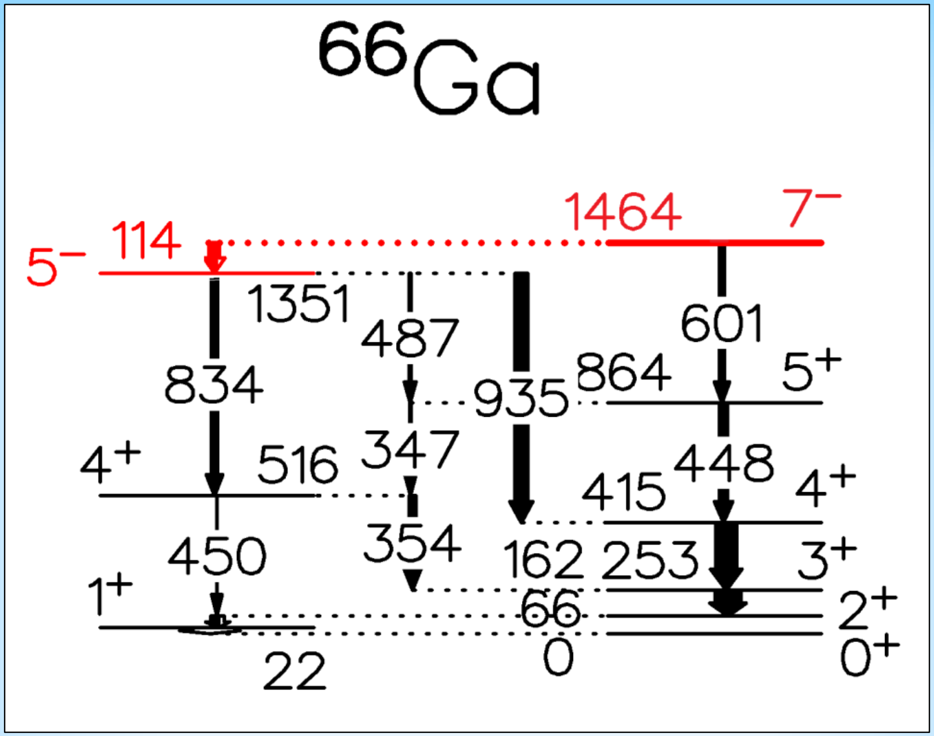


Systematic Study of ^{64,66,68,70}Ga nuclei



The excited states are described by particle-hole excitations and they are characterized by wave functions with large mixture of configurations.

Test of the calculated wave functions: ^{66}Ga 7^- Isomeric State E2 transition



$$B_{EXP}(E2) = \frac{\ln(2)\ \text{x}\ I\gamma}{1.23\text{x}10^9\ \text{x}\ T_{1/2}\ I_{total}\ E\gamma^5}$$

$$B(E2, J_i M_i \zeta \rightarrow J_f M_f \xi) = \frac{1}{2J_i+1} \left| \langle J_f \xi || \mathbf{O}_{E2} || J_i \zeta \rangle \right|$$

Calculated B(E2) for the ^{66}Ga $7^- \rightarrow 5^-$ Transition

$$B(E2, J_i M_i \zeta \rightarrow J_f M_f \xi) = \frac{1}{2J_i+1} \left| \langle J_f \xi \| \mathbf{O}_{E2} \| J_i \zeta \rangle \right|$$

interaction	J^π	Mix(%)	Configuration								J^π	Mix(%)	Configuration							
			protons				neutrons						protons				neutrons			
			$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$	$0g_{9/2}$	$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$	$0g_{9/2}$			$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$	$0g_{9/2}$	$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$	$0g_{9/2}$
JUN45	7−	10.1	2	1	0	0	4	2	0	1	5−	5.2	2	1	0	0	4	2	0	1
		4.7	2	1	0	0	3	3	0	1		4.0	2	1	0	0	3	3	0	1
		10.3	2	1	0	0	2	4	0	1		7.3	2	1	0	0	2	4	0	1
		4.6	2	1	0	0	2	2	2	1		2.5	2	1	0	0	2	2	2	1
		4.2	1	1	1	0	2	4	0	1		4.9	1	1	1	0	2	4	0	1
FPG	7−	9.5	2	1	0	0	4	2	0	1	5−	3.7	2	1	0	0	4	2	0	1
		7.0	2	1	0	0	3	2	1	1		3.4	2	1	0	0	3	2	1	1
		9.1	2	1	0	0	2	4	0	1		4.6	2	1	0	0	2	4	0	1
		8.3	2	1	0	0	2	2	2	1		2.5	2	1	0	0	2	2	2	1
												6.2	2	0	1	0	4	2	0	1
												5.0	2	0	1	0	3	2	1	1
												5.1	2	0	1	0	2	2	2	1

$B_{JUN45}(E2) = 301 \ e^2fm^4$ $B_{fpg}(E2) = 259 \ e^2fm^4$

Experimental B(E2) for the ^{66}Ga $7^- \rightarrow 5^-$ Transition

Two known values for the ^{66}Ga 7^- isomeric state:

$T_{1/2}$ = 57.3 (14) ns or $T_{1/2}$ = 39 (2) ns

A. Filevich et al., Nucl. Phys. A, 295, 513, 1978.

T. Kouda et al., Ann. Rep. 1996, Radio-isotope Center, Tohoku University, Japan, p. 19, 1997.

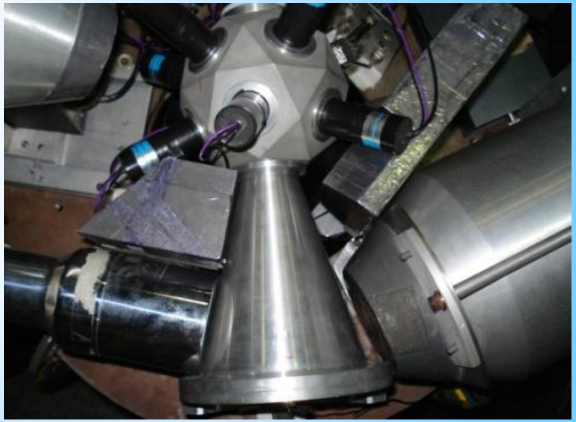
SISMEI spectrometer

^{58}Ni(^{11}B,2pn)^{66}Ga, E_{beam}= 45 MeV

$T_{1/2}$ = 58.1 (12) ns

$B_{EXP}(E2)$ = 242 (6) e^2fm^4

$$B_{JUN45}(E2) = 301\ e^2fm^4$$
$$B_{fpg}(E2) = 259\ e^2fm^4$$



D.L.Toufen, Master Thesis, Universidade de São Paulo (2008).

Conclusion

In-beam γ-ray spectroscopy

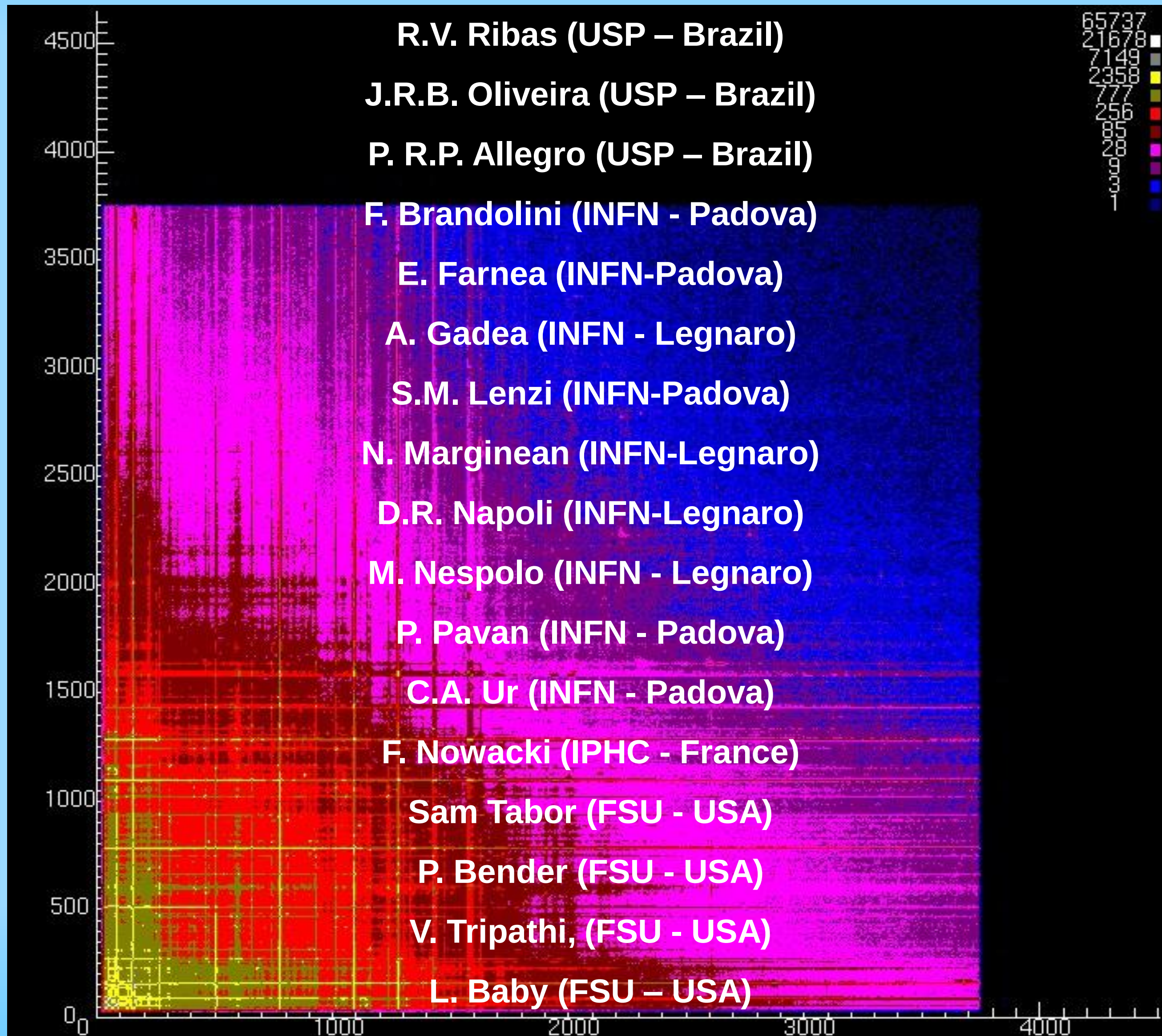
High spin states

- Nuclear Shapes
- Shape coexistence
- Superdeformed shapes

Large Scale Shell Model

- fp shell
  - $^{46,48}V$ and ^{48}Cr
- fpg shell
  - $^{64,66,68,70}Ga$

Collaborators



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Thank you for your attention