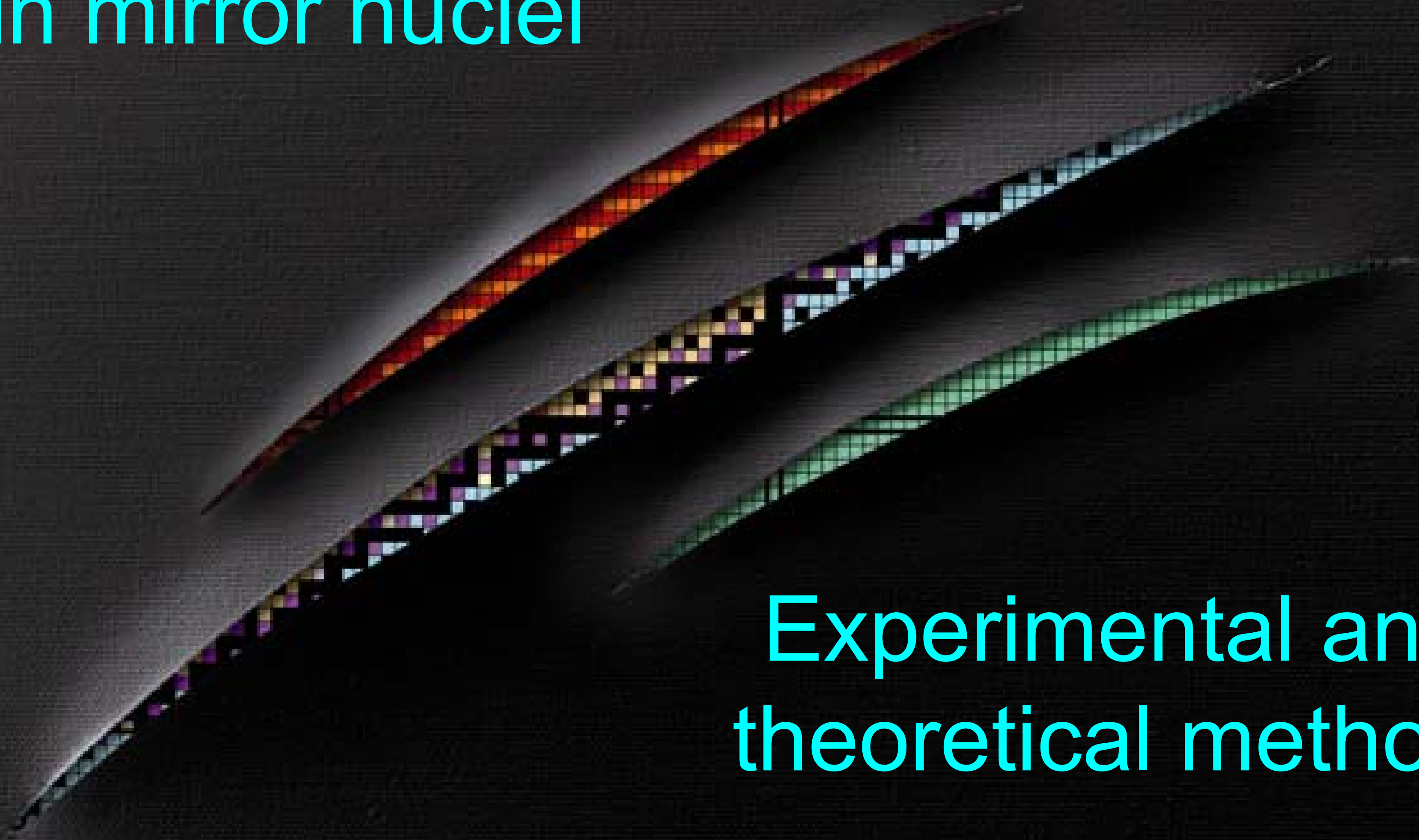
# Isospin symmetry breaking in mirror nuclei

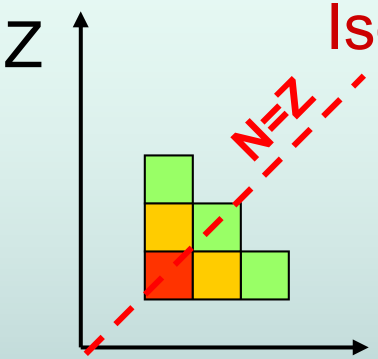


## Experimental and theoretical methods

Silvia M. Lenzi
*Dipartimento di Fisica dell'Università and INFN, Padova, Italy*

# 2. Experimental techniques for mirror spectroscopy

# Coulomb Energy Differences (CED)




Isospin symmetry manifests better along the N=Z line

Analogue states with low spin are studied in CDE (IMME)

What about the difference in excitation energy with increasing spin?

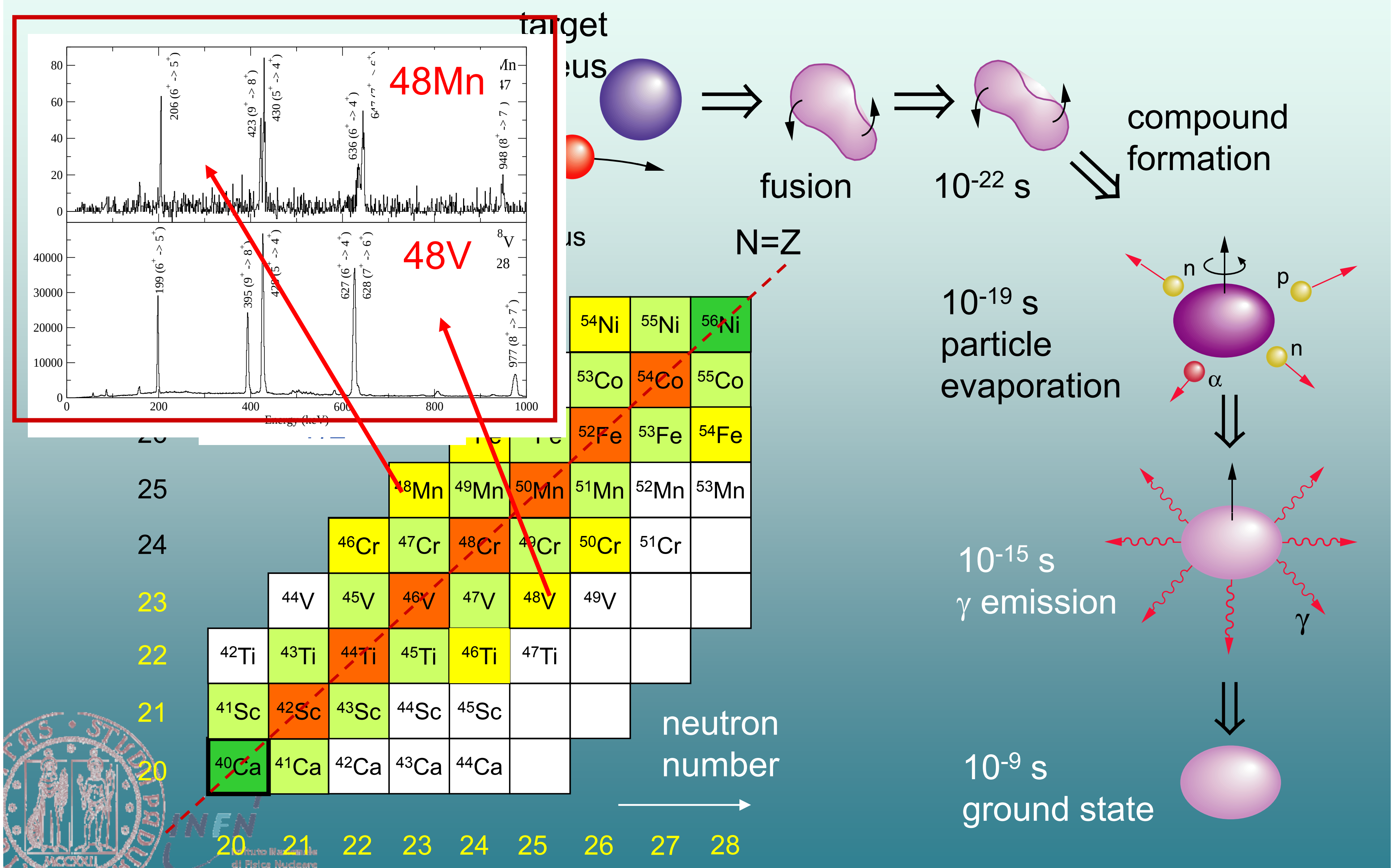
CED have been restricted for many years to low-spin states due to the difficulties in populating proton rich nuclei…

## Experimental issues

- proton-rich $T_z < 0$ isobars only weakly populated
- "mirrored" gamma-ray energies almost identical

→ we need very clean reaction channel selection…

# Populating proton-rich nuclei

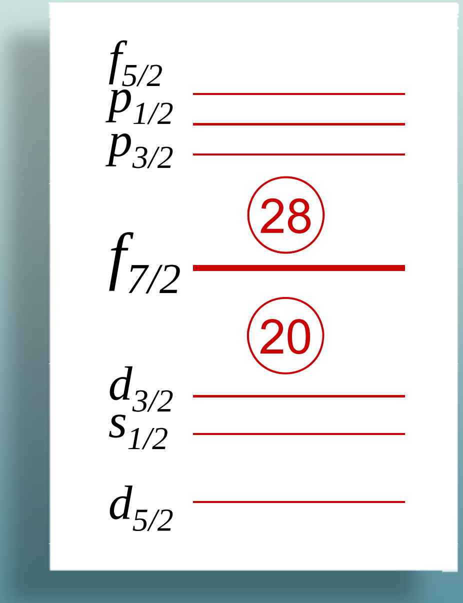


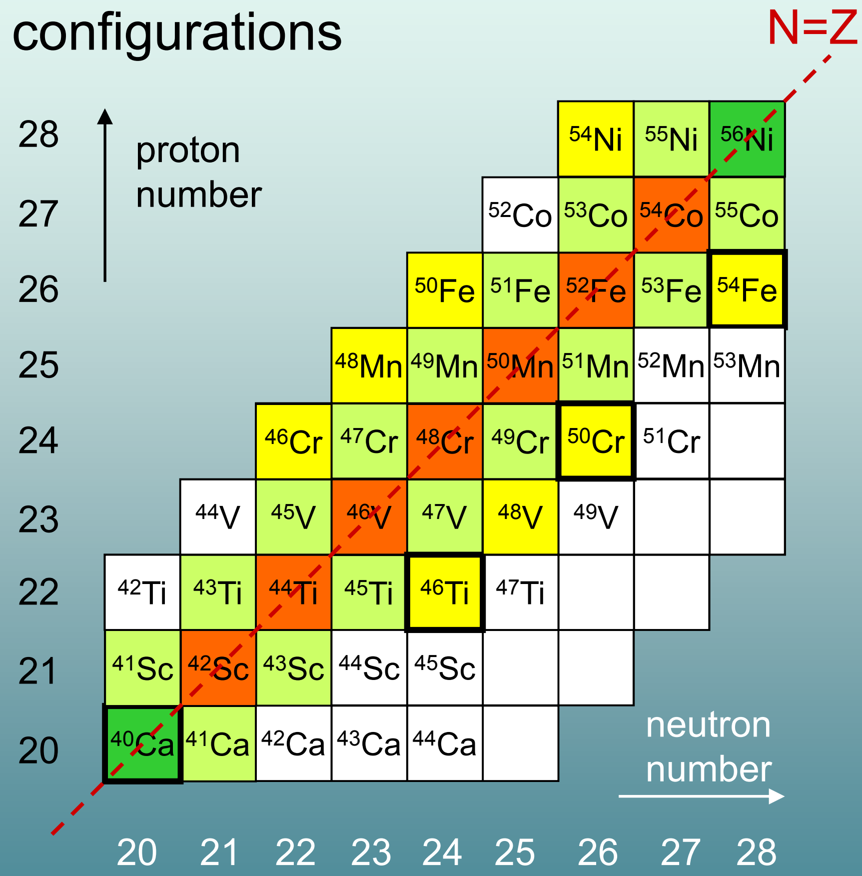
# Example: the $f_{7/2}$ shell

The $1f_{7/2}$ shell is isolated in energy from the rest of fp orbitals

Wave functions are dominated by $(1f_{7/2})^n$ configurations

High-spin states experimentally reachable



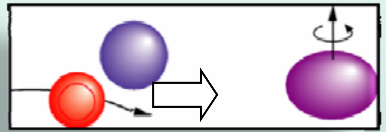

Experimental issue : proton-rich $T_z$=-1/2 isobars are weakly populated

"Mirrored" gamma ray energies almost identical – need very clean reaction channel selection…

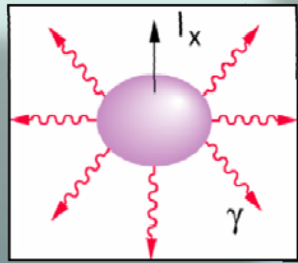
# Experimental requirements

## High efficiency and resolution for γ detection

Low cross section at high spin (small masses)

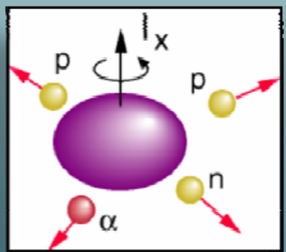


High energy transitions

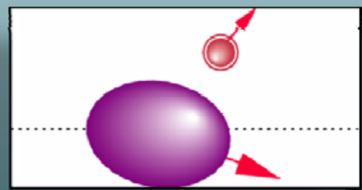



## Good selectivity: particle detectors

Many channels opened: high efficient charged-particle detectors




Kinematics reconstruction
for Doppler broadening



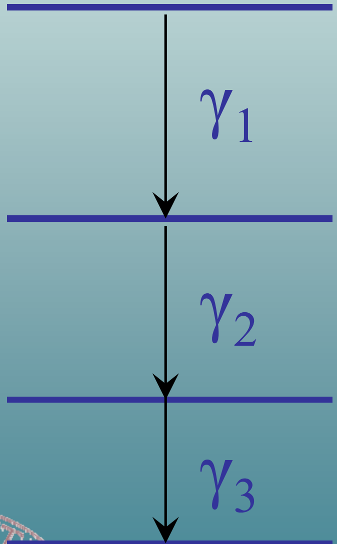
Mass spectrometers

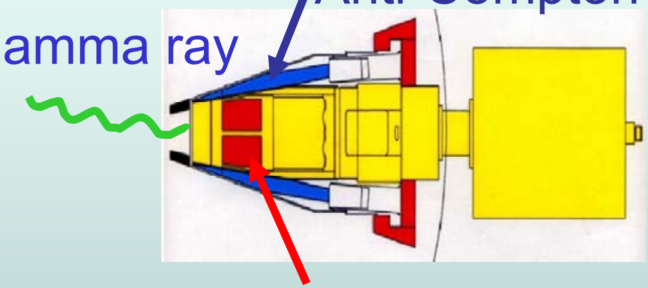
Neutron detectors to select proton-rich channels

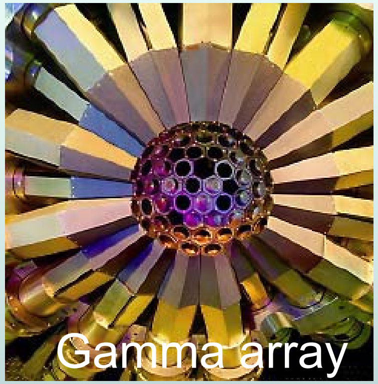
Polarimeters and granularity (**J, π, δ**)

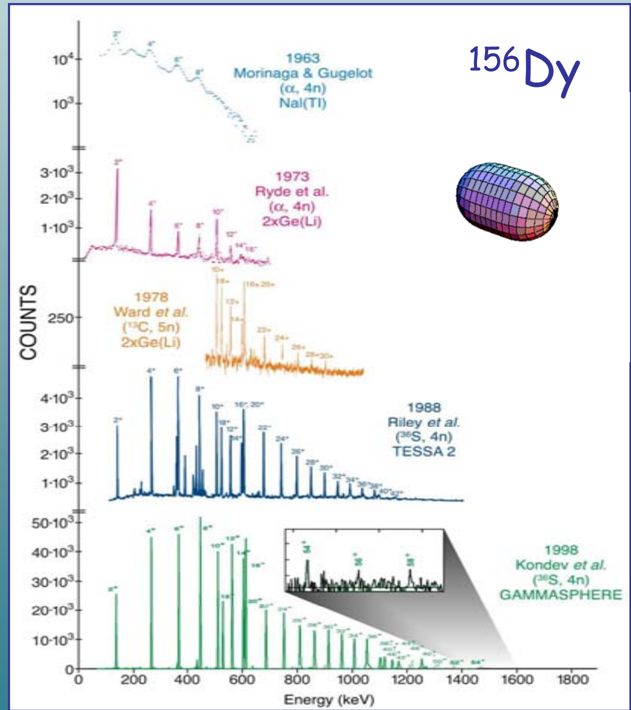
# Gamma spectroscopy

Constructing
a level scheme



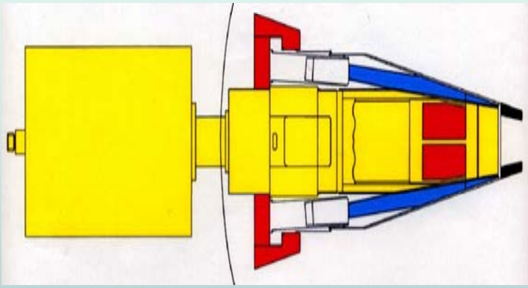



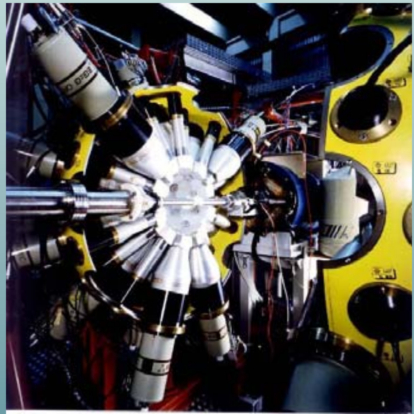



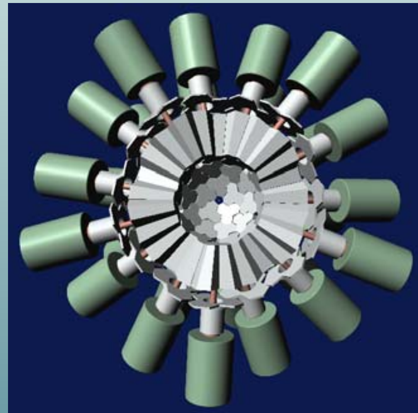
# Gamma-ray spectrometers

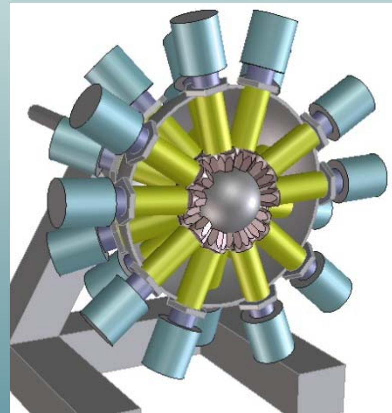
Conventional techniques

New technique: tracking









**GASP** **GAMMASPHERE** **AGATA** **GRETA**

**$\varepsilon \sim 10 — 5$ %**
**( $M_\gamma$=1 — $M_\gamma$=30)**

→

**$\varepsilon \sim 40 — 20$ %**
**( $M_\gamma$=1 — $M_\gamma$=30)**

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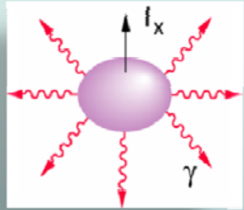
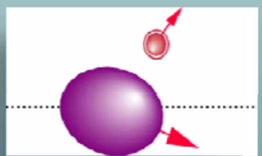
# Techniques for proton-rich spectroscopy

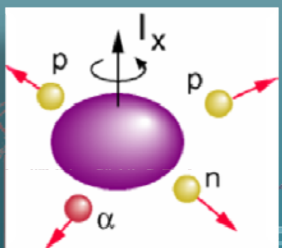
## Three basic techniques for selecting proton-rich systems




1. High efficiency & high granularity gamma-ray spectrometer
   high fold $\gamma^n$ ($n \geq 3$) coincidence spectroscopy

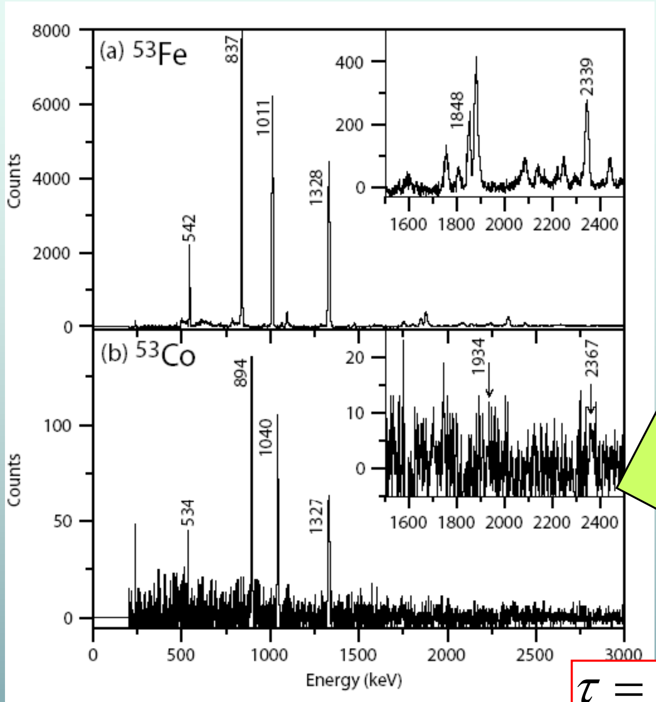


2. Gamma-ray array + mass spectrometer + focal plane detectors - identify A,Z of recoiling nucleus and ToF
   → tag emitted gamma-rays




3. Identify cleanly all emitted particles from reaction - needs a charged-particle detector array + high-efficiency & high granularity neutron detector array + γ-ray array

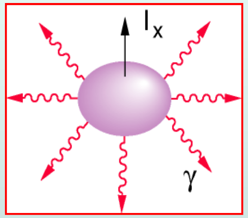
# 1. High-fold γ-coincidence spectroscopy

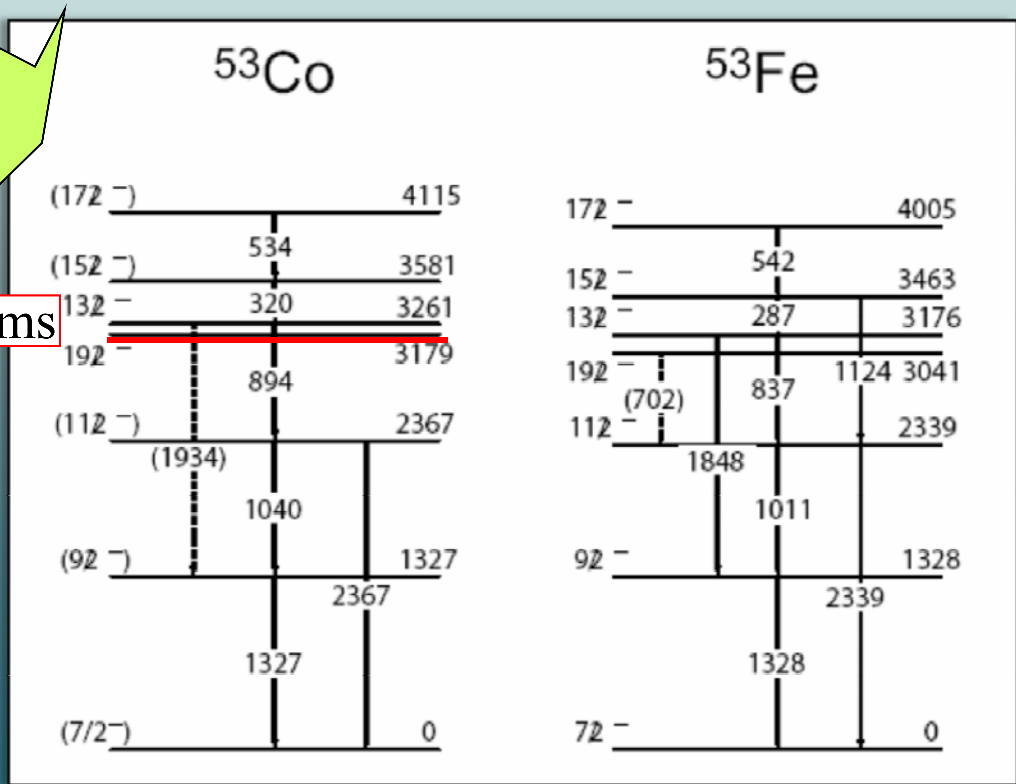



Rely on the power of the array:

- high-fold gamma ray coincidences
- high granularity…

and on the similarity between the energy of the transitions with those of the known mirror nucleus




$\tau = 260$ ms

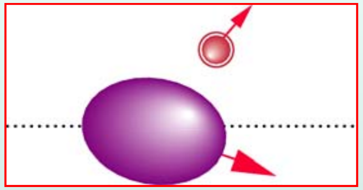
Double-coincidence spectra after gating on 2 analogue transitions

$$^{32}S\left(^{24}Mg,1p2n\right)^{53}Co$$

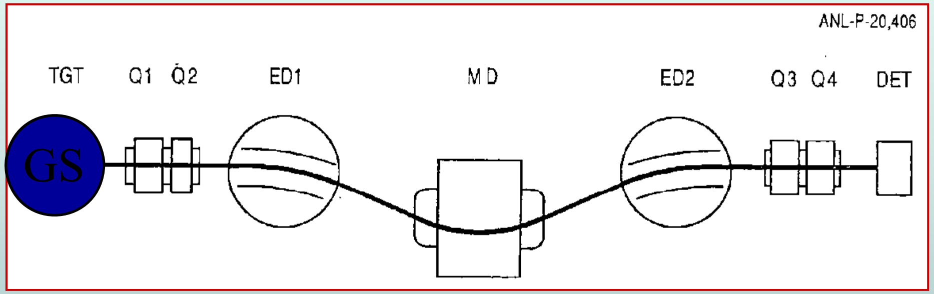
$$^{32}S\left(^{24}Mg,2p1n\right)^{53}Fe$$

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

# 2. Identify A and Z of the recoiling nucleus



Fragment Mass Analyser




- Combined electric and magnetic dipoles → beam rejection & *A/q* separation
- *A/q* identified by *x*-position at focal plane
- Z identified by energy loss (E-ΔE) in gas-filled ionisation chamber
- information used to "tag" coincident gamma-rays at target position
- Efficiency - up to ~ 15%
- Measure the final residue

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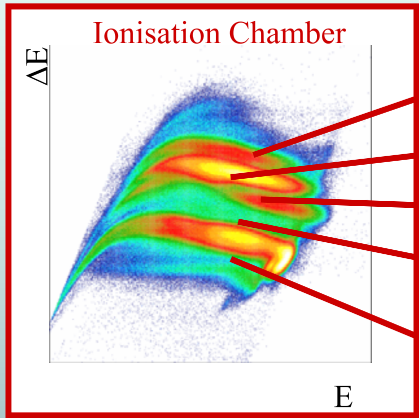
# An example: the A=48 mirror pair

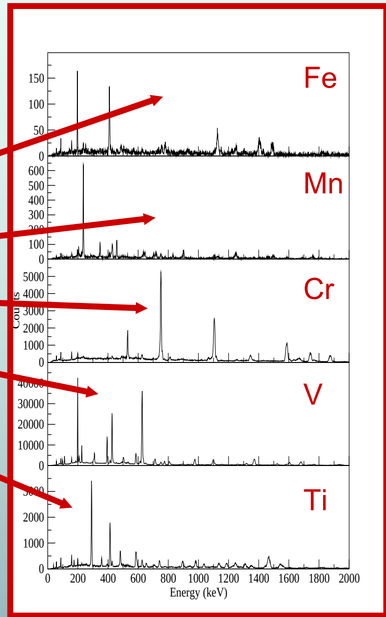
$^{48}_{25}Mn_{23}$ - $^{48}_{23}V_{25}$

$$\frac{\sigma\left(^{48}Mn\right)}{\sigma\left(^{48}V\right)} \sim 10^{-4}$$

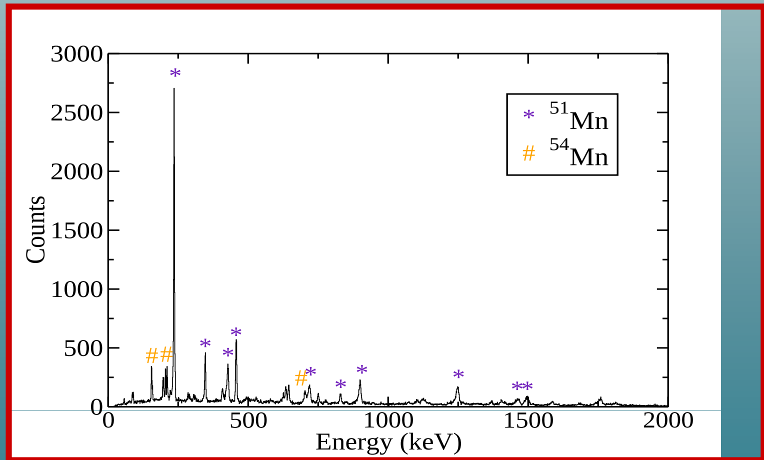
Need very good selectivity

Z identification




A/q selection
at the focal plane
+
gate on Z=25




M.A. Bentley et al.,
Phys. Rev. Lett. 93 (2006) 132501

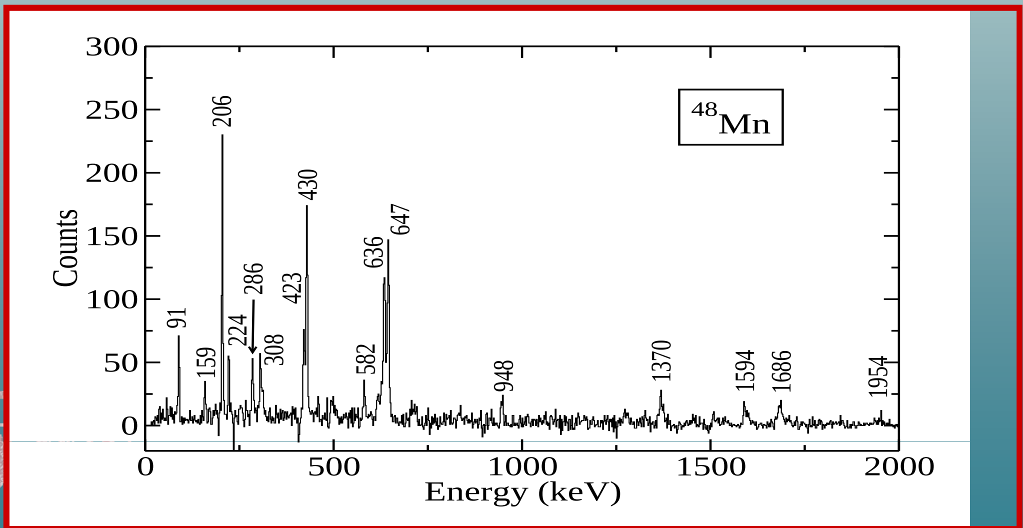
# Selecting “pure” spectra

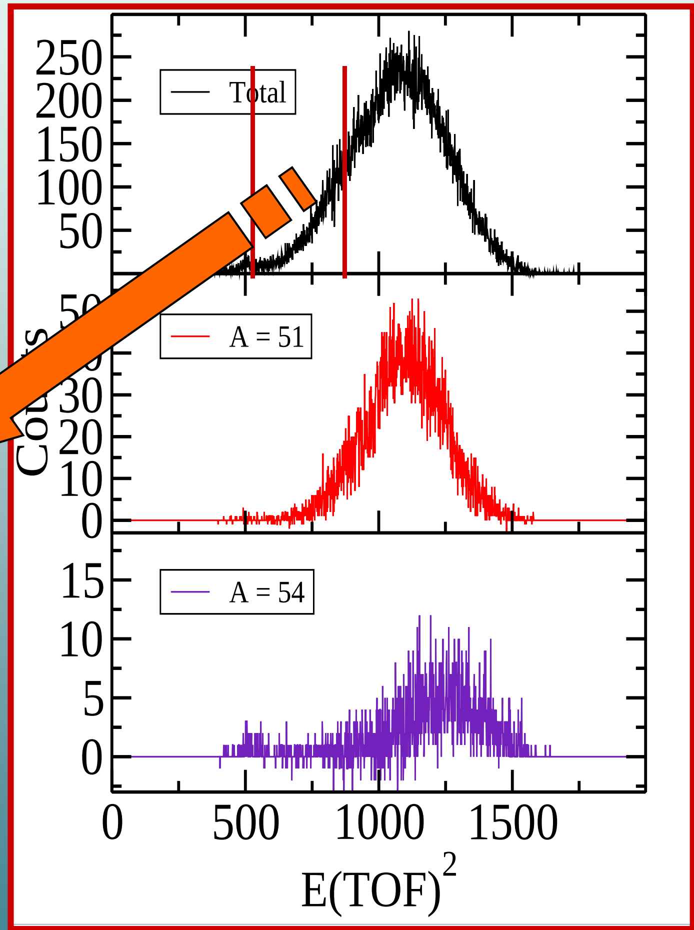
Contaminants can be removed by using the recorded total energy *E* and time-of-flight (*TOF*) of the recoils

Mass is proportional to $ET^2$

$$E = \frac{1}{2} m v^2, \qquad v = \frac{d}{TOF}$$
$$\Rightarrow m \propto E(TOF)^2$$

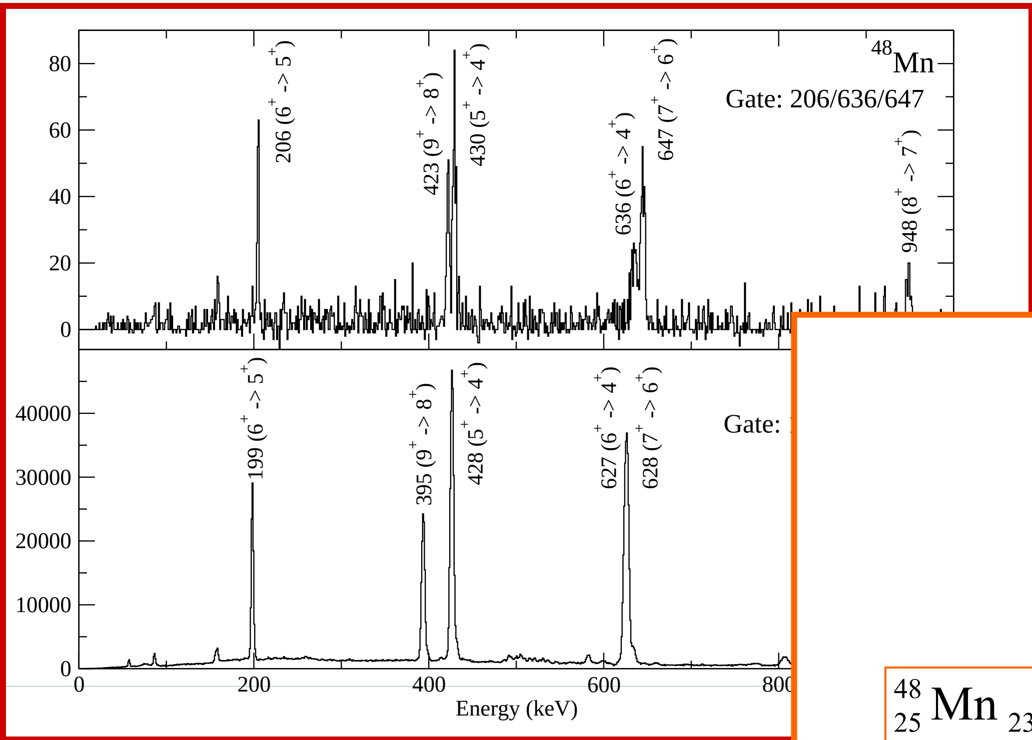
the $ET^2$ information has sufficient resolution to distinguish three mass units difference.



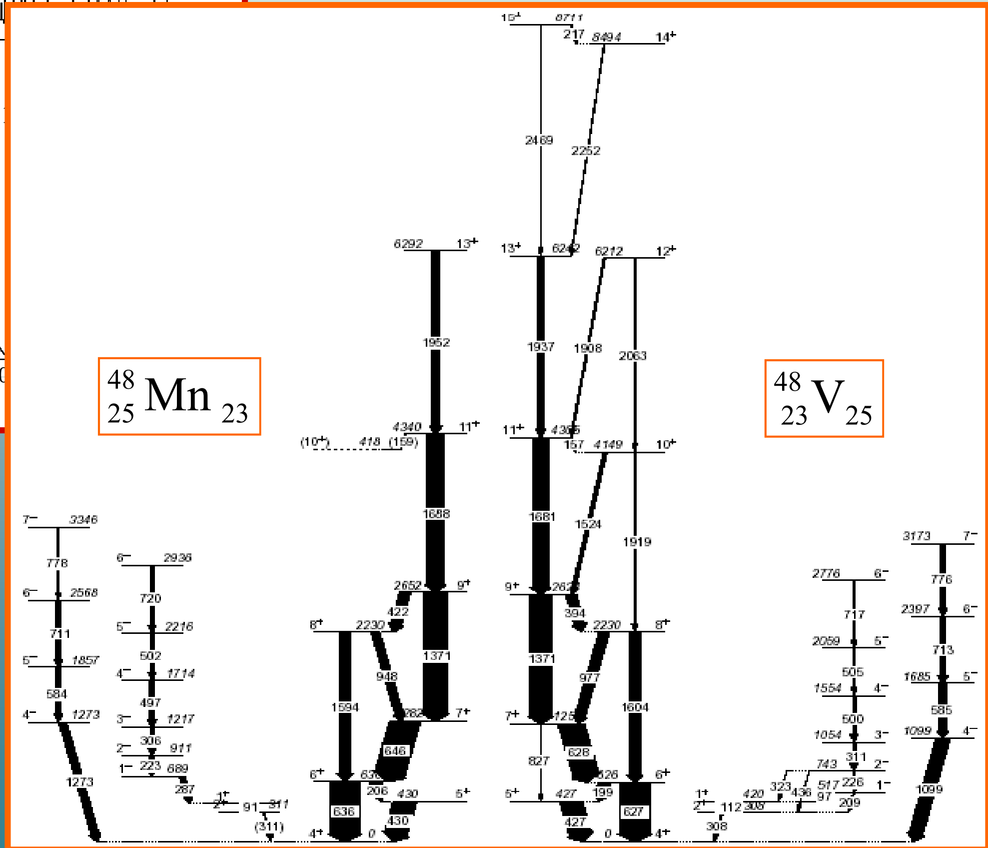

M.A. Bentley et al.,
Phys. Rev. Lett. 93 (2006) 132501

# γ-γ coincidence analysis




(A/q = 3, Z=25)-gated and E(TOF)$^2$-gated

γ-γ coincidence analysis…




M.A. Bentley et al.,
Phys. Rev. Lett., 97 (2006) 132501

# Fragmentation reactions and exotic beams

Fragmentation reactions with the removal of 5 or more particles are mainly of statistical character and populate yrast states.

One knock-out reactions are a direct process.

Two–proton knockout from neutron-rich nuclei and two–neutron knockout from proton-rich nuclei at intermediate or relativistic bombarding energies are also direct reactions.

Direct reactions selectively populate single-hole states

Between 3 and 5 nucleons removed the two processes compete

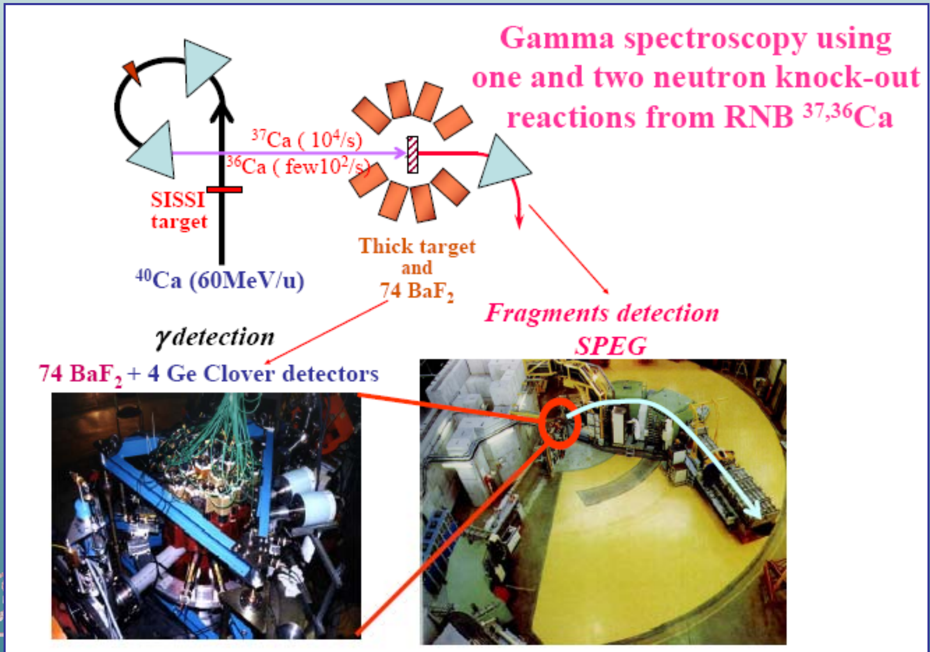
Fragmentation reactions are particularly suitable to populate mirror nuclei far from stability and near the proton dripline.

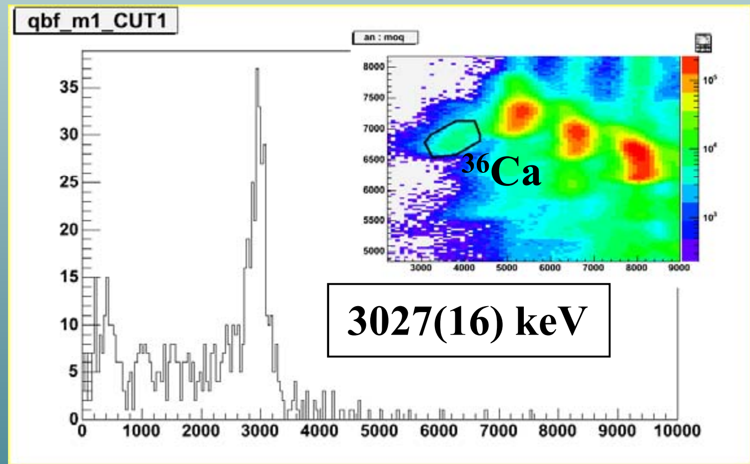
# Knockout reactions with exotic beams

**<u>Example</u>:** study the "magicity" of $^{36}$Ca – mirror of magic $^{36}$S (N=20, Z=16)

One neutron removal reaction from $^{37}$Ca beam

Technique pioneered at GANIL (Stanoiu et al. PRC 69, 034312 (2004))



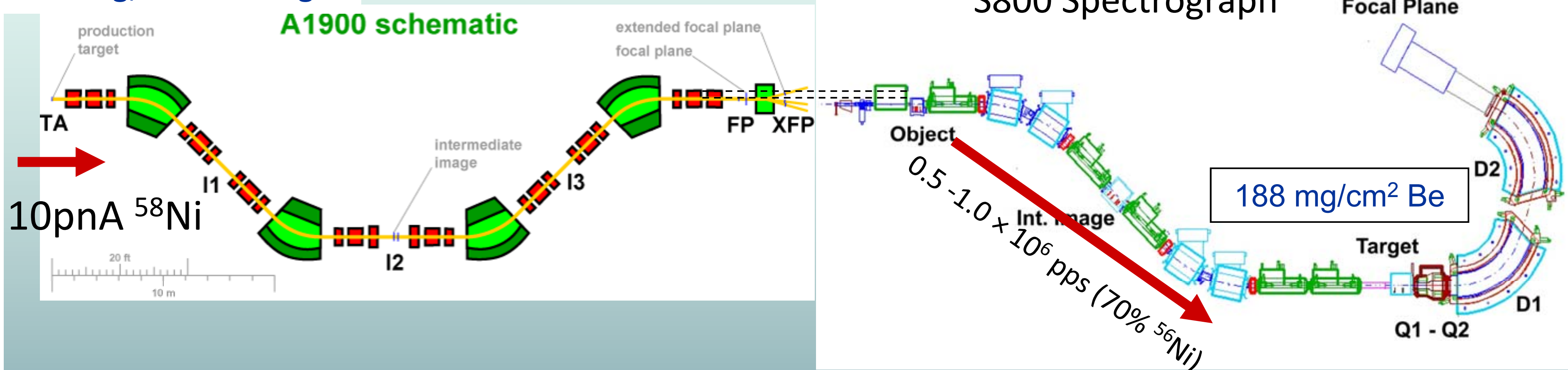




F. Azaiez et al.

# Mirrored fragmentation of N=Z nuclei

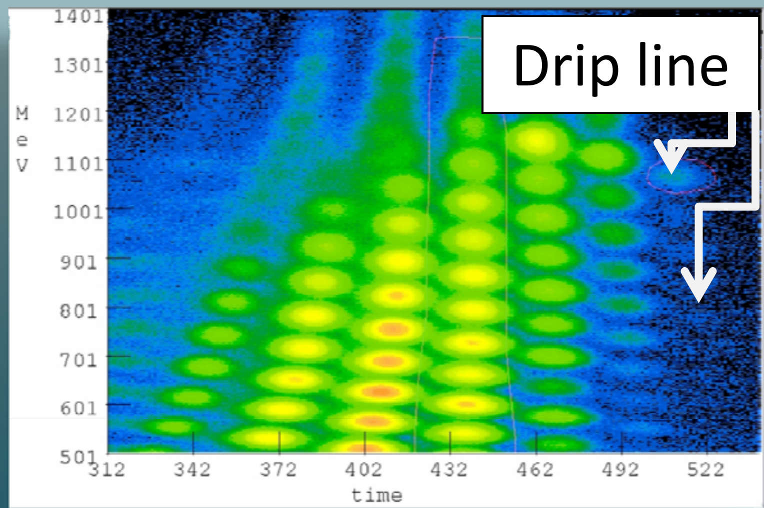
MSU experiment

600 mg/cm2 Be target




Primary → N=Z second. → “mirrored frag.”

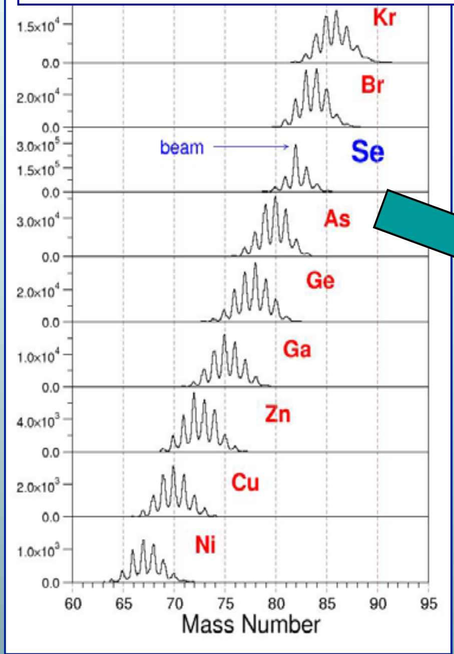
$^{58}$Ni → | $^{56}$Ni → | $^{53}$Mn, $^{53}$Ni

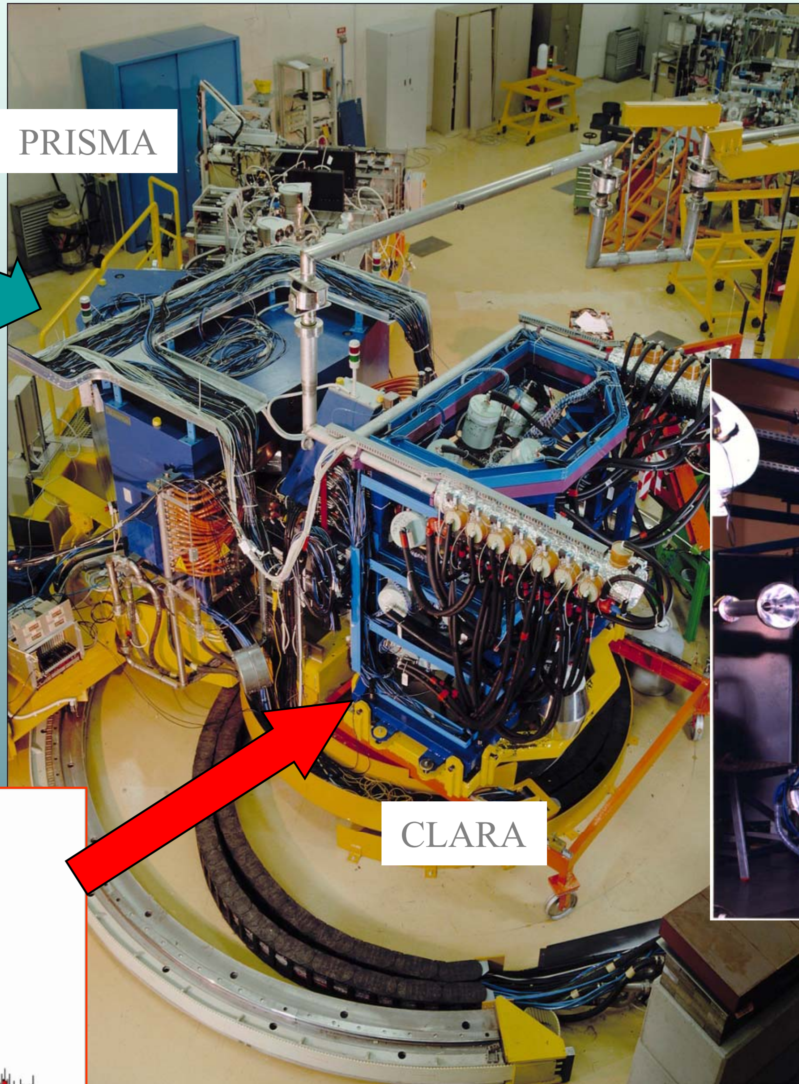



J.R. Brown et al.,
Phys. Rev. C 80, 011306(R) (2009)

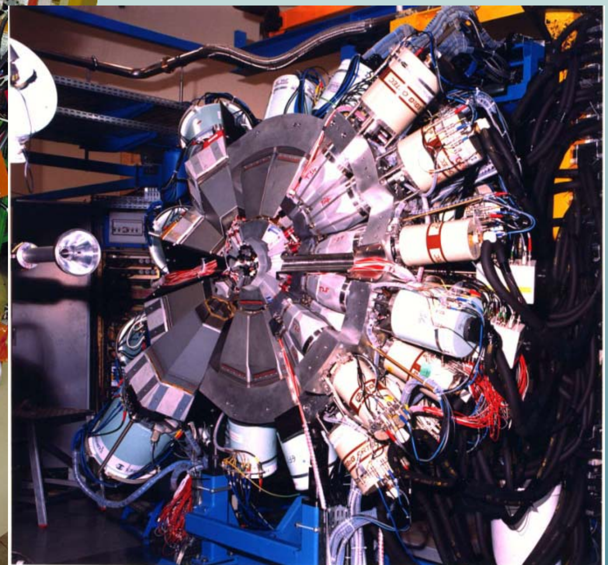
# Mirror nuclei with multinucleon transfer

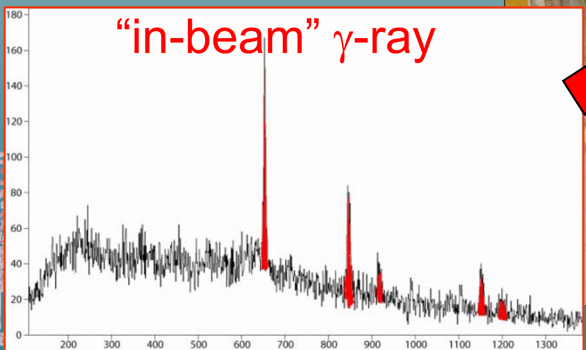
A & Z identification




Prisma + CLARA
@LNL, Italy





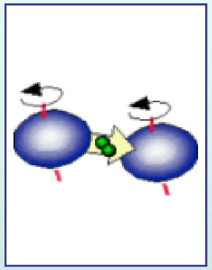

Efficiency ~ 3 %

Peak/Total ~ 50 %

FWHM ~ 10 keV @ v/c = 10%

# Mirror nuclei with multinucleon transfer

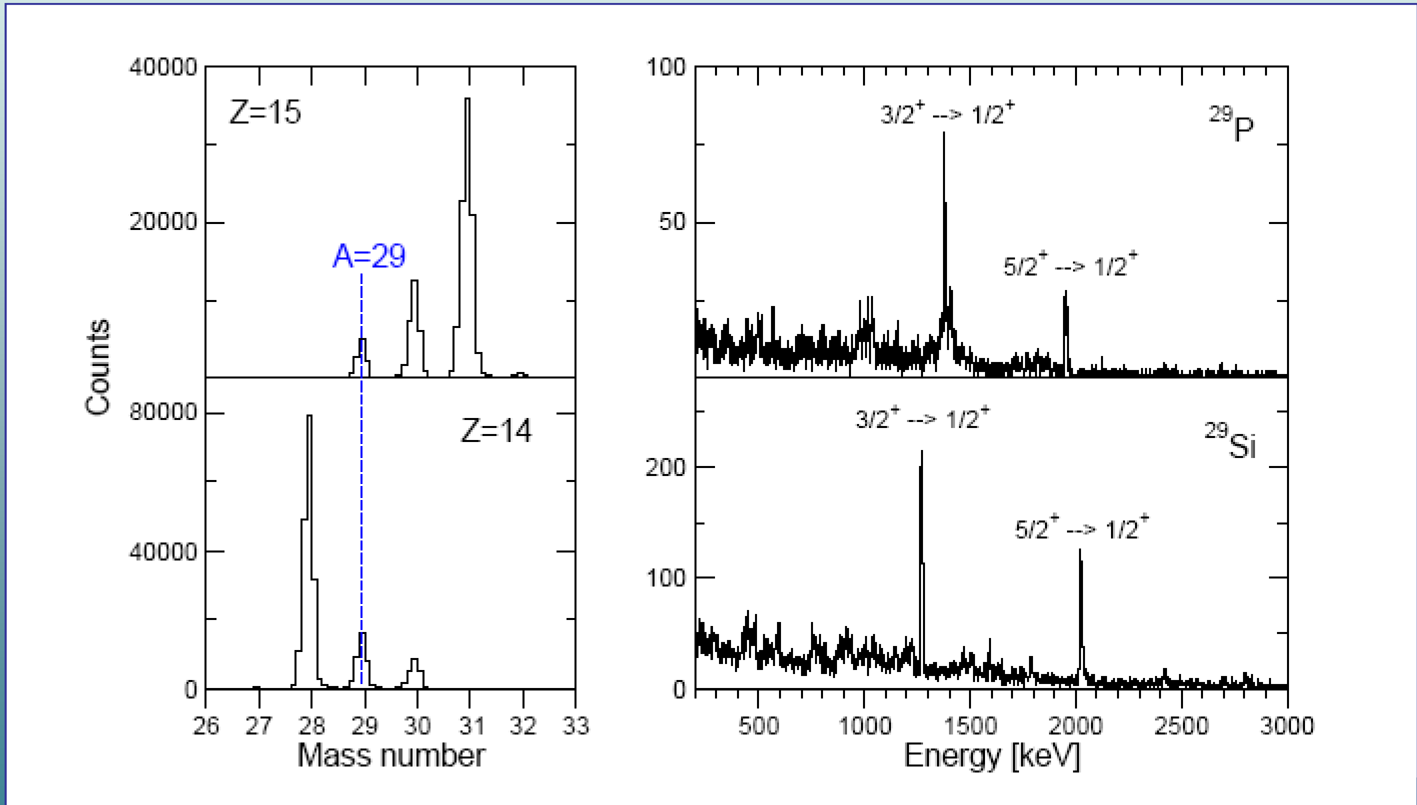
$^{32}S + ^{58}Ni$ →



→ $^{29}P + ^{61}Cu$

→ $^{29}Si + ^{61}Zn$

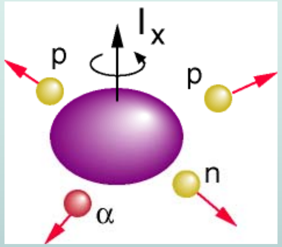
@ 135 MeV LNL, N. Marginean




PRISMA CLARA

# 3. Measuring the evaporated particles

With this method we do not measure directly the final residue but the particles emitted from the compound nucleus




charged particles

neutrons


We need detectors with high efficiency

Advantage: more flexible than recoil mass spectrometry
→ more channels can be measured!

Disadvantage: not as clean as RMS
If neutrons are needed, it may be much less efficient

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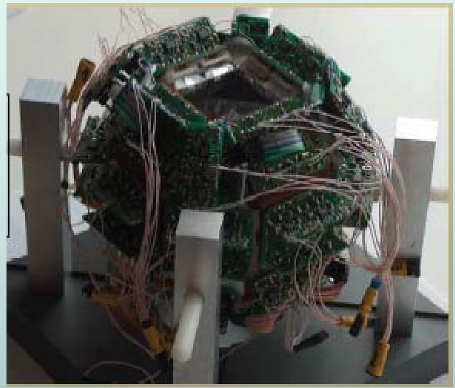
# Charged-particle detectors

DIAMANT

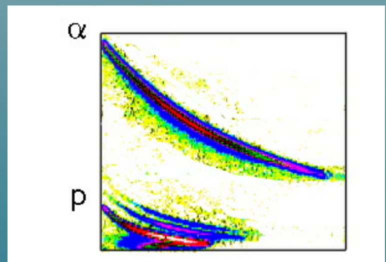


86 CsI(TI) elements scintillators

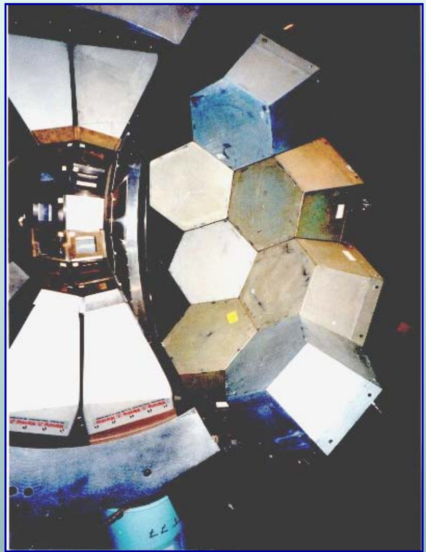
efficiency: protons ~70%
alphas ~ 50%

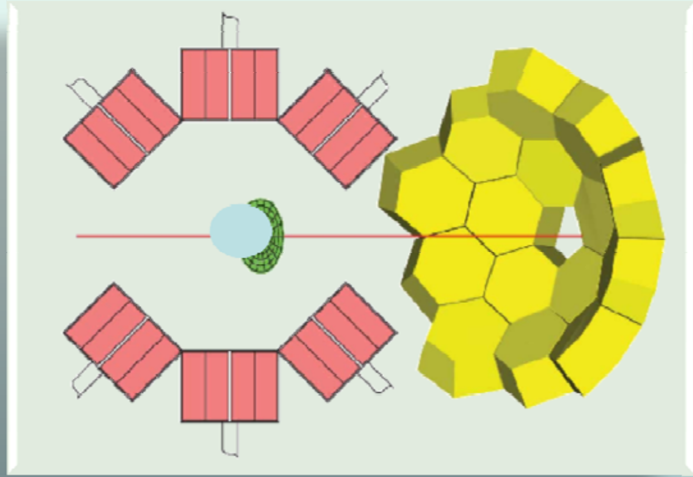
EUCLIDES

Si E-ΔE telescopes
efficiency: protons ~70%
alphas ~ 40%

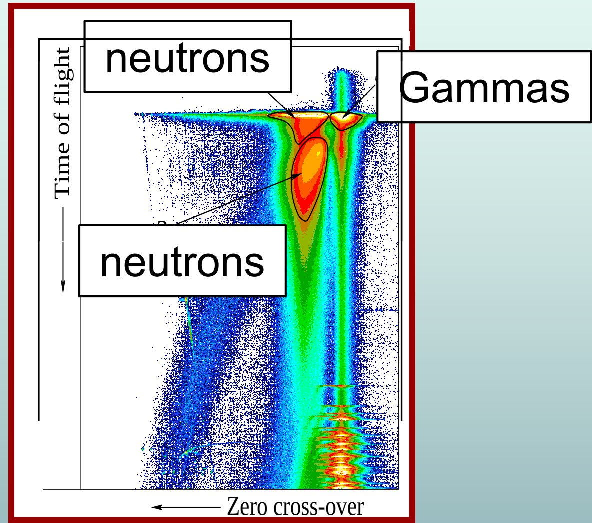


# Neutron detection systems





EXOGAM + N-Wall @ GANIL




Detectors placed downstream of the target position

Large volume liquid scintillators coupled to photo-multipliers tubes.
Usually replace some of the forward-most Ge detectors of the array

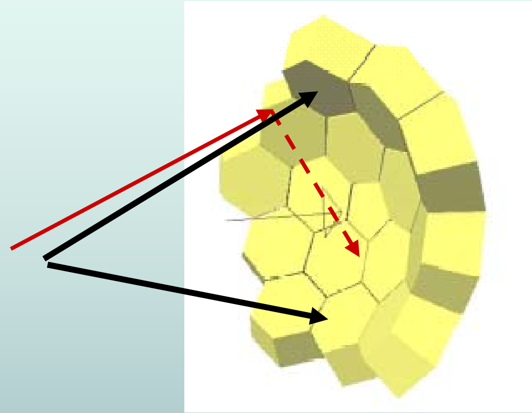
Efficiency ~ 25%

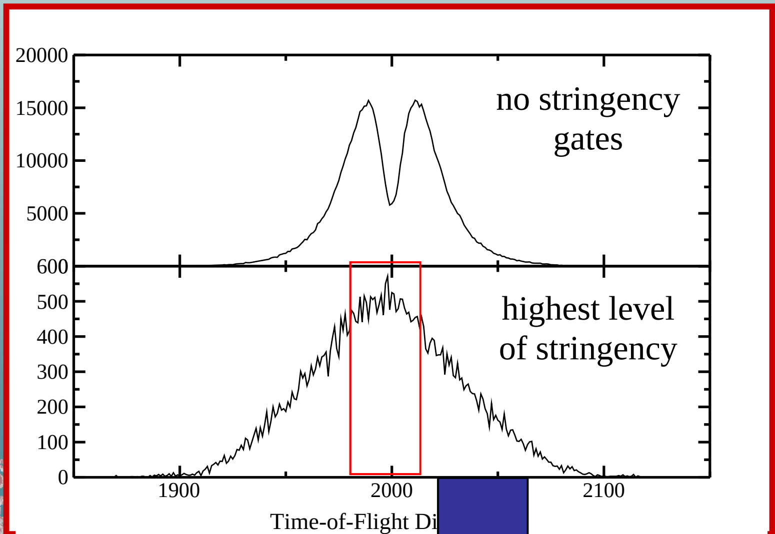
# Discrimination using time-of-flight data

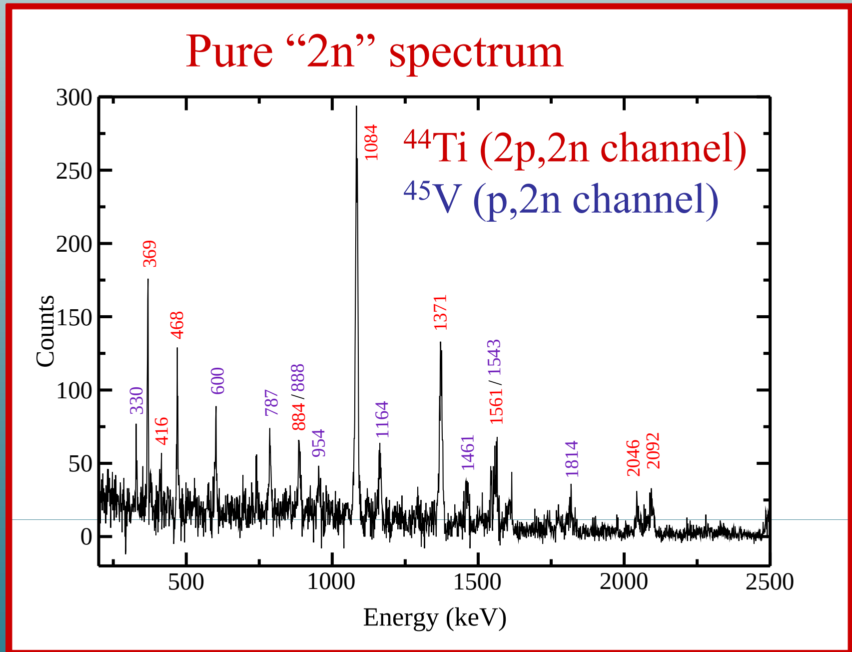
Problem: one neutron scattered between two detectors looks like two neutrons…

A single scattered neutron → different times-of-flight recorded

Genuine 2-neutron event → similar time-of-flight recorded





# An example: production of $^{50}$Fe

Experiment for $^{50}$Fe, LNL

$$^{28}_{14}\mathrm{Si}_{14} + ^{28}_{14}\mathrm{Si}_{14} \rightarrow ^{56}_{28}\mathrm{Ni}^{*}_{28}$$

$$\rightarrow ^{50}_{24}\mathrm{Cr}_{26} + \alpha 2p \qquad \sigma_{fus} \sim 300mb$$

$$\rightarrow ^{50}_{26}\mathrm{Fe}_{24} + \alpha 2n \qquad \sigma_{fus} \sim 0.3mb$$

EUROBALL: High efficiency ($e_{ph}$~8%) and high granularity (209 crystals) HpGe array.

26 Clover detectors (×4 crystals) & 15 Clusters (×7 crystals).

ISIS: Charged-particle detector array - 40 Si E-DE telescopes, total efficiency $e_p$~70% , $e_a$~40%

NEUTRON WALL: 50 detector elements - BC501A Liquid Scintillator. Efficiency (reaction dependent) $e_{1n}$~25%.

S.M. Lenzi et al., Phys. Rev. Lett 87 (2001) 122501

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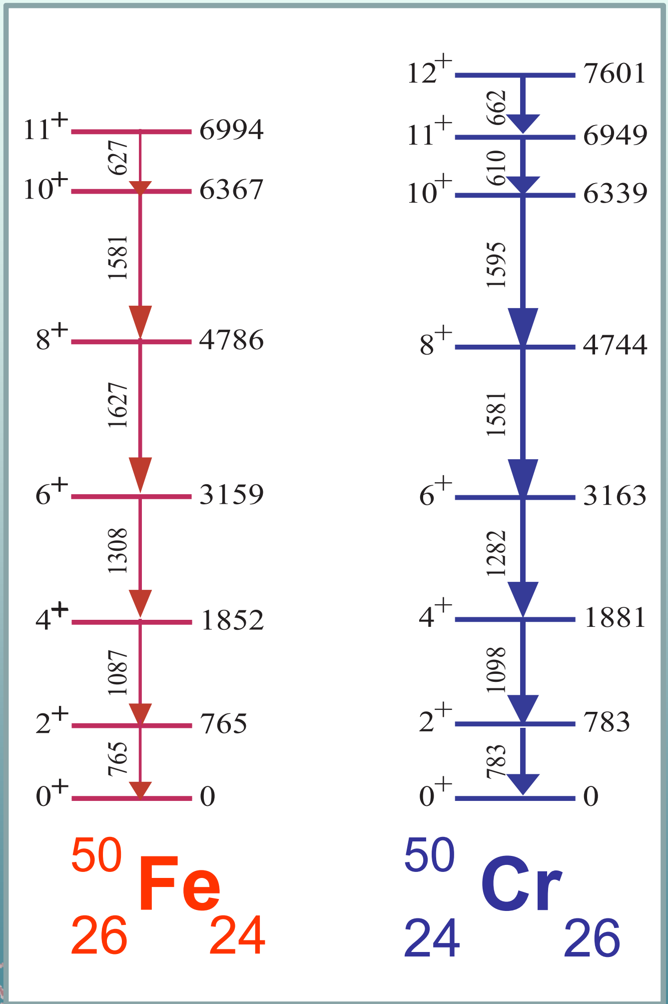
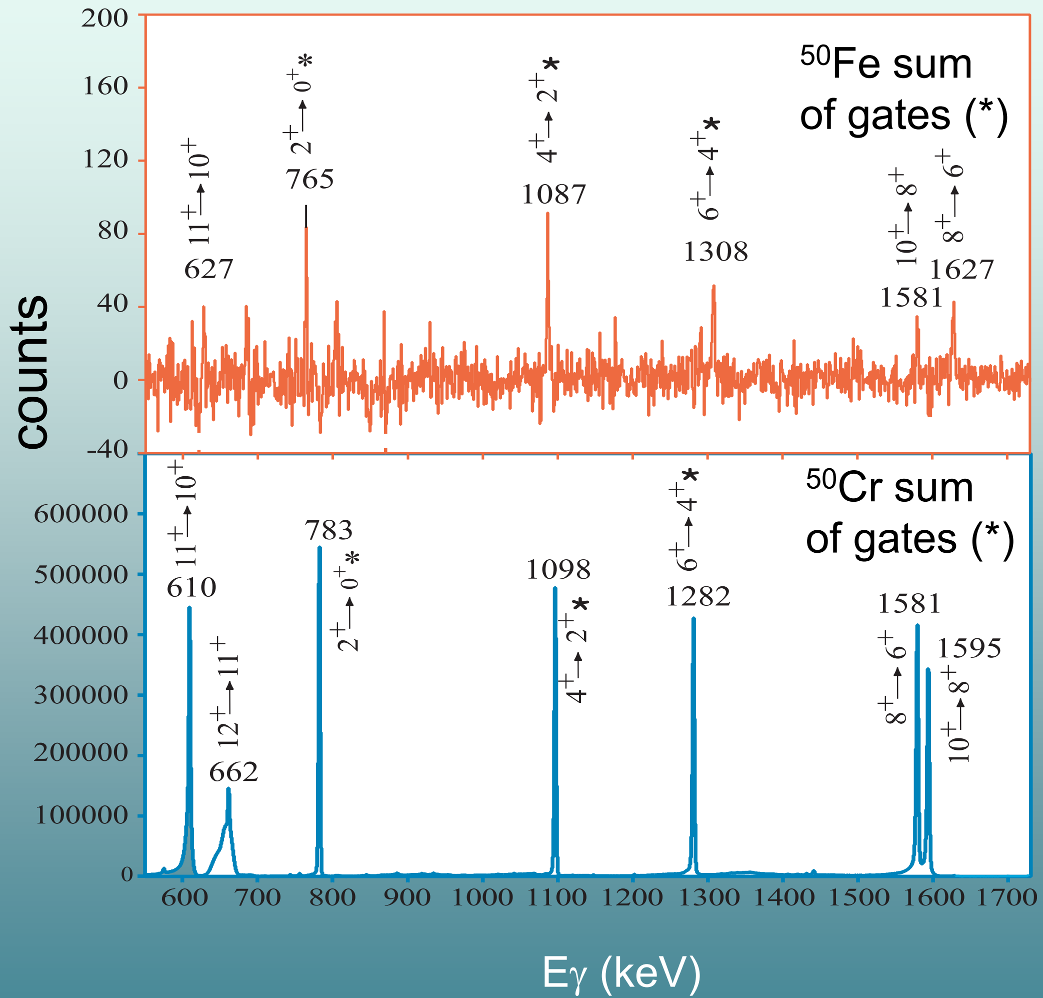
# First observation of excited states in $^{50}Fe$

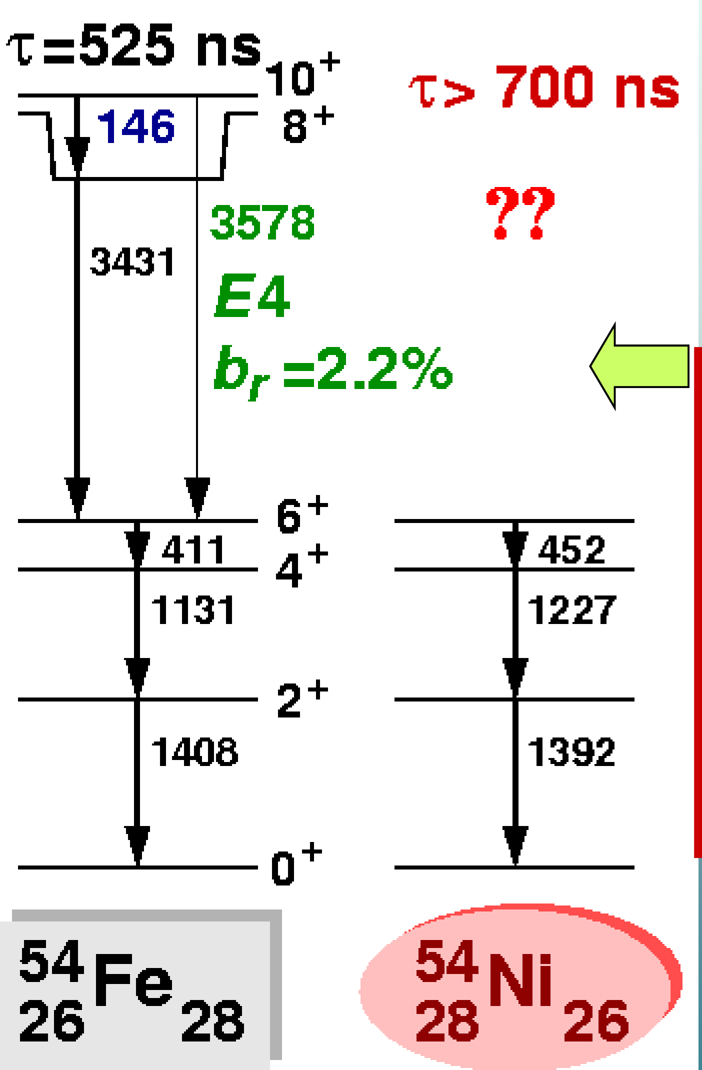


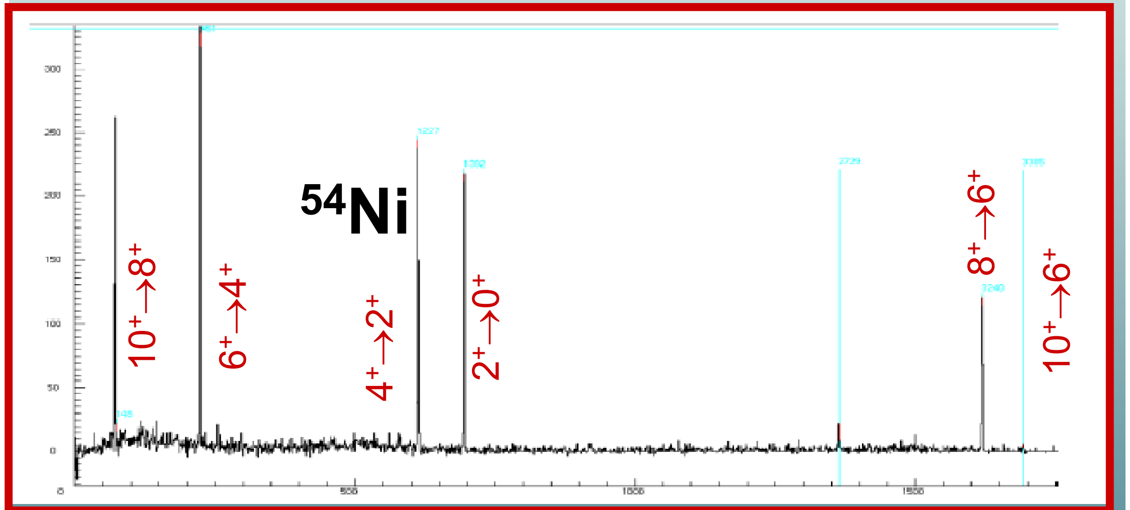

$\sigma(Fe)/\sigma(Cr) \approx 10^{-4}$

SML et al., Phys. Rev. Lett. 87, 122501 (2001)

# Spectroscopy with exotic stopped beams



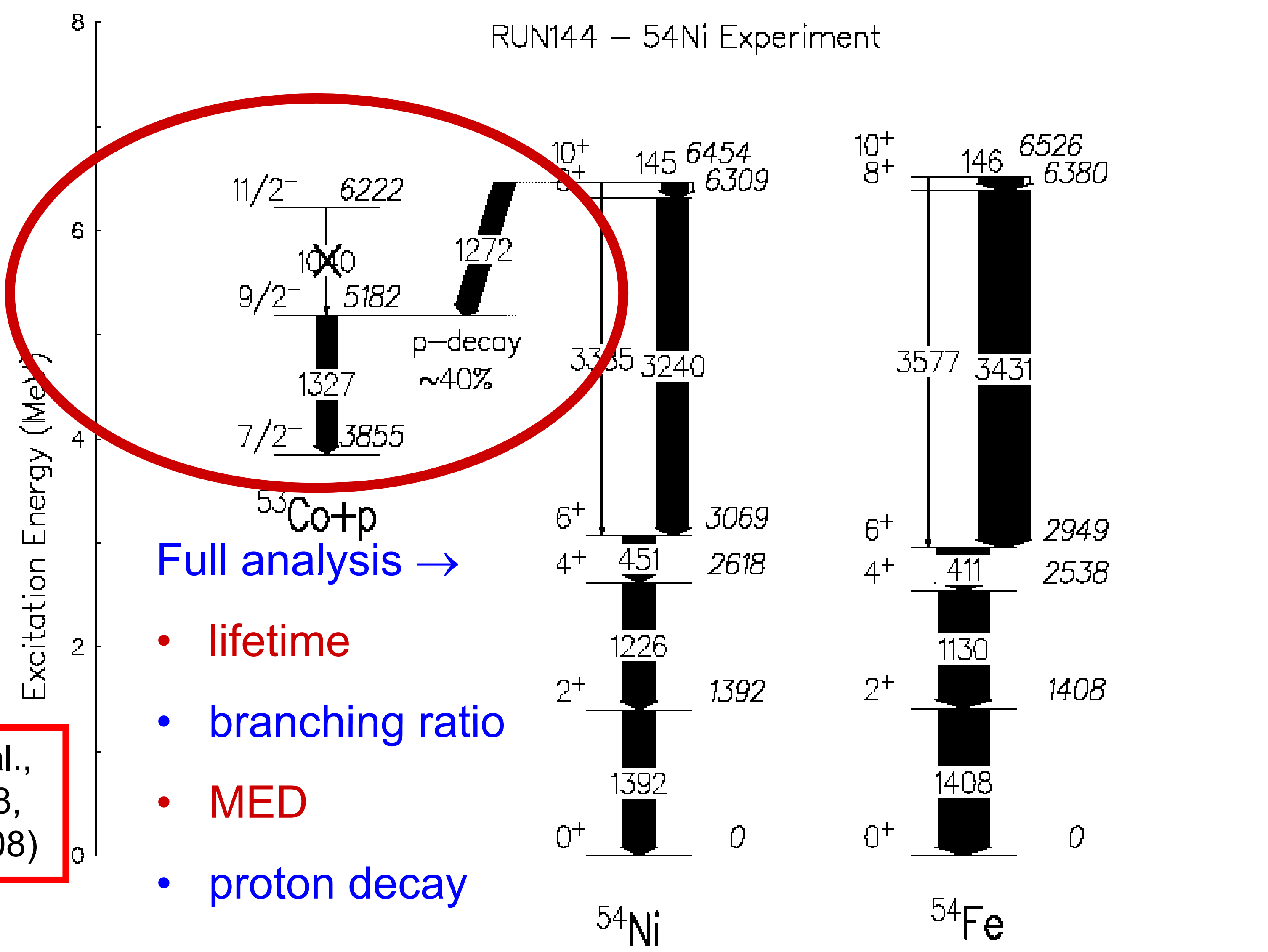

Fragmentation of $^{58}$Ni beam
Secondary beam of $^{54}$Ni in the isomeric state $10^+$




States in $^{54}$Ni known up to the $6^+$,
A.Gadea et al. Phys. Rev. Lett. 97 (2006) 152501 (EB+EUCLIDES+N-Wall)

D. Rudolph et al.,
Phys. Rev. C 78, 021301(R) (2008)

# Gamma and proton decay of $^{54}$Ni




Full analysis →

- lifetime
- branching ratio
- MED
- proton decay

D. Rudolph et al., Phys. Rev. C 78, 021301(R) (2008)

# 3. Theoretical tools for CED
# First part

# Basic Shell Model

The hamiltonian (only two-body forces)

$$H = \sum_{i=1}^{A} \frac{\vec{p}_i^{\,2}}{2m} + \frac{1}{2}\sum_{i,j=1}^{A} V_{ij}(\vec{r})$$

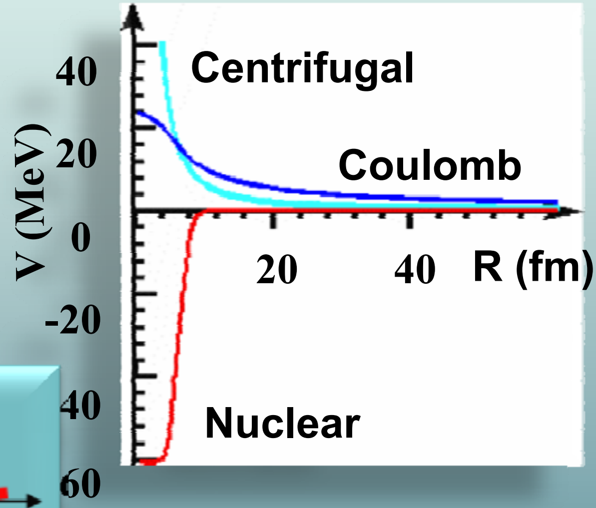
$$H = \sum_{i=1}^{A} \left(\frac{\vec{p}_i^{\,2}}{2m} + U(r_i)\right) + \sum_{i,j=1}^{A} V_{ij}(|\, r_i - r_j \,|) - \sum_{i=1}^{A} U(r_i) = H_0 + H_{res}$$

$$H_0 \phi(\mathbf{r}_1, \ldots, \mathbf{r}_A) = E_0 \phi(\mathbf{r}_1, \ldots, \mathbf{r}_A)$$

$$E_0 = \sum_i \varepsilon_i^{(0)}$$

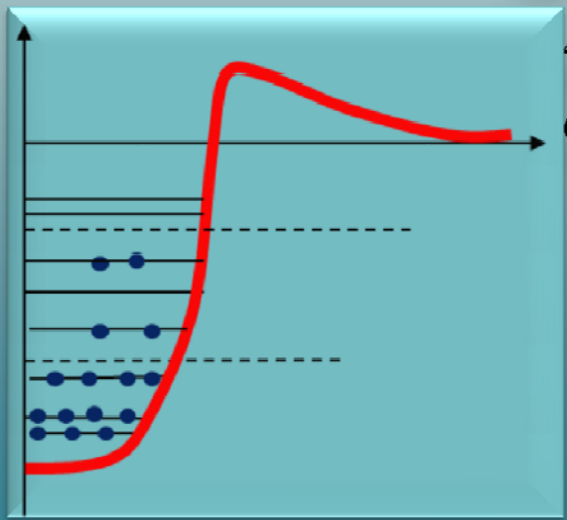
spherical mean field

U(r) is a central (1-body) potential




Configuration

$$\phi = \frac{1}{\sqrt{A!}} \det \begin{pmatrix} \psi_1(r_1) & \cdots & \psi_1(r_A) \\ \vdots & \ddots & \vdots \\ \psi_A(r_1) & \ldots & \psi_A(r_A) \end{pmatrix}$$

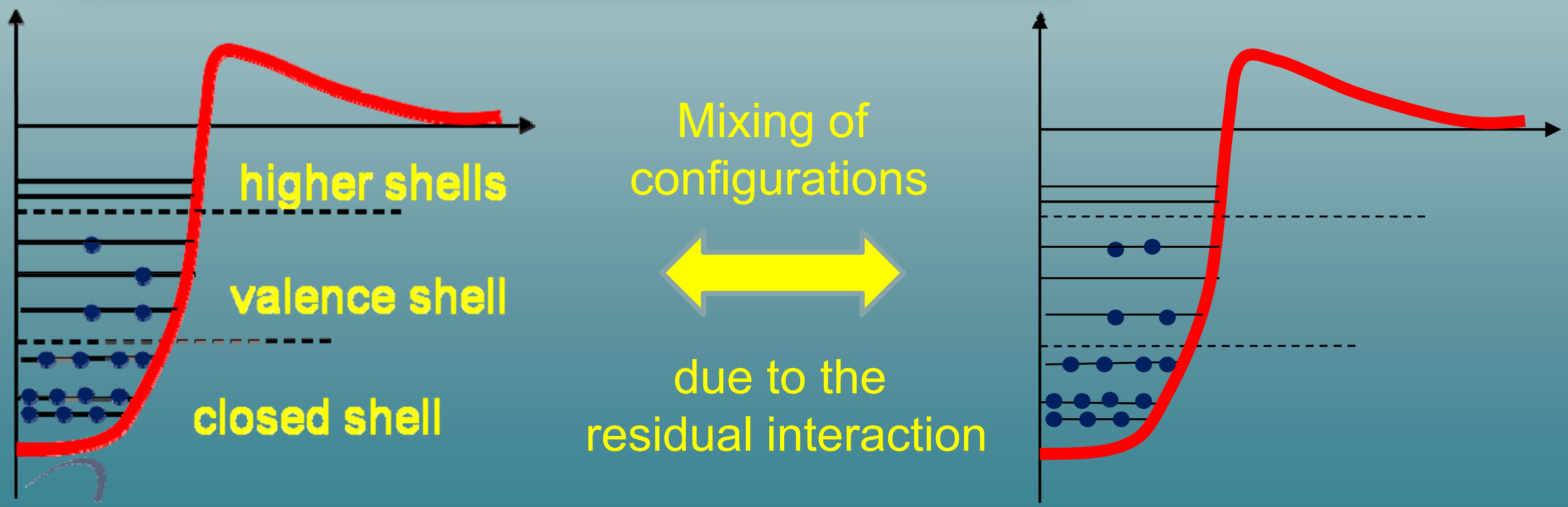


# Configuration mixing

$$\phi = \frac{1}{\sqrt{A!}} \det \begin{pmatrix} \psi_1(r_1) & \cdots & \psi_1(r_A) \\ \vdots & \ddots & \vdots \\ \psi_A(r_1) & \dots & \psi_A(r_A) \end{pmatrix}$$

$$\mathcal{H} = \begin{pmatrix} \langle\phi_1|H|\phi_1\rangle & \langle\phi_1|H|\phi_2\rangle & \dots \\ \langle\phi_2|H|\phi_1\rangle & \langle\phi_2|H|\phi_2\rangle & \dots \\ \langle\phi_3|H|\phi_1\rangle & \vdots & \end{pmatrix} = \begin{pmatrix} E_1 & & \\ & E_2 & \\ & & \ddots \end{pmatrix}$$

$$\Psi = \sum_i^{\infty} c_i \phi_i$$



# Effective Hamiltonian

We limit the space to a reduced set of shells.
The Hamiltonian becomes an effective hamiltonian $H_{eff}$ that accounts for the missing space.

$$H_{eff} = H_m + H_M$$

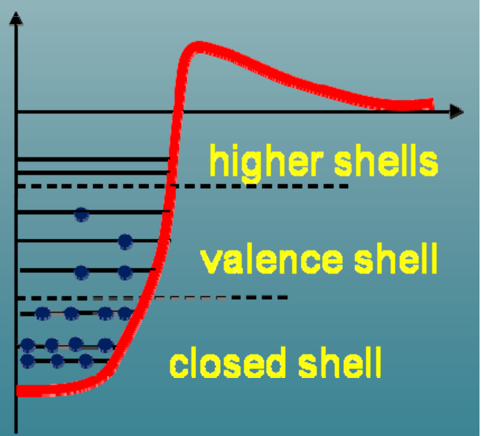
monopole Multipole

$H_m$

- "unperturbed" energy of the different configurations in which the valence nucleons are distributed
- determines the single particle energies
- dominant role far from stability

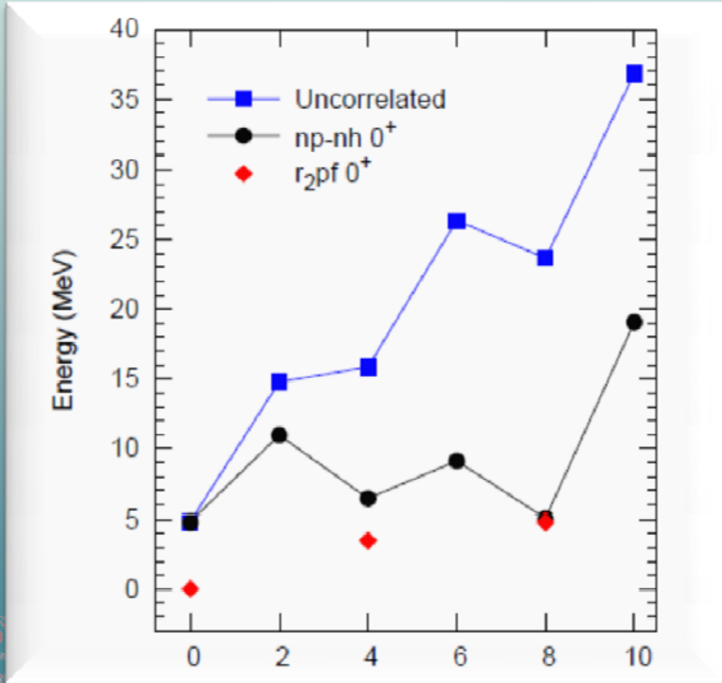
$H_M$

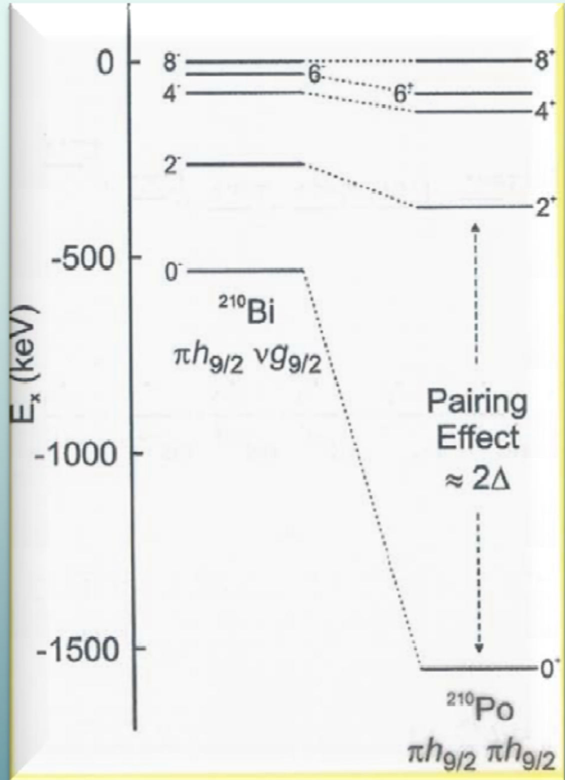
- correlations
- mixing of configurations
- coherence
- energy gains



# Effect of the correlations

The multipole Hamiltonian $H_M$
is dominated by the pairing and
the quadrupole-quadrupole forces

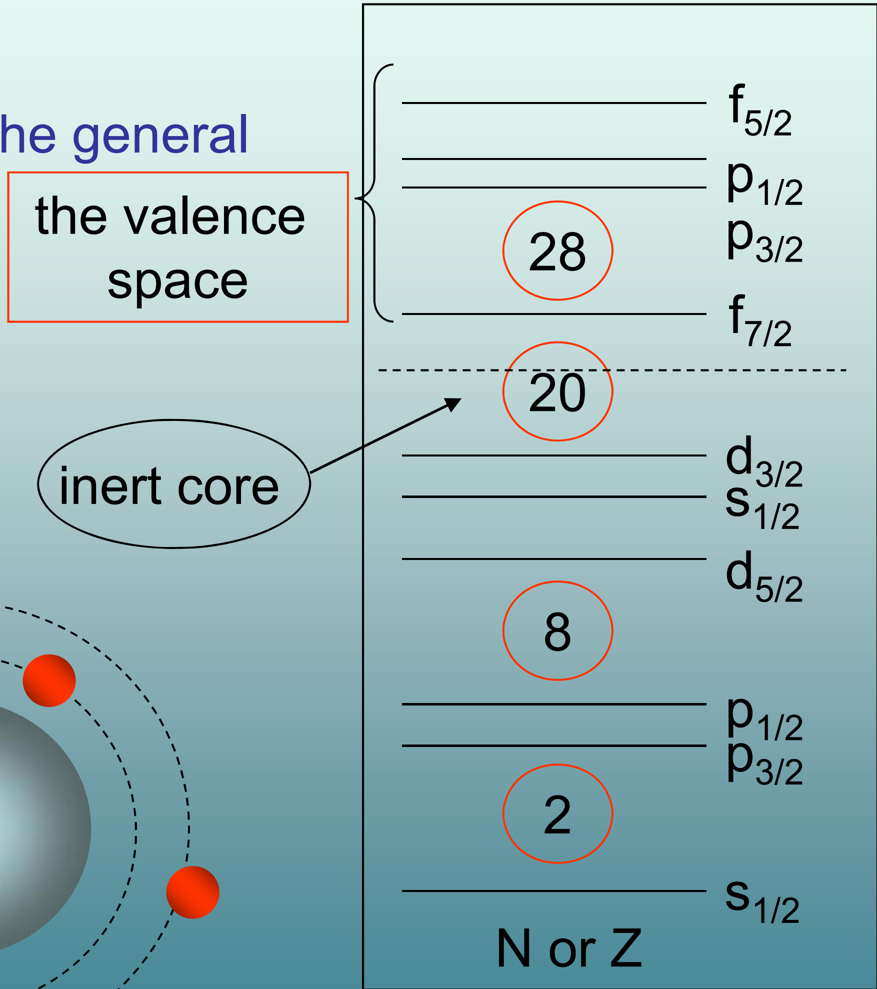



The fact that some nuclei display collective behaviour depends on the structure of the spherical field near the Fermi surface for both protons and neutrons

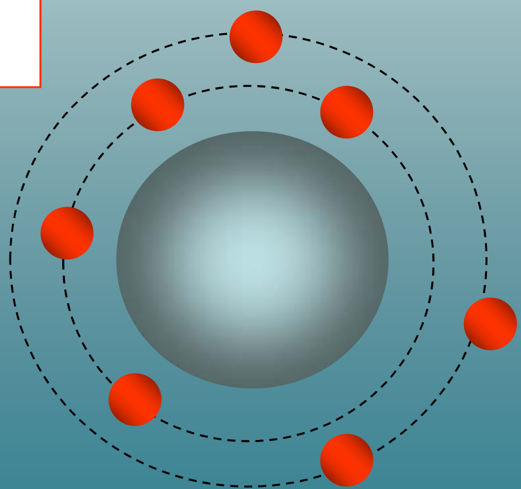
# Ingredients for the Shell Model calculations

1) an inert core
2) a valence space
3) an effective interaction that mocks up the general hamiltonian in the restricted basis

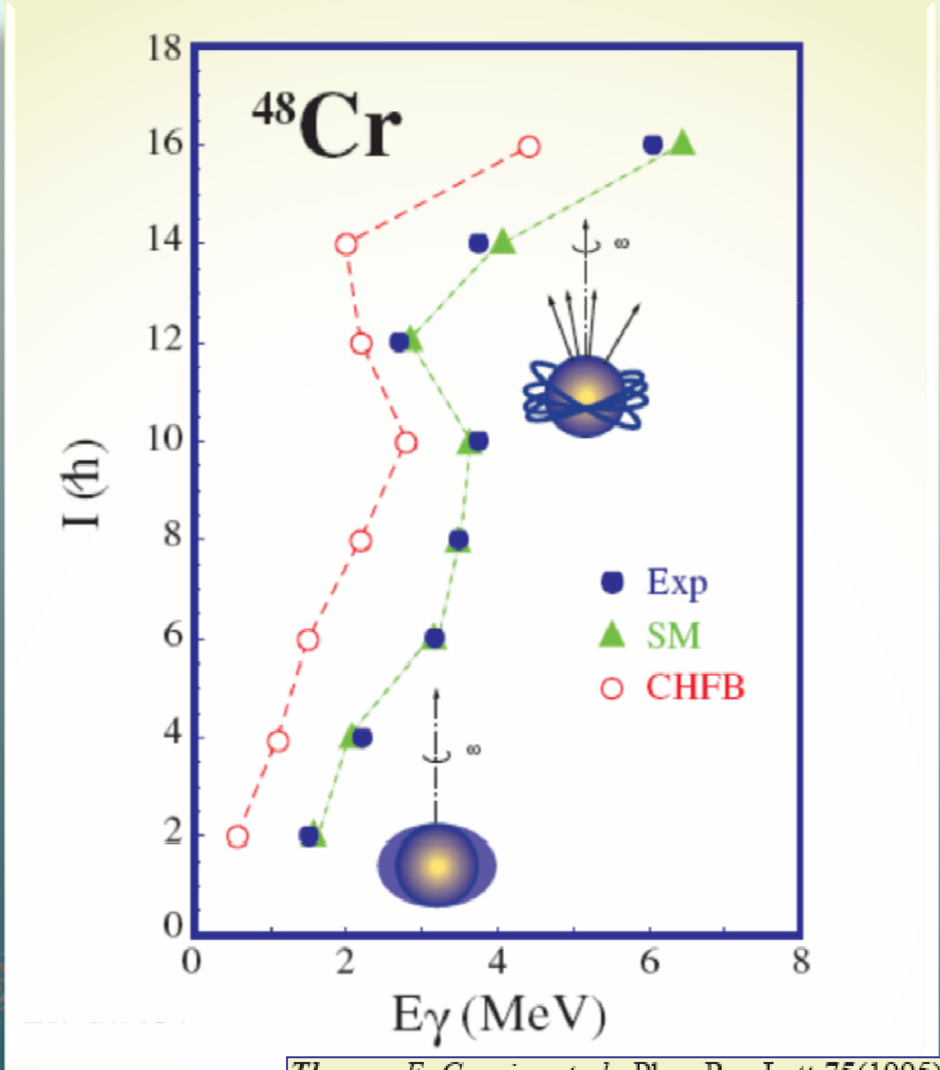



The choice is determined by the limits in computing time and memory: large dimension of the matrices to be diagonalised.

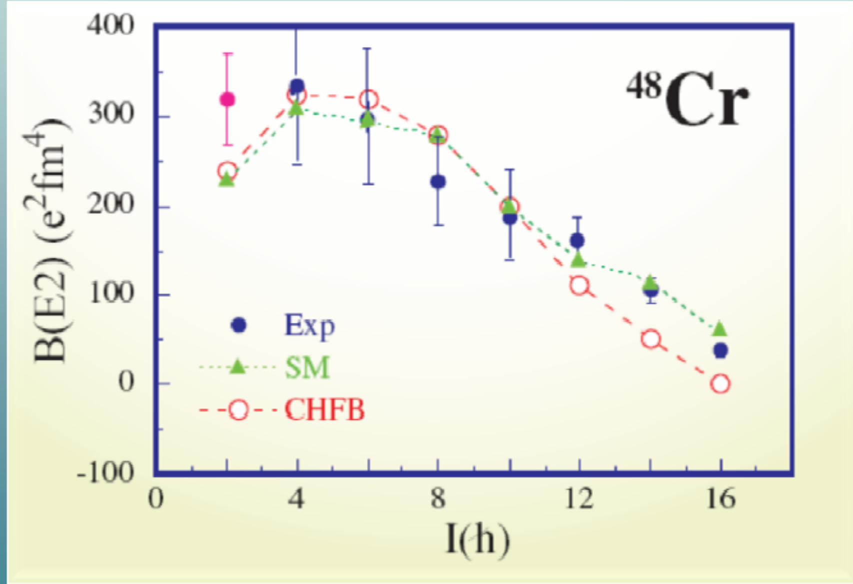
Current codes diagonalize matrices of dimension $\sim 10^{10}$



# Shell model and collective phenomena



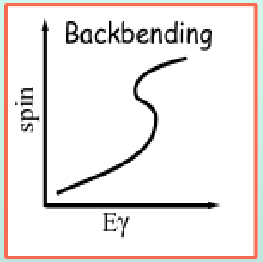

Shell model calculations in the full fp shell give an excellent description of the structure of collective rotations in nuclei of the $f_{7/2}$ shell

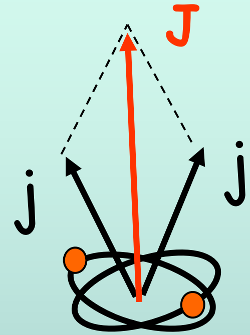



*Theory: E. Caurier et al.*, Phys.Rev.Lett.75(1995)225

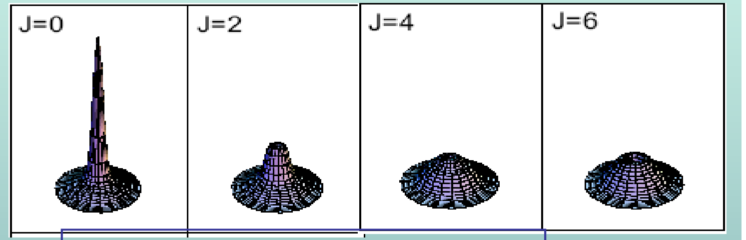
*Experiments: S. M. Lenzi et al.*, Z.Phys.**A354**(1996)117 - *F. Brandolini et al.*, Nucl.Phys.**A642**(1998)387

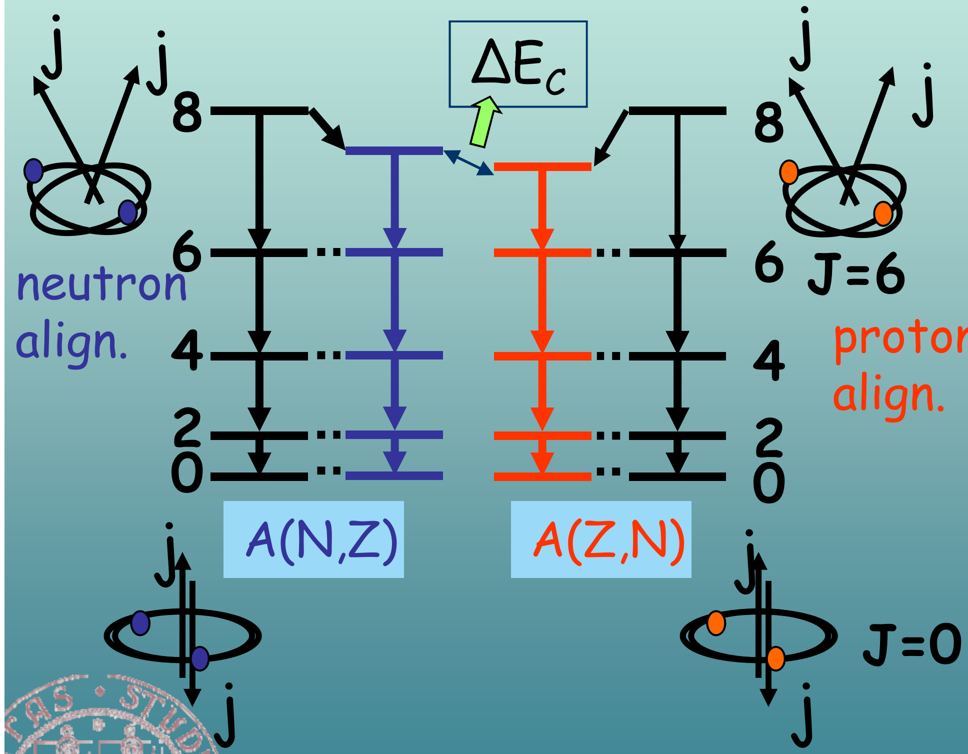
# Mirror energy differences and alignment

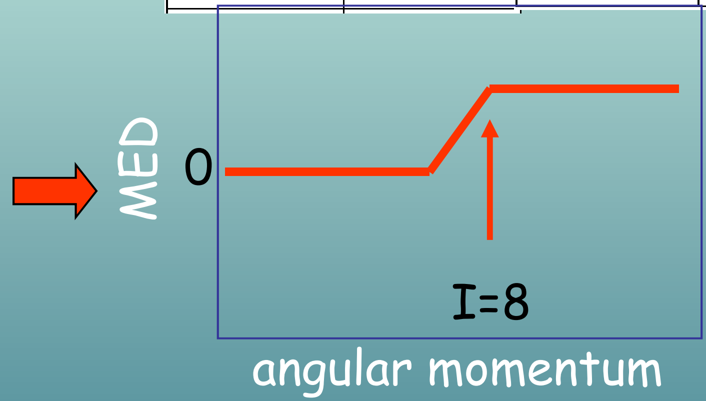



probability distribution for the relative distance of two like particles in the *f7/2* shell



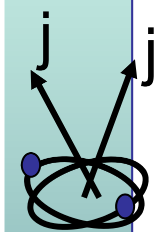



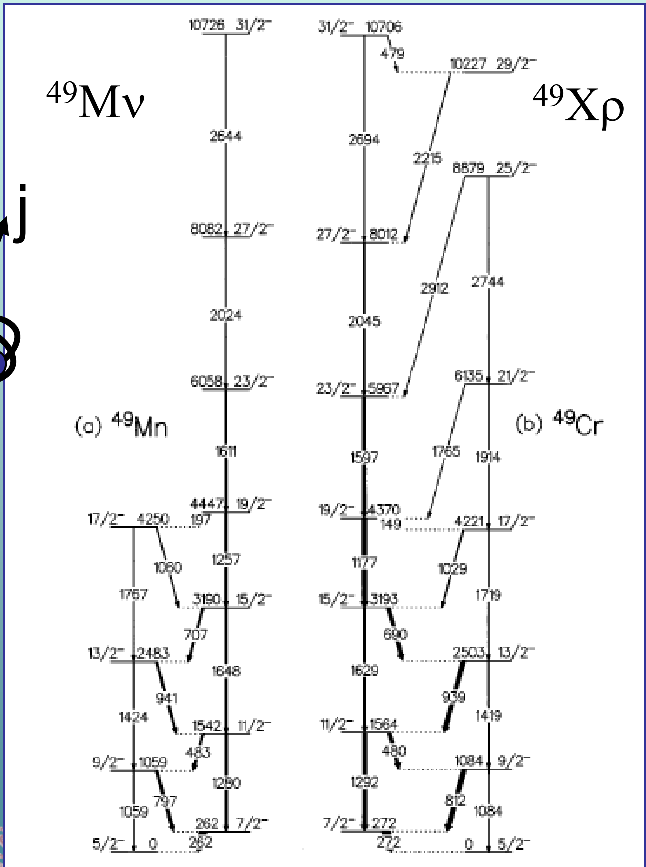

Shifts between the excitation energies of the mirror pair at the back-bend indicate the type of nucleons that are aligning

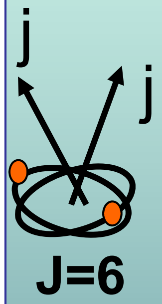
J.A. Cameron *et al.*,
Phys. Lett. B **235**, 239 (1990)

# Nucleon alignment at the backbending

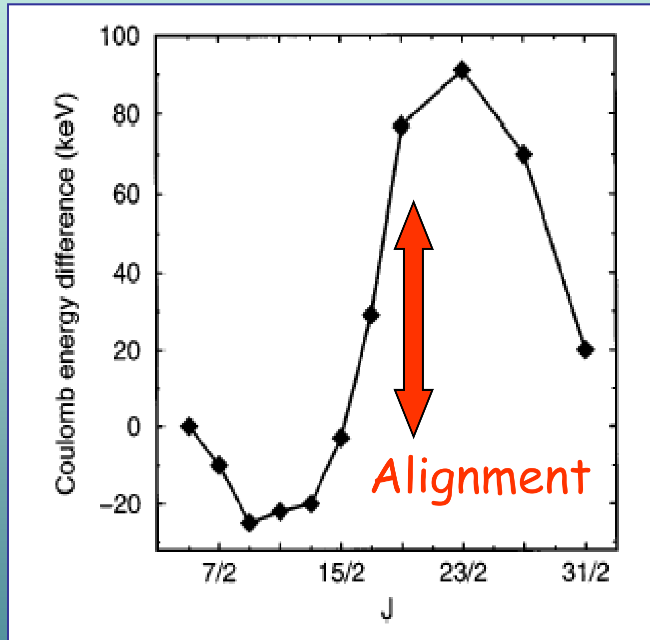
J.A. Cameron *et al.*, Phys. Lett. **B 235**, 239 (1990)
C.D. O'Leary *et al.*, Phys. Rev. Lett. 79, 4349 (1997)



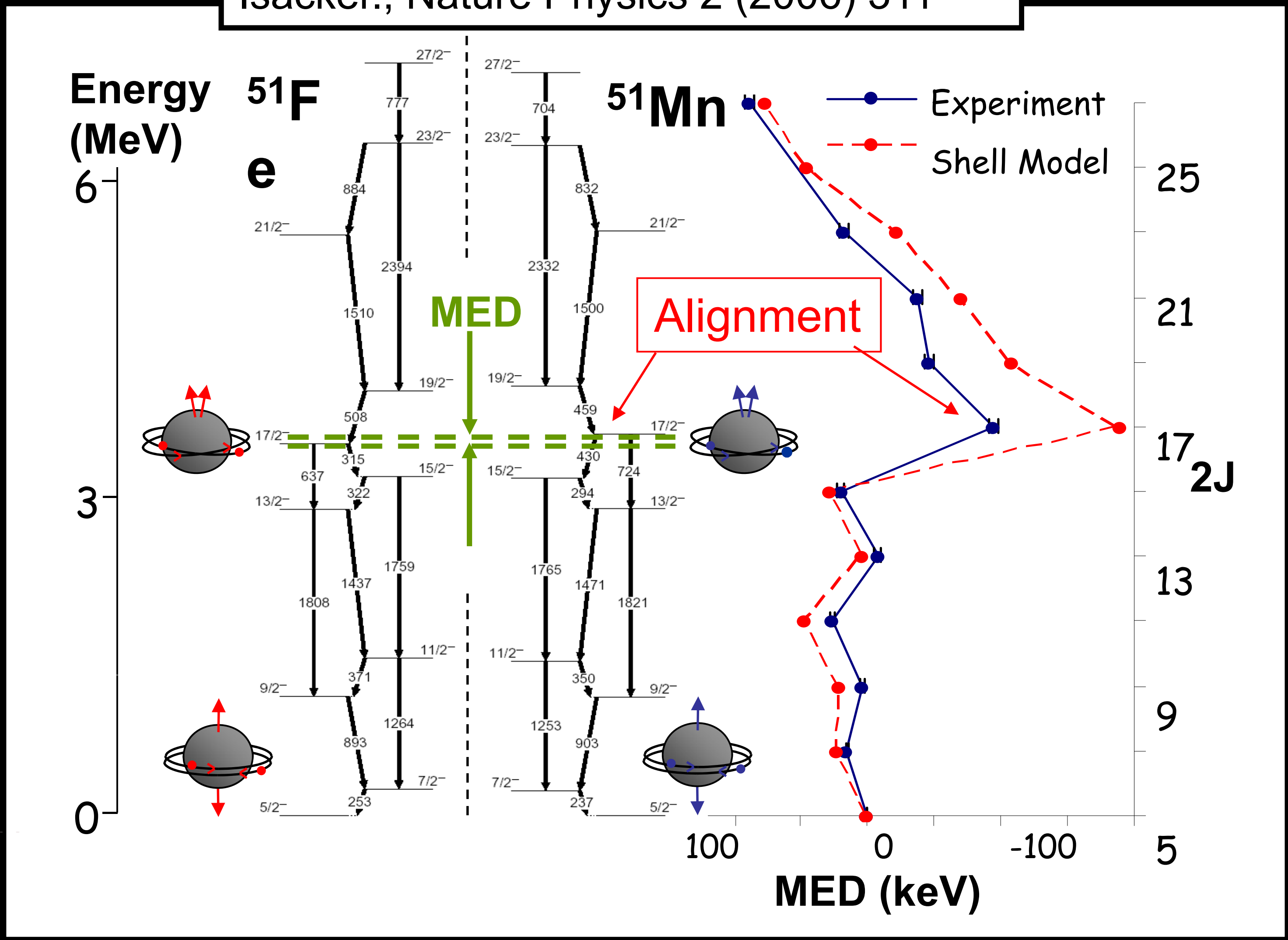

Experimental MED




MED are a probe of nuclear structure:
reflect the way the nucleus generates its angular momentum

# Nucleon alignment at the backbending

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



# Alignment and shell model

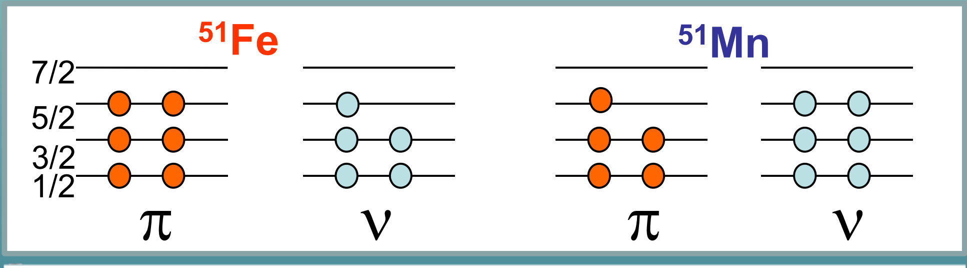
Define the operator

$$\mathbf{A}_\pi = \left[ \left(a_\pi^+ a_\pi^+\right)^{J=6} \left(a_\pi a_\pi\right)^{J=6} \right]^0$$

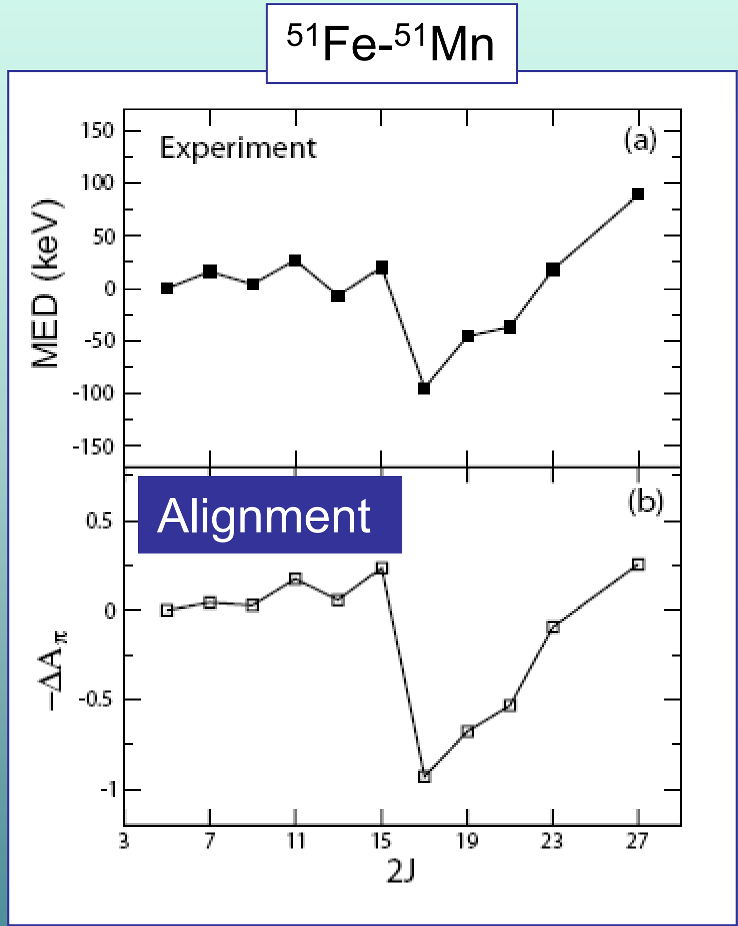
"Counts" the number of protons coupled to J=6

Calculate the difference of the expectation value in both mirror as a function of the angular momentum

$$\Delta\mathbf{A}_{\pi,J} = \langle \Phi_J | \mathbf{A}_\pi(Z_>) | \Phi_J \rangle - \langle \Phi'_J | \mathbf{A}_\pi(Z_<) | \Phi'_J \rangle$$



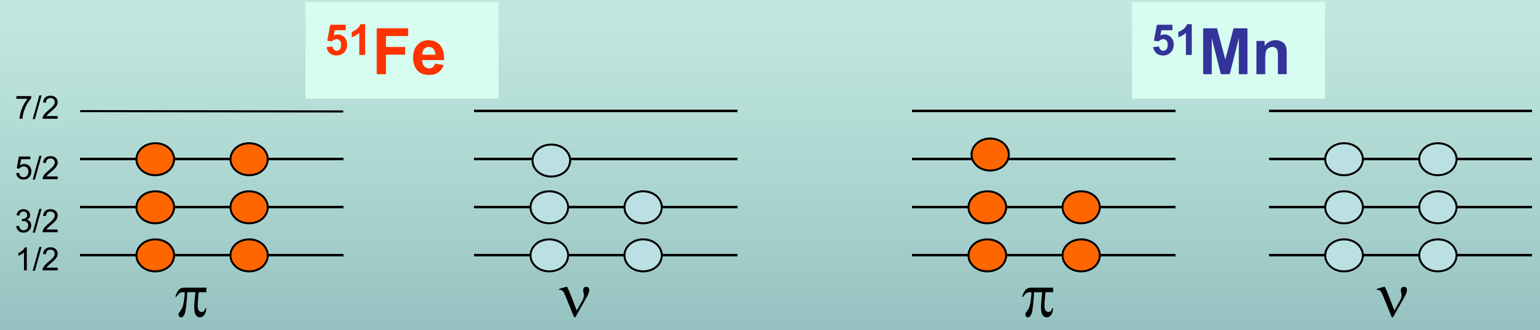

In $^{51}$Fe ($^{51}$Mn) a pair of protons (neutrons) align first and at higher frequency align the neutrons (protons)




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

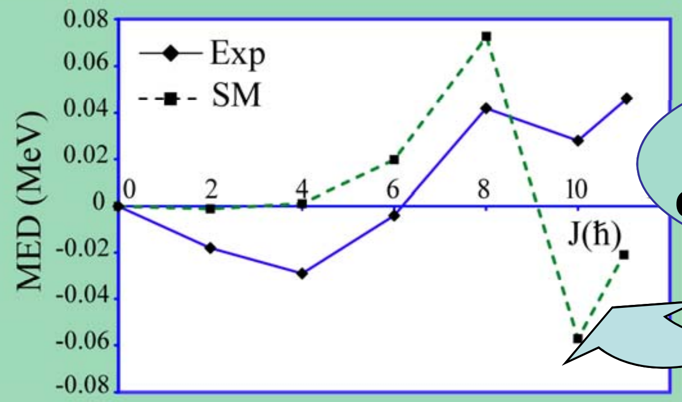
# Alignment in odd- and even-mass nuclei

In odd-mass nuclei, the type of nucleons that aligns first is determined by the **blocking effect** → the even fluid will align first




What about even-even rotating nuclei?

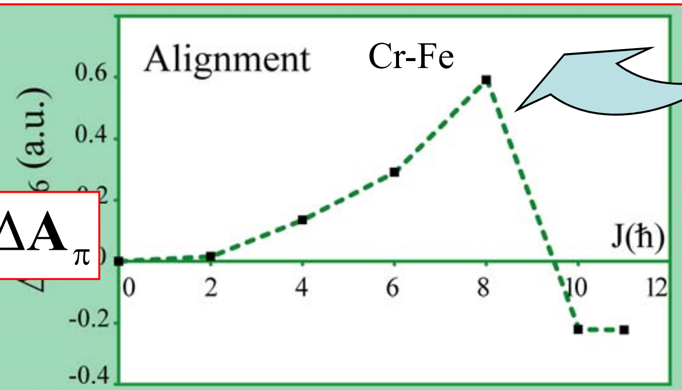
# Alignment in even-even rotating nuclei




**Renormalization of the Coulomb m.e.? Only a Coulomb effect?**

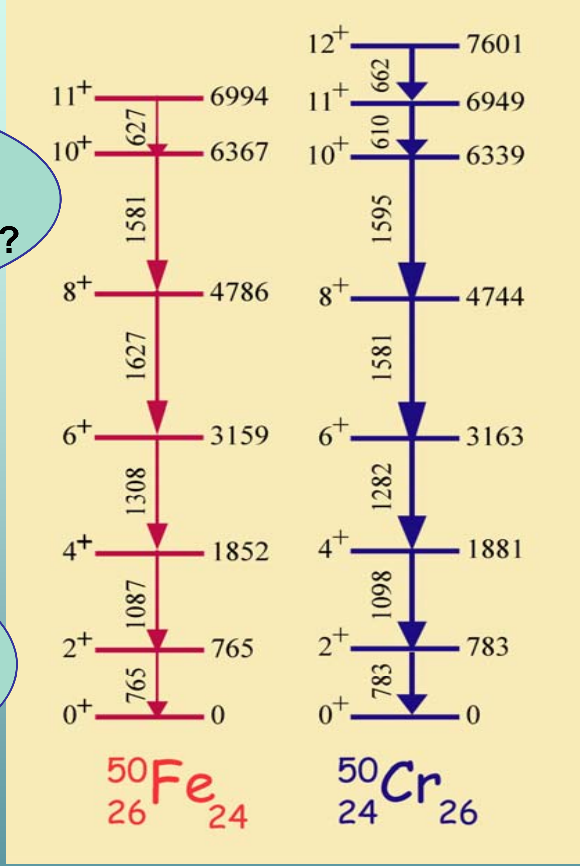
**calculate for protons in both mirrors:**

$$\Delta \mathbf{A}_\pi = \langle \Phi_J | \mathbf{A}_\pi(Z_>) | \Phi_J \rangle - \langle \Phi'_J | \mathbf{A}_\pi(Z_<) | \Phi' \ldots$$




$-\Delta \mathbf{A}_\pi$

**counts the number of aligned protons**




In $^{50}$Cr ($^{50}$Fe) a pair of protons (neutrons) align first and at higher frequency align the neutrons (protons)

S.M.Lenzi et al., Phys. Rev. Lett. 87, 122501 (2001)

can shell model do better?

# Lecture 2

## The end