Isospin symmetry breaking in mirror nuclei

Experimental and theoretical methods

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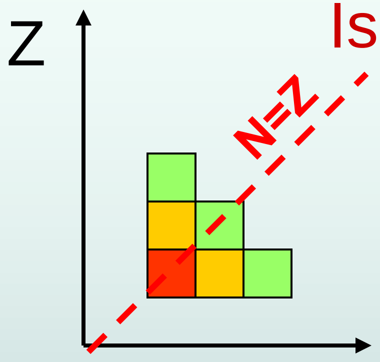
2. Experimental techniques for mirror spectroscopy

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?

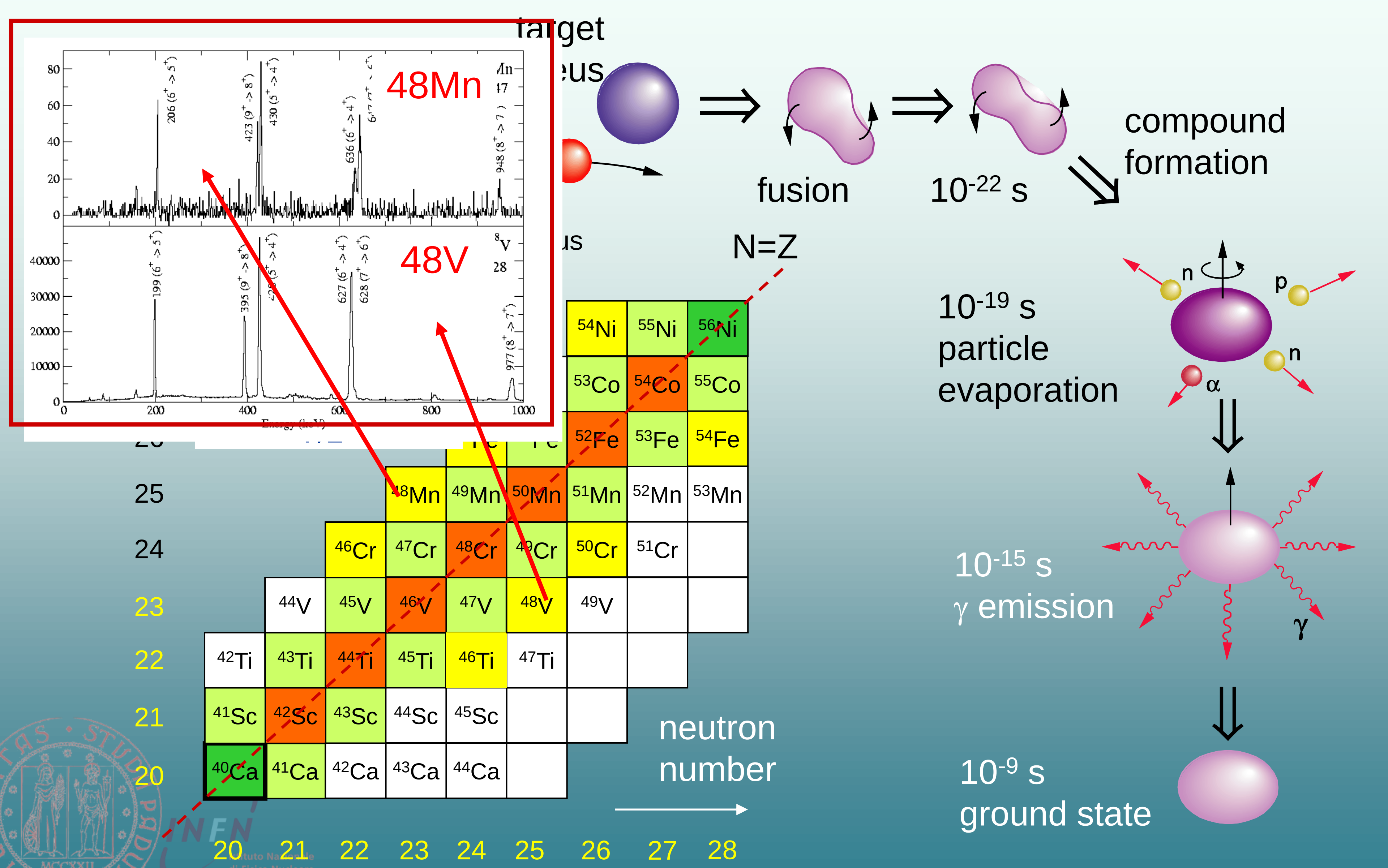
CED have been restricted for many years to low-spin states due to the difficulties in populating proton rich nuclei…

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

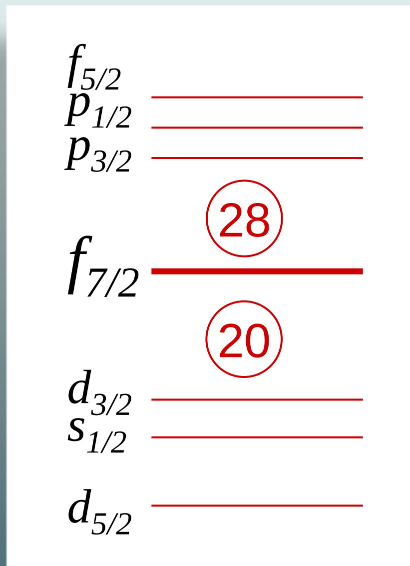


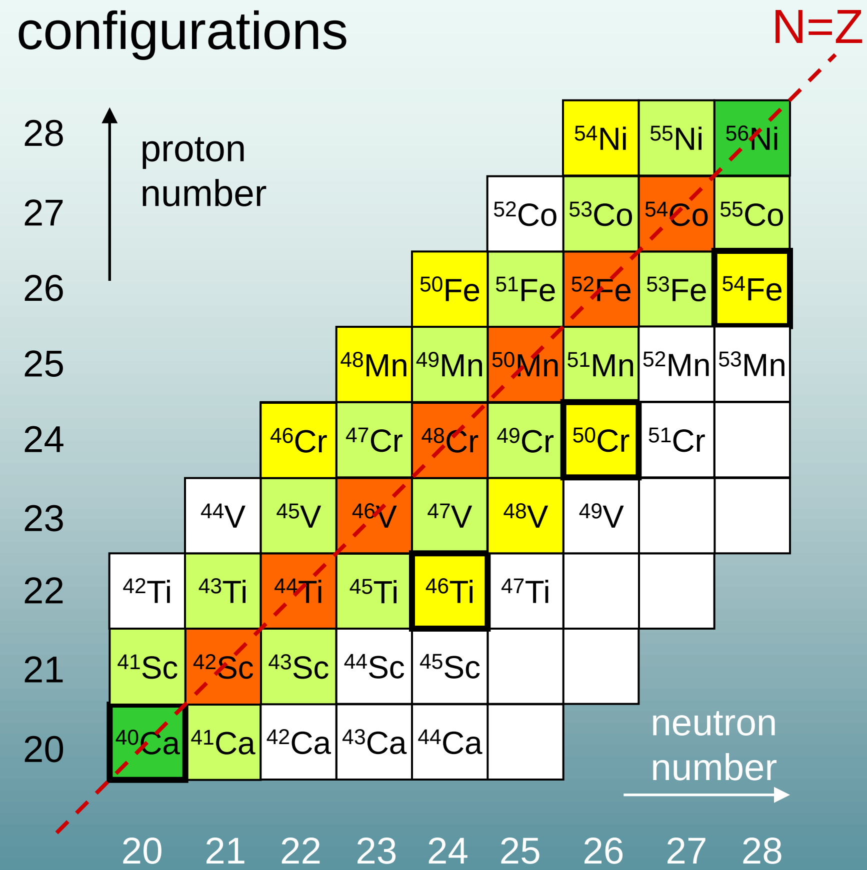
Example: the $f_{7/2}$ shell

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



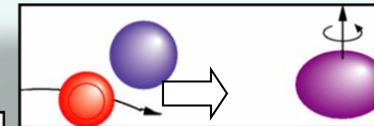


Experimental issue : proton-rich T_z=-1/2 isobars are weakly populated

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

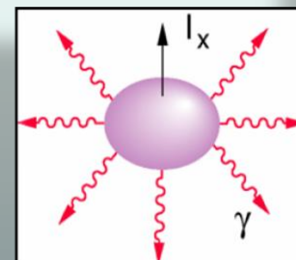
Experimental requirements

High efficiency and resolution for γ detection



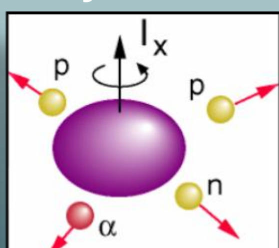
Low cross section at high spin (small masses)

High energy transitions

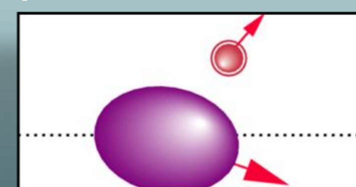


Good selectivity: particle detectors

Many channels opened: high efficient charged-particle detectors



Kinematics reconstruction
for Doppler broadening

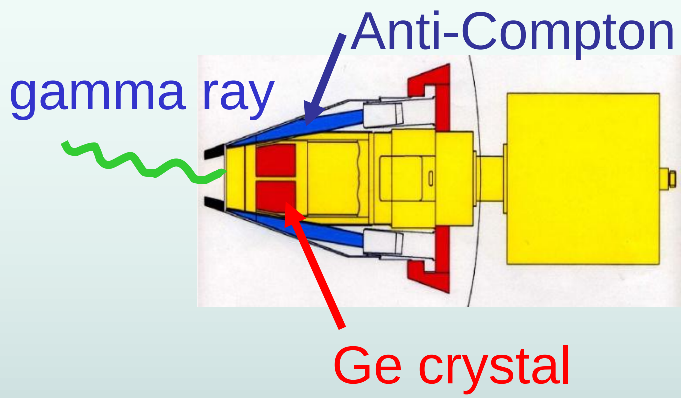


Mass spectrometers

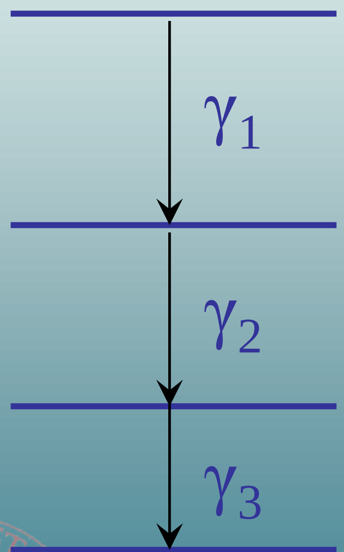
Neutron detectors to select proton-rich channels

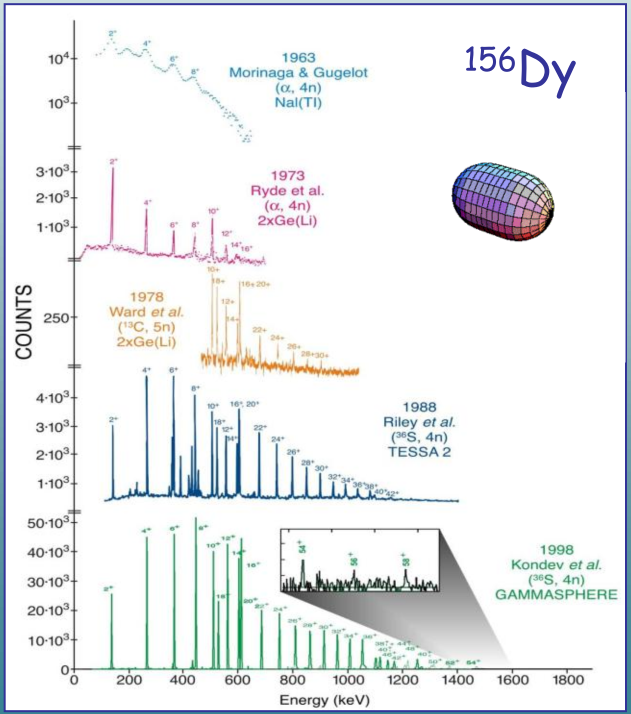
Polarimeters and granularity (**J, π, δ**)

Gamma spectroscopy



Constructing
a level scheme

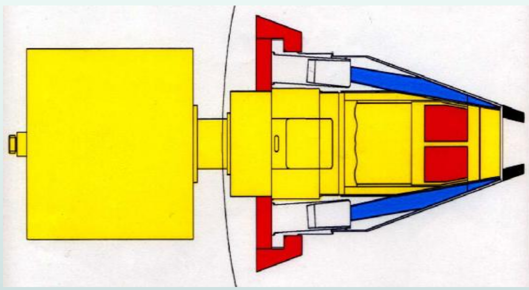


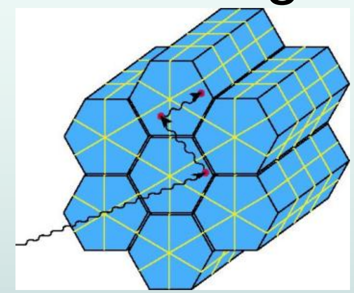


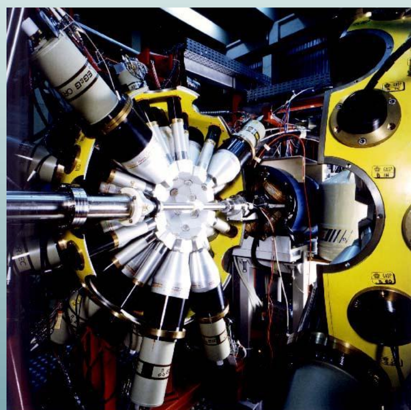
Gamma-ray spectrometers

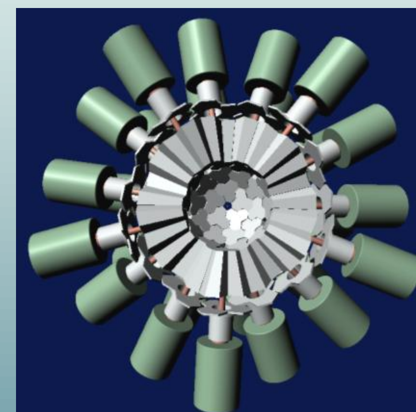
Conventional techniques

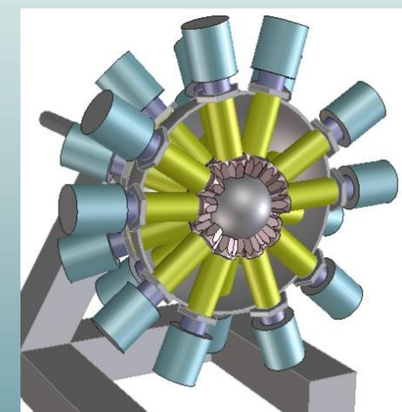
New technique: tracking











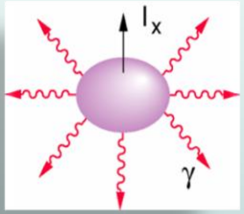
GASP **GAMMASPHERE** **AGATA** **GRETA**

$\varepsilon \sim 10 — 5\ \%$
(M_γ=1 — M_γ=30)

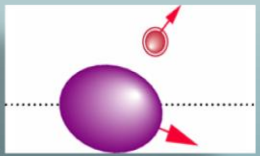
$\varepsilon \sim 40 — 20\ \%$
(M_γ=1 — M_γ=30)

Techniques for proton-rich spectroscopy

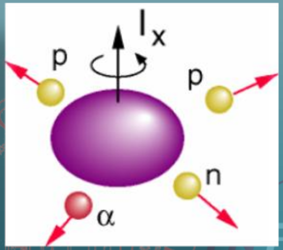
Three basic techniques for selecting proton-rich systems



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

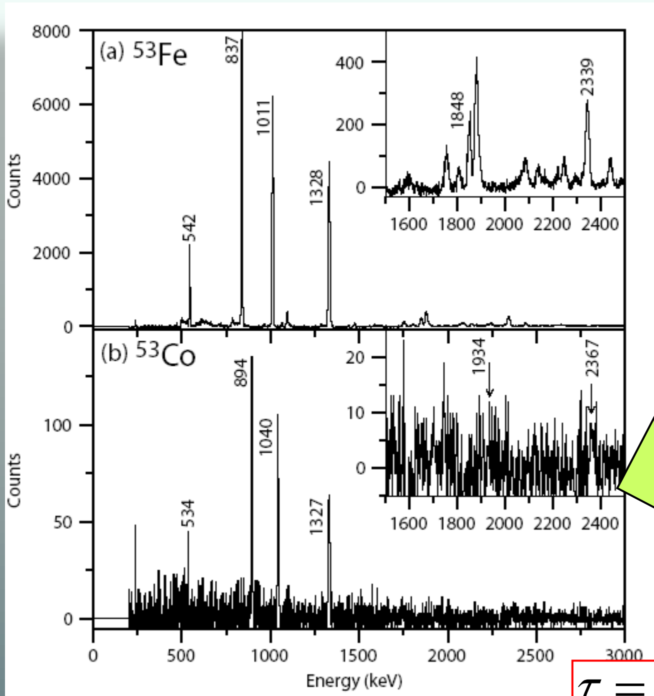


2. Gamma-ray array + mass spectrometer + focal plane detectors - identify A,Z of recoiling nucleus and ToF $\rightarrow$ tag emitted gamma-rays



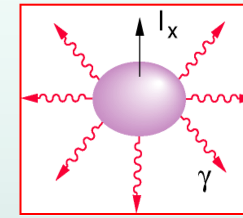
3. Identify cleanly all emitted particles from reaction - needs a charged-particle detector array + high-efficiency & high granularity neutron detector array + γ-ray array

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

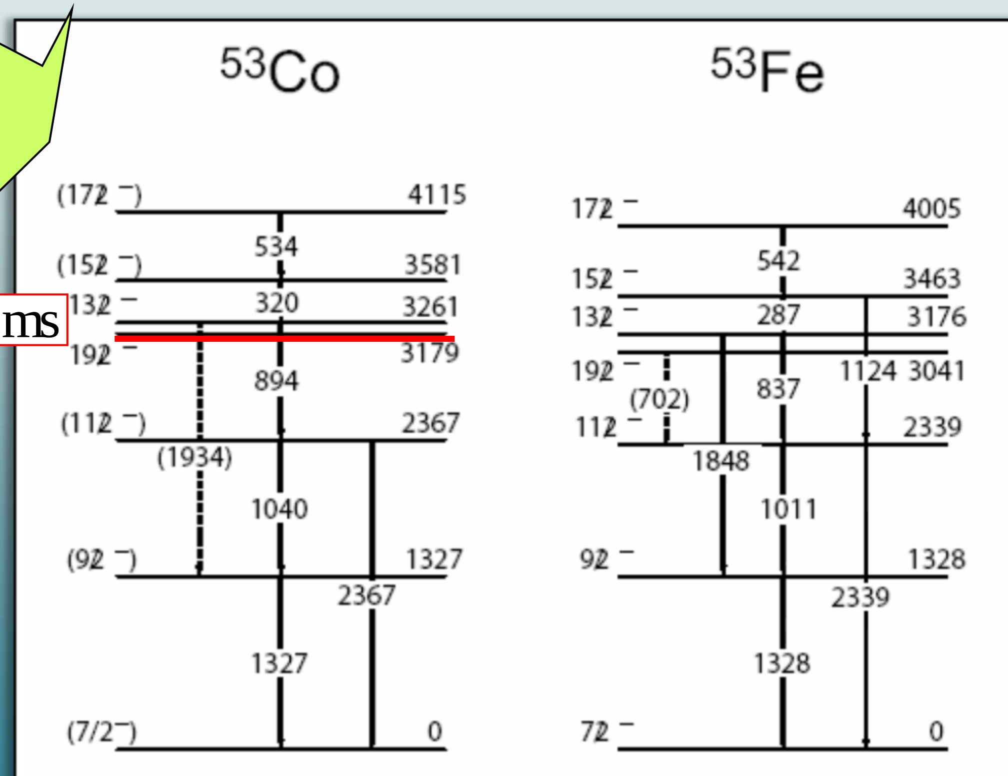


Double-coincidence spectra after gating on 2 analogue transitions

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

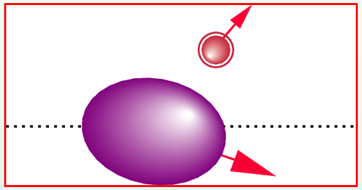
$$^{32}S\left(^{24}Mg,2p1n\right)^{53}Fe$$

$\tau = 260$ ms

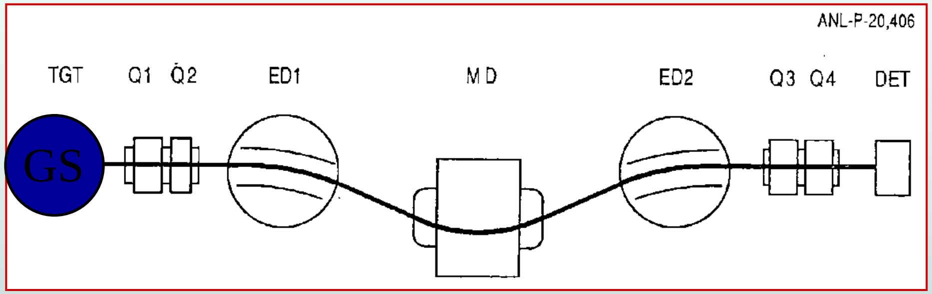


S.J. Williams et al., Phys. Rev. C 68 (2003) 011301

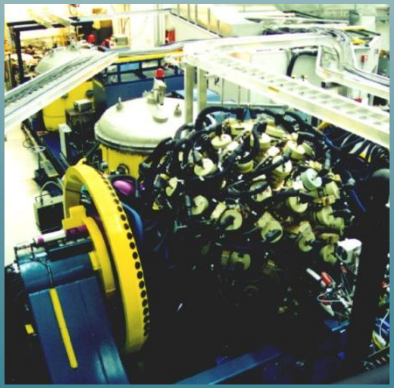
2. Identify A and Z of the recoiling nucleus



Fragment Mass Analyser



- Combined electric and magnetic dipoles $\rightarrow$ 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



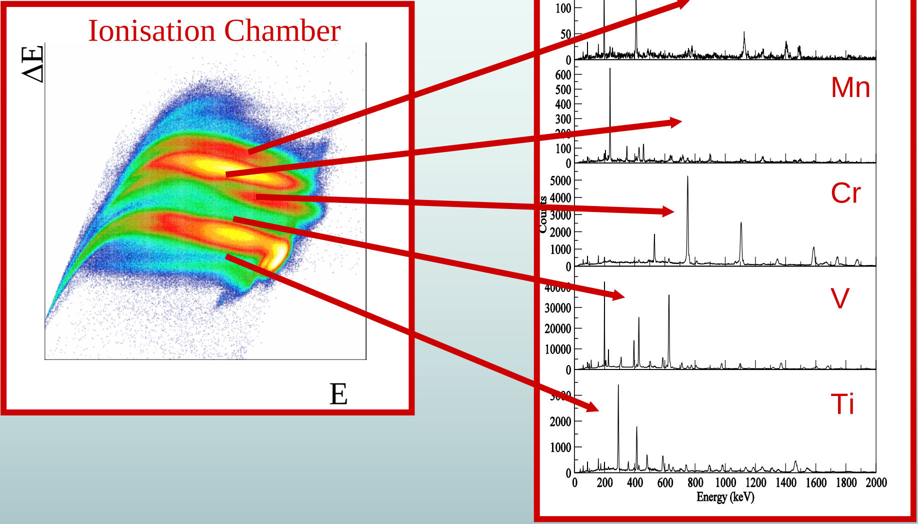
An example: the A=48 mirror pair

$$^{48}_{25}\mathrm{Mn}_{23} - \,^{48}_{23}\mathrm{V}_{25}$$

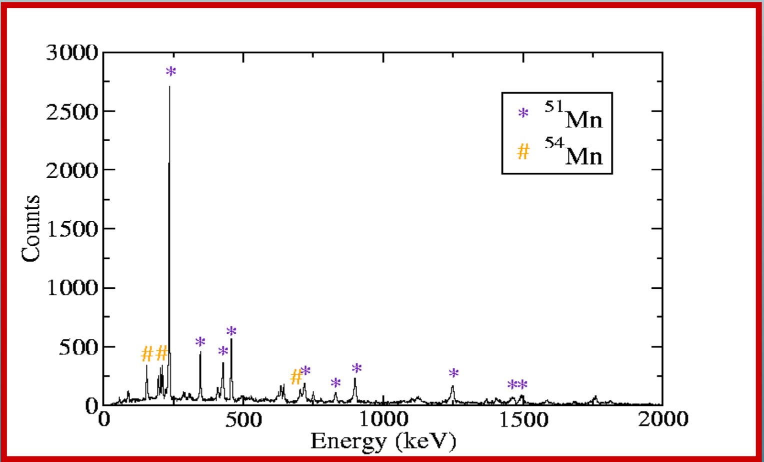
$$\frac{\sigma\left(^{48}\mathrm{Mn}\right)}{\sigma\left(^{48}\mathrm{V}\right)} \sim 10^{-4}$$

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

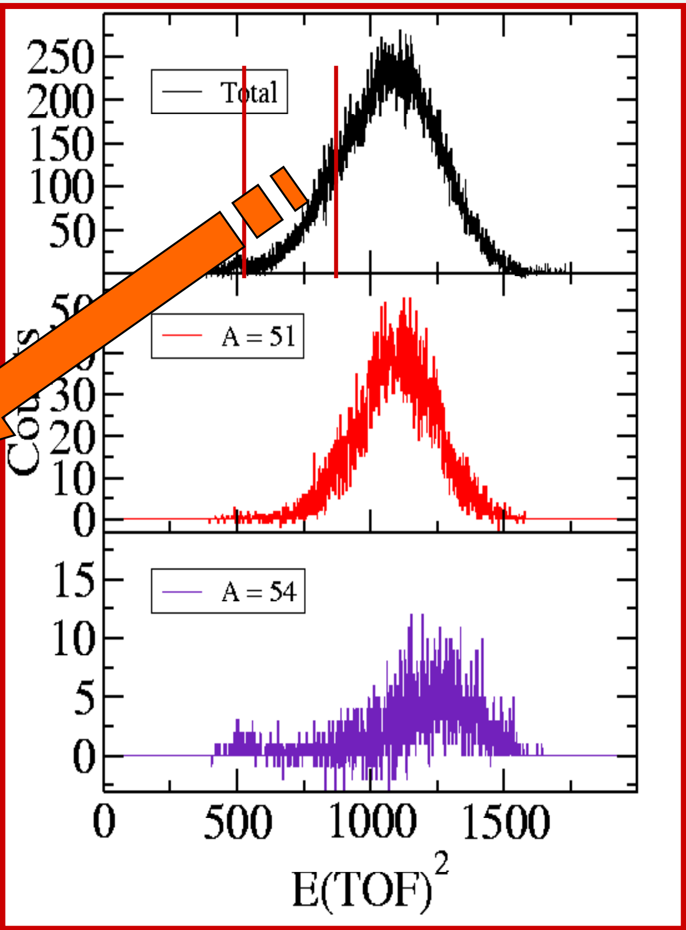
Contaminants can be removed by using the recorded total energy *E* and time-of-flight (*TOF)* of the recoils

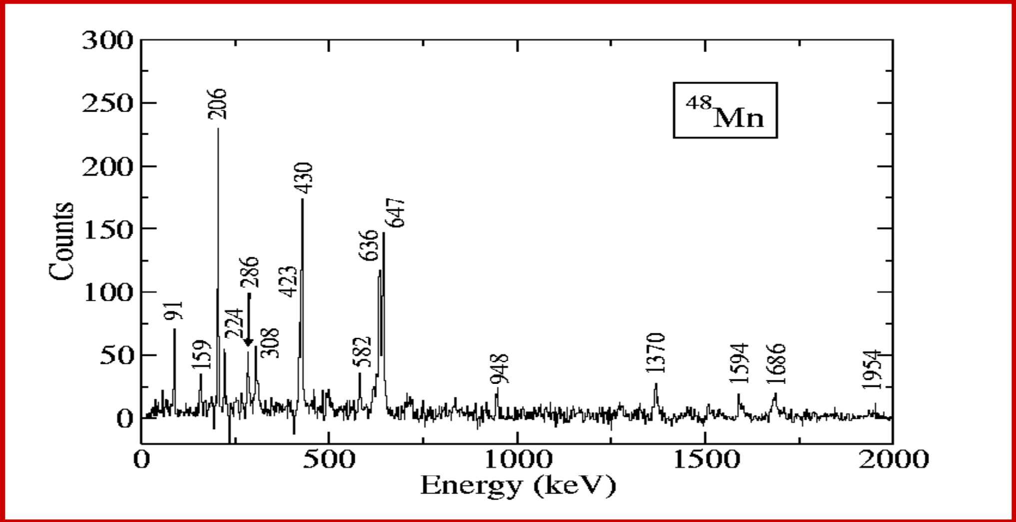
Mass is proportional to ET^2

$$E = \frac{1}{2} m v^2, \quad v = \frac{d}{TOF}$$

$$\Rightarrow m \propto E(TOF)^2$$

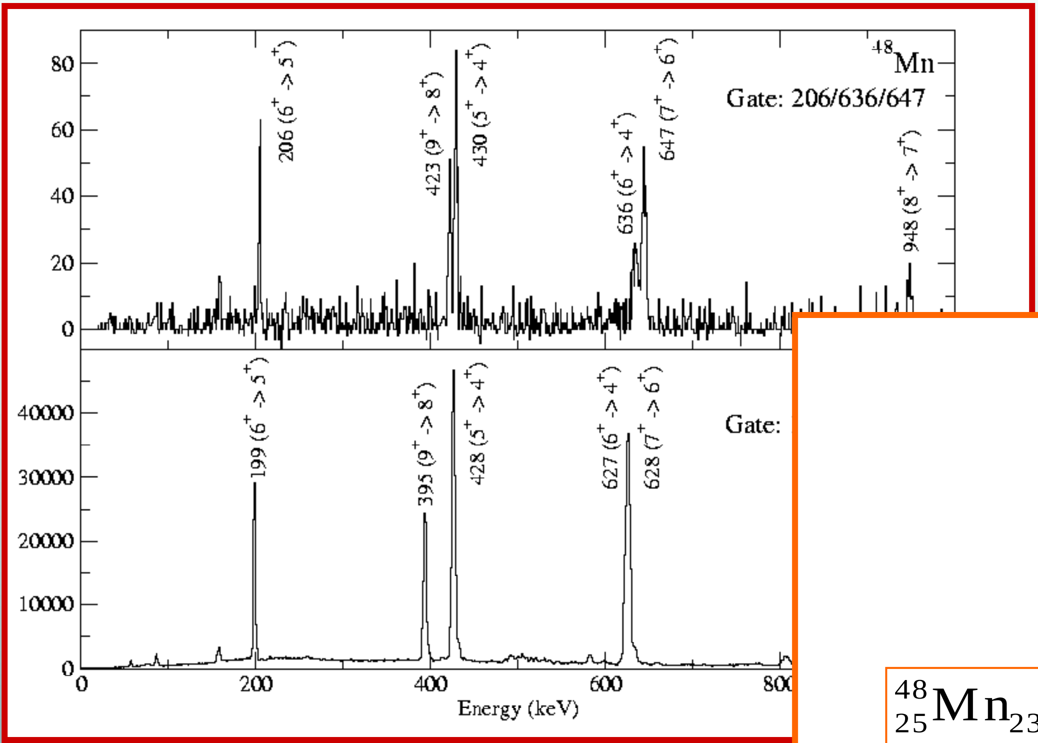
the ET^2 information has sufficient resolution to distinguish three mass units difference.





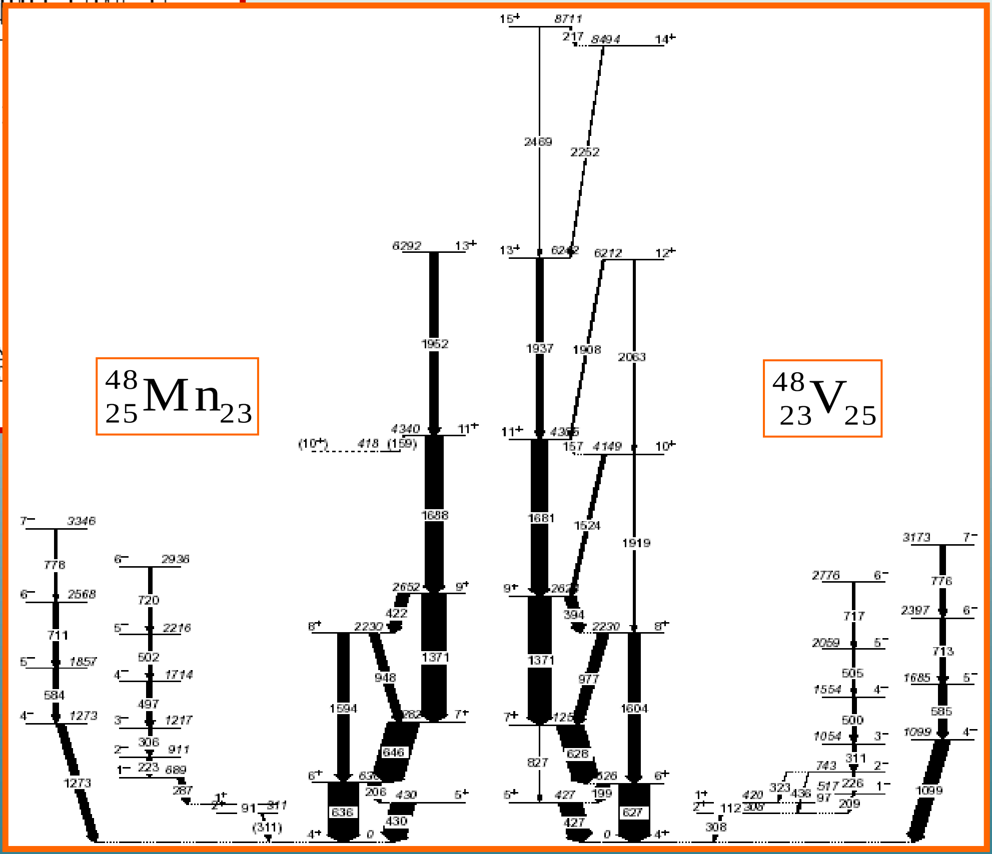
M.A. Bentley et al., Phys. Rev. Lett. 93 (2006) 132501

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

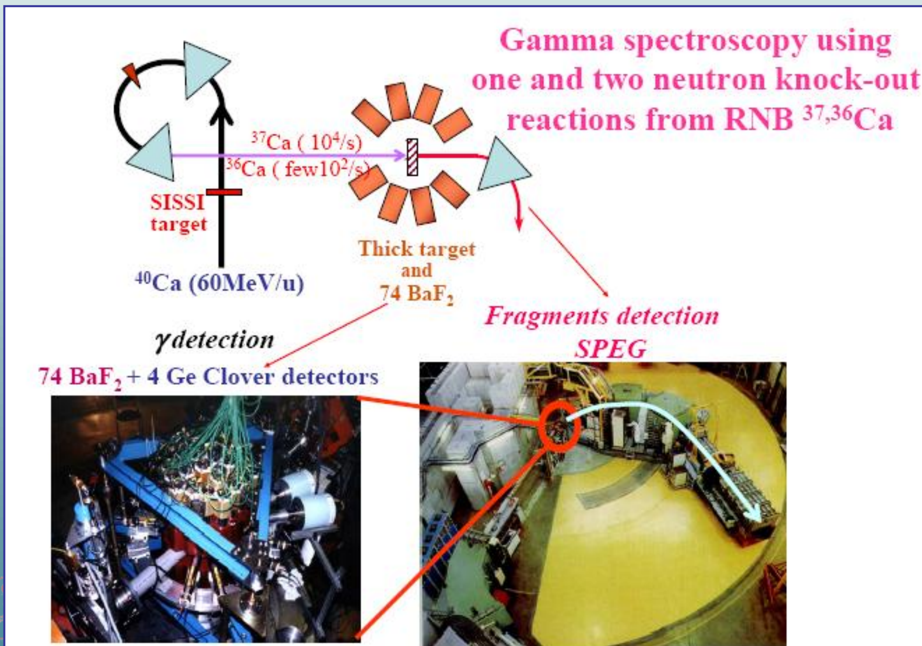
Fragmentation reactions are particularly suitable to populate mirror nuclei far from stability and near the proton dripline.

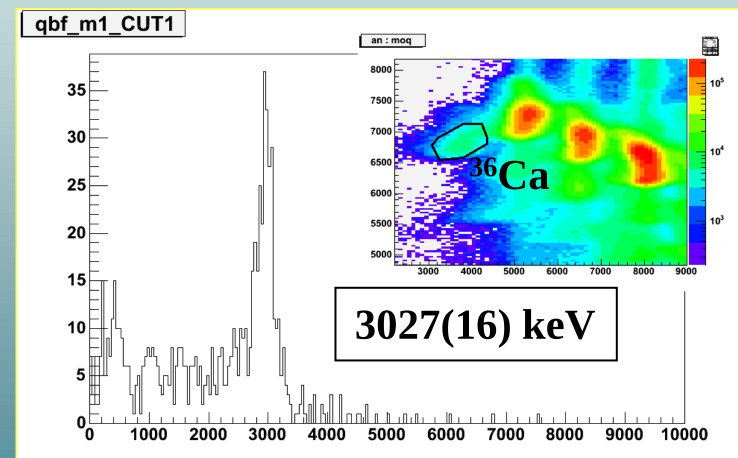
Knockout reactions with exotic beams

<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))





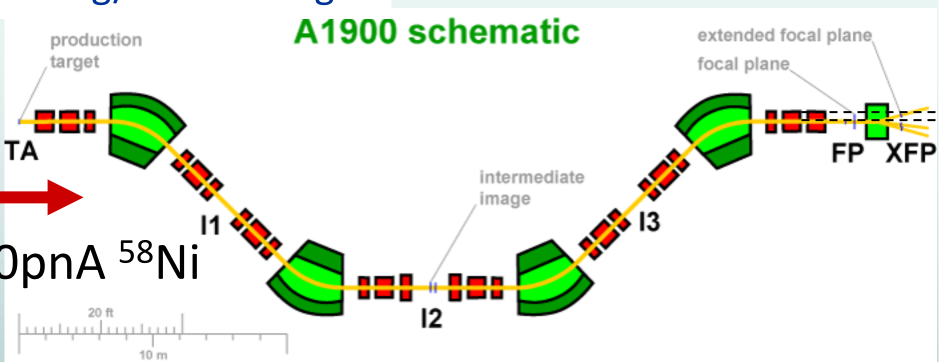
F. Azaiez et al.

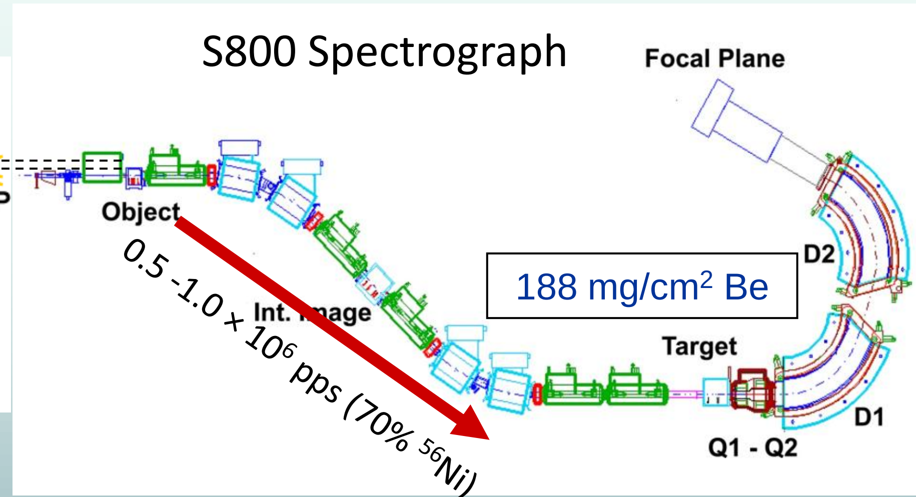
Mirrored fragmentation of N=Z nuclei

MSU experiment

600 mg/cm2 Be target

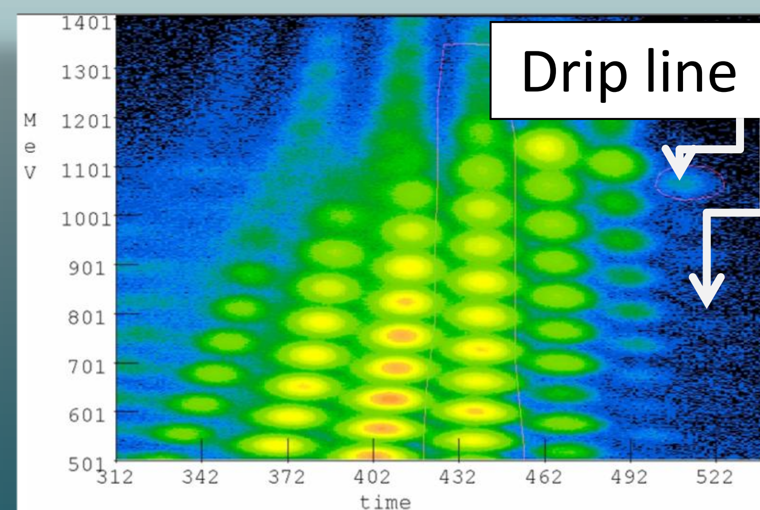
10pnA ^{58}Ni





Primary → N=Z second. → "mirrored frag."

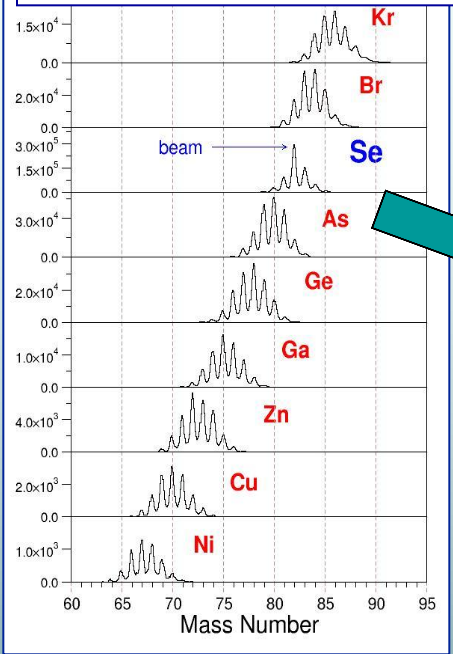
^{58}Ni → | ^{56}Ni → | ^{53}Mn, ^{53}Ni

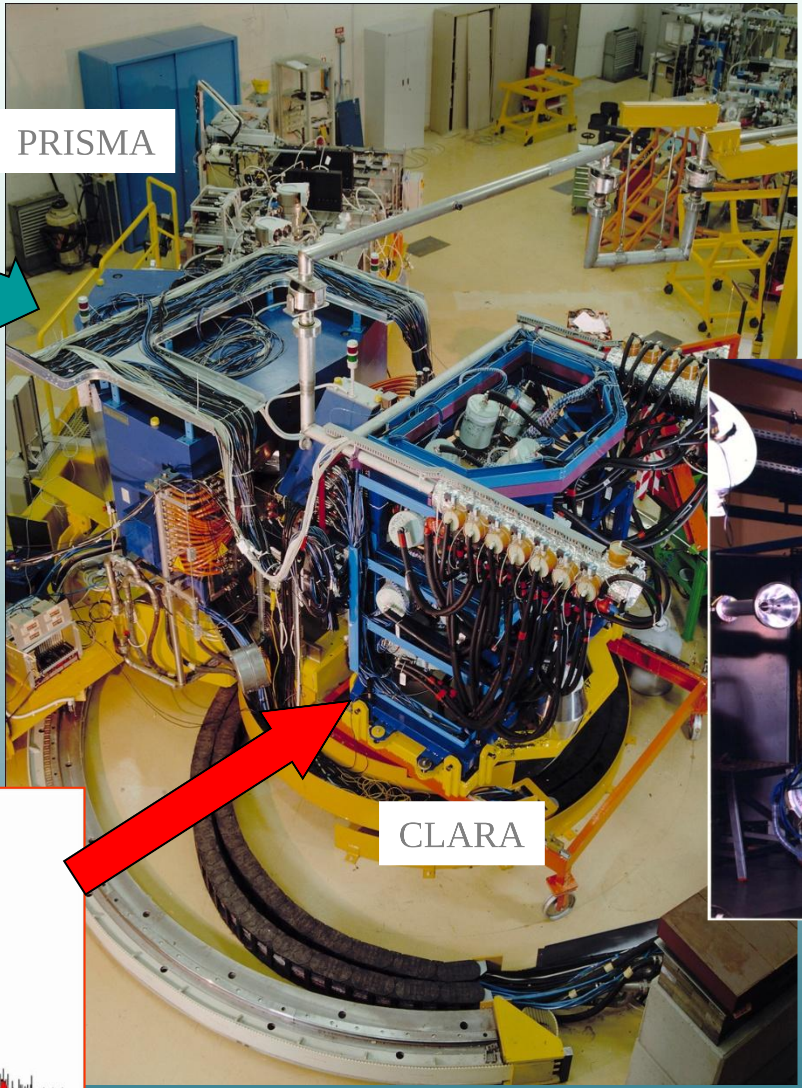


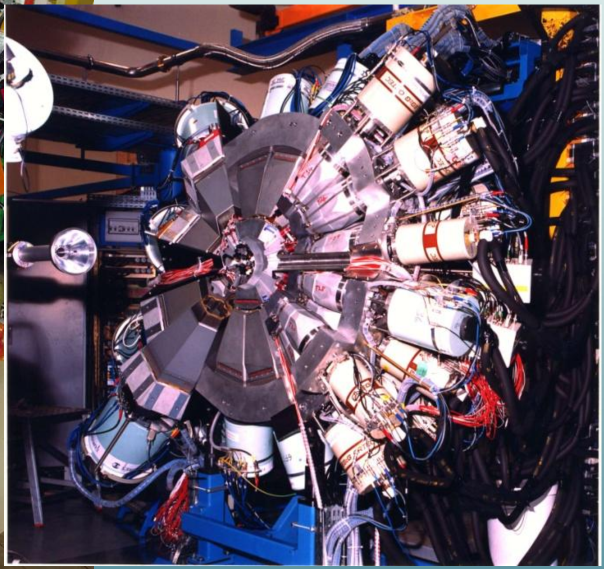
J.R. Brown et al.,
Phys. Rev. C 80, 011306(R) (2009)

Mirror nuclei with multinucleon transfer

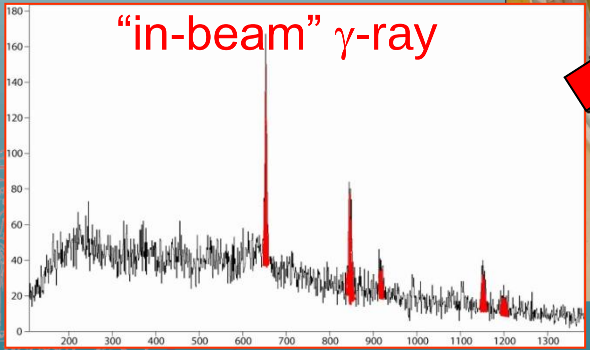
A & Z identification







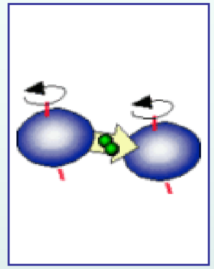
Prisma + CLARA
@LNL, Italy



Efficiency ~ 3 %
Peak/Total ~ 50 %
FWHM ~ 10 keV @ v/c = 10%

Mirror nuclei with multinucleon transfer

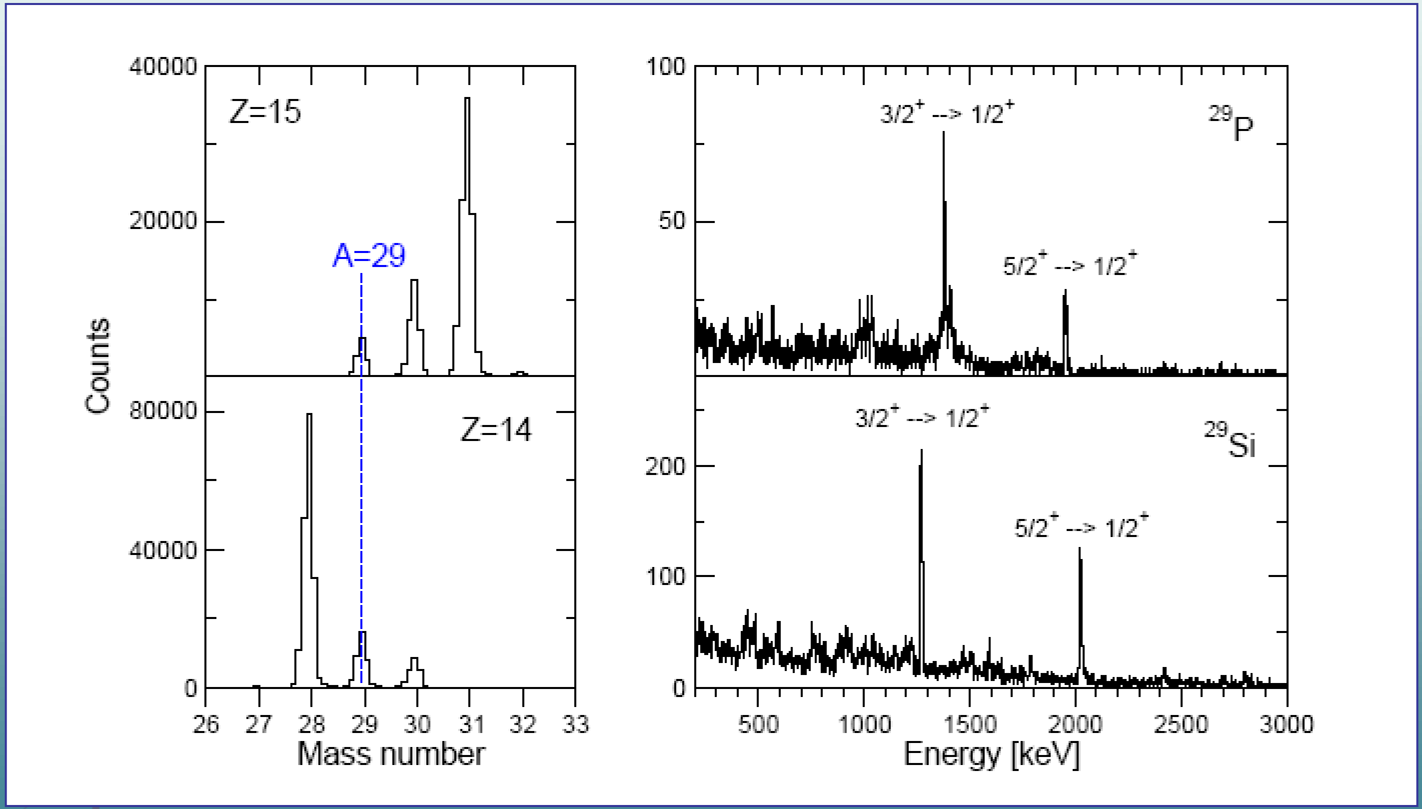
$^{32}S + ^{58}Ni \rightarrow$



$\rightarrow ^{29}P + ^{61}Cu$

$\rightarrow ^{29}Si + ^{61}Zn$

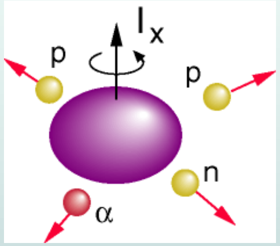
@ 135 MeV LNL, N. Marginean



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

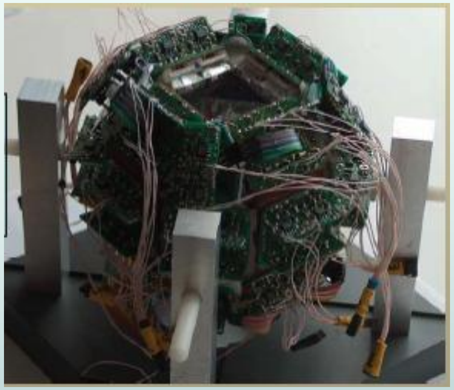
We need detectors with high efficiency

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

Charged-particle detectors

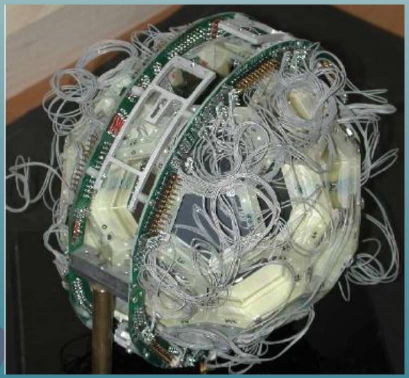
DIAMANT



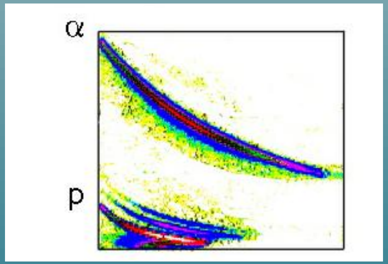
86 CsI(Tl) elements scintillators

efficiency: protons ~70%
alphas ~ 50%

EUCLIDES

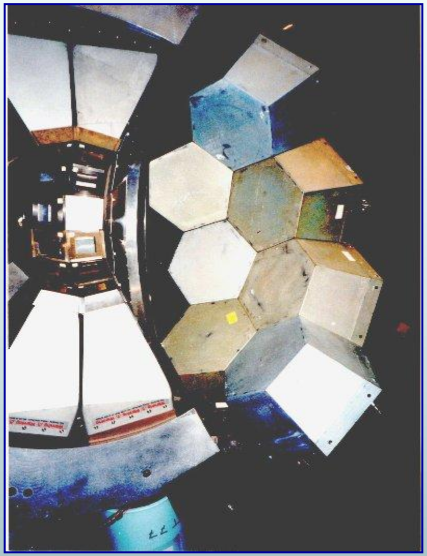


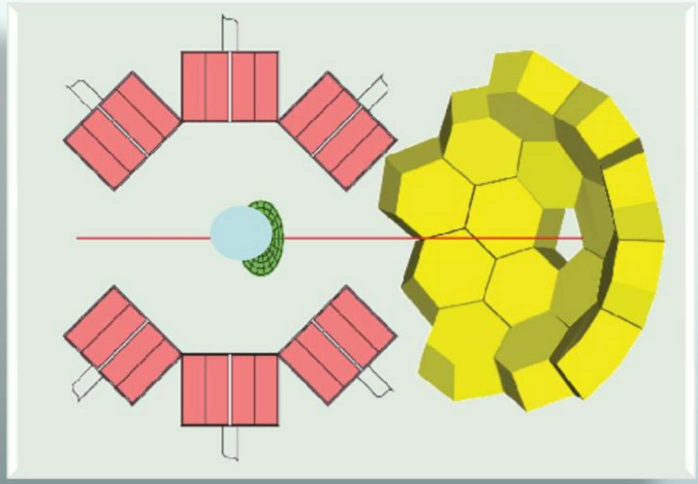
Si E-ΔE telescopes
efficiency: protons ~70%
alphas ~ 40%



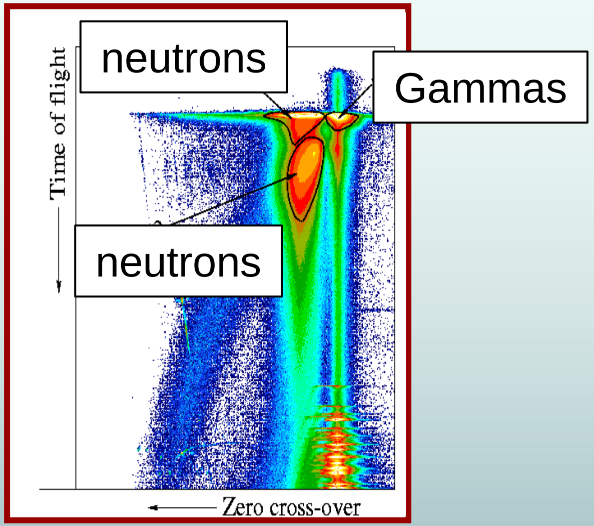
INFN Istituto Nazionale di Fisica Nucleare

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

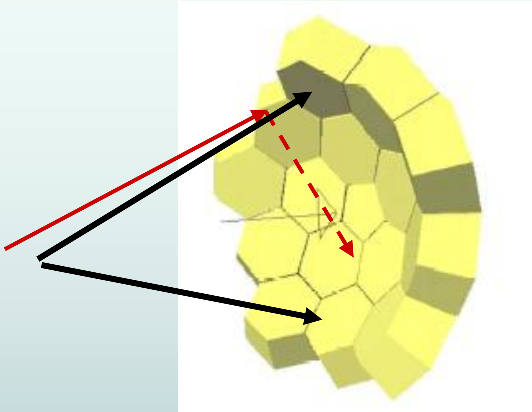
Efficiency ~ 25%

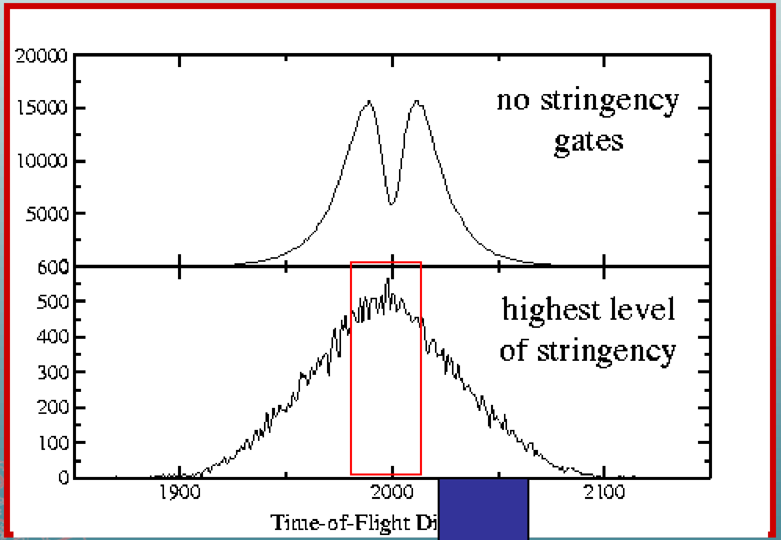
Discrimination using time-of-flight data

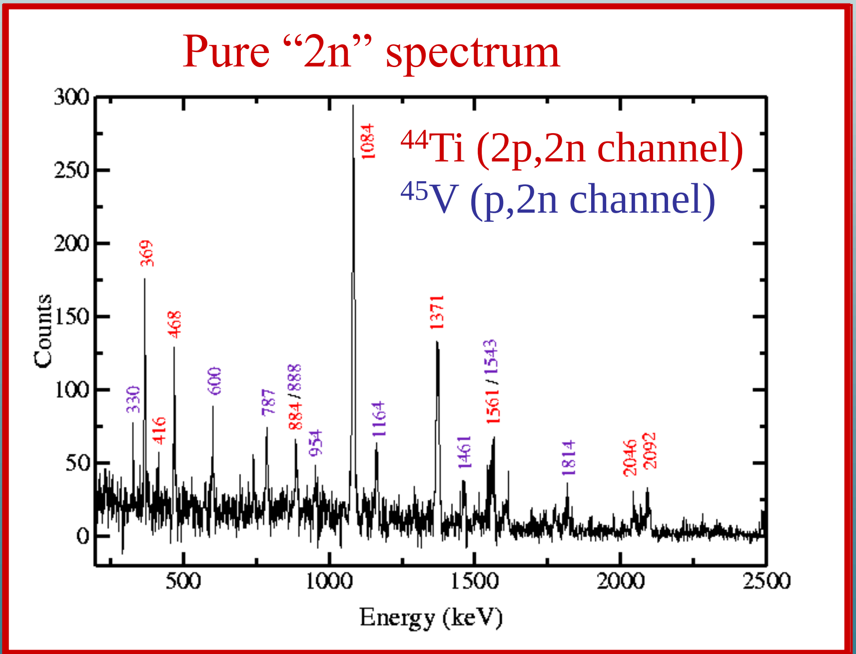
Problem: one neutron scattered between two detectors looks like two neutrons…

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

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

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

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

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

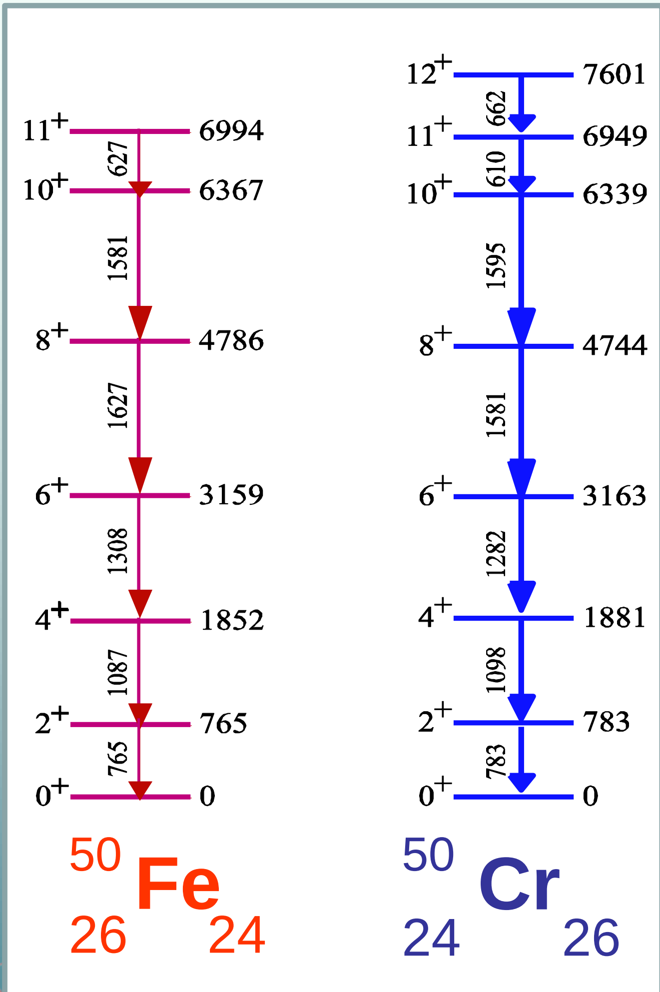
26 Clover detectors (×4 crystals) & 15 Clusters (×7 crystals).

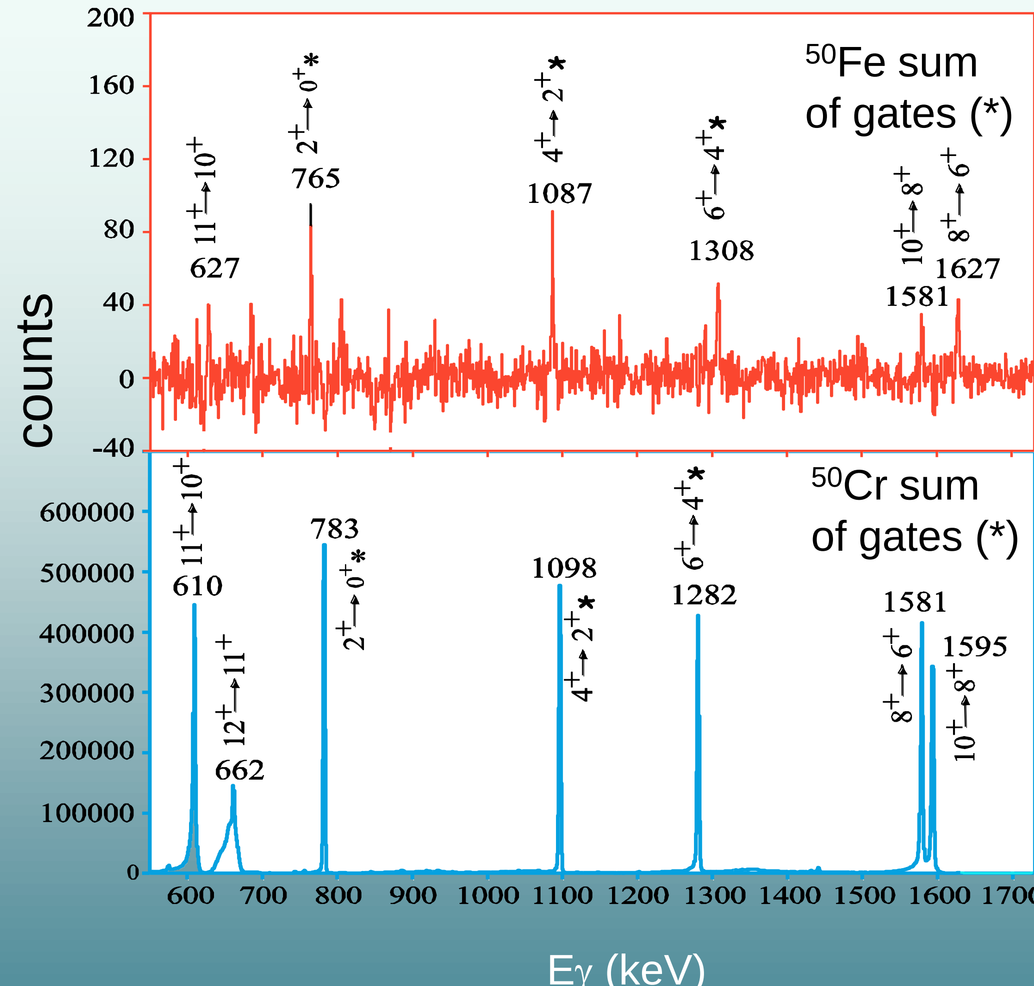
ISIS: Charged-particle detector array - 40 Si E-DE telescopes, total efficiency e_p~70% , e_a~40%

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

First observation of excited states in ^{50}Fe

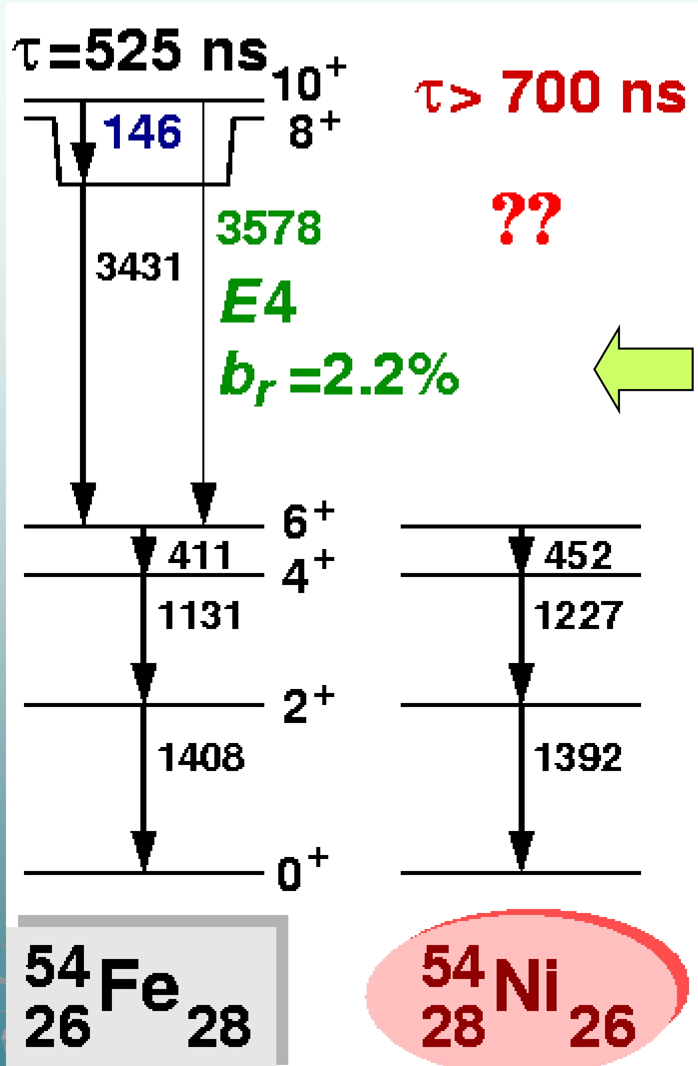




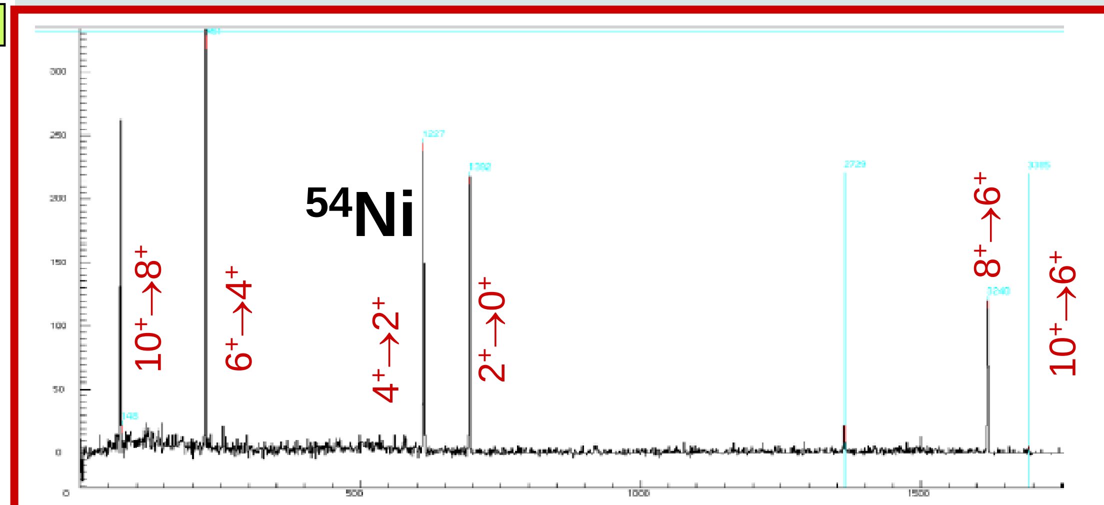
$\sigma(Fe)/\sigma(Cr) \approx 10^{-4}$

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

Spectroscopy with exotic stopped beams



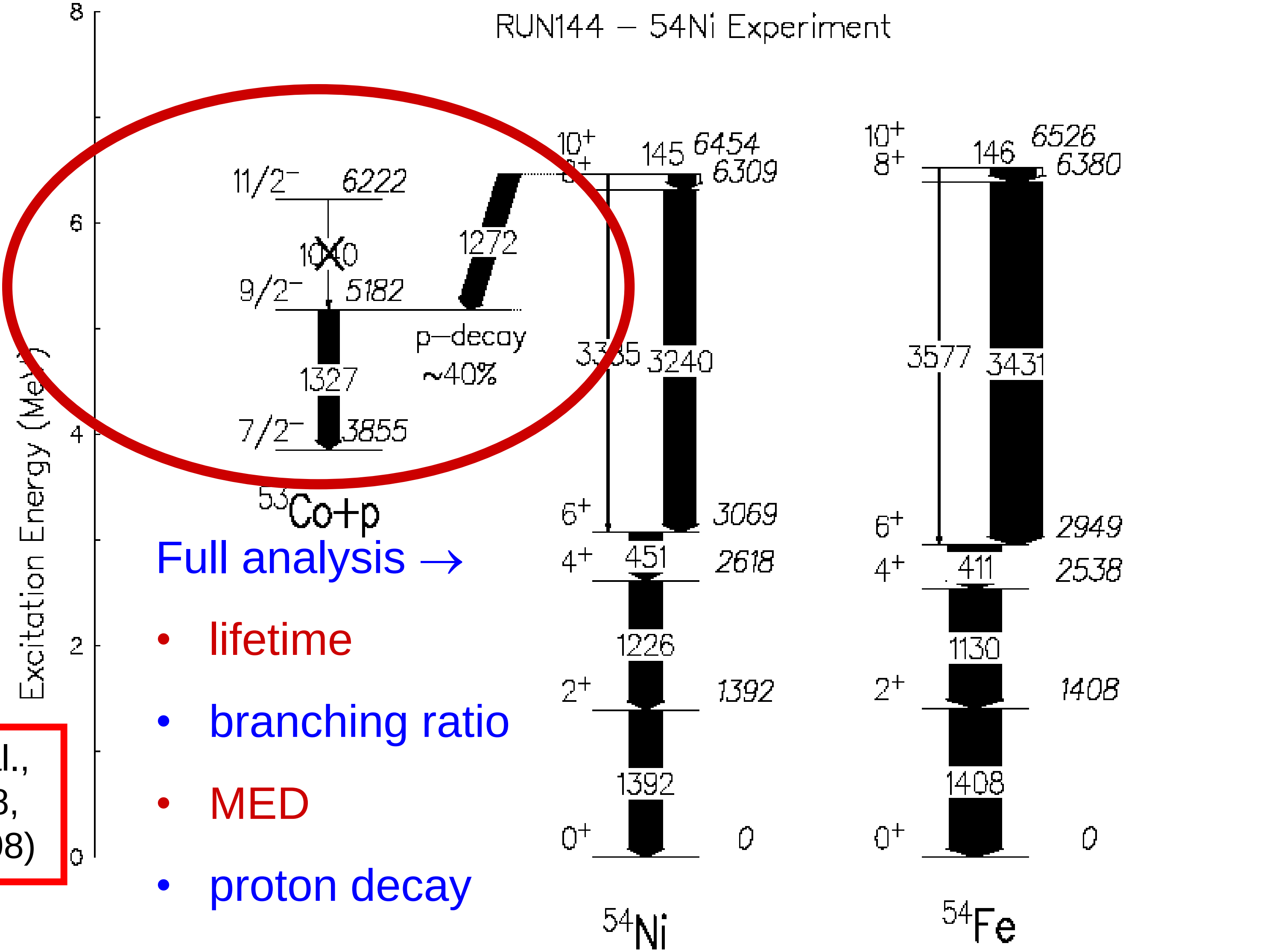
Fragmentation of ^{58}Ni beam
Secondary beam of ^{54}Ni in the isomeric state 10^+



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)

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

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

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

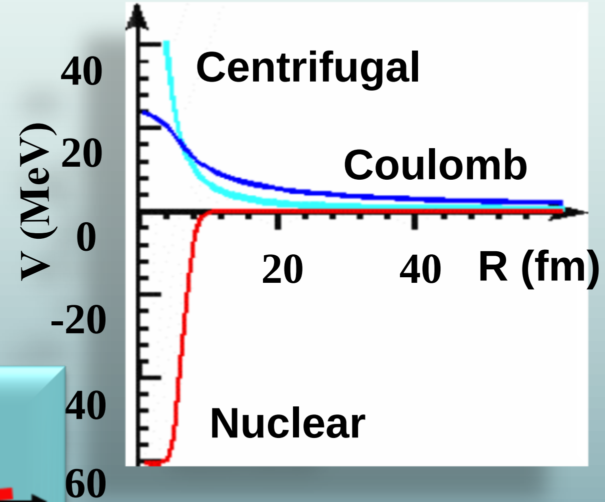
$$E_0 = \sum_i \varepsilon_i^{(0)}$$

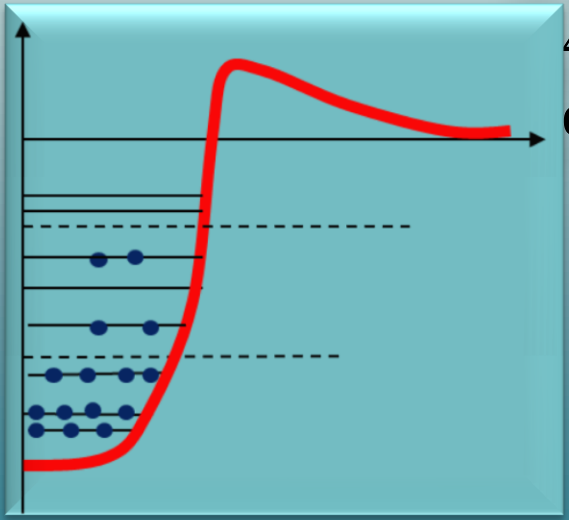
Configuration

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

spherical mean field

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



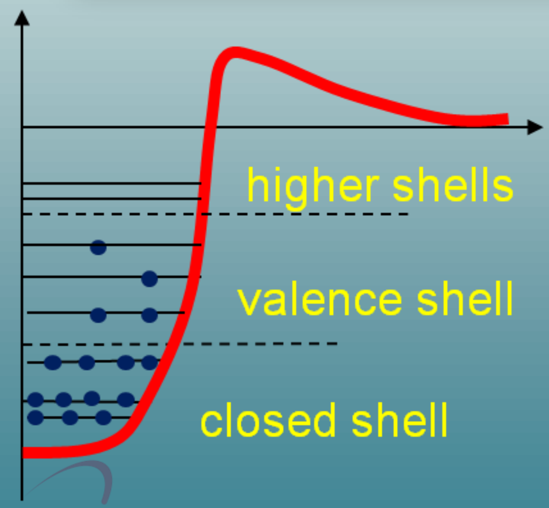


Configuration mixing

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

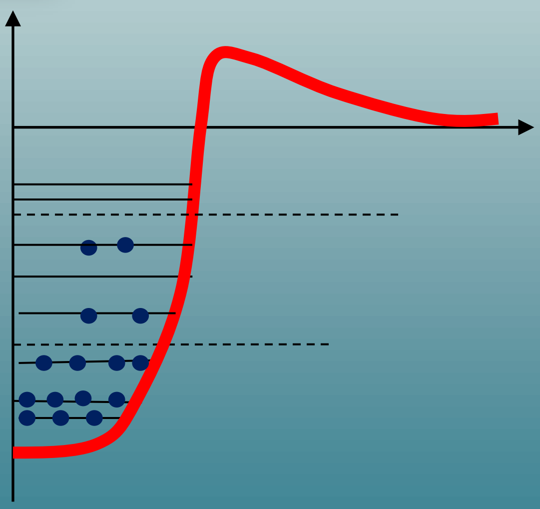
$$\mathcal{H} = \begin{pmatrix} \langle\phi_1|H|\phi_1\rangle & \langle\phi_1|H|\phi_2\rangle & \ldots \\ \langle\phi_2|H|\phi_1\rangle & \langle\phi_2|H|\phi_2\rangle & \ldots \\ \langle\phi_3|H|\phi_1\rangle & \vdots & \end{pmatrix} = \begin{pmatrix} E_1 & & \\ & E_2 & \\ & & \ddots \end{pmatrix}$$

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



Mixing of configurations

due to the residual interaction



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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.

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

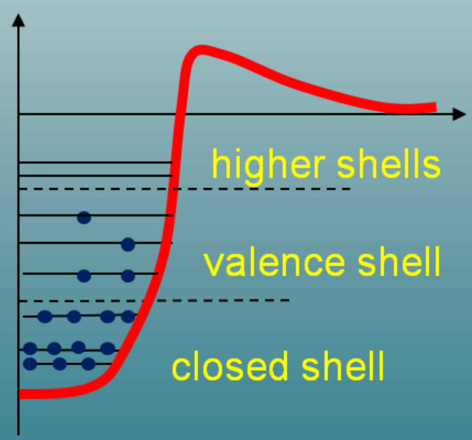
monopole Multipole

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

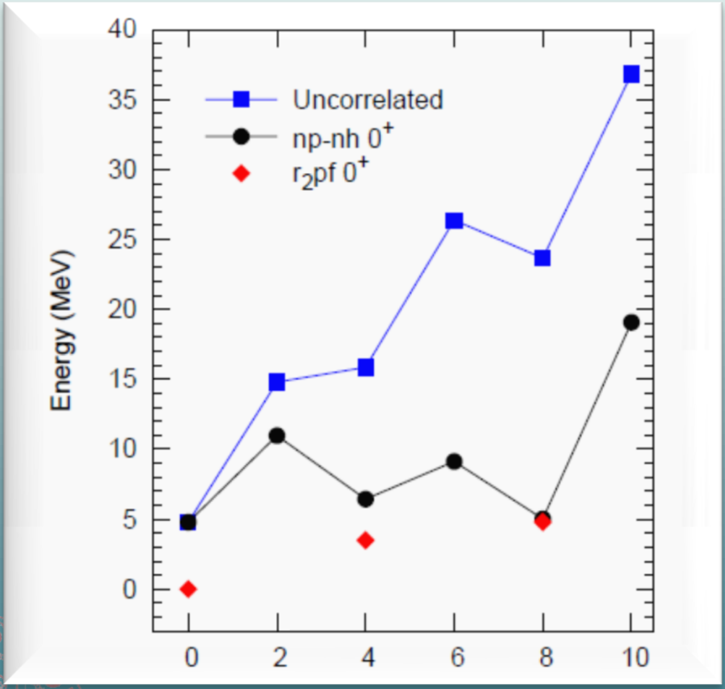
H_M

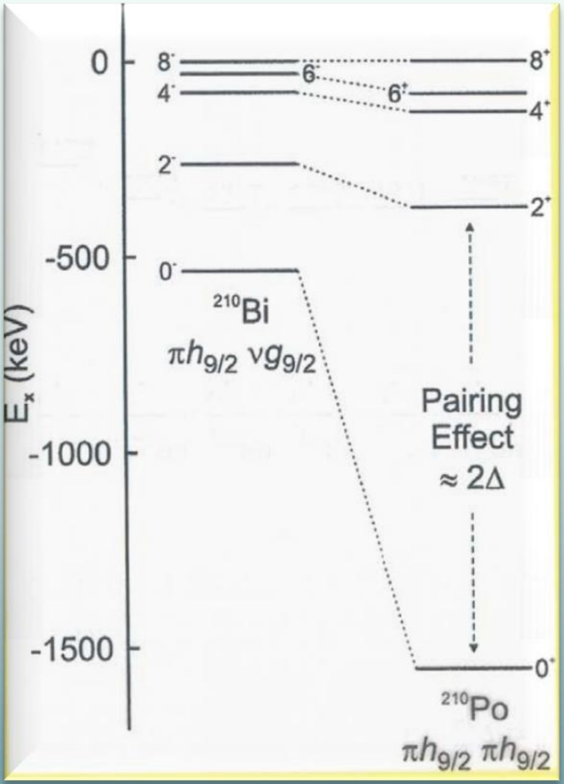
- correlations
- mixing of configurations
- coherence
- energy gains



Effect of the correlations

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

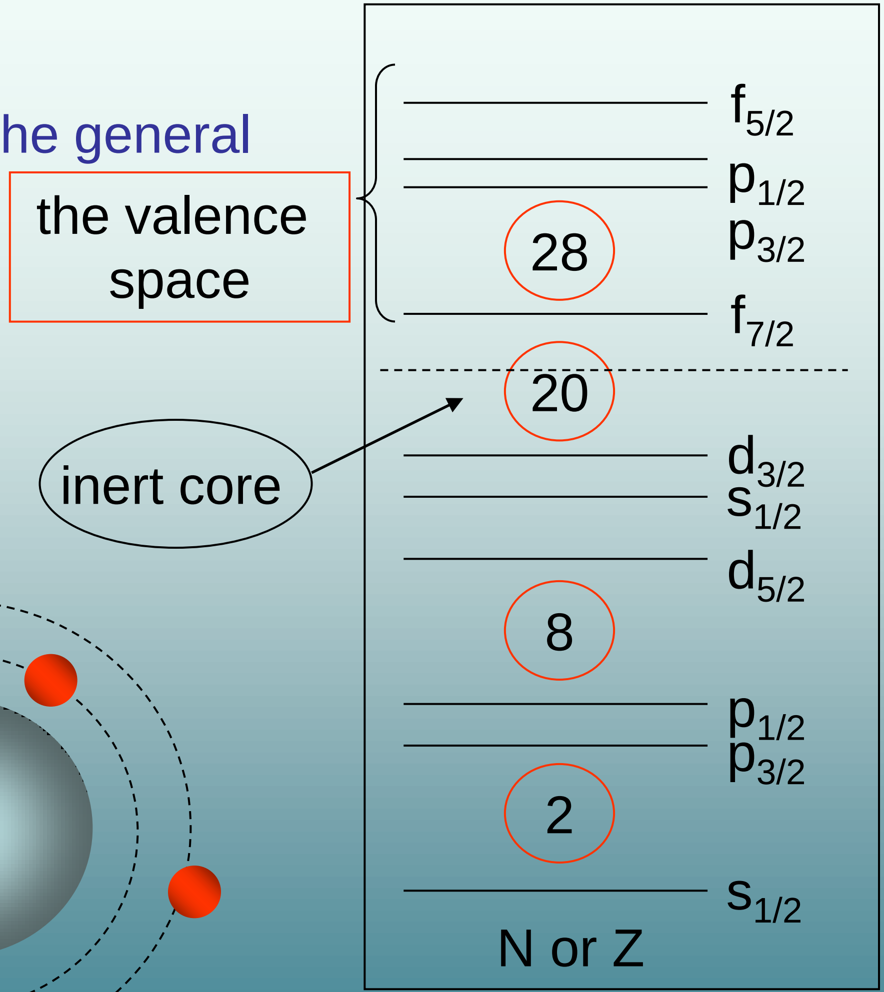




The fact that some nuclei display collective behaviour depends on the structure of the spherical field near the Fermi surface for both protons and neutrons

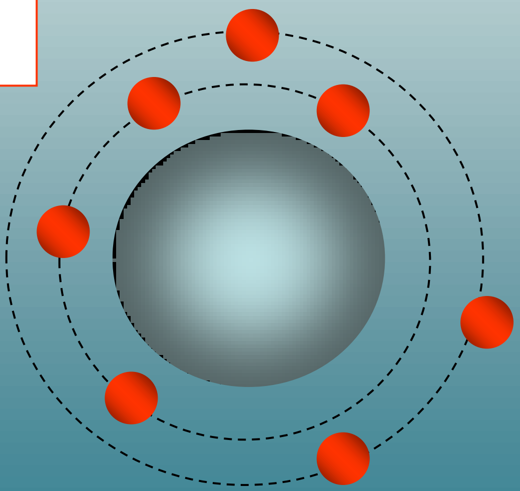
Ingredients for the Shell Model calculations

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

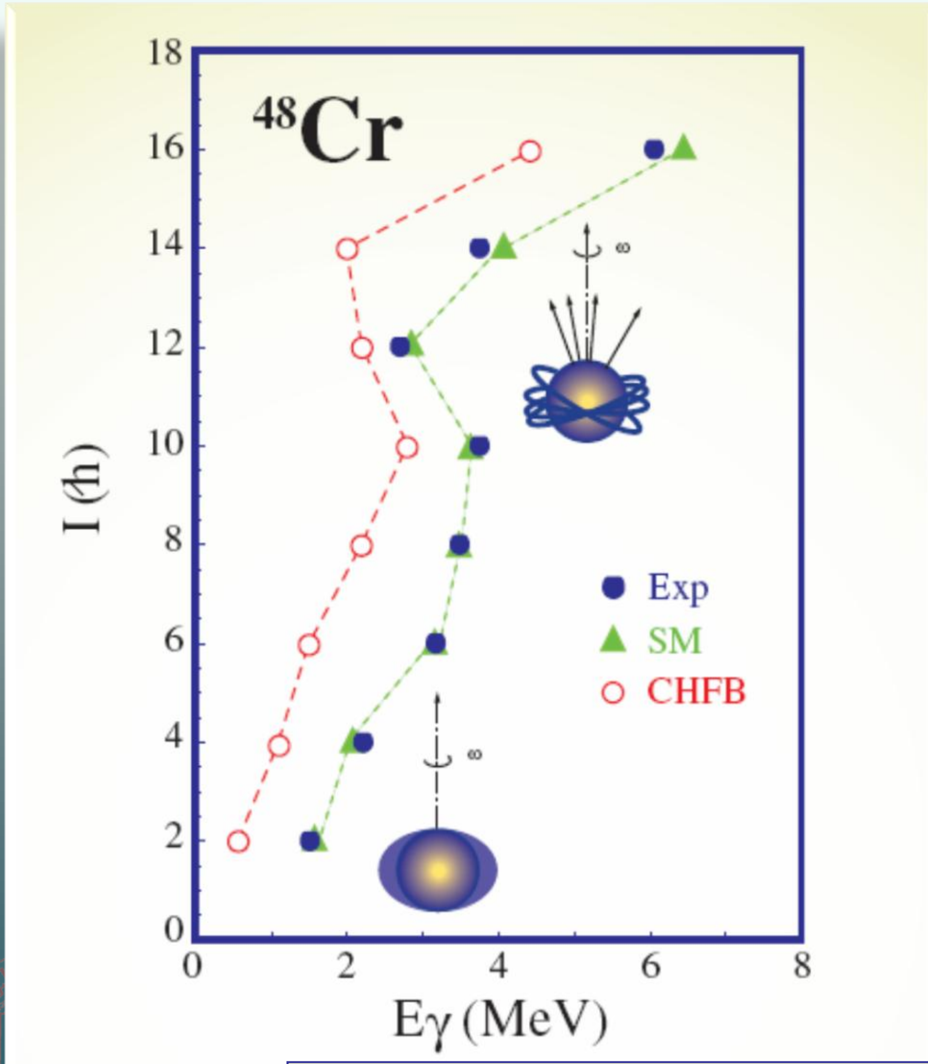


The choice is determined by the limits in computing time and memory: large dimension of the matrices to be diagonalised.

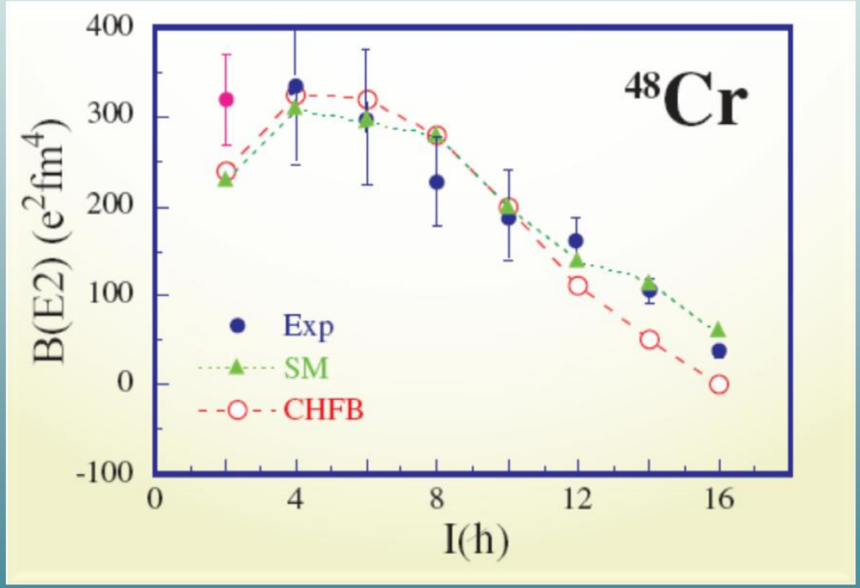
Current codes diagonalize matrices of dimension $\sim 10^{10}$



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

Lecture 2

The end