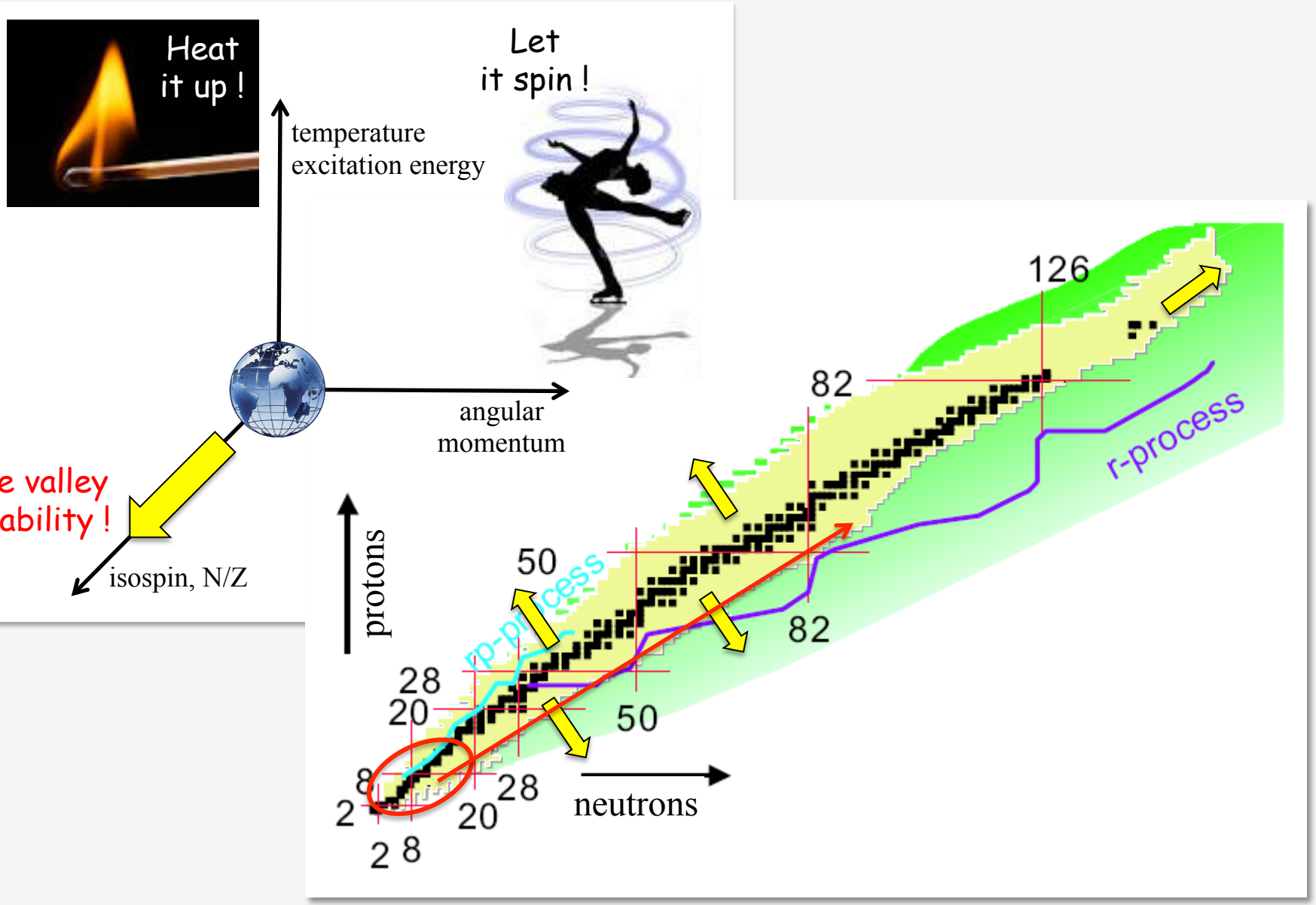
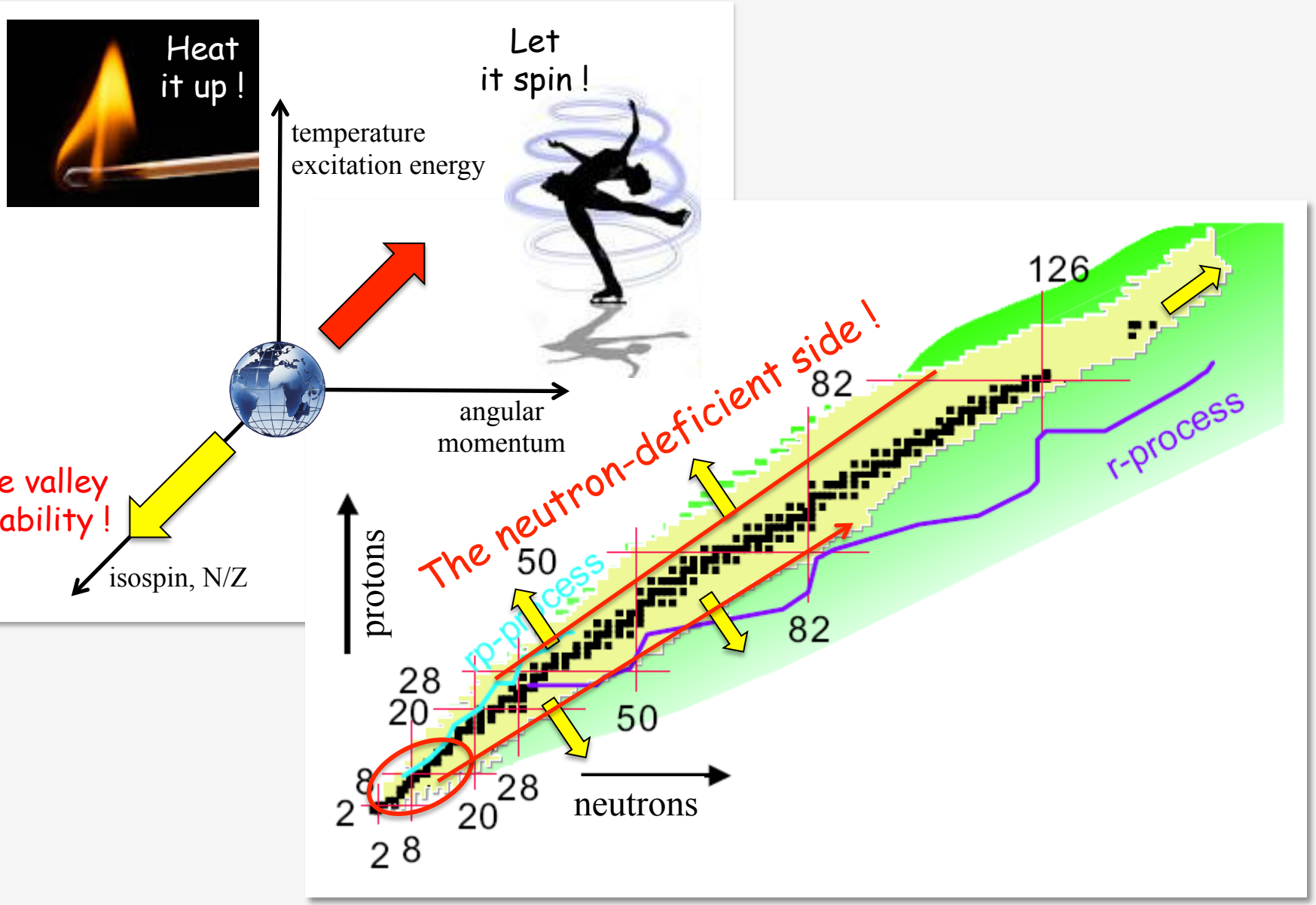
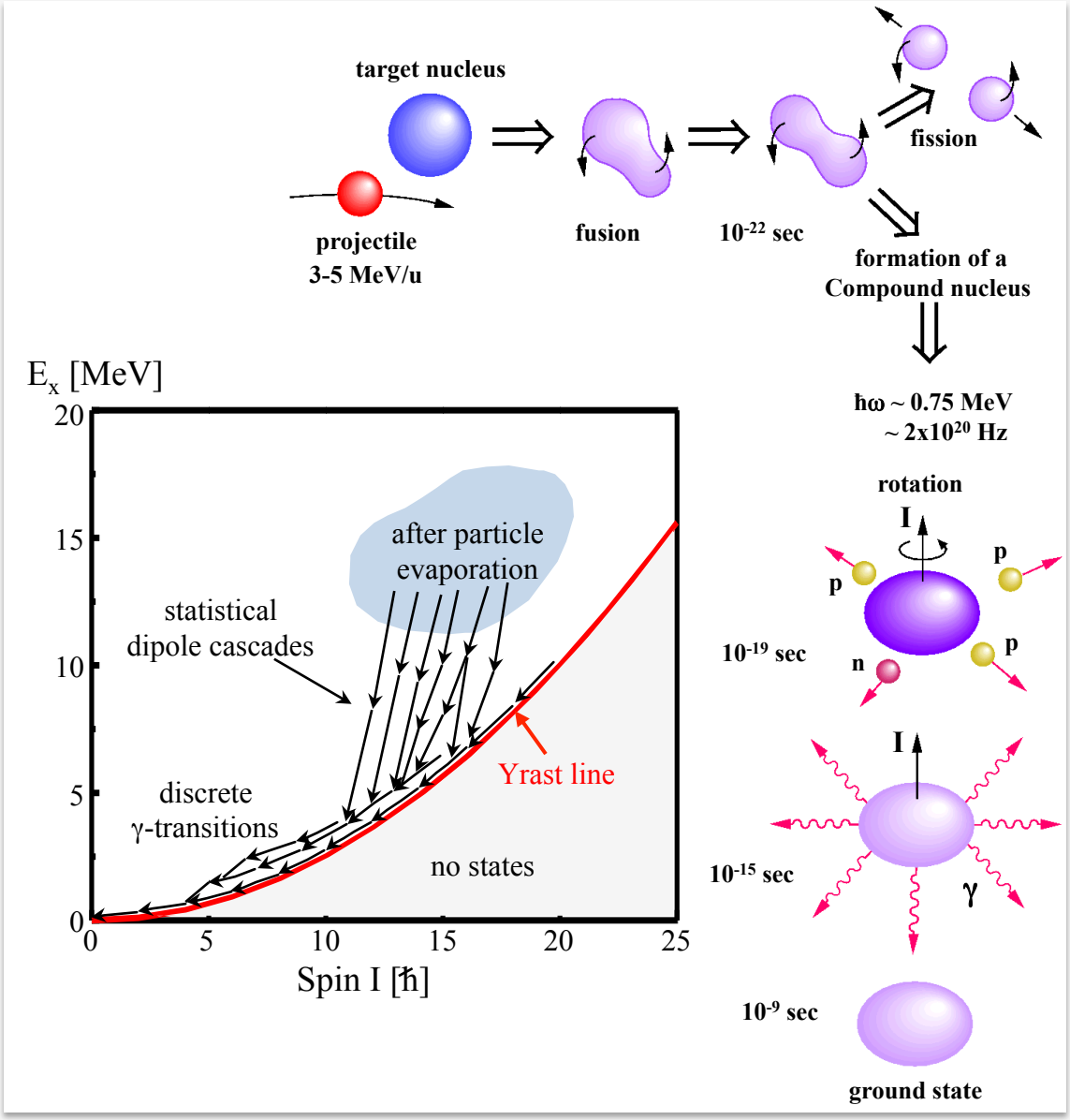
Let's play with all degrees of freedom



Let's play with all degrees of freedom



The heavy-ion induced fusion-evaporation reaction



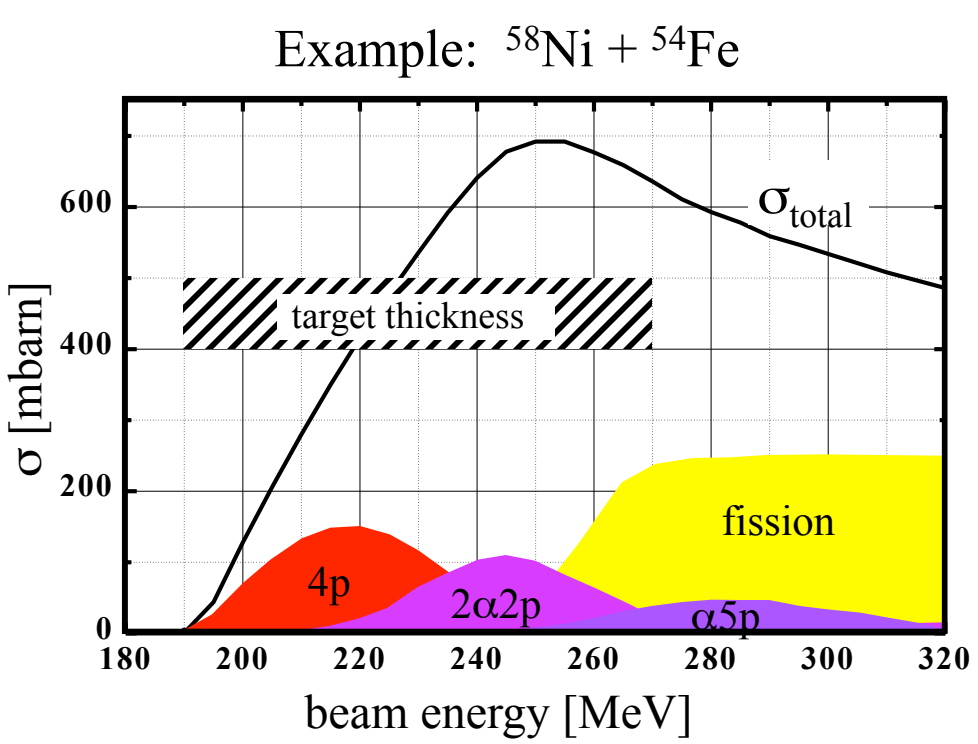
- neutron-deficient nuclei
- high spin and excitation energy
- needs heavy-ion accelerator
- many different reaction products
- large range of cross sections
- recoil velocity of reaction products v/c ≈ 1-5%

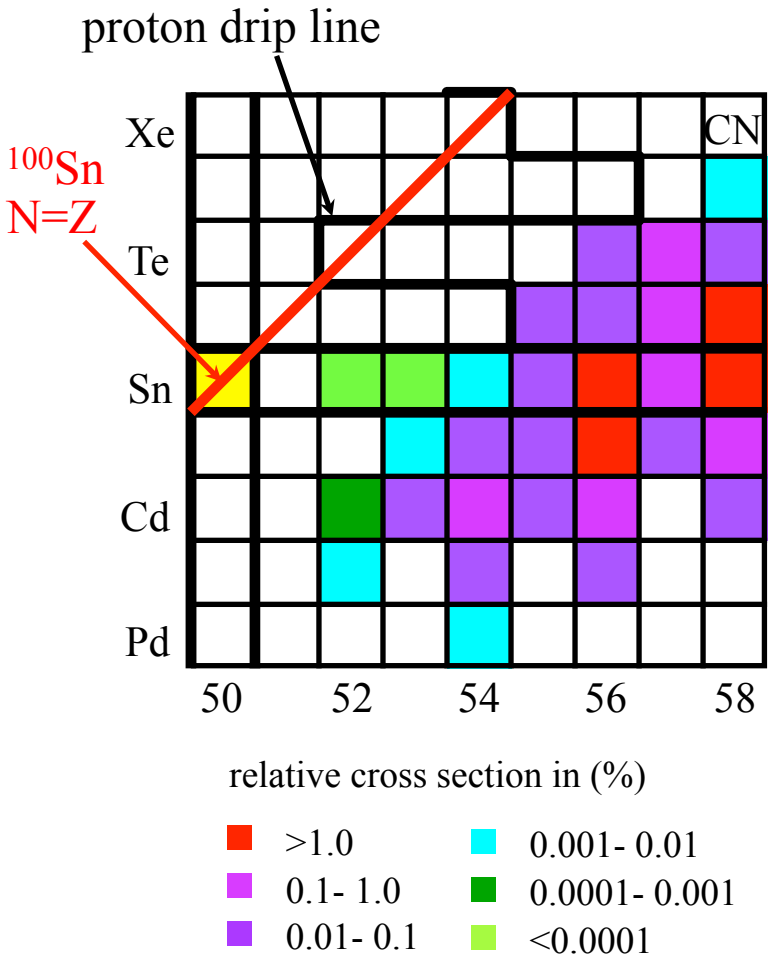
Use highly efficient γ-ray spectrometer to explore the E_x vs. I plane !

Recoil velocity crucial for many techniques to measure lifetimes, moments etc.

No time to talk about all that …

The importance of channel identification





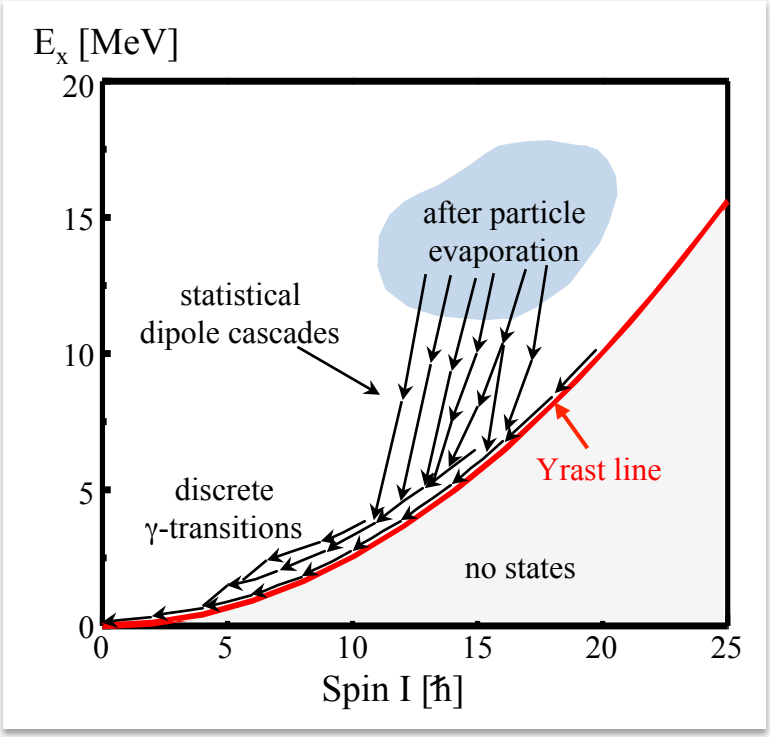
- many different reaction products
- large dynamical range

We need magnetic spectrometer, neutron detectors, charged particle detectors etc.

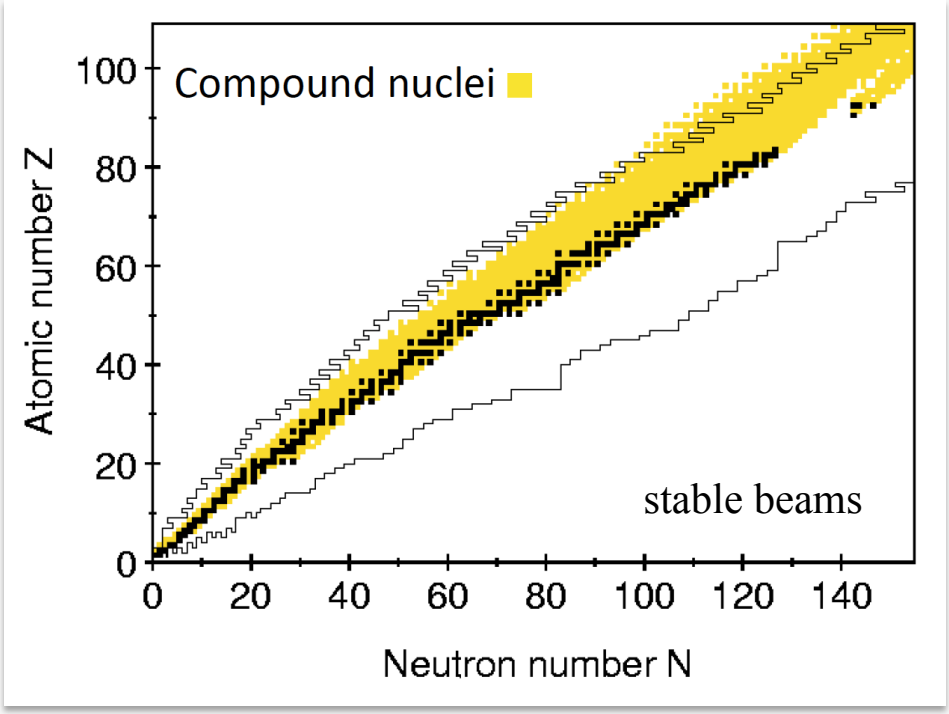
… or decay tagging !

No time to talk about all that …

The playground of fusion-evaporation reactions



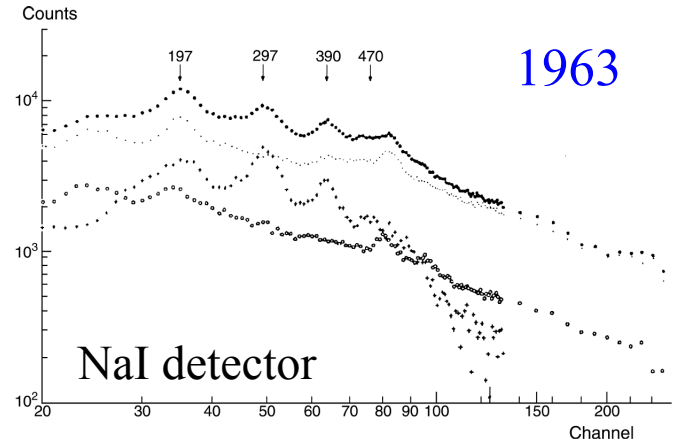
Strongly populated reaction channels:
High-spin physics !



Weakly populated reaction channels:
New physics at the extremes of isospin !

How high-spin physics started ...

α-induced fusion-evaporation reactions - $^{160}Gd(\alpha,4n)^{160}Dy$



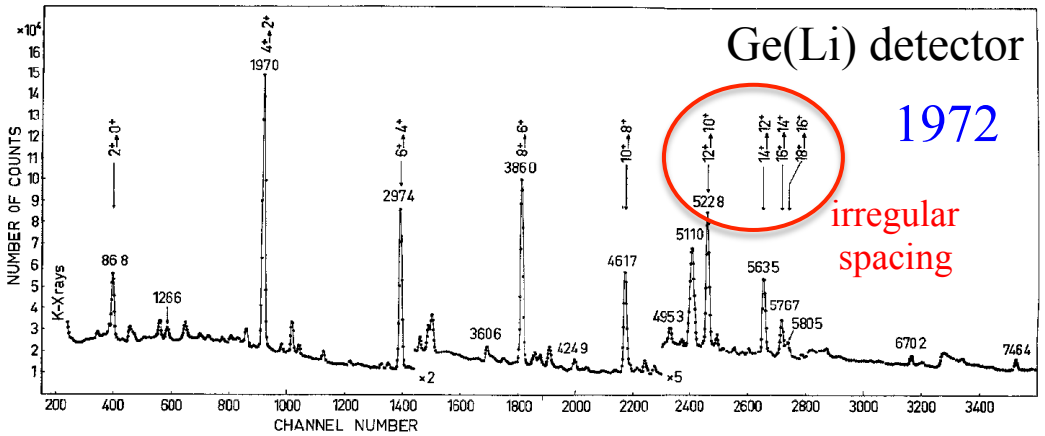
First 10^+ state !

Remember:

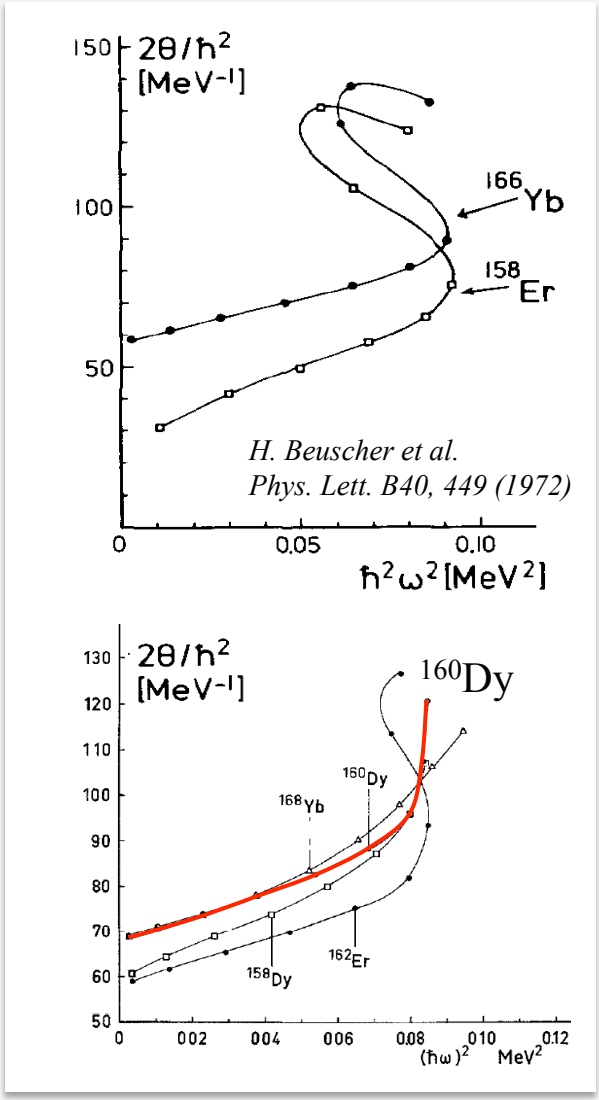
$$E_x = I(I+1)\frac{\hbar^2}{2J}$$

ΔE_γ=const.

H. Morinaga & P.C. Gugelot, Nucl. Phys. 46, 210 (1963)

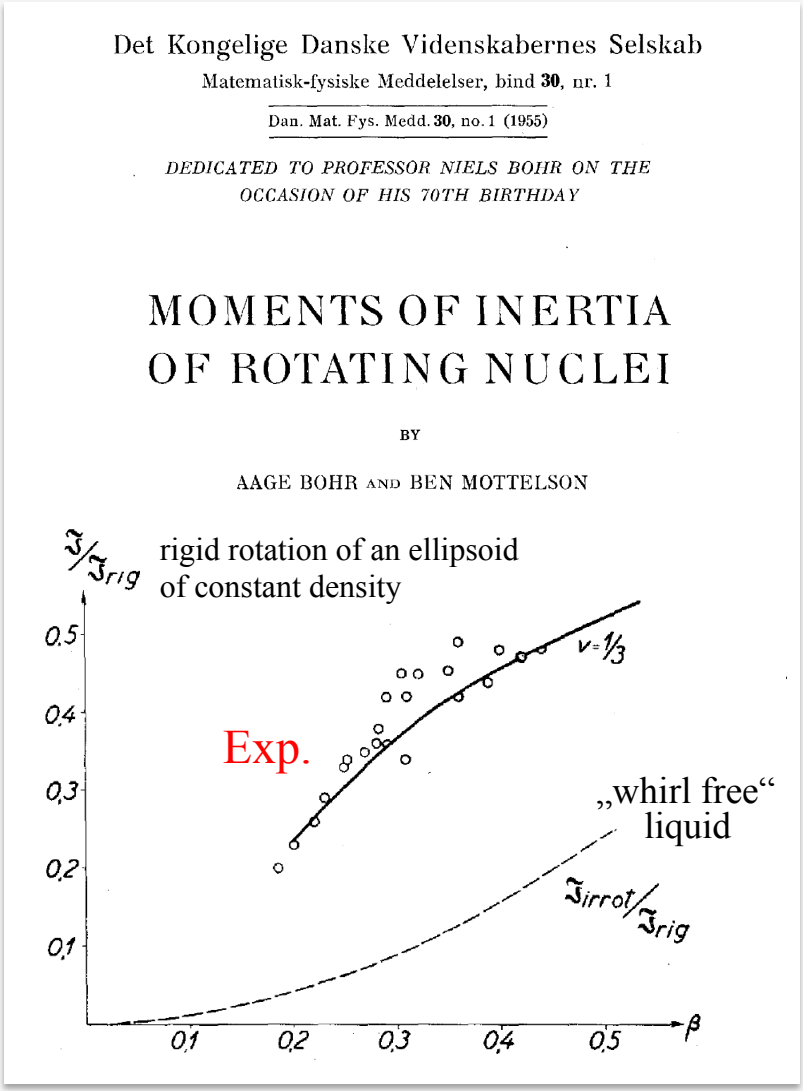


A. Johnson, H. Ryde & S.A. Hjorth, Nucl. Phys. A179, 753 (1972)



The discovery of backbending !

The problem of the "wrong" moment of inertia



Det Kongelige Danske Videnskabernes Selskab

Matematisk-fysiske Meddelelser, bind **30**, nr. 1

Dan. Mat. Fys. Medd. **30**, no. 1 (1955)

DEDICATED TO PROFESSOR NIELS BOHR ON THE OCCASION OF HIS 70TH BIRTHDAY

MOMENTS OF INERTIA OF ROTATING NUCLEI

BY

AAGE BOHR AND BEN MOTTELSON

$\mathfrak{J}/\mathfrak{J}_{rig}$

rigid rotation of an ellipsoid of constant density

0.5 0.4 0.3 0.2 0.1

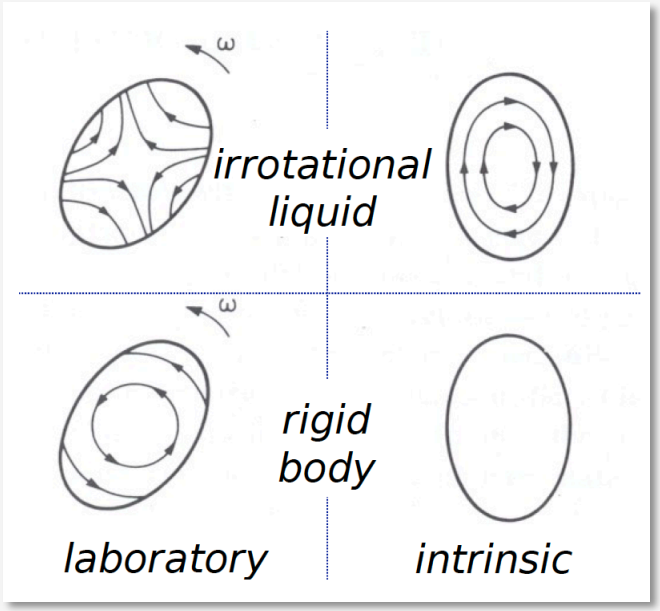
Exp.

$\nu = 1/3$

„whirl free" liquid

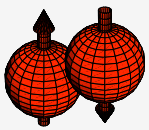
$\mathfrak{J}_{irrot}/\mathfrak{J}_{rig}$

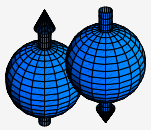
0.1 0.2 0.3 0.4 0.5 β



„Nuclei are like egg shells which are filled with a mixture of a normal and a super-conducting liquid !"

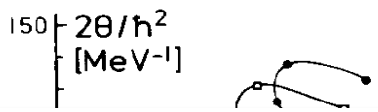
Super conductivity due to **pairing forces** in analogy to the Cooper pairs (electrons) in super conductors.





The backbending phenomenon

$^{162}Dy(\alpha,8n)^{158}Er$



1972

This work has demonstrated the feasibility of observing discrete yrast transitions of spin up to at least $30\hbar$ in (HI,xn) reactions. Three developments have made these high spins accessible. These are (1) ^{40}Ar projectiles to bring in high angular momentum; (2) the elimination of the Doppler broadening by using thin targets and observing in the forward direction; and (3) the enhancement of a particular reaction channel using γ-ray multiplicities. The observed second discontinuity in the yrast levels of ^{158}Er around $I = 28\hbar$ may be due to several possible effects, with alignment of a second pair of particles appearing most likely to us. It will be interesting to find out whether such discontinuities are a general phenomenon and also whether there is a connection between them and the population pattern in (HI,xn) reactions.

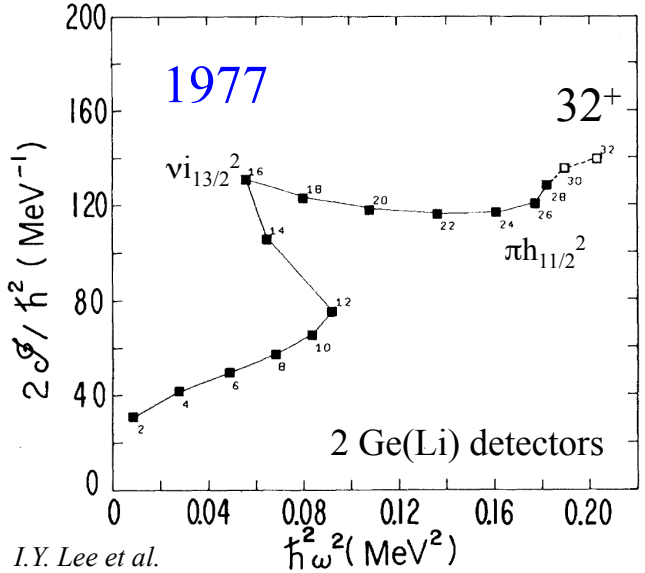
Possible explanations:

Mottelson-Valatin Coriolis antipairing effect
coherent collapse of pairing correlations,
phase transition from the superfluid to a non-superfluid state

neutrons

LBL, 2 Ge(Li) detectors

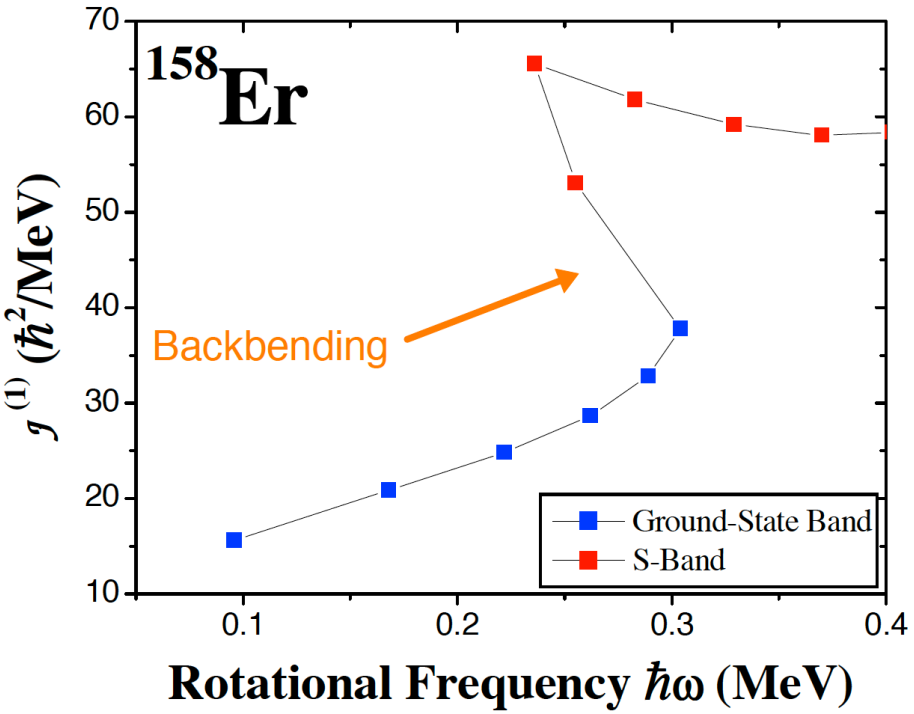
$^{122}Sn(^{40}Ar,4n)^{158}Er$



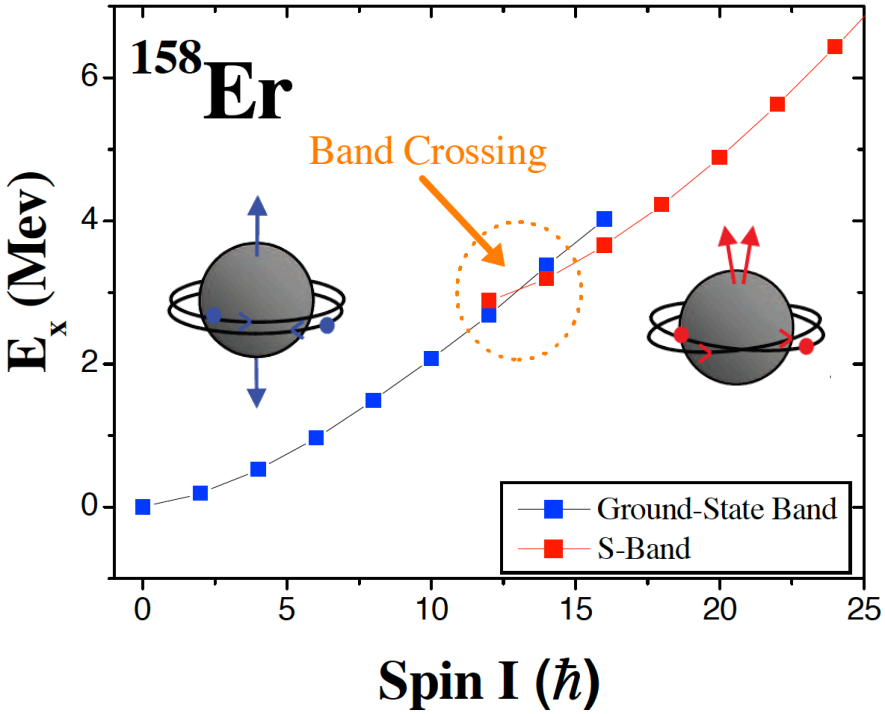
I.Y. Lee et al.
Phys. Rev. Lett. 38, 1454 (1977)

Band crossings along the Yrast line

Moment of inertia vs. rot. frequency

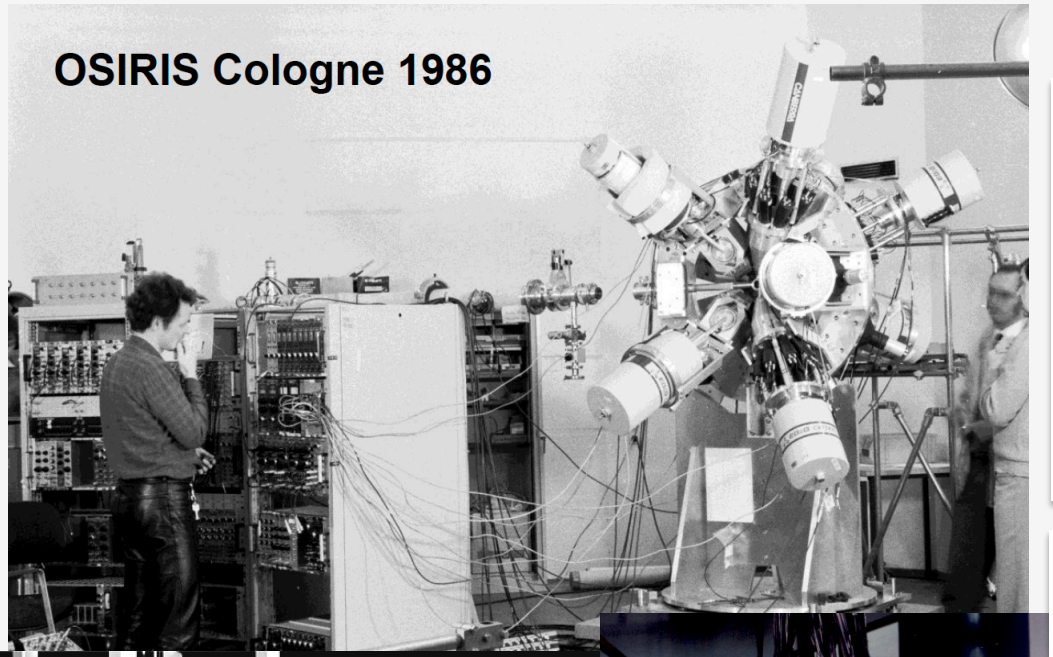


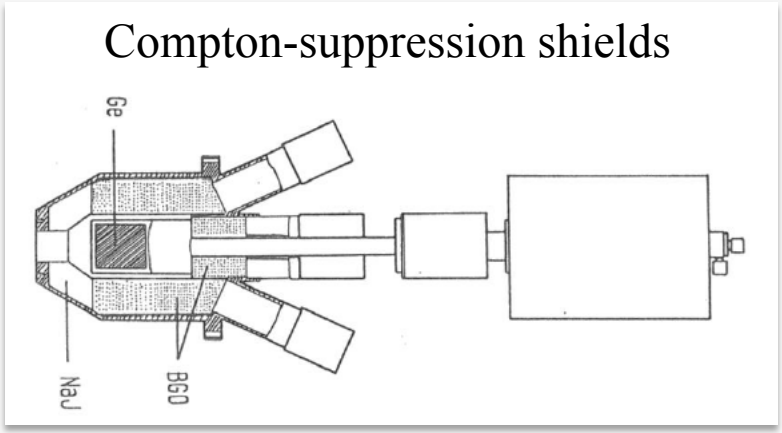
Excitation energy vs. spin

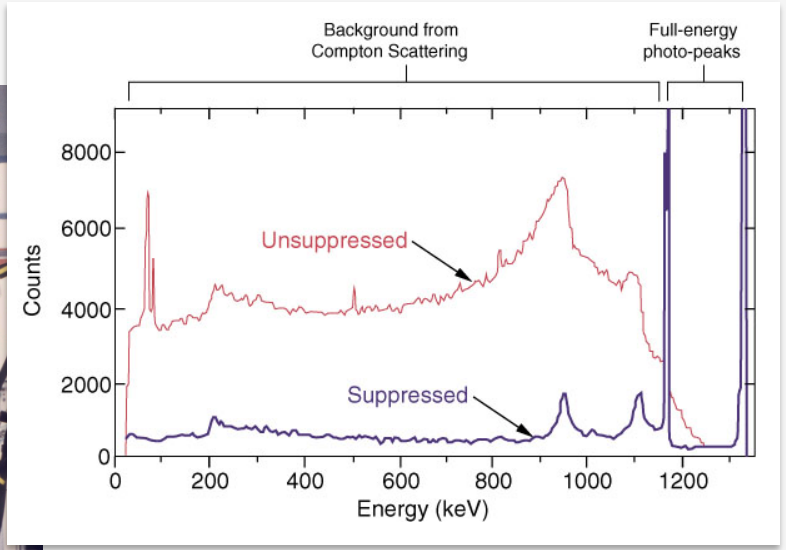


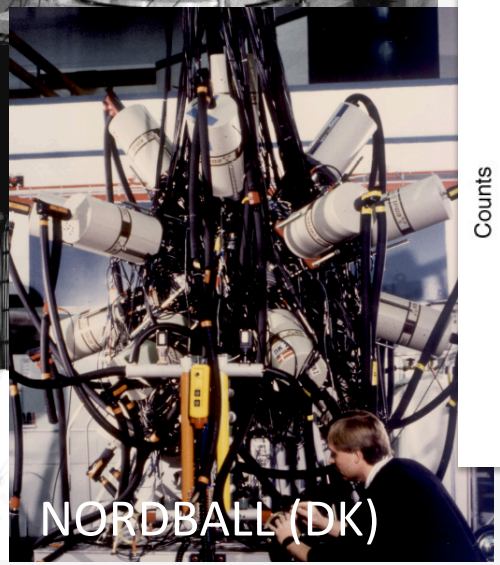
First back(up)bending corresponds to the crossing of the Stockholm band with the ground state band !

The 1980's: National arrays of HPGe detectors



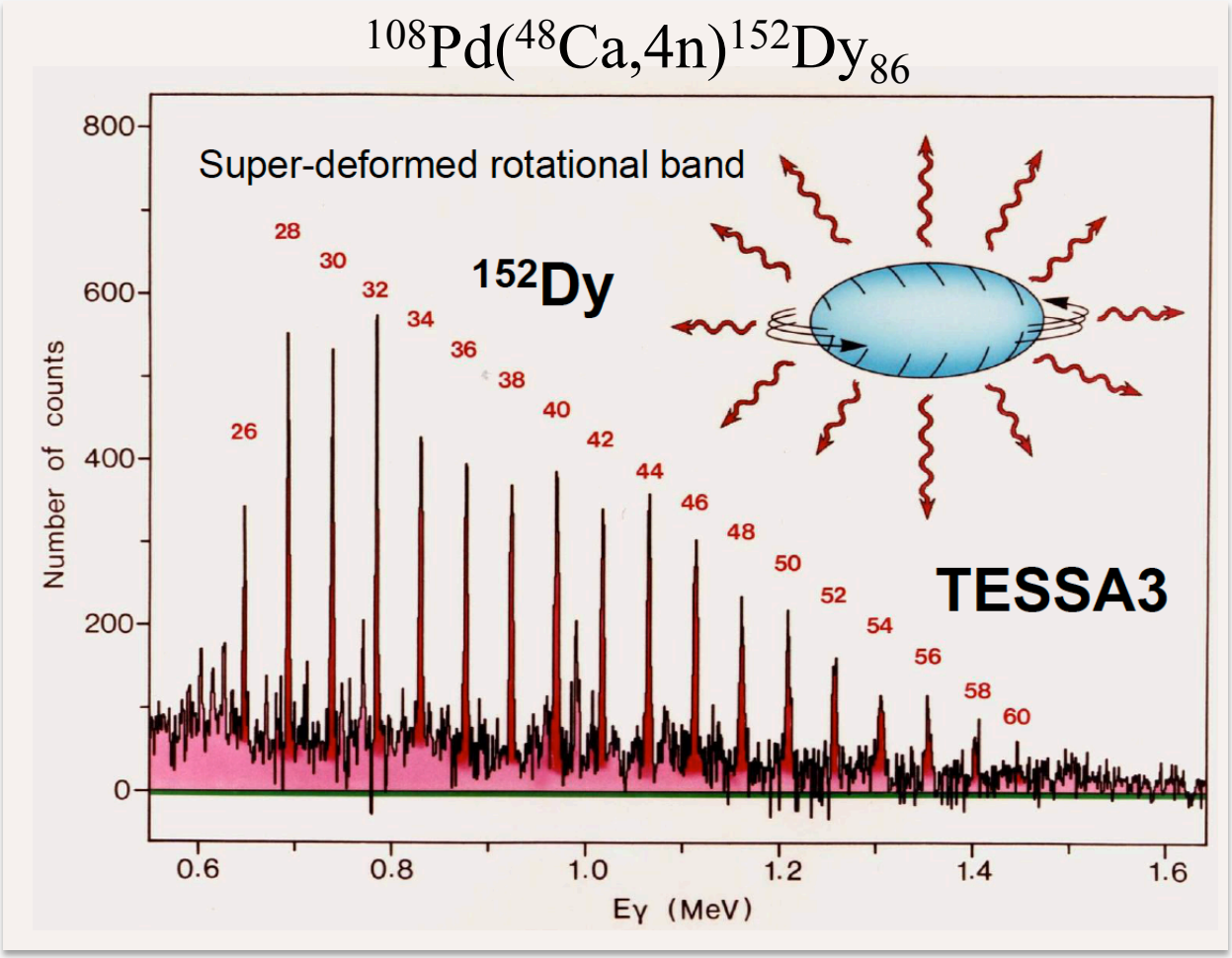






Nuclear Superdeformation: A major discovery

TESSA2: 12 escape-suppressed Ge detectors at the Daresbury Laboratory (UK)



Nearly constant spacing of 47 keV !

⇓

moment of inertia

⇓

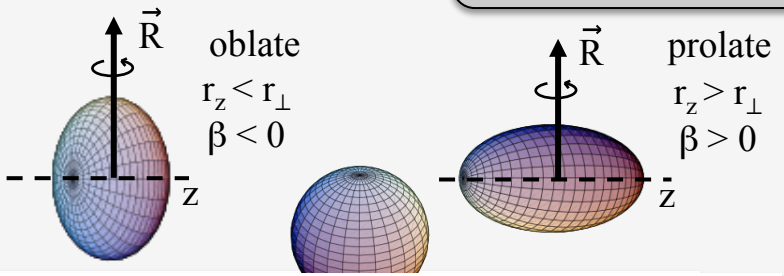
deformation

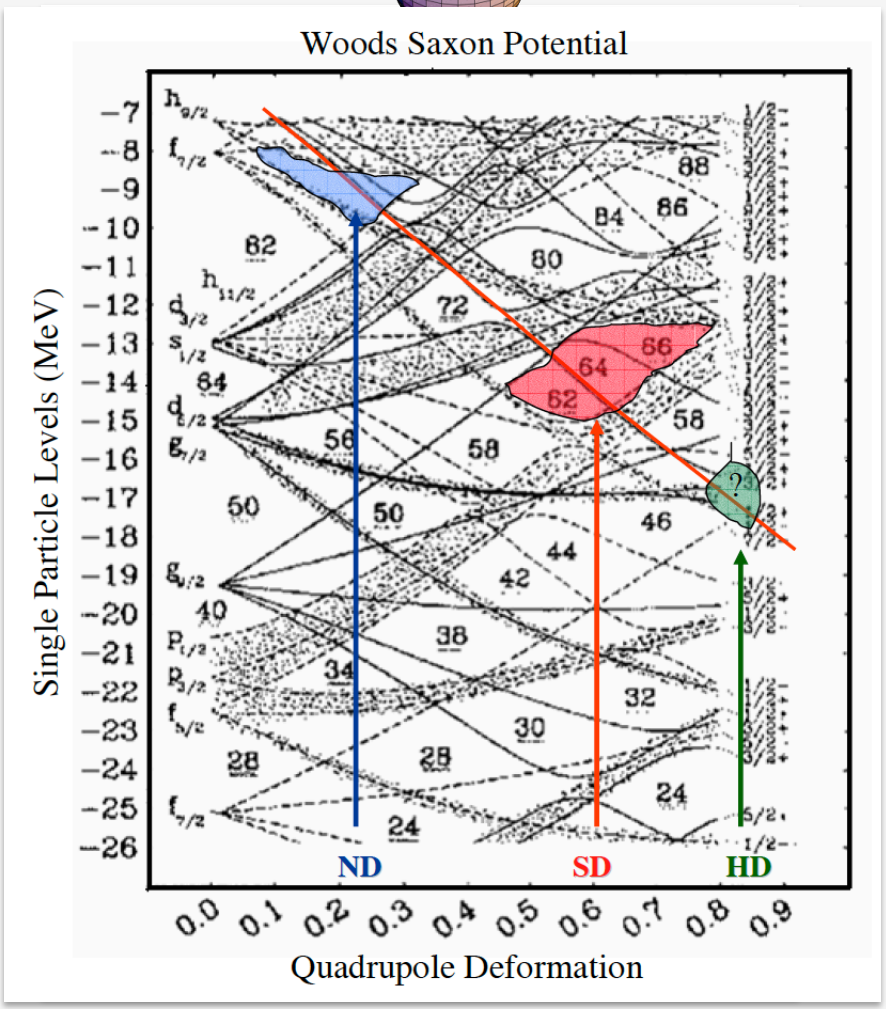
Axis ratio ~2:1 !

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

Superdeformed bands in the γ-ray continuum observed before (E2 bump).

Deformed shell gaps



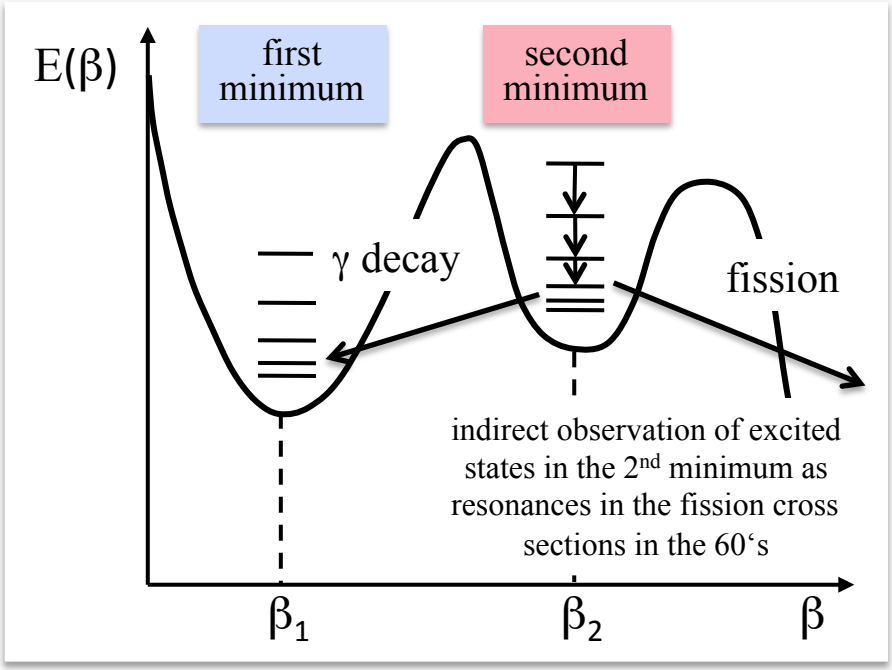


Potential energy of the nucleus as a function of the deformation:

$$E(\varepsilon) = \sum e_i(\varepsilon)$$

sum over the single-particle energies of all A nucleons

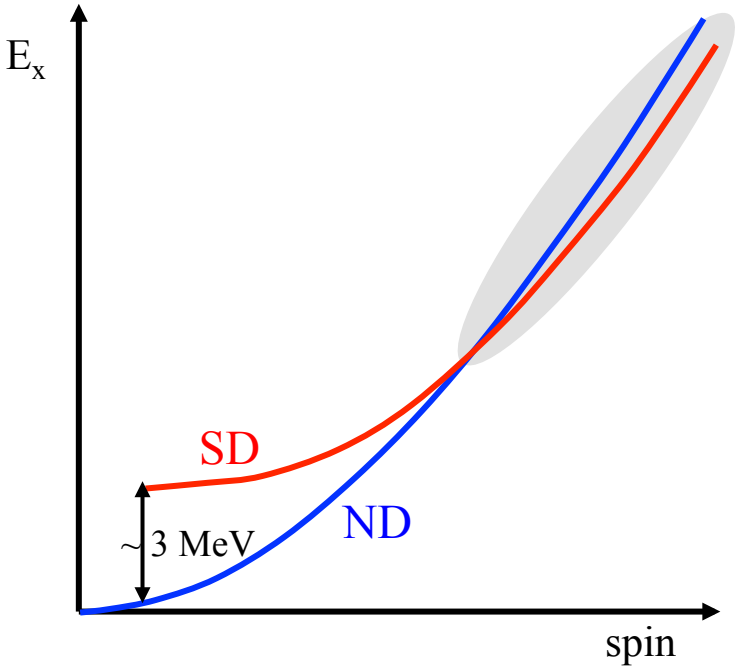
Due to the different slopes of the single-particle orbitals there might be more than one minimum for certain nucleon numbers !



Normal and superdeformed bands in the E_x vs. I plane

Moment of inertia larger for larger deformation

➡ Superdeformed rotational states energetically favoured and therefore observable at high spin !



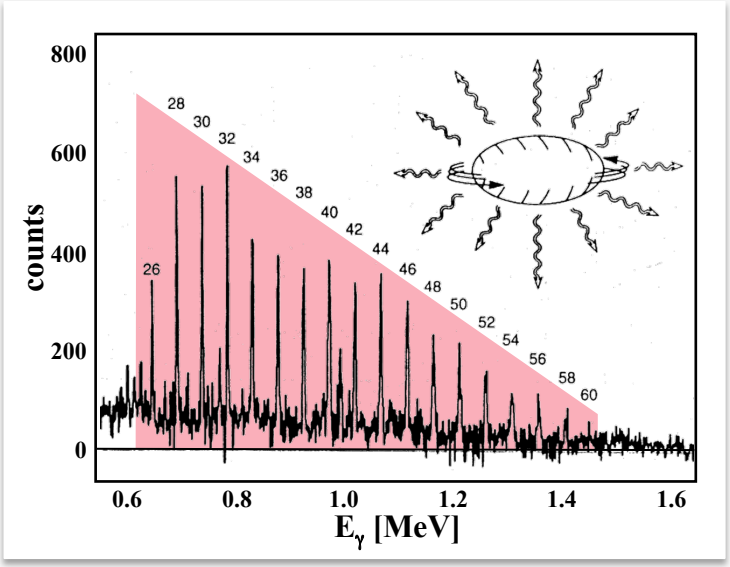
Rotational band:

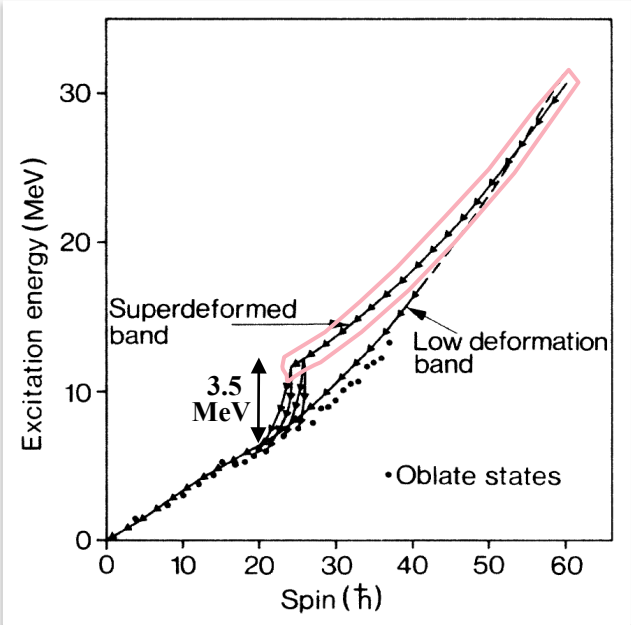
$$E_x = \frac{\hbar^2}{2J} I(I+1)$$

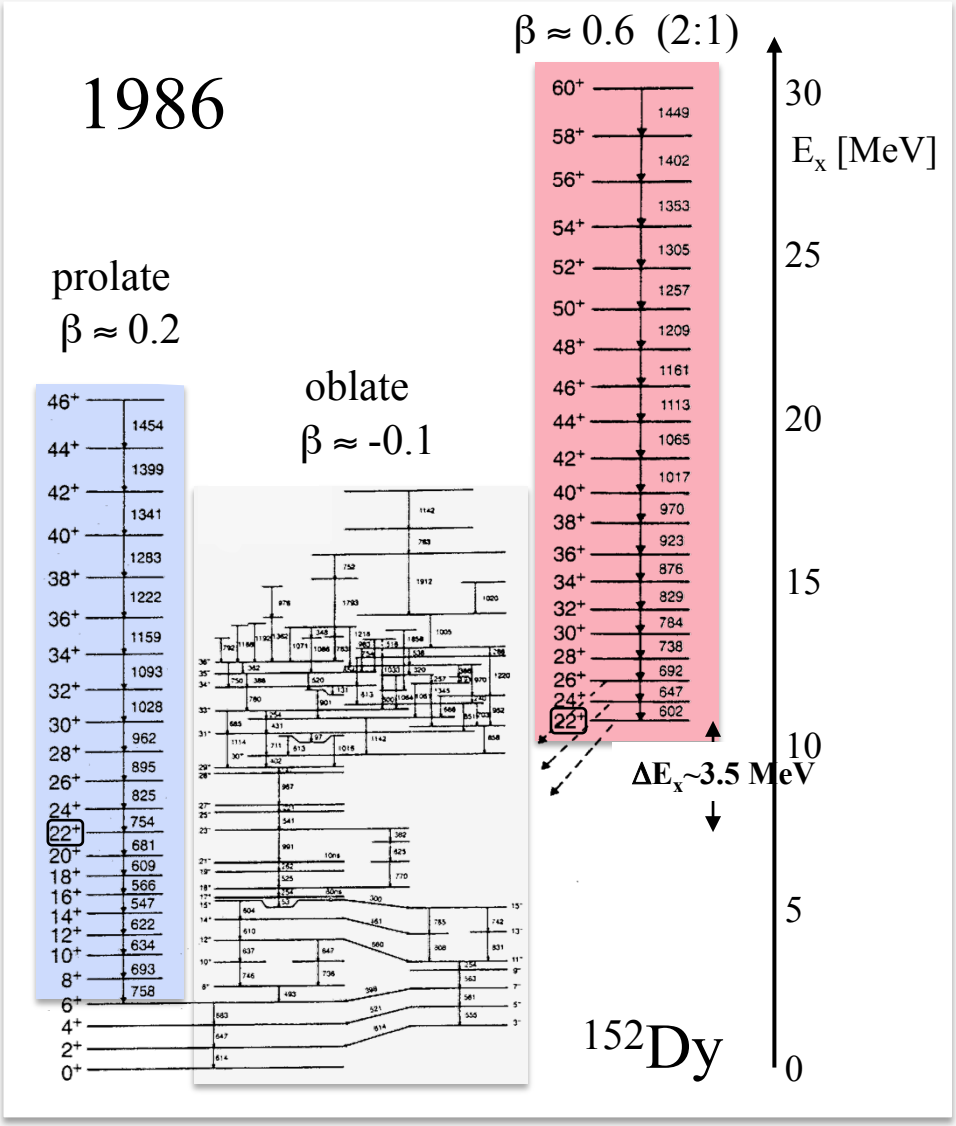
J : Moment of inertia

$$J_{SD} > J_{ND}$$

Discovery of superdeformation in $^{152}Dy_{86}$

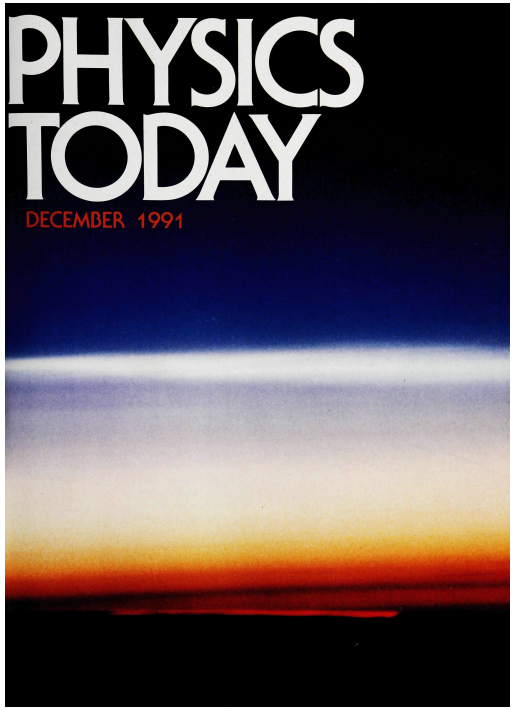






How does the SD band decay ?

Superdeformation as major physics discovery



"Top unexpected physics discoveries of the last five years!"

PHYSICS TODAY December 1991

Daniel Kleppner
Lester Wolfe Professor of Physics at MIT

High temperature superconductivity

Atom cooling and atom optics

Large-scale structure of the universe

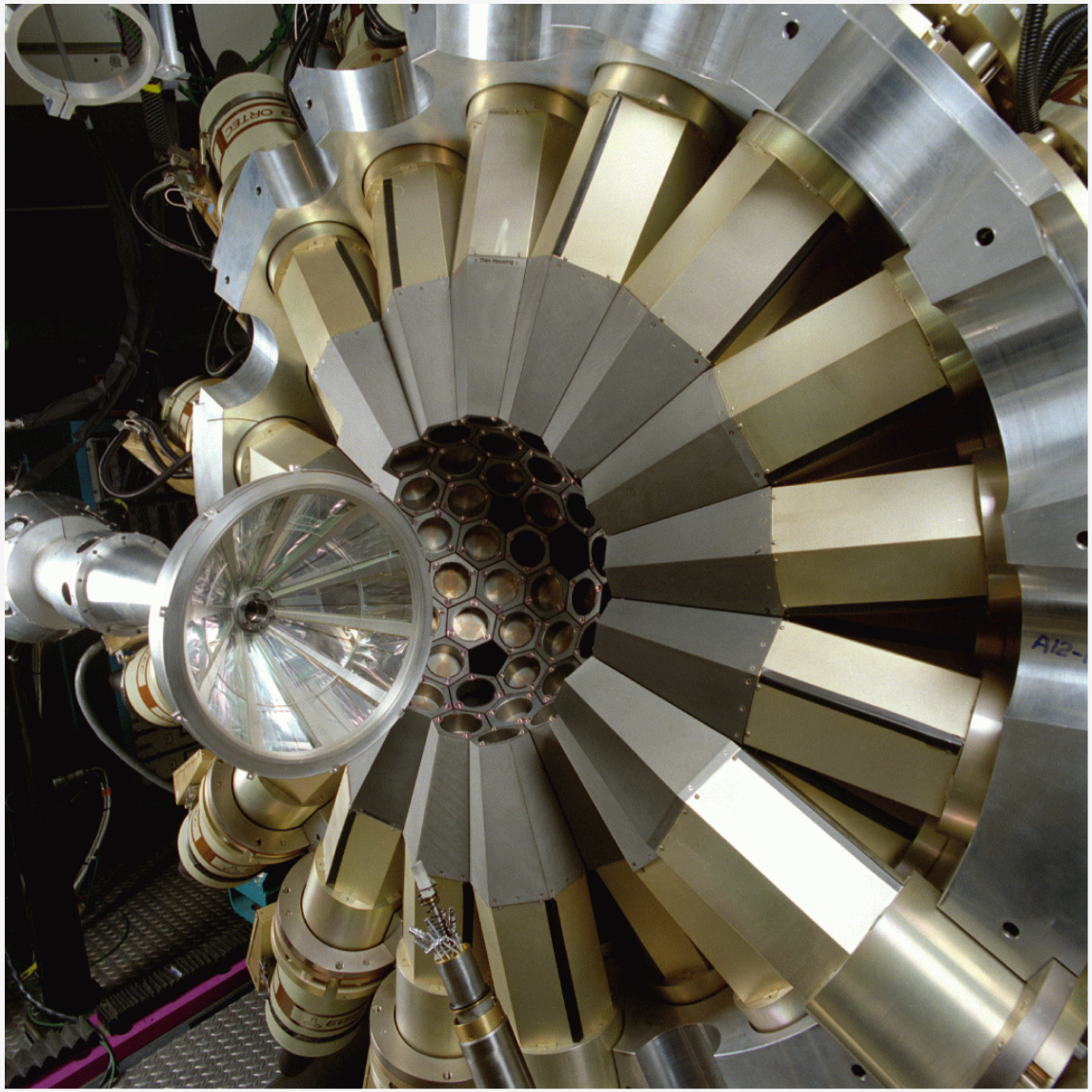
Supernova 1987A

Superdeformed nuclei

Buckyballs

Starting shot for the development of larger 4π γ-ray spectrometer !

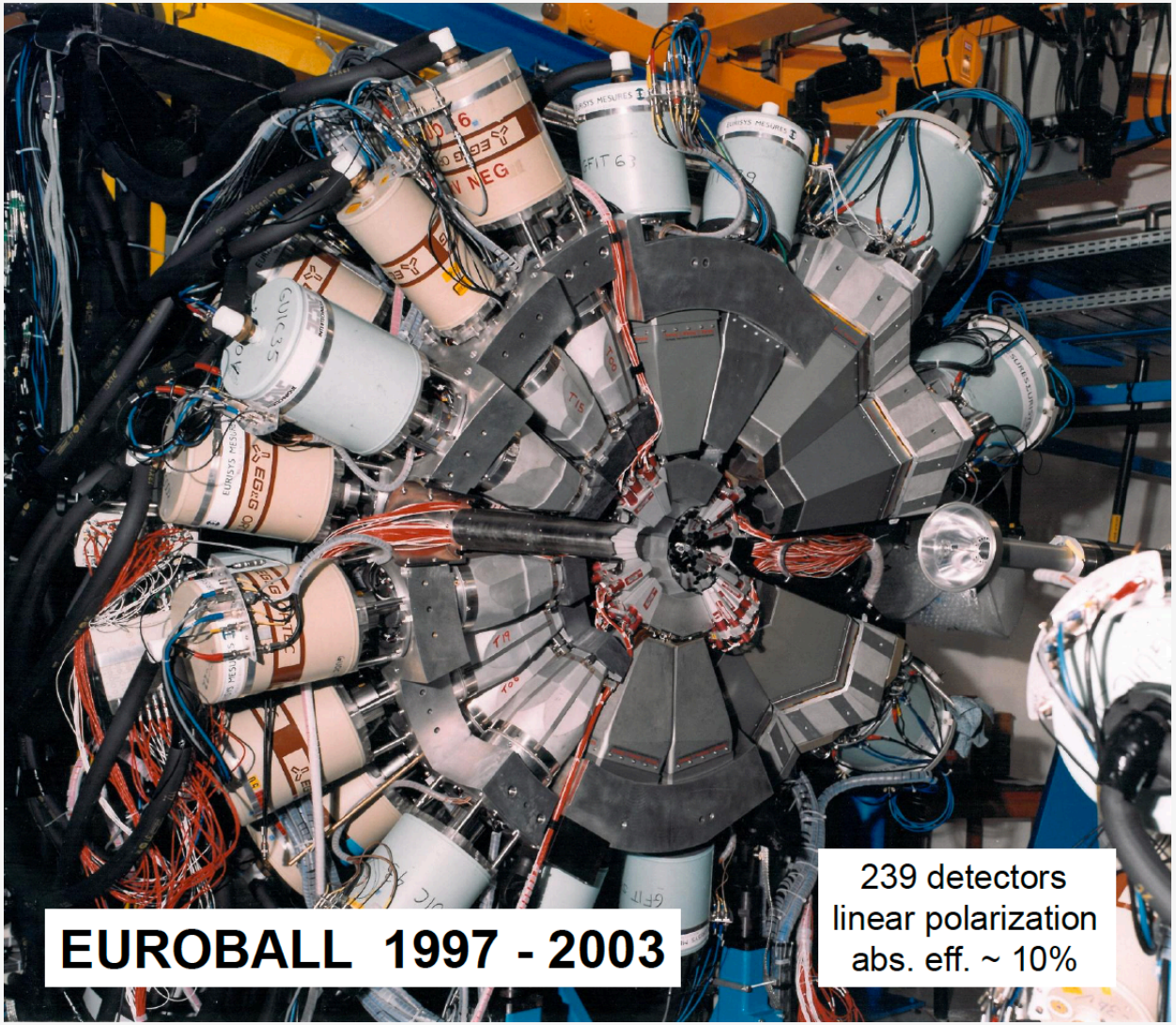
The American Gammasphere



Total photopeak efficiency around 10% !

1993-1995 :
preliminary (30 + ... Ge)
since 1996:
110 individual Ge
Berkeley - Argonne - Berkeley

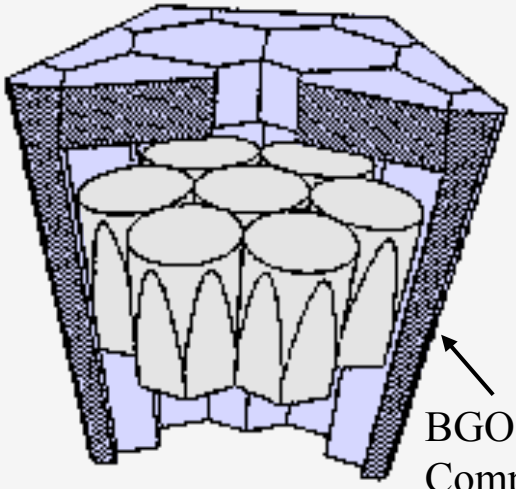
The European EUROBALL



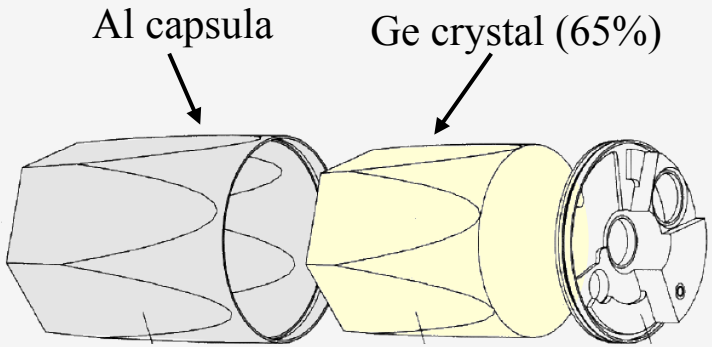
Total photopeak efficiency around 10% !

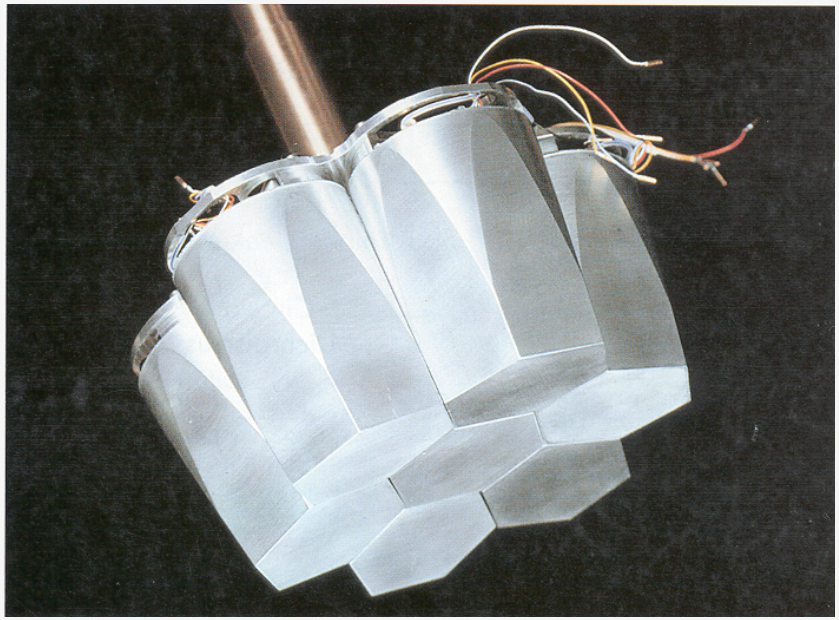
Three different types of detectors !

The composite CLUSTER detector of EUROBALL



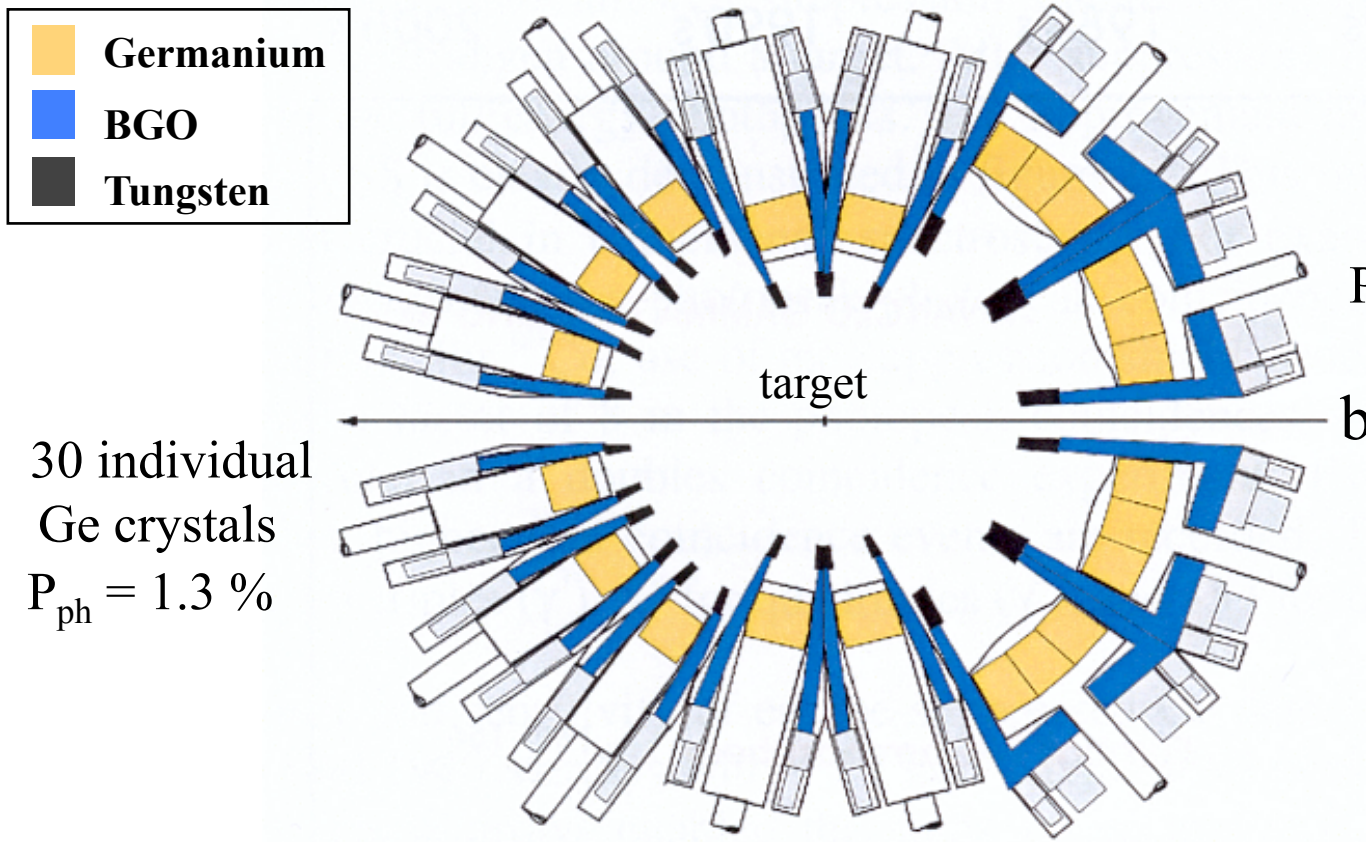
BGO crystals as
Compton suppression shield





1.5 kg of Ge each crystal

The European EUROBALL (1997-2004)



30 individual
Ge crystals
P_{ph} = 1.3 %

15 Cluster
P_{ph} = 4.4 %

Germany (8)
Italy (5)
Sweden (4)
Denmark (1)

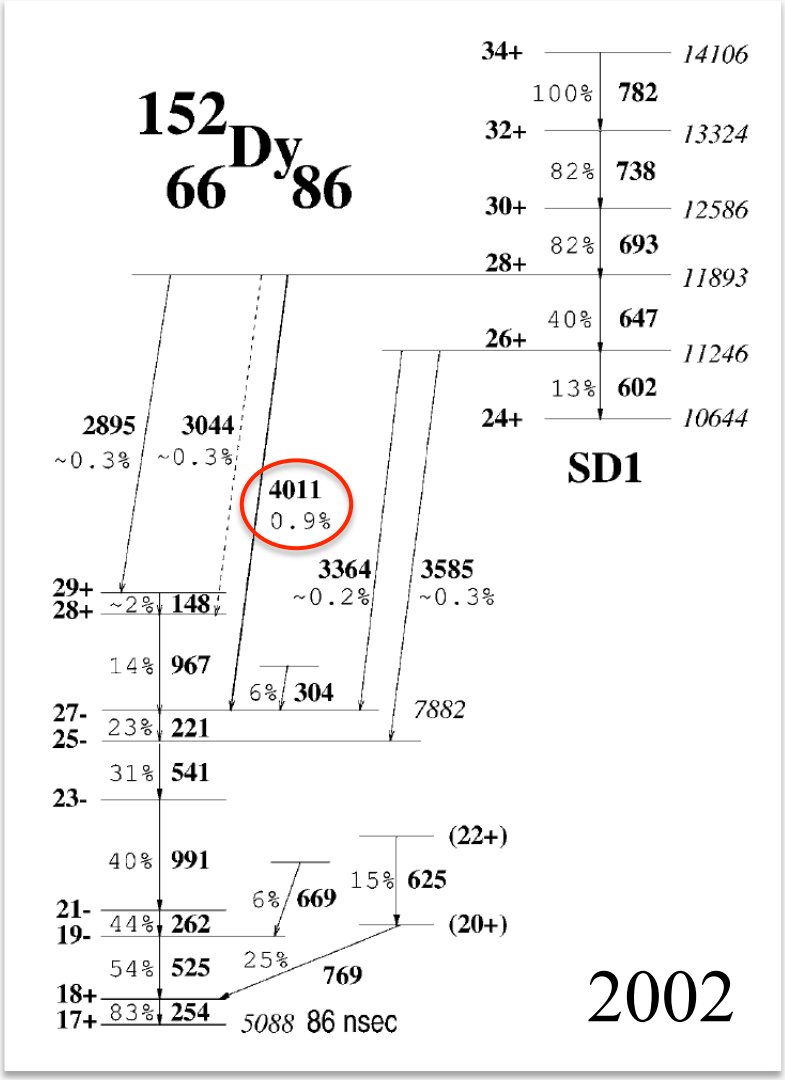
26 Clover
P_{ph} = 3.7 %

France (7 groups)
UK (5)

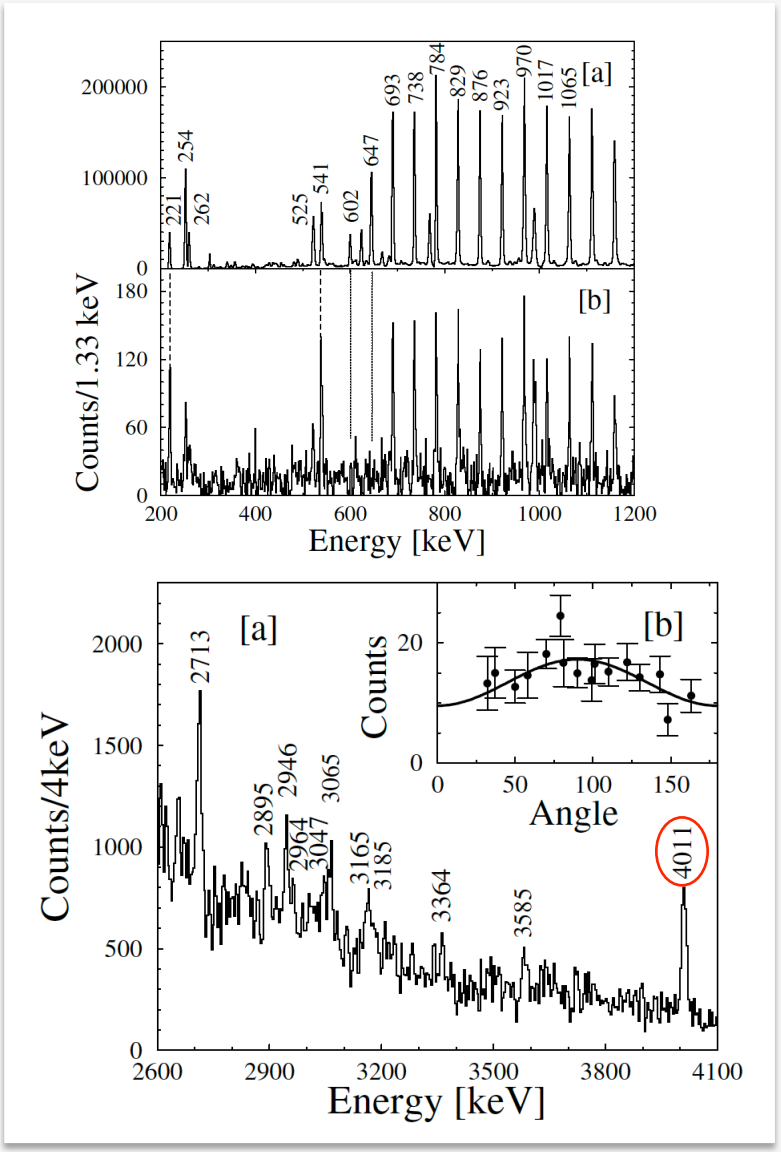
In operation at the LNL Legnaro (Italy)
and the IReS Strasbourg (France)

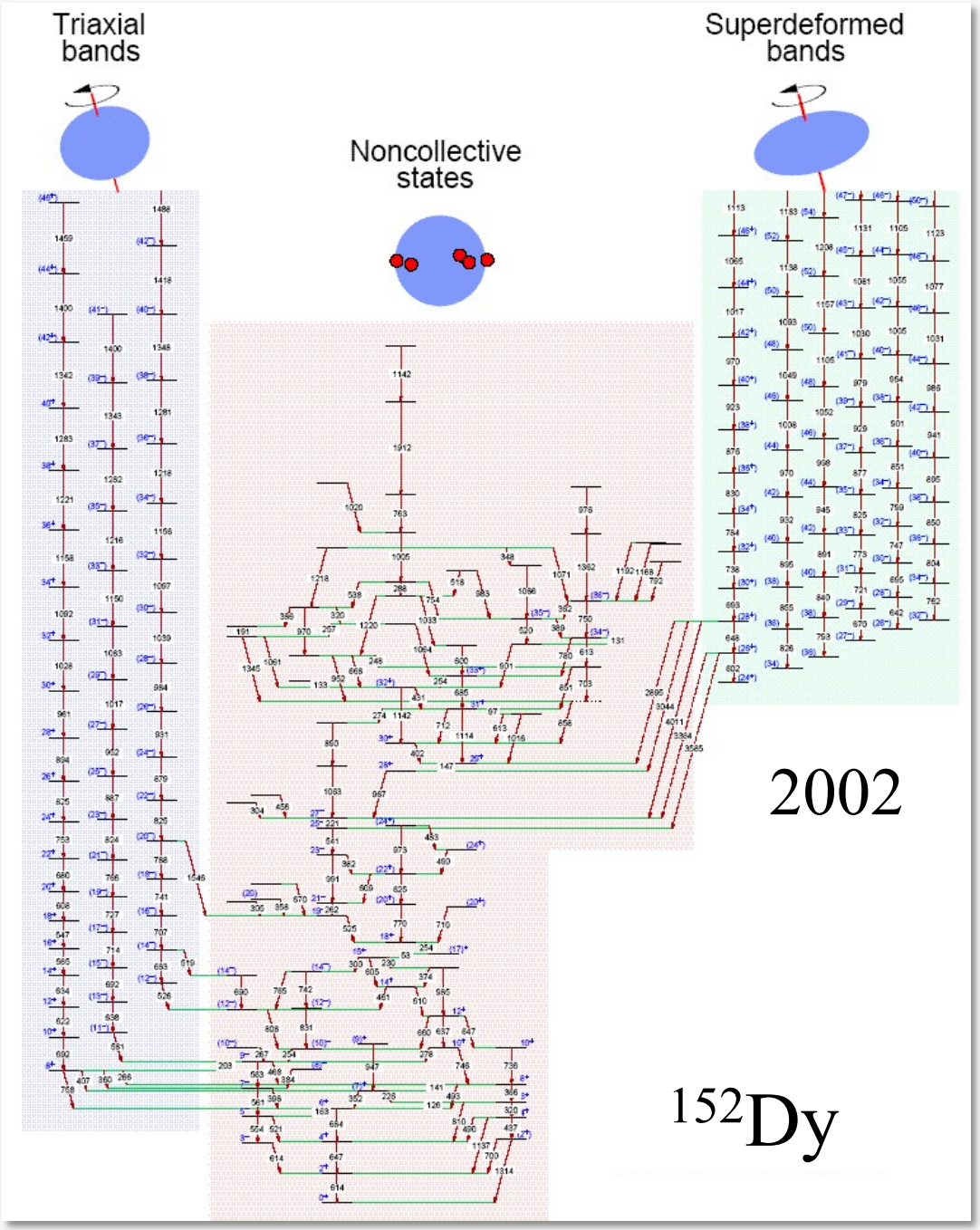
→ 239 individual Ge crystals !

The decay-out in the case of ^{152}Dy – 16 years later



T. Lauritsen et al., Phys. Rev. Lett. 88, 042501 (2002)

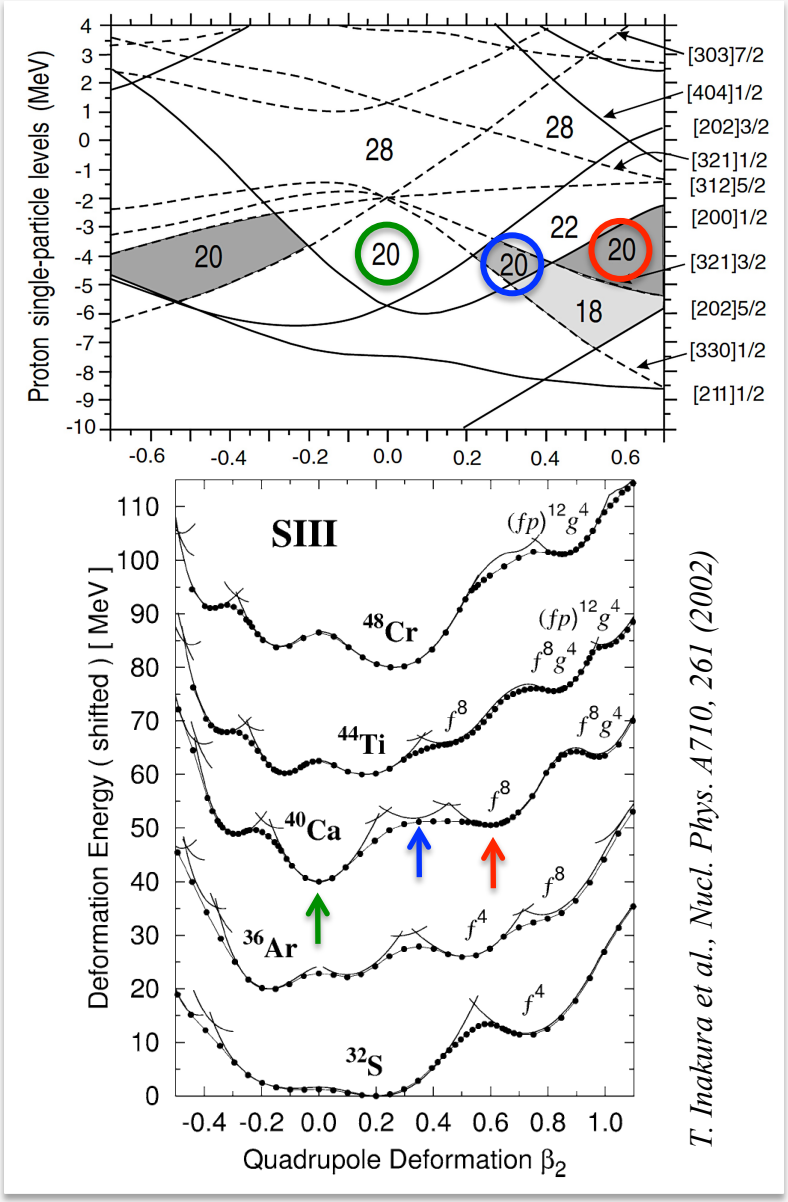


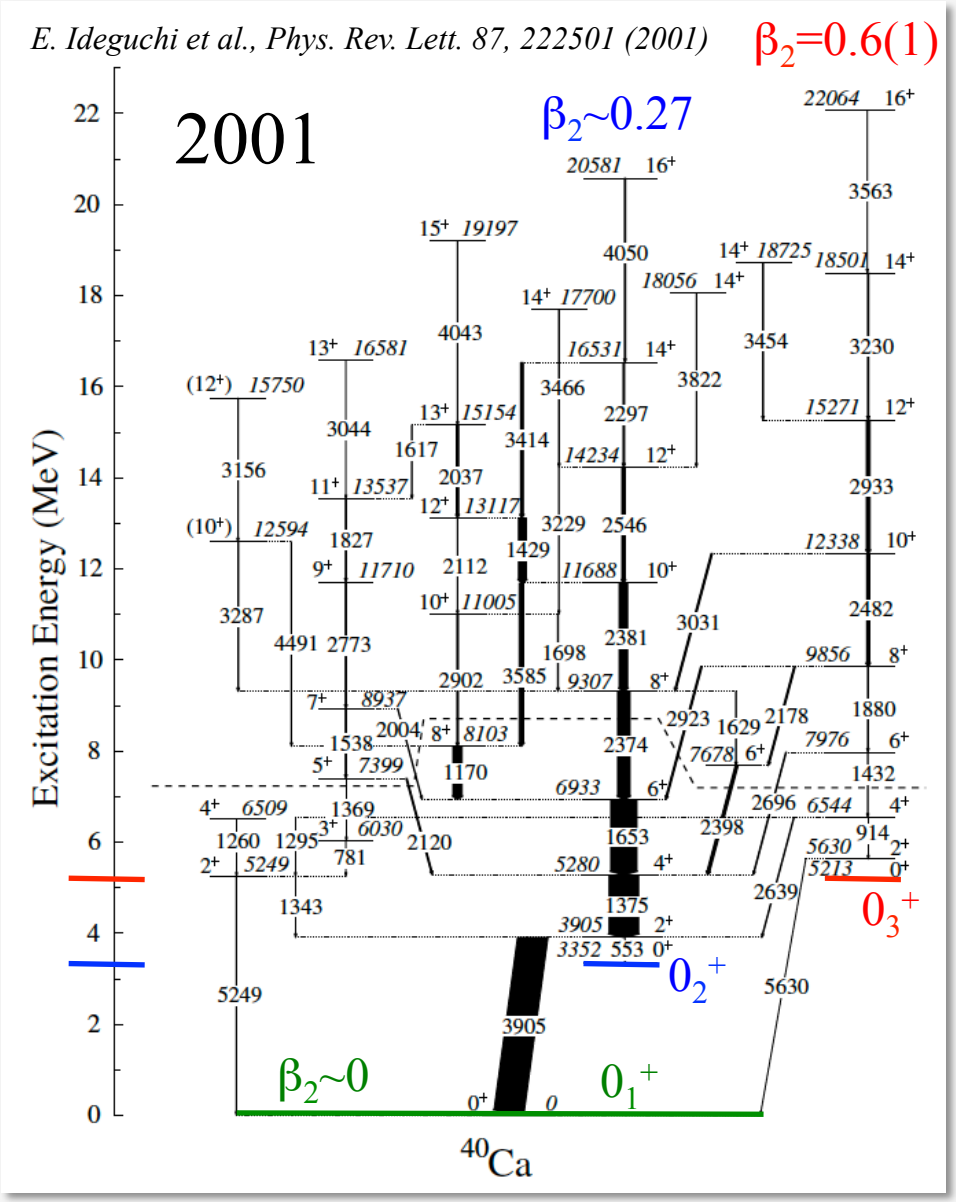


Coexistence of collective and non-collective motion

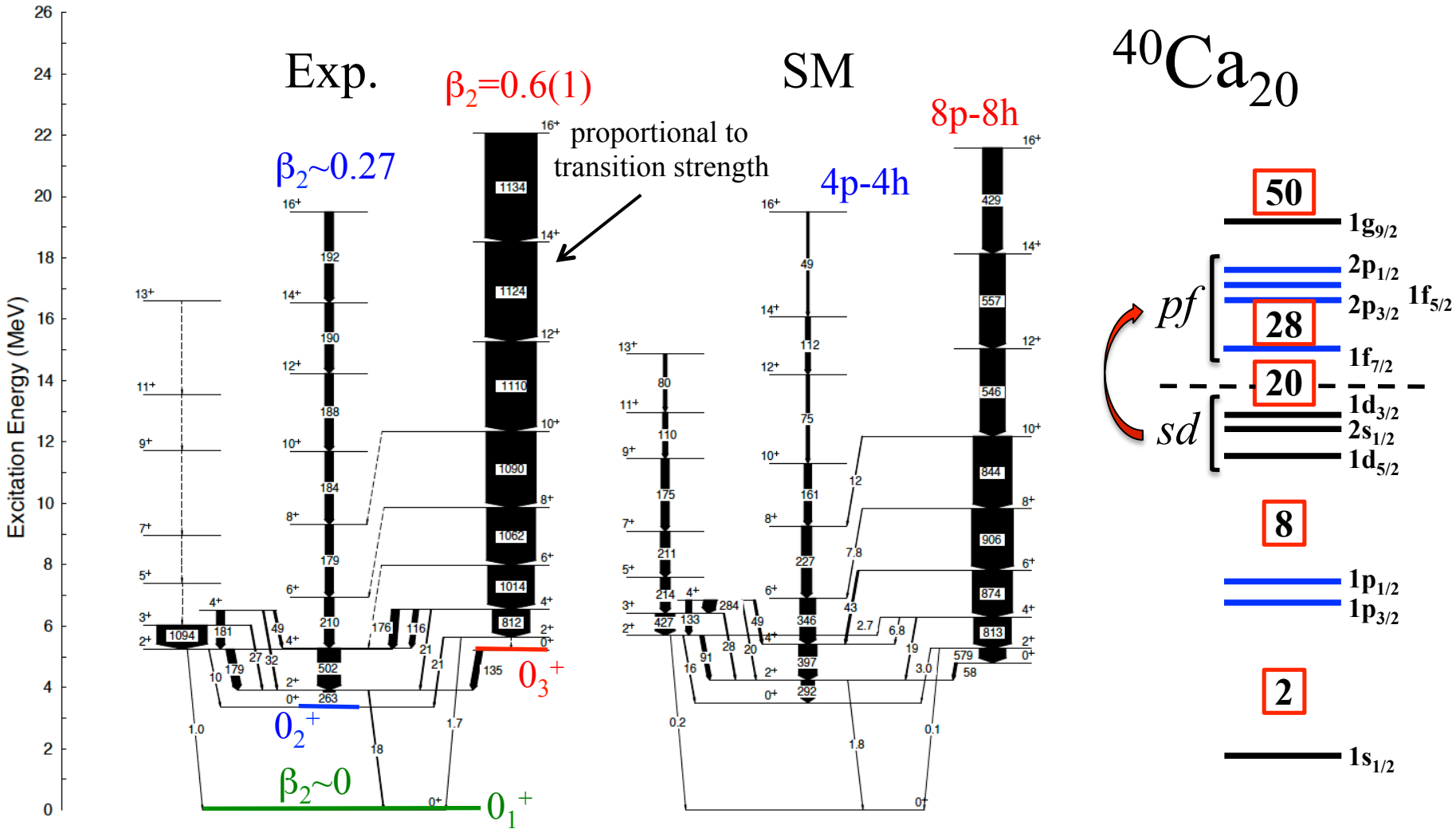
From 1986 to 2006:
>250 SD bands all over the chart of nuclei

Superdeformation in doubly-magic ^{40}Ca



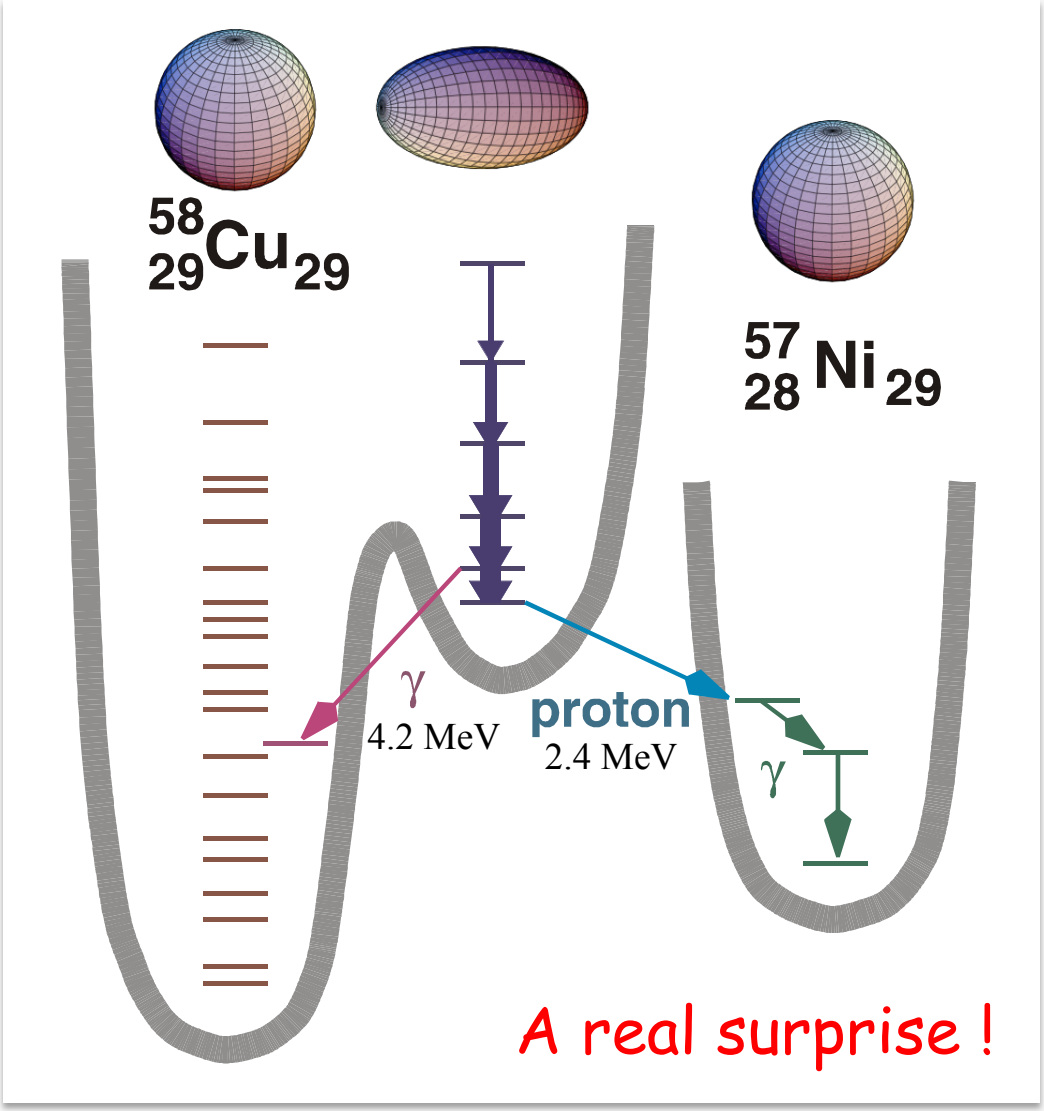


Superdeformation in the nuclear shell model



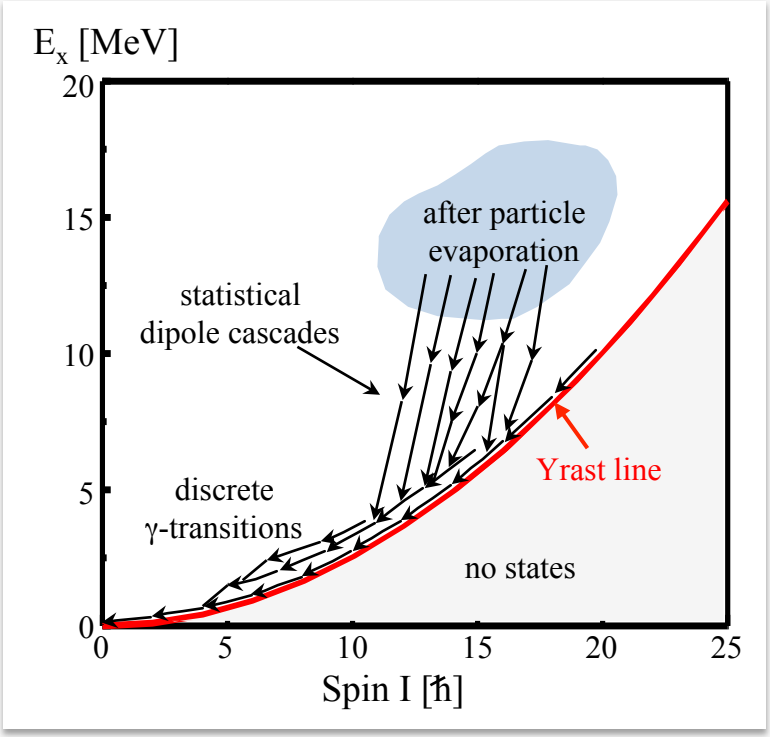
It is just a matter of configuration space …

Prompt proton decay out of the 2nd minimum

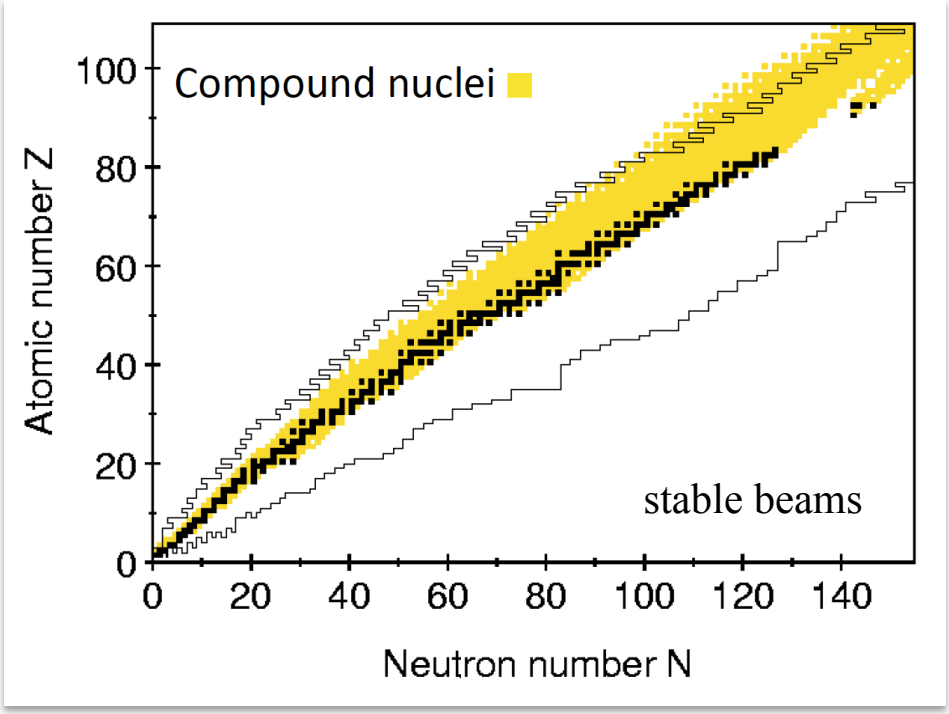


D. Rudolph et al., Phys. Rev. Lett. 80, 3018 (1998)

The playground of fusion-evaporation reactions

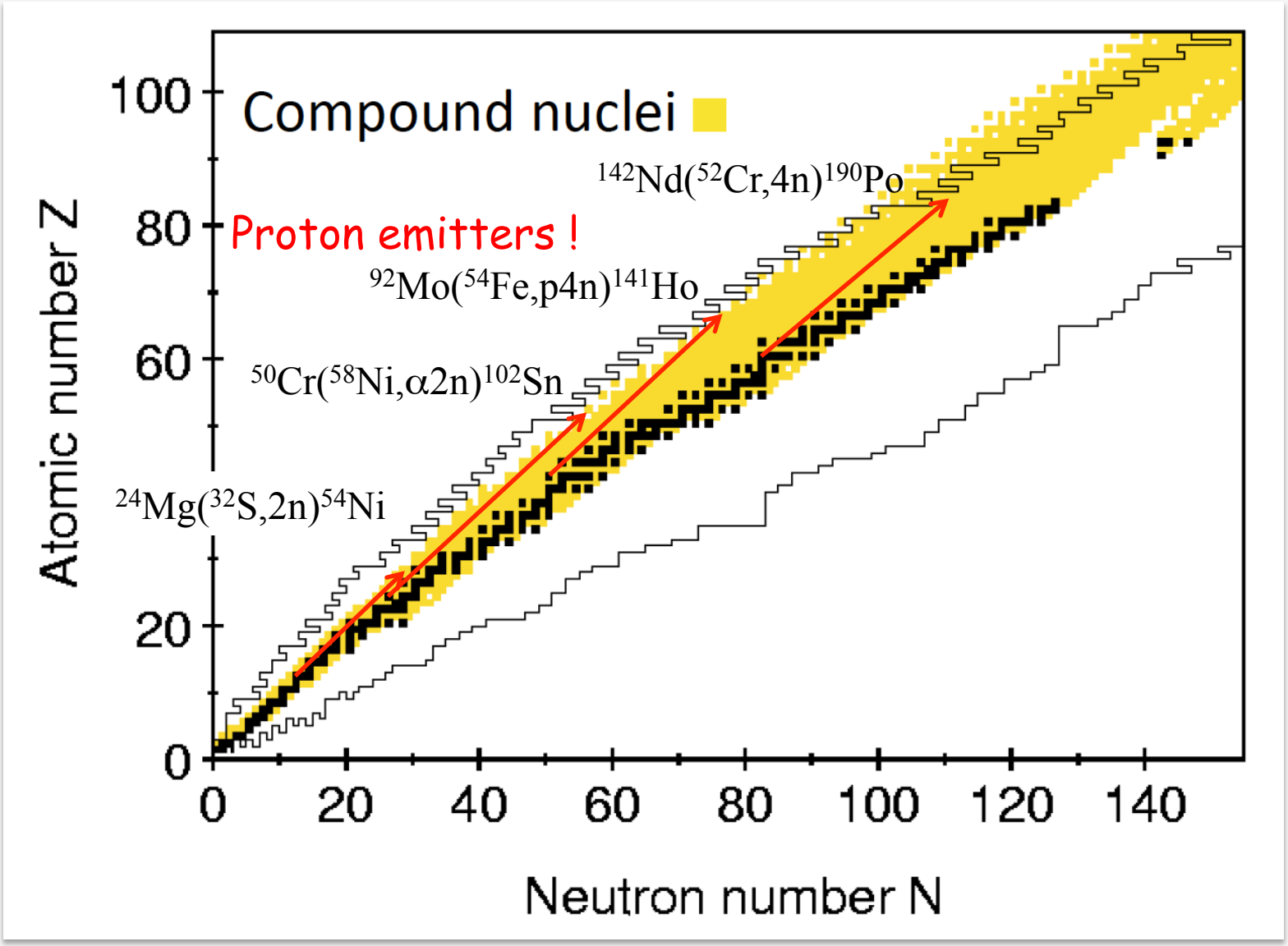


Strongly populated reaction channels:
High-spin physics !

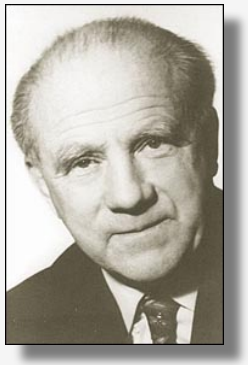


Weakly populated reaction channels:
New physics at the extremes of isospin !

The playground of fusion-evaporation reactions



Does the strong interaction conserve isospin ?

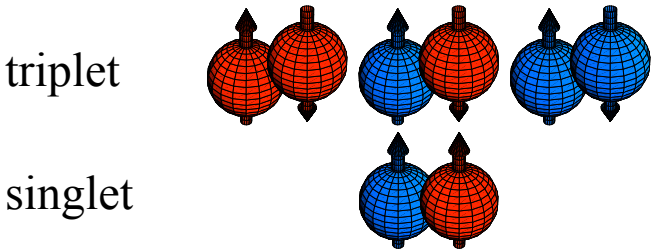


Heisenberg 1932

The strong interaction is charge symmetric and charge independent:

$$V_{pp} = V_{nn} = V_{pn}$$

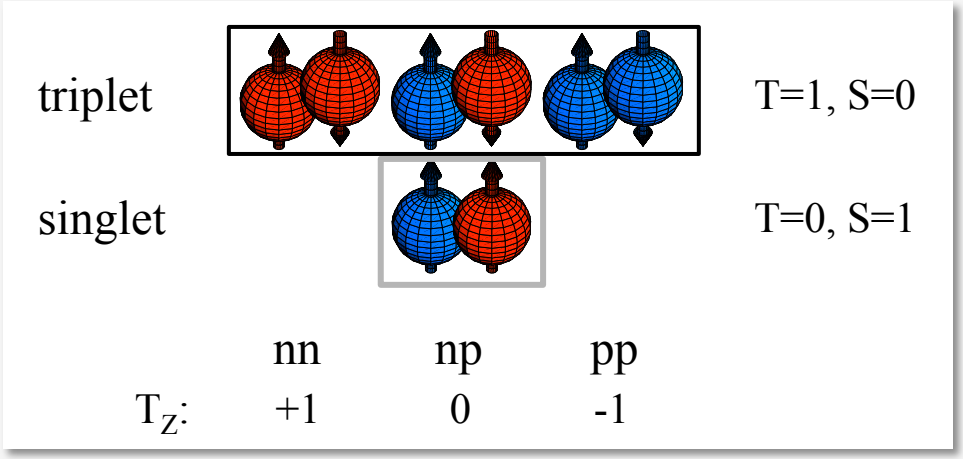
Proton and neutron can be viewed as two states of the same particle: the nucleon

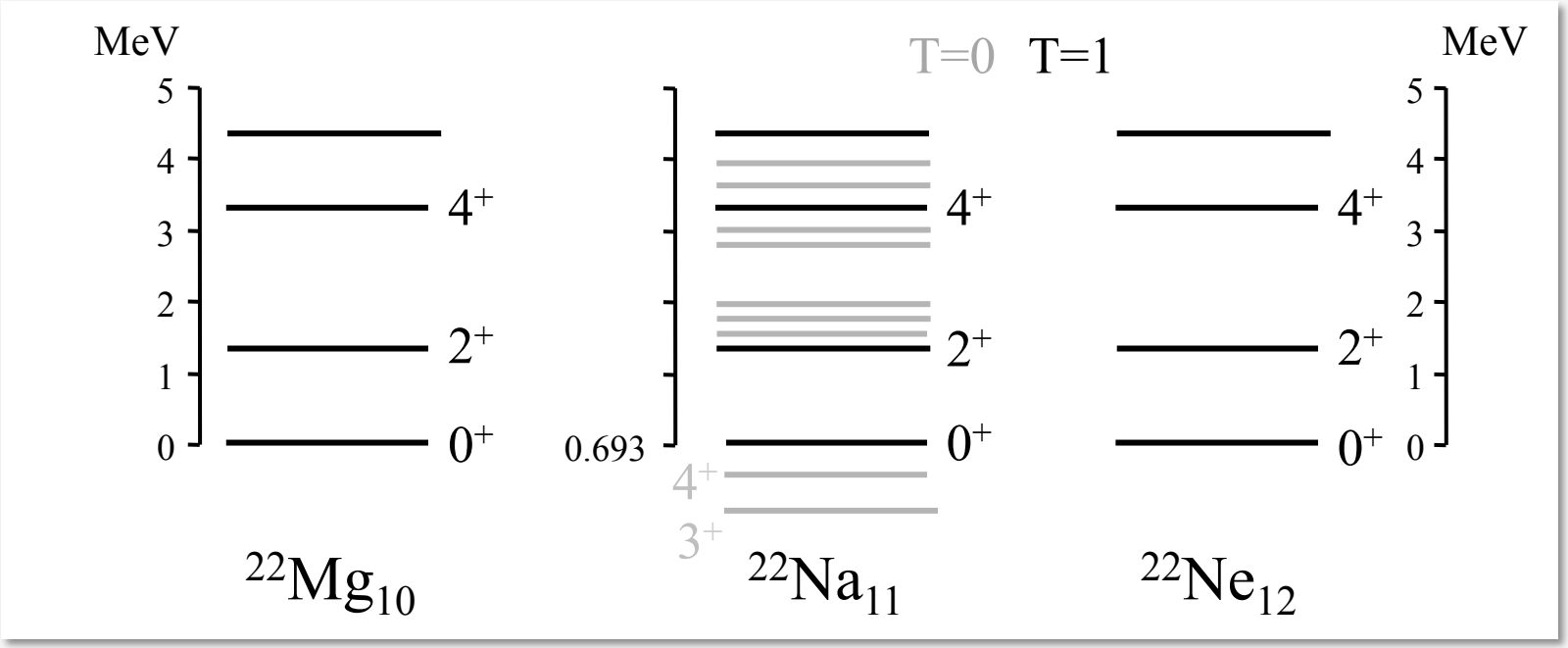


	nn	np	pp
T_Z:	+1	0	-1

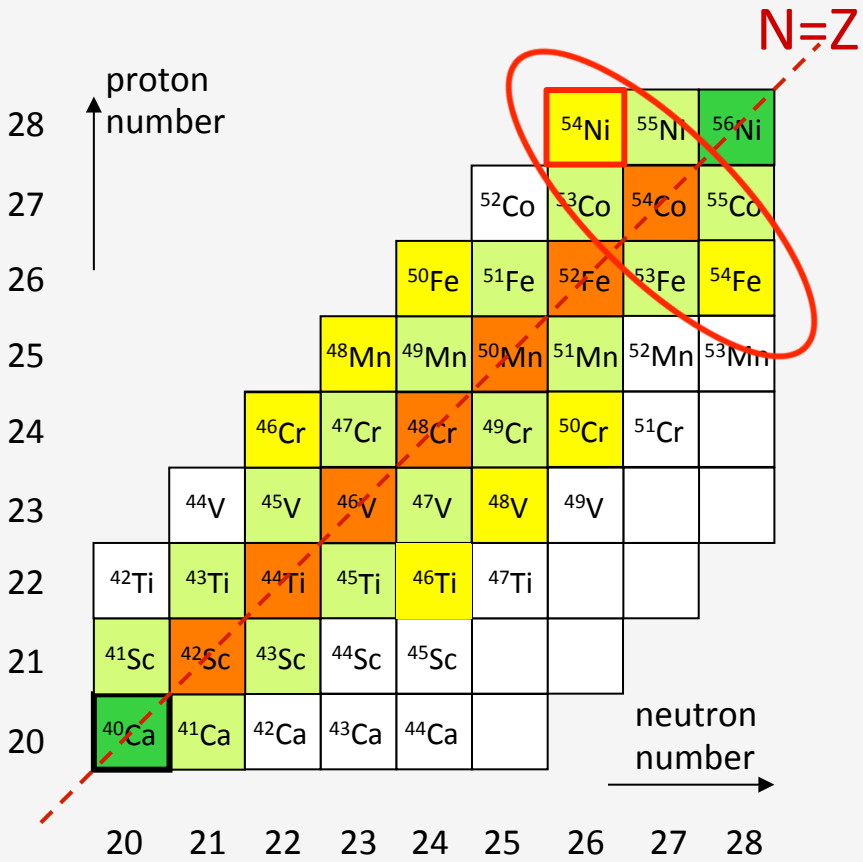
Study T=1 isobaric triplets to search for isospin breaking contributions !

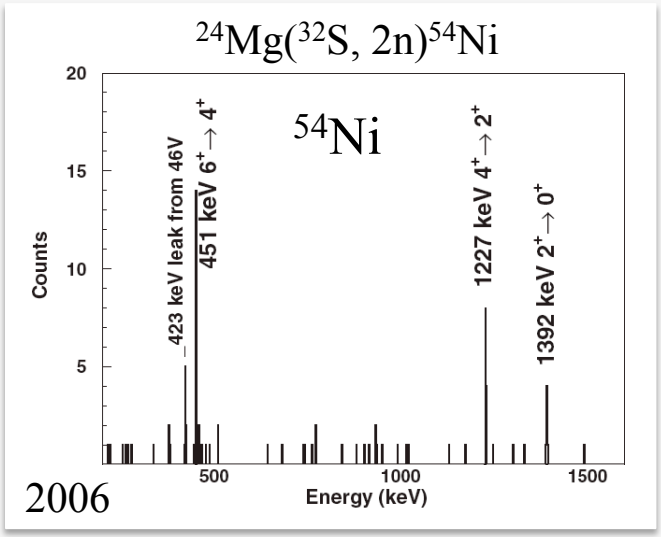
Isospin concept is known to work for light nuclei



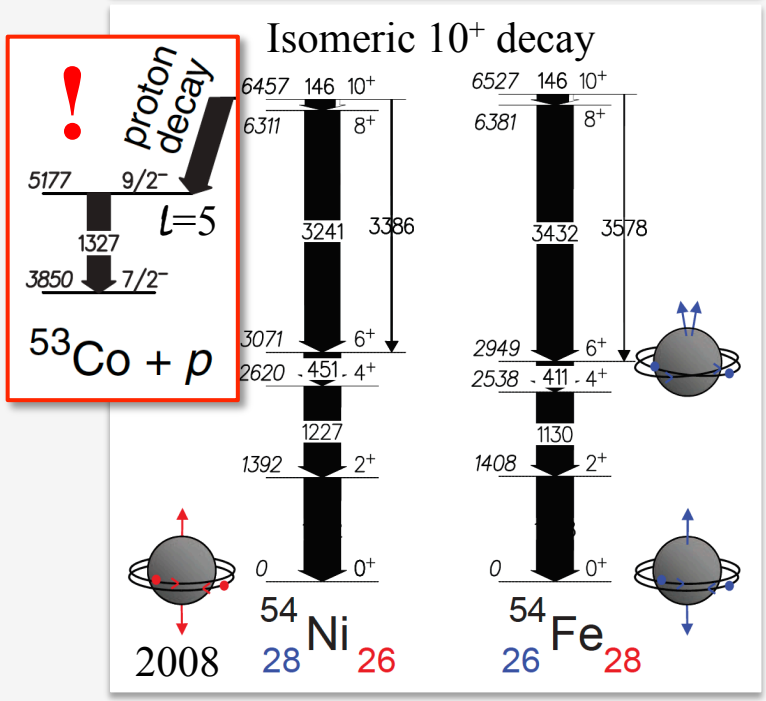


The example of the A=54 isospin triplet



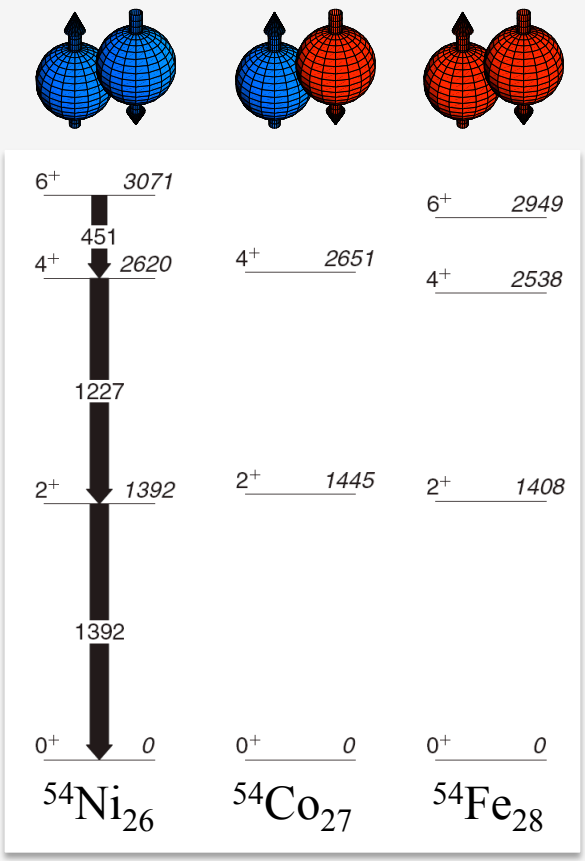


A. Gadea et al.
Phys. Rev. Lett. 97, 152501 (2006)



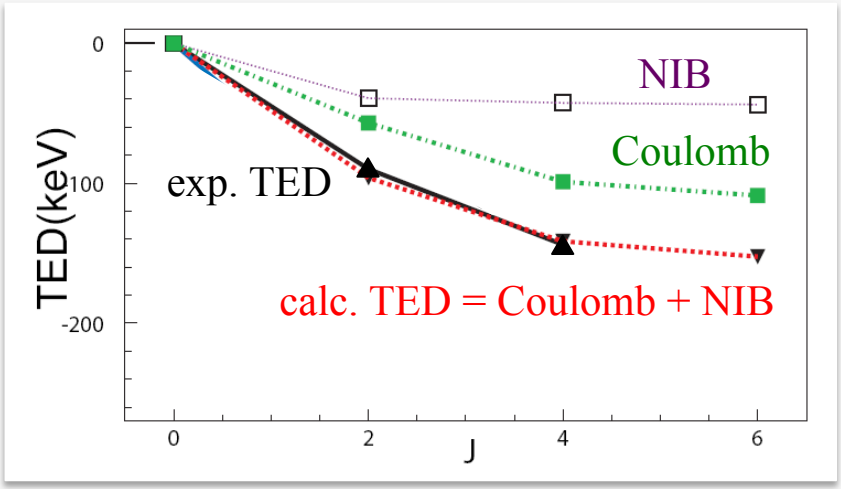
D. Rudolph et al.
Phys. Rev. C78, 021301(R) (2008)

Triplet energy differences for $^{54}Ni_{26}$-$^{54}Co_{27}$-$^{54}Fe_{28}$



Triplet energy difference:

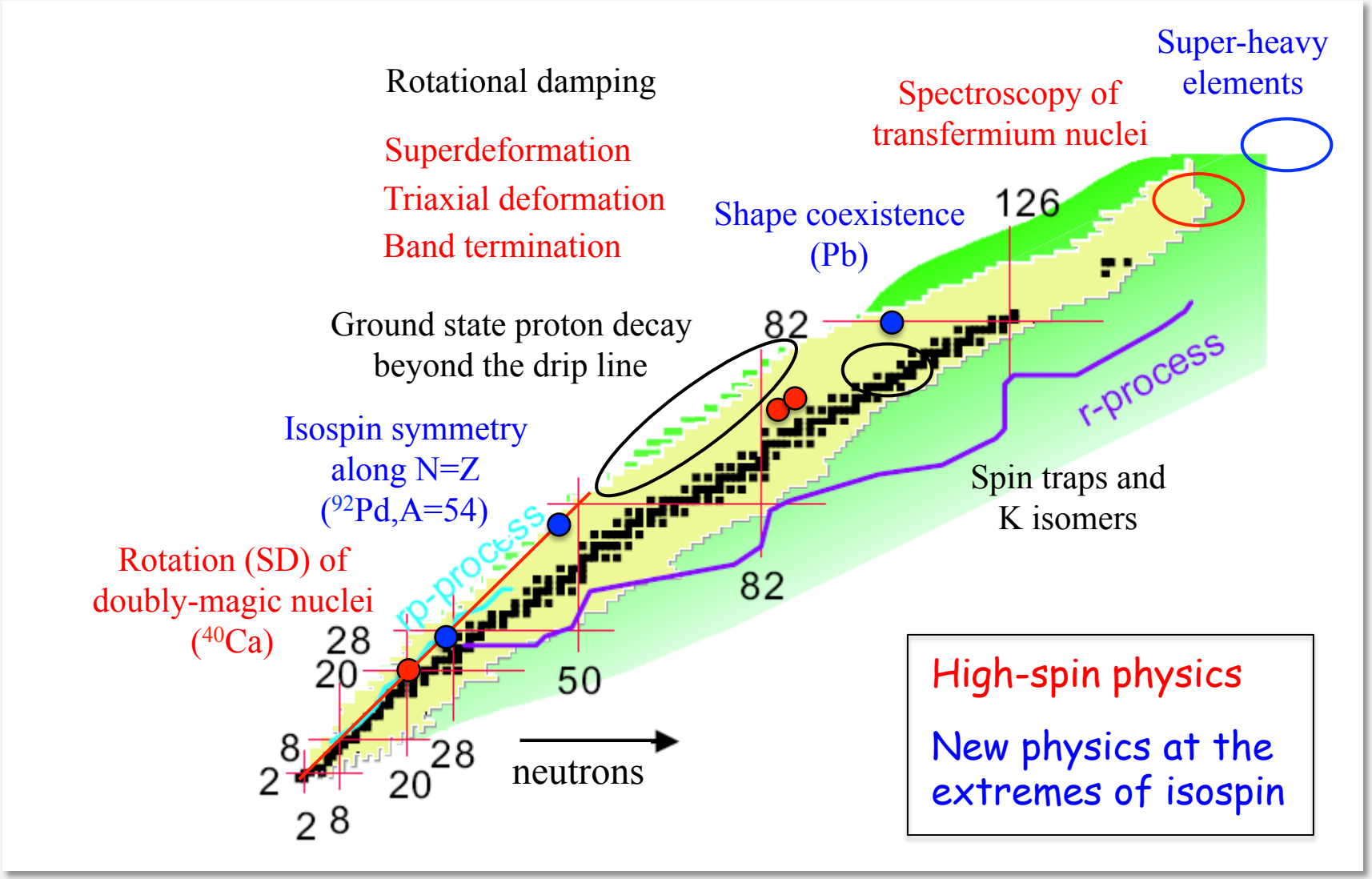
$$TED(J) = E_J(^{54}Ni) + E_J(^{54}Fe) - 2E_J(^{54}Co)$$



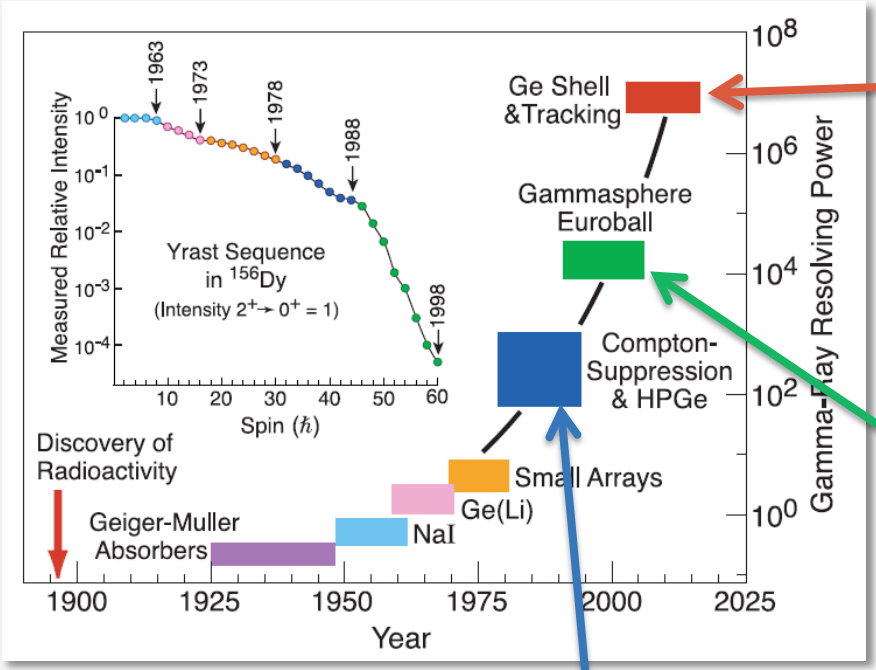
A. Gadea et al., Phys. Rev. Lett. 97, 152501 (2006)

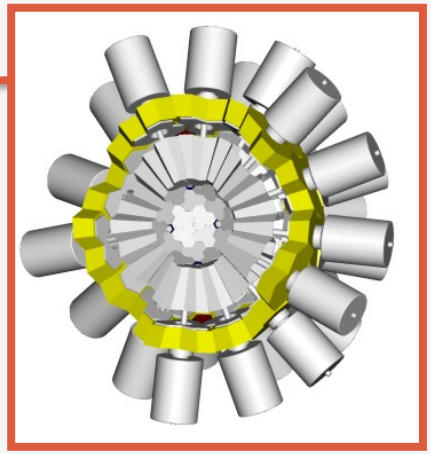
Nuclear isospin-breaking (NIB) terms are of the same order as the Coulomb contributions !

The nuclear landscape – neutron-deficient side
(with stable-beam induced fusion-evaporation reactions)

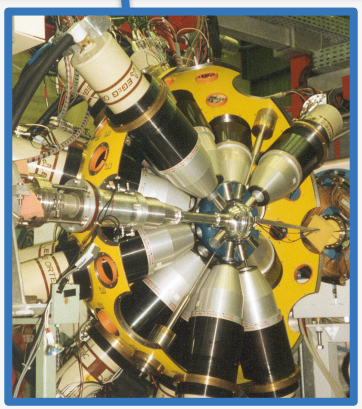


The future of γ-ray spectroscopy: Tracking arrays

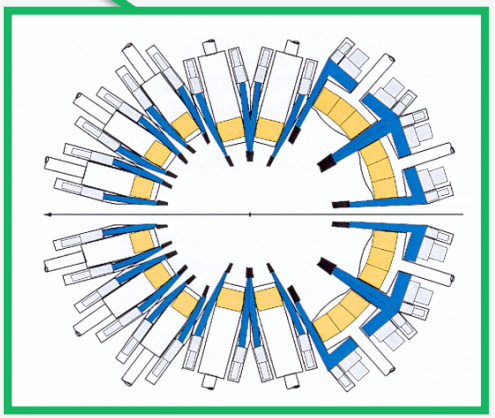




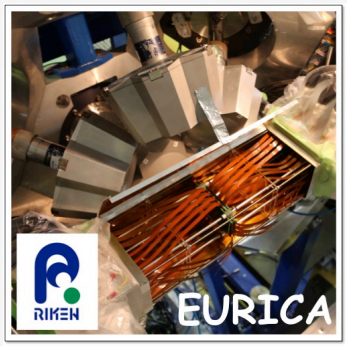
AGATA



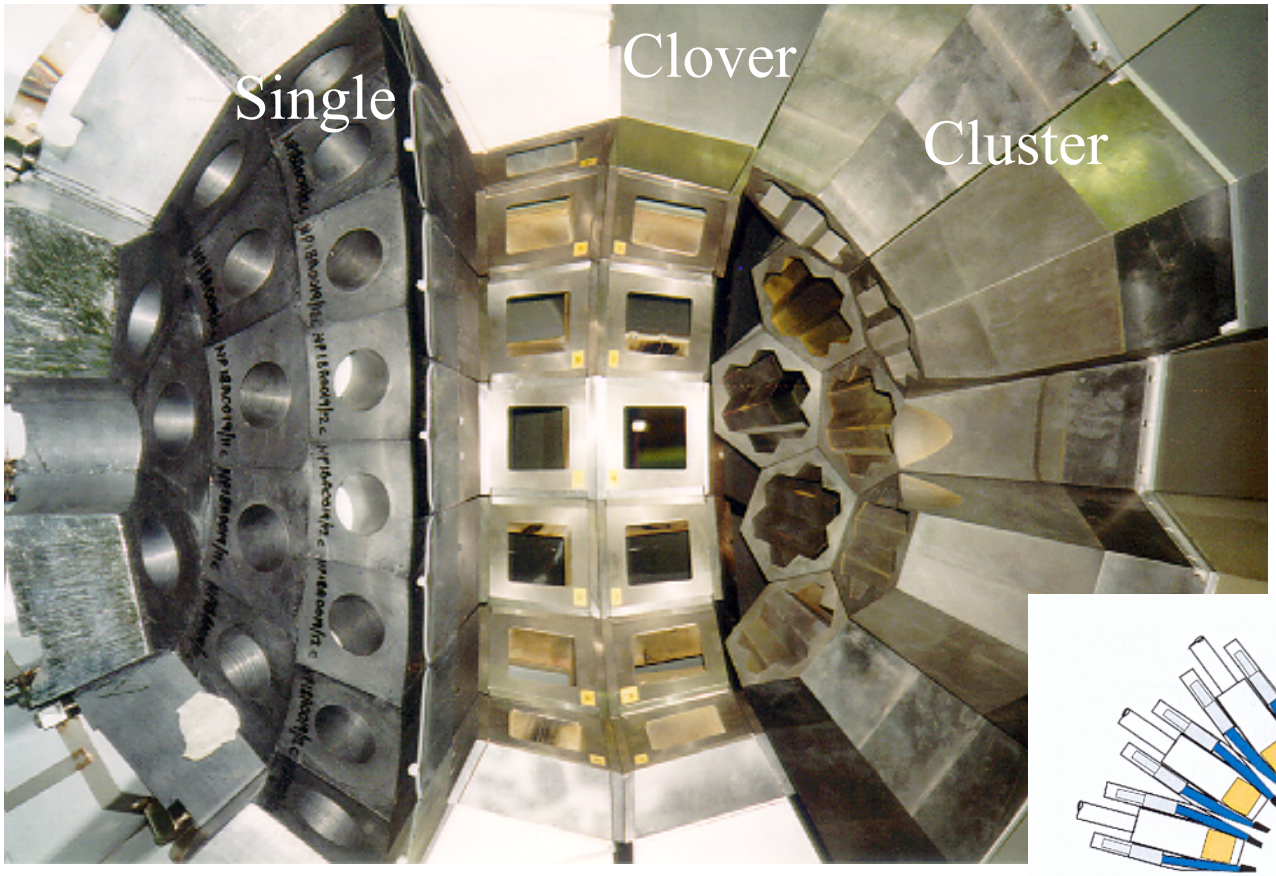
GASP

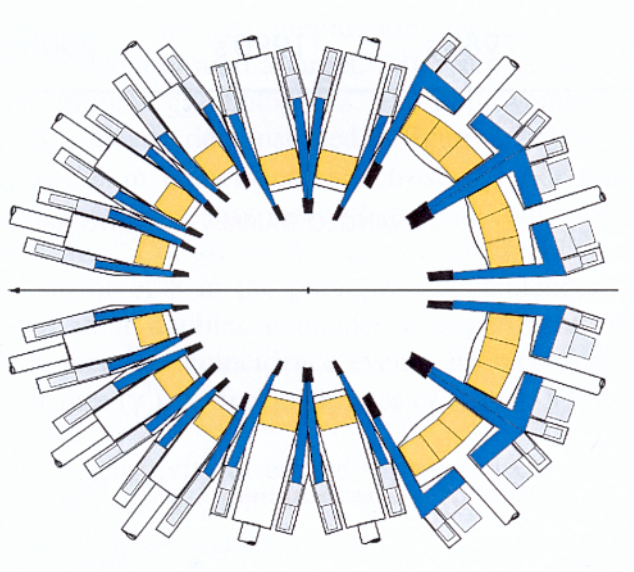


EUROBALL (1997-2003)



Target view into the collimators of EUROBALL





Large fraction of dead solid angle !

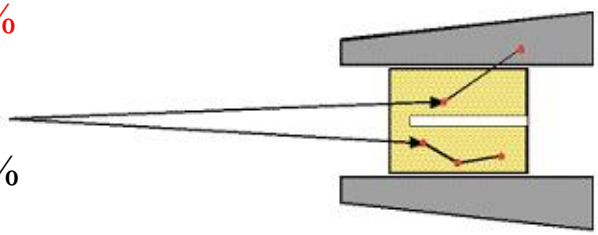
Get rid of Compton-suppression shields …

The idea of γ-ray tracking

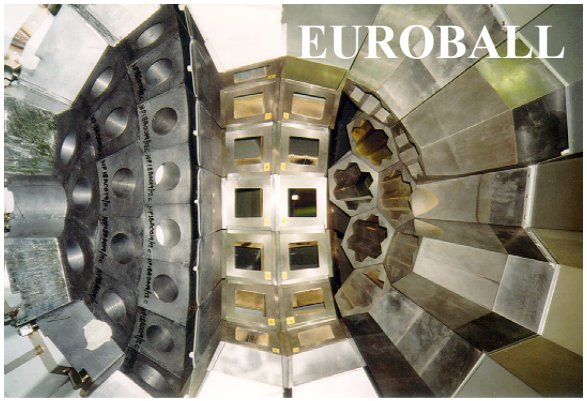
Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100

Ω ~ 40%
Δθ ~ 8°



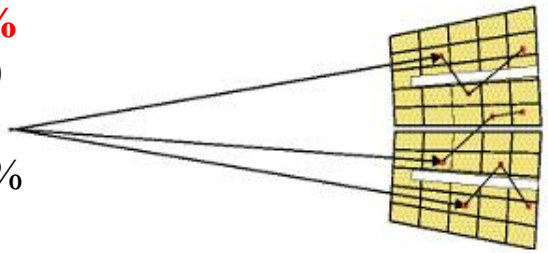
- scattered γ-rays lost
- poor definition of angle of incidence
- solid angle coverage limited by CS shields



Ge Tracking Array

ε_{ph} **~ 50%**
N_{det} ~ 100

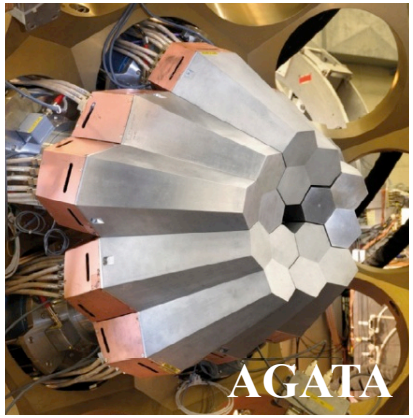
Ω ~ 80%
Δθ ~ 1°



Combination of:

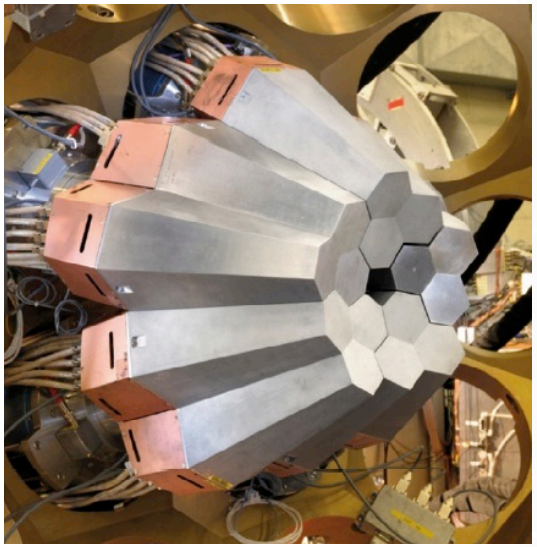
- segmented detectors
- digital electronics
- pulse shape analysis
- γ-ray tracking

➡ much improved efficiency and angle definition

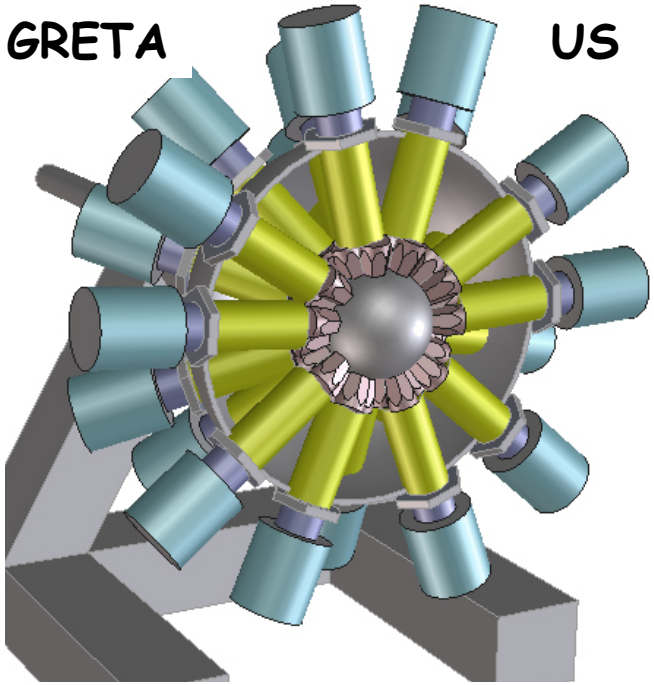


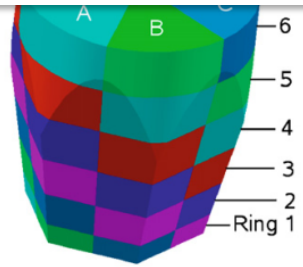
Previously, scattered gammas were wasted.
Technology is available now to track them !

The tracking arrays AGATA and GRETA



GRETA US





60 triple clusters = 180 crystals

36-fold segmentation

360 kg of Ge
200 kEuro/crystal
6660 electronics channels

AGATA and GRETA will open a new era in γ-ray spectrocopy
- with stable and radioactive ion beams !

Overview and summary

Let
it spin !

temperature
excitation energy

Shape changes and
collective motion

angular
momentum

Leave valley
of stability !

isospin

Synthesis of SHE

Spectroscopy of
transfermium nuclei

126

Shape coexistence

82

r-process

^{100}Sn

Isospin
symmetry

50

rp-process

Nuclear physics input
for the r process

82

28

20

^{78}Ni

50

Halos and Skins

Shell evolution

8

2

28

20

2 8

Both radioactive and
stable ion beams
are important !

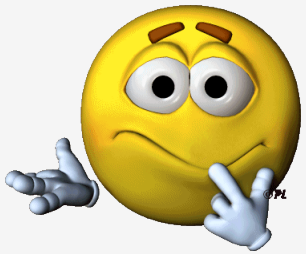
Nuclear structure research in the future

Exciting new facilities and instrumentation currently under construction – very attractive perspectives.

Still enough interesting new physics to be discovered.

But: Fewer facilities, less beamtime, experiments more and more complex, data more and more precious (and expensive).

Nuclear physics became a very diverse and highly spezialized field.



It's time to rethink our way of working !

Try to get a more global view, define clear goals, set priorities etc.

Field must stay attractive for young researchers and financing agencies !