High spin physics:
Instrumentation, experimental techniques and examples

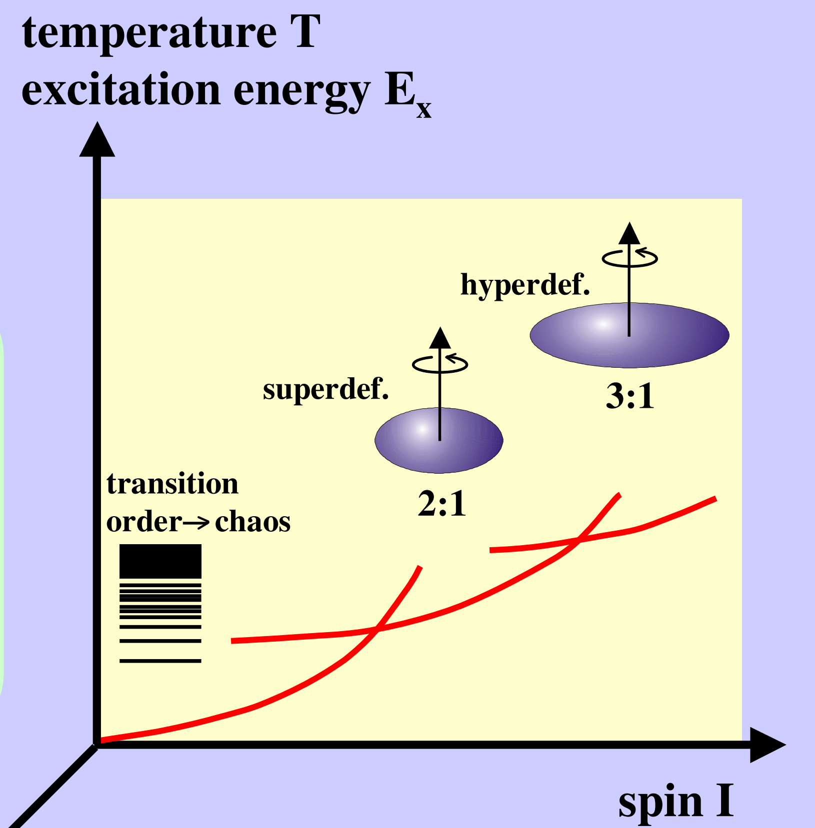
Andrea Jungclaus

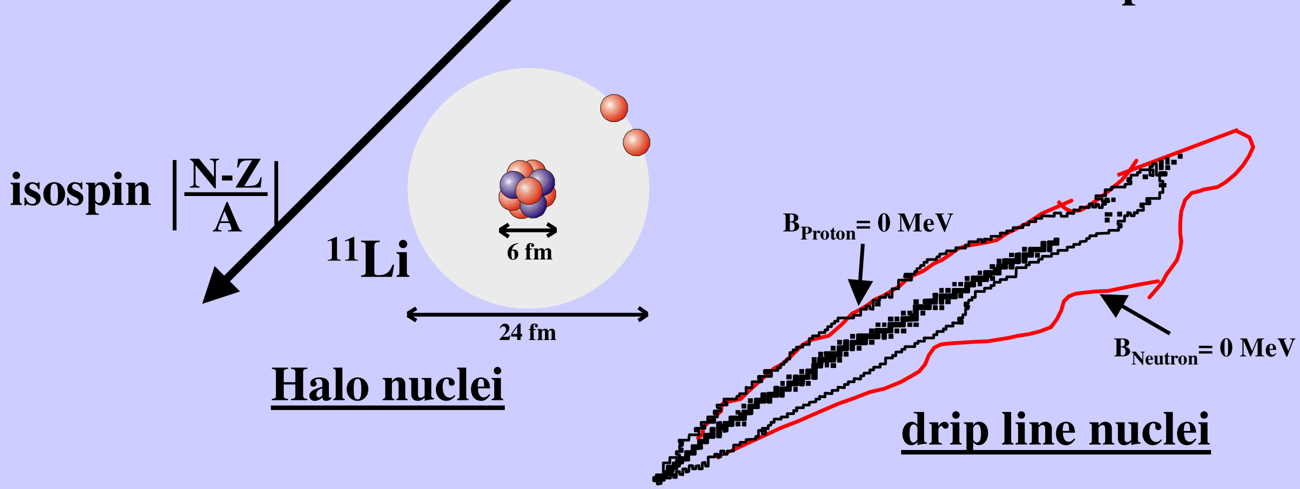
Universidad Autónoma de Madrid

- **introduction**
- **γ-ray spectrometer**
- **ancillary detectors**
- **examples:**
  - **prompt particle decay from deformed excited states**
  - **superdeformed bands**
  - **spectroscopy of transfermium nuclei**
  - **ground state proton decay**
- **next generation γ-ray spectrometer**

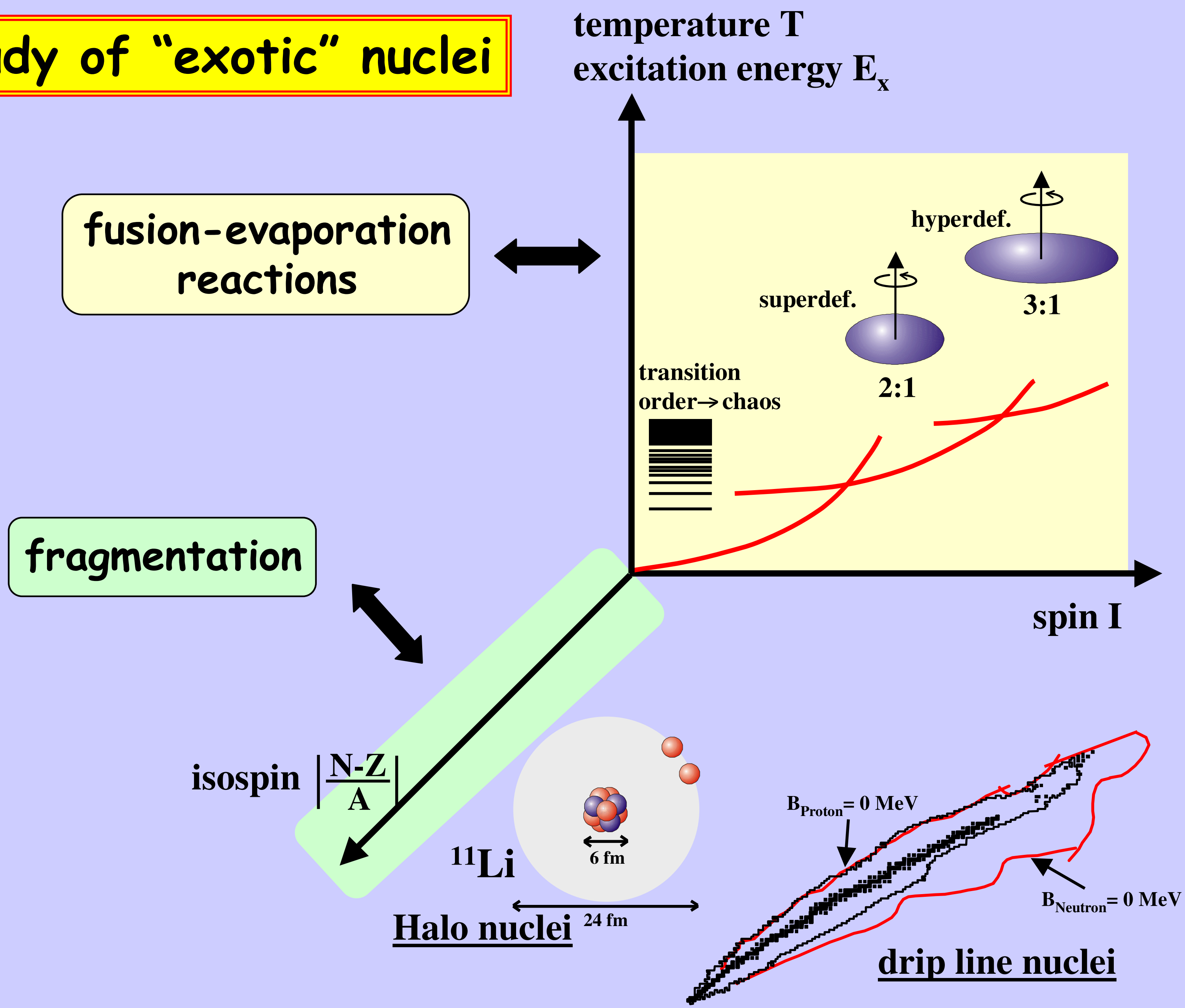
The study of "exotic" nuclei

- high **excitation energy** (hot nuclear matter)
- high **spin**
- strong **deformation** (superdef., hyperdef.)
- large **mass**, high Z (superheavies)
- extreme **isospin** (halos, skins, …)

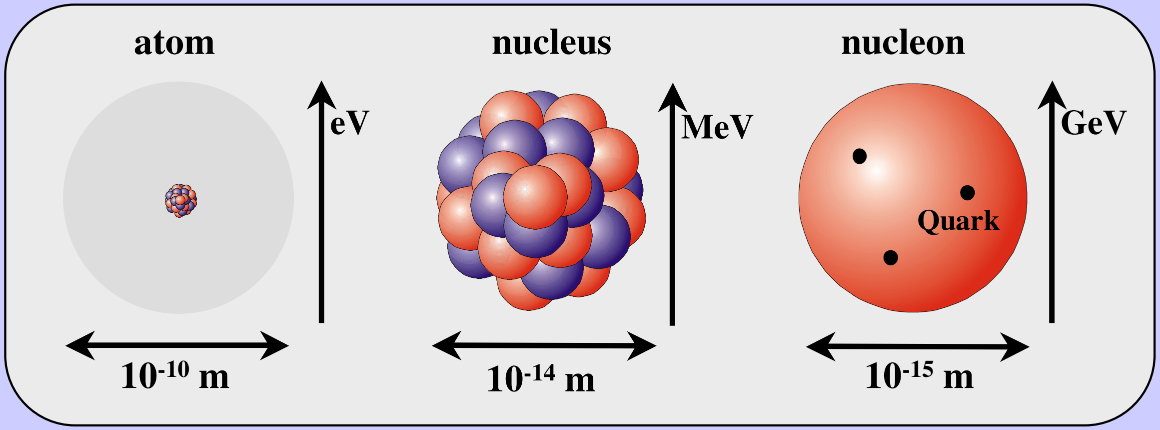




The study of "exotic" nuclei



The mesoscopic system 'atomic nucleus'

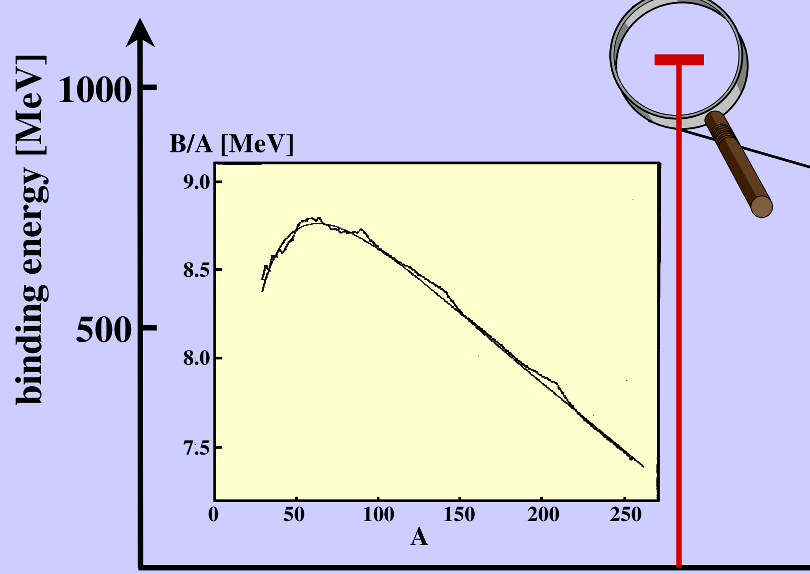


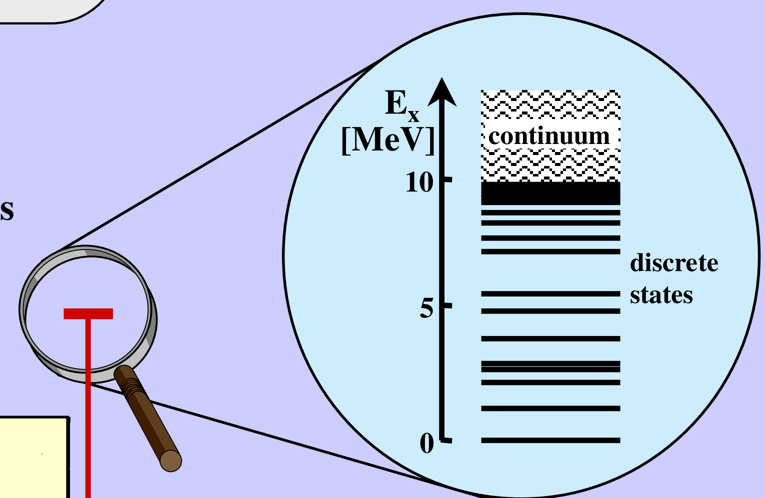
nucleon-nucleon interaction

'local fluctuations'

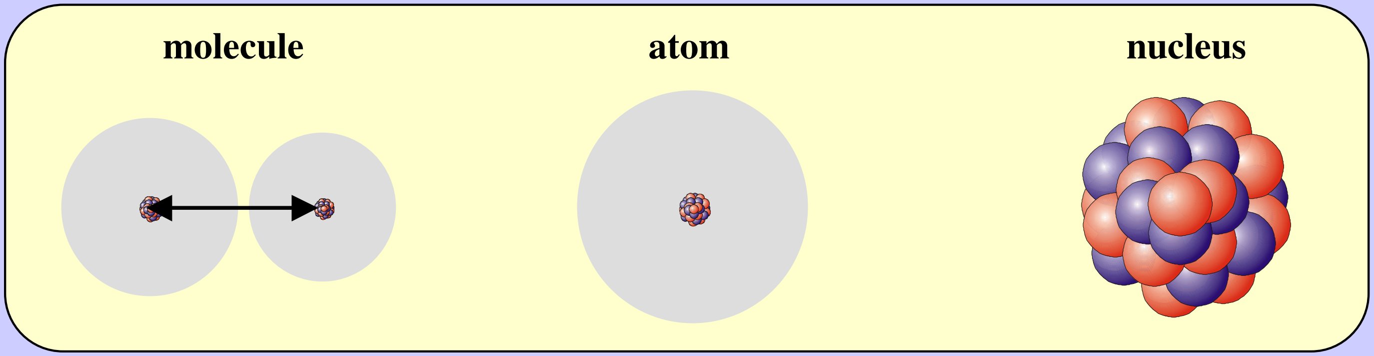
'global properties'

e.g. binding energies, radii, charge density distributions





Excitation mechanisms of different objects



molecule	atom	nucleus
• electronic • vibration • rotation	• electronic	• single-particle • vibration • rotation (def.)
$\omega_{el.} \gg \omega_{vib} \gg \omega_{rot}$		$\omega_{rot} \sim \omega_{vib} \sim \omega_{SP}$
Clear separation !		Interaction !

The special interest of nuclear physics !

An example for molecular excitations: N_2

$\omega_{el.} \gg \omega_{vib} \gg \omega_{rot}$

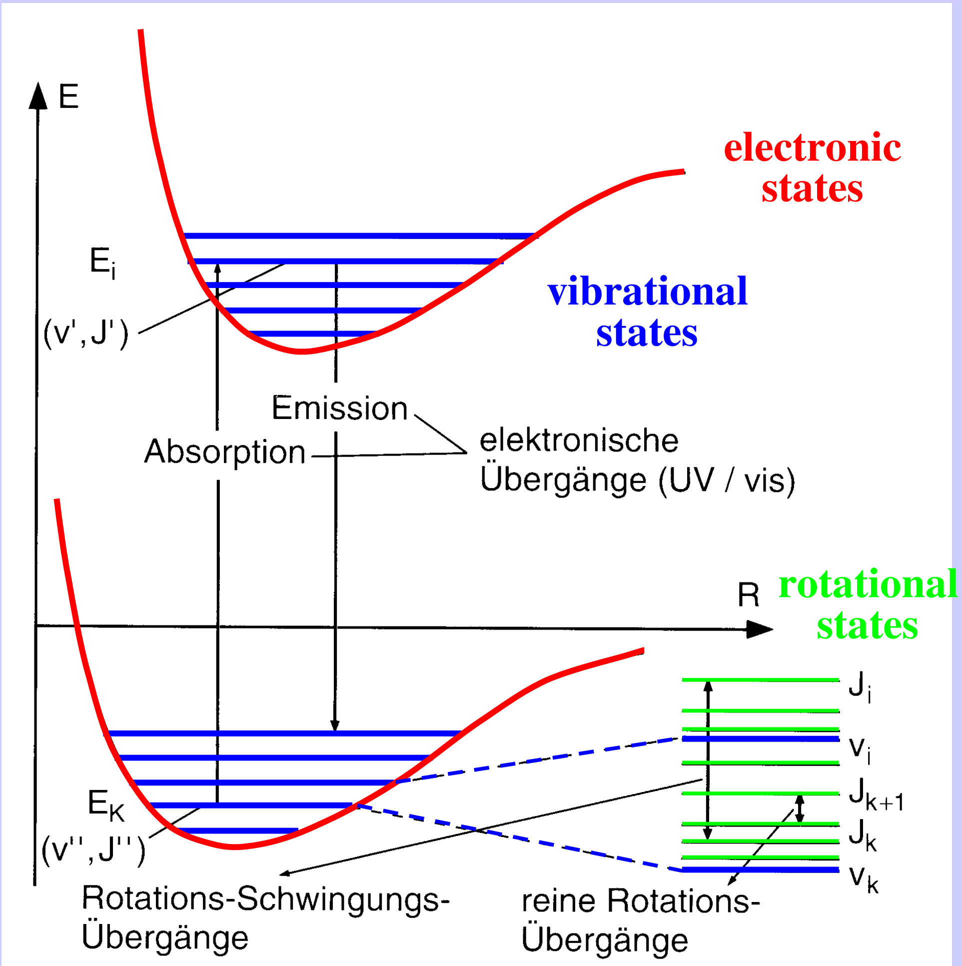
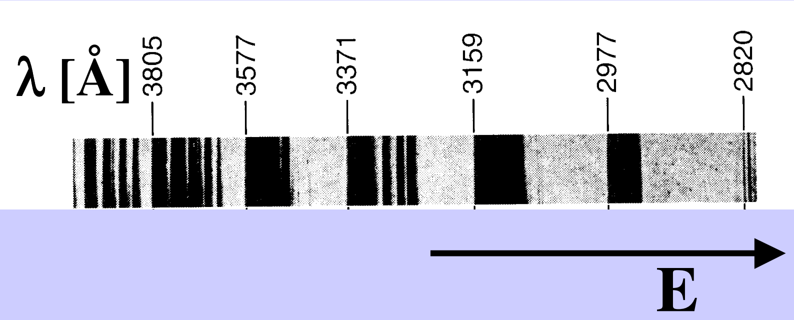


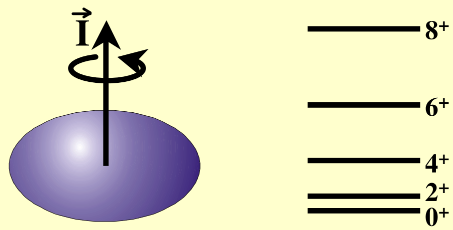
Photo of the band spectrum of the N_2 molecule built on the electronic $^3\Pi_g$ - $^3\Pi_u$ transition:



collective models

single-particle models

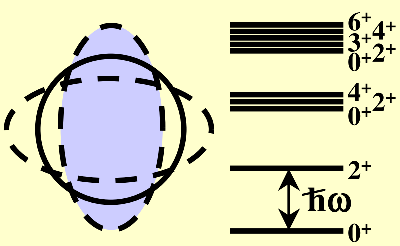
rotations – 50er Jahre



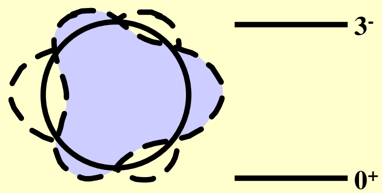
ee nucleus

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

vibrations - 50er Jahre

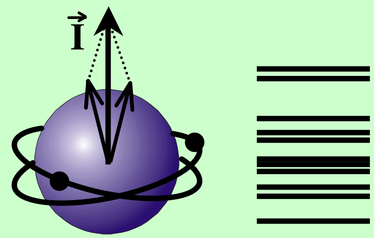


quadrupole



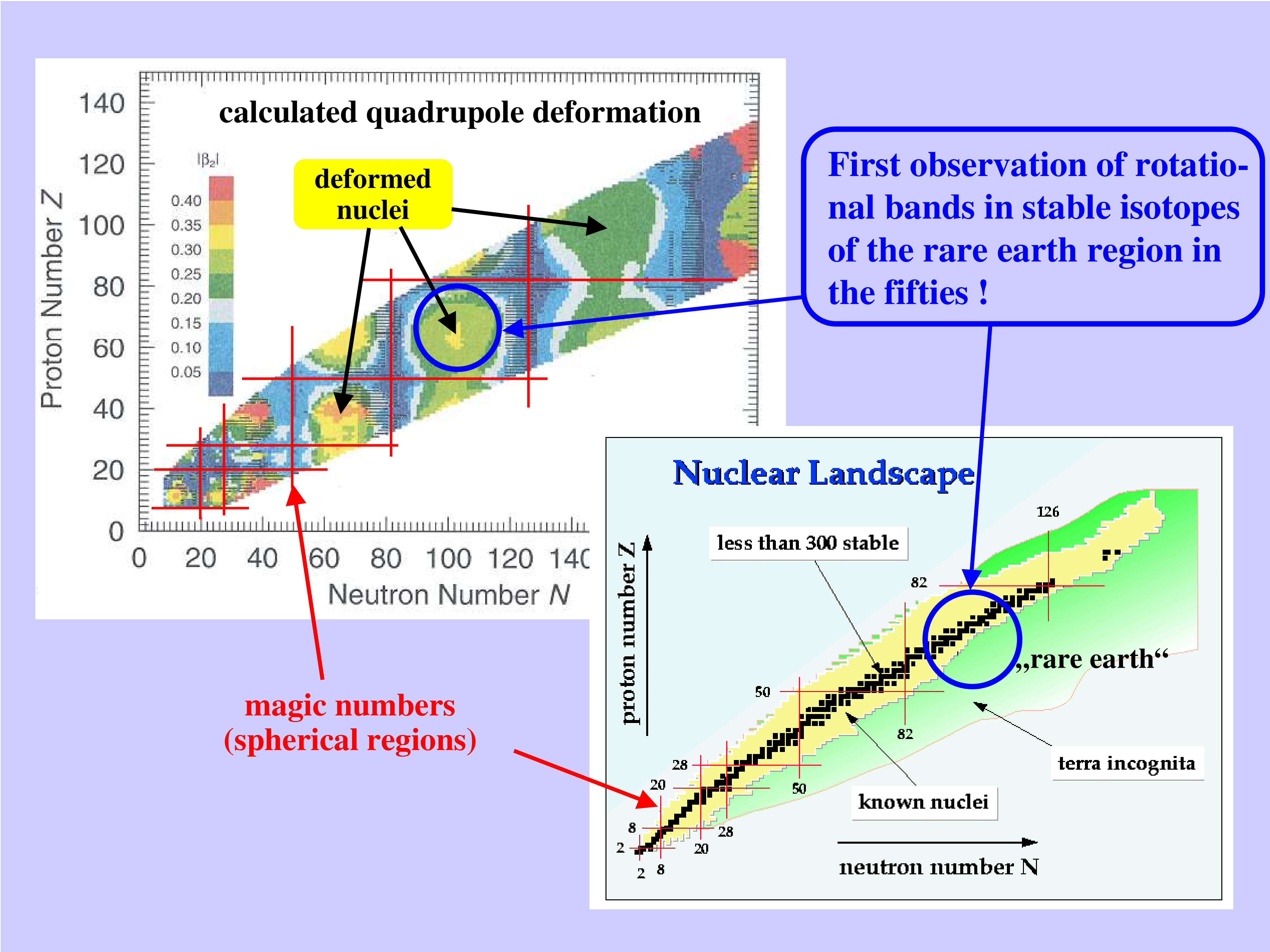
octupole

shell model - 1949

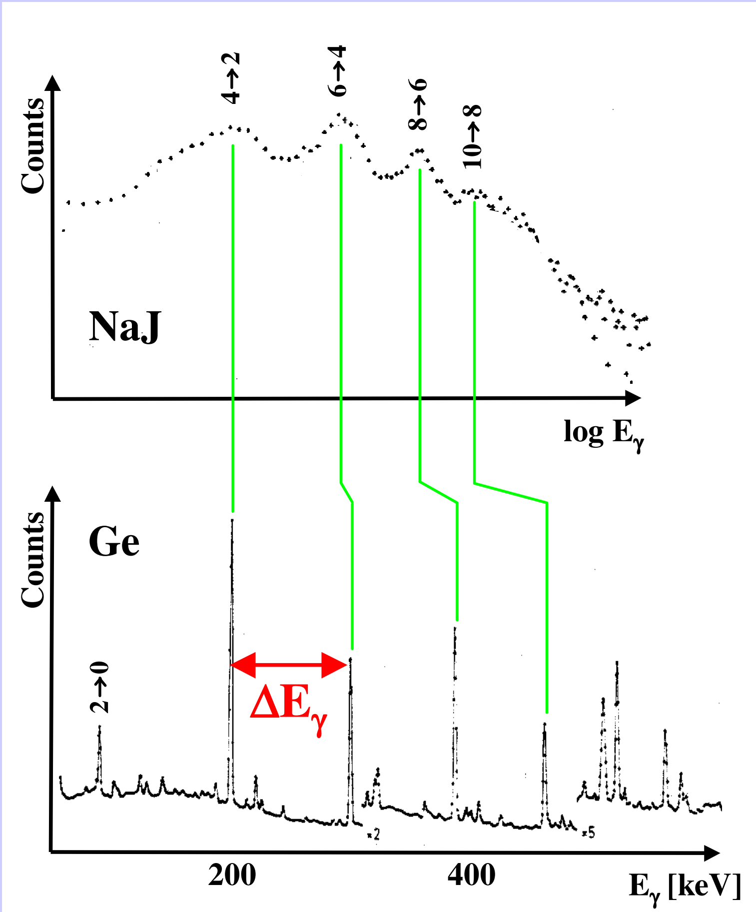


spins and magn. moments
of ground states

$$\omega_{rot} \sim \omega_{vib} \sim \omega_{SP}$$


calculated quadrupole deformation
Proton Number Z
Neutron Number N
|β2|
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
deformed nuclei
First observation of rotational bands in stable isotopes of the rare earth region in the fifties !
magic numbers (spherical regions)
Nuclear Landscape
proton number Z
neutron number N
less than 300 stable
known nuclei
terra incognita
„rare earth“
126
82
50
28
20
8
2

Morinaga und Gugelot, 1963



Johnson et al., 1972

$^{160}Gd_{96}$

Z=64 14 protons outside closed shell

N=96 14 neutrons outside closed shell

Excitation energy:

$$E_x = I(I+1)\,\hbar^2/(2J)$$

γ-ray energy:

$$E_\gamma \sim I$$

difference between E_γ:

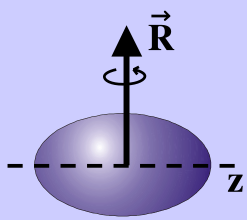
$$\Delta E_\gamma = \text{const.}$$

Collective rotation of deformed nuclei

Energy of an axial symmetric nucleus rotating around perpendicular axis:

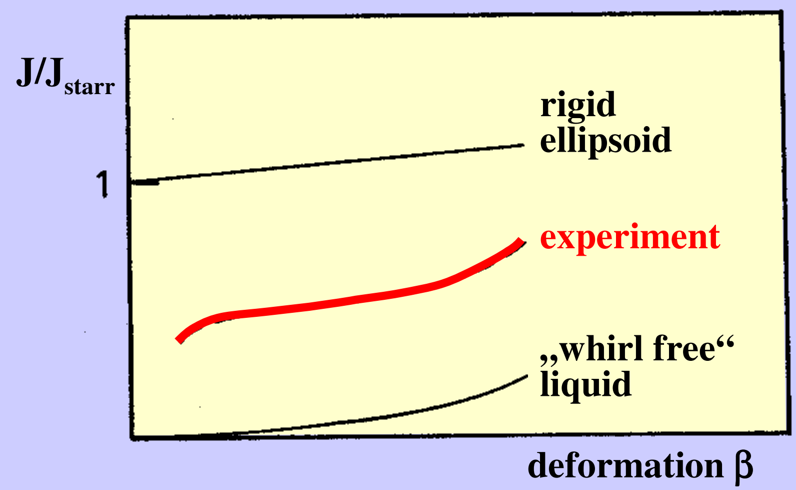
$$H_{rot} = \frac{\vec{R}^2}{2J}$$

$\vec{R}$: coll. angular momentum



spectrum: $$E_I = \frac{\hbar^2}{2J} I(I+1)$$

From the observed spectrum one can determine the moment of inertia !



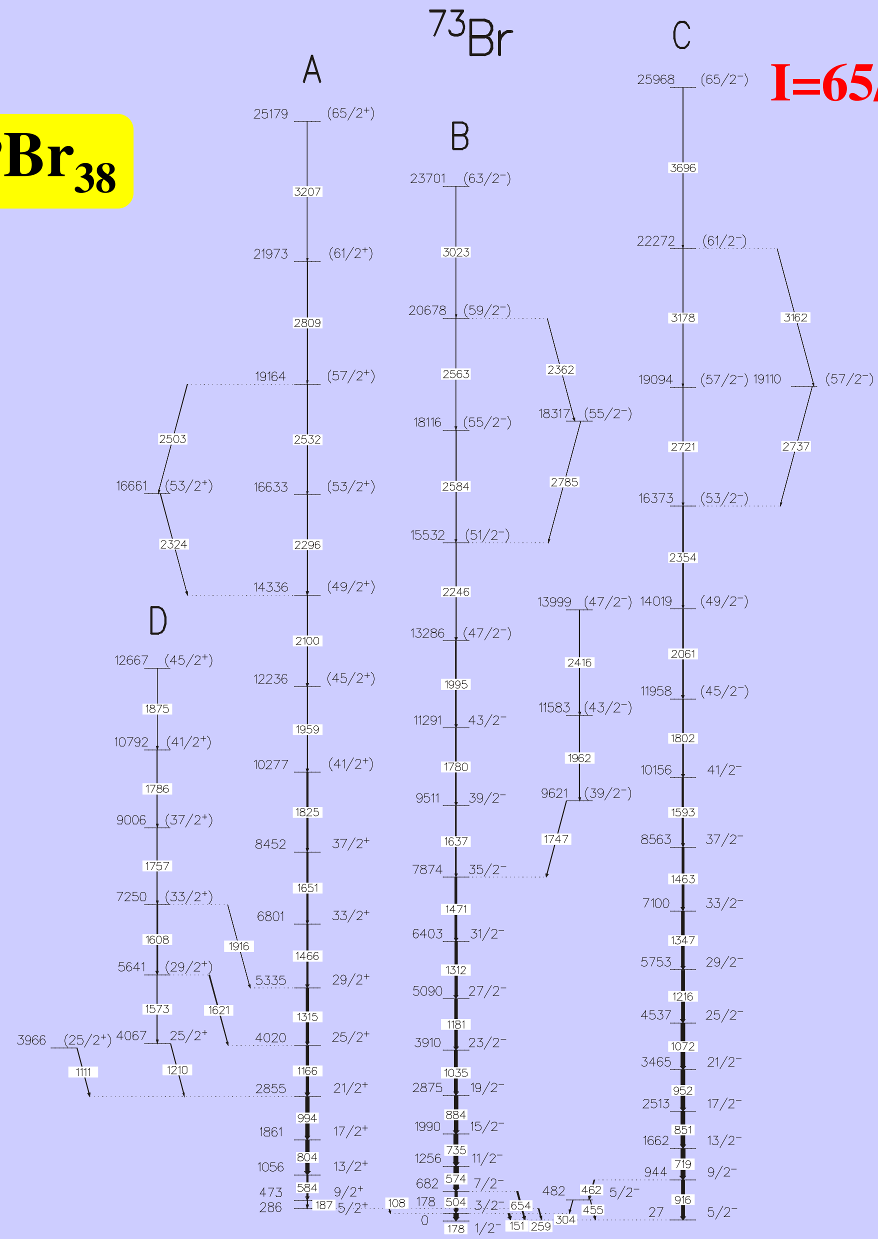
Normalized to the moment of inertia of a rigid sphere:

$$J_{starreKugel} = \frac{2}{5} M \cdot R_0^2 = \frac{2}{5} A \cdot m_n \cdot R_0^2$$

„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.

$^{73}Br_{38}$



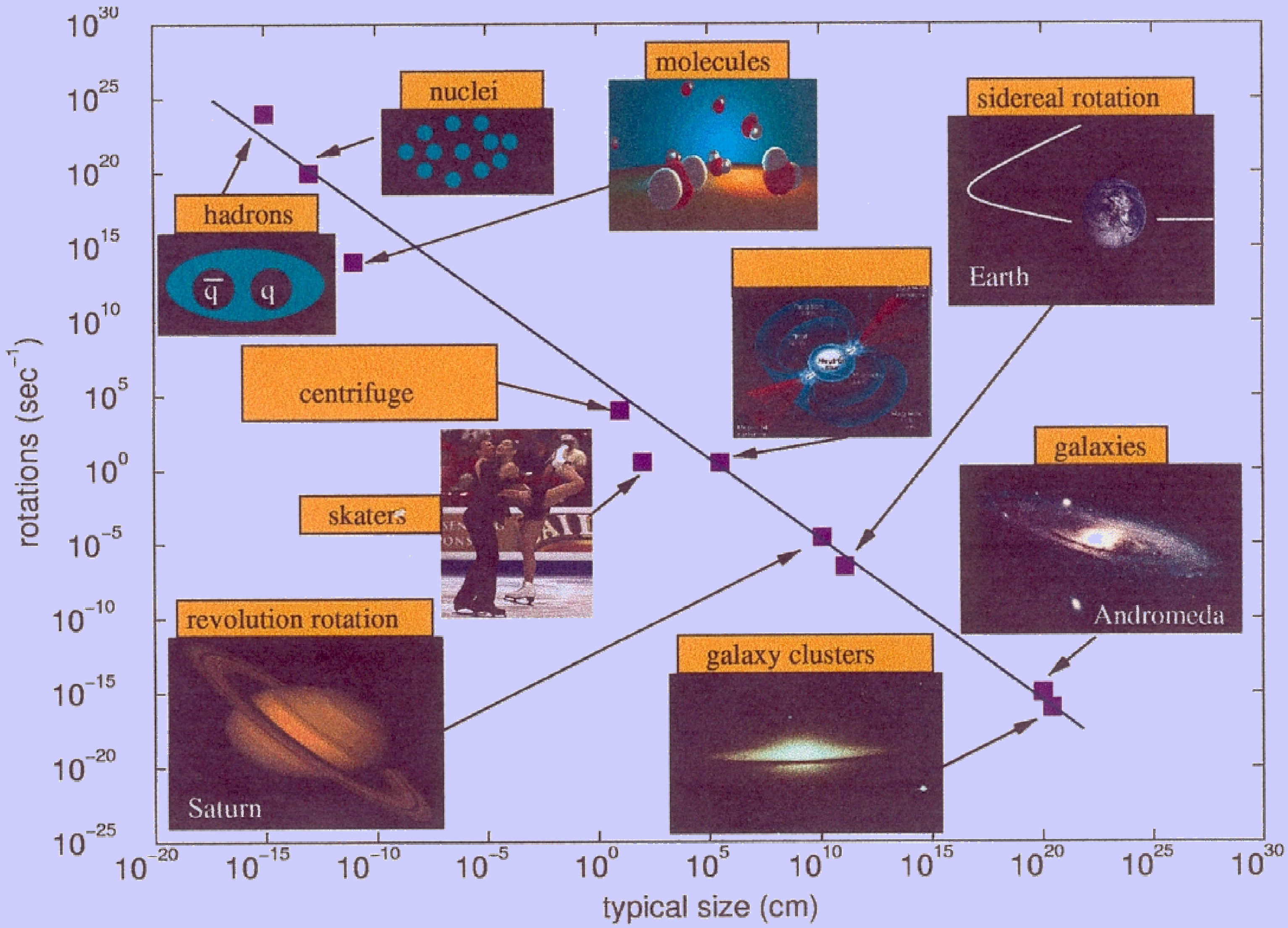
I=65/2 ħ

J **determined from excitation energies and spins: ~ 20 ħ²/MeV**

__World record:__

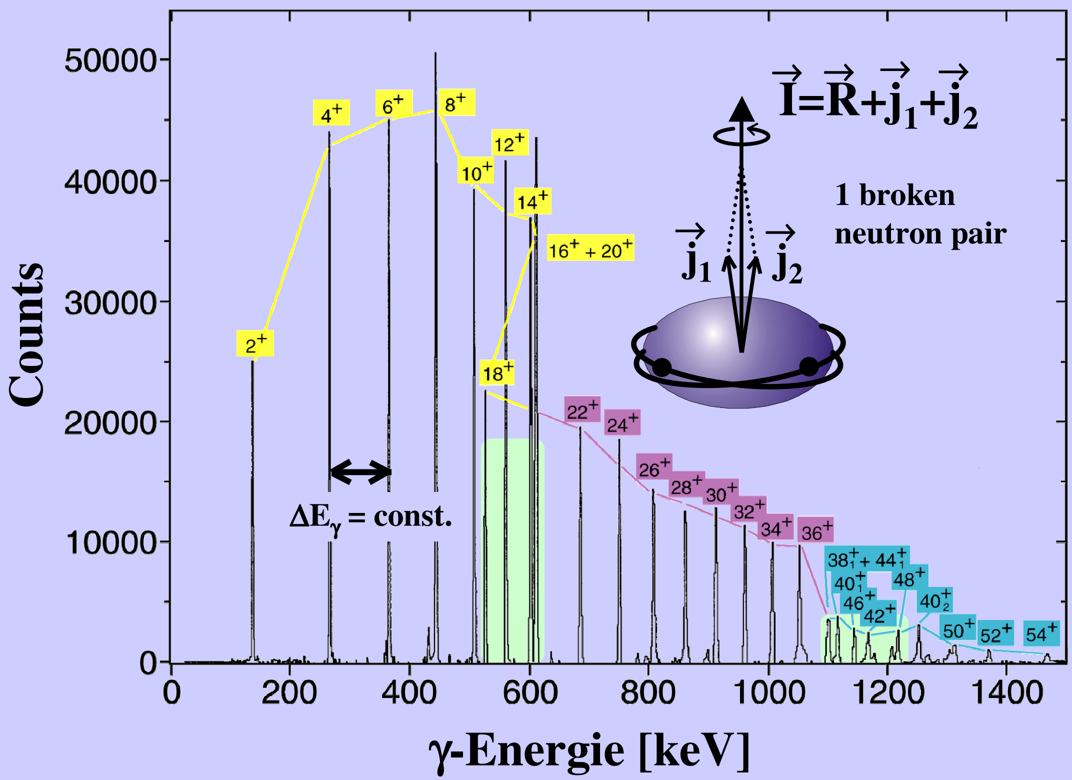
Highest rotational frequency observed in 'heavy' nuclei with A > 25 !

Rotations in the universe

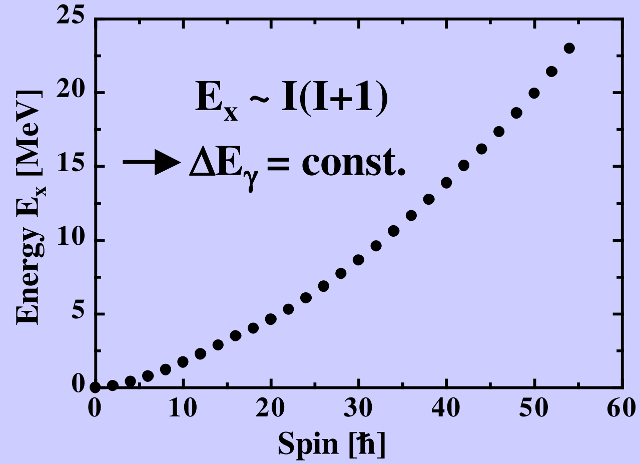


The "backbending" phenomenon

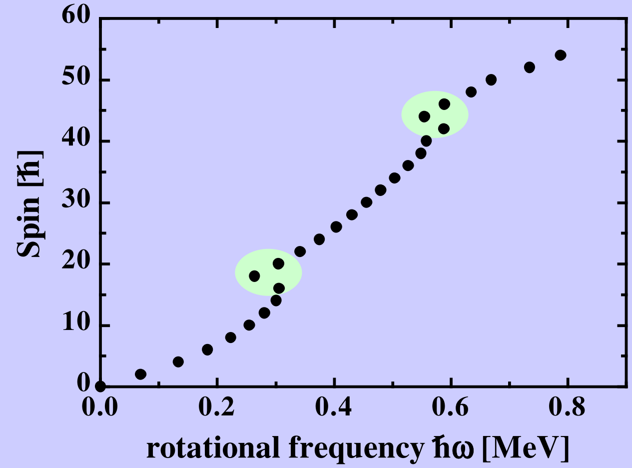
"Irregularities" in the spectrum of $^{156}Dy_{90}$



Excitation energy - spin



Spin – rotational frequency

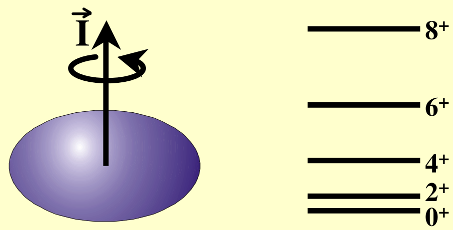


Breaking of a nucleon pair increases the total spin (and moment of inertia) while the frequency of the collective rotation decreases (skater) !

collective models

single-particle models

rotations – 50er Jahre



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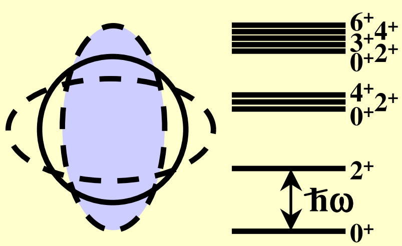
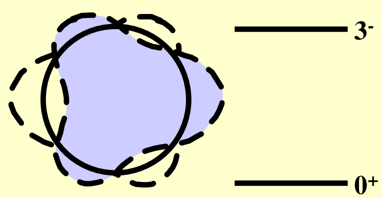
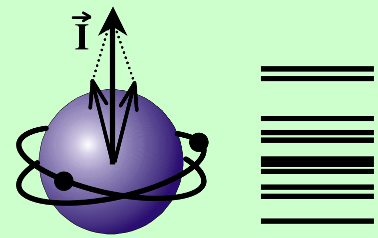


quadrupole



octupole

shell model - 1949



spins and magn. moments
of ground states

$$\omega_{rot} \sim \omega_{vib} \sim \omega_{SP}$$

1/2 premio Nobel in physics 1963: The nuclear shell model

Maria Goeppert-Mayer (1906-1972)
Hans Jensen (1907-1973)

On Closed Shells in Nuclei. II

MARIA GOEPPERT MAYER
Argonne National Laboratory and Department of Physics, University of Chicago, Chicago, Illinois

February 4, 1949

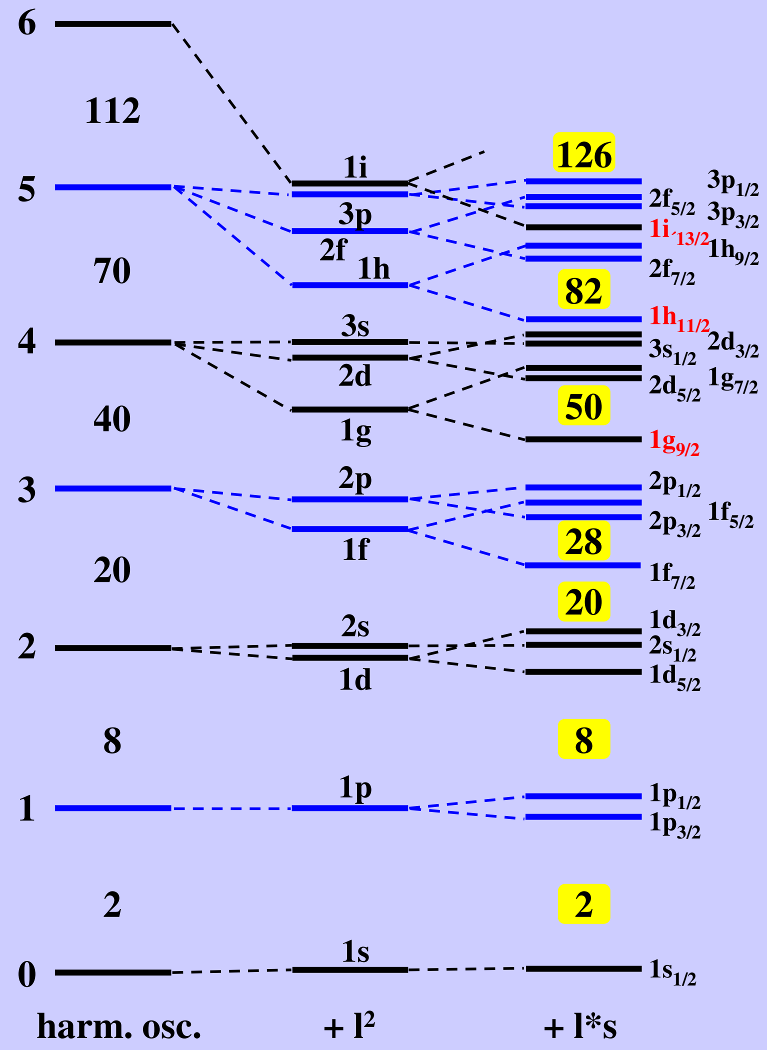
THE spins and magnetic moments of the even-odd nuclei have been used by Feenberg[1,2] and Nordheim[3] to determine the angular momentum of the eigenfunction of the odd particle. The tabulations given by them indicate that spin orbit coupling favors the state of higher total angular momentum. If strong spin-orbit coupling, increasing with angular momentum, is assumed, a level assignment different from either Feenberg or Nordheim is obtained. This assignment encounters a very few contradictions with experimental facts and requires no major crossing of the levels from those of a square well potential. The magic numbers 50, 82, and 126 occur at the place of the spin-orbit splitting of levels of high angular momentum.

....

Thanks are due to Enrico Fermi for the remark, "Is there any indication of spin-orbit coupling?" which was the origin of this paper.

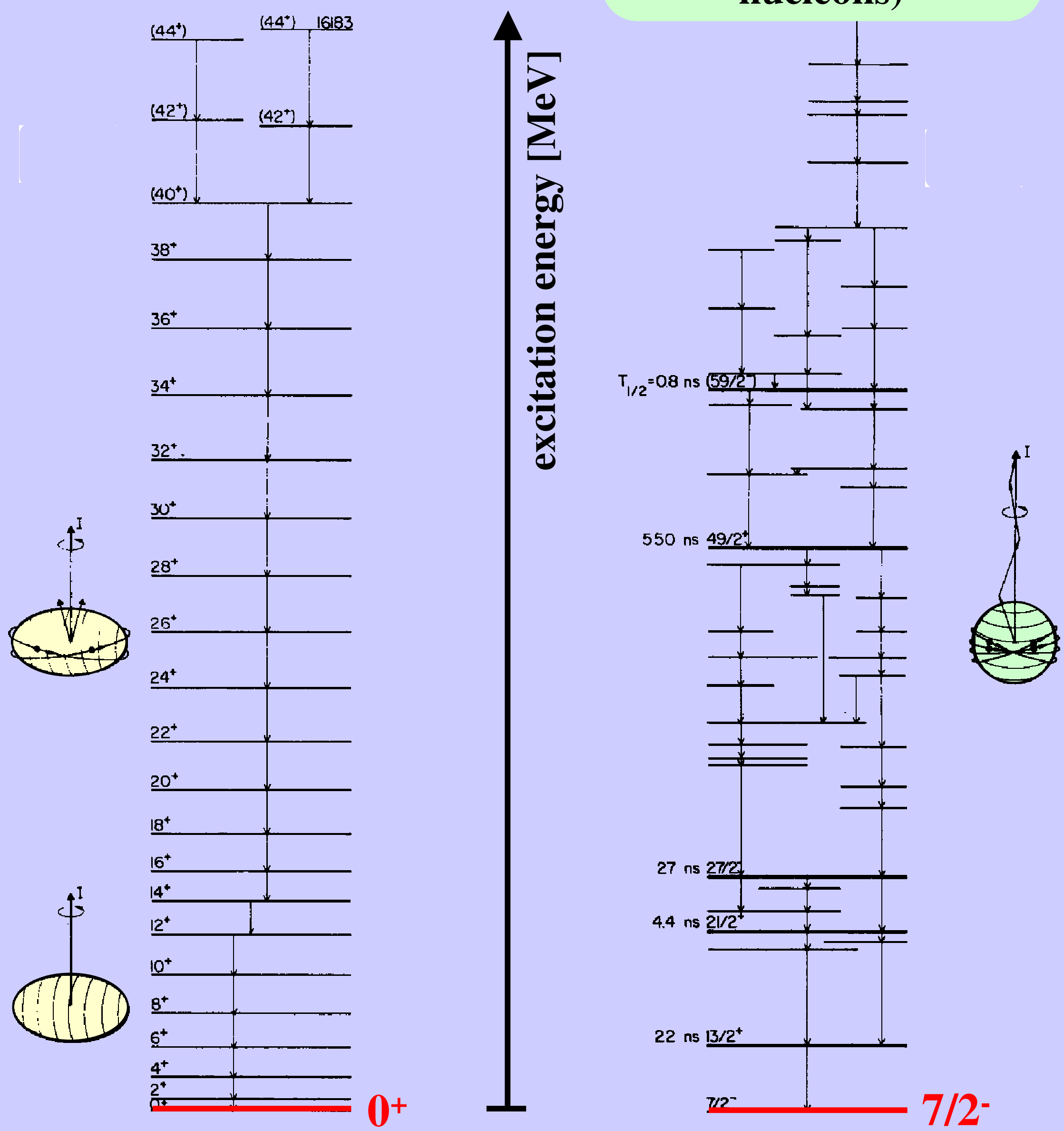
Physical Review 75 (1949)

"Magic numbers" due to strong spin-orbit splitting



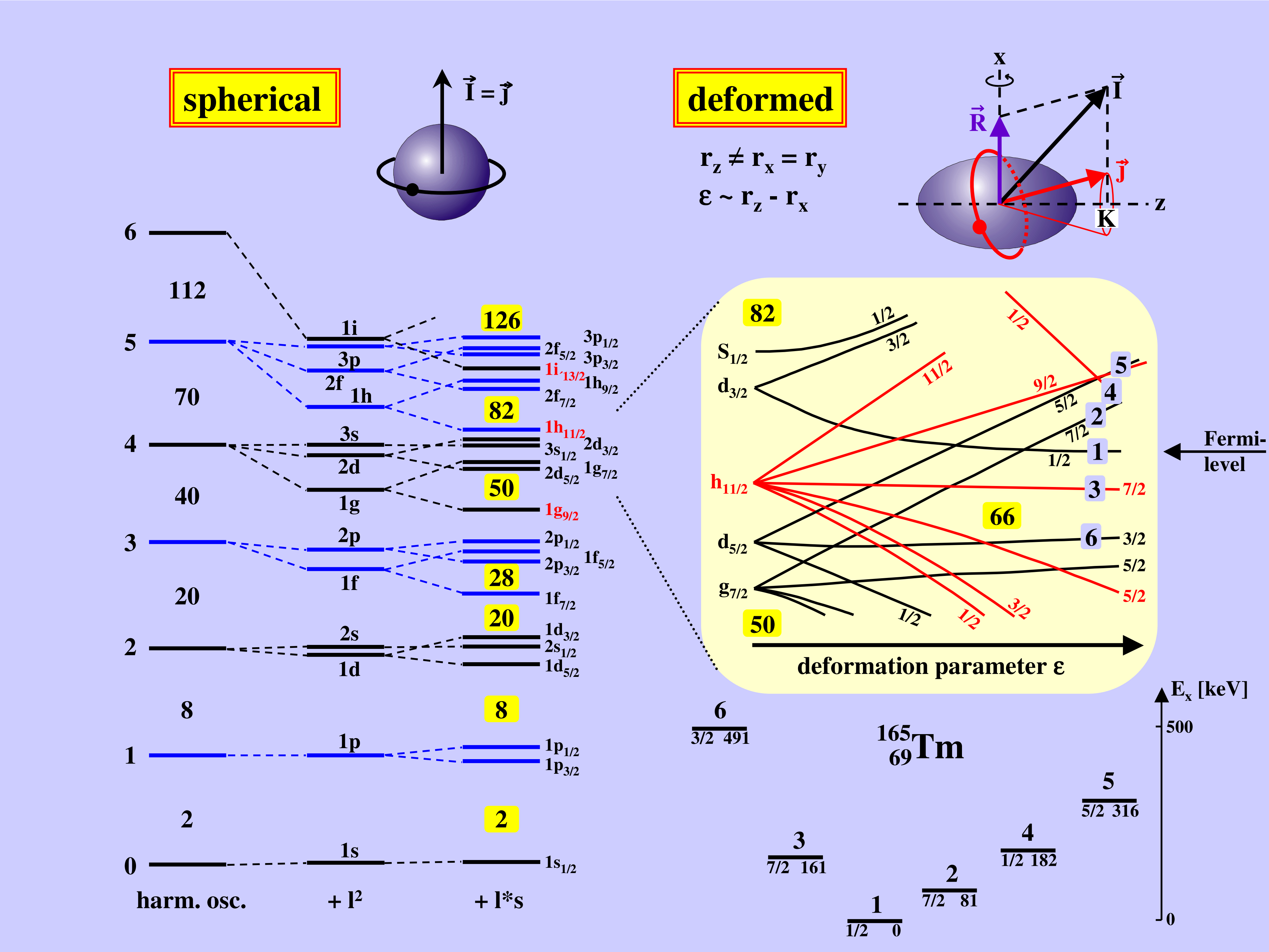
deformed nucleus:
regular rotational bands (collective movement)

spherical nucleus:
irregular structures (excitation of individual nucleons)

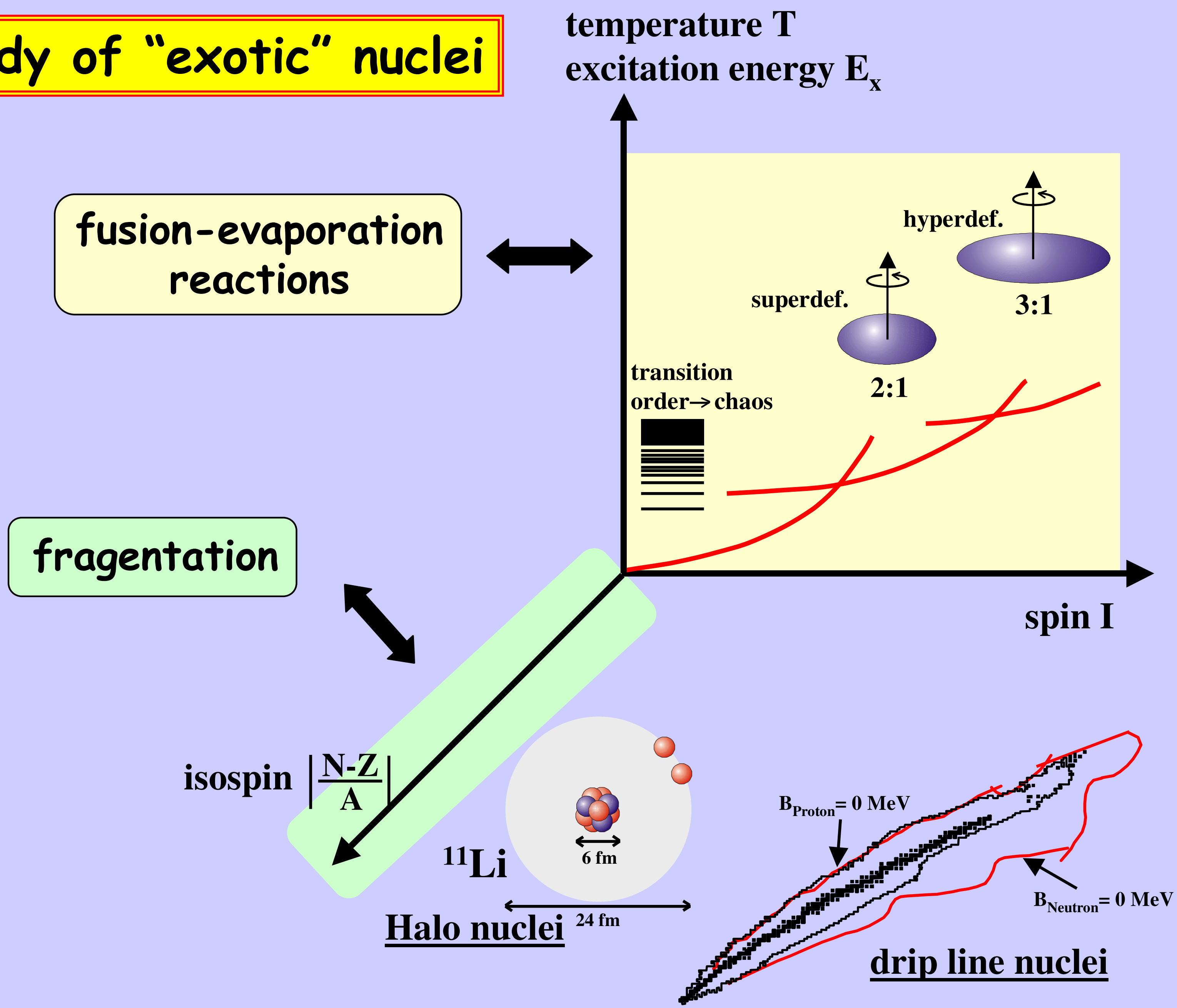


$^{158}_{68}Er_{90}$

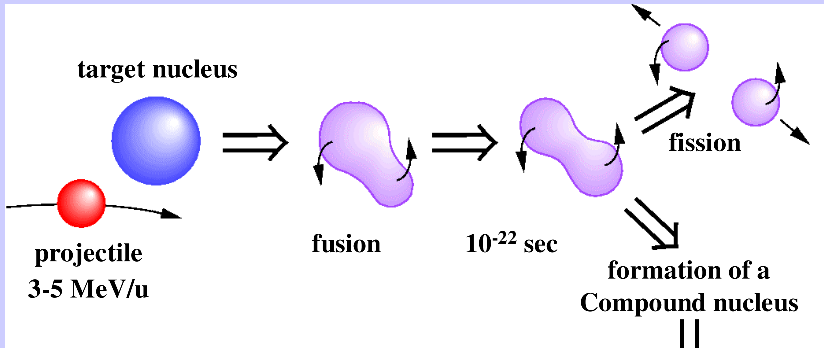
$^{147}_{64}Gd_{83}$

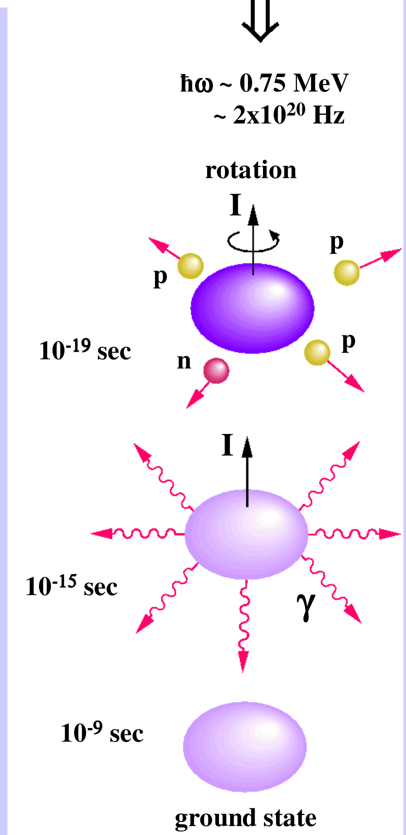

spherical
I = j
deformed
r_z ≠ r_x = r_y
ε ~ r_z - r_x
x
R
I
j
z
K
6
112
5
70
4
40
3
20
2
8
1
2
0
1i
3p
2f
1h
3s
2d
1g
2p
1f
2s
1d
1p
1s
126
82
50
28
20
8
2
2f5/2
3p1/2
3p3/2
1i13/2
1h9/2
2f7/2
1h11/2
2d3/2
3s1/2
2d5/2
1g7/2
1g9/2
2p1/2
1f5/2
2p3/2
1f7/2
1d3/2
2s1/2
1d5/2
1p1/2
1p3/2
1s1/2
harm. osc.
+ l²
+ l*s
82
S1/2
d3/2
h11/2
d5/2
g7/2
50
66
deformation parameter ε
Fermi-level
1/2
3/2
11/2
9/2
5/2
7/2
1/2
7/2
3/2
5/2
5/2
1/2
1/2
3/2
165 69 Tm
Ex [keV]
500
0
6
3/2 491
5
5/2 316
4
1/2 182
3
7/2 161
2
7/2 81
1
1/2 0

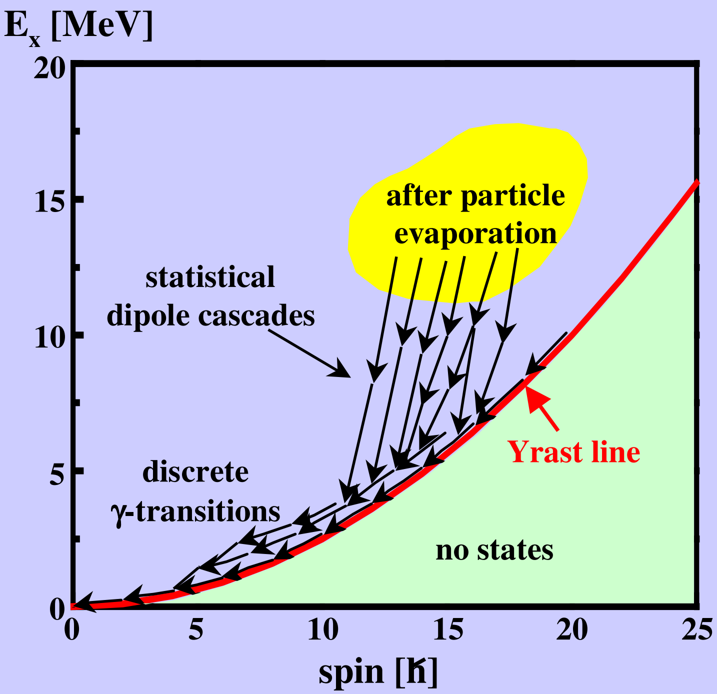
The study of "exotic" nuclei



The heavy-ion induced fusion-evaporation reaction



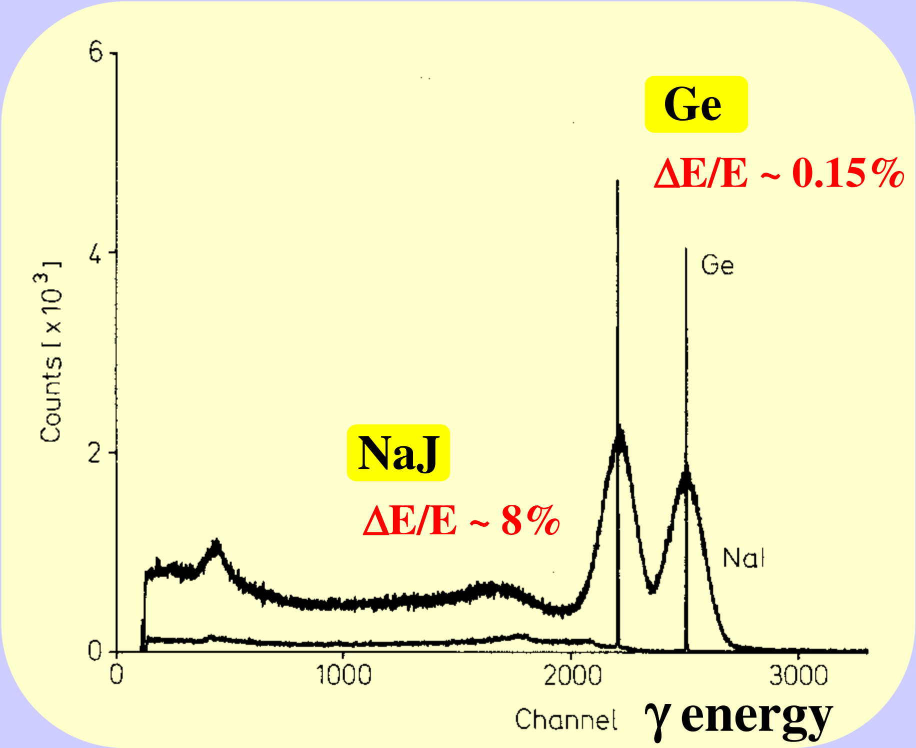




- neutron-deficient nuclei
- high spin and exc. energy
- needs an accelerator
- many different reaction products
- large range of cross sections
- recoil velocity of reaction products v/c ≈ 1-5%

Detectors for γ-radiation

γ-spectrum of a ^{60}Co source



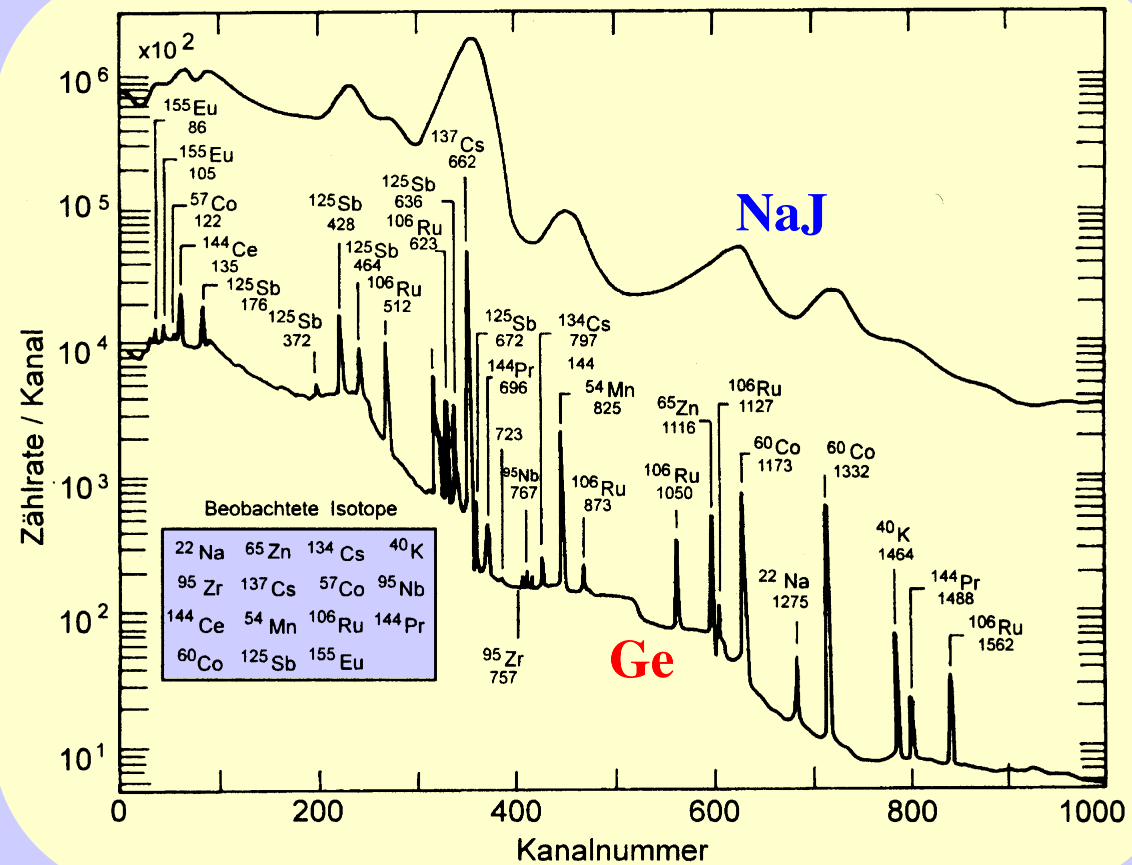
Ge detector has much **better energy resolution** but much **worse efficiency** than a scintillator !

<u>Three characteristic quantities for γ-ray spectrometer:</u>

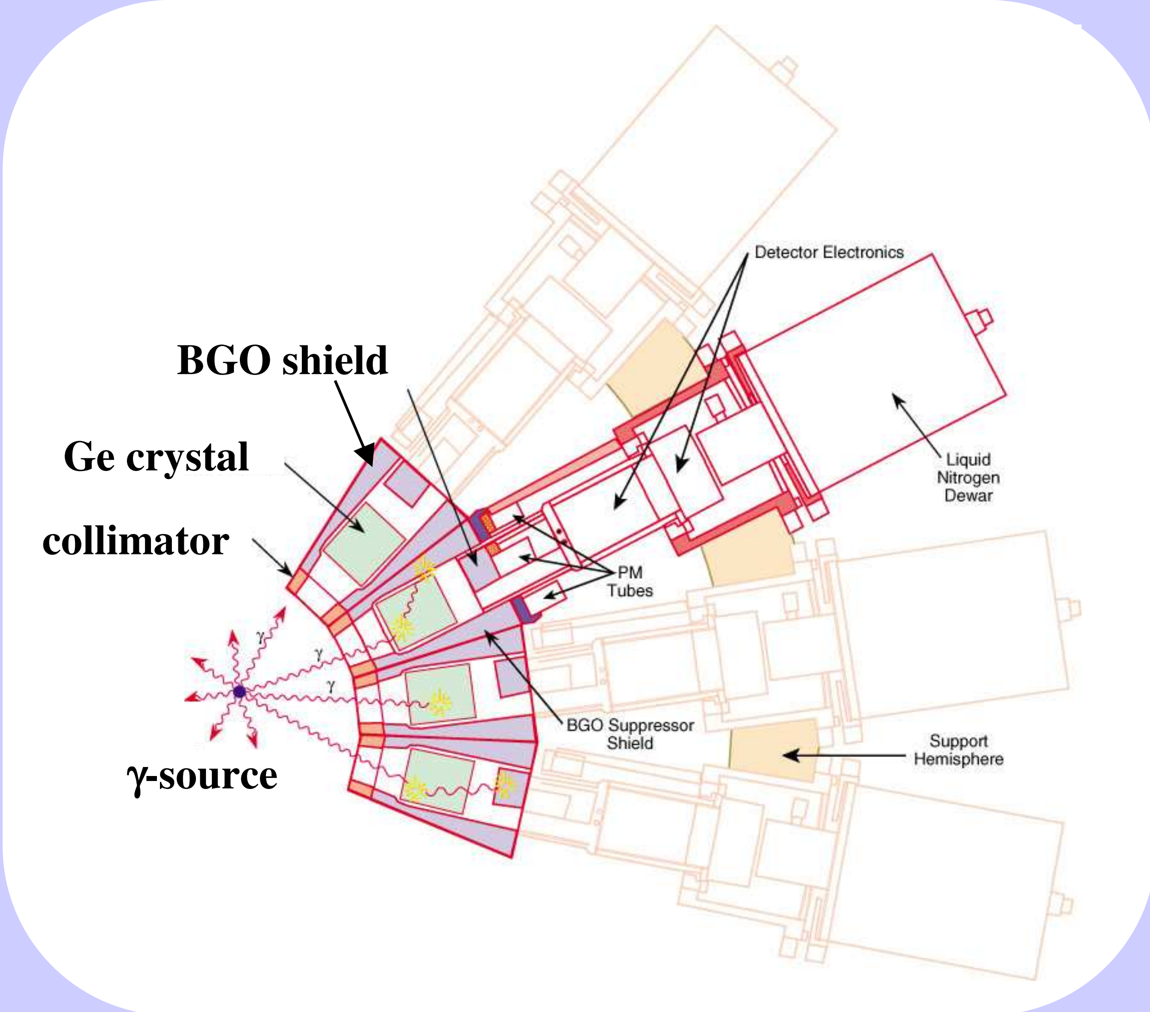
a) **energy resolution**: FWHM of photopeak (1.33 MeV γ quant from ^{60}Co)
b) **detection efficiency**, given relative to a 7.6 cm x 7.6 cm NaI crystal (source at a distance of 25 cm)
c) **peak-to-total P/T**: area of photopeak relative to total area

→ How to improve P/T ?

γ–ray spectrum of an air filter with radioactive aerosols, whose activity stems from the atmospheric nuclear wapon expriments between 1958 und 1963.



The BGO Compton supression shield



Half widths $d_{1/2}$ of γ-radiation in different detector materials