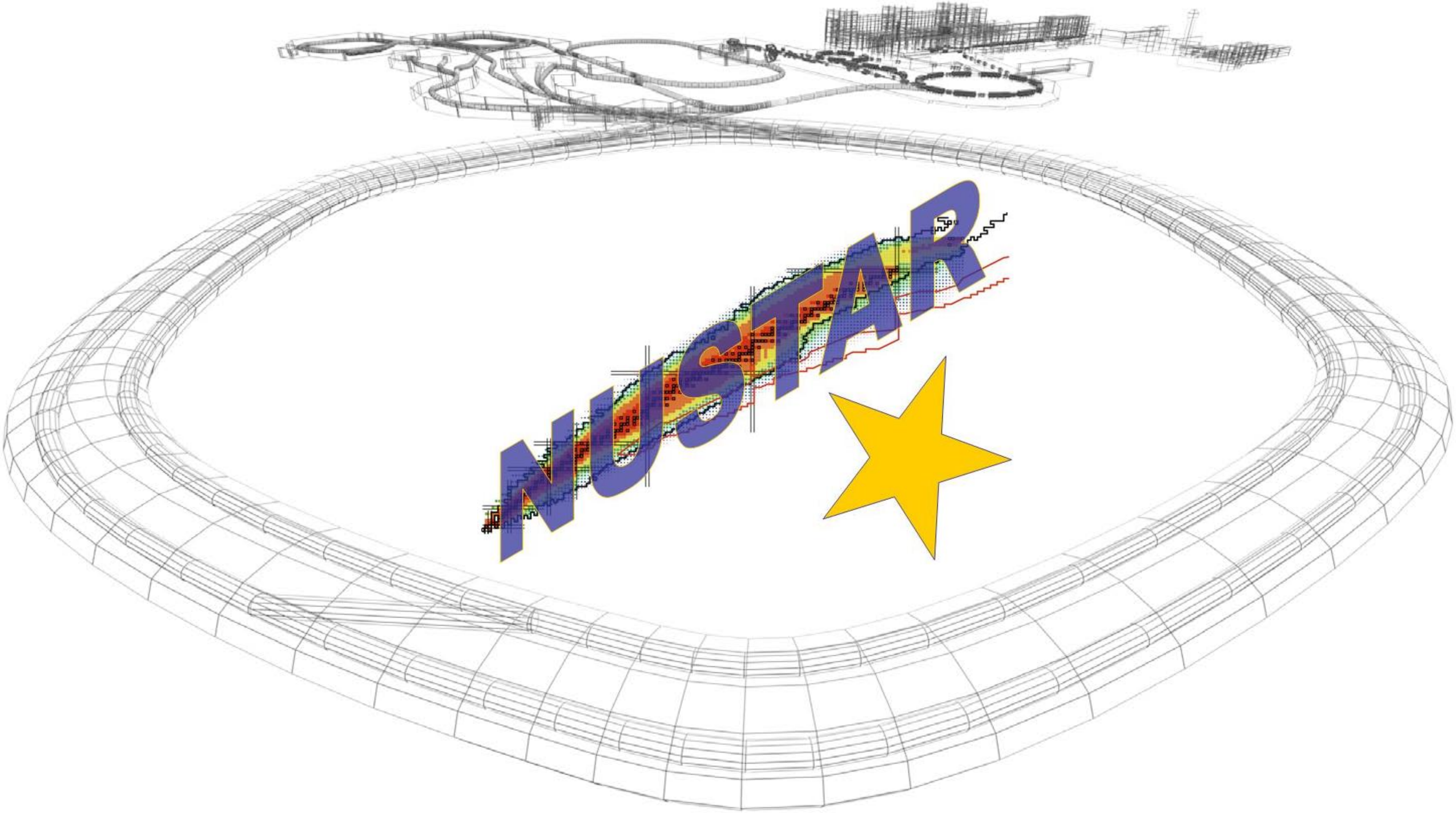
Physics with Exotic Nuclei

Hans-Jürgen Wollersheim



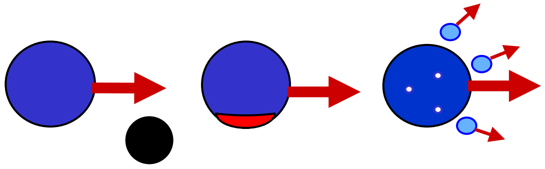
Outline

- **Excited Fragments – Gateway to Nuclear Structure**

  - Nuclear Isomers (shape-, spin-, K-traps)
  - In-Flight Separation of excited **R**adioactive **I**on **B**eams
  - Stopped Beam Experiments and Limitations to Decay Spectroscopy
  - Nuclear Shell Closure in ^{98}Cd and ^{132}Cd
  - Seniority Isomers in ^{210}Pb, ^{212}Pb, ^{214}Pb, ^{216}Pb
  - T=1 Isospin Symmetry – Mirror Nuclei
  - Silicon Implantation Detector – β-Decay of ^{100}Sn

- Scattering Experiments with **RIB**s – Nuclear Structure Results

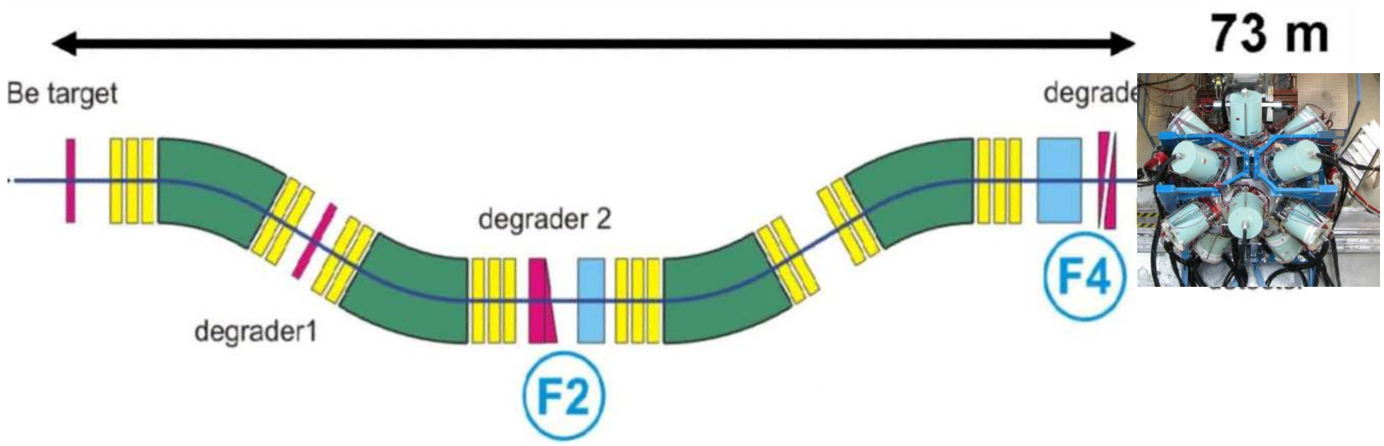
Production of Radioactive Ion Beams



Fragmentation

in ~20% of all cases the fragment is excited

primary beam



time-of-flight through the fragment separator FRS ~300 ns

Isomeric states can be investigated!

What is a Nuclear Isomer?

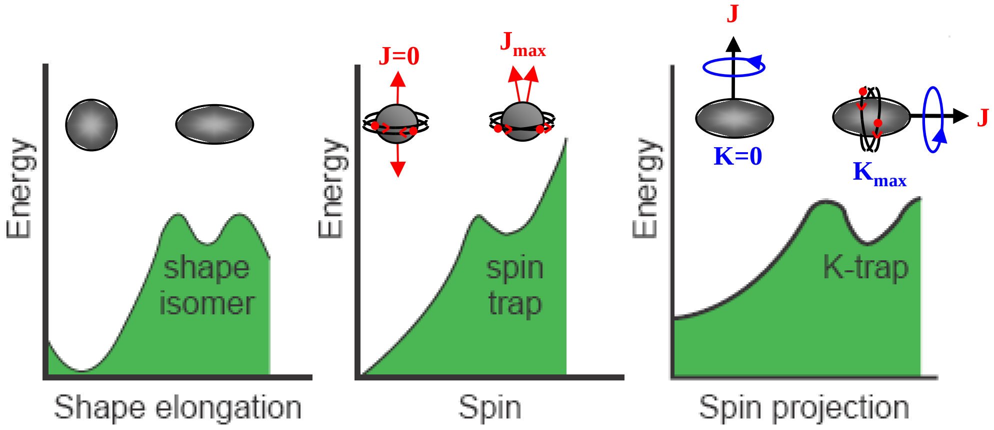
Nuclear Isomer – a *long-lived excited nuclear state* ($T_{1/2} > 1$ *ns*)

decays by emission of α, β, γ, *p, fission, cluster*

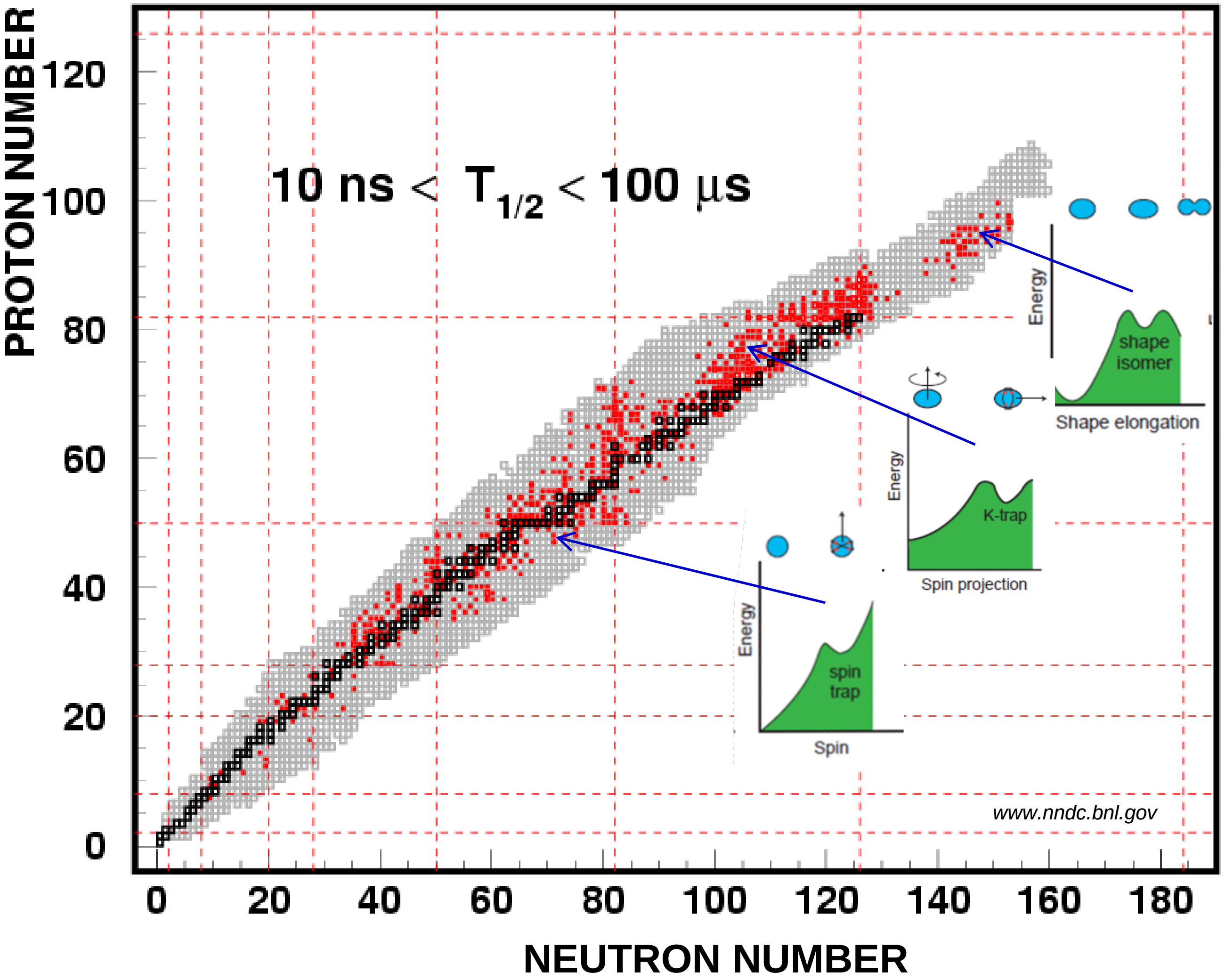
The first one discovered by O. Hahn in Berlin in 1921 – decay of ^{234}Pa (70 s)

von Weizsacker, A. Bohr & B. Mottelson

$$1/\tau \sim E_\gamma^{\,2\lambda+1}\, |\langle\, \psi_f \,|\, \mathbf{T} \,|\, \psi_i \,\rangle|$$



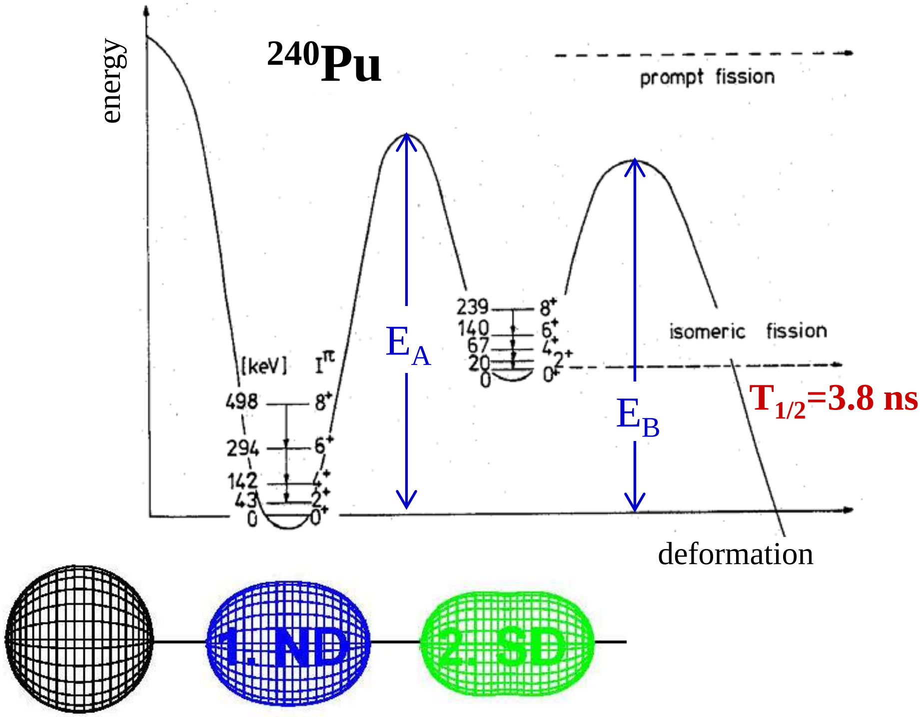
Three Types of Isomers



www.nndc.bnl.gov

1. Shape Isomers

- fission isomer (discovered by S.M. Polikanov Sov. Phys. JEPT 15 (1962) 105)



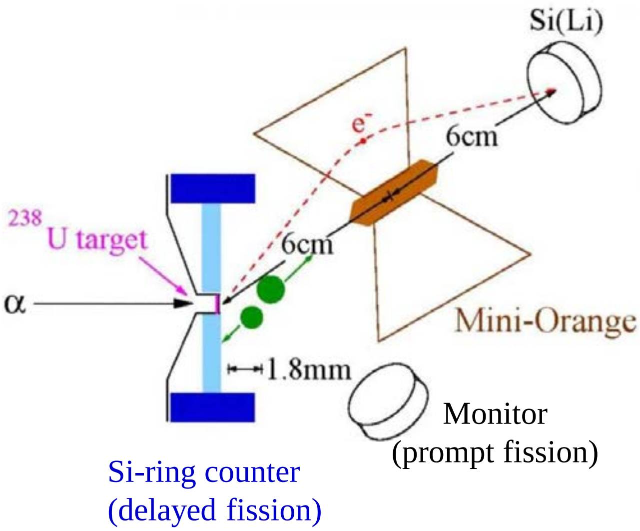
$$\boxed{\frac{\hbar^2}{2\Im} = 3.34\ keV}$$

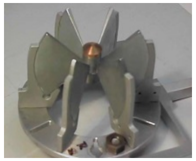
axis ratio 2:1

$E_A = 5.8 \pm 0.3$ MeV

$E_B = 5.45 \pm 0.3$ MeV

$^{238}U(\alpha,2n)^{240f}Pu,\ E_\alpha = 25$ MeV

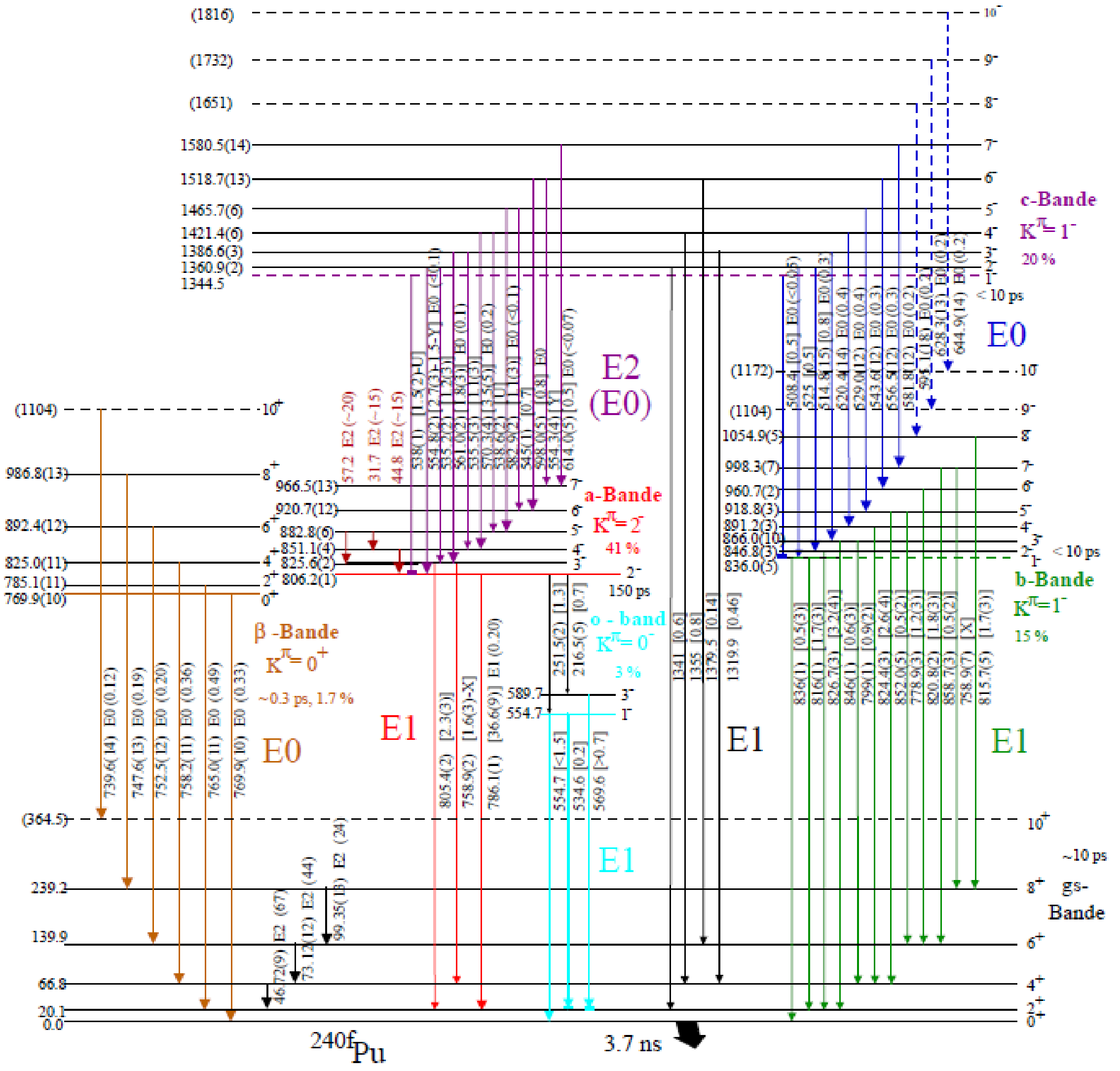




D. Pansegrau et al., Phys. Lett. B484 (2000) 1
D. Gassmann et al., Phys. Lett. B497 (2001) 181

H. Specht et al. Phys.Lett. B41 (1972) 43

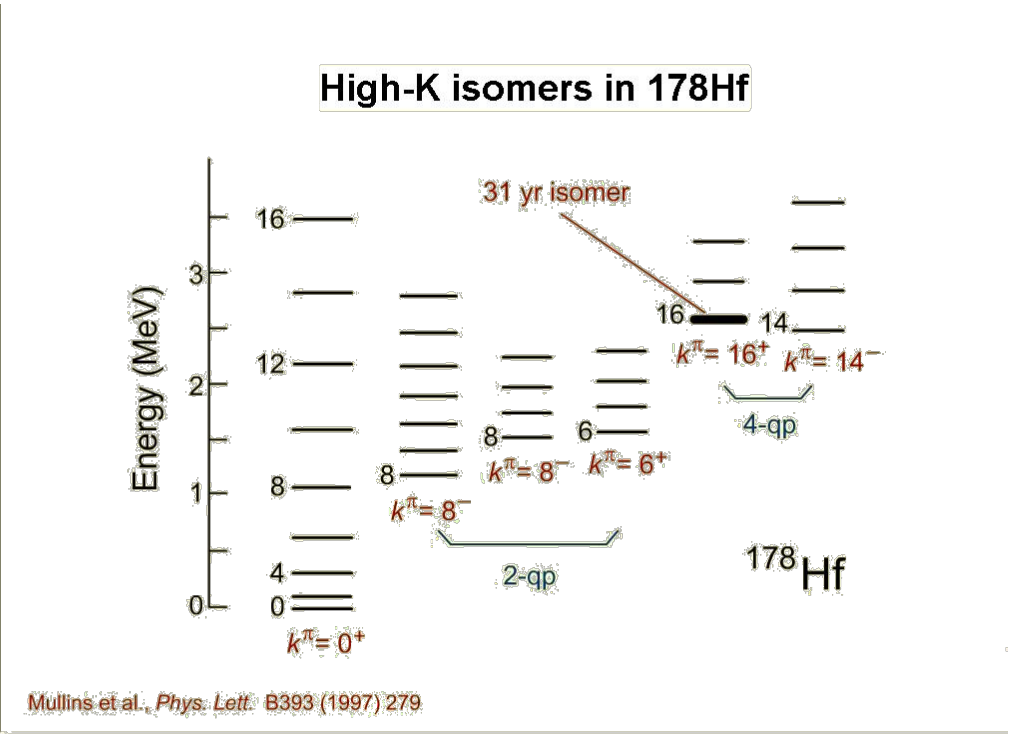
1. Shape Isomers



D. Gassmann et al., Phys.Lett. B497 (2001) 181

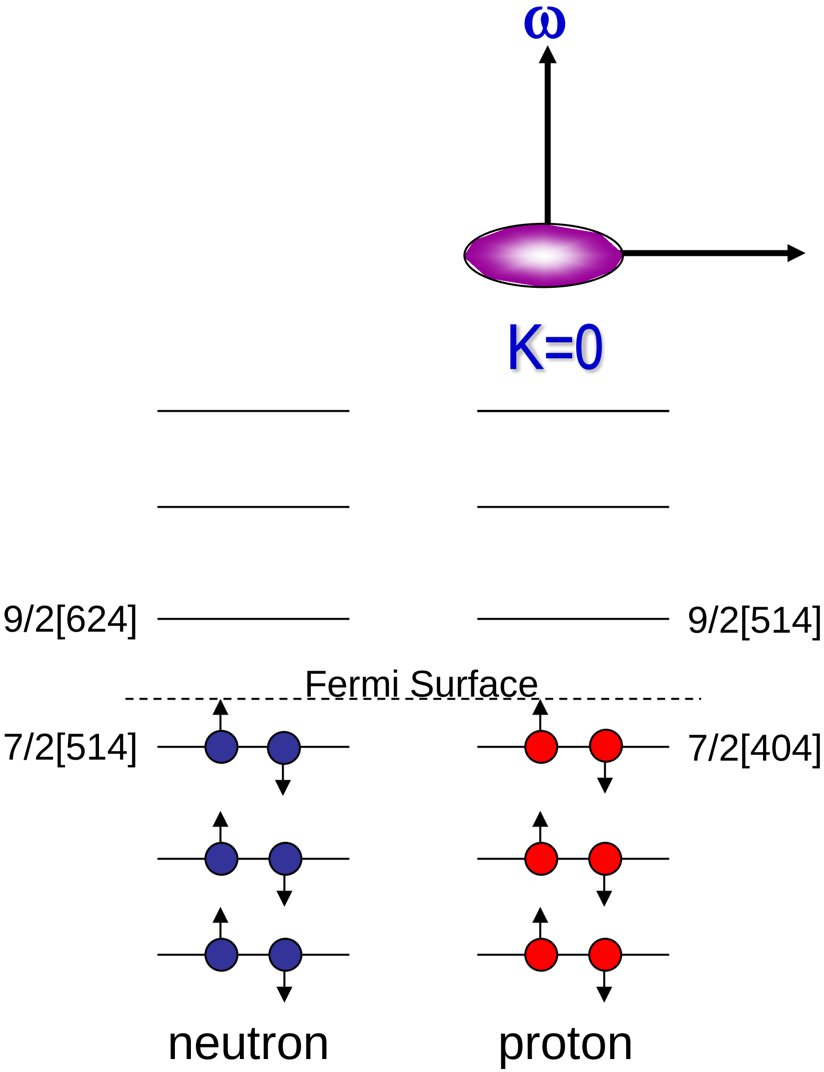
2. K Isomers

- A well-known example:



High-K isomers in 178Hf

Mullins et al., *Phys. Lett.* B393 (1997) 279



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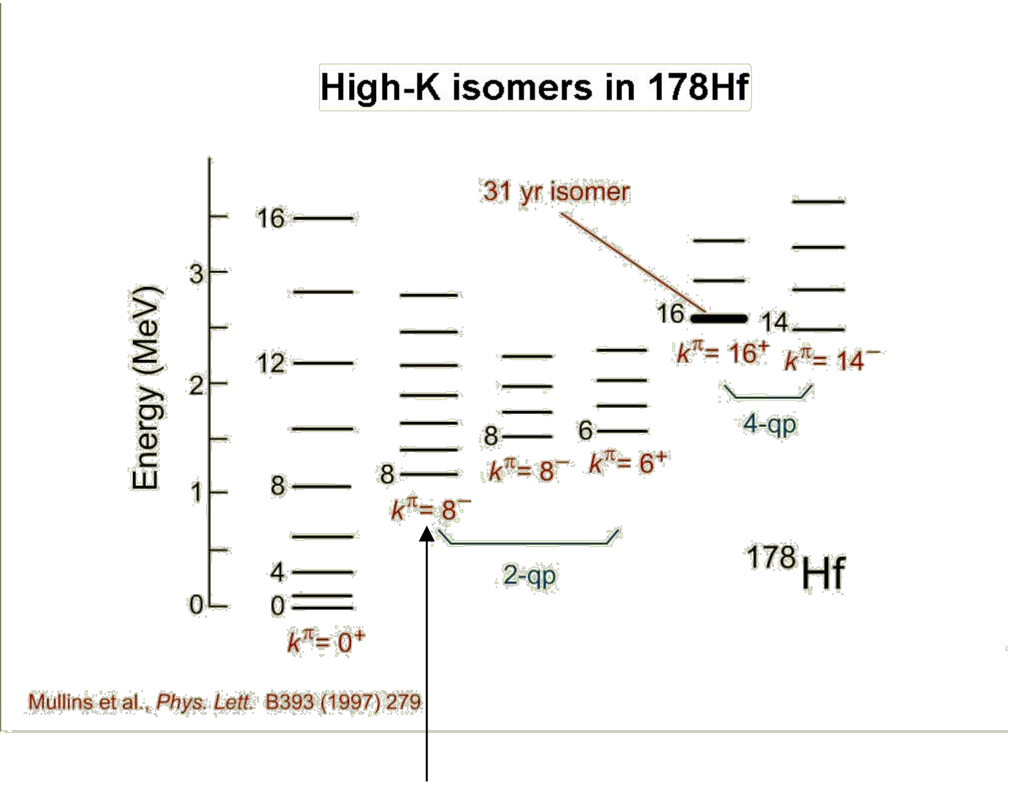
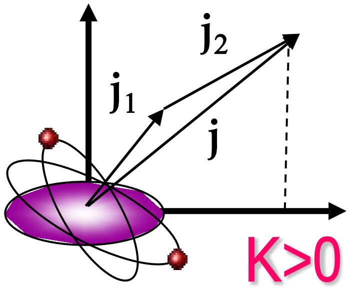

High-K isomers in 178Hf

Mullins et al., *Phys. Lett.* B393 (1997) 279

$\nu^2_{8^-}$



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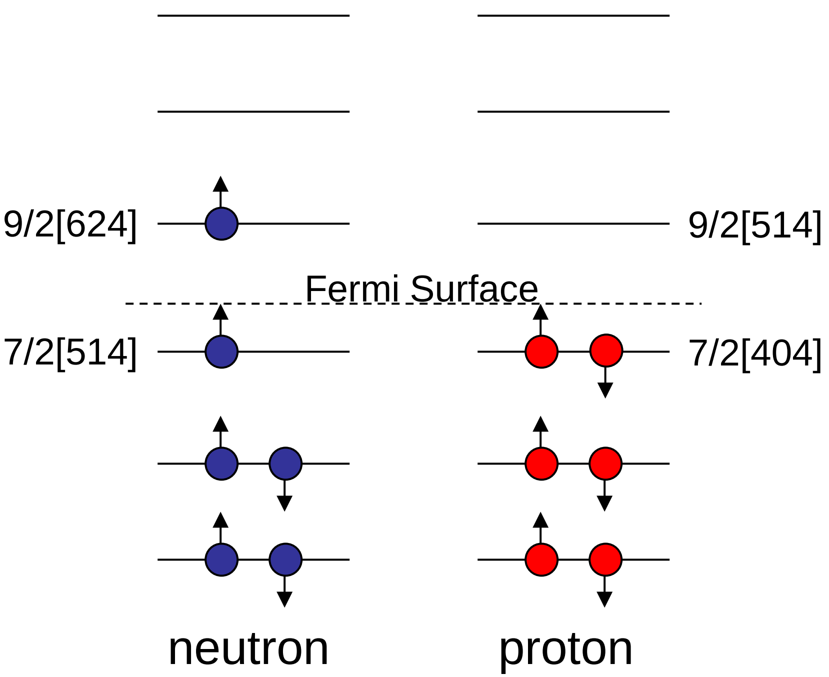

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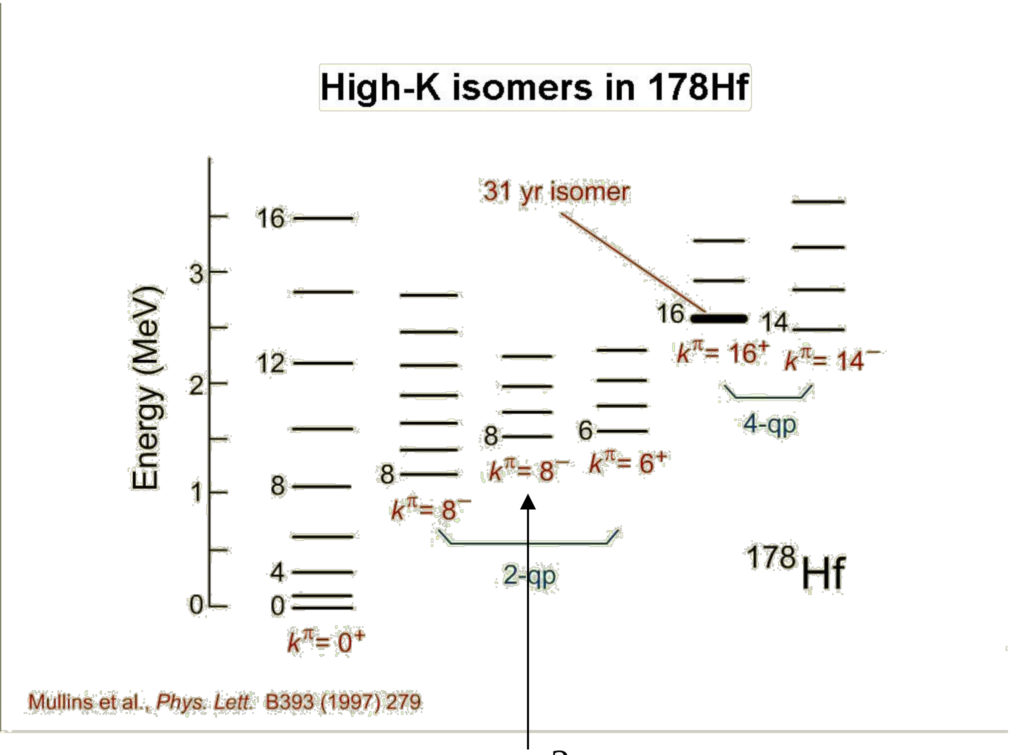
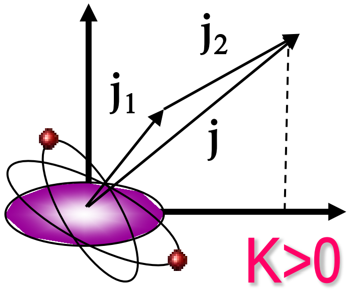
High-K isomers in 178Hf

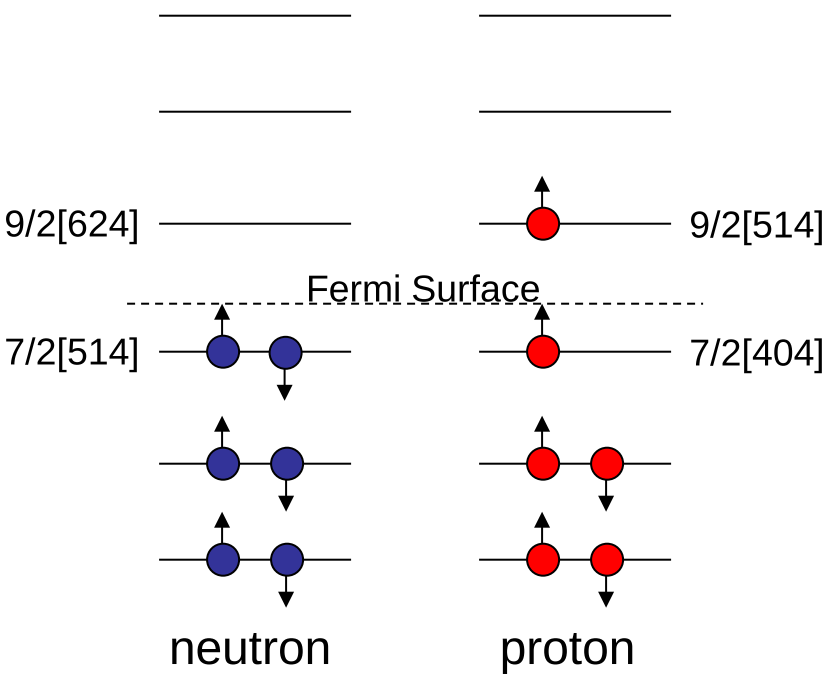


Mullins et al., *Phys. Lett.* B393 (1997) 279

$\pi^2_{8^-}$

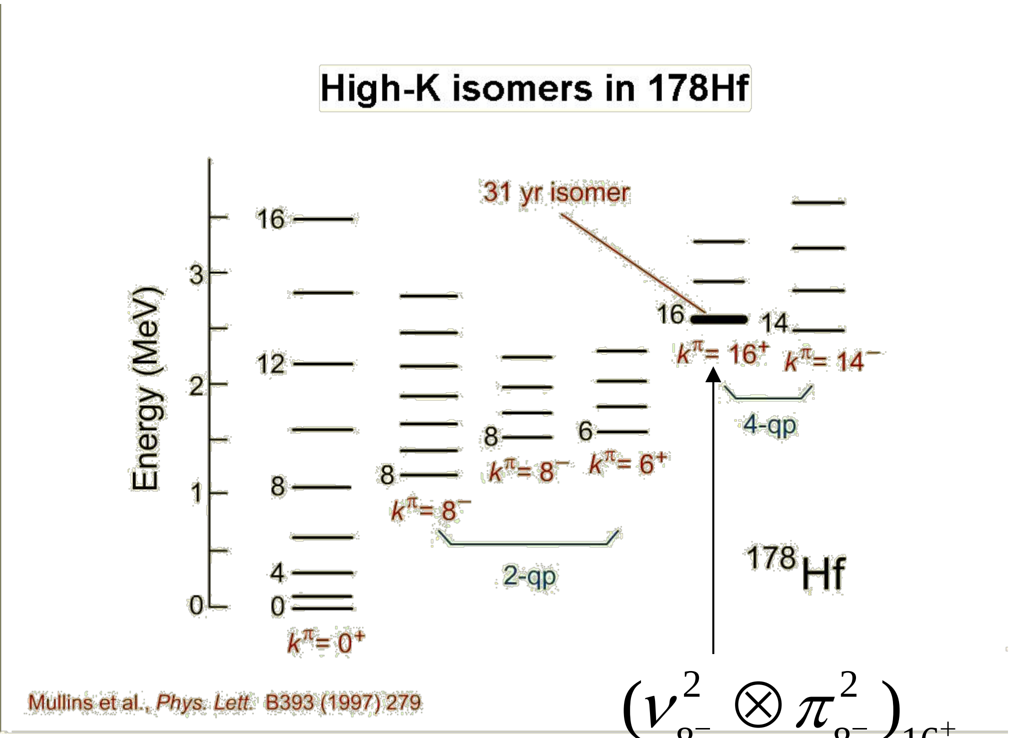


$\pi^2_{8^-}$



2. K Isomers

- A well-known example:



Mullins et al., *Phys. Lett.* B393 (1997) 279

$$(\nu^2_{8^-} \otimes \pi^2_{8^-})_{16^+}$$

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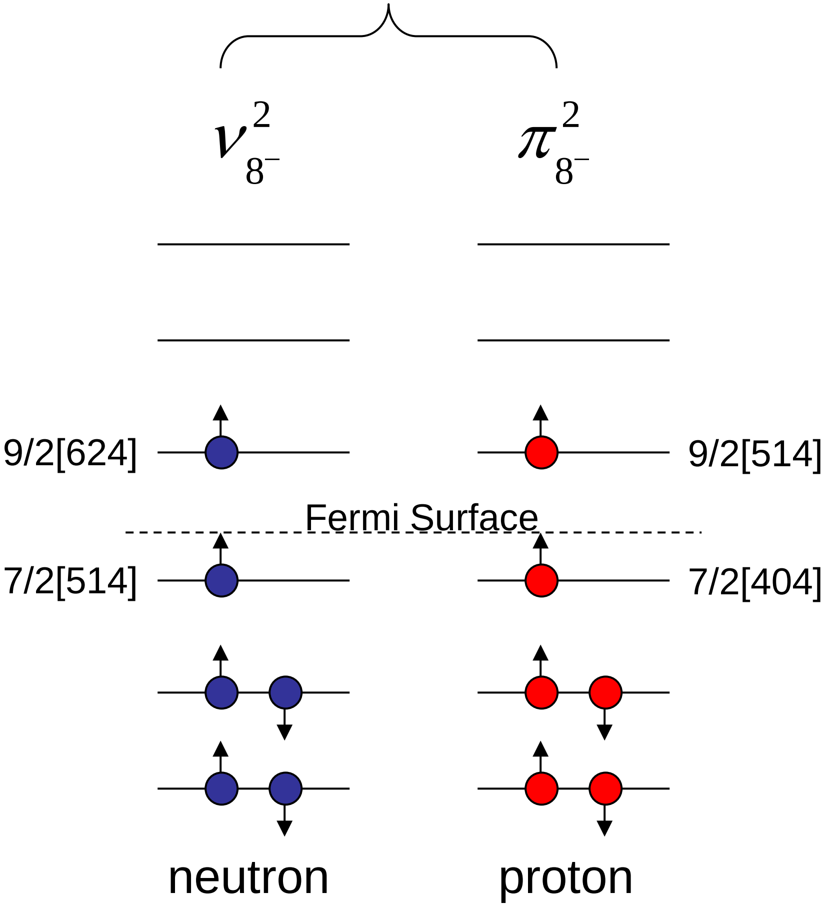


3. Spin Isomers

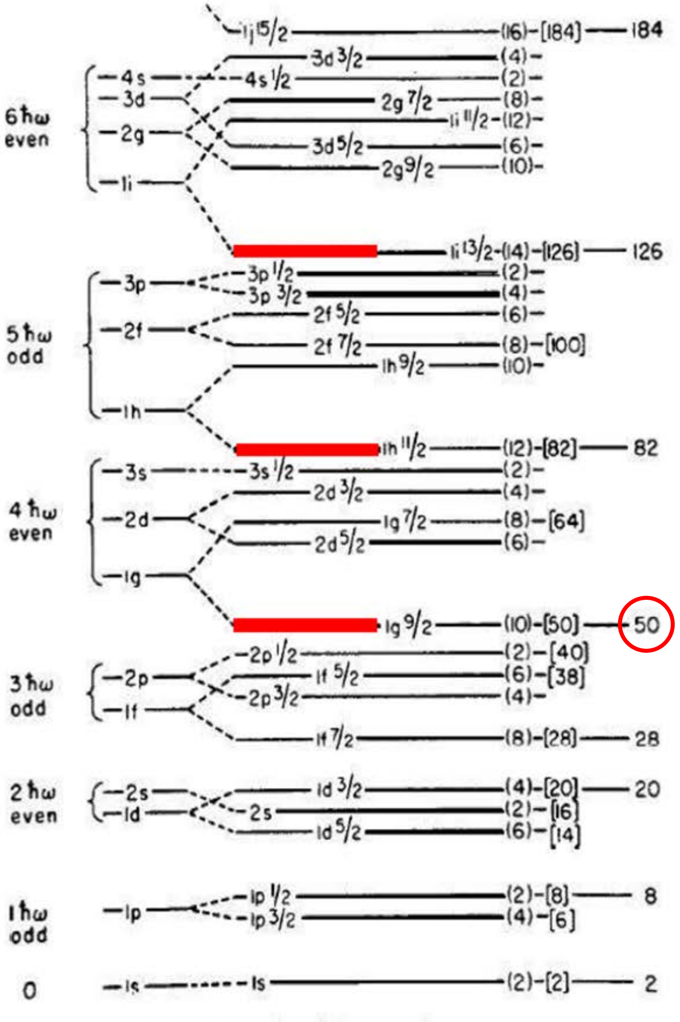
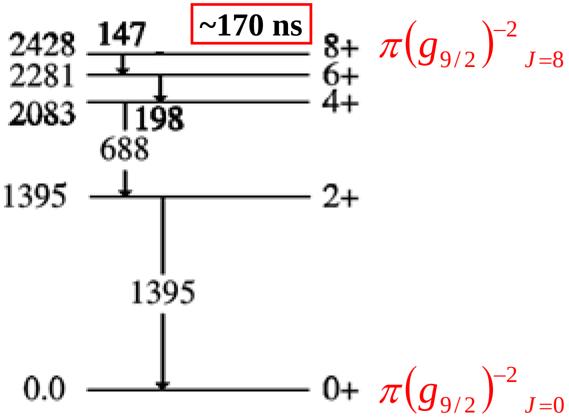


Fig. 7. Realistic level diagram for protons.

$^{98}_{48}\mathrm{Cd}_{50}$



A. Blazhev et al., Phys.Rev.C69 (2004) 064304

3. Spin Isomers

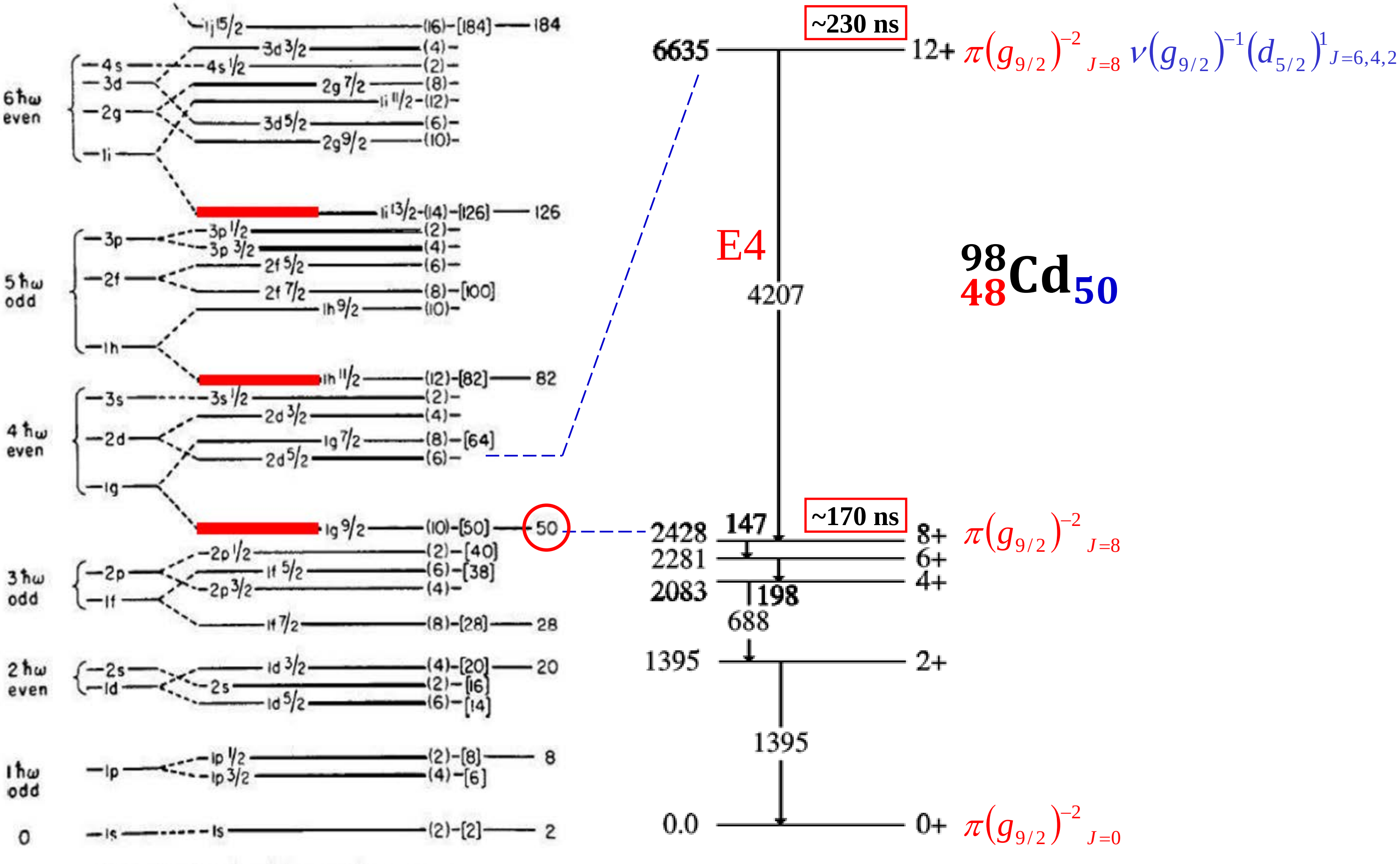
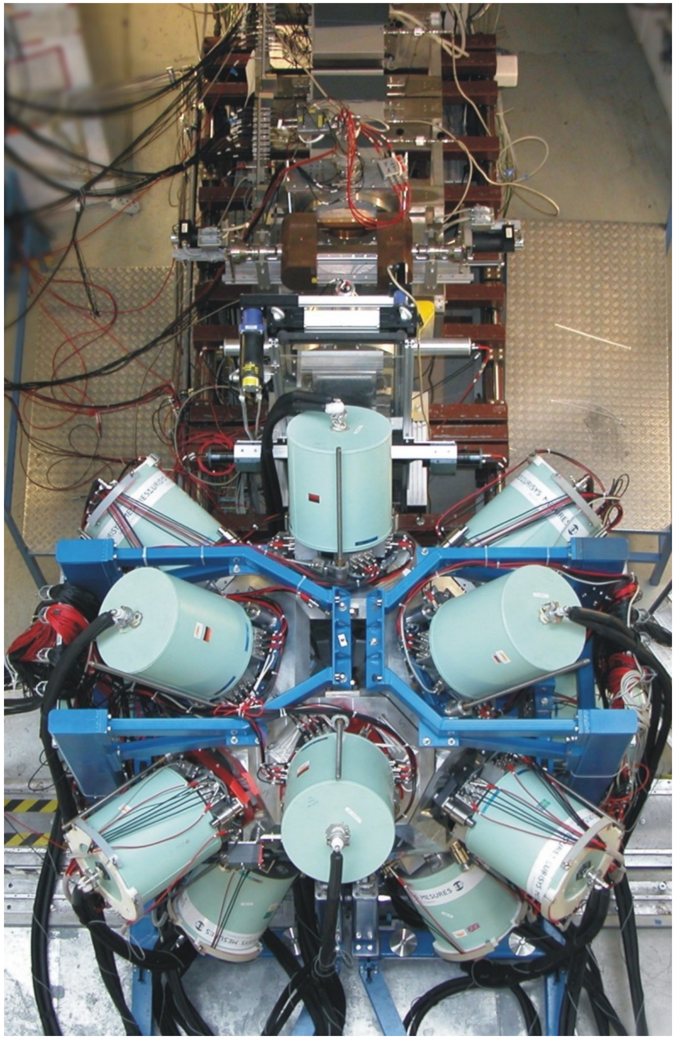
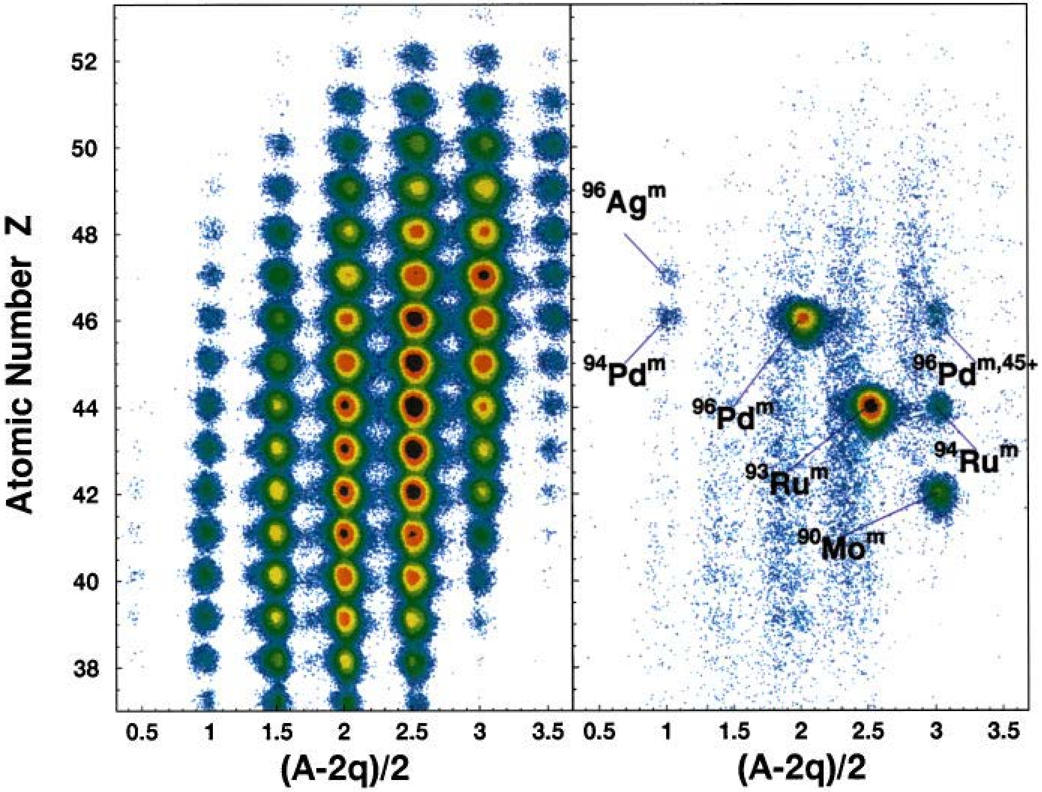


Fig. 7. Realistic level diagram for protons.

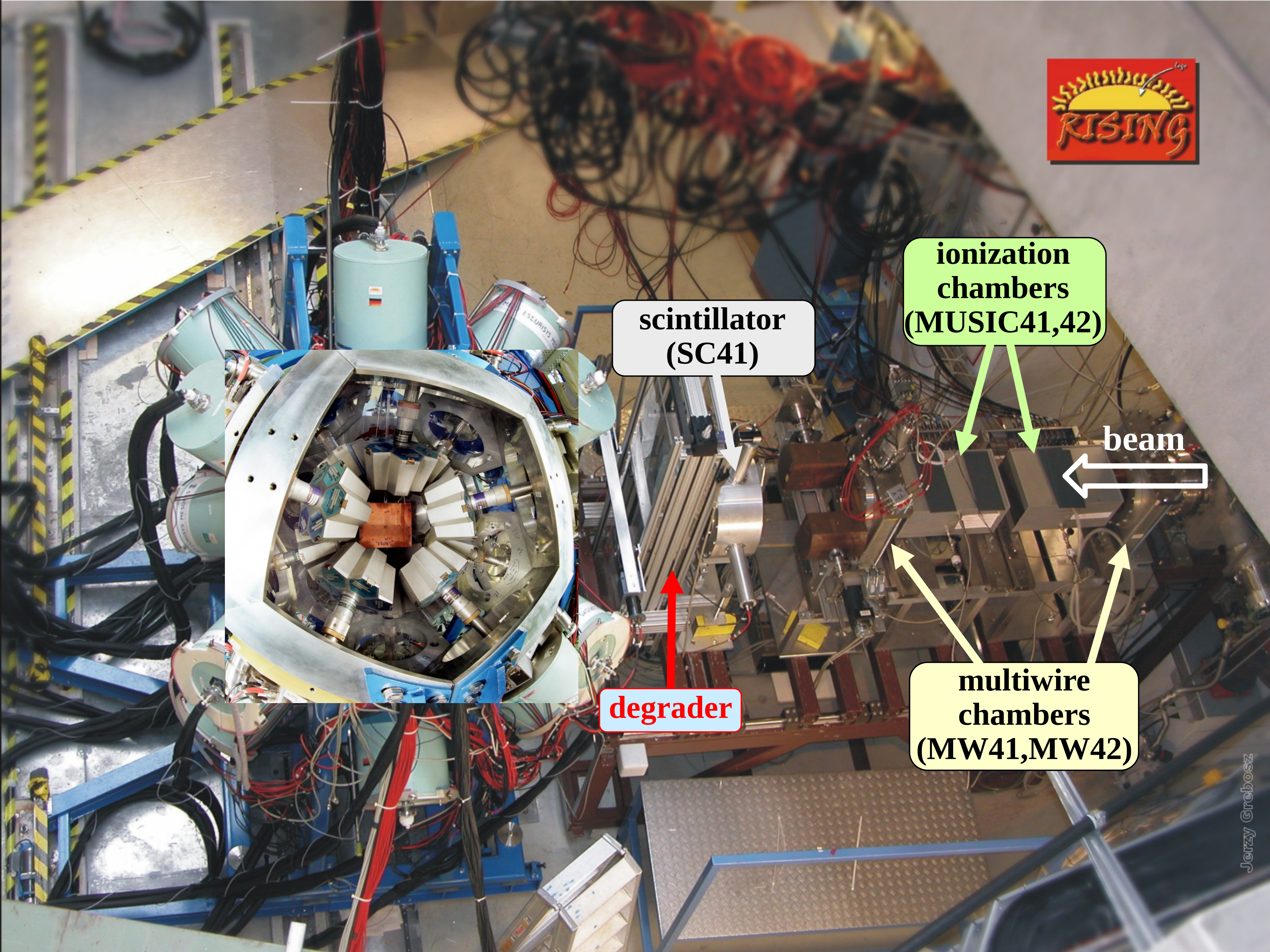
A. Blazhev et al., Phys.Rev.C69 (2004) 064304

Experimental set-up for isomer decay





R. Grzywacz et al., Phys. Rev C55 ,1126 (1[illegible]97)



scintillator (SC41)

ionization chambers (MUSIC41,42)

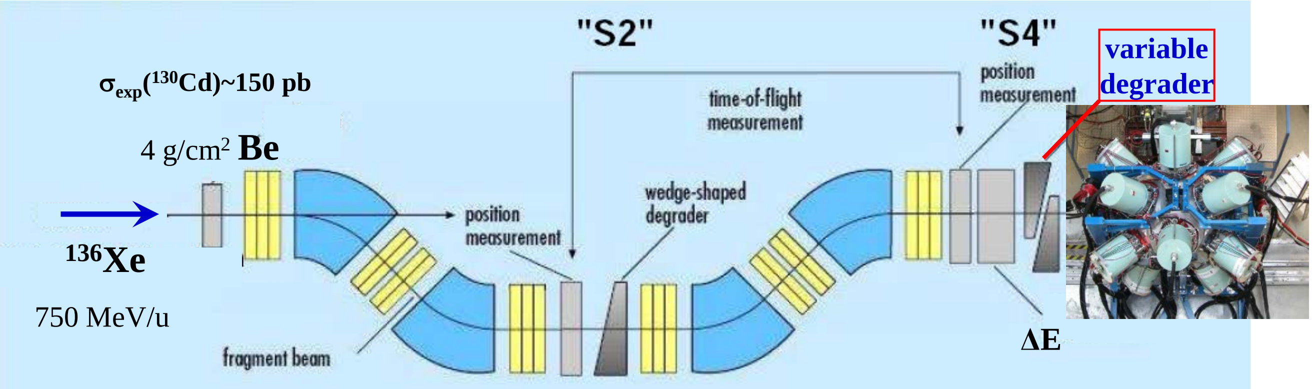
beam

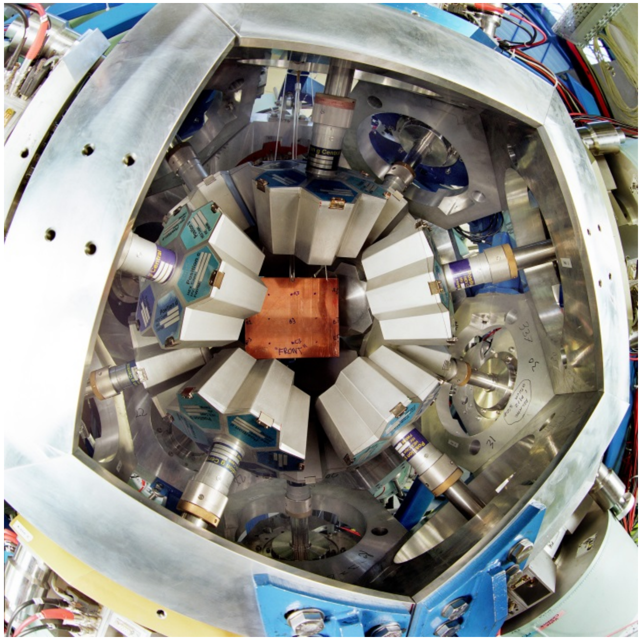
degrader

multiwire chambers (MW41,MW42)

Jerzy Grebosz

Experimental set-up with passive target

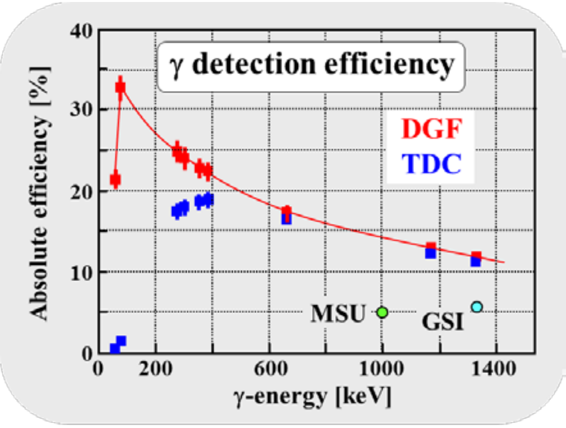




implantation in Cu-plate

15 Cluster detectors with 105 Ge crystals

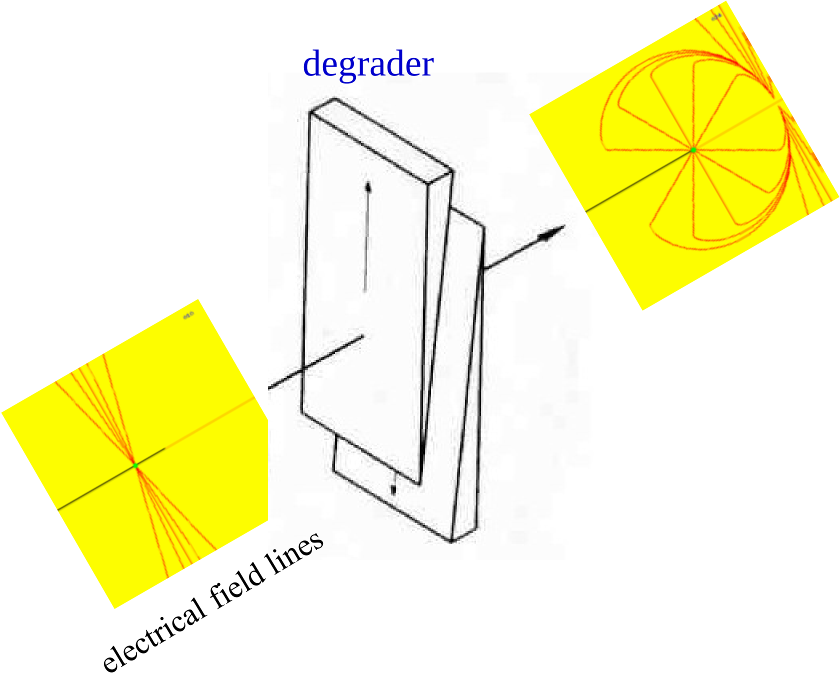
ε_γ = 11% at 1.3 MeV, 20% at 550 keV, 35% at 100 keV

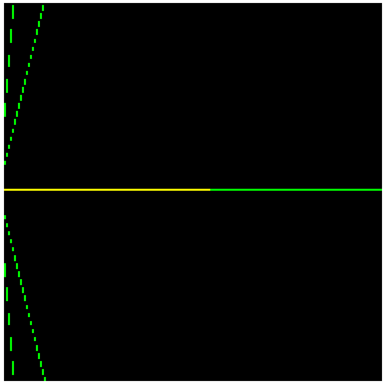


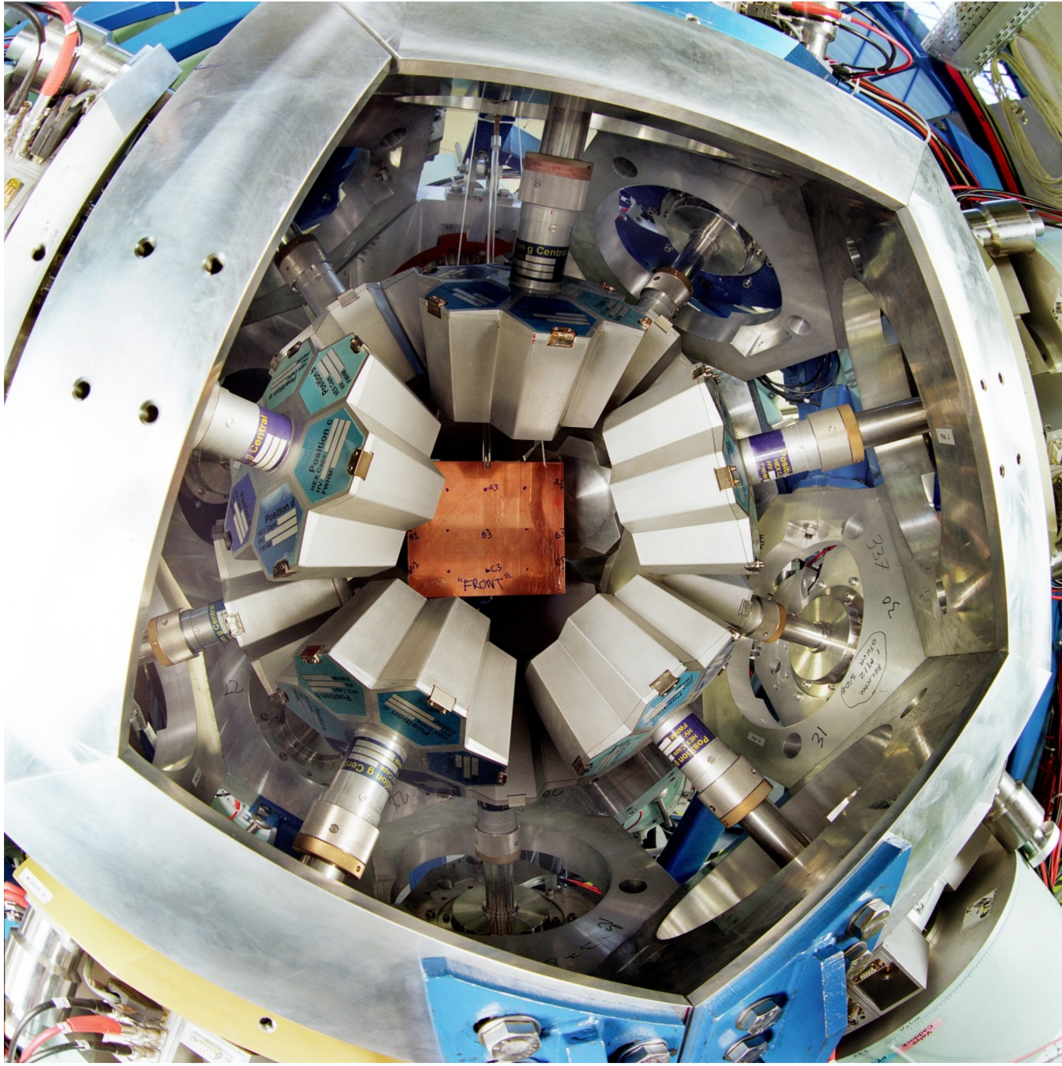
- very high γ-ray efficiency
- high granularity (prompt flash problem)

S. Pietri et al., NIM B261 (2007), 1079

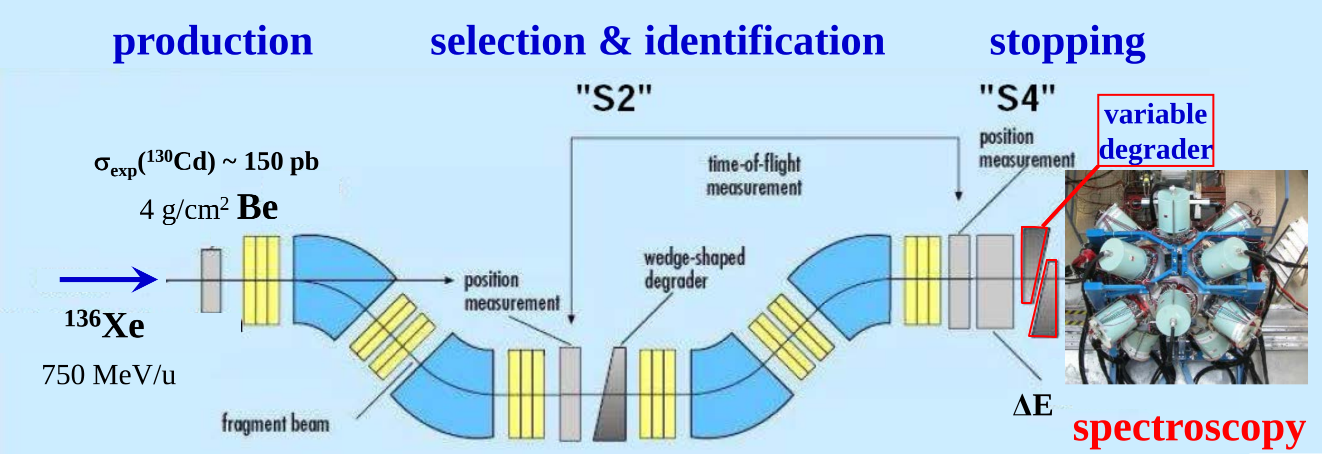
Limitations to Isomer Spectroscopy







Identification of $^{130}_{48}\mathrm{Cd}_{82}$



production **selection & identification** **stopping**

$\sigma_{exp}(^{130}\mathrm{Cd}) \sim 150$ pb

4 g/cm^2 **Be**

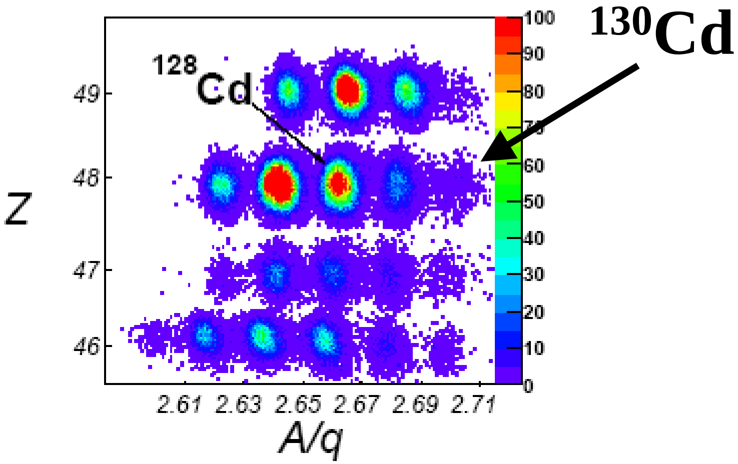
^{136}**Xe**

750 MeV/u

variable degrader

ΔE

spectroscopy

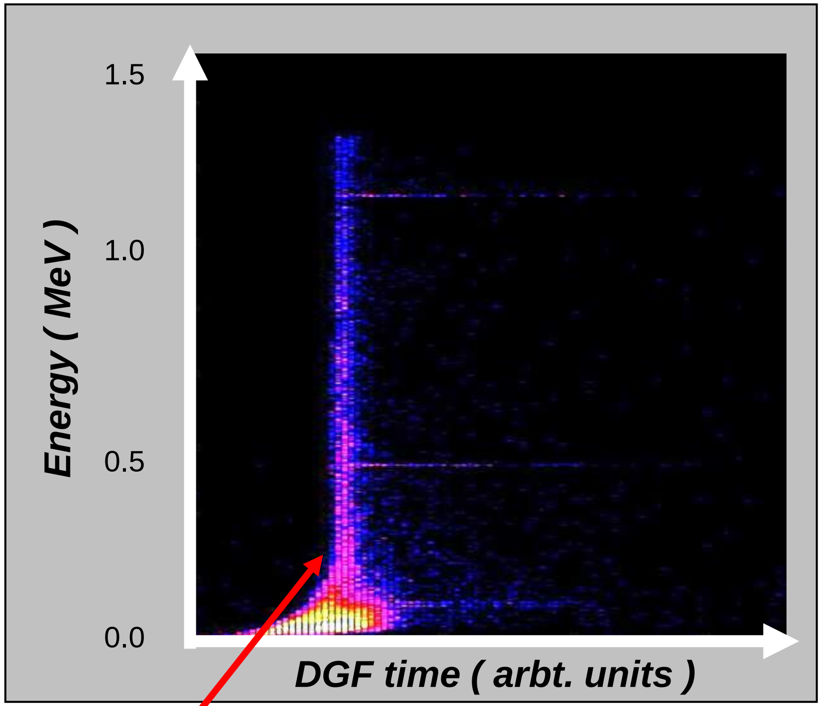


^{130}**Cd**

⇒ **4000 identified ^{130}Cd ions in fragmentation**

Limitations to Isomer Spectroscopy

^{130}Cd: DGF-timing



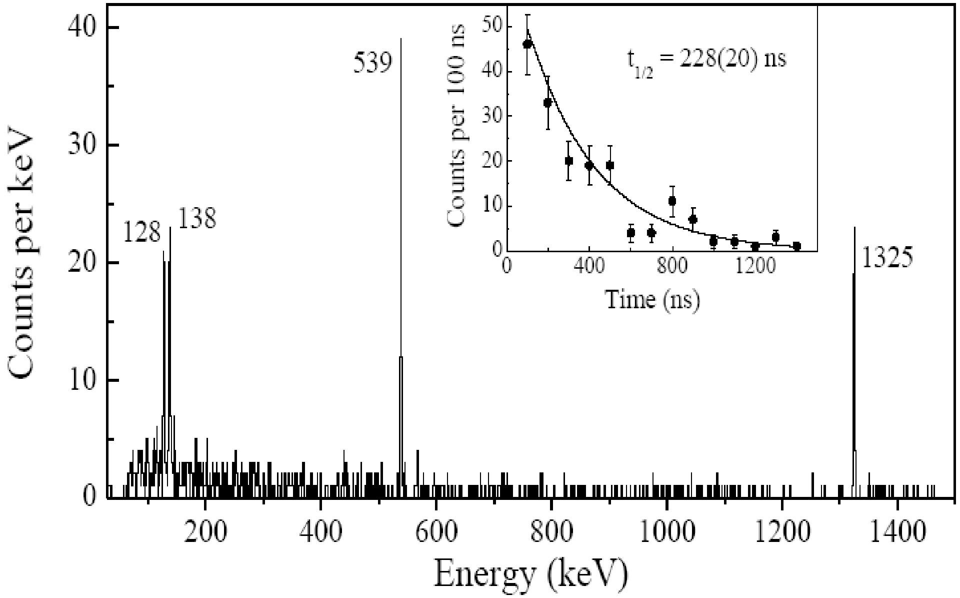
Prompt γ-flash

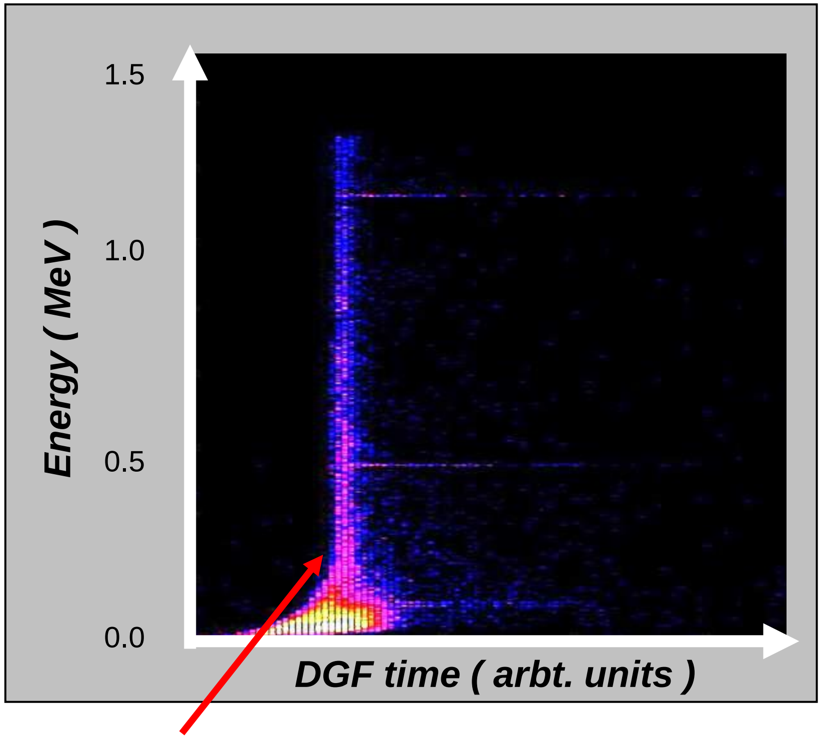
Decay time range: 20 ns ... 20 µs

A. Jungclaus et al., Phys. Rev. Lett 99, 132501 (2007)

Decay Spectroscopy Probes Shell Closures

^{130}Cd: DGF-timing





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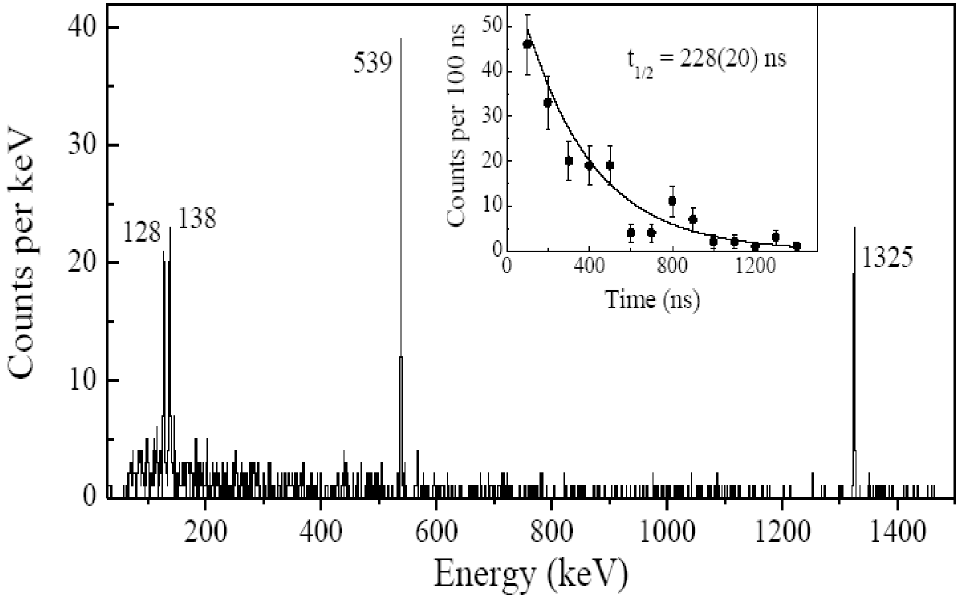
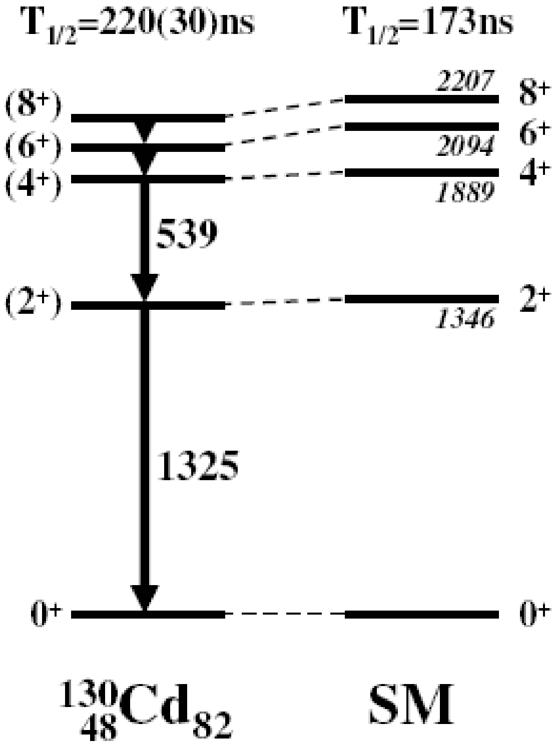
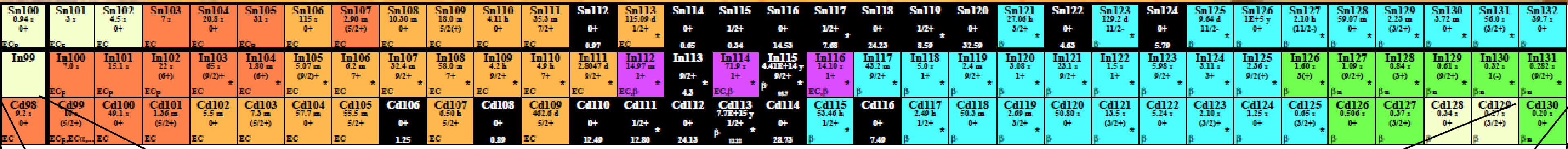




No Shell quenching observed

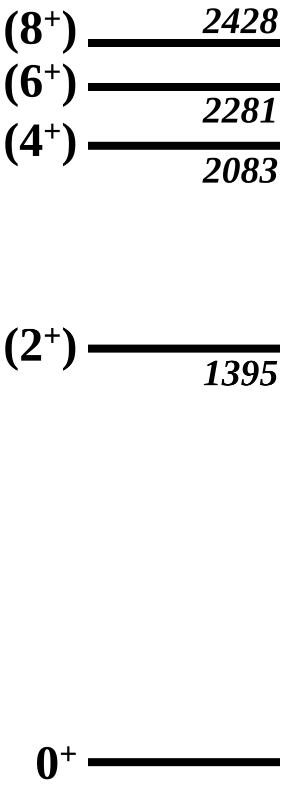
A. Jungclaus et al., Phys. Rev. Lett 99, 132501 (2007)

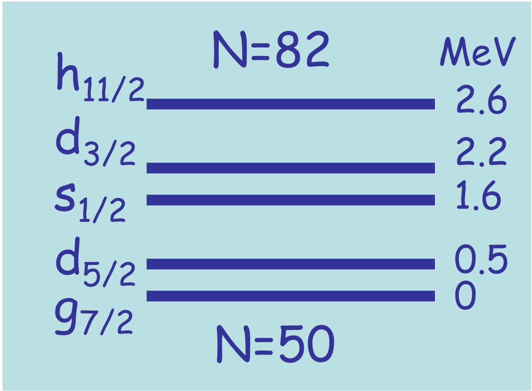
$8^+(g_{9/2})^{-2}$ Seniority Isomers in ^{98}Cd and ^{130}Cd



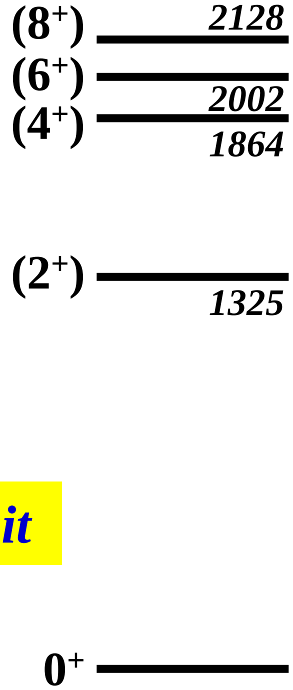
Cd98
9.2 s
0+
EC

N=50
Z=48





participating neutron-orbitals



Cd130
0.20 s
0+
β-n

N=82
Z=48

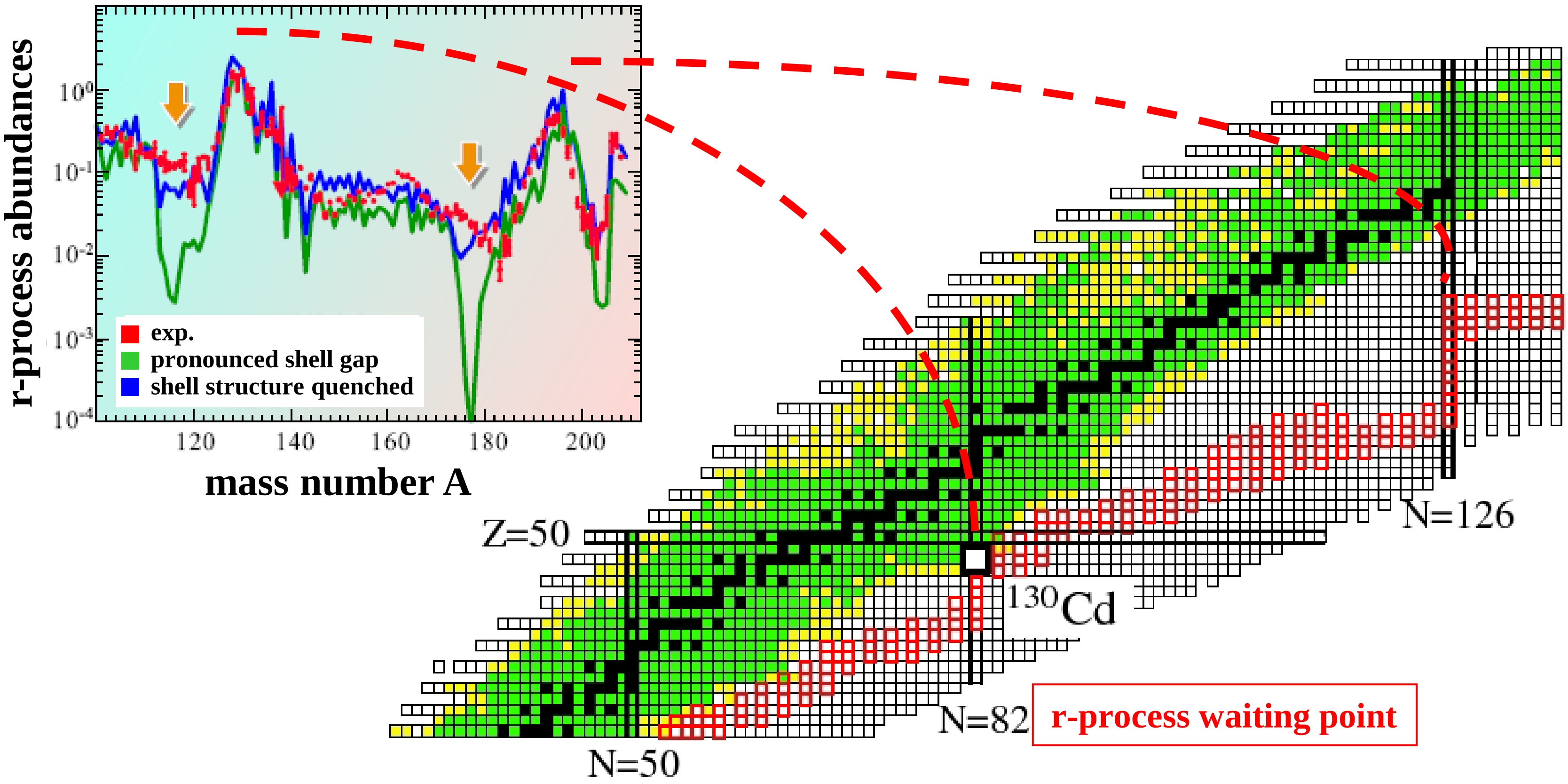
two proton holes in the $g_{9/2}$ orbit

No dramatic shell quenching!

A. Blazhev et al., Phys. Rev. C69 (2004) 064304

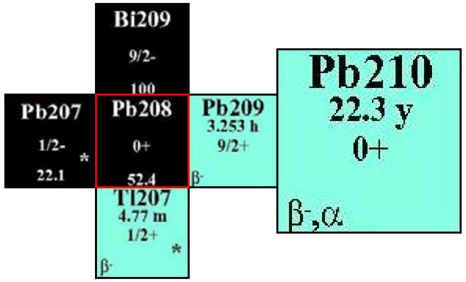
A. Jungclaus et al., Phys. Rev. Lett. 99 (2007), 132501

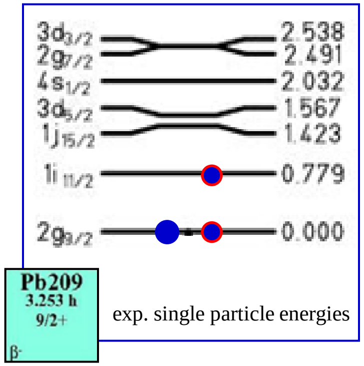
The astrophysical r-process 'path'



Assumption of a N=82 shell quenching leads to a considerable improvement in the global abundance fit in r-process calculations !

Level Scheme of ^{210}Pb





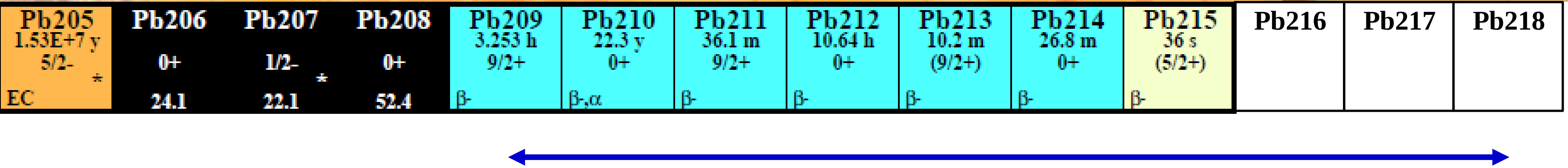
exp. single particle energies

airing energy)

esidual interaction !

M. Rejmund Z.Phys. A359 (1997), 243

Level Schemes in Neutron-Rich Pb Isotopes



Pb205	Pb206	Pb207	Pb208	Pb209	Pb210	Pb211	Pb212	Pb213	Pb214	Pb215	Pb216	Pb217	Pb218
1.53E+7 y				3.253 h	22.3 y	36.1 m	10.64 h	10.2 m	26.8 m	36 s			
5/2- *	0+	1/2- *	0+	9/2+	0+	9/2+	0+	(9/2+)	0+	(5/2+)			
EC	24.1	22.1	52.4	β-	β-,α	β-	β-	β-	β-	β-			

$g_{9/2}$

^{210}Pb

$t_{1/2}$ = 0.201(17) μs

^{212}Pb

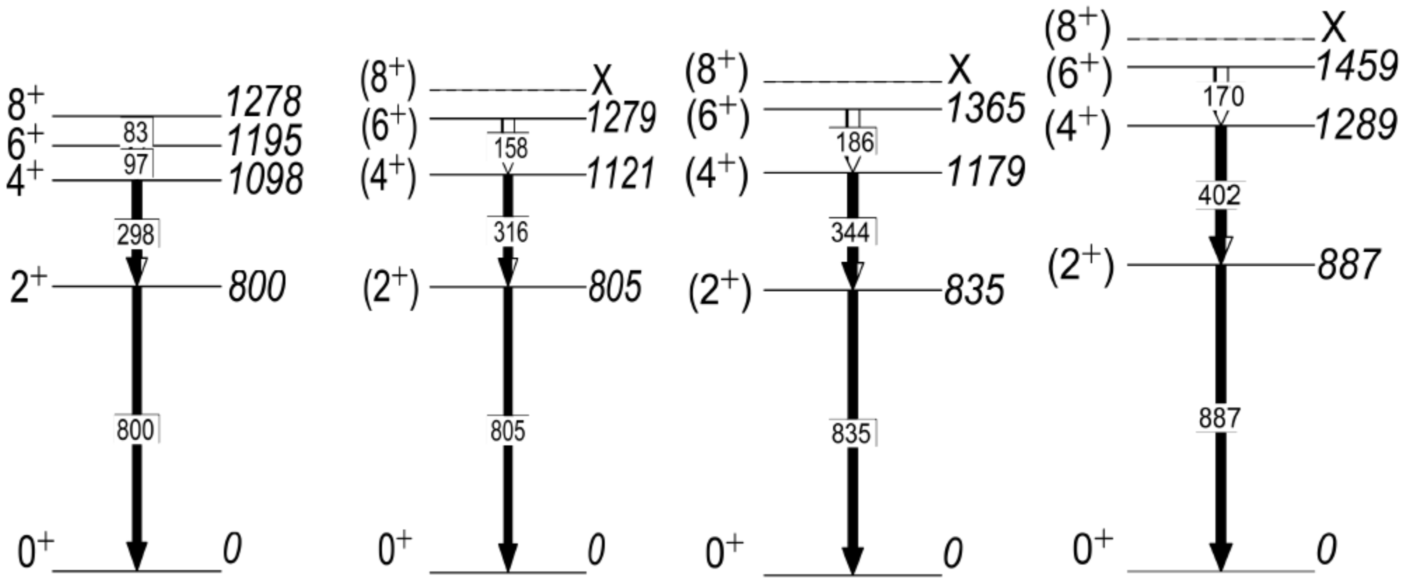
$t_{1/2}$ = 6.0(8) μs

^{214}Pb

$t_{1/2}$ = 6.2(3) μs

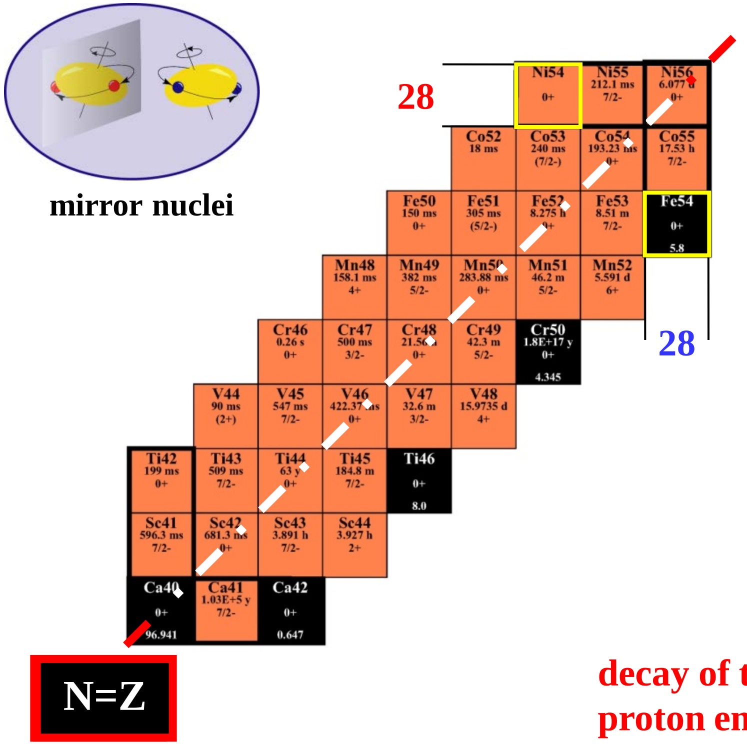
^{216}Pb

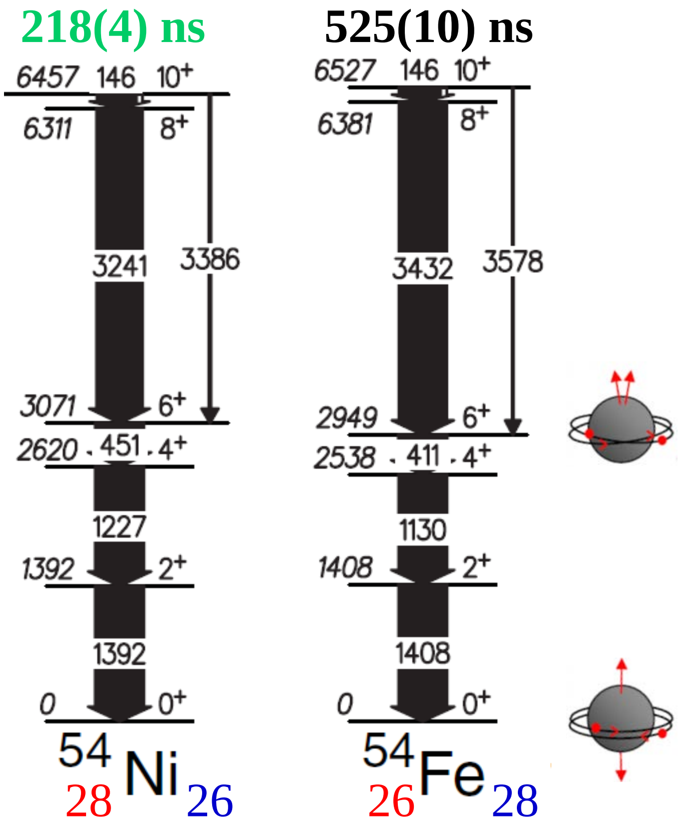
$t_{1/2}$ = 0.4(4) μs



T=1 Isospin Symmetry in pf-shell Nuclei

search for isospin breaking effects



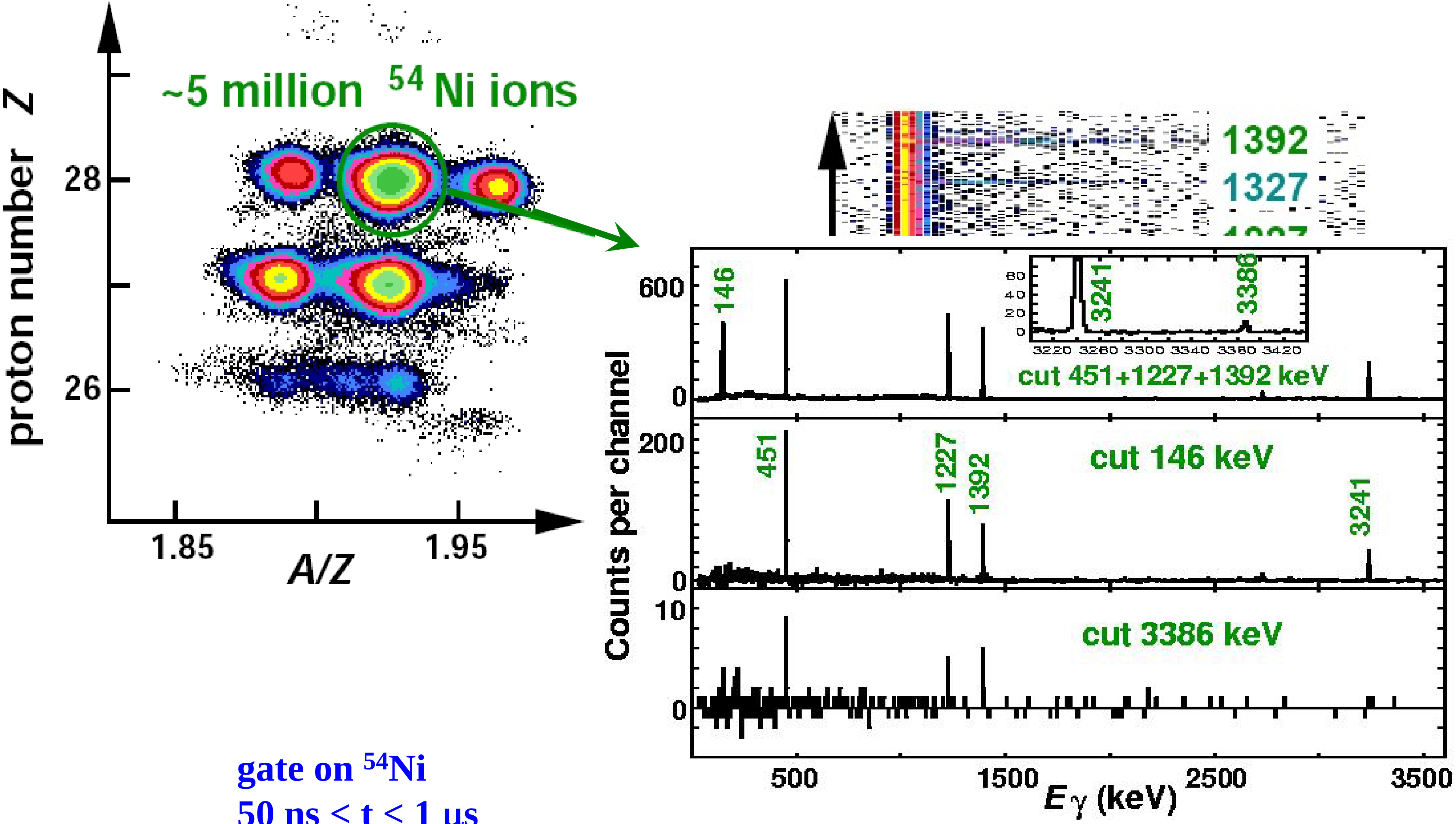


decay of the excited 10^+-state by proton emission and γ-radiation

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

^{54}Fe / ^{54}Ni: π / ν $(f_{7/2})^{-2}$

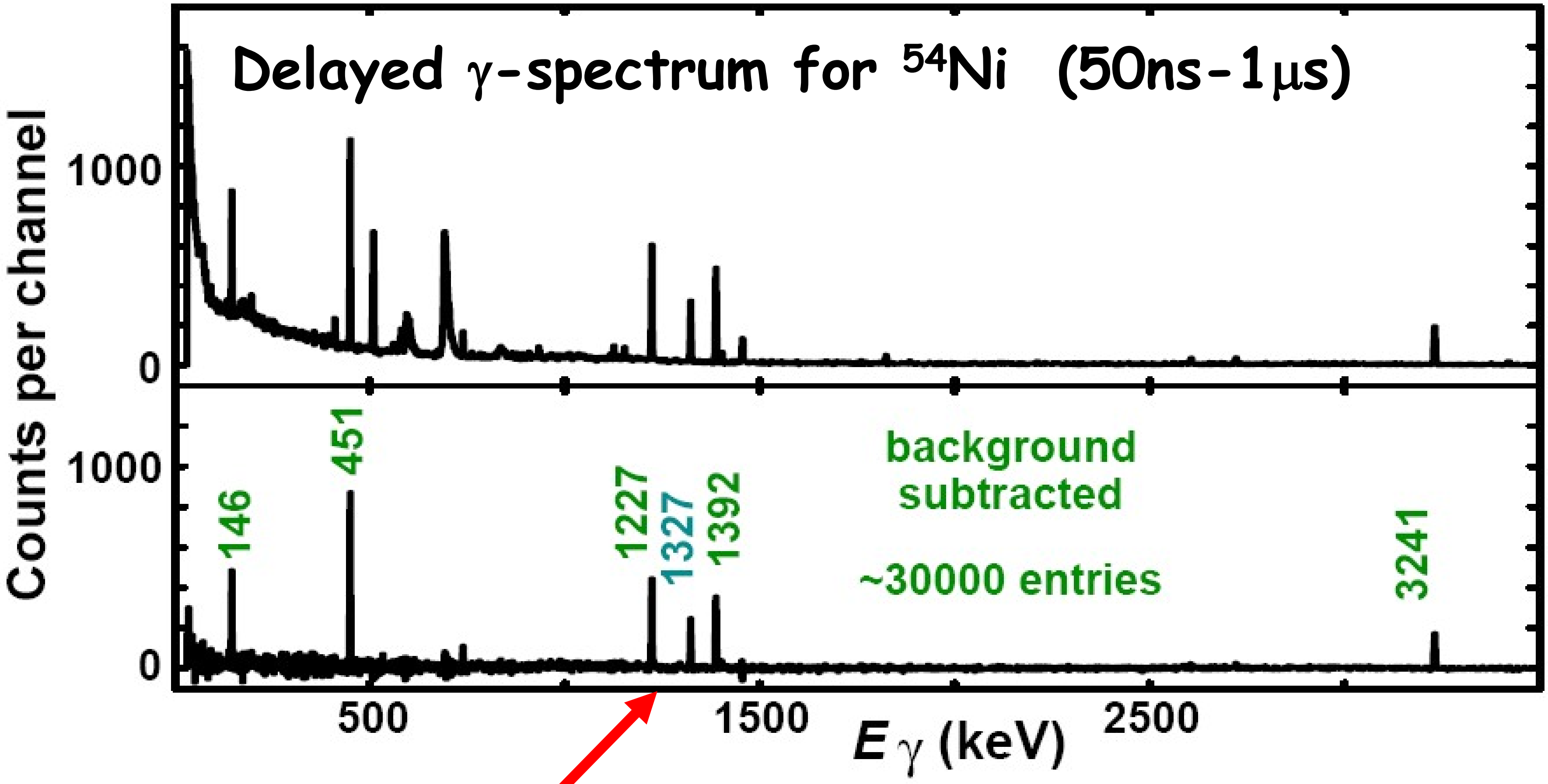
Identification of ^{54}Ni



gate on ^{54}Ni

50 ns < t < 1 μs

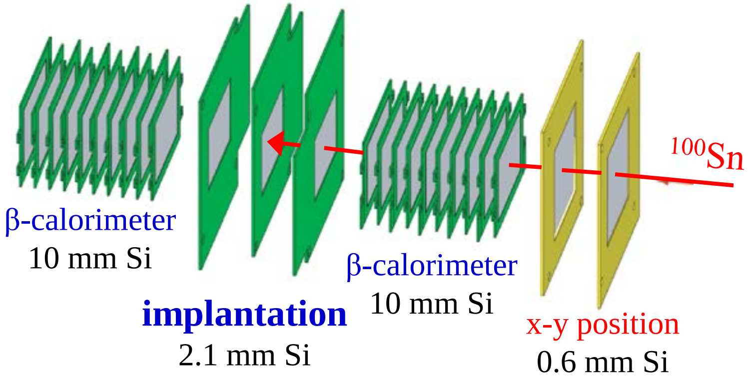
The big surprise ...

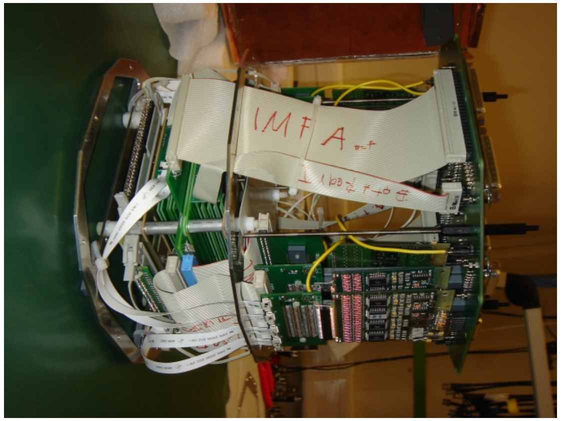


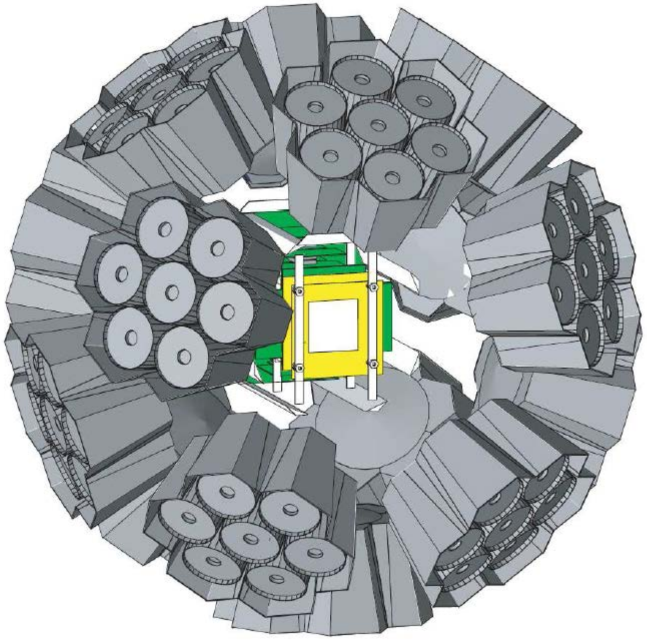
Where does the 1327 keV line come from ???

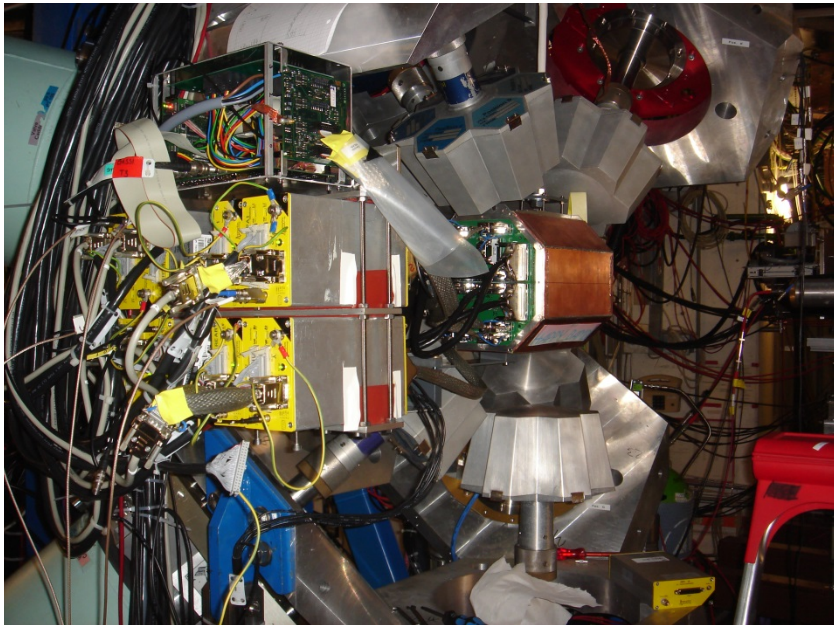
Active Target

Silicon IMplantation Detector and Beta Absorber

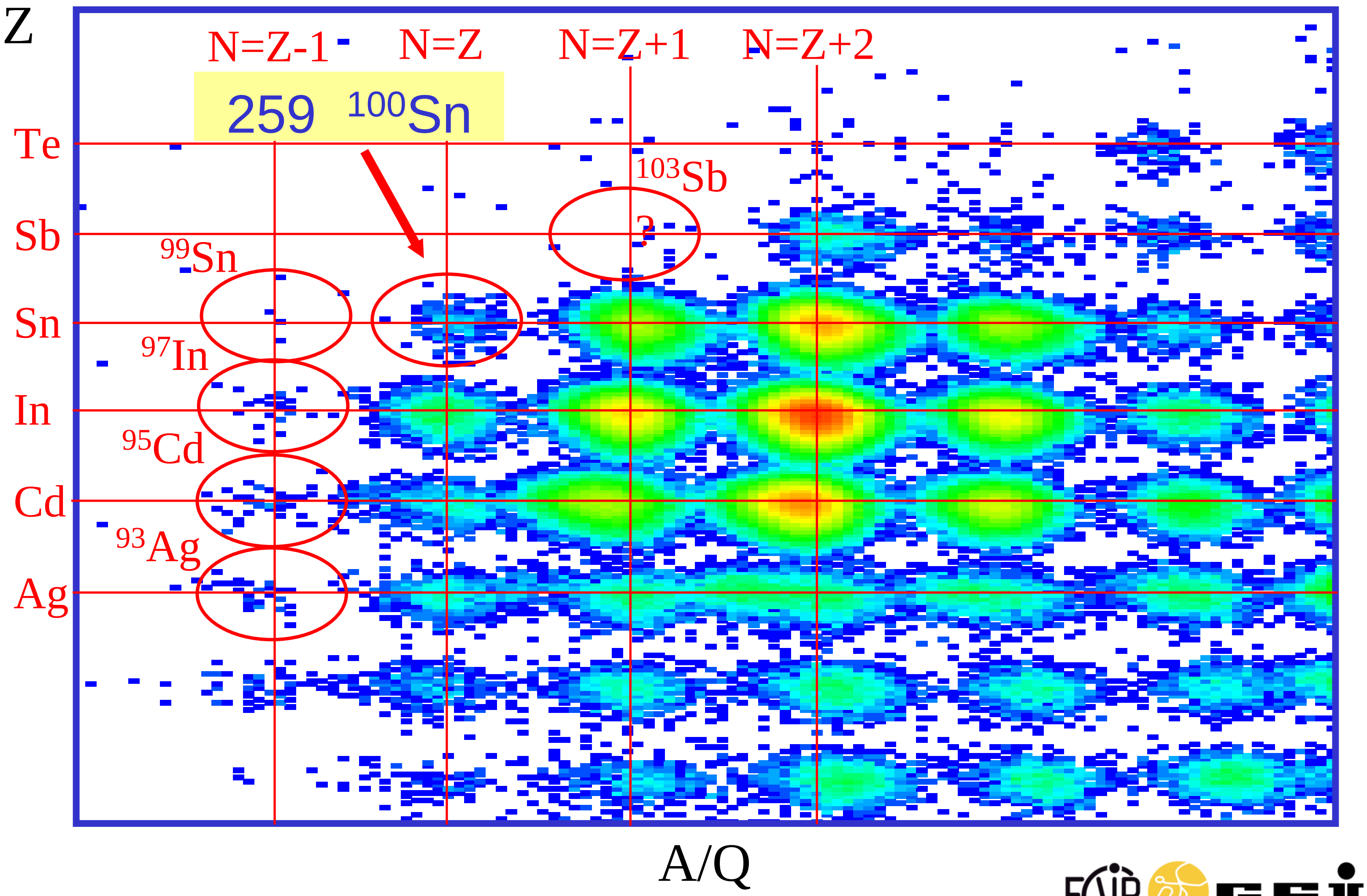






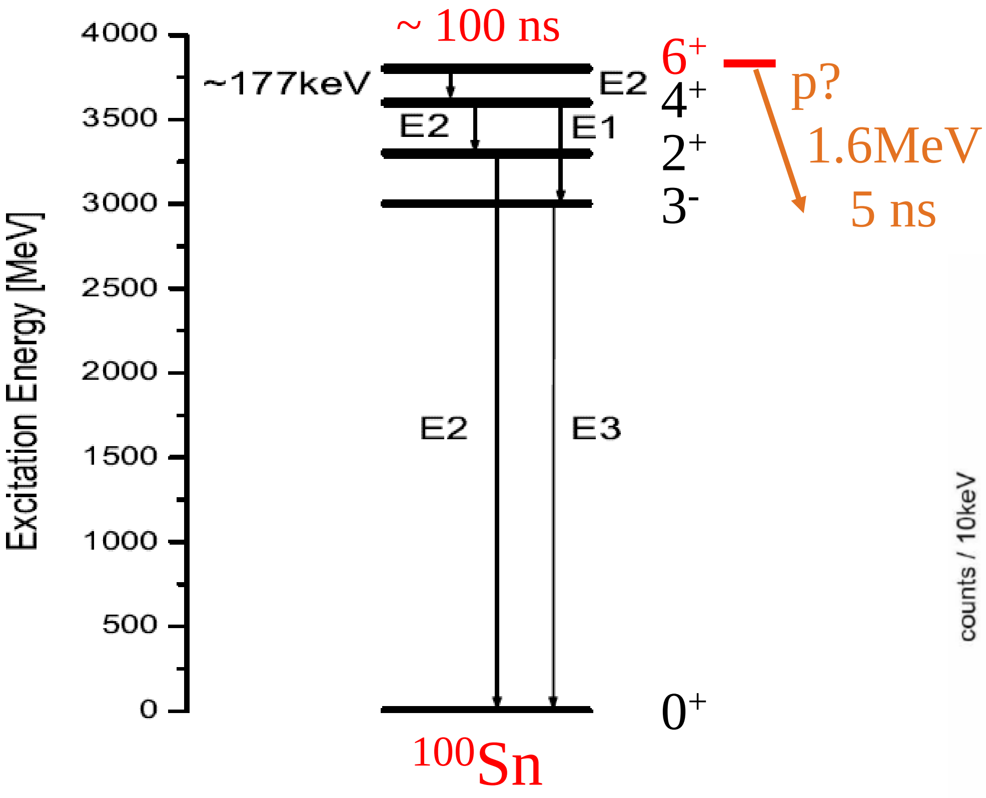


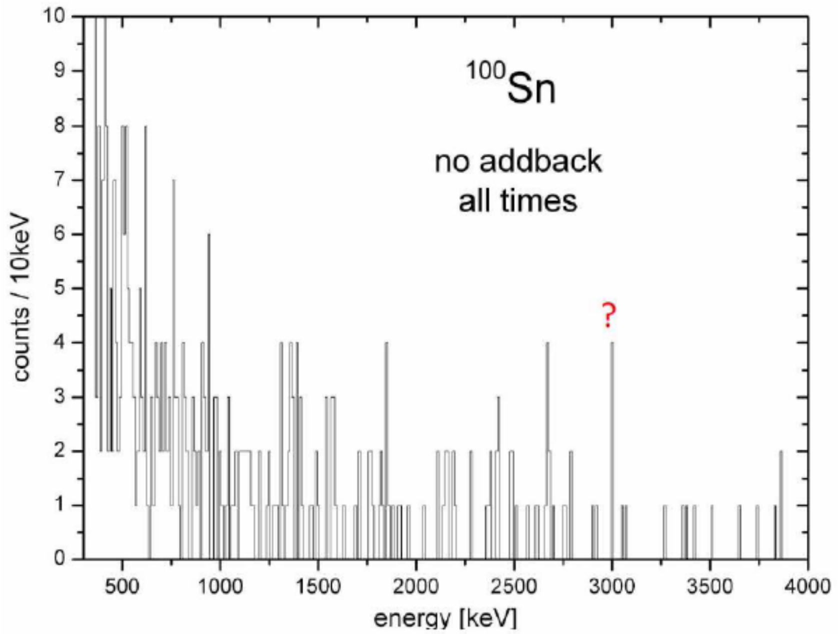
Spectroscopy of the doubly magic nucleus ^{100}Sn and its decay



Spectroscopy of the doubly magic nucleus ^{100}Sn and its decay

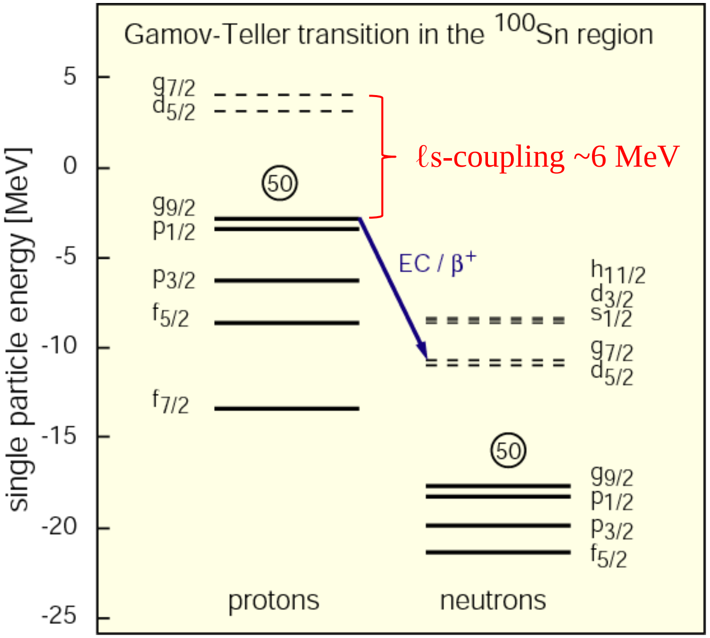
Theoretical predictions for the ^{100}Sn level schemes





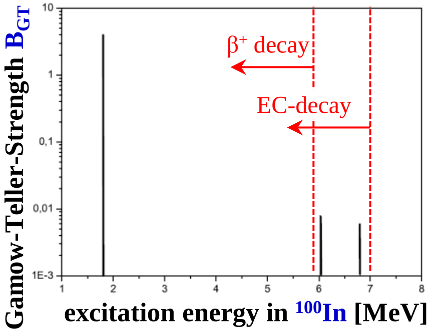
Gamov-Teller strength and Q_{EC} value in the β-decay of ^{100}Sn

Single particle energies for shell model orbitals in ^{100}Sn



β^+: $Q=M(Z+1)c^2-M(Z)c^2-2m_ec^2$

EC: $Q=M(Z+1)c^2-M(Z)c^2-BE(\text{K-electron})$



- ^{100}Sn is an ideal testing ground to investigate GT-strength:

pure GT spin-flip transition: $0^+ \Rightarrow (\pi g_{9/2}^{-1}\ \nu g_{7/2})\ 1^+$

- Almost the whole strength of the GT resonance is covered by the energy window of the β^+-decay

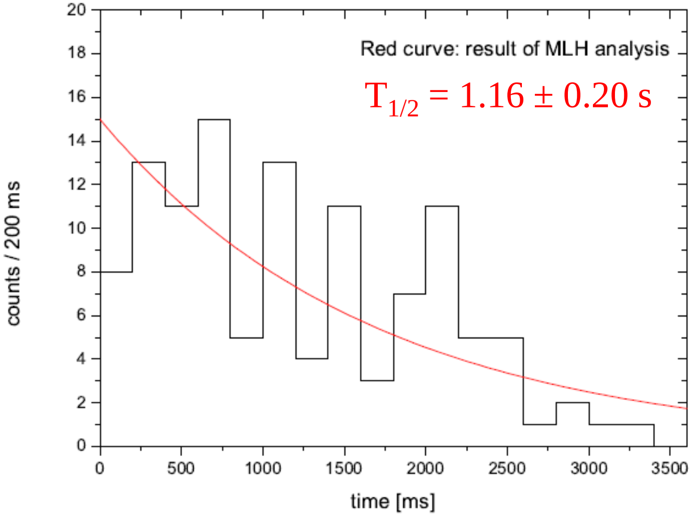
Theoretical calculation of the distribution of the GT-strength:

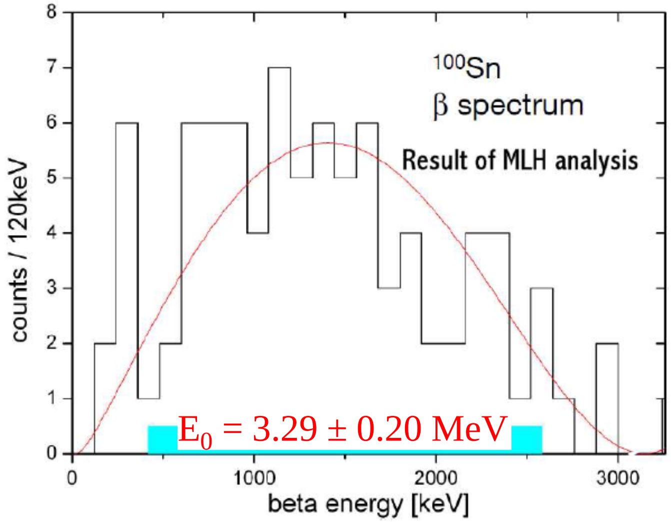
97% of the whole strength is concentrated in a single state, which is accessible in the β^+-decay

$$B_{GT}(ESM) = \frac{4\ell}{2\ell+1}\cdot\left(1-\frac{N_{\nu g_{7/2}}}{8}\right)\cdot N_{\pi g_{9/2}} = 17.78$$

with $\ell=4$ $N_{\nu g7/2}=0$ $N_{\pi g9/2}=10$

Gamow-Teller strength and Q_{EC} value in the β-decay of ^{100}Sn





The **Gamow-Teller Strength B_{GT}** (only one final state populated) can be calculated from the half life $T_{1/2}$ and the Fermi Phasespace Integral $f(Z,E_0)$:

$$f(Z,E_0)\cdot T_{1/2} = \frac{2\pi^3\hbar^7}{m_e{}^5c^4G_F{}^2}\cdot\frac{ln2}{g_v{}^2\cdot|M_F|^2+g_A{}^2\cdot|M_{GT}|^2}$$

$G_F/(\hbar c)^3 = 1.16637(1)\cdot 10^{-5}\ \mathrm{GeV}^{-2}$, $g_A/g_V = 1.2695 \pm 0.0029$

$$f(Z,E_0)\cdot T_{1/2} = \frac{6142.8s}{B_F + (g_A/g_V)^2\cdot B_{GT}}$$

In the case of a pure Gamow-Teller decay the transition strength can be calculated in the following way:

$$B_{GT} = \frac{3811.5s}{f(Z,E_0)\cdot T_{1/2}} \quad = 9.1^{+4.8}_{-2.3}$$

Fermi-integral with LOGFT program NNDC

Gamov-Teller strength and Q_{EC} value in the β-decay of ^{100}Sn

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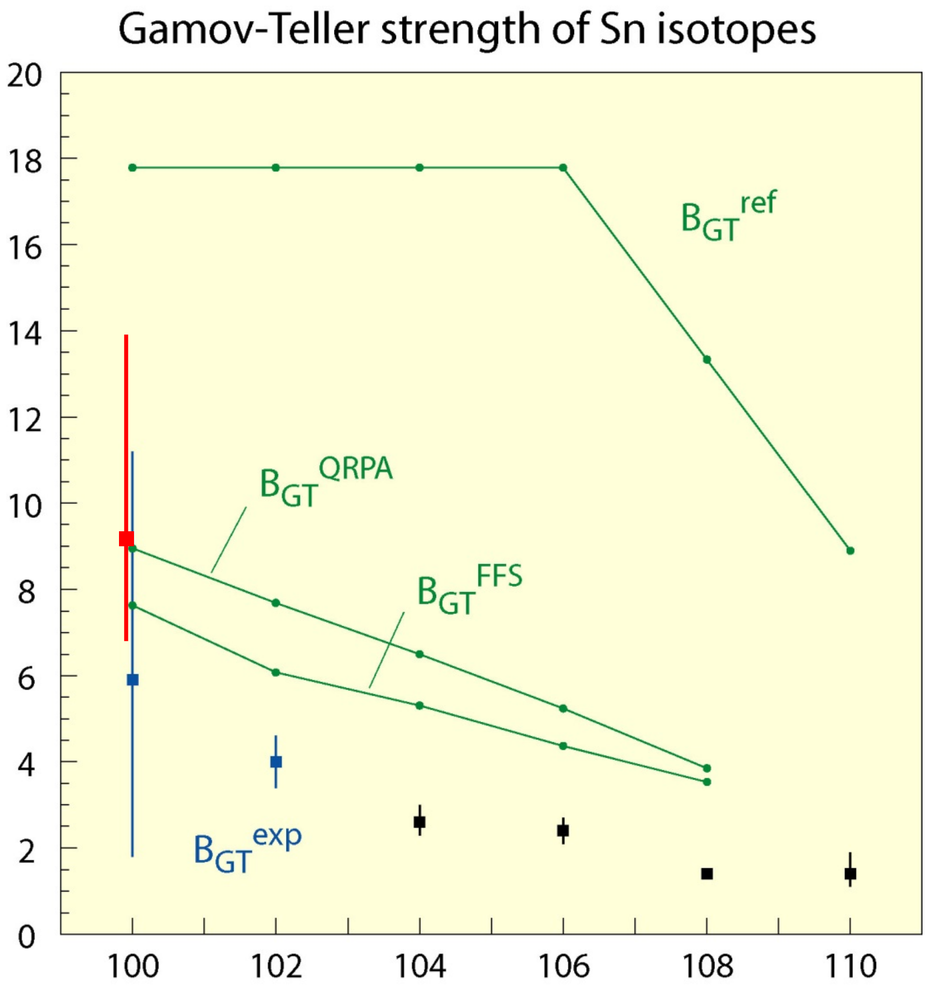
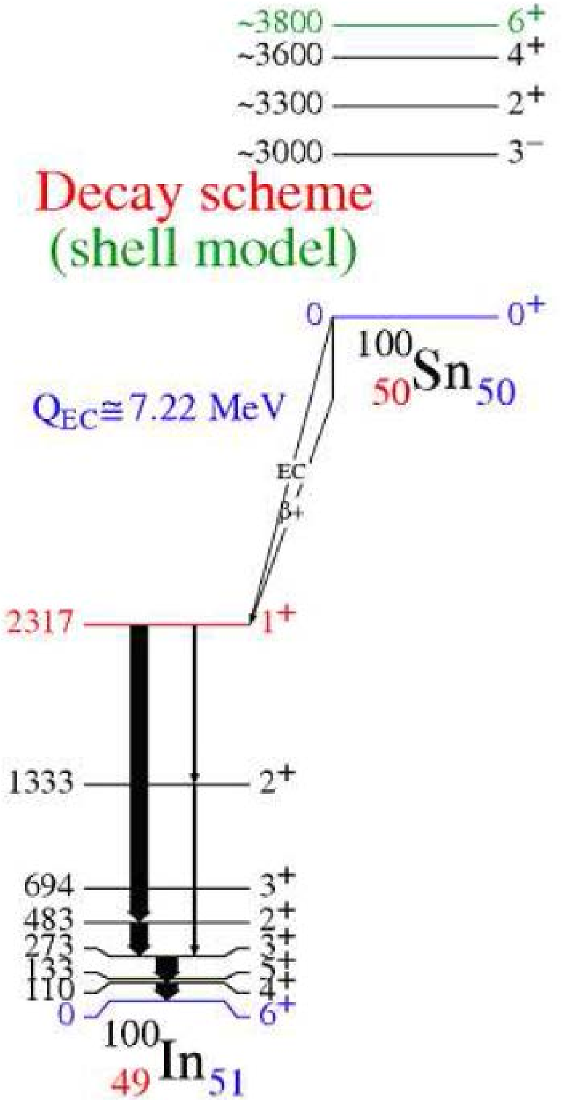
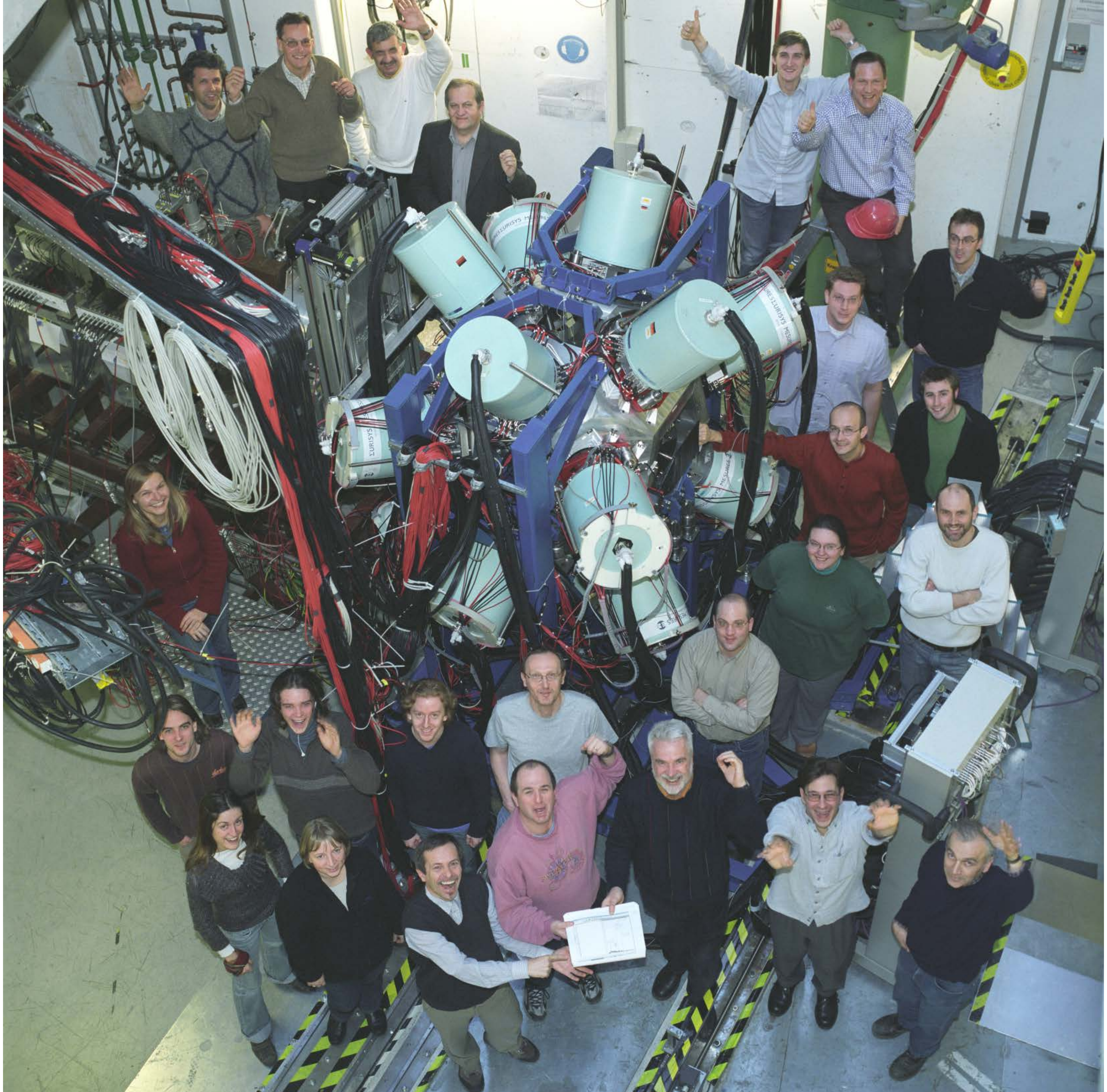
The main condition for the existence of isolated **Super Gamow-Teller transition** is that the spin-orbit gap between the ℓ+1/2 and ℓ-1/2 orbits (in ^{100}Sn ℓ=4 orbitals $\pi g_{9/2}$,$\upsilon g_{7/2}$) be sufficiently small compared to the shell gap for protons and neutrons (6 MeV), so that the 1-particle-1-hole states are isolated below the 2-particle-2-hole states.



Gamov-Teller strength and Q_{EC} value in the β-decay of ^{100}Sn

$Q_{EC} = E_\beta + E(1^+) + 2m_ec^2$

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