Outline: Nuclear isomers

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Kernphysik Skript

1. nuclear isomers (shape-, spin-, K-traps)
2. In-flight separation of excited **R**adioactive **I**on **B**eams
3. nuclear shell closure in ^{98}Cd and ^{130}Cd
4. T=1 isospin symmetry – mirror nuclei

What is a nuclear isomer?

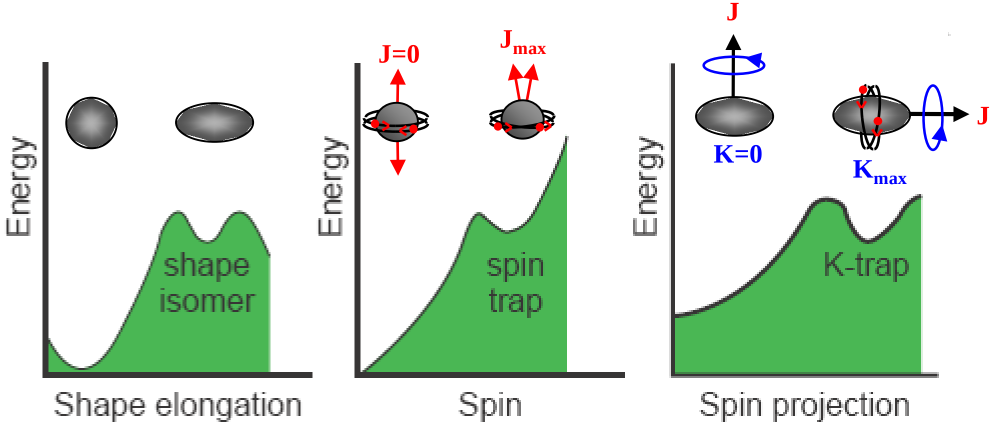
Nuclear Isomer – a *long-lived excited nuclear state* ($T_{1/2} > 1$ *ns*)

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

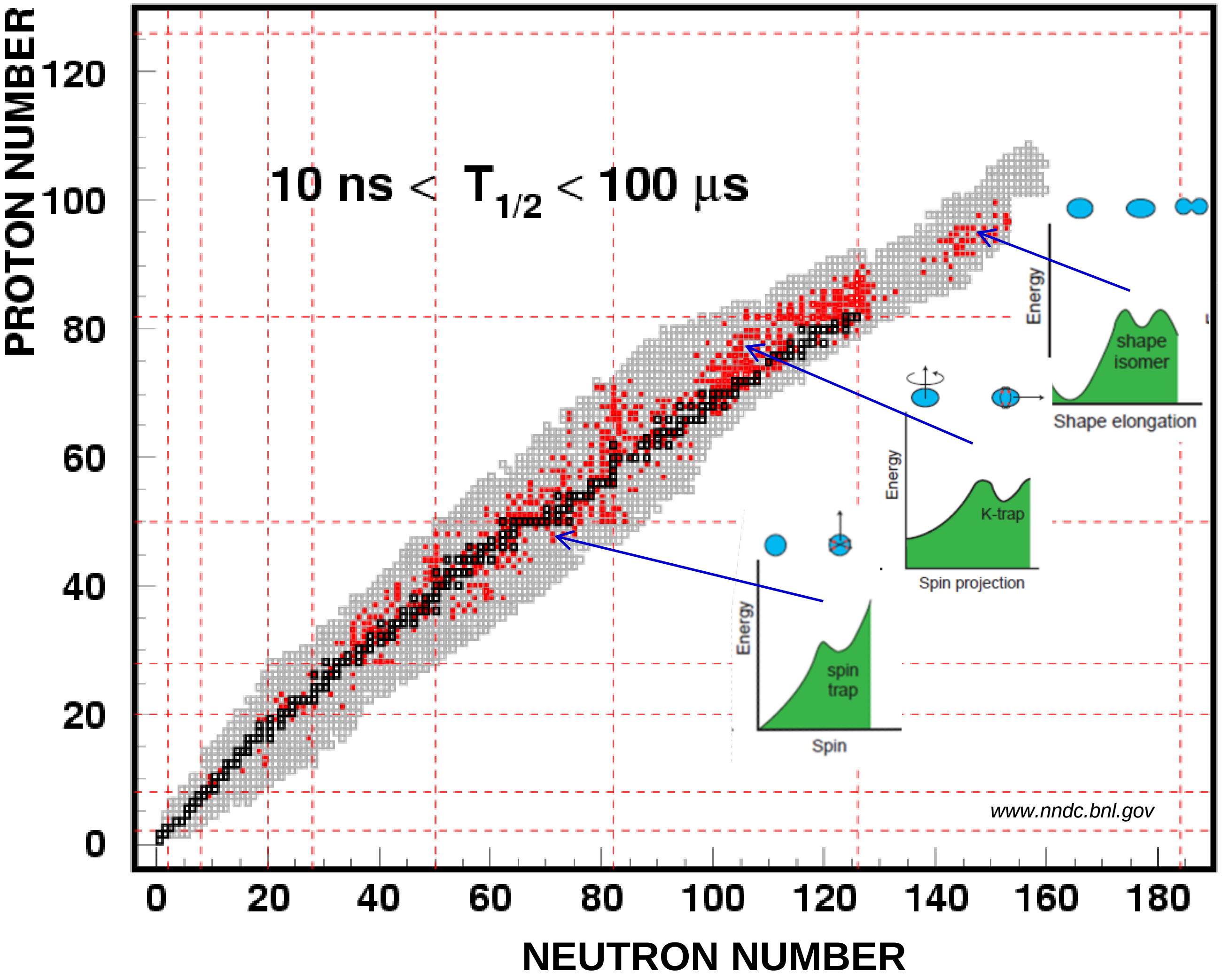
The first one discovered by O. Hahn in Berlin in 1921 – decay of ^{234}Pa (70 s)

von Weizsacker, A. Bohr & B. Mottelson

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

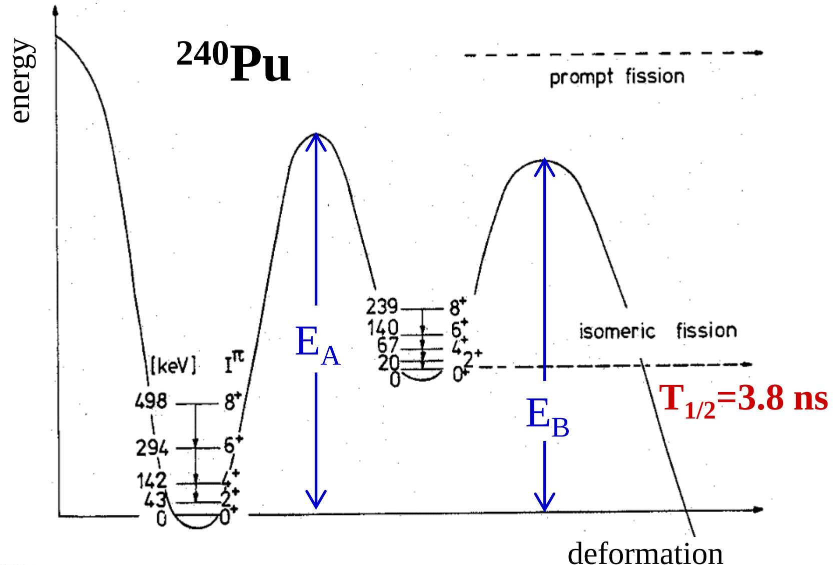


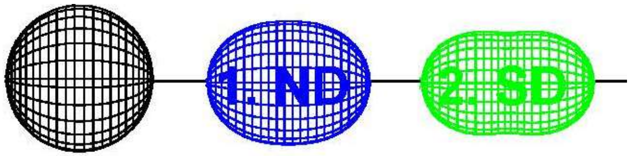
Three types of isomers



1. Shape isomers

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





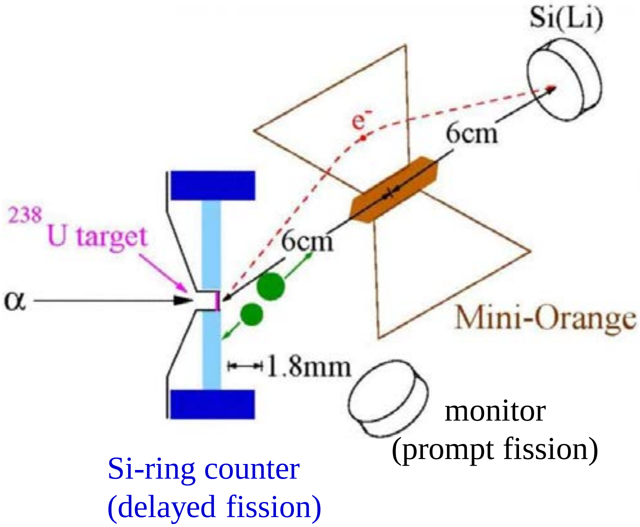
$$\boxed{\frac{\hbar^2}{2\mathfrak{J}} = 3.34\ keV}$$

axis ratio 2:1

E_A=5.8±0.3 MeV

E_B=5.45±0.3 MeV

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

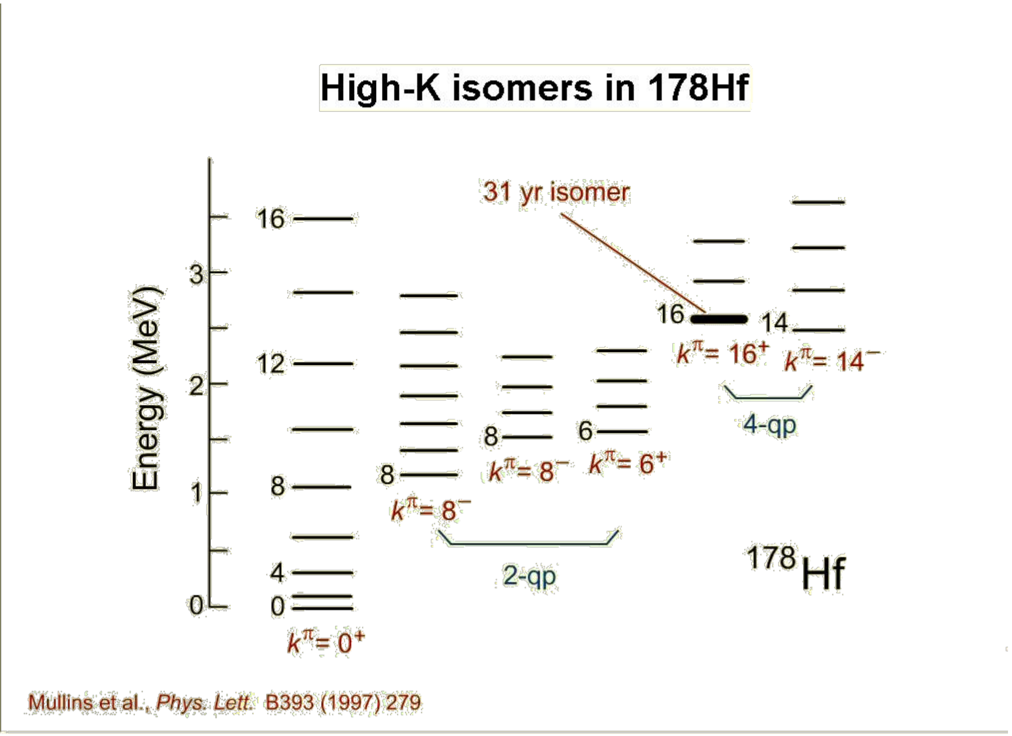


D. Pansegrau et al., Phys. Lett. B484 (2000) 1
D. Gassmann et al., Phys. Lett. B497 (2001) 181

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

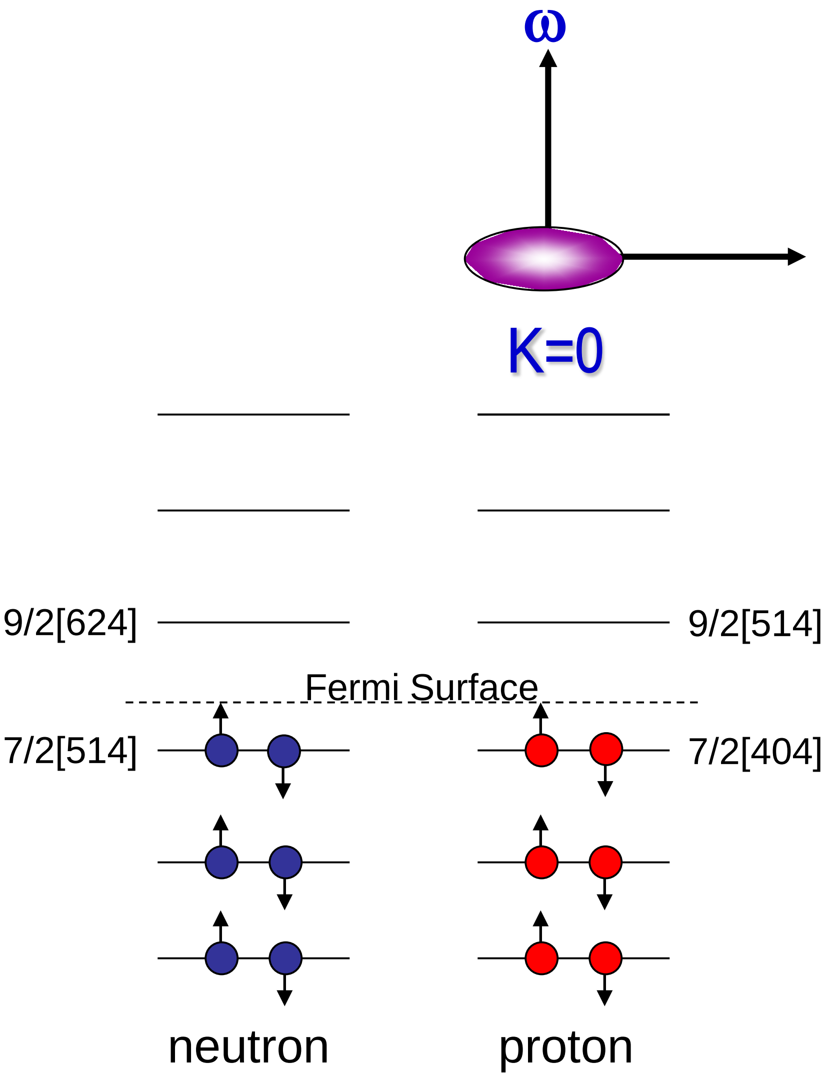
2. K-isomers

- A well-known example:



High-K isomers in 178Hf

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



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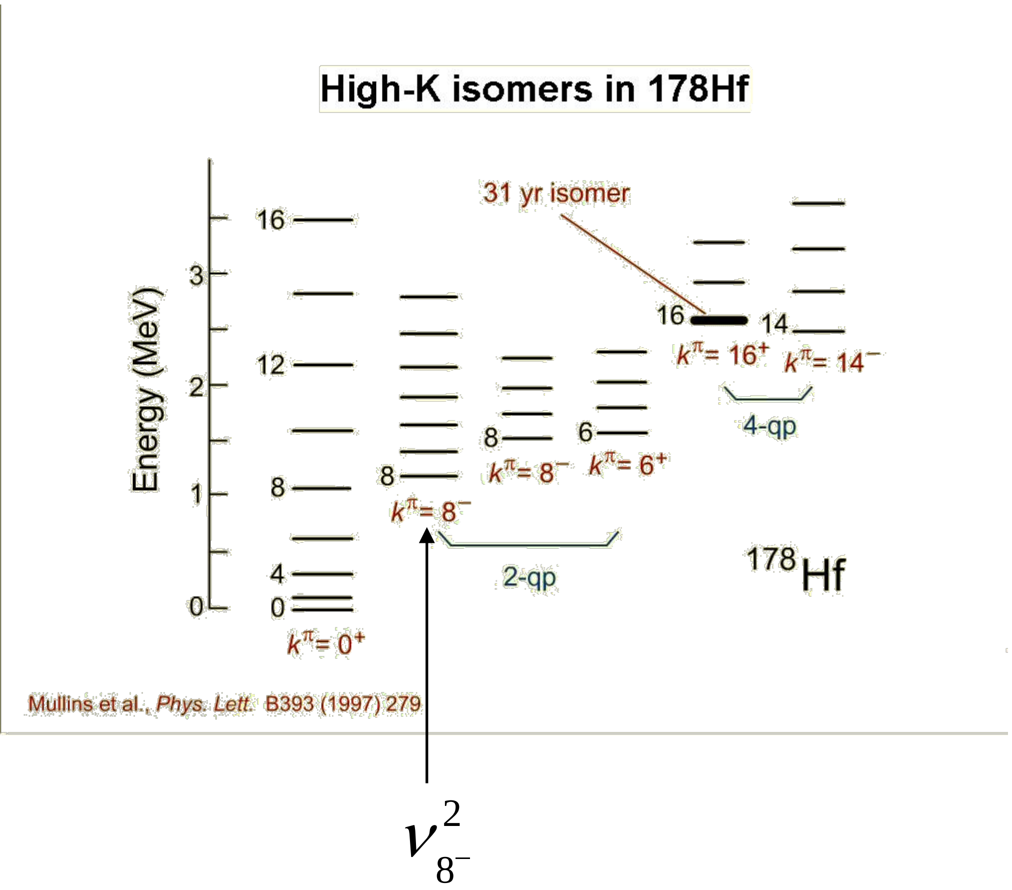
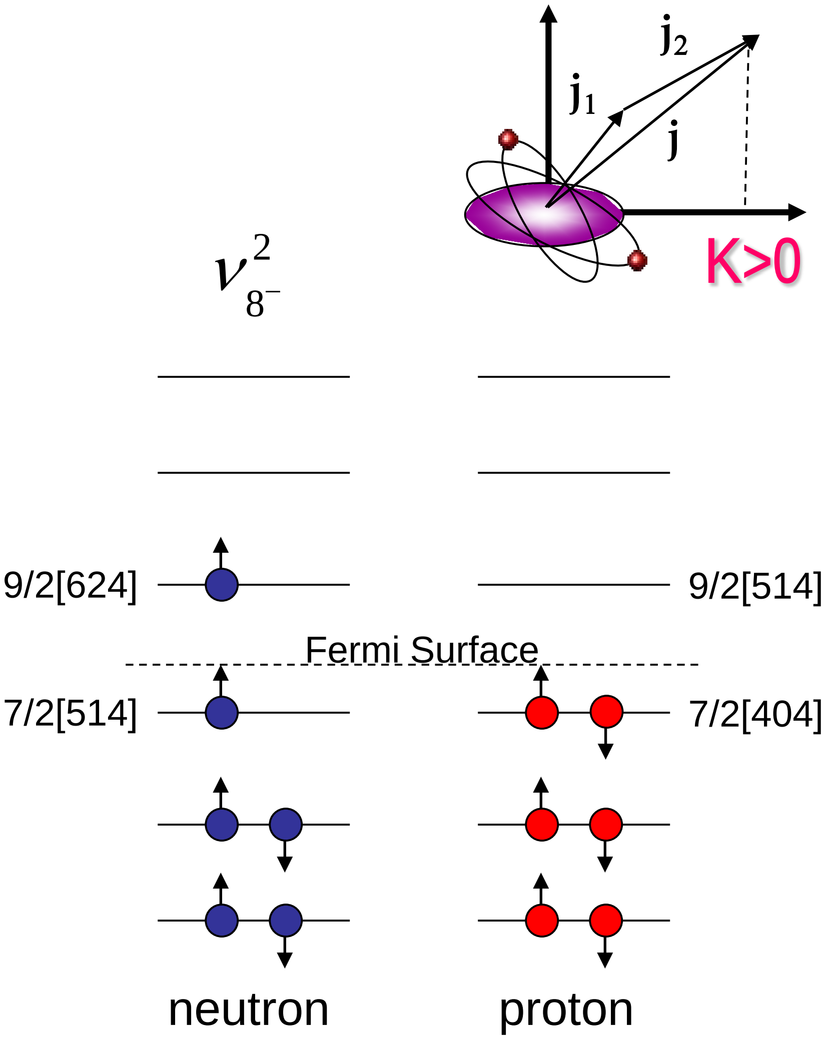


Mullins et al., *Phys. Lett.* B393 (1997) 279



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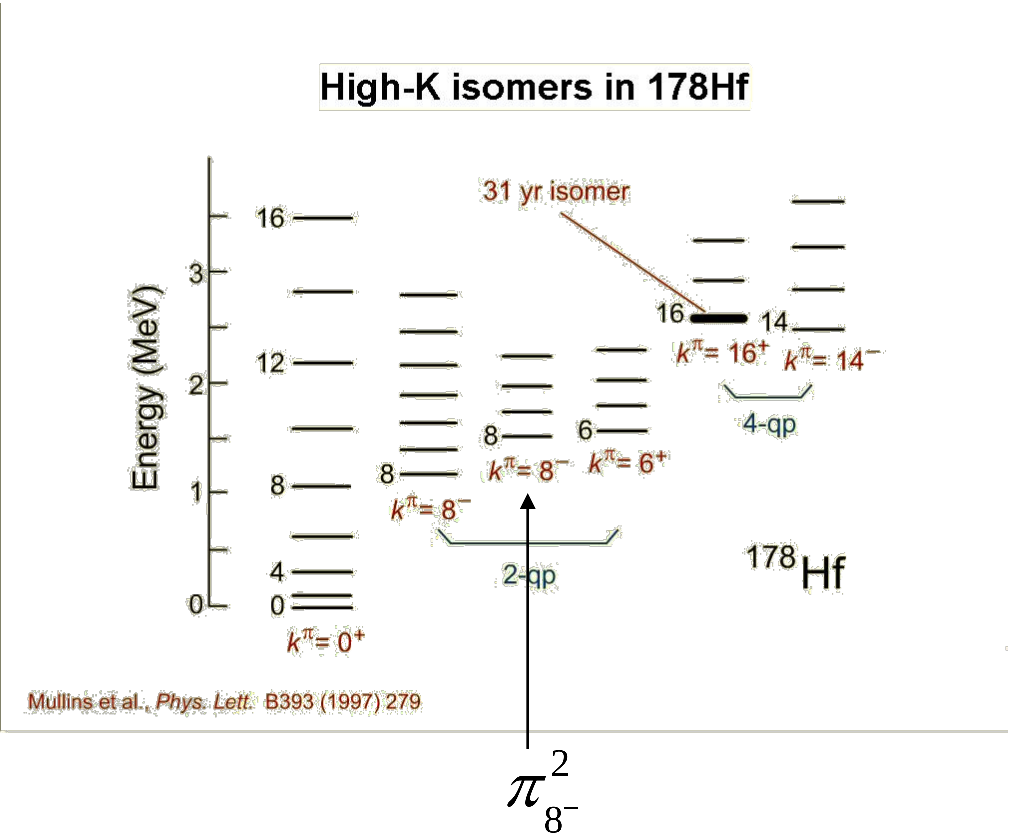
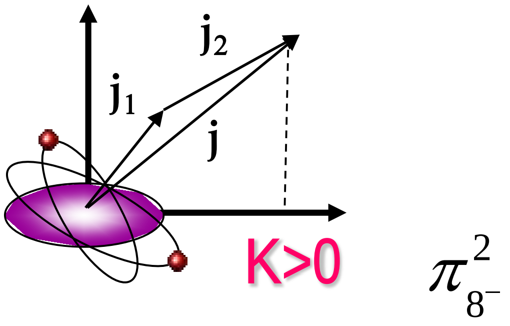
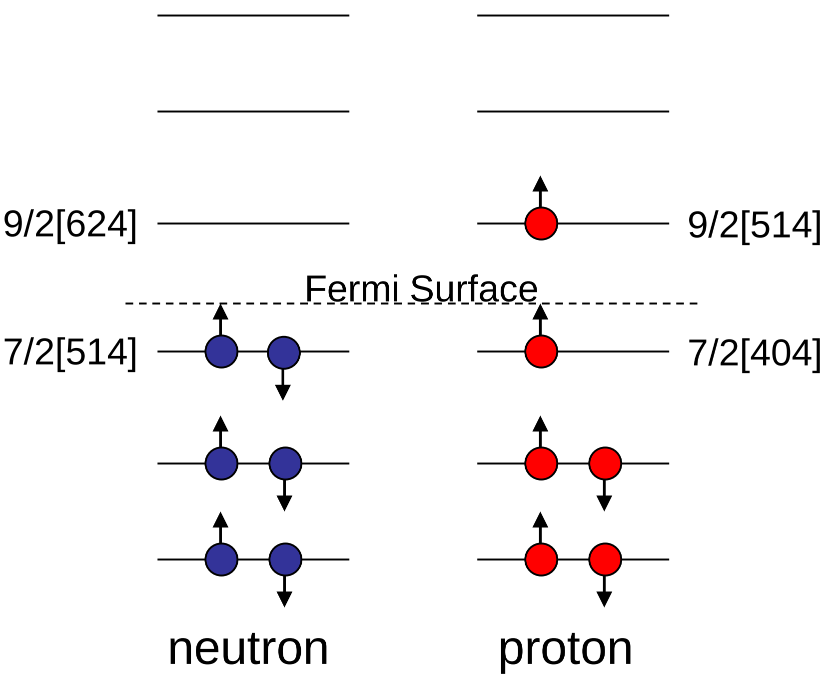


Mullins et al., *Phys. Lett.* B393 (1997) 279





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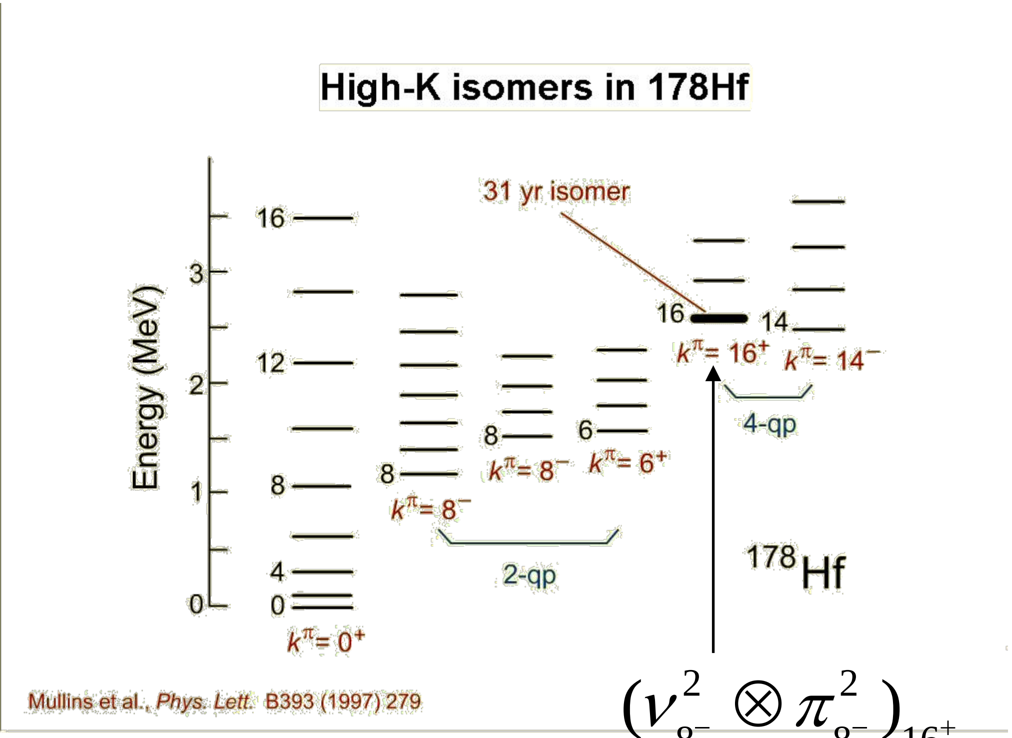
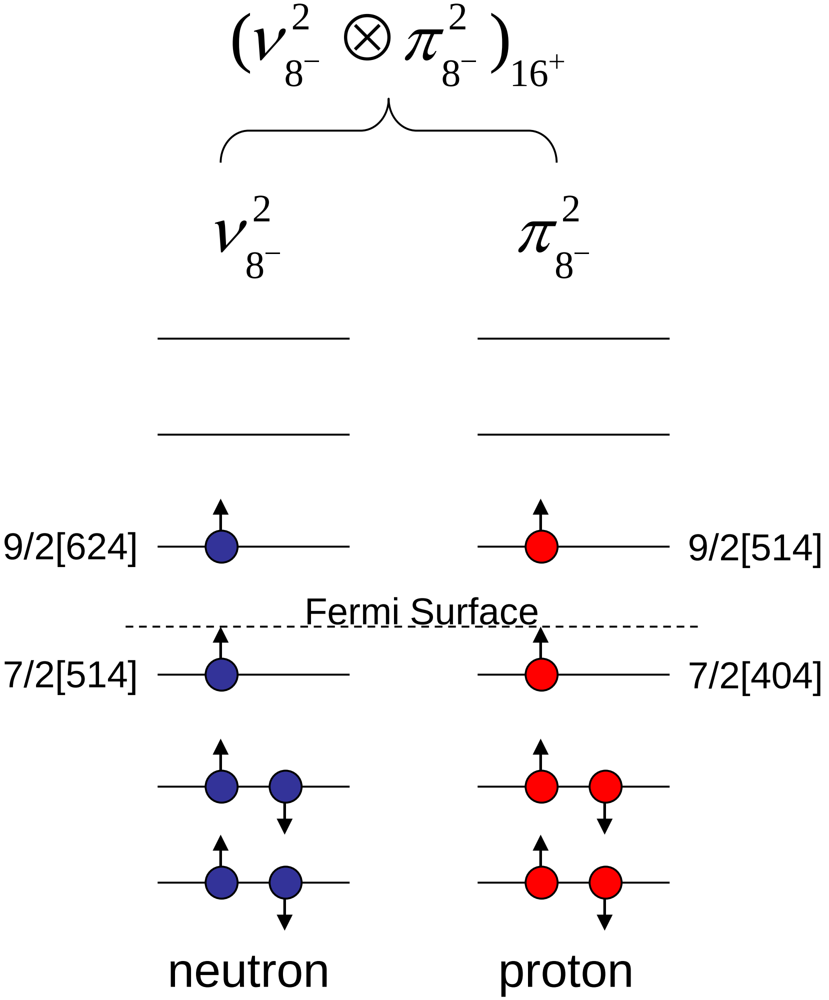


Mullins et al., *Phys. Lett.* B393 (1997) 279

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



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

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

REMINDER

Magnetic moments in ^{178}Hf

$$g(j)=\begin{cases}\dfrac{2\cdot\ell\cdot g_\ell+g_s}{2\cdot\ell+1} & for\quad j=\ell+1/2\\[2ex] \dfrac{2\cdot(\ell+1)\cdot g_\ell-g_s}{2\cdot\ell+1} & for\quad j=\ell-1/2\end{cases}$$

proton $g_\ell=1\quad g_s=5.59$

neutron $g_\ell=0\quad g_s=-3.83$

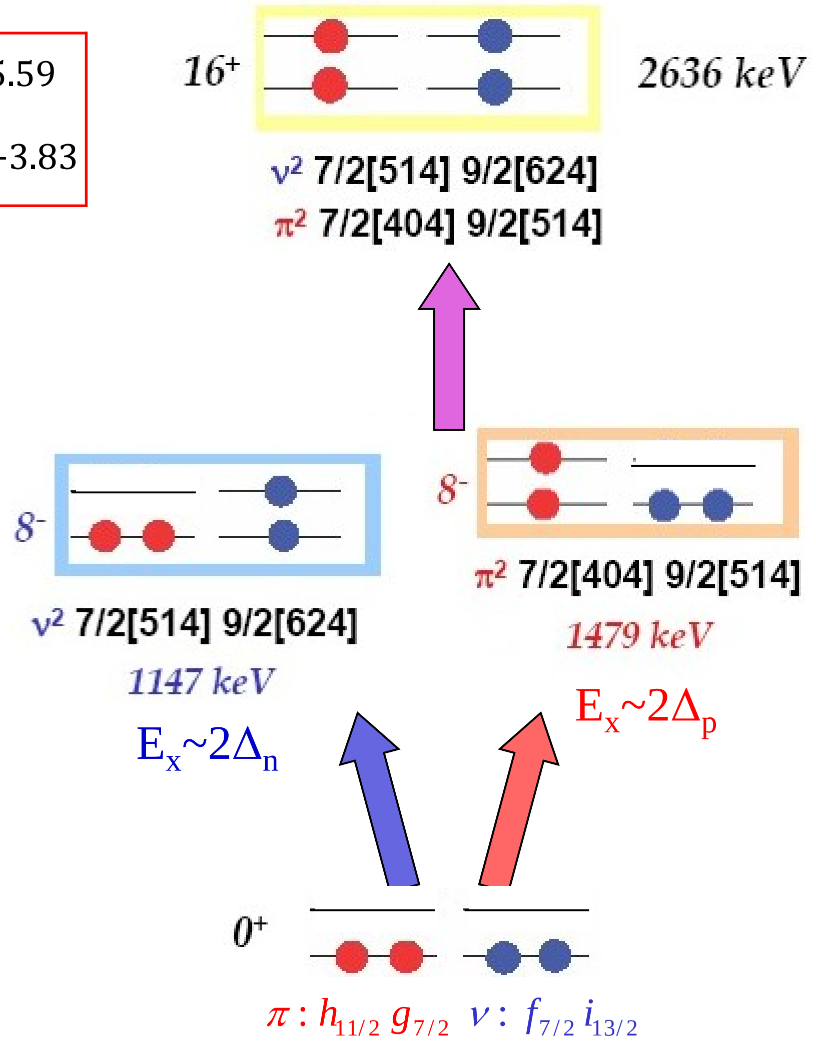
$g(h_{11/2}) = 1.42$ $g(g_{7/2}) = 0.49$ $g(f_{7/2}) = -0.55$ $g(i_{13/2}) = -0.29$

$$g(j_1\times j_2;J)=\frac{1}{2}\cdot(g_1+g_2)+\frac{j_1\cdot(j_1+1)-j_2\cdot(j_2+1)}{2\cdot J\cdot(J+1)}\cdot(g_1-g_2)$$

$g(h_{11/2} \times g_{7/2}; 8^-) = 1.08$ $g(f_{7/2} \times i_{13/2}) = -0.36$

$\boxed{g(8^- \times 8^-; 16^+) = 0.36 \quad\rightarrow\quad \mu = g\cdot I = 5.76\ \text{nm}}$

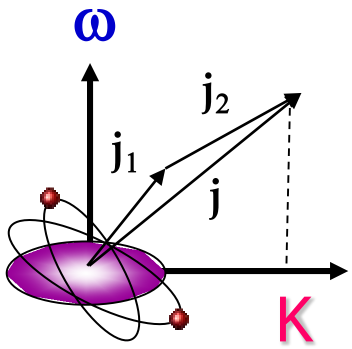
$\boxed{7.26\pm0.16\ \text{nm}}$



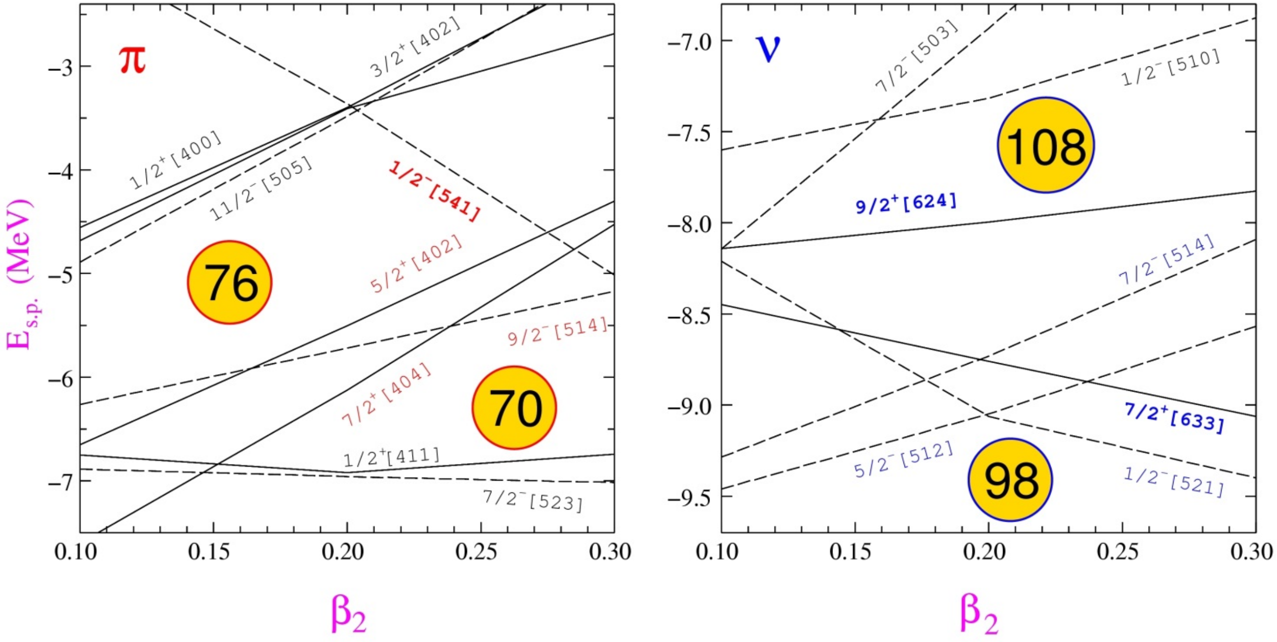
Helmer & Reich; Nucl. Phys. A114 (1968), 649

K-isomers: where to find them?

- Deformed nuclei with axially-symmetric shape



Mass 180 region : Yb (Z=70) **_- Ir_** (Z=77)



- High-K orbitals near the Fermi surface

π: 7/2[404], 9/2[514], 5/2[402]

ν: 7/2[514], 9/2[624], 5/2[512], 7/2[633]

3. Spin isomers

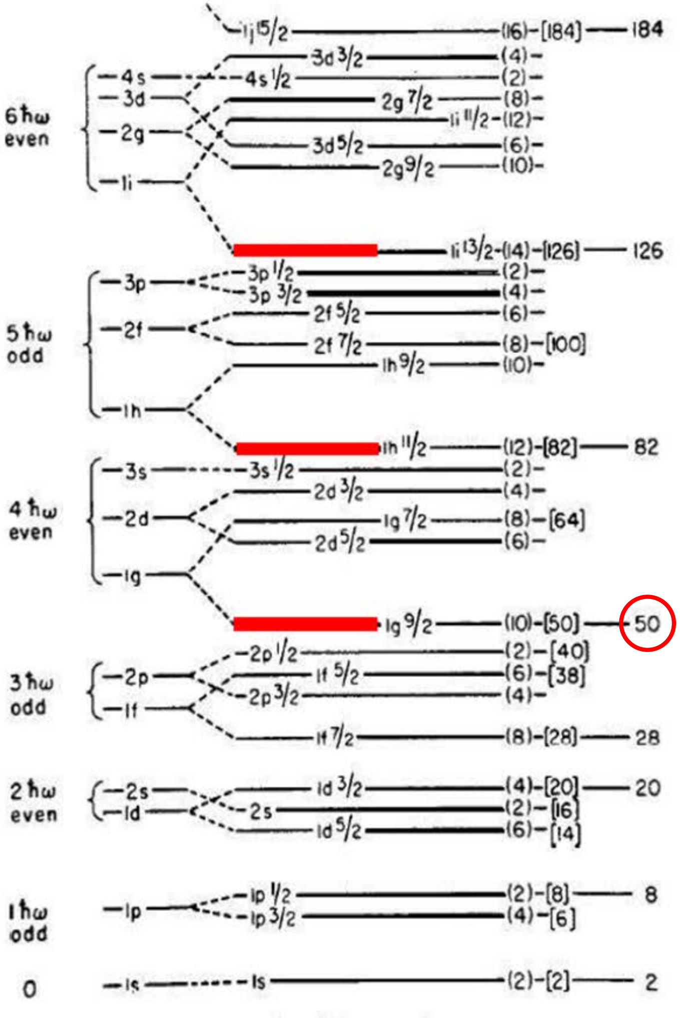
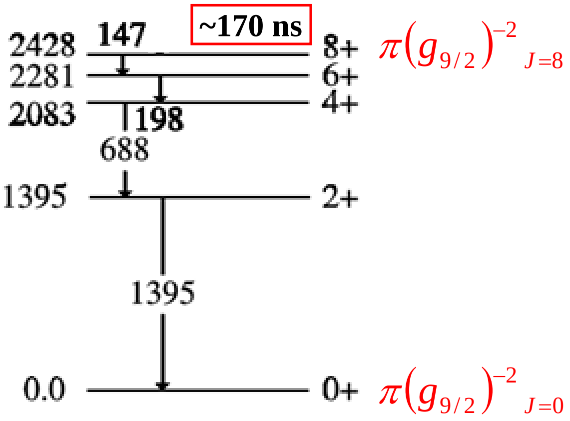


Fig. 7. Realistic level diagram for protons.

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



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

3. Spin isomers

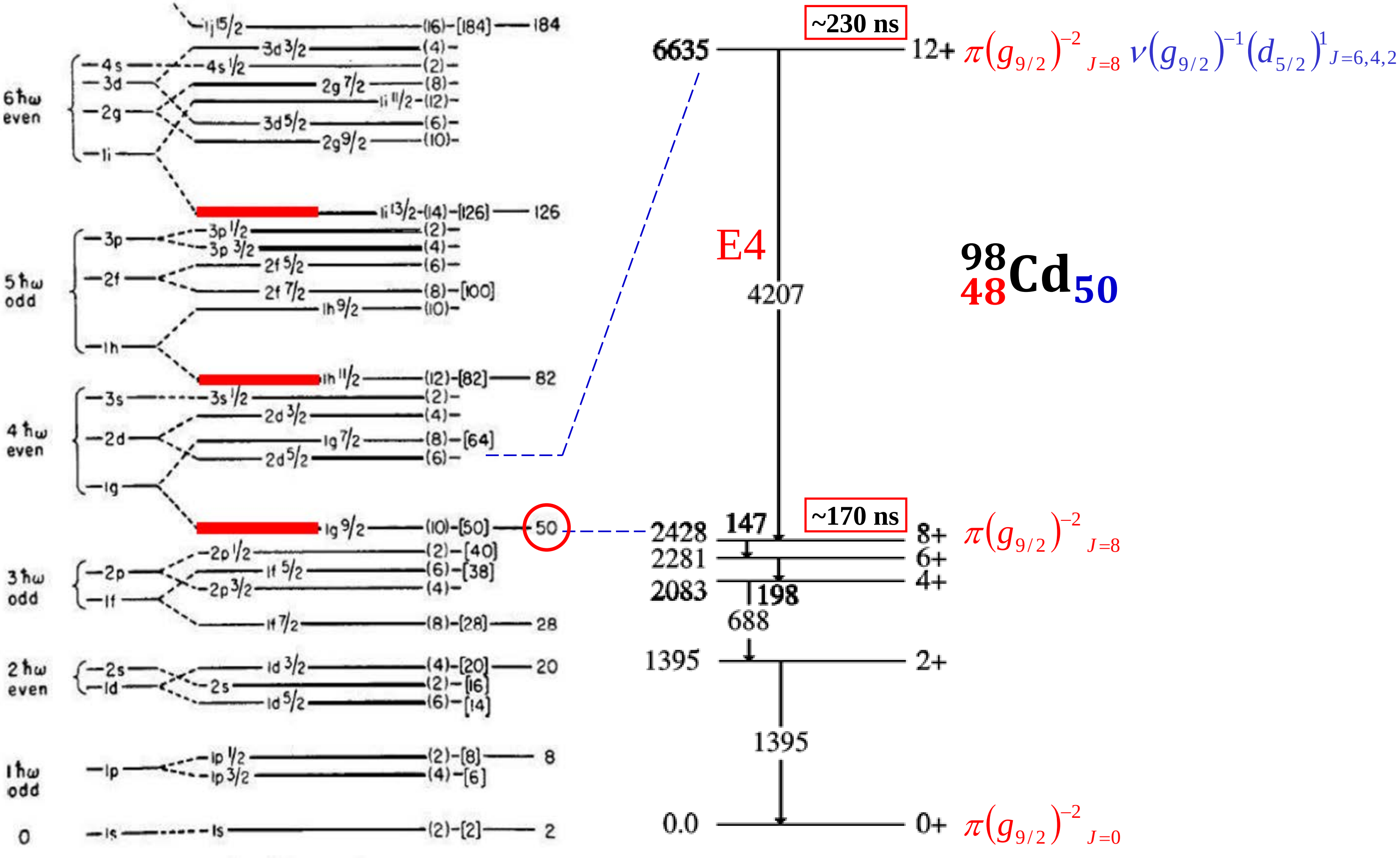
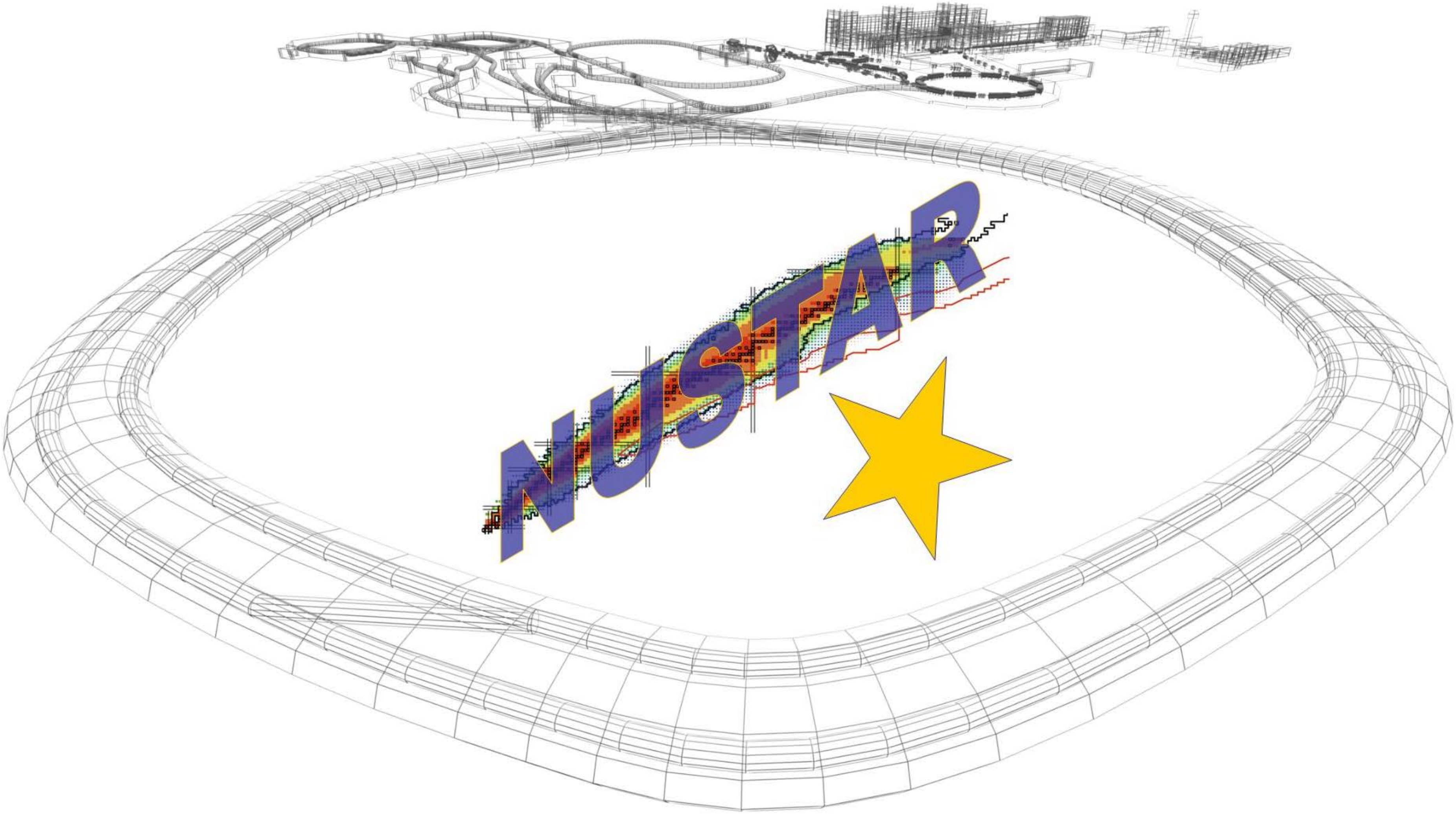


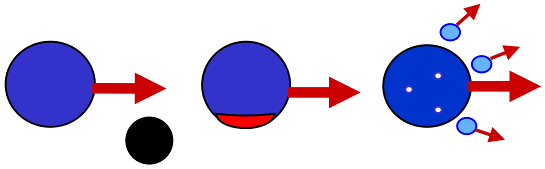
Fig. 7. Realistic level diagram for protons.

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

Physics with exotic nuclei

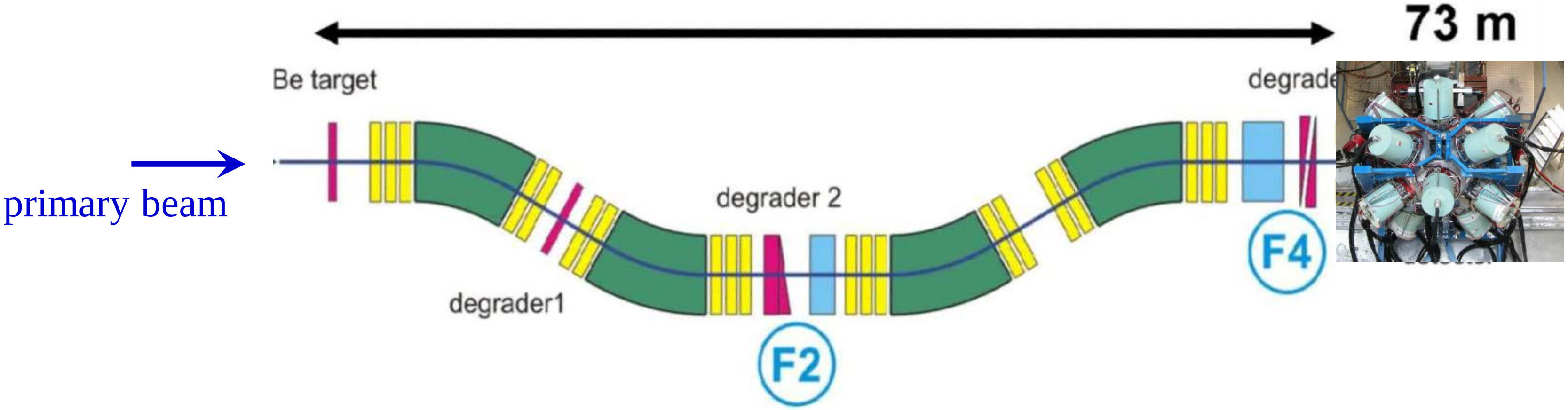


Production of Radioactive Ion Beams



Fragmentation

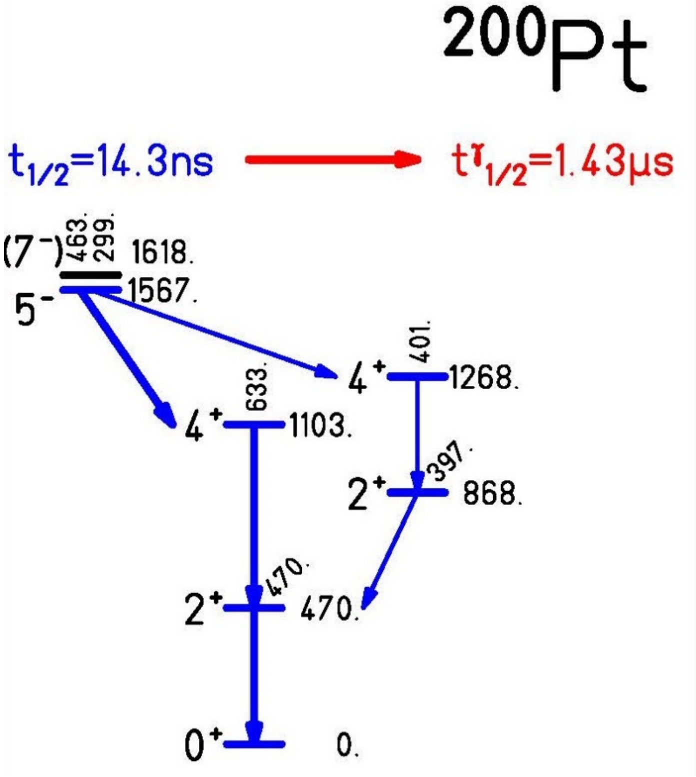
in ~20% of all cases the fragment is excited

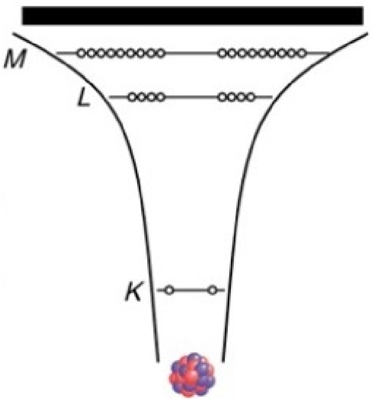


time-of-flight through the fragment separator FRS ~300 ns

Isomeric states can be investigated!

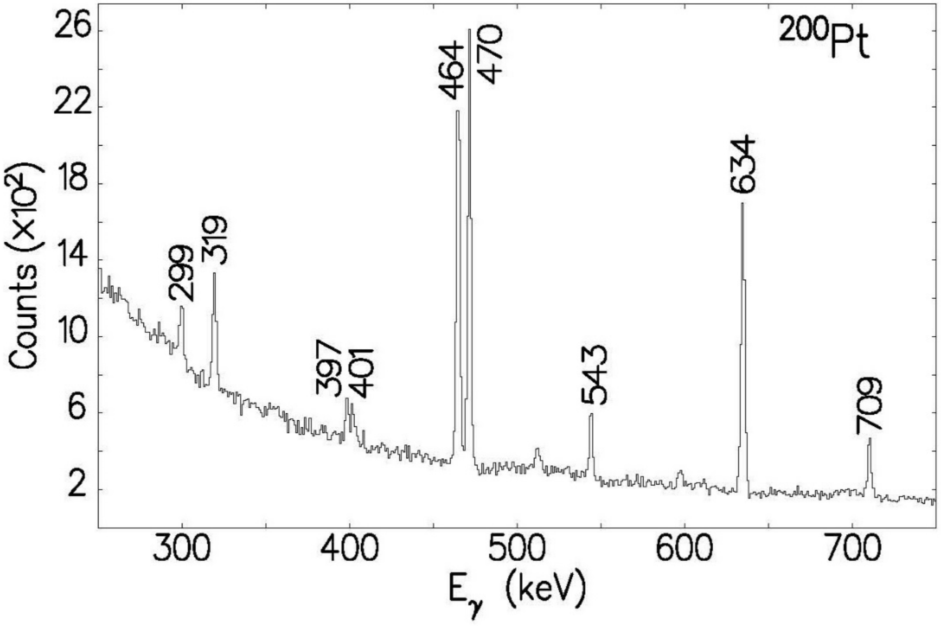
Longer lifetime for bare atoms



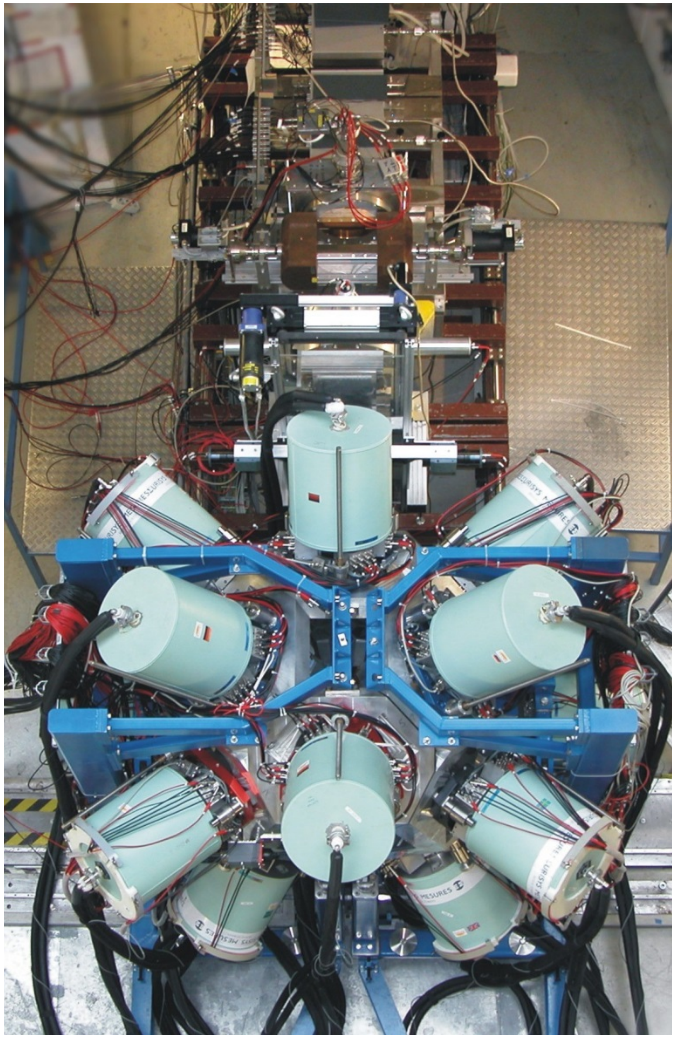


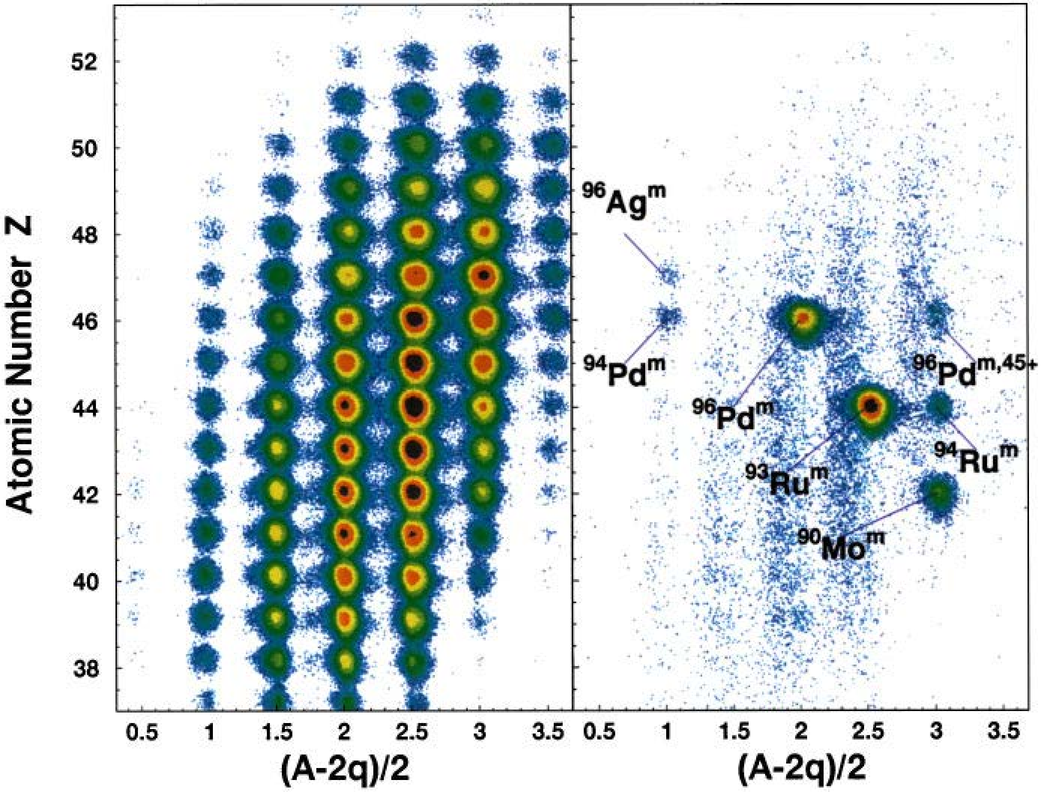
no conversion electrons

γ-spectrum after ~300 ns ToF

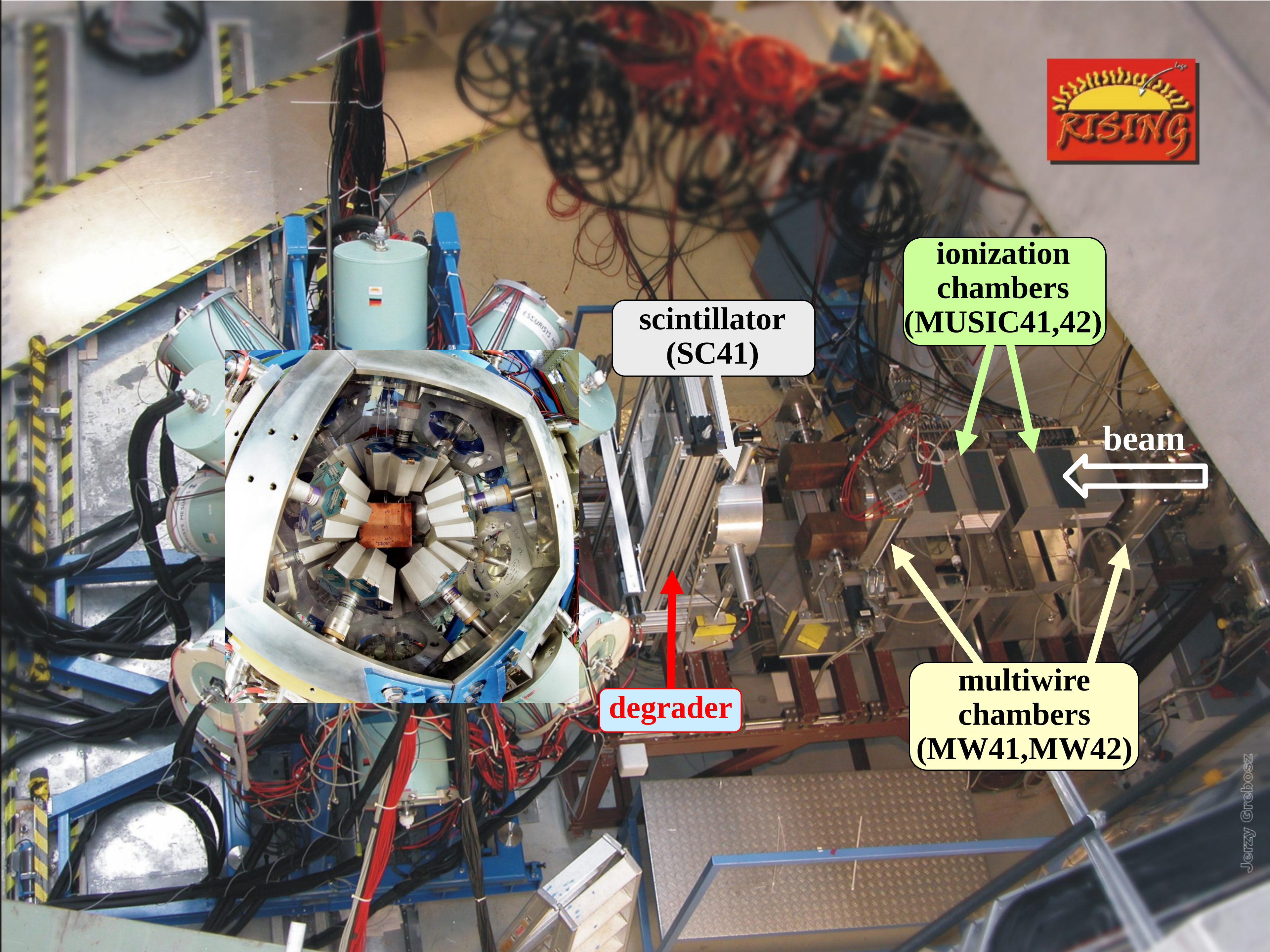


Experimental set-up for isomer decay gateway to nuclear structure





R. Grzywacz et al., Phys. Rev C55 ,1126 (1997)



ionization chambers (MUSIC41,42)

scintillator (SC41)

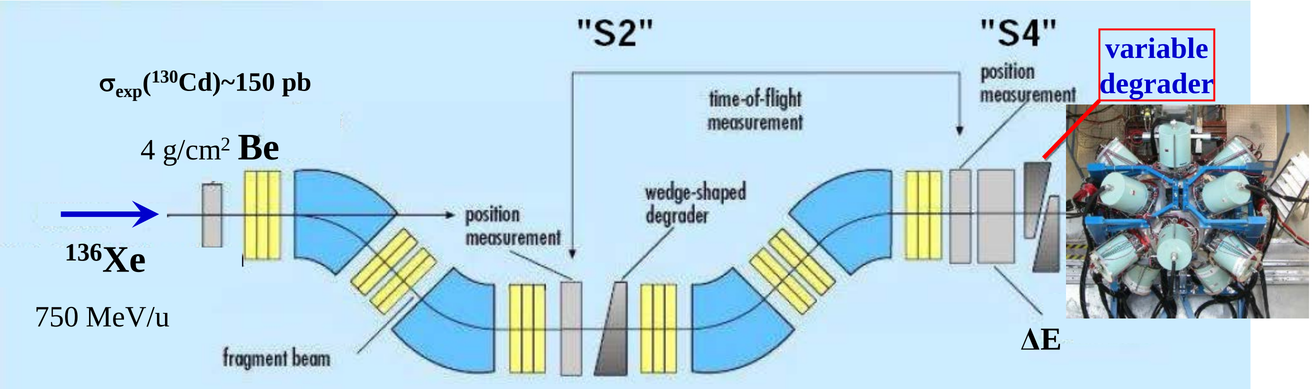
beam

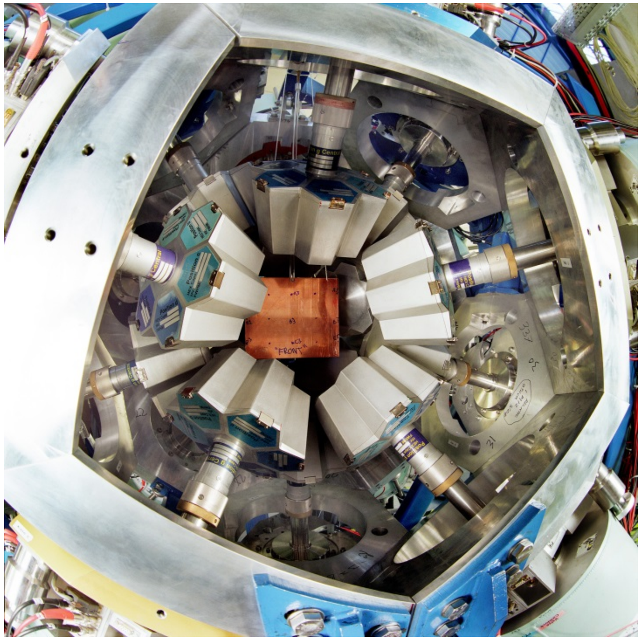
degrader

multiwire chambers (MW41,MW42)

Jerzy Grebosz

Experimental set-up with passive target

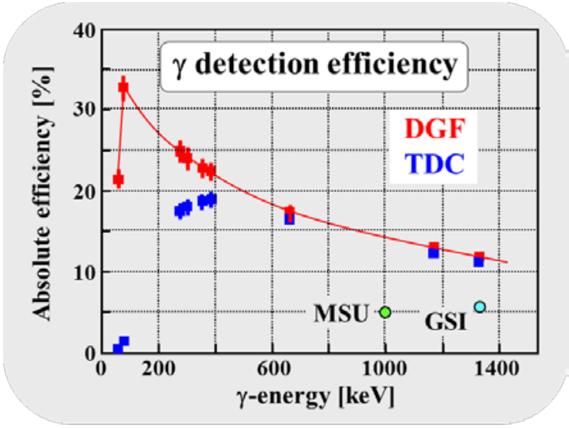




implantation in Cu-plate

15 Cluster detectors with 105 Ge crystals

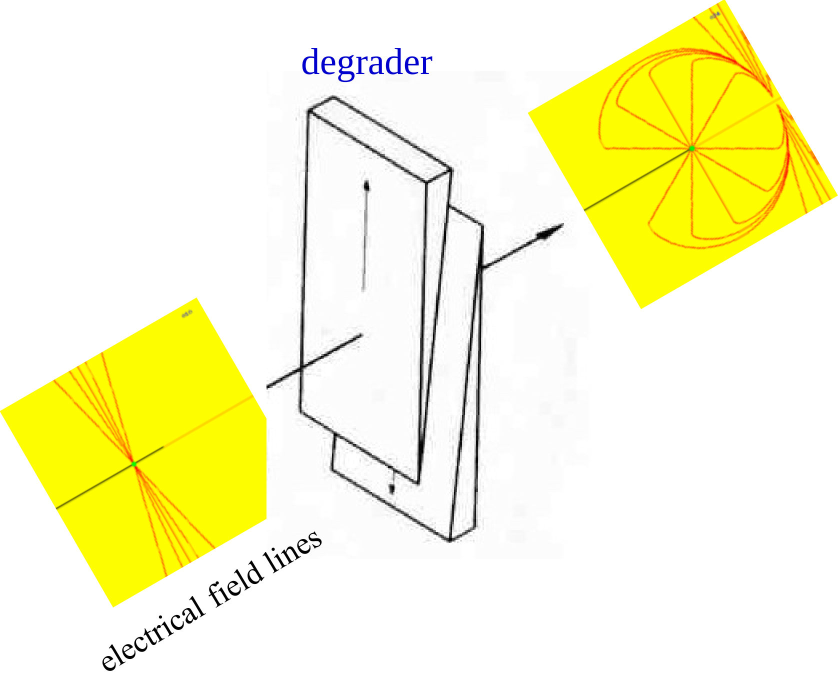
ε_γ = 11% at 1.3 MeV, 20% at 550 keV, 35% at 100 keV

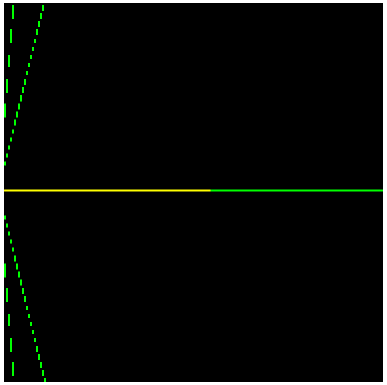


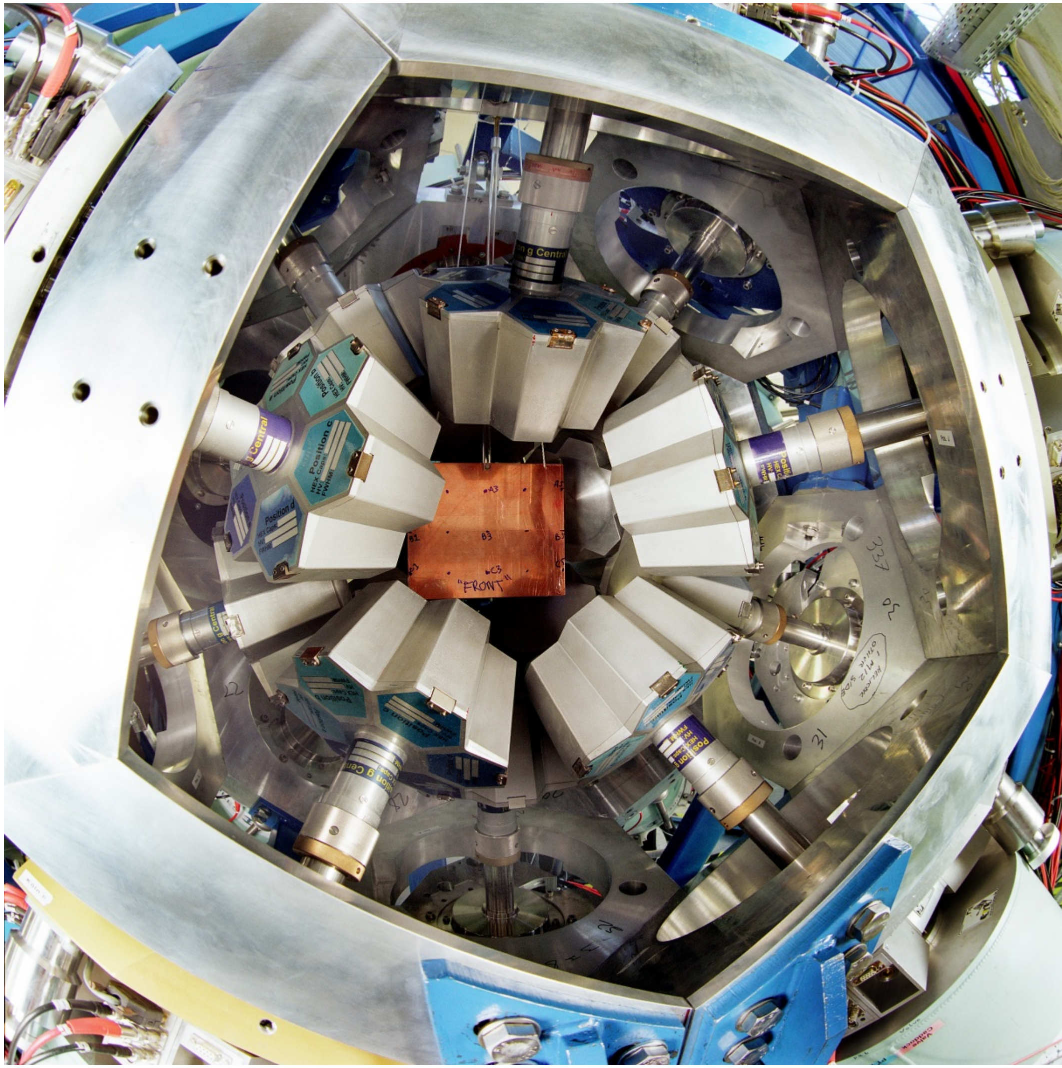
- very high γ-ray efficiency
- high granularity (prompt flash problem)

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

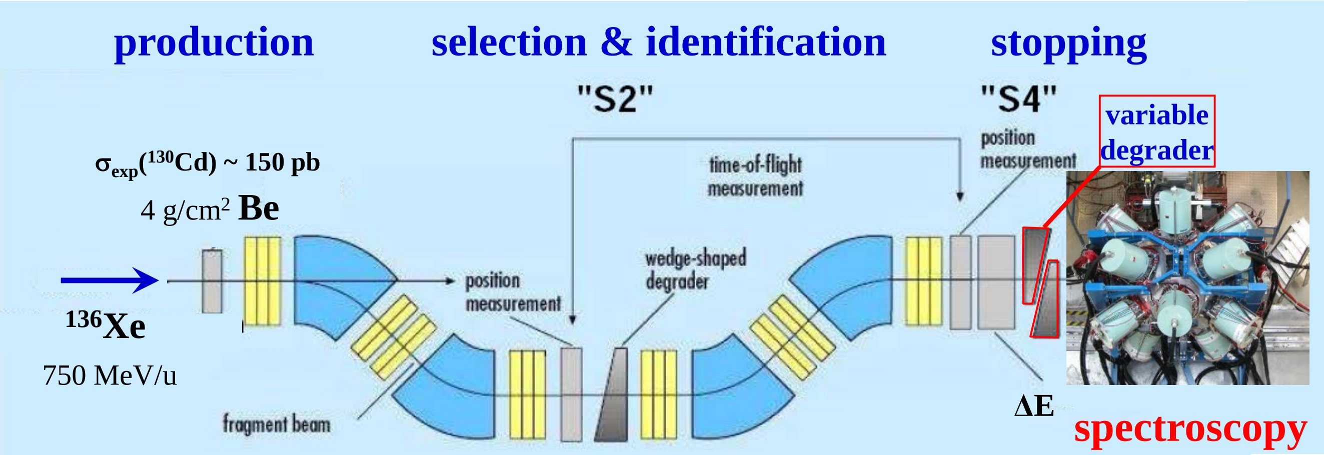
Limitations in isomeric spectroscopy

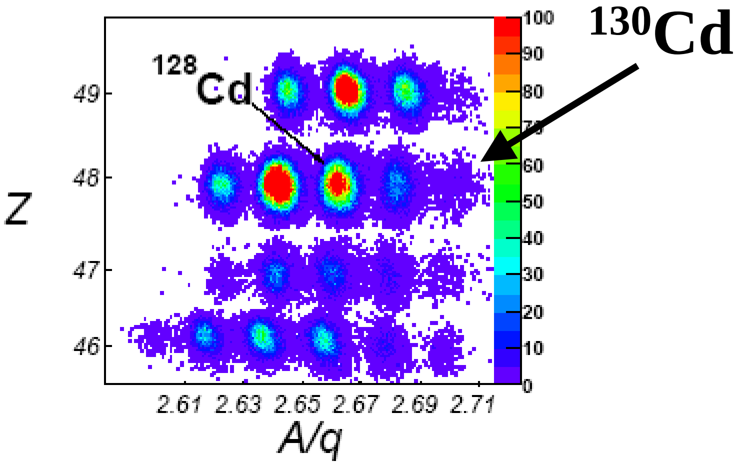






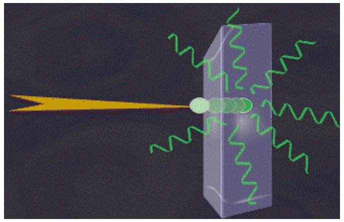
Identification of $^{130}_{48}Cd_{82}$



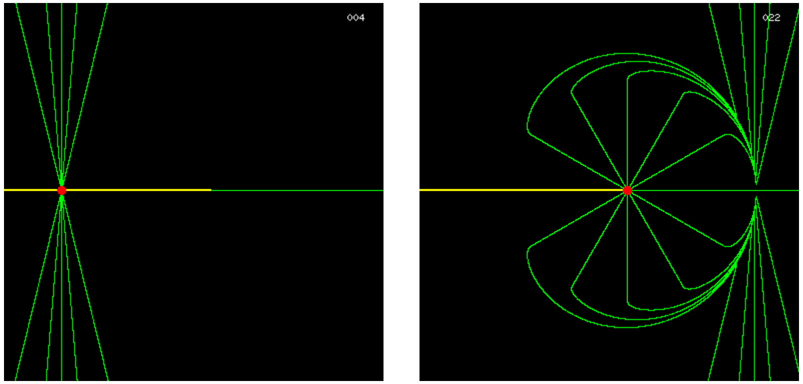


4000 identified ^{130}Cd ions in fragmentation

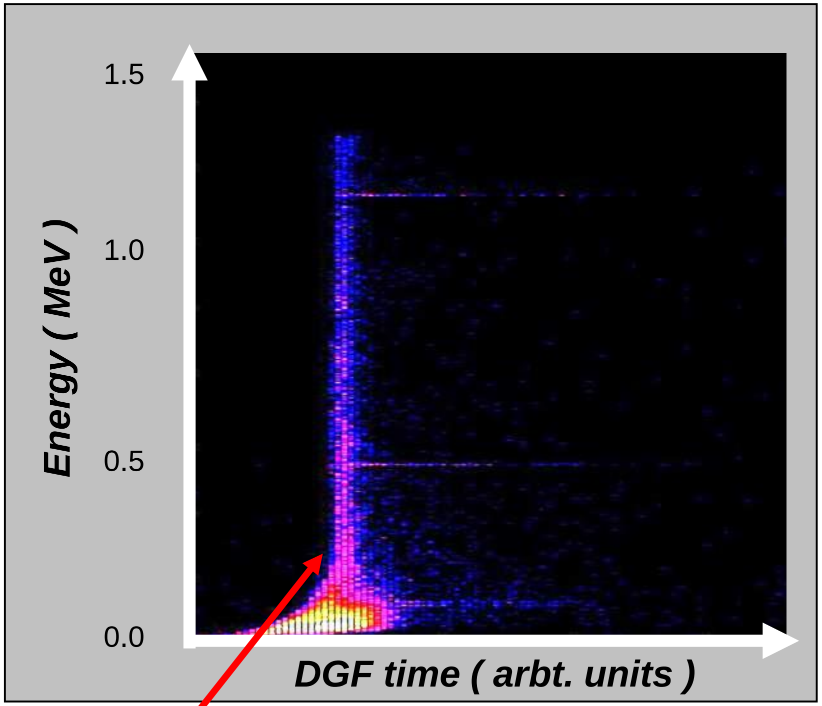
Limitations in isomer spectroscopy



slowing down of a
moving point-charge



^{130}Cd: DGF-timing

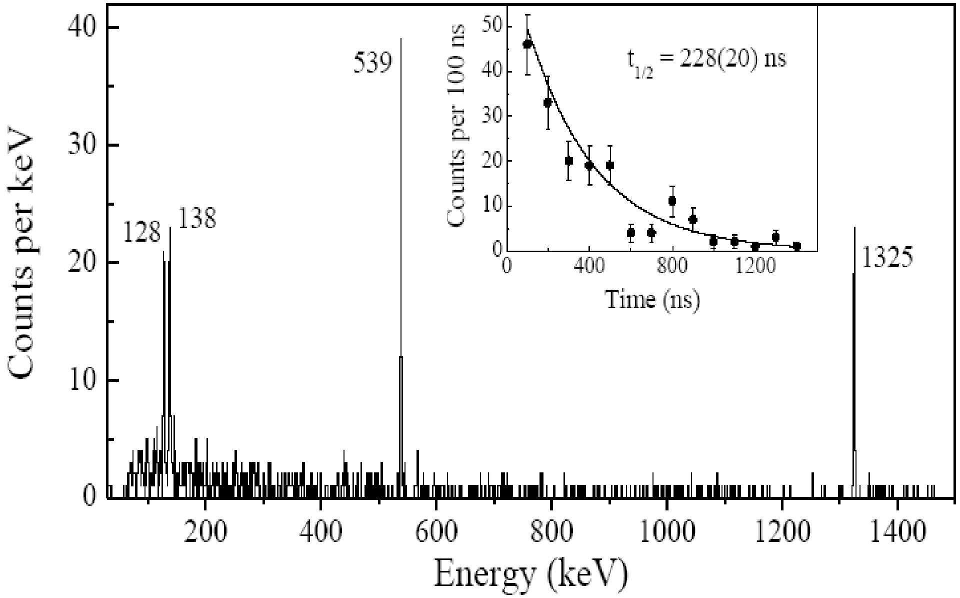


Prompt γ-flash

Decay time range: 20 ns ... 20 μs

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

Decay spectroscopy probes shell closures



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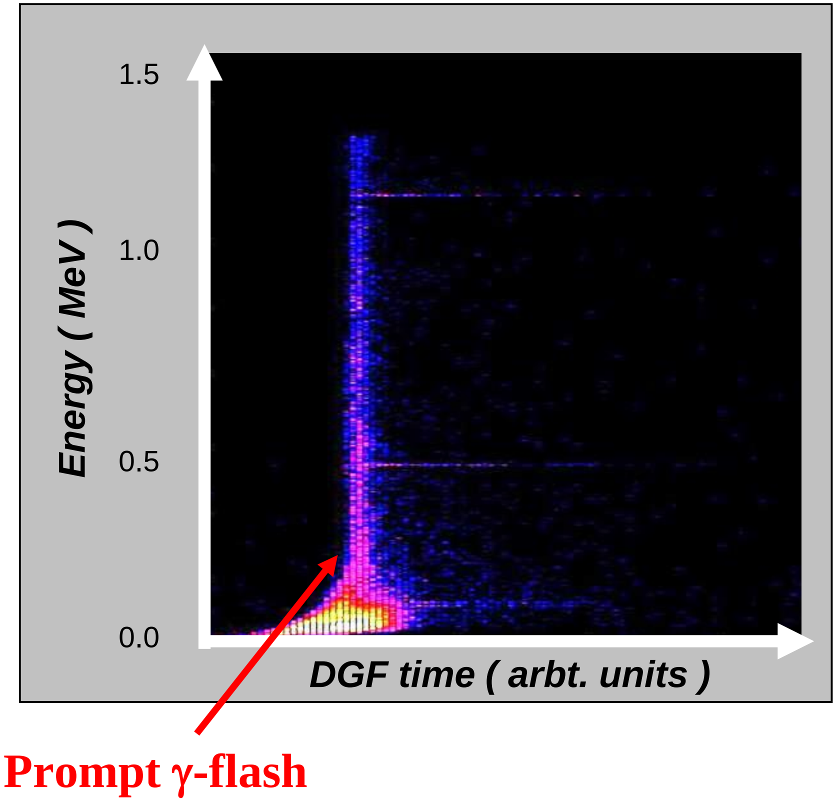

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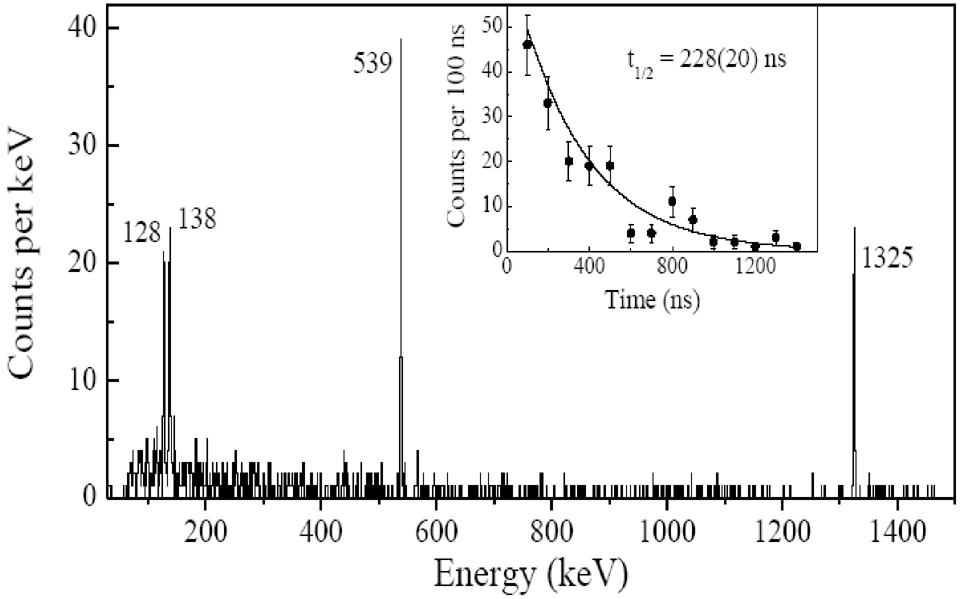
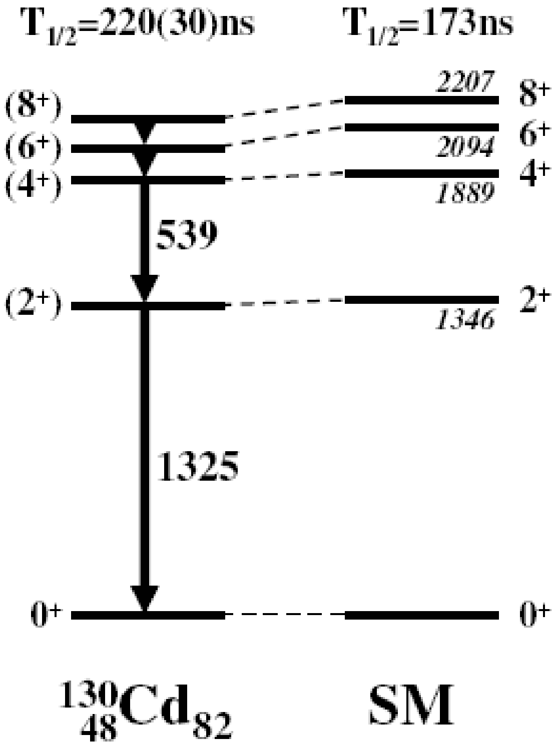
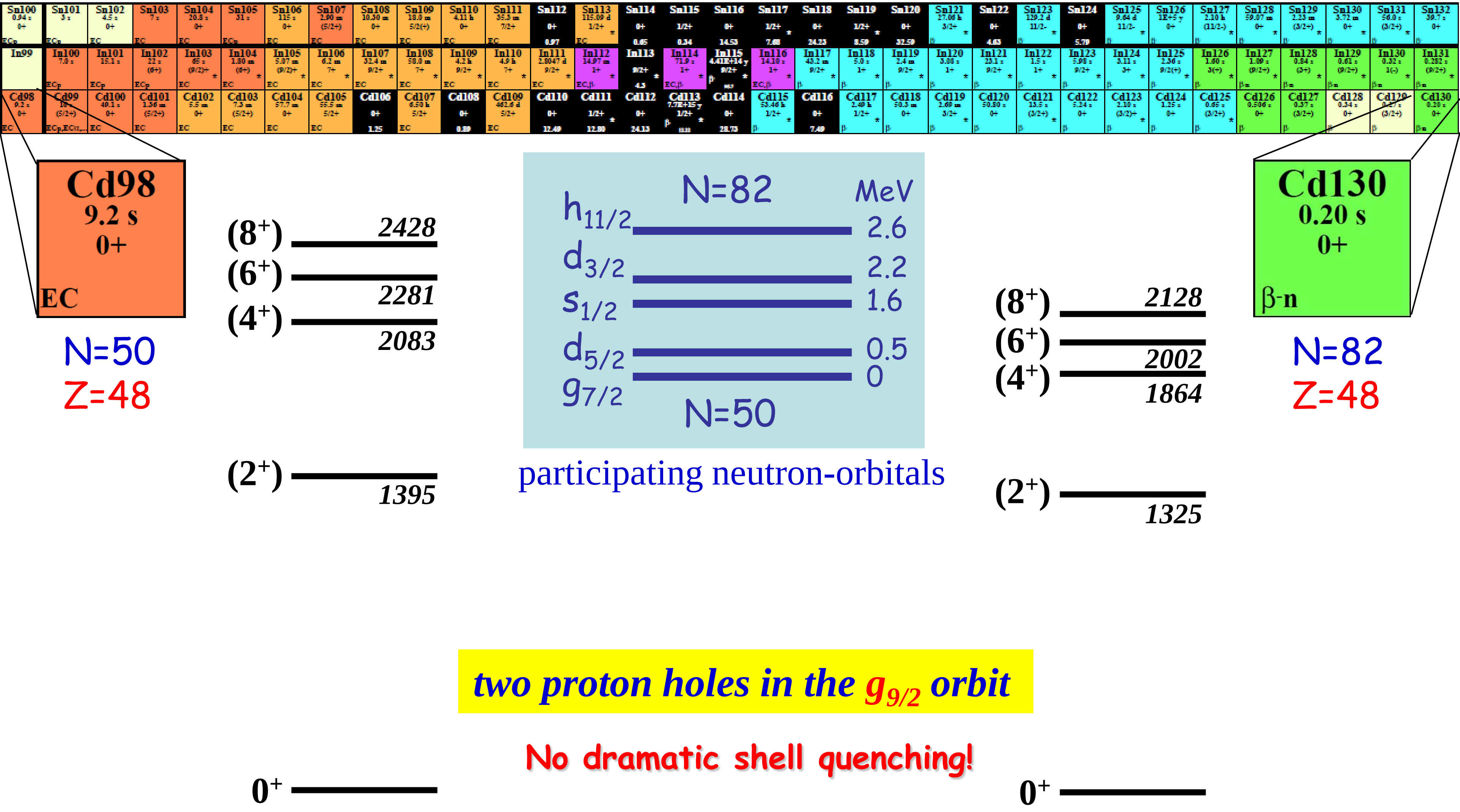




No Shell quenching observed

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

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



participating neutron-orbitals

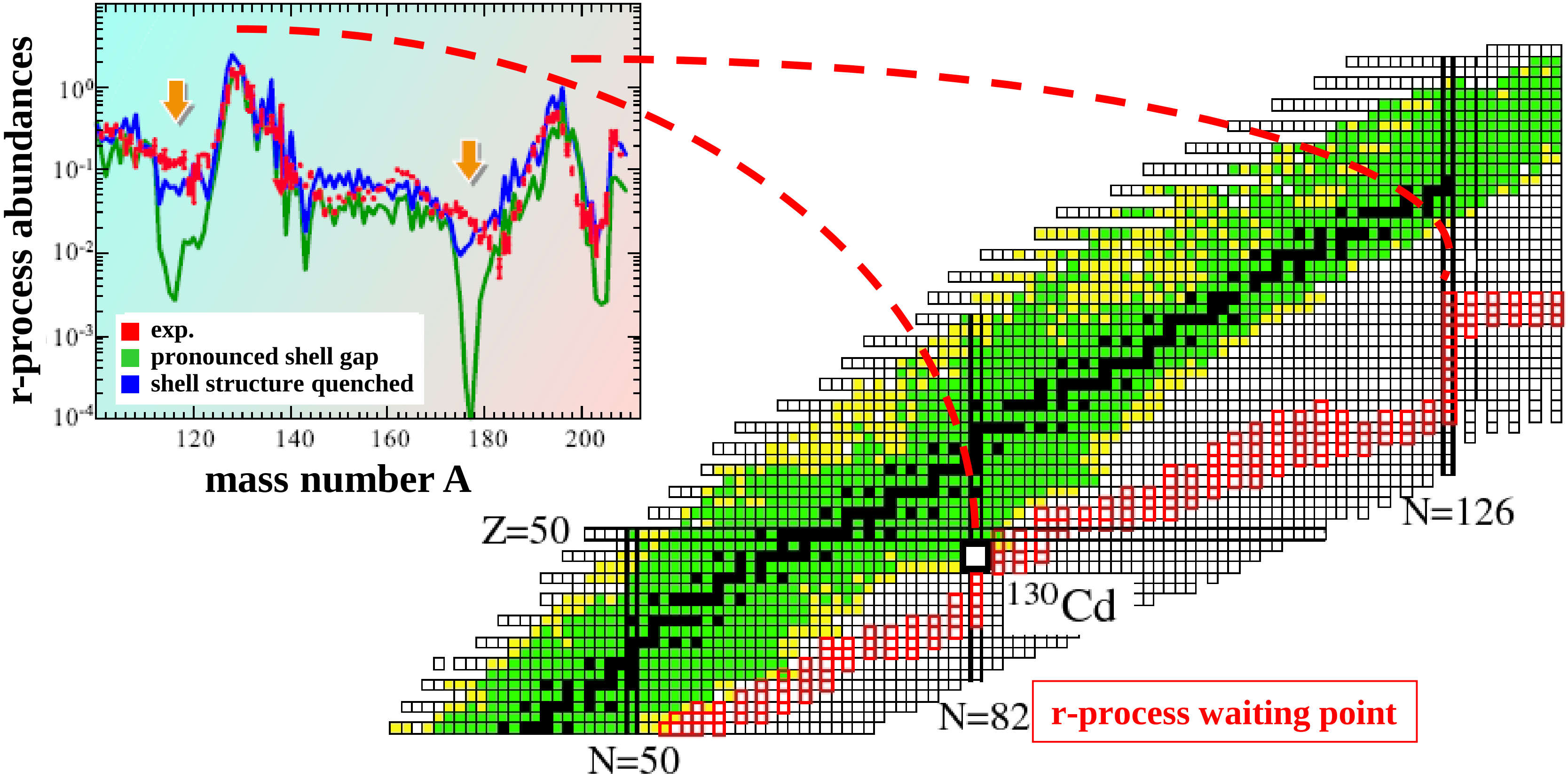
two proton holes in the $g_{9/2}$ orbit

No dramatic shell quenching!

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

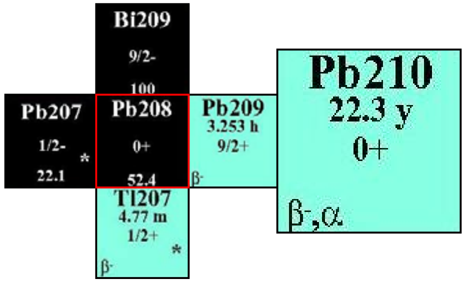
A. Jungclaus et al., Phys. Rev. Lett. 99 (2007), 132501

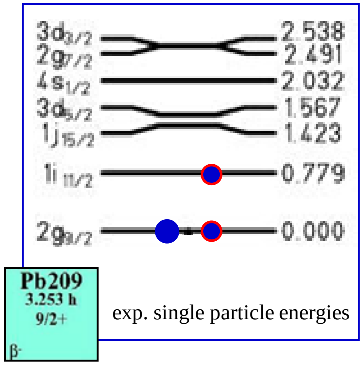
The astrophysical r-process ´path´



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)

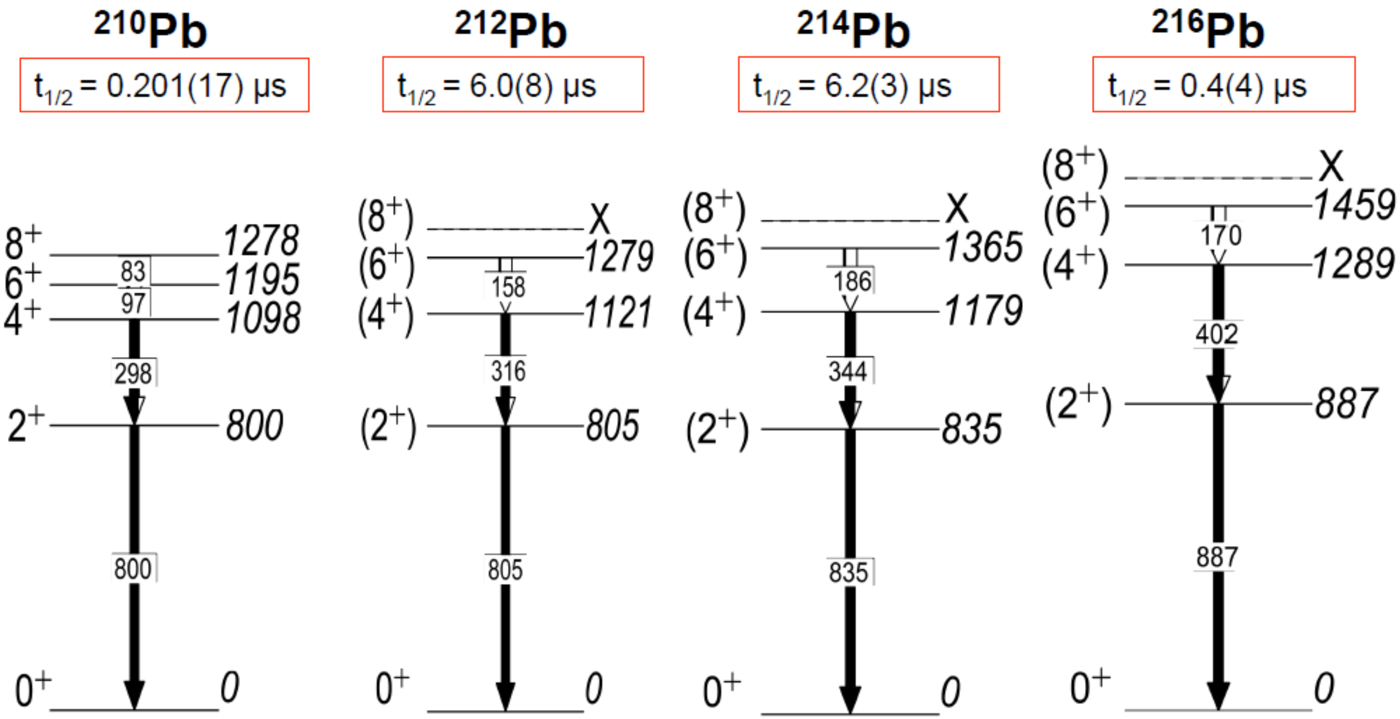
esidual interaction !

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

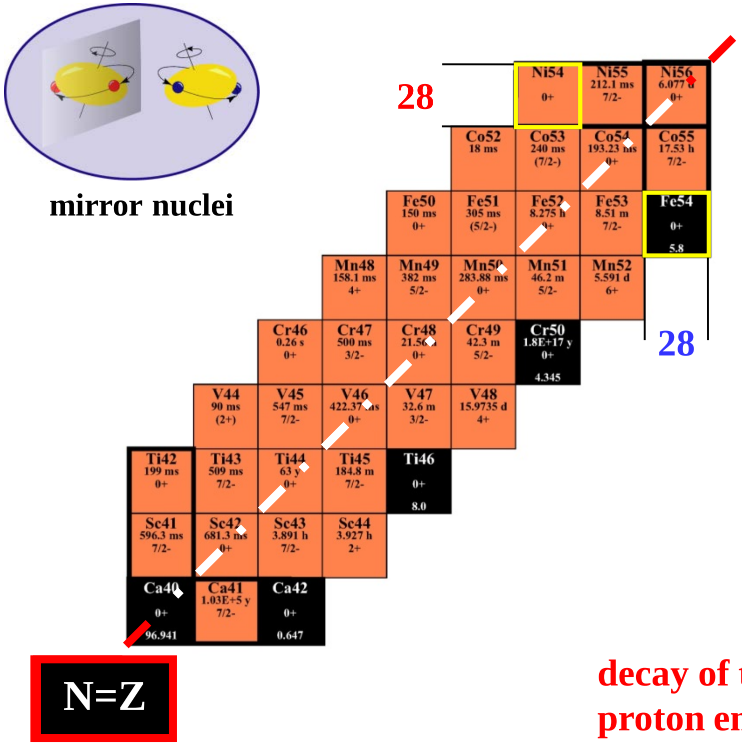
Level schemes of neutron-rich Pb-isotopes

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-			

$g_{9/2}$

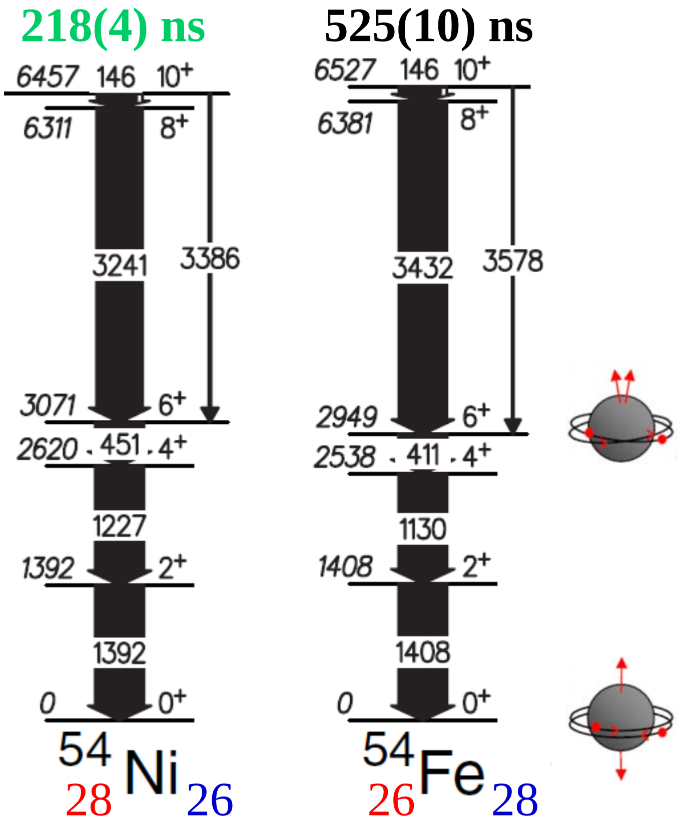


T=1 isospin symmetry in pf-shell nuclei search for isospin breaking effects



mirror nuclei

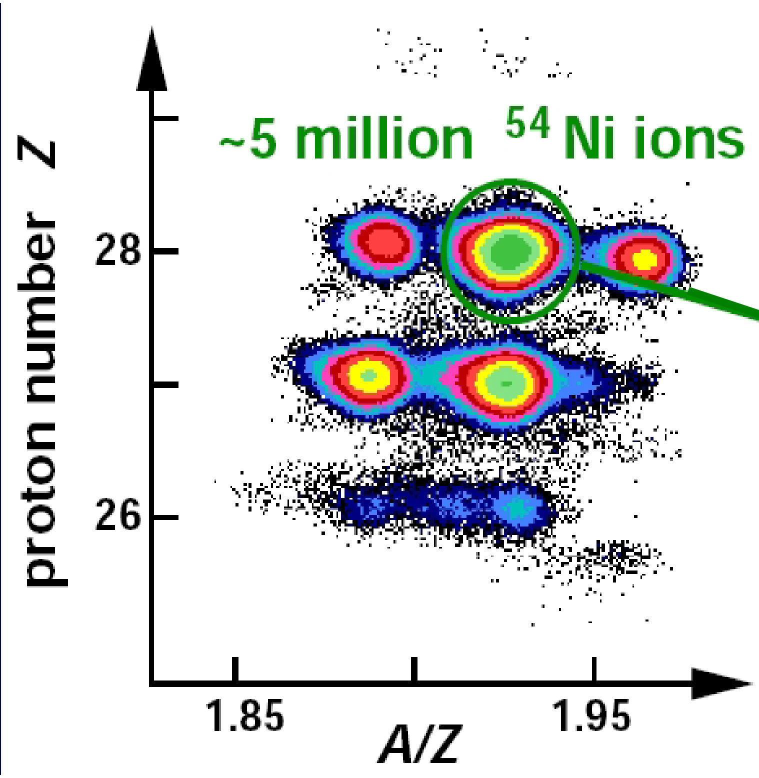
decay of the excited 10^+-state by proton emission and γ-radiation

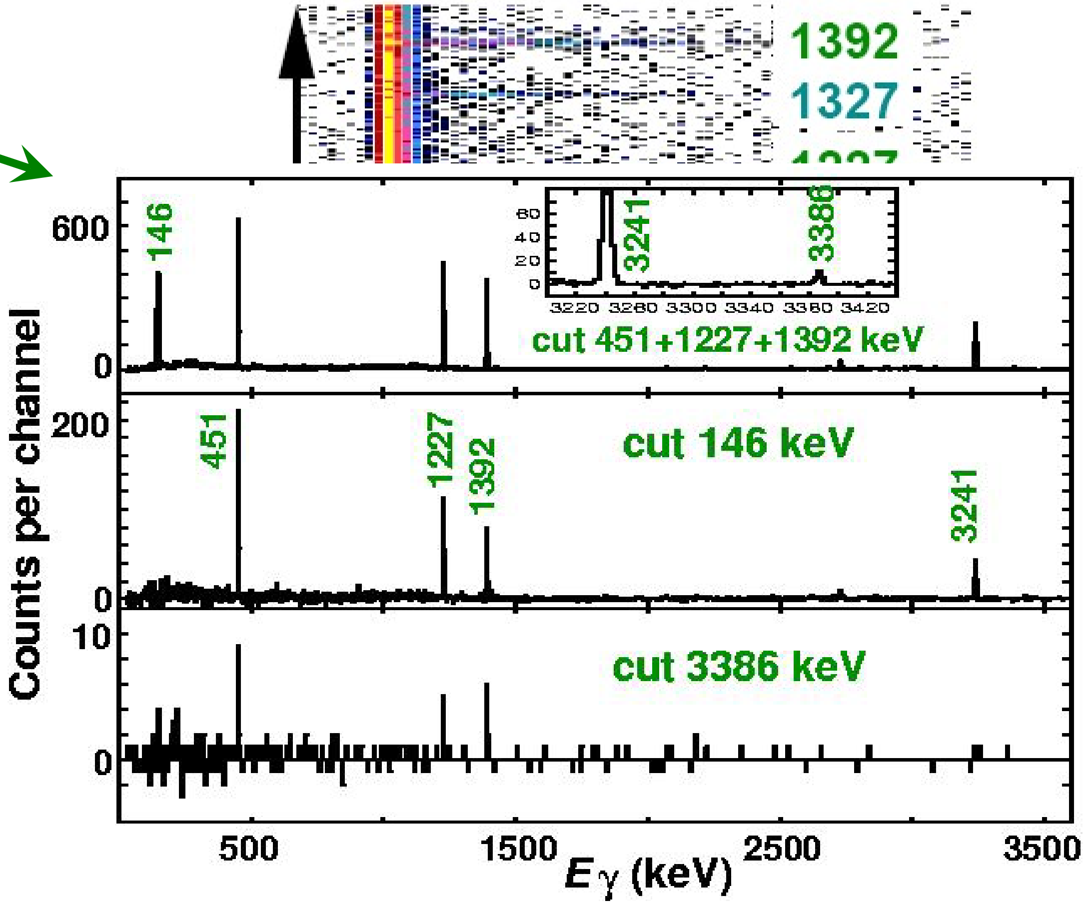


^{54}Fe / ^{54}Ni: π / ν $(f_{7/2})^{-2}$

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

Identification of ^{54}Ni

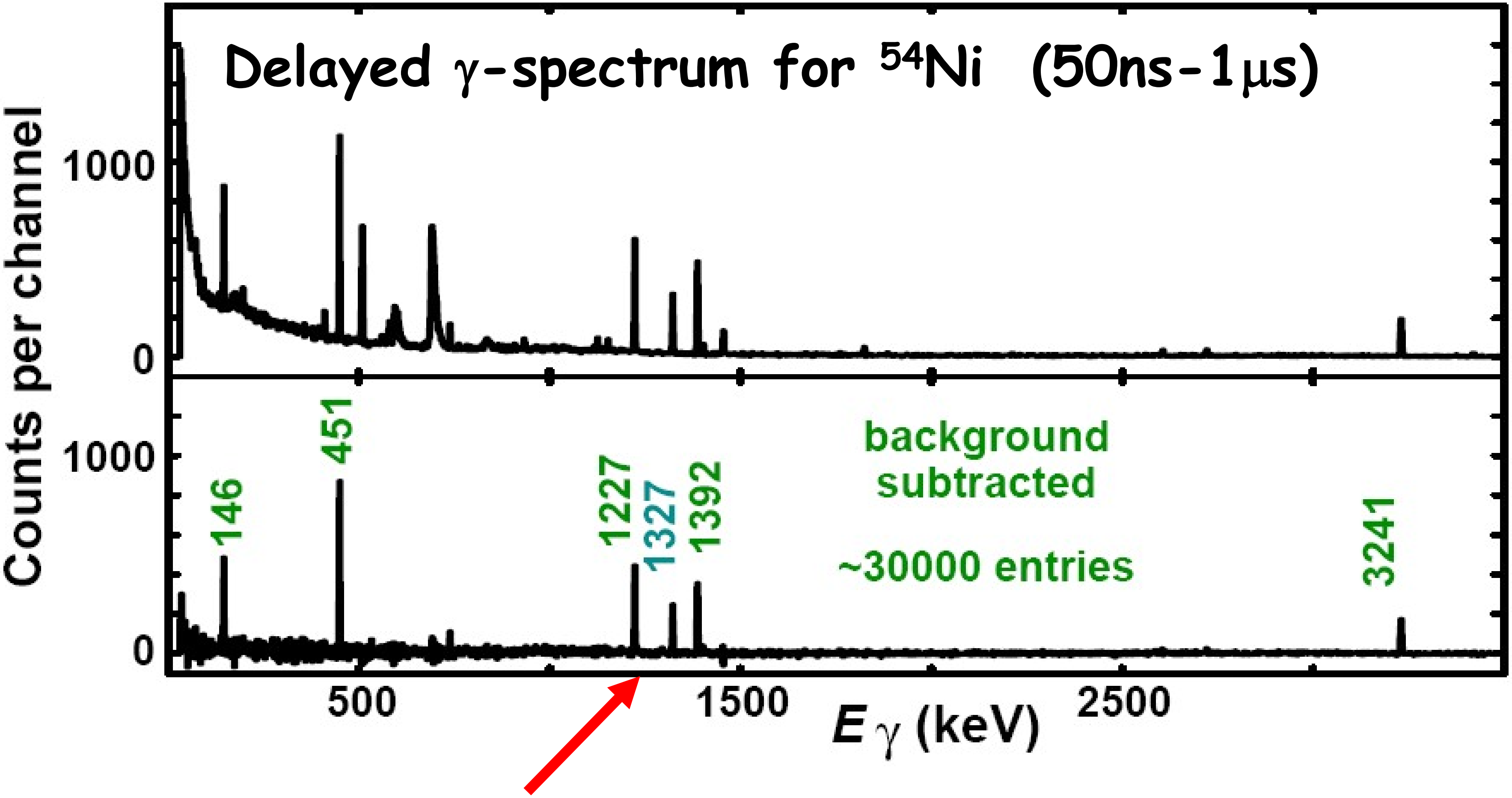




gate on ^{54}Ni

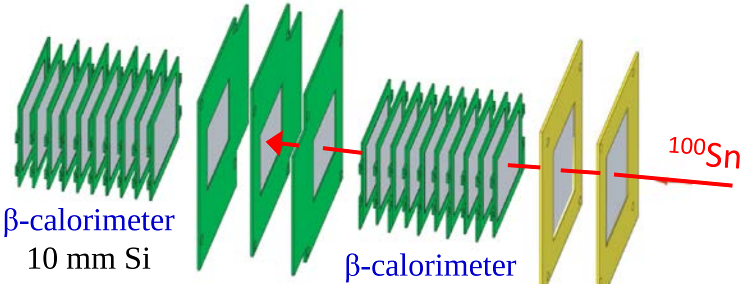
50 ns < t < 1 μs

The big surprise …



Where does the 1327 keV line come from ???

Active target SIlicon IMplantation detector and Beta Absorber



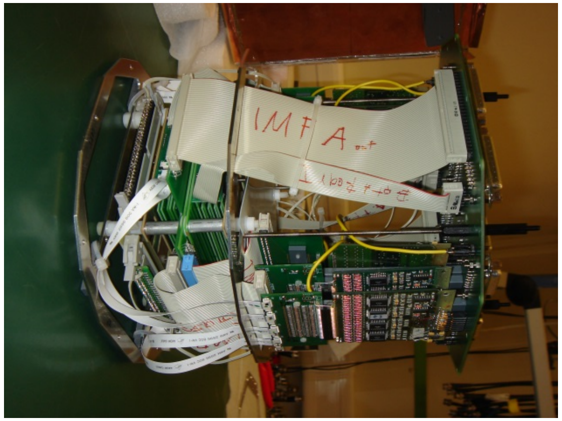
^{100}Sn

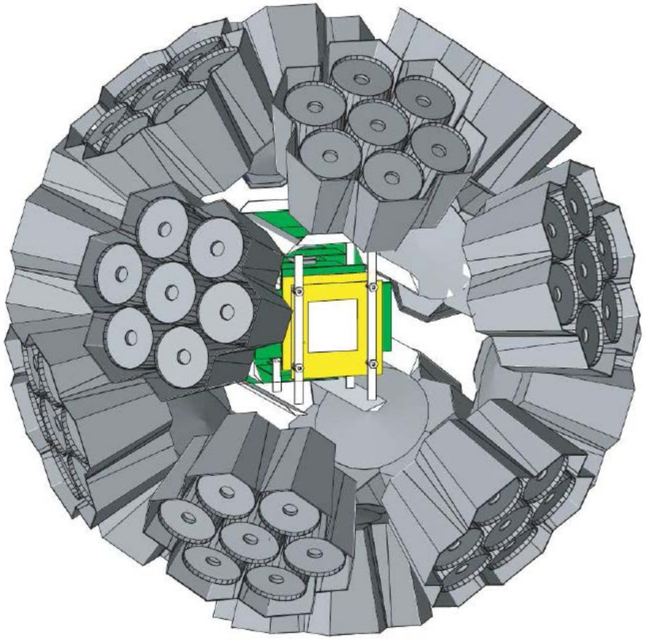
β-calorimeter
10 mm Si

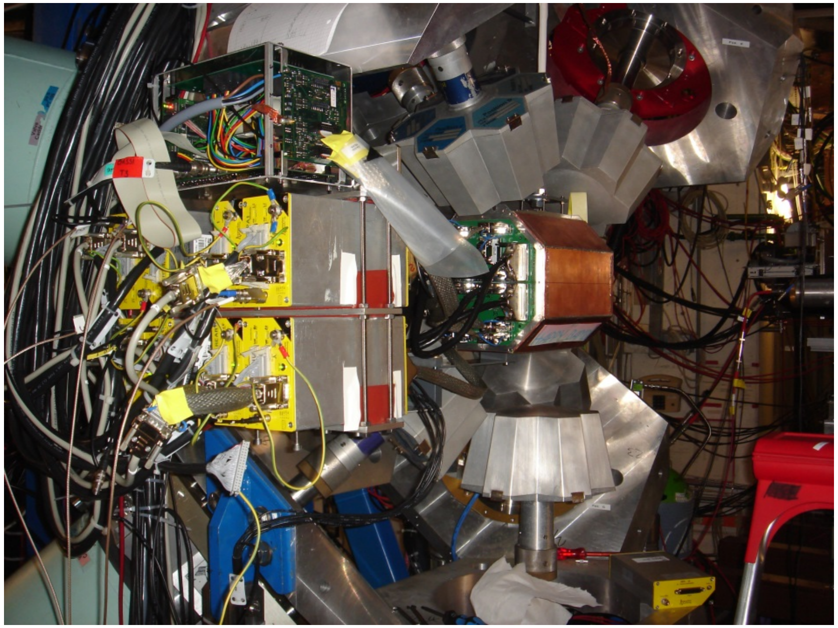
implantation
2.1 mm Si

β-calorimeter
10 mm Si

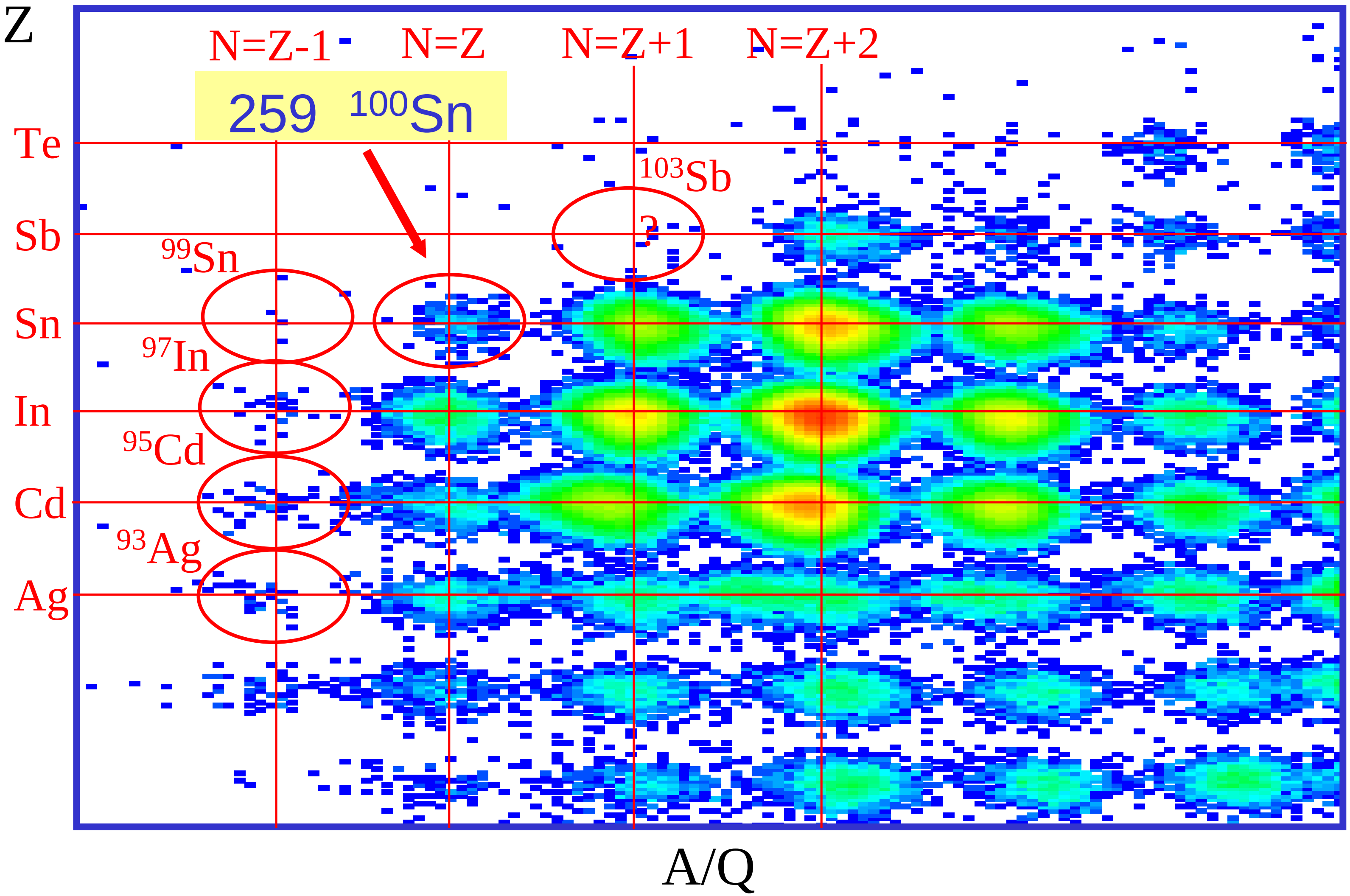
x-y position
0.6 mm Si





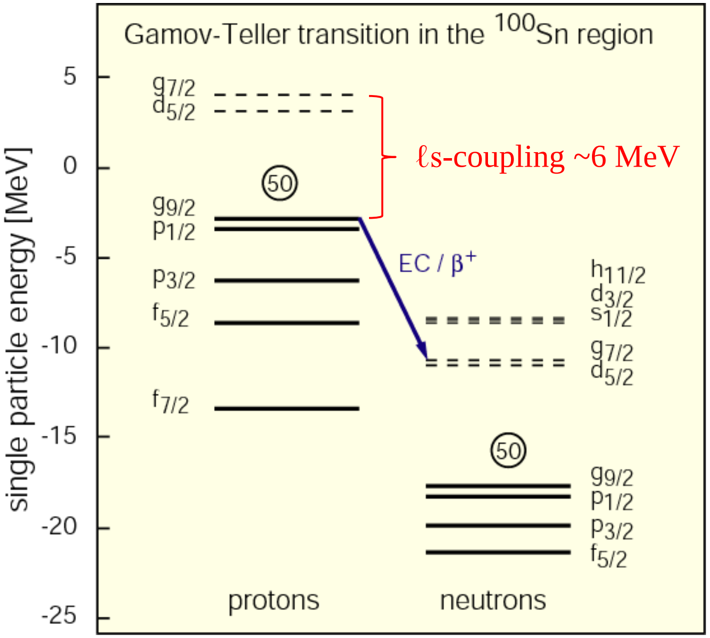


Spectroscopy of the doubly magic nucleus ^{100}Sn and its decay



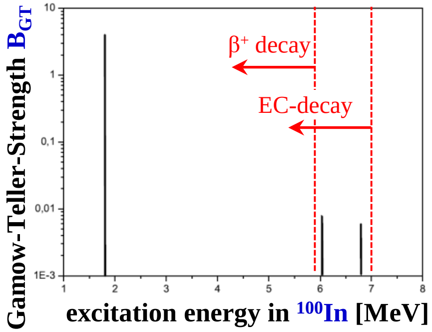
Gamow-Teller Strength and Q_{EC} value in the β-decay of ^{100}Sn

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



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

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

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

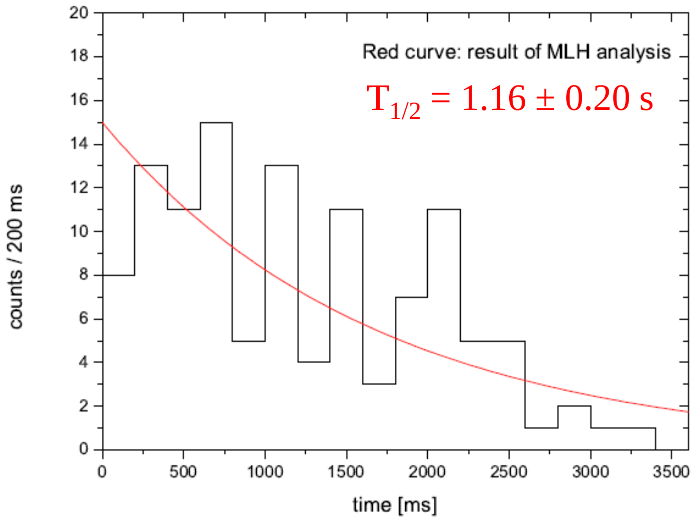
Theoretical calculation of the distribution of the GT-strength:

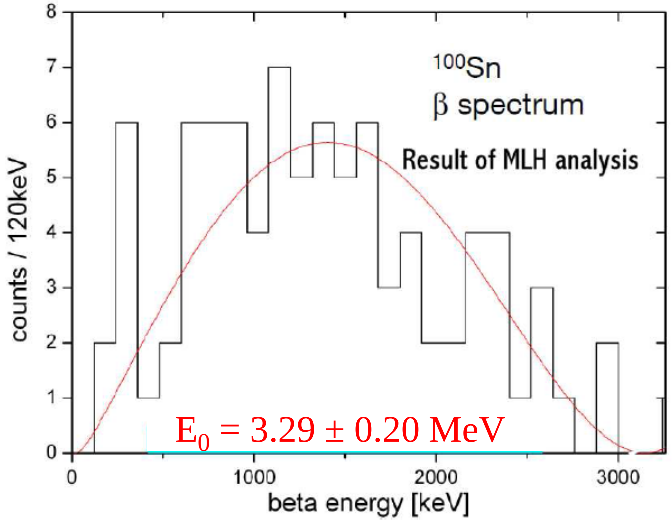
97% of the whole strength is concentrated in a single state, which is accessible in the β^+-decay

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

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 $f(Z,E_0)$:

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

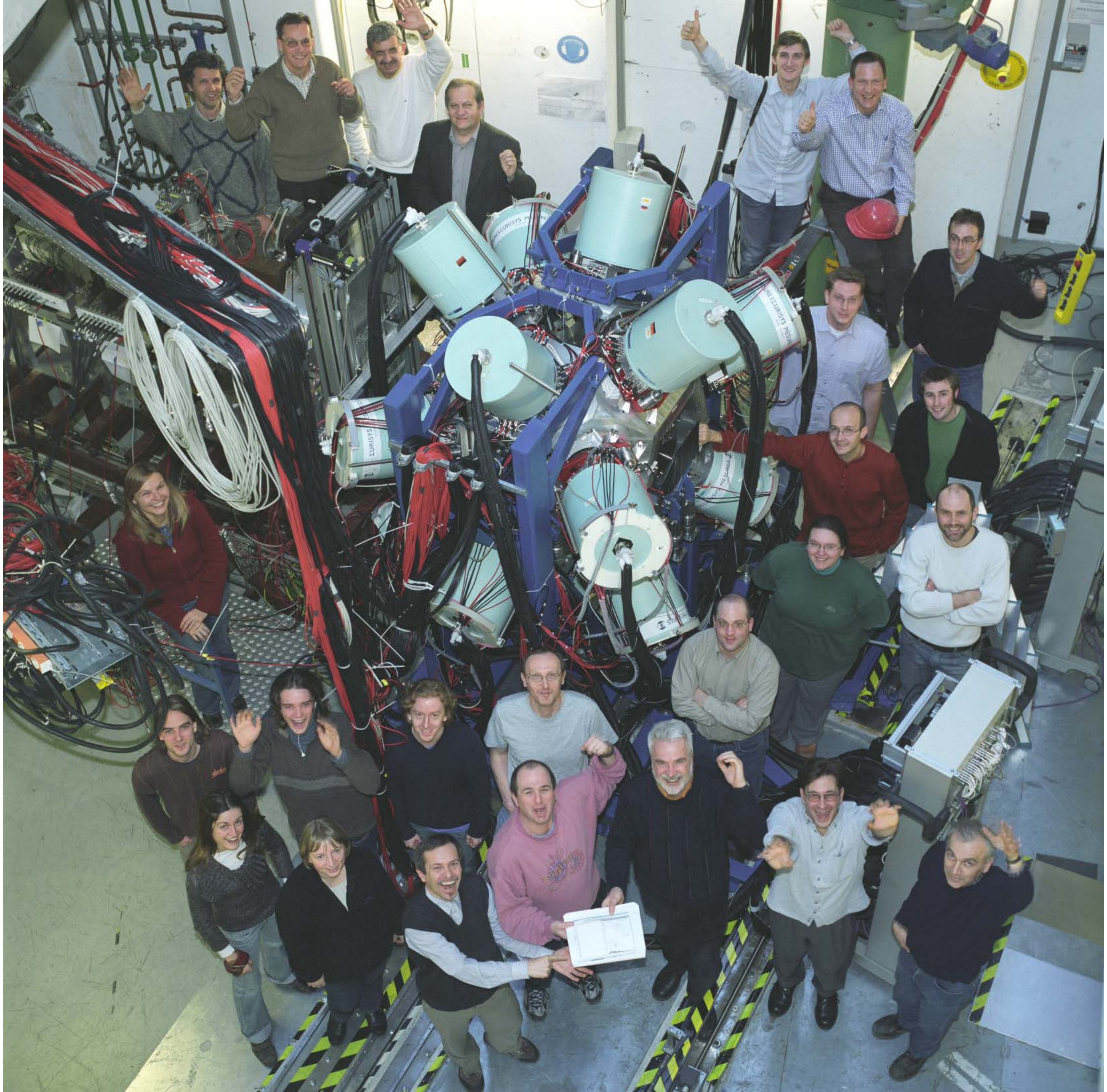
$G_F/(\hbar c)^3 = 1.16637(1)\cdot10^{-5}$ GeV^{-2}, $g_A/g_V = 1.2695 \pm 0.0029$

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

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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