Physics with Exotic Nuclei
Hans-Jürgen Wollersheim
Excited Fragments – Gateway to Nuclear Structure

- Nuclear Isomers (shape-, spin-, K-traps)
- In-Flight Separation of excited Radioactive Ion Beams
- 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 – $\beta$-Decay of $^{100}$Sn

Scattering Experiments with RIBs – Nuclear Structure Results
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!
What is a Nuclear Isomer?

Nuclear Isomer – a long-lived excited nuclear state \((T_{1/2} > 1 \text{ ns})\) decays by emission of \(\alpha, \beta, \gamma, p, \text{fission, cluster}\)

The first one discovered by O. Hahn in Berlin in 1921 – decay of \(^{234}\text{Pa}\) (70 s) von Weizsacker, A. Bohr & B. Mottelson

\[
\frac{1}{\tau} \sim E_\gamma^{2\lambda+1} |< \psi_f | T | \psi_i >|
\]
Three Types of Isomers

$10 \text{ ns} < T_{1/2} < 100 \mu\text{s}$
1. Shape Isomers

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

\[ \text{EA} = 5.8 \pm 0.3 \text{ MeV} \]
\[ \text{EB} = 5.45 \pm 0.3 \text{ MeV} \]
\[ T_{1/2} = 3.8 \text{ ns} \]

\[ \alpha \]

\[ {^{238}}\text{U}(\alpha,2n)^{240}\text{Pu}, \ E_\alpha = 25 \text{ MeV} \]

1. Shape Isomers

2. K Isomers

- A well-known example:

\[
\begin{align*}
\text{Fermi Surface} \\
\begin{array}{c}
\text{neutron} \\
\text{proton}
\end{array}
\end{align*}
\]
2. K Isomers

A well-known example:
2. K Isomers

- A well-known example:

![High-K isomers in 178Hf diagram](image-url)
2. K Isomers

- A well-known example:

\[
(n^2 \otimes \pi^2)_{16^+}
\]

\[
\nu^2_{8^-} \otimes \pi^2_{8^-}
\]

High-K isomers in $^{178}$Hf

\[\begin{align*}
\text{Energy (MeV)} & \\
\text{31 yr isomer} & \\
16 & \\
12 & \\
8 & \\
6 & \\
4 & \\
0 & \\
\end{align*}\]

Müller et al., *Phys. Lett.* B393 (1997) 279
3. Spin Isomers

\[ J_g \pi (8 \rightarrow 2) = -J_g \pi (8 \rightarrow 2) \approx 170 \text{ ns} \]

\[ J_g \pi (2, 4, 6 \rightarrow 1) = -J_g \pi (2, 4, 6 \rightarrow 1) \approx 230 \text{ ns} \]

\[ 98^{\text{Cd}}_{50} \]

\[ \pi (g_{9/2})^{-2} \text{ } J=8 \]

\[ \pi (g_{9/2})^{-2} \text{ } J=0 \]

Fig. 7. Realistic level diagram for protons.

3. Spin Isomers

\[ \pi(g_{9/2})^2 J=8 \nu(g_{9/2})^1 (d_{5/2})^1 J=6,4,2 \]

\[ \sim 230 \text{ ns} \] \[ \sim 170 \text{ ns} \]

Experimental set-up for isomer decay
ionization chambers (MUSIC41,42)
scintillator (SC41)
degraded
multiwire chambers (MW41,MW42)
Experimental set-up with passive target

\[ \sigma_{\text{exp}}^{(136}\text{Cd}) \approx 150 \text{ pb} \]

4 g/cm² Be

\[ ^{136}\text{Xe} \]

750 MeV/u

\( \Delta E \)

15 Cluster detectors with 105 Ge crystals

\( \epsilon_\gamma = 11\% \) at 1.3 MeV, 20\% at 550 keV, 35\% at 100 keV

\( \gamma \) detection efficiency

- very high \( \gamma \)-ray efficiency
- high granularity (prompt flash problem)

S. Pietri et al., NIM B261 (2007), 1079
Limitations to Isomer Spectroscopy

degraded

electrical field lines
Identification of $^{130}_{48}\text{Cd}_{82}$

Production:
- $\sigma_{\text{exp}}^{(130}\text{Cd}) \sim 150 \text{ pb}$
- $4 \text{ g/cm}^2 \text{ Be}$
- $^{136}\text{Xe}$
- $750 \text{ MeV/u}$

Selection & Identification:
- "S2"
- "S4"
- Time-of-flight measurement
- Position measurement
- Wedge-shaped degrader
- $\Delta E$

Stopping:
- "S4"

Variable degrader

Spectroscopy

4000 identified $^{130}\text{Cd}$ ions in fragmentation
Limitations to Isomer Spectroscopy

$^{130}$Cd: DGF-timing

Prompt $\gamma$-flash

Decay time range: 20 ns ... 20 $\mu$s

Decay Spectroscopy Probes Shell Closures

$
^{130}\text{Cd}: \text{DGF-timing}
$

Decay Spectroscopy Probes Shell Closures

No Shell quenching observed
$8^+(g_{9/2})^{-2}$ Seniority Isomers in $^{98}$Cd and $^{130}$Cd

N=50
Z=48

Cd$^{98}$
9.2 s
$0^+$

EC

N=50
Z=48

$2^+$

1395

participating neutron-orbitals

N=82
MeV

2.6

h$_{11/2}$

2.2

d$_{3/2}$

1.6

s$_{1/2}$

0.5

d$_{5/2}$

0

g$_{7/2}$


(8$^+$) 2428
(6$^+$) 2281
(4$^+$) 2083

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

No dramatic shell quenching!

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

Cd$^{130}$
0.20 s
$0^+$

N=82
Z=48

(2$^+$) 1325

β-n


Assumption of a $N=82$ shell quenching leads to a considerable improvement in the global abundance fit in r-process calculations!
Level Scheme of $^{210}\text{Pb}$
Level Schemes in Neutron-Rich Pb Isotopes

\[ g_{9/2} \]

\( ^{210}\text{Pb} \)  
\[ t_{1/2} = 0.201(17) \mu s \]

\( ^{212}\text{Pb} \)  
\[ t_{1/2} = 6.0(8) \mu s \]

\( ^{214}\text{Pb} \)  
\[ t_{1/2} = 6.2(3) \mu s \]

\( ^{216}\text{Pb} \)  
\[ t_{1/2} = 0.4(4) \mu s \]
T=1 Isospin Symmetry in pf-shell Nuclei

search for isospin breaking effects

decay of the excited 10\(^+\)-state by proton emission and \(\gamma\)-radiation

Identification of $^{54}$Ni

$\sim$5 million $^{54}$Ni ions

gate on $^{54}$Ni

50 ns < t < 1 µs

Counts per channel

$E_\gamma$ (keV)

FAIR GSI
The big surprise ...

Delayed $\gamma$-spectrum for $^{54}$Ni (50ns-1µs)

Where does the 1327 keV line come from ???
Active Target
Silicon IMplantation Detector and Beta Absorber

\[\text{implantation} \quad 2.1 \text{ mm Si} \]
\[10 \text{ mm Si} \]

\[\text{β-calorimeter} \quad 10 \text{ mm Si} \]

\[100\text{Sn} \]

\[\text{x-y position} \quad 0.6 \text{ mm Si} \]
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

- $^{100}$Sn
- $0^+$
- $1.6$ MeV
- $5$ ns
- $6^+$
- $4^+$
- $2^+$
- $3^-$
- $\approx 100$ ns

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

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

- $^{100}$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 $\beta^+$-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 $\beta^+$-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 $\ell=4$ $N_{\nu g_{7/2}}=0$ $N_{\pi g_{9/2}}=10$
Gamov-Teller strength and $Q_{EC}$ value in the $\beta$-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 $f(Z,E_0)$:

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

$$G_F/(hc)^3 = 1.16637(1) \cdot 10^{-5} \text{ GeV}^2; \quad g_A/g_v = 1.2695 \pm 0.0029$$

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

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

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

Fermi-integral with LOGFT program NNDC
Gamov-Teller strength and $Q_{EC}$ value in the $\beta$-decay of $^{100}$Sn

\[ B_{GT}(ESM) = \frac{4\ell}{2\ell + 1} \cdot \left(1 - \frac{N_{\nu g7/2}}{8}\right) \cdot N_{\pi g9/2} = 17.78 \]

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

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

The main condition for the existence of isolated Super Gamow-Teller transition is that the spin-orbit gap between the $\ell+1/2$ and $\ell-1/2$ orbits (in $^{100}$Sn $\ell = 4$ orbitals $\pi g9/2, \nu g7/2$) 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 $\beta$-decay of $^{100}$Sn

\[ Q_{EC} = E_\beta + E(1^+) + 2m_e c^2 \]