Mini-Workshop on Future In-Beam Conversion Electron Spectroscopy  
ISKP Bonn, 23./24. January 2003  

Conversion Electron Spectroscopy  
in the Second Minimum of Actinides  

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- Introduction: double-humped fission barrier, fission isomers  
- Experiments in the superdeformed 2. minimum: $^{240f}$Pu  
  - $\gamma$-spectroscopy  
  - conversion electron spectroscopy  
- Predictions from phenomenological systematics  
- Summary and Outlook
2. minimum and fission isomers

- double-humped fission barrier:

\[
\text{(macroscopic) droplet model} + \text{(microscopic) shell corrections (Strutinsky, 1967)}
\]

- \( ^{240}\text{Pu} \):

\[
\text{1. minimum} \quad \text{2. minimum}
\]

- magic neutron number \( N=146 \), fission isomer: \( t_{1/2} = 3.8 \text{ ns} \)

- pioneer experiment by Specht et al. (1972):
  conversion electron spectroscopy after \( ^{238}\text{U} (\alpha 2n) ^{240}\text{Pu} \)
  first identification of fission isomeric ground state rotational band
\( \gamma \) spectroscopy in \( ^{240f}\text{Pu} \)

- 6 Ge-CLUSTER of German EUROBALL Collaboration: 42 detectors
- \( ^{238}\text{U}(\alpha, 2n)\ ^{240f}\text{Pu} \) \( t_{1/2} = 3.8 \text{ ns} \), 440 hrs. beamtime
- delayed coincidence with fission fragments

- single intensive \( \gamma \)-line (786.1 keV, 36.6 \%) + weaker lines
- regular rotational band structure: starting point for level scheme

**Mini Orange setup for conversion electron spectroscopy**

**Principle:**

- Mini-Oranges: 3x annular Si detector (delayed fission)
- 238 U Target
- α
- wedge-shaped permanent magnets around central Pb absorber
- toroidal magnetic field
- 2 configurations:
  - $300 \leq E_e (\text{keV}) \leq 600$
  - $600 \leq E_e (\text{keV}) \leq 800$
- Si(Li)-detectors: $\Delta E \sim 3.1 \text{ keV}$
- total efficiency: 5.4 % (625 keV)
Experimental Setup for Conversion Electron Spectroscopy
Conversion electrons from $^{240f}$Pu

- from 2 series of experiments (ca. 570 hrs. beamtime):
  transmission optimized for 300-600 keV, 600-800 keV
- reaction: $^{238}\text{U}(\alpha,2n)^{240f}\text{Pu}$ $E_\alpha = 25 \text{ MeV}$
- electrons in delayed coincidence with fission fragments

![Graph showing electron energy distribution and transmission efficiency]
**β bands in $^{236f,238(f)}U$ and $^{240}Pu$**

1. minimum:

![Graph showing β bands and α, α' reaction](image)


2. minimum:

![Graph showing U(d,pn) reactions](image)


- $I_β$ - $I_g$ - degeneracy removed
**Combined analysis: γ’s + conversion electrons**

- all strong electron lines are E0 transitions
- conversion coefficient of 786.1 keV transition: E1
- first excited β-vibrational phonon: 769.9 keV
- connecting E0 transitions between excited rotational bands

excluded states in 2$^+_1$ manifold: ca. 98% negative parity

\[ K^\pi = 0^+ \]
\[ K^\pi = 1^+ \]
\[ K^\pi = 2^+ \]
\[ K^\pi = 0^+ \]

\[ \beta \text{ band} \]
\[ \alpha \text{ band} \]
\[ \gamma \text{ band} \]

\[ 3.7 \text{ ns} \]
\[ < 10 \text{ ps} \]
\[ 150 \text{ ps} \]

\[ 10 \text{ s} \]
\[ 4 \text{ ns} \]
\[ 8 \text{ ps} \]

\[ 10^{-8} \]
\[ 10^{-6} \]
\[ 10^{-4} \]

\[ 10^{-3} \]
\[ 10^{-2} \]
\[ 10^{-1} \]

\[ E^0 \]
\[ E^1 \]

\[ \Delta E = 0.19 \]
\[ \Delta E = 0.20 \]
\[ \Delta E = 0.36 \]
\[ \Delta E = 0.49 \]
\[ \Delta E = 0.33 \]

\[ 46.72(9) \ E^2 (67) \]
\[ 73.12(12) \ E^2 (44) \]
\[ 99.35(13) \ E^2 (24) \]

\[ 535.2(2) \ [1.2(3)] \]
\[ 535.5(3) \ [1.1(3)] \]
\[ 538.6(2) \ [U] \]
\[ 545.1(1) \ [0.7] \]
\[ 554.3(4) \ [Y] \]

\[ 598.0(5) \ [0.8] \]
\[ 570.3(4) \ [3.5(5)] \]

\[ 826.7(3) \ [3.2(4)] \]

\[ 739.6(14) \ E^0 (0.12) \]

\[ 561.0(2) \ [1.8(3)] \]

\[ 538(1) \ [1.5(2)-U] \]

\[ 1332 \]
\[ 1816 \]

\[ 1580.5(14) \]
\[ 1518.7(13) \]
\[ 1465.7(6) \]
\[ 1421.4(6) \]
\[ 1386.6(3) \]
\[ 1360.9(2) \]
\[ 1344.5 \]

\[ 986.8(13) \]
\[ 892.4(12) \]
\[ 825.0(11) \]
\[ 785.1(11) \]
\[ 769.9(10) \]

\[ 666.5(13) \]
\[ 920.7(12) \]
\[ 882.8(6) \]
\[ 851.1(4) \]
\[ 826.2(2) \]
\[ 806.2(1) \]

\[ 44.8 \ E^2 (~15) \]
\[ 31.7 \ E^2 (~15) \]
\[ 57.2 \ E^2 (~20) \]

\[ \Delta E = 0.3 \]

\[ < 10 \text{ ps} \]

\[ \beta \text{ band} \]
\[ \alpha \text{ band} \]
\[ \gamma \text{ band} \]

\[ 514.8(15) \ E^0 (0.3) \]
\[ 520.4(14) \ E^0 (0.4) \]
\[ 529.0(12) \ E^0 (0.4) \]
\[ 543.6(12) \ E^0 (0.3) \]
\[ 556.5(12) \ E^0 (0.3) \]
\[ 581.8(12) \ E^0 (0.2) \]
\[ 595.1(18) \ E^0 (0.2) \]
\[ 628.3(13) \ E^0 (0.2) \]
\[ 644.9(14) \ E^0 (0.2) \]
\[ 508.4 \ E^0 (<0.05) \]
\[ 525 \ E^0 (0.5) \]

\[ 515 \]

\[ 10^{-8} \]
\[ 10^{-6} \]
\[ 10^{-4} \]
\[ 10^{-2} \]
\[ 10^{-1} \]

Level scheme of 240Pu
Moments of Inertia

(dynamical) moments of inertia:

\[ E = \left( \frac{\hbar^2}{2\Theta} \right) (I (I + 1)) \]

\[ \Theta/\hbar^2 = \frac{2 I - 1}{(E_I - E_{I-2})} \]

Variation of moments of inertia:
- in \( \beta \) band from rigid rotor limit (low I) to value of gs band (high I)
- odd-even staggering in b band known from \( K = 1^- \) bands in 1. minimum of actinides
- separately smooth behaviour for even/odd spins in b band
Systematics of collective excitations

- VCS: ’Valence Correlation Scheme’:
  Sum of valence nucleon pairs as ordering scheme

1. Minimum:
   - \( \gamma \) band

\[ E(2^+_{\gamma}) \ [\text{keV}] \]
\[ (N_p + N_n)/2 \]

2. Minimum:
   - \( \gamma \) band

\[ E(2^+_{\gamma}) \ [\text{keV}] \]
\[ (N_p + N_n)/2 \]

- enables prediction of phonon energies in 2. minimum
- exp. determination of new magic numbers in 2. minimum
Extension of the Grodzins Systematics

- Grodzins (/Raman): \( B(E2) \ E(2^+) = 2.6 \ Z^2 \ A^{-2/3} \)
- Actinide region: data plotted as function of quadrupole moment \( Q_0 \)

\[
B(E2) = \frac{5}{16} \pi \ |e\ Q_0|^2 \quad \text{(Single shell asymptotic Nilsson model)}
\]

converted from Sobiczewski et al.
Outlook:

- Study of a fission isomer with odd neutron number
  - measurement of single particle energies

\[ \gamma \text{ spectroscopy:} \]
- measurement of Nilsson orbitals in odd fission isomer \( ^{237f}\text{Pu} \)
  \[ \rightarrow \text{MINIBALL (new Germanium spectrometer)} \]

Conversion electrons:
- identification of \( \beta \)-vibrational bands in \( ^{237f}\text{Pu} \)
  \[ \rightarrow \text{Mini Oranges} \]

- Improvement of models for description of superheavy elements
  - main objective of MAFF project at new research reactor FRM–II
Expected Properties of $^{237}\text{fPu}$

- **Single Particle structure:** for neutrons at deformation of second well

- **Decay properties:**

  - **Conversion electron spectroscopy**
    - (prepared at Garching)
  
  - **$\gamma$-ray spectroscopy**
    - (MINIBALL)

M.H. Rafailovich et al., PRL 48 (1982) 982
Population of the Second Minimum

- Excitation function:

Reaction:

\[ ^{235}\text{U}(\alpha,2n)^{237}\text{Pu} \]

- Isomeric cross section:

\[
\begin{array}{c|c}
^{237}\text{Pu}: & ^{240}\text{Pu}: \\
^{235}\text{U}(\alpha,2n)^{237}\text{Pu} & ^{238}\text{U}(\alpha,2n)^{240}\text{Pu} \\
E_\alpha = 24 \text{ MeV} & E_\alpha = 24 \text{ MeV} \\
\sigma_{\text{delay}} = 1-2 \mu\text{b} & \sigma_{\text{delay}} = 10 \mu\text{b} \\
\frac{\sigma_{\text{delay}}}{\sigma_{\text{prompt}}} = 1.2 \times 10^{-5} & \frac{\sigma_{\text{delay}}}{\sigma_{\text{prompt}}} = (6-8) \times 10^{-5} \\
\frac{\sigma_{\text{short}}}{\sigma_{\text{long}}} = 1.1 & \\
\end{array}
\]

S. de Barros et al., Z. Phys. A 323 (1986) 101


Summary/Outlook

- **Advantage of fission isomers:**
  - low angular momenta, few K mixing
  - clear separation between vibrational and rotational excitations

- **Conversion electron spectroscopy indispensable tool:**
  - complementary to γ-ray spectroscopy: removal of ambiguities

- **Superdeformed 2. minimum:**
  - identification of superdeformed collective bands
  - determination of β phonon energy
  - detailed level scheme
  - predictive power for phonon energies in 2. minimum
  - exp. determination of new magic numbers in 2. minimum
  - extension of the Grodzins systematics

- **Outlook:**
  - identification of Nilsson single particle states
    - candidate: $^{237f}\text{Pu}$ with conversion electron, γ spectroscopy
  - (in beam) identification of the fission isomer in $^{239}\text{U}$
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