Observation of non-exponential orbital electron-capture decay of H-like $^{140}$Pr and $^{142}$Pm ions and possible implications for the neutrino masses

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Nuclear physics seminar at Warsaw University, May 14, 2008
Outline

1. Production, storage and cooling of highly-charged ions at GSI
2. Two-body beta decay of stored and cooled highly-charged ions
3. Experimental results for orbital electron capture of H-like $^{140}\text{Pr}$ and $^{142}\text{Pm}$ by means of single-ion decay spectroscopy
4. Tentative explanation(s) of the observed non-exponential decays
5. Summary, questions and outlook
Schottky Mass Spectrometry (SMS) - Collaboration

...back to our roots: stellar nucleosynthesis
Pathways of stellar nucleosynthesis

• Key parameters:
  • Masses, beta-lifetimes, n- capture-, n-γ cross-sections
    • Masses determine the pathways of s-, p-, rp- and r- processes
    • Beta-lifetimes the accumulated abundances
  • Hot stellar environment: atoms are highly-ionized
1. Production, storage and cooling of HCI at GSI
Secondary Beams of Short-Lived Nuclei
Production & Separation of Exotic Nuclei

Highly-Charged Ions
In-Flight separation
Cocktail or mono-isotopic beams
500 MeV/u primary beam $^{152}$Sm
400 MeV/u stored beam $^{140}$Pr, $^{142}$Pm
The ESR: $E_{\text{max}} = 420$ MeV/u, 10 Tm, electron-, stochastic-, and laser cooling.
Specifications of the ESR

- **Fast Injection**
  - $e^-$ cooler
  - $I = 10...500$ mA

- **Re-injection to SIS**
  - $p = 2 \cdot 10^{-11}$ mbar
  - $E = 3...420$ MeV/u
  - $f \approx 1...2$ MHz
  - $\beta = 0.08...0.73$
  - $Q \approx 2.65$

- **Extraction**
  - $L = 108$ m $= \frac{1}{2} L_{\text{SIS}}$

- **Magnets**
  - 6 Dipoles, 1.6 Tesla
  - 4 Triplet lenses
  - 4 Duplet lenses
  - 8 Sextupole lenses

- **Magnet Power**
  - Dipoles: 3.7 kA at 1.6 kV
  - Field Ramp max. 1 T/s

- **RF Acceleration**
  - 2 Cavities at 5 kV
  - Frequency Span 0.8 - 5 MHz

- **Vacuum**
  - operational $10^{-11}$ Torr
  - bakable to 300 °C

- **Beam Diagnosis**
  - 12 Position Monitors
  - 1 DC Transformer
  - 1 fast Transformer
  - 1 Profile Harp
  - 1 Faraday Cup
  - 1 Beam Scaper

- **Particle detectors**

- **Schottky pick-ups**

- **Gas jet**
Stochastic cooling is in particular efficient for hot ion beams.
"Cooling": enhancing the phase space density

**Electron cooling: G. Budker, 1967 Novosibirsk**

Momentum exchange with a cold, collinear $e^-$ beam. The ions get the sharp velocity of the electrons, small size and small angular divergence.
"Phase transition" to a linear ion chain

ESR: circumference ≈ $10^4$ cm

For 1000 stored ions, the mean distance amounts to about 10 cm

At mean distances of about 10 cm and larger, intra-beam-scattering disappeared.

M. Steck et al., PRL 77 (1996) 3803
Recording the Schottky-noise

\[ \frac{\Delta f}{f} = -\frac{1}{\gamma_t^2} \frac{\Delta (m/q)}{m/q} + \frac{\Delta v}{v} \left( 1 - \frac{\gamma_t^2}{\gamma^2} \right) \]

Real time analyzer Sony-Tektronix 3066

128 msec

→ FFT

64 msec

→ FFT
time

Electron Cooler

\[ \frac{\Delta v}{v} \to 0 \]
\[ \sin(\omega_1) \sin(\omega_2) \sin(\omega_3) \sin(\omega_4) \]

Fast Fourier Transform

SMS
Three-body beta decay, e.g. $\beta^+: \, p \rightarrow n + e^+ + v_e$

both, mass ($m$) and charge state ($q$) change

→ quite different revolution frequencies and orbits

Two-body beta decay, e.g. EC: $p + e^-_b \rightarrow n + v_e$

only difference of mass, $q$ remains the same

→ small difference in revolution frequency, (almost) same orbit
Small-band Schottky frequency spectra

\[ m/\Delta m \approx 700000 \]
2. Two-body beta decay of stored and cooled HCl
First direct observation of bound-state $\beta$ decay

T. Ohtsubo et al., PRL 95 (2005) 052501

Parent and daughter ions are in the same spectrum
Cooling
Present EC-experiments: Decay schemes

140\(^{58}\)Ce

140\(^{59}\)Pr

Q\(_{EC}\) = 3388 keV

3.39 min

142\(^{61}\)Pm

Q\(_{EC}\) = 4870 keV

40.5 s

\(\beta^+ = 76.8\%\)

\(\varepsilon = 19.7\%\)

\(99.4\%\)

\(96.4\%\)

stable

stable
Two-body β decay:

- $f$ scales as $m/q$
- $q$ does not change
- Change of $f$ only due to change of mass
EC in Hydrogen-like Ions

\[ \lambda_{\beta+}/\lambda_{\text{EC}} \text{(neutral atom)} \approx 1 \]

Expectations:
\[ \lambda_{\text{EC}}(\text{H-like})/\lambda_{\text{EC}}(\text{He-like}) \approx 0.5 \]

FRS-ESR Experiment

\[ \lambda(\text{neutral}) = 0.00341(1) \text{ s}^{-1} \]
G. Audi et al., NPA729 (2003) 3

\[ \lambda_{\beta+}(\text{bare}) = 0.00158(8) \text{ s}^{-1} \text{(decay of }^{140}\text{Pr}^{59+}) \]

\[ \lambda_{\text{EC}}(\text{H-like}) = 0.00219(6) \text{ s}^{-1} \text{(decay of }^{140}\text{Pr}^{58+}) \]

\[ \lambda_{\text{EC}}(\text{He-like}) = 0.00147(7) \text{ s}^{-1} \text{(decay of }^{140}\text{Pr}^{57+}) \]

\[ \lambda_{\text{EC}}(\text{H-like})/\lambda_{\text{EC}}(\text{He-like}) = 1.49(8) \]

Yu. Litvinov et al., PRL 99 (2007) 262501
Electron Capture in Hydrogen-like Ions

Gamow-Teller transition $1^+ \rightarrow 0^+$

Theory: Z. Patyk et al., PR C77 (2008) 014306
The H-like ion really decays by 20% faster than the neutral atom!

$\lambda(H)/\lambda(He) = (2I+1)/(2F+1)$

S. Typel and L. Grigorenko
$\mu = +2.7812 \mu_N$ (calc.)

Probability of EC Decay
- Neutral $^{140}$Pr: $P = 2.381$
- He-like $^{140}$Pr: $P = 2$
- H-like $^{140}$Pr: $P = 3$

$F(^{140}$Pr$^{58+}) = 1 \pm 1/2 = \begin{cases} 3/2 \\ 1/2 \end{cases}$

$F(^{140}$Ce$^{58+} + e) = 1/2$
Single-Particle Decay Spectroscopy

Sensitivity to single stored ions

Well-defined creation time $t_0$

Well-defined quantum states

Two-body $\beta$-decay (g.s. $\rightarrow$ g.s.)
emission of flavour eigenstate $\nu_e$
Entanglement of $\nu_e$ and daughter atom by momentum and energy

Recording the correlated changes of peak intensities of mother- and daughter ions defines the decay

Time-dependence of detection efficiency and other systematical errors are nearly excluded

Restricted counting statistics

F. Bosch et al., Int. J. Mass Spectr. 251 (2006) 212
Nuclear Decay of Stored Single Ions

- Time after injection / s

- Noise power density / arb. u.

- Frequency / kHz

- $^{155}$Ho$^{65+}$
- $^{155}$Dy$^{65+}$

- Height of 1 particle

- Nuclear e$^-$ capture

- Nuclear decay of stored single ions
Nuclear Decay of Stored Single Ions

Time after injection / s

Frequency / kHz

Time/channel = 30 sec.
Examples of measured time-frequency traces

$^{140}\text{Pr}^{58+}$

Time/ch. = 640 msec

$^{140}\text{Ce}^{58+}$

$^{142}\text{Pm}^{60+}$

$^{142}\text{Nd}^{60+}$

$\beta^+$ or loss

$\text{EC}$

$t=49.92 \text{ s}$

$t=18.64 \text{ s}$

$t=67.84 \text{ s}$

Revolution frequency - 59260 [kHz]

Revolution frequency - 59270 [kHz]
2 $^{140}$Pr$^{58+}$

1 $^{140}$Pr$^{58+}$

1 $^{140}$Ce$^{58+}$

↑ Time/ch. = 64 msec
Properties of measured time-frequency traces

1. Continuous observation
2. Parent/daughter correlation
3. Detection of all EC decays
4. Delay between decay and "appearance" due to cooling
5. $^{140}$Pr: $E_R = 44$ eV
   Delay: 900 (300) msec
\[ ^{142}\text{Pm: } E_R = 90 \text{ eV} \]
   Delay: 1400 (400) msec

Measured frequency:

$^p$ transformed to $n$ (hadronic vertex)
bound $e^-$ annihilated (leptonic vertex)
$\rightarrow \nu$ in flavour eigenstate $\nu_e$ created at $t_d$
if lepton number conservation holds
Charged-Current event at SNO

Appearance of two protons and of a fast electron:

\[ \nu_e + n \rightarrow p + e^- \]

\[ \nu_e = \cos \theta |v_1> + \sin \theta |v_2> \]
Why we have to restrict onto 3 injected ions at maximum?

The variance of the amplitudes gets larger than the step 3→4 ions.

Amplitude distributions corresponding to 1,2,3-particles; 1 frame = 64 msec.

The presented final data suppose agreement within +- 320 msec. between computer- and "manual" evaluation; always the "appearance" time has been taken.
Frequency-time characteristics of an EC decay
EC in H-like ions for nuclear g.s. → g.s. transitions

Decay identified by a change of atomic mass at time $t_d$

→ Appearance of the recoiling daughter ion shortly later (cooling)

Distribution of delays due to emission characteristics of the neutrino

No third particle involved

→ daughter nucleus and neutrino entangled by momentum- and energy conservation → EPR scenario
3. Experimental results of EC of H-like $^{140}$Pr and $^{142}$Pm

Decay statistics of $^{140}\text{Pr}^{58+}$ EC-decays
$^{140}$Pr all runs: 2650 EC decays from 7102 injections
Fast Fourier Transform of the data

Frequency peak at $f = 0.142$ Hz
$^{142}\text{Pm}$: 2740 EC decays from 7011 injections
$^{142}\text{Pm}$: zoom on the first 33 s after injection
Fits with pure exponential (1) and superimposed oscillation (2)

\[ \frac{dN_{EC}(t)}{dt} = N_0 \exp\{-\lambda t\} \lambda_{EC} ; \quad \lambda = \lambda_{\beta^+} + \lambda_{EC} + \lambda_{\text{loss}} \] (1)

\[ \frac{dN_{EC}(t)}{dt} = N_0 \exp\{-\lambda t\} \lambda_{EC}(t) ; \quad \lambda_{EC}(t) = \lambda_{EC}[1+a \cos(\omega t+\phi)] \] (2)

<table>
<thead>
<tr>
<th>Eq.</th>
<th>(N_0\lambda_{EC})</th>
<th>(\lambda)</th>
<th>(a)</th>
<th>(\omega)</th>
<th>(\chi^2/\text{DoF})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.9(18)</td>
<td>0.00138(10)</td>
<td>-</td>
<td>-</td>
<td>107.2/73</td>
</tr>
<tr>
<td>2</td>
<td>35.4(18)</td>
<td>0.00147(10)</td>
<td>0.18(3)</td>
<td>0.89(1)</td>
<td>67.18/70</td>
</tr>
</tbody>
</table>

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<tr>
<th>Eq.</th>
<th>(N_0\lambda_{EC})</th>
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<th>(a)</th>
<th>(\omega)</th>
<th>(\chi^2/\text{DoF})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46.8(40)</td>
<td>0.0240(42)</td>
<td>-</td>
<td>-</td>
<td>63.77/38</td>
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<tr>
<td>2</td>
<td>46.0(39)</td>
<td>0.0224(41)</td>
<td>0.23(4)</td>
<td>0.89(3)</td>
<td>31.82/35</td>
</tr>
</tbody>
</table>

\(T = 7.06 (8) \text{ s}\)
\(\phi = -0.3 (3)\)

\(T = 7.10 (22) \text{ s}\)
\(\phi = -1.3 (4)\)
4. Tentative explanation(s)
periodic "holes"?

no
1. Are the periodic modulations real?  
   → artefacts nearly excluded, but 
   **statistical significance only** $3.5 \sigma$ **at present**

2. Can periodic beats be preserved over macroscopic times for a motion **confined in an electromagnetic potential** and at **continuous observation**?

"In the first version of this addendum I incorrectly claimed that the GSI anomaly cannot be due to a quantum effect in nuclear decay. I would like to thank Yu.A. Litvinov for an enlightening discussion on this point...

...The GSI anomaly could be due to the quantum interference between two coherent states of the decaying ion if the interaction with the measuring apparatus does not distinguish between the two states. In order to produce quantum beats with the observed period of about 7 s, the energy splitting between the two states must be of the order of $10^{-16}$ eV...

The problem is to find the origin of such a small energy splitting.... It is difficult to find a [corresponding] energy splitting."
"Classical" quantum beats

Coherent excitation of an electron in two quantum states, separated by $\Delta E$ at time $t_0$, e.g. $^3P_0$ and $^3P_2$

Observation of the decay photon(s) as a function of $(t-t_0)$

Exponential decay modulated by $\cos(\Delta E/\hbar \, 2\pi \, (t-t_0))$

if $\Delta T << \Delta t = \hbar / (2\pi \Delta E)$

$\rightarrow$ no information whether $E_1$ or $E_2$

"which path"? addition of amplitudes

Fig. 24. Zero-field oscillations between the 1s $3p \, ^3P_1$ and 1s $3p \, ^3P_2$ states in He I (659 MHz), Wittmann [248]. The oscillations are superimposed on the exponential decay of the 1s $3p \, ^3P$ term (96 ns). To record this decay curve about 10 hours beam time (a few $\mu$A) and more than 20 carbon foils were needed.

Chow et al., PR A11(1975) 1380
Quantum beats from the hyperfine states

Coherent excitation of the 1s hyperfine states $F = 1/2 \& F = 3/2$

Beat period $T = \frac{h}{\Delta E} \approx 10^{-15}$ s

Decay can occur only from the $F=1/2$ (ground) state

Periodic spin flip to "sterile" $F=3/2$? $\rightarrow \lambda_{EC}$ reduced

$\mu = +2.7812 \, \mu_N$ (calc.)
1. Decay constants for H-like $^{140}$Pr and $^{142}$Pm should get smaller than expected. $\rightarrow$ NO

2. Statistical population in these states after $t \approx \max [1/\lambda_{\text{flip}}, 1/\lambda_{\text{dec.}}]$?

3. Phase matching over many days of beam time?
Quantum beats
- two well-defined initial states
- excited atom moves free in space
- observation time nanoseconds - microseconds

EC - decay of H-like ions stored in a ring
- parent atom created by nuclear reaction
- moves confined by electromagnetic forces
- interacts with e\textsuperscript{-} of the cooler, atoms, beam pipe.. 
- observation time some 10 seconds
Beats due to neutrino being not a mass eigenstate?

The electron neutrino appears as coherent superposition of mass eigenstates.

The recoils appear as coherent superpositions of states entangled with the electron neutrino mass eigenstates by momentum- and energy conservation.

\[ \Delta E_{\nu} \approx \Delta^2 m/2M = 3.1 \cdot 10^{-16} \text{ eV} \]

\[ \Delta p_{\nu} \approx -\Delta^2 m/2 \langle p_{\nu} \rangle = 2 \cdot 10^{-11} \text{ eV} \]
\[ \cos \left( \frac{\Delta E}{\hbar \, t} \right) \quad \text{with} \quad T_{\text{lab}} = \frac{h \, \gamma}{\Delta E} \approx 7 \, \text{s} \]

a) \( M = 140 \, \text{amu}, \quad E_\nu = 3.39 \, \text{MeV} \) (Pr)

b) \( M = 142 \, \text{amu}, \quad E_\nu = 4.87 \, \text{MeV} \) (Pm)

\( M = 141 \, \text{amu}, \quad \gamma = 1.43, \quad \Delta^2 m_{12} = 8 \cdot 10^{-5} \, \text{eV}^2 \)

\[ \Delta E = \frac{h \gamma}{T_{\text{lab}}} = 8.4 \cdot 10^{-16} \, \text{eV} \]

\[ \Delta E_\nu = \frac{\Delta^2 m}{2 \, M} = 3.1 \cdot 10^{-16} \, \text{eV} \]
The initial nuclear state has a momentum spread required by Heisenberg. The wave packet contains pairs of components with different momenta which can produce neutrinos in two mass eigenstates with exactly the same energy and different momenta.

These neutrino amplitudes mix to produce a single electron-neutrino state with the same energy. Since there is no information on which mass eigenstates produced the neutrino this is a typical quantum mechanics 'two-slit' or 'which path' experiment. A transition between the same initial and a final states can go via two paths with a phase difference producing interference and oscillations.
The final 'electron-neutrino' state is a linear combination of mass eigenstates with the same energy, different momenta and a well defined phase. During the passage of the radioactive nucleus between the point where it enters the apparatus and the point where the decay transition takes place the relative phases between the momentum eigenstate components of the initial wave function change linearly with the distance.

Thus the probability that the decay will take place to the final electron neutrino state oscillates with the distance \([X]\) travelled by the nucleus along its trajectory in space. The wave length of the oscillation depends upon the momentum difference which in turn depends upon the mass differences between the mass eigenstates. 

\[
P_1 - P_2 = f (p_1 - p_2, p_\nu, m_{\text{recoil}}))
\]
* Same energy of the $v$ mass eigenstates (Lipkin)

$$E_v(1) = E_v(2) = E_v \rightarrow \text{two different initial energies } E_1, E_2$$

\[
E_1 - E_2 = \Delta E
\]

\[
\nu_e (m_i, p_i, E_v)
\]

\[
M + \frac{p_1^2}{2M} + E_v = E_1
\]

\[
M + \frac{p_2^2}{2M} + E_v = E_2
\]

$$\Delta E = \frac{(E_v^2 - m_1^2 - E_v^2 + m_2^2)}{2M} = -\frac{\Delta^2 m}{2M} \approx -3 \cdot 10^{-16} \text{ eV}$$

$$\Delta p_v = -\frac{\Delta^2 m}{2\langle p_v \rangle} \approx -2 \cdot 10^{-11} \text{ eV}$$
H. Lipkin arXiv: 0801.1465v1,2 [hep-ph]
A. Ivanov, P. Kienle et al., arXiv: 0801.2121 [nucl-th]
M. Faber arXiv: 0801.3262 [nucl-th]

**Beats due to emitted neutrino being not a mass eigenstate**

C. Giunti (and many others) arXiv: 0801.4639v1,2,3 [hep-ph]

**Could only happen**

if there would be **two different initial states**, separated by $\approx 10^{-16}$ eV...
Beats due to neutrino being not a mass eigenstate?

A few out of many objections:

1. No coherence due to the orthogonality of mass eigenstates


\[ | \nu_e(t) > = \sum A_k(t) | \nu_k > \quad (\text{eq. 9}) \]

\[ \rightarrow \text{decay amplitude } A(t) = (\sum |\alpha_k A_k(t)|^2)^{1/2} \]

At \( t_d \) one has to project \( | \nu(t) > \) onto the flavour eigenstate \( | \nu_e > \)

\[ | \nu(t_d) > = \sum A_k(t_d) | \nu_e > <\nu_e | \nu_k > \]

\[ \rightarrow \text{decay amplitude } A(t_d) = (\sum |\beta_k A_k(t_d)|^2)^{1/2} \]
Beats due to neutrino being not a mass eigenstate?

2. One does not observe the neutrino: → no interference (EPR?)

3. Beats are only possible if the flavour is determined at both the generation and the decay (M. Lindner)

4. One observes the quantum state of the system continuously: → no beats (Giunti V2), except the two states cannot be distinguished (Giunti V3)
Beats due to neutrino being **not** a mass eigenstate?

We have **no information** on which neutrino mass eigenstate was created.

\[ \alpha_1 \left[ \left| \nu_1 \right> (E_{\nu_1}, p_{\nu_1}, m_1, p_1) \right] \rightarrow \text{Rec.}_1 > \]

\[ \alpha_2 \left[ \left| \nu_2 \right> (E_{\nu_2}, p_{\nu_2}, m_2, p_2) \right] \rightarrow \text{Rec.}_2 > \]

"which path" experiment → addition of the **amplitudes**

if there would be **two different initial** (parent) states
5. Summary, questions and outlook
For the two-body EC decays of H-like $^{140}$Pr and $^{142}$Pm periodic modulations according to $e^{-\lambda t} \left[1+a \cos(\omega t+\phi)\right]$ with $T_{\text{lab}} = \frac{2\pi}{\omega} = 7\text{s}$, $a \approx 0.20 \ (4)$ were found

Statistical fluctuations are not excluded on a c.l. $> 3.5\sigma$

Supposing $\Delta E = h \gamma / T_{\text{lab}} = \frac{\Delta^2 m_{12}}{2M}$ ($\gamma = 1.43$)

$\rightarrow \Delta^2 m_{12} = (2M h \gamma) / T_{\text{lab}} = 2.20 \cdot 10^{-4} \text{ eV}^2$

Things get really interesting only if

1. Oscillations would be observed for other two-body beta decays at other periods (proportional to nuclear mass ??)

2. A reasonable argument for two initial states separated by about $10^{-16} \text{ eV}$ could be found
Outlook

1. Other two-body beta decays (EC, bound beta ($\beta_b$) decay):
   - bare $^{205}$Hg (1/2$^-$) $\beta_b \rightarrow ^{205}$Tl (1/2$^+$), $\beta_b$ - branch $\approx$ 12%; $\approx$ 80% into K shell
   - H-like $^{118}$Sb (1$^+$) EC $\rightarrow ^{118}$Sn (0$^+$) accepted proposal

2. Improving detection (signal-to-noise) $\rightarrow$ more statistics

3. Evaluation of three-body $\beta^+$ decays

4. Two-body decays to excited states
Decay scheme of $^{118}\text{Sb}$

- $^{118}\text{Sb}$
  - $Q_{EC} = 3657$ keV
  - $\mu = 2.47(7) \mu_N$

Stable

$^{118}\text{Sn}$

- $\beta^+ \sim 65\%$
- $\varepsilon \sim 35\%$

$118\text{Sn}$

- 0 +
- 0 → 97.5\%
Time-frequency relation

$\beta_b$ -decay of bare $^{205}\text{Hg}^{80+} \rightarrow \text{H-like} \, ^{205}\text{Tl}^{80+}$

test in 2006

Cooled 16:40:42 2006-08-30 Workspace/norm0016