Time-modulation of electron-capture decay factor detected at GSI, Darmstadt

Byung Kyu Park

Department of Physics
University of California, Berkeley

Physics 250
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Outline

1. The Experiment
2. Hypotheses
3. Neutrino Oscillation
4. Prospects
The Facility

Gesellschaft für Schwerionenforschung, Darmstadt

1http://www.gsi.de/
What they study

Decay schemes for neutral Pr-140 and Pm-142

Atomic charge state affects decay rates and branching ratio.
Heavy-ion production and storage

For runs 1 and 2

Schematic layout of the facility with heavy-ion synchrotron SIS, the fragment separator FRS, and the storage-cooler ring ESR highlighted.

Injection from UNILAC

Primary beam $^{242}\text{Sm}$

Production target 1032 mg/cm$^2$ Be

Degraded 731 mg/cm$^2$ Al

400 MeV/u $^{146}\text{Pr}^{58+}$

Electron-cooled to $\Delta v/v \approx 5 \times 10^{-7}$

Schematic layout of the facility with heavy-ion synchrotron SIS, the fragment separator FRS, and the storage-cooler ring ESR highlighted.$^2$

$^2$Yu. A. Litvinov et al., arXiv:nucl-ex/0509019
Revolution frequency of ions in storage is measured by Schottky mass spectroscopy. This experiment is described in detail by Litvinov.\(^3\)

\(^3\)Yu. A. Litvinov et al., arXiv:0801.2079v1
### Tabulated experimental parameters for all runs

<table>
<thead>
<tr>
<th>run</th>
<th>ion</th>
<th>$E^{152}\text{Sm}$ [MeV/u]</th>
<th>$L^{9}\text{Be}$ [mg/cm$^2$]</th>
<th>#inj</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^{140}\text{Pr}^{58+}$</td>
<td>507.8</td>
<td>1032</td>
<td>453</td>
</tr>
<tr>
<td>2</td>
<td>$^{140}\text{Pr}^{58+}$</td>
<td>507.8</td>
<td>1032</td>
<td>842</td>
</tr>
<tr>
<td>3</td>
<td>$^{140}\text{Pr}^{58+}$</td>
<td>601.1</td>
<td>2513</td>
<td>5807</td>
</tr>
<tr>
<td>4</td>
<td>$^{142}\text{Pm}^{60+}$</td>
<td>607.4</td>
<td>2513</td>
<td>7011</td>
</tr>
</tbody>
</table>
Weak decay

Example signal

- **electron-capture**: $^{140}\text{Pr}^{58+} \rightarrow ^{140}\text{Ce}^{58+} + \nu_e + \text{KE}, \Delta f \approx 300 \text{ Hz}
- **$\beta^+$ decay**: $^{142}\text{Pm}^{60+} \rightarrow ^{142}\text{Nd}^{59+} + e^+ + \nu_e + \text{KE}, \Delta f \approx -150 \text{ kHz}$
Weak decay

**Example signal**

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Experimental result

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

![Graph showing number of EC decays per second vs. time after injection into the ESR [sec].]
Experimental result

with $^{140}\text{Pr}^{58+}$
Experimental result

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Experimental result

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

Exponential decay with a modulation at a period of $\approx 7$ s.
Experimental result

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

Inset shows Fourier transform of the data showing a peak at $f = 0.14$ Hz again.

Data with the sinusoidal fit for first 36 seconds
### Experimental result

#### Fit parameters

<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>

**Fit parameters of \(^{140}\text{Pr} \) data**

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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>
</tr>
<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>

**Fit parameters of \(^{142}\text{Pm} \) data**

Null hypothesis of pure exponential decay is excluded to 99% confidence level based on \( \chi^2 \) tests.
Hypotheses: (1) technical artifact?

**Pro**
- common period of 7 s for $^{140}\text{Pr}^{58+}$ and $^{142}\text{Pm}^{60+}$.

**Con**
- apparatus sensitive to single ion
- Pr and Pm ions coast on different orbits in ESR
- uncertainty of decay time ($\approx 1$ s) less than observed period.
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Hypotheses: (2) quantum beat of hyperfine states

**Pro**
- $^{140}\text{Pr}$ and $^{142}\text{Pm}$ have nuclear spin $I = 1$.
- H-like ions probably produced in coherent superposition of two 1s hyperfine states with $F = 1/2$ and $F = 3/2$.
- Final state (daughter ion plus $\nu_e$) has $F = 1/2$.
- EC-decay from $F = 3/2$ state is not allowed.

**Con**
- The well-known hyperfine splitting in hydrogen is in microwave range ($\nu = \Delta E/h = 1420$ MHz), with period of,
\[ T = \frac{h}{\Delta E} = 0.7 \text{ ns}, \]
and $T$ for $^{140}\text{Pr}^{58+}$ is even smaller by a factor of $\approx 10^5$. 
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Hypotheses: (3) neutrino oscillation

Suggestive kinematic consideration

- For two mass eigenstates, $m_1$ and $m_2$,

\[
\begin{aligned}
E_1 + \frac{p_1^2}{2M} & = Q_{EC} \\
E_2 + \frac{p_2^2}{2M} & = Q_{EC}
\end{aligned}
\]

- In approximation $(E_1 + E_2)/2M \ll 1$

\[\Delta E = E_2 - E_1 = (m_2^2 - m_1^2)/2M\]

- From KamLAND data\(^4\), with $M = 140$ amu,

\[\Delta E \approx 6 \times 10^{-16} \text{ eV}, \text{ and } T = h/E \approx 7 \text{ s}\]

\(^4\text{Phys. Rev. Lett. 94, 081801 (2005), } \Delta m^2 \approx 8 \times 10^{-5} \text{ eV}^2\]
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- Flavor (e, \(\mu\), \(\tau\)) eigenstates: \(|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle\)
- Mass (1, 2, 3) eigenstates: \(|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle\)

Mixing matrix for two neutrinos:

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U = \begin{pmatrix}
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\]

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[Graph: Oscillation Probabilities vs. L/E (km/GeV)]

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\[ \text{oscillation probabilities} \]

\[ \begin{array}{c}
1 \\
0 \\
0 \\
0 \\
0
\end{array} \]

\[ \text{L/E (km/GeV)} \]

1000 2000 3000
Decay amplitude, coherent or incoherent sum?

According to Ivanov et al., decay amplitude is given by,

\[ A(t) = \sum_{k=1,2,3} A_k(t) = \sum_k \int_0^t d\tau \langle l_f, \nu_k | H_W(\tau) | l_i \rangle. \]

Giunti argues that \( A(t) \) is an incoherent sum over different channels, because,

\[ |\nu_e\rangle = \sum_k U_{ek}^* |\nu_k\rangle, \]

and in the time-dependent perturbation theory,

\[ |\nu_e(t)\rangle = \left( \sum_j |A_j(t)|^2 \right)^{-1/2} \sum_k A_k(t) |\nu_k\rangle. \]

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Uncertainty in momentum allows wavefunctions to overlap and coherently interfere.

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\[ |\nu_1\rangle \]

\[ |\nu_2\rangle \]

If momentum is well defined, wavefunctions do not overlap and the amplitude is incoherent sum.

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\[ |\nu_1\rangle \]

Without second path, no interference occurs

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Experimental verification

- “It is obvious that our findings must be corroborated by the study of other two-body beta decays (EC and $\beta_b$).”

- “A similar analysis can be applied to a K-capture experiment ... Here there are a number of initial states having different degrees of ionization. Interference can only occur between initial states having the same degree of ionization. Otherwise the analysis is the same.”

New method for studying neutrino mixing

- If the effect is real and realistic theoretical model can be set up, this is a new method to study neutrino oscillation without the need to directly detect neutrinos.

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9 Yu. A. Litvinov et al., arXiv:0801.2079v1
10 Lipkin, arXiv:0801.1465v2
References