The background simulation of experiment for searching of 2K-capture in $^{124}\text{Xe}$

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Candidates for measurement of $2\nu2\beta^+$-decay

<table>
<thead>
<tr>
<th>Transition</th>
<th>$E_{2K},\text{MeV}$</th>
<th>Isotopic abundance, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{78}\text{Kr}\rightarrow^{78}\text{Se}$</td>
<td>2.867</td>
<td>0.35</td>
</tr>
<tr>
<td>$^{96}\text{Ru}\rightarrow^{96}\text{Mo}$</td>
<td>2.724</td>
<td>5.52</td>
</tr>
<tr>
<td>$^{106}\text{Cd}\rightarrow^{106}\text{Pd}$</td>
<td>2.771</td>
<td>1.25</td>
</tr>
<tr>
<td>$^{124}\text{Xe}\rightarrow^{124}\text{Te}$</td>
<td>2.866</td>
<td>0.10</td>
</tr>
<tr>
<td>$^{130}\text{Ba}\rightarrow^{130}\text{Xe}$</td>
<td>2.610</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{136}\text{Ce}\rightarrow^{136}\text{Ba}$</td>
<td>2.401</td>
<td>0.20</td>
</tr>
</tbody>
</table>

$(Z, A)\rightarrow(Z-2, A) + 2\beta^+ (+ 2\nu_e), \quad e_b + (Z, A)\rightarrow(Z-2, A) + \beta^+ (+ 2\nu_e), \quad e_b + e + (Z, A)\rightarrow(Z-2, A) + 2\nu_e + 2X, \quad e_b + e_b + (Z, A)\rightarrow(Z-2, A)^*\rightarrow(Z-2, A) + \gamma + 2X.$
\[
\begin{align*}
\text{Te*} & \quad \text{Te*} \\
\begin{array}{c|c|c}
\text{e}_a & \text{e}_a & 0.142^2 = 0.020 \\
\text{e}_a & \text{K} & 0.246 \\
\text{K} & \text{e}_a & 0.857^2 = 0.734
\end{array}
\end{align*}
\]

\[\text{Te}^{*\ast\ast} \rightarrow \text{Te}^{*\ast} + \text{Te}^{\ast}\]

\begin{align*}
K_{ab} &= 31.8 \text{ keV} \\
E_{2k} &= 64.46 \text{ keV} \\
\omega_k &= 0.857 - \text{characteristic quantum} \\
\omega_e &= 0.142 - \text{Auger electron}
\end{align*}

The energies of characteristic photons and an Auger-electron in 2K-capture are determined under the assumption that the filling of the double vacancy of K-shell in one atom is identical to filling two K-shell vacancies, each in a separate atom; the total energy release being 64.46 keV.

The probability of the emission of two characteristic X-ray photons and auger electron equal to 73.4%.

\[
\begin{align*}
K_{\alpha 1} &= 27.47 \text{ keV} \quad 52.2\% \\
K_{\alpha 2} &= 27.20 \text{ keV} \quad 27.7\% \\
K_{\beta 1} &= 30.99 \text{ keV} \quad 16.2\% \\
K_{\beta 2} &= 31.70 \text{ keV} \quad 3.9\%
\end{align*}
\]
Schematic view of Proportional Counter

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Material</td>
<td>Cu</td>
</tr>
<tr>
<td>2. Total length, mm</td>
<td>1160</td>
</tr>
<tr>
<td>3. Fiducial length, mm</td>
<td>595</td>
</tr>
<tr>
<td>4. Outer diameter, mm</td>
<td>150</td>
</tr>
<tr>
<td>5. Inner diameter, mm</td>
<td>137</td>
</tr>
<tr>
<td>6. Anode wire diameter, mm</td>
<td>0.010</td>
</tr>
<tr>
<td>7. Total volume, l</td>
<td>10.37</td>
</tr>
<tr>
<td>8. Fiducial volume, l</td>
<td>8.77</td>
</tr>
<tr>
<td>9. Pressure, at</td>
<td>5</td>
</tr>
<tr>
<td>10. Capacity, pF</td>
<td>31</td>
</tr>
<tr>
<td>11. Anode resistance, Ohm</td>
<td>613</td>
</tr>
</tbody>
</table>
Location of the experimental setup

- 18 cm – copper (M1)
- 15 cm – lead
- 8 cm – borated polyethylene
- depth-4900 m.w.e., $\phi_\mu = 2.23 \times 10^{-9}$ cm$^{-2}$s$^{-1}$
The spectrum of the Cd-109 calibration source, 88 keV gamma-line

Black – All events
Blue - one point events
Green – two point events
Red – three point events
The distribution of events versus parameter β:

**Black – All events**
**Blue – one point events**
**Green – two point events**
**Red – three point events**

**Blue spectrum** – distribution for background events
**Red spectrum** – distribution for calibration source Cd109 (88 keV)

10-21-32
Am
Am
Am

fit ~ 150 μs
afterpulse

\[
\begin{align*}
\{ A_1 \} & \Rightarrow \{ m_0 \} \\
\{ A_2 \} & \Rightarrow \{ m_1 \} \\
\{ A_3 \} & \Rightarrow \{ m_2 \}
\end{align*}
\]

1,2,3,4,5,6,7 run

\[ \Delta T = 150 \text{ h} \]

(3.2 < \( \tau_{\text{pulse rise}} \) < 12) μs

10-26 October 2018, MEPhi, Moscow
Measurement results for 15427 hours

Search area of $2\kappa(2\nu)$-capture of Xe-124 from $64.46-13=51.46(52)$ to $64.46+13=77.46$

$8 < \lambda < 12$

$m_1/m_2 \geq 0.7$

$5\text{keV} \leq m_0 \leq 13\text{keV}$
Geant4 model of low-background shield

1 - Borated polyethylene
2 - Lead
3 - Copper
Cian – Copper
Red – Prop Counter
Blue – Full gas volume
Green – Fiducial volume

Geant4-10.4.2
G4DecayPhysics
G4RadioactiveDecayPhysics
G4EmPenelopePhysics
G4EmLivermorePhysics (for test)
G4HadronPhysicsQGSP_BIC_HP
Test of Geant4 model

Black – All events
Blue - one point events
Green – two point events
Red – three point events
Comparison of background and simulation

Red – Sum of 1, 2 and 3 (.)-events
Black – Geant4 result
Blue – 1(.)-events
Green – 2(.)-events
Purple – 3(.)-events

\[3.2 < \tau_{\text{rise pulse}} < 12]\mu s

46.5 keV

\[8 < \lambda < 12\]

\[m_1/m_2 \geq 0.7\]

5keV \leq m_0 \leq 13keV

Search area of 2K(2\nu)-capture of Xe-124 from 64.46-13= 51.46(52) to 64.46+13=77.46

\[t_{\text{meas}}=15427\ \text{hour}\]
The calculation of $^{125}$I isotope background events

The $^{125}$I is produced from $^{125}$Xe and $^{125m}$Xe created by thermal neutron capture on $^{124}$Xe with a total cross section of 165±11 barn. $^{125}$I decays by 100% capture via an excited state of $^{125}$Te into the ground state of $^{125}$Te.

We have several measurements of neutrons in our laboratory.

1) Some features and results of thermal neutron background measurements with the [ZnS(Ag)+6LiF] scintillation detector (NIM A 841 (2017), 156–161, http://dx.doi.org/10.1016/j.nima.2016.10.038)

<table>
<thead>
<tr>
<th>Eγ (keV)</th>
<th>Iγ (%)</th>
<th>Decay mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,4919</td>
<td>6.68</td>
<td>ε</td>
</tr>
</tbody>
</table>

Neutron flux with energies < 0.5 eV estimated to be (2.6±0.4)*10^{-5} cm^{-2} s^{-1}

Calculating the number of neutrons from the G4 simulation: 0 neutrons/year


<table>
<thead>
<tr>
<th>E (keV)</th>
<th>I (%)</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.335</td>
<td>0.233</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>3.606</td>
<td>0.112</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>3.759</td>
<td>0.637</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>3.769</td>
<td>5.66</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.020</td>
<td>3.54</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.069</td>
<td>0.429</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.121</td>
<td>0.70</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.173</td>
<td>0.043</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.302</td>
<td>1.01</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.572</td>
<td>0.455</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.829</td>
<td>0.103</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>4.829</td>
<td>0.165</td>
<td>Te L_{\gamma}</td>
</tr>
<tr>
<td>26.875</td>
<td>0.032</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>27.202</td>
<td>4.612</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>27.472</td>
<td>5.758</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>30.944</td>
<td>6.83</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>30.995</td>
<td>13.24</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>31.237</td>
<td>0.121</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>31.704</td>
<td>3.81</td>
<td>Te K_{\gamma}</td>
</tr>
<tr>
<td>31.774</td>
<td>0.58</td>
<td>Te K_{\gamma}</td>
</tr>
</tbody>
</table>

Neutron flux with energies above 700 keV estimated to be between 5.3*10^{-7} and 1.8*10^{-7} cm^{-2} s^{-1}

Calculating the number of thermal neutrons from the G4 simulation: 2.5 neutrons/year

0.0114 $^{125}$I atoms per year in counter

http://nucleardata.nuclear.lu.se/toi
Comparison with other experimental results and theoretical predictions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>2K capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>XENON 100 [1] (2017)</td>
<td>( \geq 6.5 \times 10^{20} \text{yr.} )</td>
</tr>
<tr>
<td>XMASS-I [2] (2018)</td>
<td>( \geq 2.1 \times 10^{22} \text{yr.} )</td>
</tr>
<tr>
<td>BNO INR RAS [3] (2017)</td>
<td>( \geq 7.7 \times 10^{21} \text{yr.} )</td>
</tr>
</tbody>
</table>

Calculated half-lives for the 2\( \nu \) ECEC capture \(^{124}\text{Xe}\)

<table>
<thead>
<tr>
<th>2( \nu ) ECEC ((10^{21})) yr.</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9-7.3</td>
<td>M. Hirsch et al., Z. Phys. A 1999</td>
</tr>
<tr>
<td>0.4-8.8</td>
<td>J. Suhonen Journal of Physics G 2013</td>
</tr>
</tbody>
</table>

Thank You!
Backup
Candidates for 2K-capture events

\[ \text{Amplitude (arb. units)} \]

- A1=30 keV
- A2=5 keV
- A3=25 keV

\[ \tau_p \]

\[ t, \mu s \]

- A1=24 keV
- A2=32 keV
- A3=5 keV

\[ \text{Amplitude (arb. units)} \]

- A1=31 keV
- A2=29 keV
- A3=6 keV

\[ \tau_p \]

\[ t, \mu s \]

- A1=9 keV
- A2=27 keV
- A3=31 keV

22-26 October 2018, MEPhI, Moscow
\[ T_{1/2} \geq \ln 2 \times N \times t_{\text{meas}} \left( \eta / n_{\text{exp}} \right) \]

\[ N = 2.85 \times 10^{23} \text{ - the number of } ^{124}\text{Xe atoms} \]

\[ \eta = \omega^{2K} \cdot \varepsilon_p \cdot \varepsilon_3 \cdot \alpha_k \cdot k_\lambda \text{ – the full efficiency of registration} \]

\[ \omega^{2K} = 0.772 \text{ - fluorescence yield for } 2K \text{ capture} \]

\[ \varepsilon_p = 0.809 \text{ - the probability of absorption of three-point event} \]

\[ \varepsilon_3 = 0.51 \pm 0.05 \text{ - the efficiency of three-point event identification} \]

\[ \alpha_k = 0.985 \pm 0.005 \text{ - the coefficient of detection of } 2K\text{-photons and Auger elections as three-point events} \]

\[ K_\lambda = 0.89 \pm 0.01 \text{ - the efficiency of } \lambda\text{-selection} \]

\[ n_{\text{exp}} = 7^{+5.5}_{-3.4} \]

\[ t_{\text{meas}} = 1.76 \text{ year} \]

\[ T_{1/2} \geq 7.7 \times 10^{21} \text{ yr. (90\% C.L.)} \]
Fig. 4. Energy spectra for the \(\beta\)-depleted samples (top), \(\beta\)-enriched samples (middle), and \(^{214}\text{Bi}\) samples (bottom). The observed data spectra (points) are overlaid with the best-fit \(2\nu2K\) signal and background spectra (colored stacked histograms). Colored histograms are the \(2\nu2K\) signal (red filled), \(^{125}\text{I}\) (green hatched), \(^{131}\text{mXe}\) (red hatched), \(^{133}\text{Xe}\) (blue hatched), \(^{14}\text{C}\) (orange filled), \(^{39}\text{Ar}\) (magenta filled), \(^{85}\text{Kr}\) (blue filled), \(^{214}\text{Pb}\) (cyan filled), \(^{214}\text{Bi}\) (green filled), \(^{136}\text{Xe}\) \(2\nu\beta\beta\) (brown filled), and external backgrounds (gray filled).