A high-resolution CMOS imaging detector for the search of neutrinoless double $\beta$ decay in $^{82}$Se

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Neutrinoless double $\beta$ decay ($0\nu\beta\beta$)

$2\nu\beta\beta$: $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$

$0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z + 2) + 2e^-

> Neutrinos are Majorana particles
> Explicit violation of lepton number
> Indication of neutrino mass

Half-life of $0\nu\beta\beta$

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu} |\mathcal{M}|^2 |m_{\beta\beta}|^2$$

Phase space factor

Nuclear matrix element

$$\mathcal{M} \propto g_A^2$$

Effective Majorana mass

$$g_A = \begin{cases} 
    g_{\text{nucleon}} & = 1.269 \\
    g_{\text{quark}} & = 1 \\
    g_{\text{phen.}} & = g_{\text{nucleon}} \cdot A^{-0.18}
\end{cases}$$

↑ Possible values of axial coupling constant

Predictions on $m_{\beta\beta}$ from oscillations as a function of the lightest neutrino mass and combined experimental limit from $^{136}\text{Xe}$

[arXiv:1601.07512 [hep-ph]]

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Erice 2017
Selenium

$^{82}\text{Se}$ is a good candidate for the search of $0\nu\beta\beta$

- High $Q_{\beta\beta}$. Large phase space and low background
- Long $2\nu\beta\beta$ life time
  \[ T_{1/2}^{2\nu} = 1 \times 10^{20}\text{y} \]
- Relatively high abundance

LUCIFER: ZnSe


SuperNEMO: Tracking Chamber

*The European Physical Journal C-Particles and Fields* 70.4 (2010): 927-943.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>isotopic abundance (%)</th>
<th>$Q_{\beta\beta}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>0.187</td>
<td>4.263</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.8</td>
<td>2.039</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>9.2</td>
<td>2.998</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>2.8</td>
<td>3.348</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>9.6</td>
<td>3.035</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>7.6</td>
<td>2.813</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>34.08</td>
<td>2.527</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>8.9</td>
<td>2.459</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>5.6</td>
<td>3.371</td>
</tr>
</tbody>
</table>
Conceptual design

Amorphous $^{82}$Se deposits on CMOS arrays. Long exposure $O(10s)$

“Background free”:

$$M \cdot T \cdot B \cdot \Delta \leq 1$$

- Compact and modular design, easy to scale up
- Fine energy resolution
- Low background + track geometry discrimination
Selenium X-ray plate detector

Se X-ray detectors are used in medical imaging. (e.g. 720 cm$^2$, 1 mm thick, 85 um pixel size.)

Large band gap, negligible dark current at room temperature. Bias voltage ~20V/um.

Replace current TFT pixel array to CMOS pixel array to achieve < 100 e-h/pixel noise
Operating at very low read out rate.
Particle track imaging

\( \beta \) Bragg peak (end)

\( \alpha \) and \( \beta \) (right: an example from silicon CCD)
\( \beta \) stopping power \(<\alpha \) stopping power


Identification of \( \beta \) track initial vertex:
Time information is lost. Look for Bragg peak.

10^{-3} rejection of single beta decay achieved with 50% double beta acceptance.

Limitations on finer pixel size:
CMOS noise, leakage current…

Limitations on Se layer thickness:
Dead volume fraction (CMOS layer)
Energy resolution

a-Se, CMOS, dead layer

Fano factor = 0.6
(Intrinsic value = 0.03~0.06)
e-h recombination reduces Fano factor.

W = 15eV/ehp

Higher energy beta has lower ionization density
-> lower recombination and higher energy resolution

Experiments on going.

J. Appl. Phys., Vol. 85, No. 11, 1 June 1999

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Simulated double beta decay spectrum.

Expected energy resolution at $Q_{\beta\beta}$: FWHM = 24 keV

Simulated single rate in ROI = $4.0 \times 10^{-8} / (\text{kg y})$

$2\nu\beta\beta$ background in ROI = $0.51 \times 10^{-8} / (\text{kg y})$

Simulation result of $m_{\beta\beta} = 1$ meV and a strongly quenched nucleon axial coupling constant
Background estimation

Only $\beta$ tracks which total energy falls in ROI are regard as background.

$\beta$ from decay chain $^{238}\text{U}$, $^{232}\text{Th}$:
- Se: < 110$\mu$Bq/kg
- CMOS array: < 0.01$\mu$Bq/cm$^2$
- Surface $^{210}\text{Po}$: < 0.1$\mu$Bq/cm$^2$
- Cosmogenic $^{83}\text{Se}$: < 0.02 $\mu$Bq/kg
  78,80,81,82As: < 0.3 nBq/kg
  EXO, JCAP 1308 (Aug., 2013) 049.
  EXO, JCAP 2016 (Apr., 2016) 029.

$\gamma$ with energy > ROI:
- $(\alpha,n)$ reaction
- Cosmogenic $^{56}\text{Co}$: < 0.02 $\mu$Bq/kg
Background rejection

- Multi-tracks with same vertex
- Spatial correlation
- Discrimination of single and double $\beta$ track

<table>
<thead>
<tr>
<th>Radioactive background source</th>
<th>Raw background rate [1/(kg y)]</th>
<th>Rate after discrimination [1/(kg y)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$-decay (bulk)</td>
<td>$&lt;3.3 \times 10^{-1}$</td>
<td>$&lt;3.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\beta$-decay (surface)</td>
<td>$&lt;4.1 \times 10^{-1}$</td>
<td>$&lt;1.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\beta$-decay (cosmogenic.)</td>
<td>$&lt;9.9 \times 10^{-5}$</td>
<td>$&lt;1.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\gamma$-ray (photoelectric)</td>
<td>$&lt;1.0 \times 10^{-3}$</td>
<td>$&lt;1.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\gamma$-ray (Compton)</td>
<td>$&lt;1.6 \times 10^{-3}$</td>
<td>$&lt;4.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\gamma$-ray (pair production)</td>
<td>$&lt;1.9 \times 10^{-6}$</td>
<td>$&lt;1.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>Solar $^8$B $\nu$</td>
<td>$3.2 \times 10^{-6}$</td>
<td>$3.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>Total</td>
<td>$&lt;7.4 \times 10^{-1}$</td>
<td>$&lt;1.8 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Conclusion

The predicted signal and background rate, assuming $m_{\beta\beta} = 1 \text{ meV}$

<table>
<thead>
<tr>
<th>Coupling constant</th>
<th>Total signal rate [1/(kg y)]</th>
<th>ROI [keV]</th>
<th>Final signal rate [1/(kg y)]</th>
<th>Final background rate [1/(kg y)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{\text{phen.}}$</td>
<td>$3.0 \times 10^{-7}$</td>
<td>2996–3017</td>
<td>$2.0 \times 10^{-8}$</td>
<td>$&lt;1.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$g_{\text{nucl.}}$</td>
<td>$7.1 \times 10^{-6}$</td>
<td>2984–3005</td>
<td>$8.2 \times 10^{-7}$</td>
<td>$&lt;1.7 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Advantages:
- modular design, compactness and simplicity in operation
- modest radio-purity requirements — which relies on high resolution imaging and the choice of $^{82}\text{Se}$
- scalability of the technology — which relies on widespread fabrication processes in the semiconductor industry

Experimental demonstration of the predicted performance is on going.
Outlook

Magnetic field:
Simulation with 20T magnetic field

Track reconstruction algorithm:
$\delta$-ray and more complex topology

Single atom counting of $^{82}$Kr