Development of Si detectors for high precision beta decay experiments

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Capabilities for beta decay

• What beta decay experiments want:
  • beta energy
  • beta timing
  • proton/recoil detection
  • particle position

![Diagram of beta decay]

• What silicon detectors offer:
  • great energy resolution
  • fast timing
  • low noise
  • position sensitivity
  • stable performance
Beta decay correlations & spectroscopy

- Nab / pNab [see Pocanic talk]
  - Goal $\Delta a/a \sim 10^{-3}$, $\Delta b \sim 3 \times 10^{-3}$, $\Delta A/A \sim 8 \times 10^{-4}$ requires proton detection, accurate/fast timing, $\beta$ spectroscopy

- UCNA+ [see Plaster talk] / UCNB
  - Goal $\Delta A/A \sim 10^{-3}$, $\Delta B/B \sim 10^{-3}$ requires proton detection, beta energy/direction, fast timing

- $^{45}$Ca Fierz Measurement:
  - Goal $\Delta b \sim 10^{-2}$ requires beta spectroscopy

- Shared detector development (Micron Semiconductor)
aSPECT

• aSPECT [Baessler talk]
  • \( a = -0.10430(84) \) from proton spectrum
  • MAC-E filter: accurate proton counting

• Silicon drift detector (SDD) by PNSensor – reduced capacitance compared to PIN diode (but worse timing)

• Energy dependent backscattering results in energy dependent detection efficiency

KATRIN + TRISTAN

- **KATRIN**: precise determination of tritium end-point (18.6 keV) to determine neutrino mass
- **TRISTAN project**: spectral kink from sterile neutrino
  - exceptional E resolution, detector response, high counting rates

(Thanks S. Mertens for content)
Beam Lifetime

- BL1: 0.4 s systematic uncertainty due to backscattering extrapolation [Wietfeldt talk]
- BL3: current concept to use larger Nab style detector to detect second backscatter, reduce systematic [Fomin talk]

(Thanks N. Fomin for content)
Important detection system effects

• Detector effects
  • Deadlayer (entrance window)
  • Position dependent charge collection
  • Depleted volume/incomplete charge collection
  • Radiation damage

• Noise
  • Noise and energy resolution
  • Noise stability and efficiency variations

• Detector and electronics effects
  • Calibration (gain/offset/linearity)
  • Temperature stability and gain

• Related physics
  • Backscattering
  • Bremsstrahlung
  • Backgrounds
  • Rate-dependent effects

As we push precision boundaries we need to characterize these in greater detail.
Impact of dead layer

- Dead layer: energy deposition does not result in detector signal (e.g. in implanted n or p contact)
  - Critical for <751 eV protons in neutron beta decay: defines required accelerating voltage, absolute detection efficiency for lifetime/aSPECT, relative efficiency for Nab
  - Also impacts beta spectroscopy, bounce history

- TRISTAN project R&D for thinner dead layer in large area detector
  - HLL ~ 50 nm dead layers measured in several prototypes (10 nm demonstrated but leakage current higher)
  - R&D ongoing for < 10 nm dead layer

- G. Konrad talk Thursday ~ 10 nm dead layer from Barcelona group

Impact of dead layer on proton detection

<table>
<thead>
<tr>
<th>Silicon dead layer</th>
<th>Energy after dead layer (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 keV</td>
</tr>
<tr>
<td>100 nm</td>
<td>26</td>
</tr>
<tr>
<td>50 nm</td>
<td>20</td>
</tr>
<tr>
<td>30 nm</td>
<td>18</td>
</tr>
<tr>
<td>10 nm</td>
<td>16</td>
</tr>
</tbody>
</table>

(SRIM calculation)
10 nm dead layer?

SHUT UP AND TAKE MY MONEY
Dead layer modeling

- Naive slab model of dead layer not sufficiently accurate for some applications
- Accuracy of charge collection efficiency important for aSPECT: semi-empirical dead layer model
- KATRIN/TRISTAN: slab model + single parameter fractional collection

\[
f_{\text{CCE}}(z) = \begin{cases} 
0 & \text{if } z < 0 \\
S + B \left( \frac{z}{l} \right)^c & \text{if } 0 \leq z \leq l, \\
1 - A e^{-\frac{z-l}{\tau}} & \text{if } l \leq z \leq D
\end{cases}
\]

Detector charge collection

- Use Shockley-Ramo theorem to calculate signal on detector contact due to motion of charges
  - \( i(t) = qE_W v_{drift} \)
    1. Calculate \( v_{drift} \) in electric field
    2. \( E_W \) is “weighting” field
- Cross-talk near pixel boundaries
- Position dependent drift time variations in SDDs
Impact on timing

- Nab requires $<0.3$ ns bias on $\Delta$TOF(p-e), $O(10$ ns) shifts in waveform (vs. depth and edges)

- Actual e-/h mobilities depend on crystal orientation, electric field, temperature, impurity concentration
  - Variations (especially radial) expected due to manufacturing process

- Measure drift velocities per detector
  - e.g. Transient Current Technique: use incident alphas + fast amp

Charge cloud and diffusion

- Energy deposited in detector in a charge cloud, experiences Coulomb repulsion and diffusion $O(10 \mu m)$
  - Cloud grows with drift time $\rightarrow$ position (and therefore energy) dependent
  - Energy dependence to charge sharing probability
- Important effect for small pixels
  - $\sim10\%$ charge sharing with 1 mm pixels in TRISTAN due to charge cloud
- Multiplicity creates losses due to threshold and incorrect energy assignment
Point spread function

- Position distribution of particles emitted from point source and transported through a magnetic spectrometer
- TOF depends on emission angle: strong radial dependence at detector
  - Phase averages at long distances: with isotropic emission obtain uniform probability inside gyradius
- Can use relative rates in pixelated detector to precisely locate source position (and align detectors)

\[ \frac{dP}{dR}(R, \theta) = \frac{1}{\pi r_0} \frac{1}{\sqrt{\sin^2 \theta - (R/2r_0)^2}} \]

Ratio of counts in pixel at R=1 cm / R = 0 cm

Dubbers et al, NIMA 763 112 (2014)
Sjue et al, RSI 86 023102 (2015)
Depleted volume

- C-V curve measures area and thickness (d’) of depleted volume
- Knee = full depletion, but C will still decrease with lateral depletion in Case A
- With small pixel separation (e.g. Nab) expect full depletion (Case B)

\[ C = \frac{dQ}{dV} \quad [\text{a.u.}] \]
Depleted volume

- (Unknown) details of detector manufacturing process can result in significant position dependence
- Observed variation in “turn-on voltage” in Nab
  - Different thickness detectors and different pixel isolation strategies
  - Impact on charge collection – need position dependent characterizations

Example: P-stop vs P-spray

Depletion voltage

- Energy resolution in Nab improves beyond “full depletion”
- Drift velocities slow near n-type electrode due to decreasing E field
- Too-short shaping looks like incomplete charge collection
- Larger bias voltages desirable for increased drift time (at cost of leakage current)
Backscattering and bremsstrahlung

- Reflection of electrons: corrections required for direction assignment, E loss in deadlayer
  - Nab can account in data by examining tails from source studies
  - Suppress backscatter with second detector

- Backscattering systematic large systematic for Beam Lifetime (see Wietfeldt, Hoogerheide, Fomin talk)

- Bremsstrahlung needs improvement for precision spectroscopy – need external study (challenging)
Sources and types of noise

• Analyzing filter freq. dependent--classify noise
  • leakage current: thermally gen. e/h pairs. reduce T
  • Thermal noise: voltage (e.g. bias resistor) and current (e.g. in series resistance) sources
  • Amplifier noise (voltage and current sources)
  • Voltage sources depend on capacitance: reduce area, avoid stray C (short leads)
  • 1/f noise: charge trapping/untrapping

• Optimize filter shaping time based on dominant sources

\[ \text{enc}^2 = \left( 2eI_{\text{leak}} + \frac{4k_B T}{R_b} \right) F_1 t_{\text{peak}} + (4k_B T R_s + e_{na}) F_2 \frac{C^2}{t_{\text{peak}}} + F_3 A_f C^2 \]

K. Altenmüller, PhD thesis (2019) TUM
Characterizations R&D

• R&D for precision sources also needed
• U Manitoba: rasterable proton source for position dependent proton efficiency (vs MCP) and physical cross talk
• UVA: highly stable rate proton source for slope of proton efficiency
• TUNL: pulsed electron gun for back-scattering, bremsstrahlung, timing studies
• ORNL: in situ and ex situ timing source for charge collection studies

Goal specs:
- $40 \text{ keV} < E < 1 \text{ MeV}$, $\pm 1\%$ resolution

- $1 \text{ ns}$ pulse width, $1 \text{ kHz}$ rate

133$^{\text{Ba}}$ in CeBr$_3$
A. Jezghani, UKY

$\Delta T(\gamma-e)$
CeBr$_3$ - Si

A. Jezghani, UKY
Implementation R&D

• Accelerating voltage: breakdowns, detector damage
  • Lessons learned from aSPECT, NIST groups to achieve long term stability in UCNB, Nab

• Cryogenic temperatures for lowest noise, fastest drift times, with good stability and control
  • + ultra-high vacuum to avoid cryopumping extra dead layer onto detector

• Robustness and flexibility of connections: pogo-pins, fuzz buttons, bump bonds
Summary

• Silicon detectors are a natural solution to many of the detection challenges in neutron and nuclear beta decay

• New developments in ultrathin dead layer technology (potentially sub 10 nm) are particularly interesting and might guide next-generation experimental approaches

• Requirements for understanding detector performance are unique but not intractable

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