Search for Neutrinoless Double-Beta Decay Using Fast Photo-Detectors and Quantum-Dot-Doped Scintillators

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Outline

- What is neutrinoless double-beta decay?
  - why is it interesting?
  - what are the challenges?
- Ideas for next generation experiments
- Requirements for the detectors
  - timing characteristics
  - scintillators properties
- Summary
What is $0\nu\beta\beta$?

Compare to normal beta decay: $Z \rightarrow (Z+1), e^-, \nu_e$
If observed, neutrino is a Majorana particle, i.e. own antiparticle.
What are the challenges?

Rare process (e.g. $T_{1/2}[^{136}\text{Xe}] > 10^{25}$ years): need to get bigger
What are the challenges?

Tough backgrounds: need to get smarter

2νββ

0νββ

taken from NIMA 650, 1, 73-78

EXO collaboration
PRL 109 (2012)
032505

SS

MS
Ideas for $0\nu\beta\beta$ experiments

- Total energy in signal events is well defined.
- Use scintillation light for energy measurements
- Use event topology to suppress backgrounds
  - signal is two, mostly, “back-to-back” electrons
- Electrons are $\sim 1\text{MeV} \rightarrow$ above Cherenkov threshold
- Use Cherenkov light to extract directionality of the two electrons
  - all light can be used to constrain location of the vertex
  - Cherenkov light arrives early because of longer wavelength and delay of the scintillation process
Emission Spectra

Simulation of 5 MeV electrons in KamLAND scintillator

All photons below 360nm get absorbed
Cherenkov vs Scintillation

Use early light to extract directionality

A shift between cherenkov and scintillation spectra is a plus
Directionality of 5 MeV $e^-$

Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors

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Large liquid-scintillator-based detectors have proven to be exceptionally effective for low energy neutrino measurements due to their good energy resolution and scalability to large volumes. The addition of directional information using Cherenkov light and fast timing would enhance the scientific reach of these detectors, especially for searches for neutrino-less double-beta decay. In this paper, we develop a technique for extracting particle direction using the difference in arrival times for Cherenkov and scintillation light, and evaluate several detector advances in timing, photodetector spectral response, and scintillator emission spectra that could be used to make direction reconstruction a reality in a kiloton-scale detector.
Can we do better with photo-detectors?

Large Area Picosecond Photo Detectors (LAPPD)

- Large area
- Fast timing
- Inexpensive
Glass Package (20x20cm²)

- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object
  - designed for fast timing

Ceramic body packaging is a parallel (and collaborative) effort at Berkeley SSL
Detector Prototype: "Demountable"

Demountable 1.0  
(May 2012)

Demountable 3.0  
(Sep-Dec 2012)
"Demountable" Performance

PSEC-4 readout

Oscilloscope readout

- PSEC-4 readout
  - 90-cm long anode!

- PSEC-4 readout
  - ~80ps

- Oscilloscope readout
  - ~35ps

- Entries: 4279
- Mean: 7.722
- RMS: 0.03558
- $\chi^2$/ndf: 8.625/12
- Prob: 0.7346
- Constant: 957.7
- Mean: 7.722
- Sigma: 0.03558
Can we do better with liquid scintillators?

Quantum Dots Doping

Need:
- Narrow the scintillation spectrum
- Shift scintillation spectrum to shorter wavelength
- Dope with metals which can undergo 0vbb

Solution: Quantum Dots

- Quantum dots are semiconducting nanocrystals
- A shell of organic molecules is used to suspend them in an organic solvent (toluene) or water
- Common materials are CdS, CdSe, CdTe...
More Details on QDots
## Candidate Isotopes for 0νββ

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<tr>
<th>Isotope</th>
<th>Endpoint</th>
<th>Abundance</th>
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<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.271 MeV</td>
<td>0.0035%</td>
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<tr>
<td>$^{150}$Nd</td>
<td>3.367 MeV</td>
<td>5.6%</td>
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<tr>
<td>$^{96}$Zr</td>
<td>3.350 MeV</td>
<td>2.8%</td>
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<tr>
<td>$^{100}$Mo</td>
<td>3.034 MeV</td>
<td>9.6%</td>
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<tr>
<td>$^{82}$Se</td>
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<tr>
<td>$^{116}$Cd</td>
<td>2.802 MeV</td>
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<tr>
<td>$^{130}$Te</td>
<td>2.533 MeV</td>
<td>34.5%</td>
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<tr>
<td>$^{136}$Xe</td>
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<td>8.9%</td>
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<tr>
<td>$^{76}$Ge</td>
<td>2.039 MeV</td>
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<tr>
<td>$^{128}$Te</td>
<td>0.868 MeV</td>
<td>31.7%</td>
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</tbody>
</table>
Quantum Dots Properties

- Because of their small size, their electrical and optical properties are more similar to atoms than bulk semiconductors.

- The optical properties of quantum dots with diameter < 10nm are completely determined by their size.

- Their size is easily regulated during synthesis.
Example of CdS Quantum Dot Spectra

Surface states which can be eliminated with a second shell
Trilite450 QDots vs KamLAND Scintillator

384nm not yet available, but is the goal of future work

No surface states. Narrow emission spectrum.
The new Trilite dots have attenuation length longer than 2m
Summary

- We propose to use Cherenkov light to reconstruct $0\nu\beta\beta$ event topology

- The following emerging technologies can make a big difference

  - Fast Photo-Detectors with TTS<$100$ps for separation early Cherenkov light from scintillation light

  - Quantum Dot Doped Scintillators to control and tune scintillator properties (light yield, emission spectrum and transparency)