Investigation of Large Area Avalanche Photodiodes for the KDK experiment

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5) Heavy Ion Laboratory, University of Warsaw

Electronic Support from Paul Davis, University of Alberta, MRS
K-40 Decay Scheme

- K-40 (0.0117%) can be found in natural potassium
- This background poses a challenge to any interpretation of the DAMA results
  
  Important Decay Channels:
  - 10.55 % to Ar-40* through electron capture, EC*
    - De-excitation produces 1460 keV gamma and 3 keV X-ray or Auger electron
  - 0.2 % to Ar-40 through electron capture, EC
    - Never been experimentally measured
    - Produces a sole 3 keV X-ray or Auger electron
  - The DAMA collaboration can remove part of the events from the EC* channel by tagging the 1460 keV gamma rays

• Perform a dedicated measurement of the BR of K-40 EC decay into ground state
• A small, inner detector will trigger on the X-rays and Auger electrons from K-40

• The inner detector will be completely surrounded by an outer detector in order to tag the 1460 keV gammas
• This will allow us to separate the events caused by the EC* decay from the direct EC.
• Interior Detector has multiple options: APD or Potassium rich scintillator (KSI supplied by the University of Tennessee)
• KSI is further talked about in a talk by Philippe Di Stefano, on Thurs. June 16
The proposed outer detector will be the Modular Total Absorption Spectrometer (MTAS) at Oak Ridge National Lab (ORNL)

The MTAS detector consists of 19 NaI(Tl) hexagonal shaped detectors (53cm x 20cm) [2] weighing in at ~54 kg each

MTAS can provide a ~98-99% (SNR=2) efficiency on tagging the 1460 keV gammas and ~4π coverage

A high efficiency is needed to avoid false positives from the EC* channel and other background sources
APD: Internal X-ray Detector

Interior Detector Requirements

• High efficiency to detect the ~3 keV X-ray and Auger Electrons
• Low threshold (~1 keV) and transparent to E > 10 keV in order to reduce background noise
• Small detector size to fit in the 6 cm MTAS opening

• One method is to use a Large Area Avalanche Photodiode

• A liquid cooling system was set up in order to cool the APD to a target goal of -20°C and increase it’s performance

FIG 5: APD Setup for insertion into MTAS
APD Operating Principal

- Incident particles create electron-hole pairs and these move towards the PN junctions
- The p-n\(^+\) junction at the back of the APD has a high local field
- Electron impact with the crystal lattice in this region forming new electron hole pairs
- Which in turn will be accelerated leading to further collisions
- Forming an Avalanche process

FIG 6: Basic Operating Principal of an APD\textsuperscript{[3]}

Results: Calibration Sources

• Sources for testing are required in order for calibration of APD, MTAS veto efficiency and feasibility of experiment.

• Zn-65 and Mn-54 provide excellent calibration sources.

Fig 7: Decay Scheme for the calibration source Zn-65\(^{\text{[3]}}\) (Left) and Mn-54\(^{\text{[3]}}\) (Right).

Results: Zn-65 Coincidence

**Run Parameters:**
- APD High Voltage: 1700 V
- APD Temperature: -9.0°C
- Total Run Time: 1h30

**Conclusions:**
- Successfully able to see coincidence events between APD and MTAS
- Able to recreate Zn-65 BR to first order
- Natural K-40 background present here

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**Fig 8:** Experimental Run of Zn-65 with APD and MTAS in coincidence
Results: Calibration

Fig 9: Calibration of APD from Mn-54 and Zn-65. Dotted curve show the predicted 3 keV bump from K-40.
Conclusion

- With MTAS and APD we are able to detect the coincidence between high energy gamma and low energy x-rays
- Two Source calibration (Mn-54 and Zn-65) indicates that 3 keV X-rays are above our current noise threshold and should be visible in our APD, at current temperature and settings
- Optimal APD temperature is around -20°C. Current runs were only able to reach a maximum of -8°C. Improvements will be made to the cooling architecture in order to reach this goal
- Lower energy calibration is required. Possible use of fluorescent sources
- Future work to distinguish between low energy electrons and x-rays in the APD
  - This will aid for the elimination of the large β- minus background and in dealing with the plentiful Auger electrons
Acknowledgment

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References


Extra Slides
Source

• Thin Film (~1cm x 1cm x 1μm) implanted with enriched with $^{40}$K.
• Target Rate(EC): 5730 events/day/cm³
• KCL from American Instruments can be enriched with $^{40}$K up to 10%
• ORNL will implant the $^{40}$K atoms onto a thin sheet of Titanium
• Thin source can be removed in order to perform a background measurement

Background

• Other decay channels produce a significant background
• Major source of background is the $\beta$- spectrum
• This is a factor when selecting internal detector.
Linear Fit Calibration (FIG 10)
APD X-Ray Test: Results

- Second, smaller pulse can be discriminated by a longer rise time
- Similar thing is seen in Diepold et al, 2015.
- X-Rays stopping region III undergo only partial amplification, resulting in lower amplitude
- X-Rays stopping in region I generates electron which are only slowly transferred to the other regions (low field strength), lengthening the pulse and causing amplitude reduction

Electrons from K-40

- All EC+EC* events will produce X-rays and Auger Electrons.
- X-rays and Auger Electrons are modeled by Gaussians centered around their average energy with their area equal to the likelihood of occurrence.
- 90% of all EC and EC* will produce Auger Electrons.
- Looking for possible material to remove electrons but not X-rays.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy (keV)</th>
<th>Particles per 100 disintegrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger Electron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- KLL</td>
<td>2.511 - 2.669</td>
<td>5.89</td>
</tr>
<tr>
<td>- KLX</td>
<td>2.831 - 2.942</td>
<td>1.27</td>
</tr>
<tr>
<td>- KXY</td>
<td>3.149 - 3.174</td>
<td>0.0685</td>
</tr>
<tr>
<td>X-Ray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- K-Alpha</td>
<td>2.95</td>
<td>0.891</td>
</tr>
<tr>
<td>- K-Beta</td>
<td>3.19</td>
<td>0.096</td>
</tr>
</tbody>
</table>

TABLE 2: K-40 Decay Scheme


FIG 13: Signal To Noise of the Beta Background for EC only
Fluorescence

• Lower energy calibration is required. Possible fluorescence sources

<table>
<thead>
<tr>
<th>Target</th>
<th>Expected Fluorescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium (Ti)</td>
<td></td>
</tr>
<tr>
<td>Ti:</td>
<td>$K_{\alpha}$: 4.51 keV $K_{\beta}$: 4.93 keV (VISIBLE)</td>
</tr>
<tr>
<td>Potassium Chloride (KCL) Window</td>
<td></td>
</tr>
<tr>
<td>K:</td>
<td>$K_{\alpha}$: 3.31 keV $K_{\beta}$: 3.59 keV (VISIBLE)</td>
</tr>
<tr>
<td>CL:</td>
<td>$K_{\alpha}$: 2.62 keV $K_{\beta}$: 2.82 keV (VISIBLE)</td>
</tr>
<tr>
<td>Gypsum (CaSO$_4$) Crystal</td>
<td></td>
</tr>
<tr>
<td>Ca:</td>
<td>$K_{\alpha}$: 3.69 keV $K_{\beta}$: 4.01 keV (VISIBLE)</td>
</tr>
<tr>
<td>S:</td>
<td>$K_{\alpha}$: 2.31 keV $K_{\beta}$: 2.46 keV (VISIBLE)</td>
</tr>
<tr>
<td>O:</td>
<td>$K_{\alpha}$: 0.526 keV (Not Visible)</td>
</tr>
</tbody>
</table>
Effect of K-40 on DAMA

- Total event rate in the presence of dark matter signal $R(t)$
  - $R(t) = B_o + S_o + S_m \cos w(t - t_o)$
    - $B_o$, is background
    - $S_o$, is unmodulated rate
    - $S_m$, is modulated rate
    - $w = 2\pi/1\text{yr}$
    - $T_o$, 140 days

- Graph shows required modulation fraction of $S_m / S_o$ of a DM signal at 3 keVee nuclear recoil energy in the presence of a flat background
- Solid lines are contours in the parameters BR and contamination with background contribution
- Dotted lines are contours in the parameters BR and contamination without background contribution
- Red region is when $S_m / S_o$ is greater than 100%
- The horizontal dashed line is the quoted upper limit on the DAMA contamination
- The vertical gray band indicates the nominal value for BR and its uncertainty as quoted

FIG 14: Required Modulation Fraction