Investigation of Large Area Avalanche Photodiodes for the KDK experiment

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For the CAP Congress 2016

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3) University of Tennessee

4) Perimeter Institute and McMaster University

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[1]
- 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

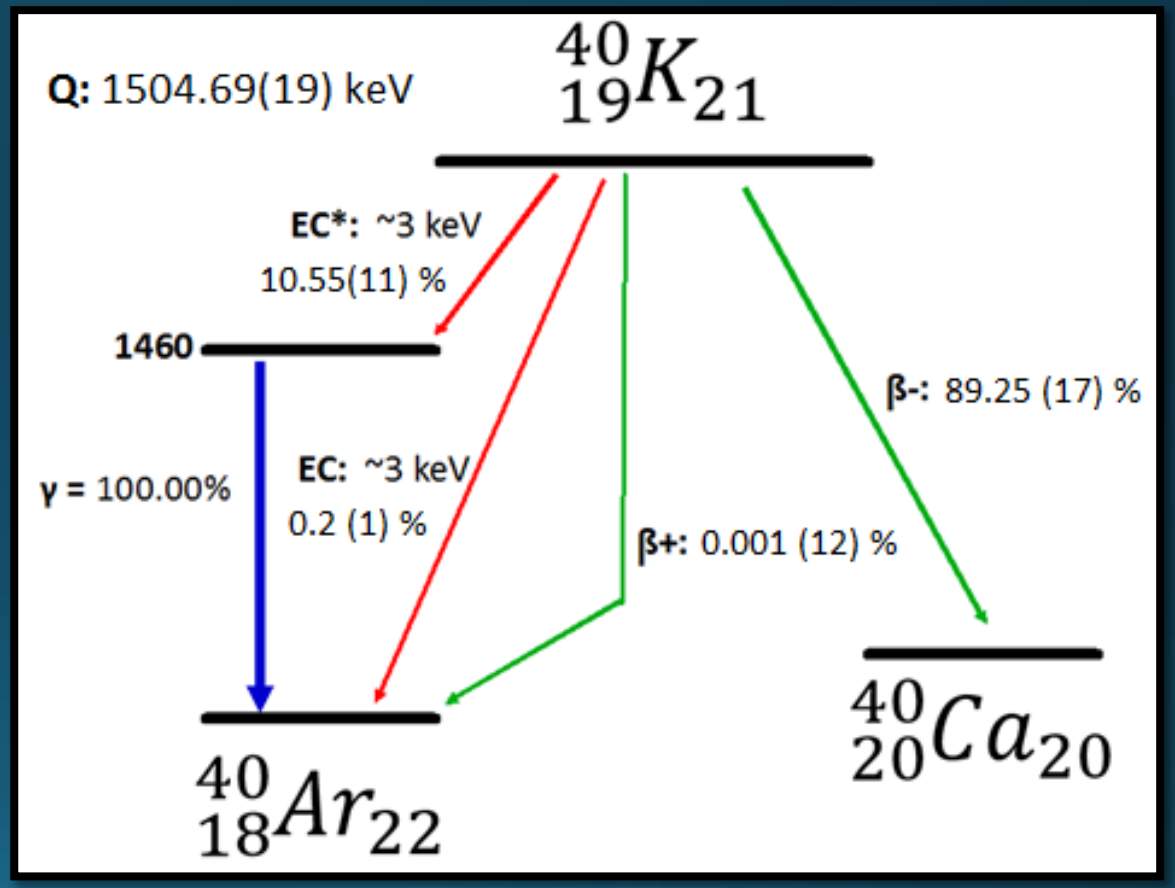


FIG 1: K-40 Decay Chain

[1] Pradler, J., Singh, B. and Yavin, I., 2013. On an unverified nuclear decay and its role in the DAMA experiment. *Physics Letters B*, *720*(4), pp.399-404.

KDK Experiment

- 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

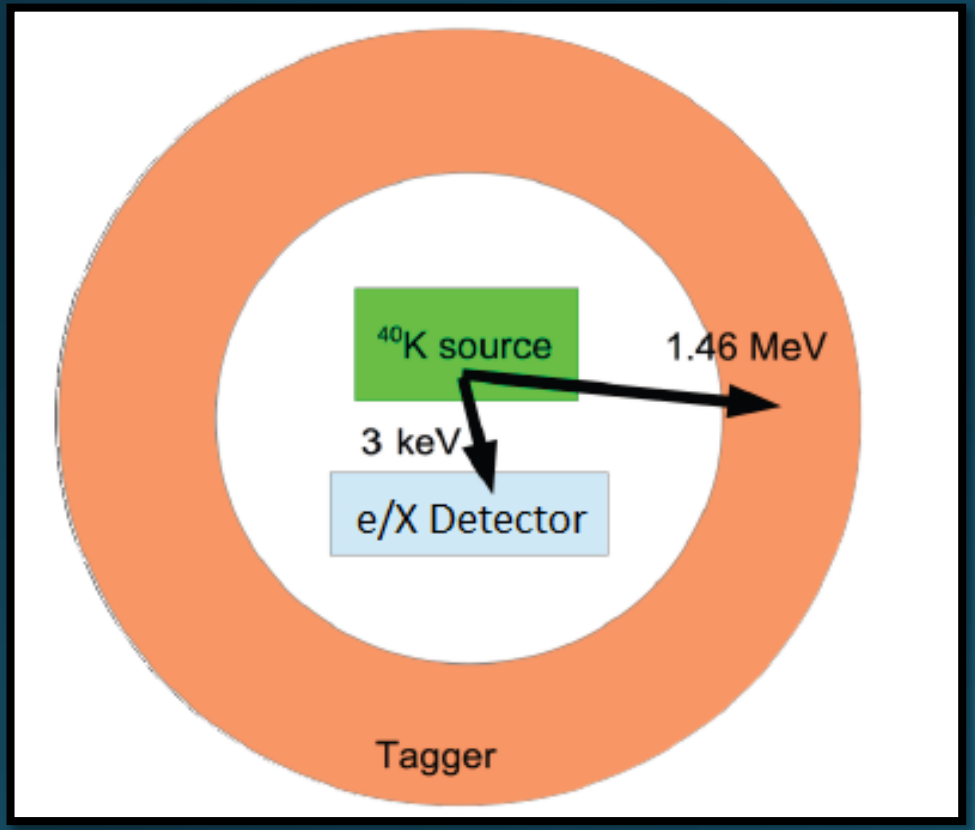


FIG 2: KDK Experimental Outline

- 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

MTAS: External Detector

- 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

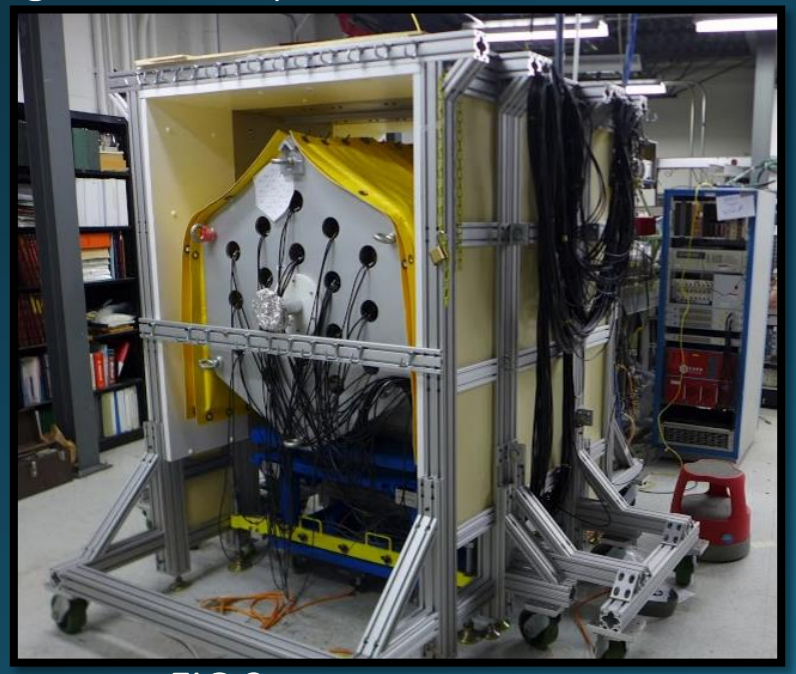


FIG 3: MTAS at ORNL

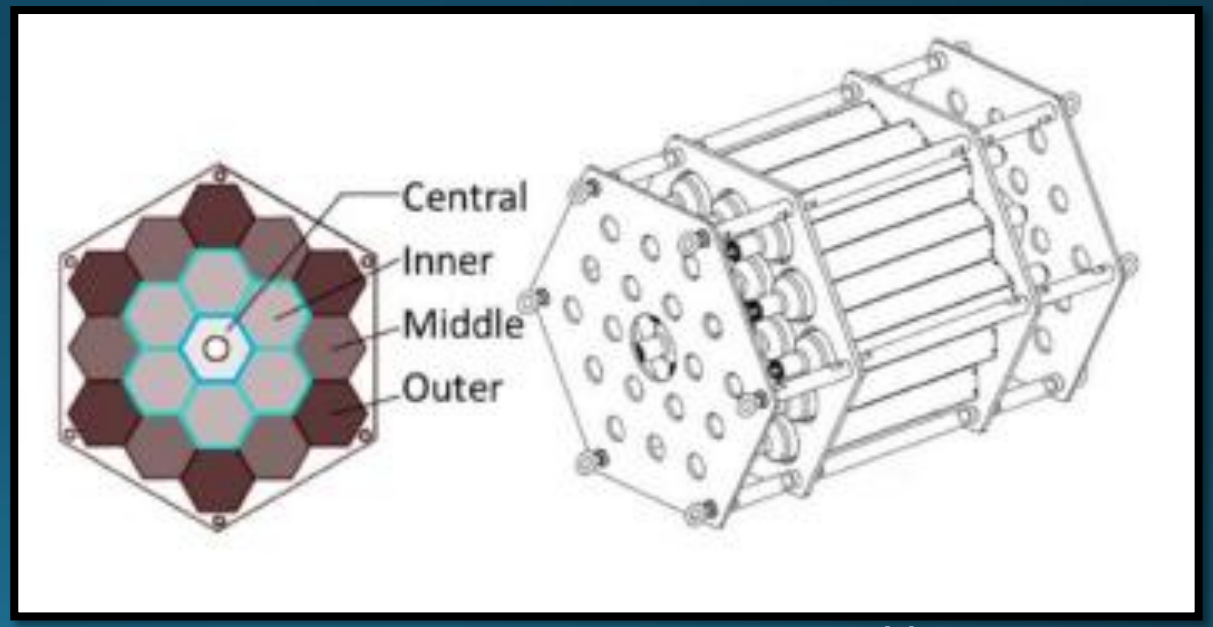


FIG 4: MTAS Schematic view[2]

[2] Wolińska-Cichocka, M., Rykaczewski, K.P., Fijałkowska, A., Karny, M., Grzywacz, R.K., Gross, C.J., Johnson, J.W., Rasco, B.C. and Zganjar, E.F., 2014. Modular Total Absorption Spectrometer at the HRIBF (ORNL, Oak Ridge). *Nuclear Data Sheets*, *120*, pp.22-25.

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

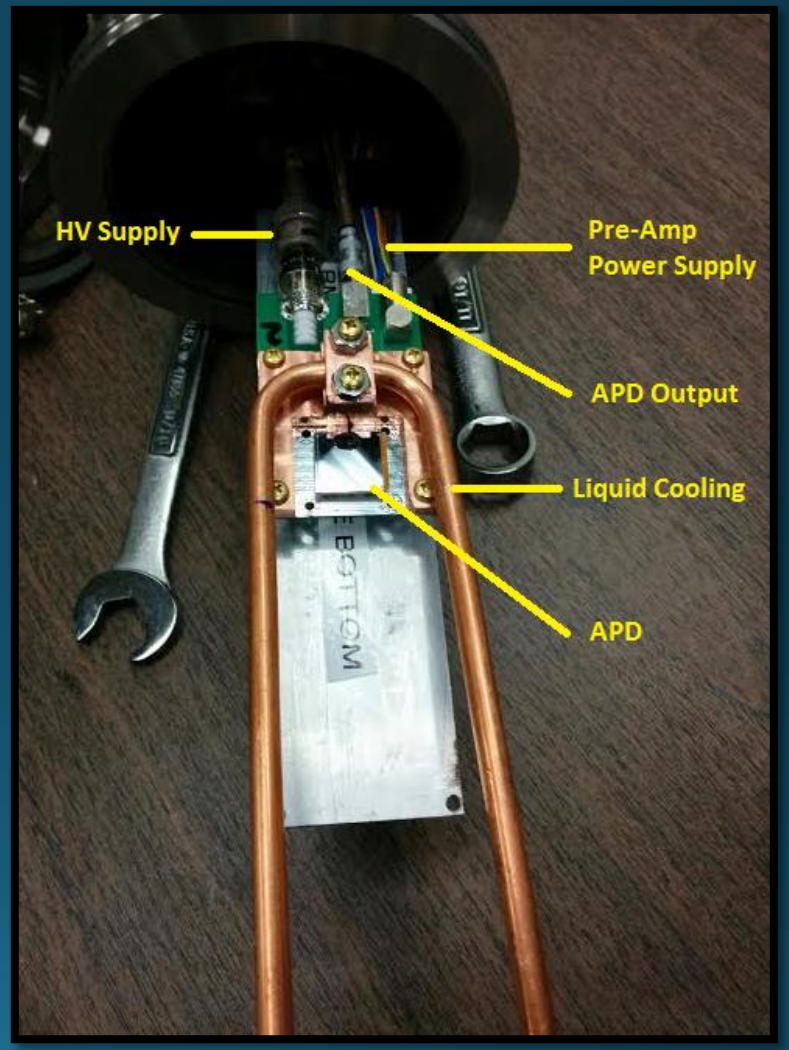


FIG 5: APD Setup for insertion into MTAS

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

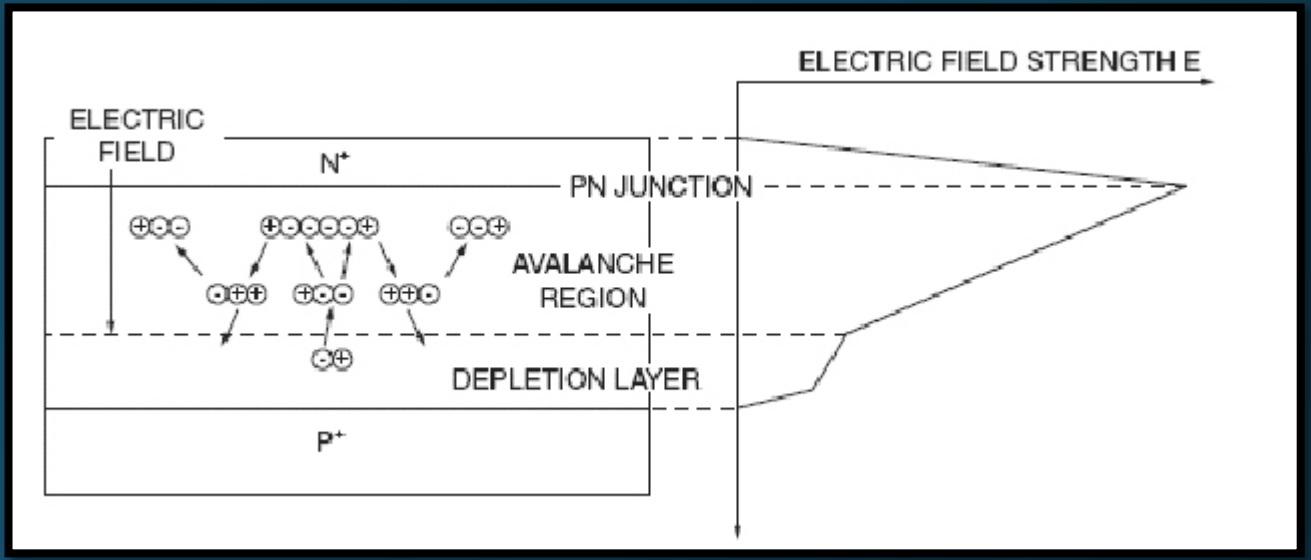
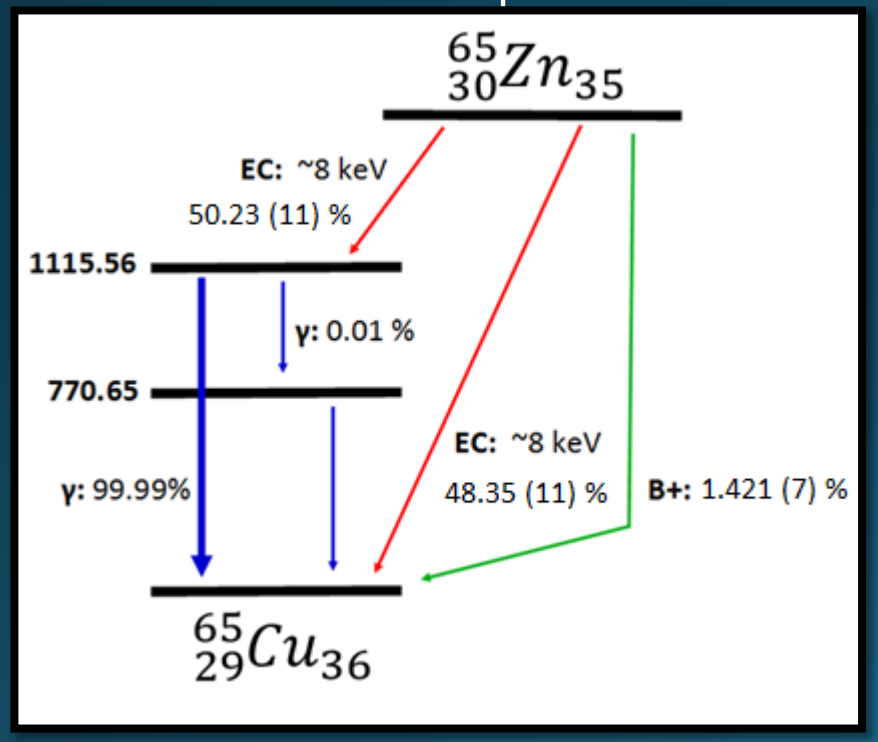


FIG 6: Basic Operating Principal of an APD[3]

[3] Tutorial : Avalanche Photodiodes Theory And Applications. 2016. *Tutorial : Avalanche Photodiodes Theory And Applications*. [ONLINE] Available at: http://www.photonicsonline.com/doc/avalanche-photodiodes-theory-and-applications-0001.

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.



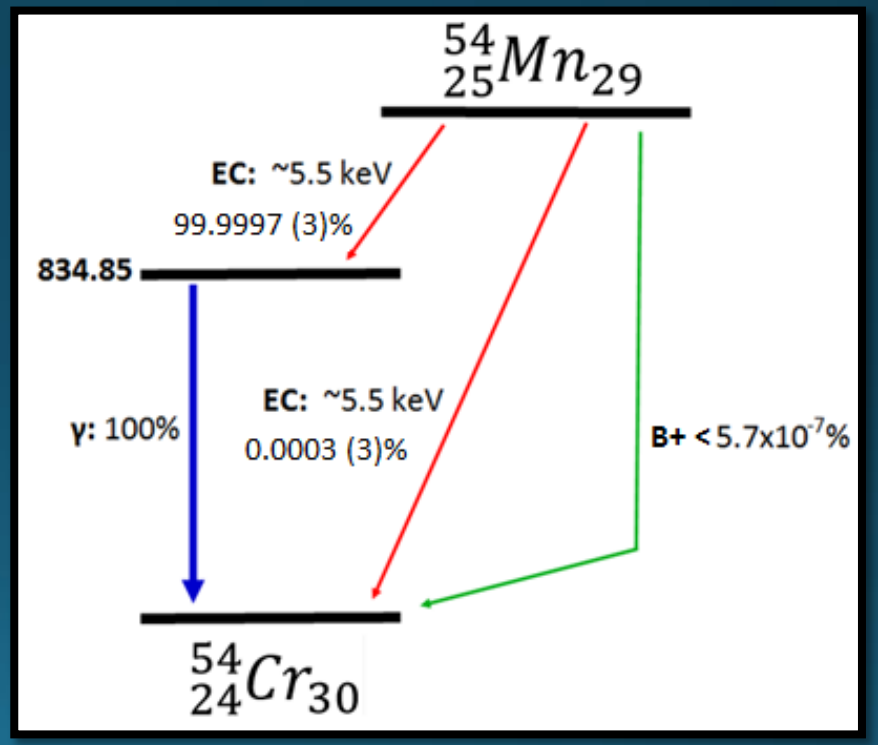
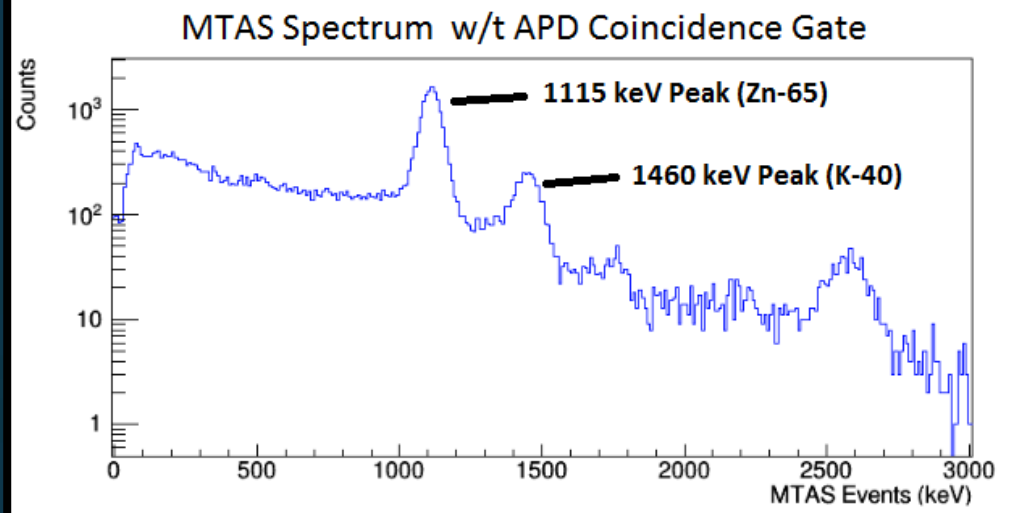


Fig 7: Decay Scheme for the calibration source Zn-65[3] (Left) and Mn-54[3] (Right).

[4] Bé, M.M., Chisté, V., Dulieu, C., Browne, E., Baglin, C., Chechev, V., Kuzmenco, N., Helmer, R., Kondev, F., MacMahon, D. and Lee, K.B., 2006. Table of Radionuclides (vol. 3–A= 3 to 244). *Monographie BIPM*, *5*.

Results: Zn-65 Coincidence

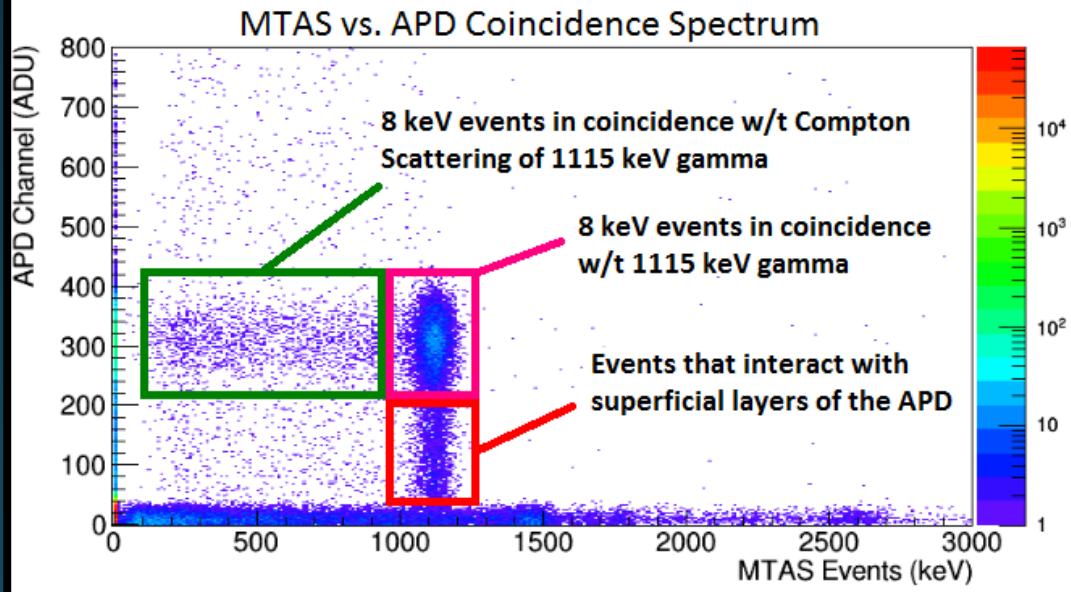


Run Parameters:

- APD High Voltage: 1700 V
- APD Temperature: -9.0^{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



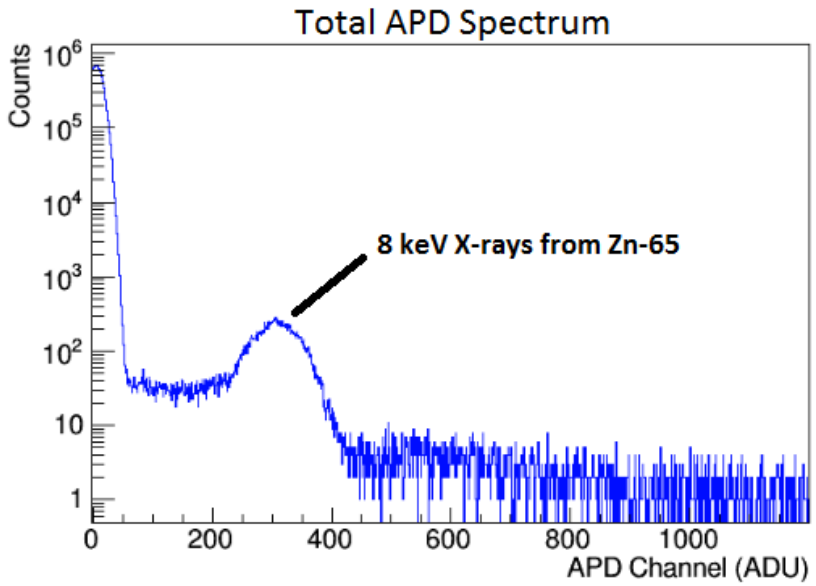


Fig 8: Experimental Run of Zn-65 with APD and MTAS in coincidence

Results: Calibration

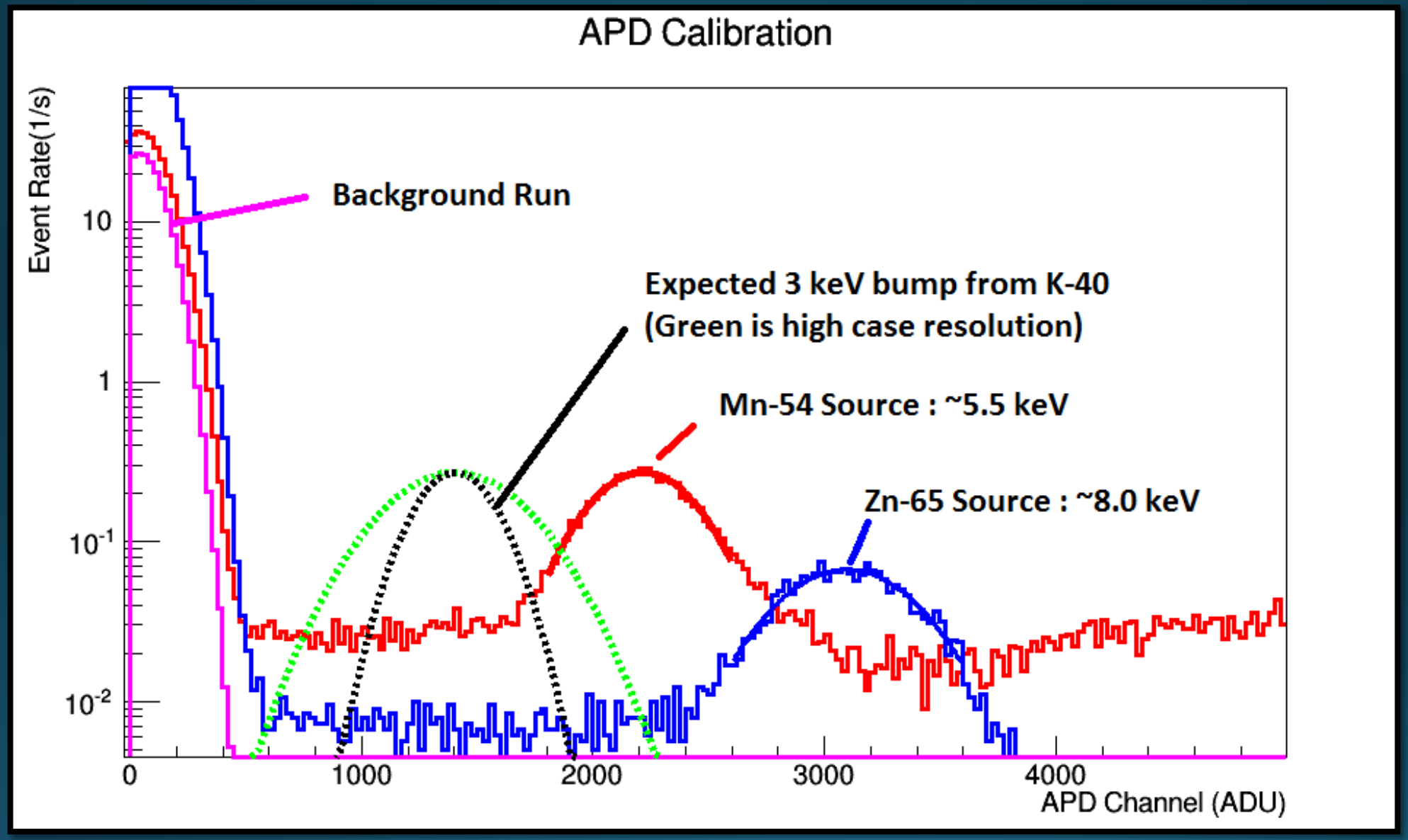


Fig 9: Calibration of APD from Mn-54 and Zn-65. Dotted curve show the predicted 3 keV bump from K-40

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

- KDK (Potassium-40 Decay) Team:
- Nathan Brewer[1],Philippe Di Stefano[2], Robert Grzywacz[3], Yuan Liu[1], Eric Daniel Lukosi[3], Chuck Melcher[3] , Charlie Rasco[1], Krzysztof Piotr Rykaczewski[1],Luis Stand[3],Matthew Stukel[2], Marzena Wolińska-Cichocka [1][3][5], Itay Yavin[4]

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References

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2) Wolińska-Cichocka, M., Rykaczewski, K.P., Fijałkowska, A., Karny, M., Grzywacz, R.K., Gross, C.J., Johnson, J.W., Rasco, B.C. and Zganjar, E.F., 2014. Modular Total Absorption Spectrometer at the HRIBF (ORNL, Oak Ridge). *Nuclear Data Sheets*, *120*, pp.22-25

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4) Bé, M.M., Chisté, V., Dulieu, C., Browne, E., Baglin, C., Chechev, V., Kuzmenco, N., Helmer, R., Kondev, F., MacMahon, D. and Lee, K.B., 2006. Table of Radionuclides (vol. 3–A= 3 to 244). *Monographie BIPM*, *5*.

Extra Slides

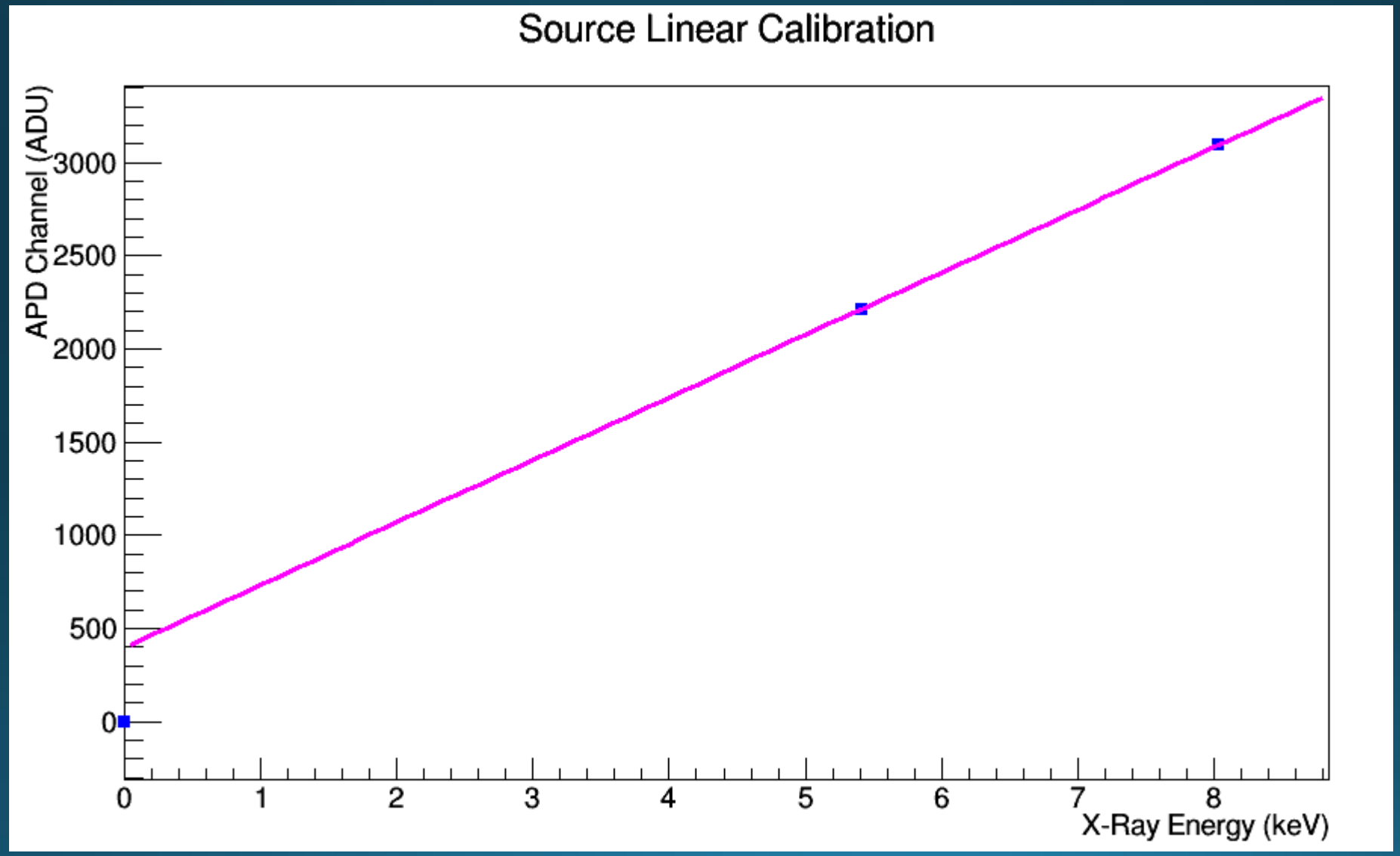
Source

- Thin Film (~1cm x1cm 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 β- 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

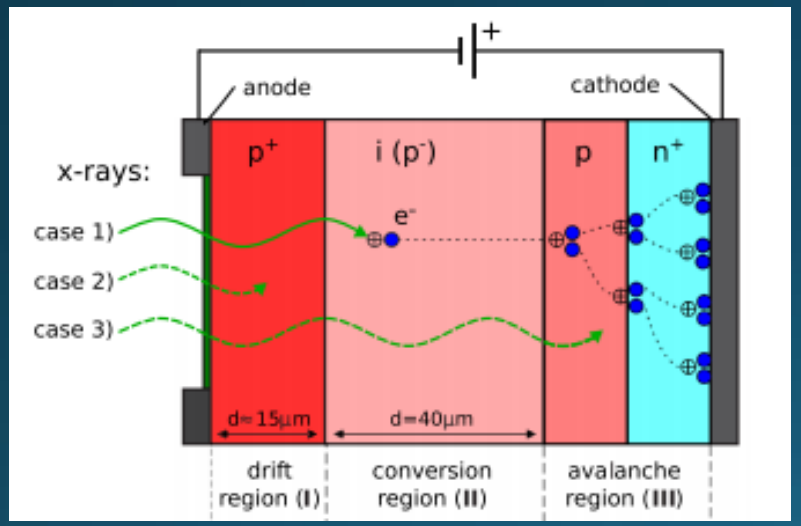


FIG 11: Schematic Diagram of APD showing interaction occurring in different regions [2]

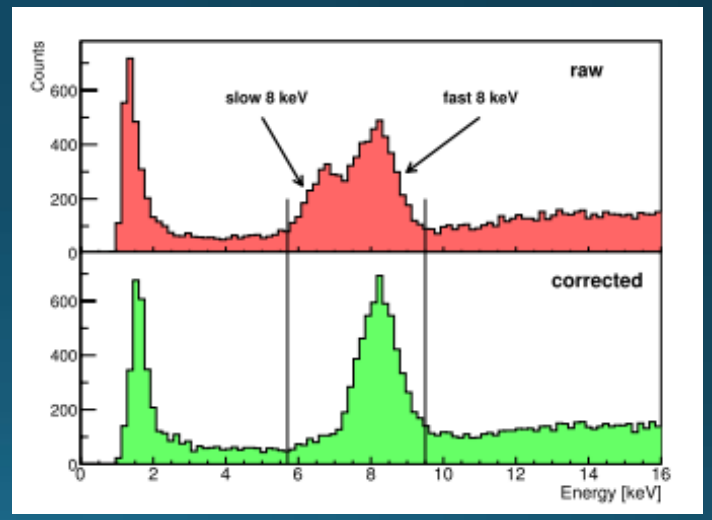


FIG 12: Muonic Helium Spectrum showing slow pulses and possible reconstruction[2]

[2] Diepold, M., Fernandes, L.M., Machado, J., Amaro, P., Abdou-Ahmed, M., Amaro, F.D., Antognini, A., Biraben, F., Chen, T.L., Covita, D.S. and Dax, A.J., 2015. Improved x-ray detection and particle identification with avalanche photodiodes. *Review of Scientific Instruments*, *86*(5), p.053102.

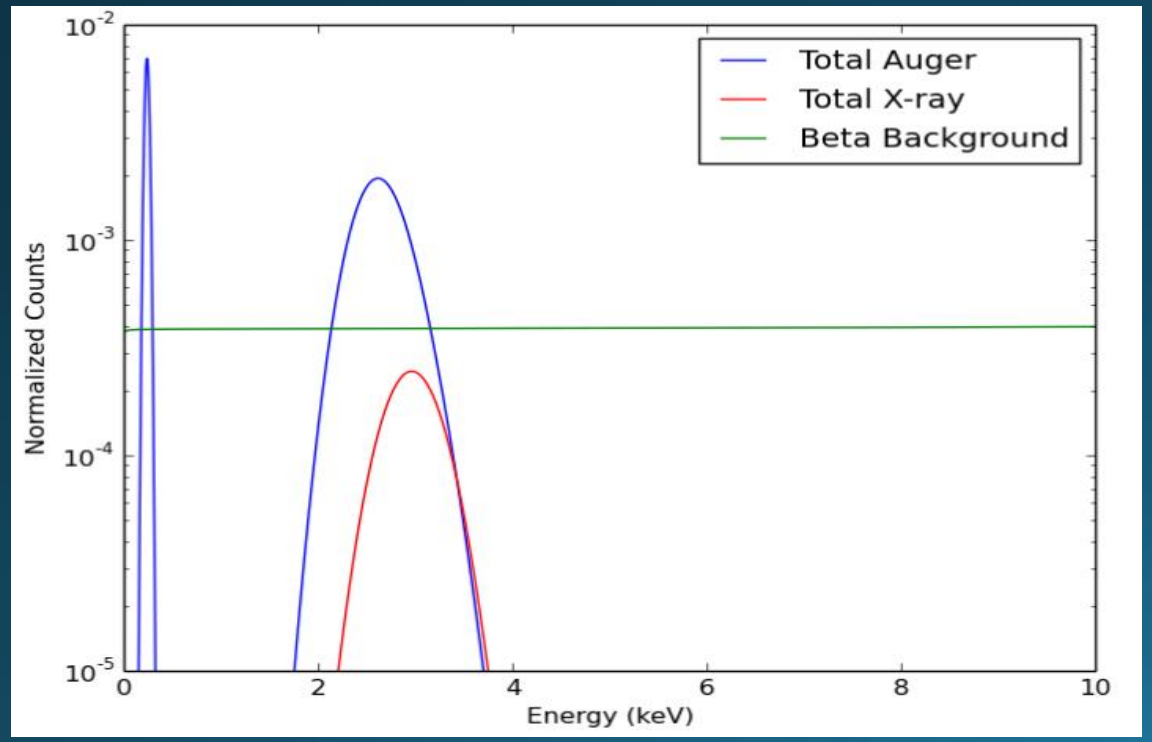
Electrons from K-40

- 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

Particle	Energy (keV)	Particles per 100 disintegrations
Auger Electron		
- KLL	2.511 - 2.669	5.89
- KLX	2.831 - 2.942	1.27
- KXY	3.149 - 3.174	0.0685
X-Ray		
- K-Alpha	2.95	0.891
- K-Beta	3.19	0.096

TABLE 2: K-40 Decay Scheme

http://www.nucleide.org/DDEP_WG/Nuclides/K-40_tables.pdf



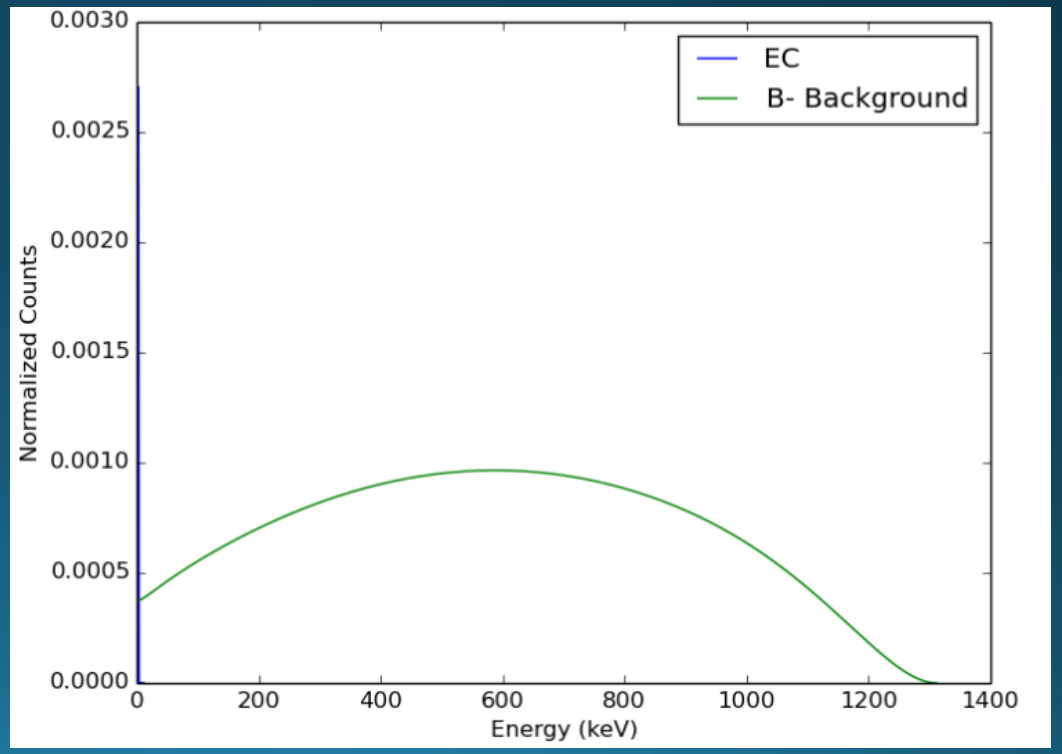


FIG 13: Signal To Noise of the Beta Background for EC only

Fluorescence

- Lower energy calibration is required. Possible fluorescence sources

Target	Expected Fluorescence
Titanium (Ti)	
Ti:	K_α: 4.51 keV K_β: 4.93 keV **(VISIBLE)**
Potassium Chloride (KCL) Window	
K:	K_α: 3.31 keV K_β: 3.59 keV **(VISIBLE)**
CL:	K_α: 2.62 keV K_β: 2.82 keV **(VISIBLE)**
Gypsum ($CaSO_4$) Crystal	
Ca:	K_α: 3.69 keV K_β: 4.01 keV **(VISIBLE)**
S:	K_α: 2.31 keV K_β: 2.46 keV **(VISIBLE)**
O:	K_α: 0.526 keV **(Not Visible)**

Effect of K-40 on DAMA

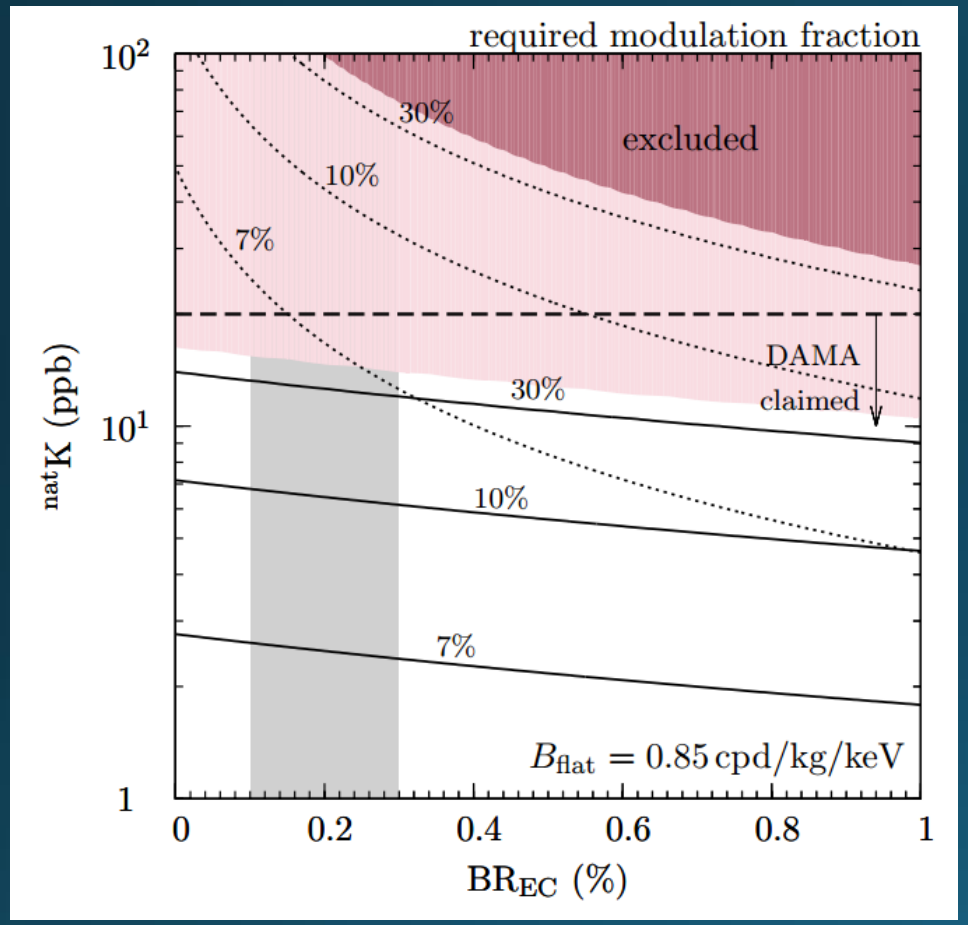


FIG 14: Required Modulation Fraction

- 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 = 2pi/1yr
  - 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

[1] Pradler, J., Singh, B. and Yavin, I., 2013. On an unverified nuclear decay and its role in the DAMA experiment. *Physics Letters B*, *720*(4), pp.399-404.