Investigation of Large Area Avalanche Photodiodes for the Experimental Measurement of the Electron Capture Decay of ^{40}K: KDK Project

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For the CAP Congress 2017

^{40}K Decay Scheme

- ^{40}K (0.0117%) can be found in natural potassium
- Contaminant in many rare event searches
- Has been shown to have an implication on the long standing claim of the DAMA/LIBRA experiment
- Important Decay Channels:
  - 10.55 % to $^{40}Ar^*$, EC*
  - 0.2 % to ^{40}Ar, EC
- <u>Branching ratio of electron capture to ground state has never been experimentally measured</u>
- Only known example of a unique-third forbidden transition.

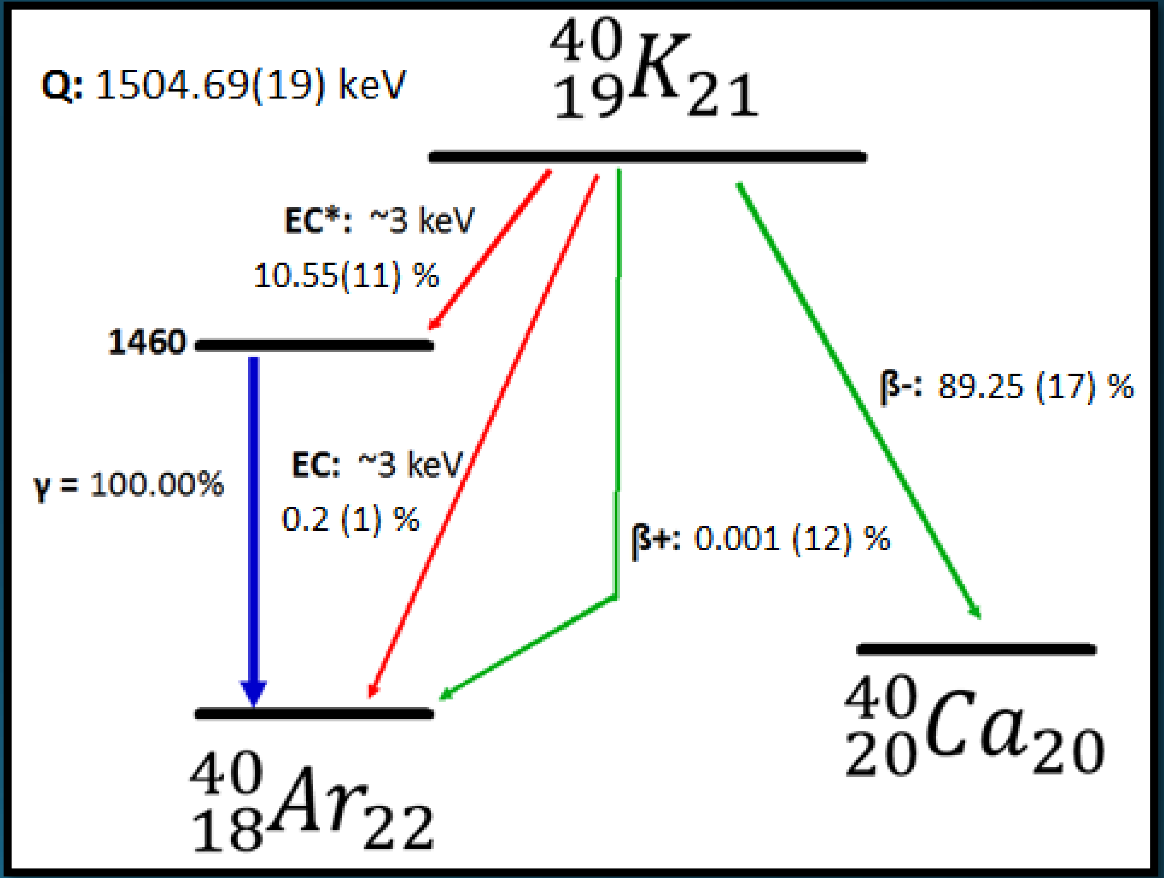


FIG 1: ^{40}K Decay Chain [4]

[4] Be, M.M., Chiste, V., Dulieu, C., Browne, E., Baglin, C., Chechev, V., Kuzmenco, N., Helmer, R., MACMAHON, D. and LEE, K., 2004. Table of Radionuclides (Comments on evaluation). *Monographie BIPM-5*, 7.

KDK Experiment

KDK Experiment Idea

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

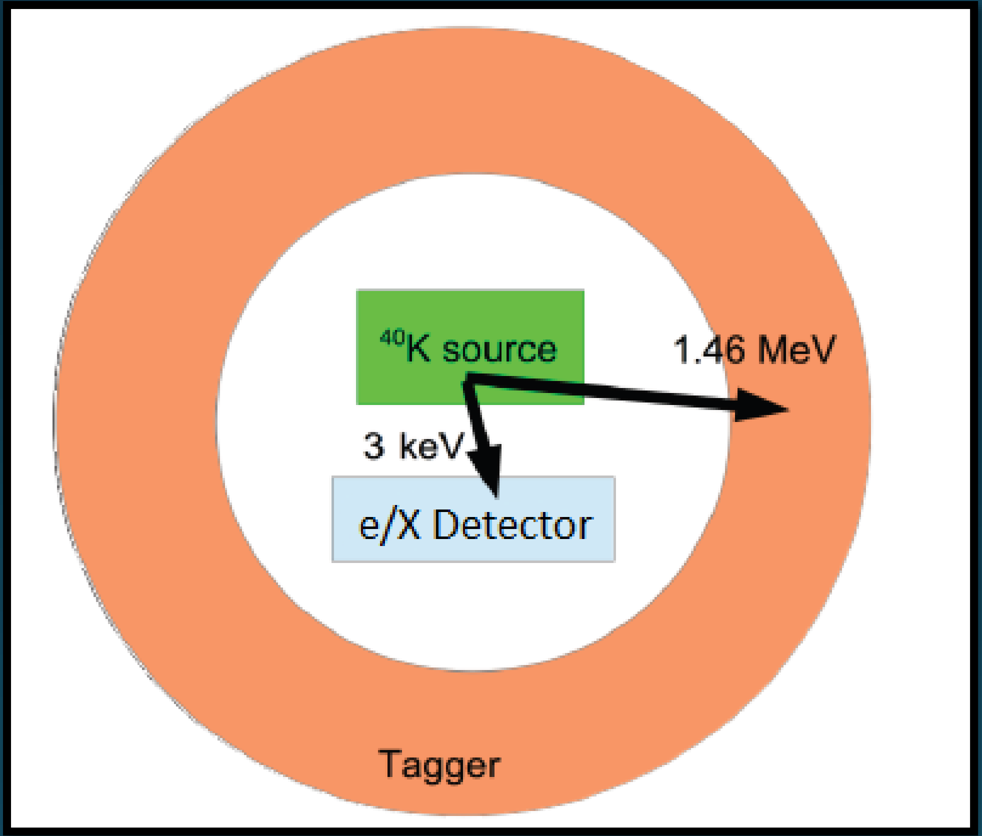


FIG 2: KDK Experimental Setup

- Outer detector used to tag the 1460 keV gammas: MTAS (Modular Total Absorption Spectrometer)
- Separates the events caused by the EC* decay from the direct EC.
- Interior Detector has multiple options: APD (Avalanche Photodiode) or Potassium rich scintillator (KSI supplied by the University of Tennessee)

APD Operating Principal

- APD are silicon based detectors
- 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
- Electrons 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

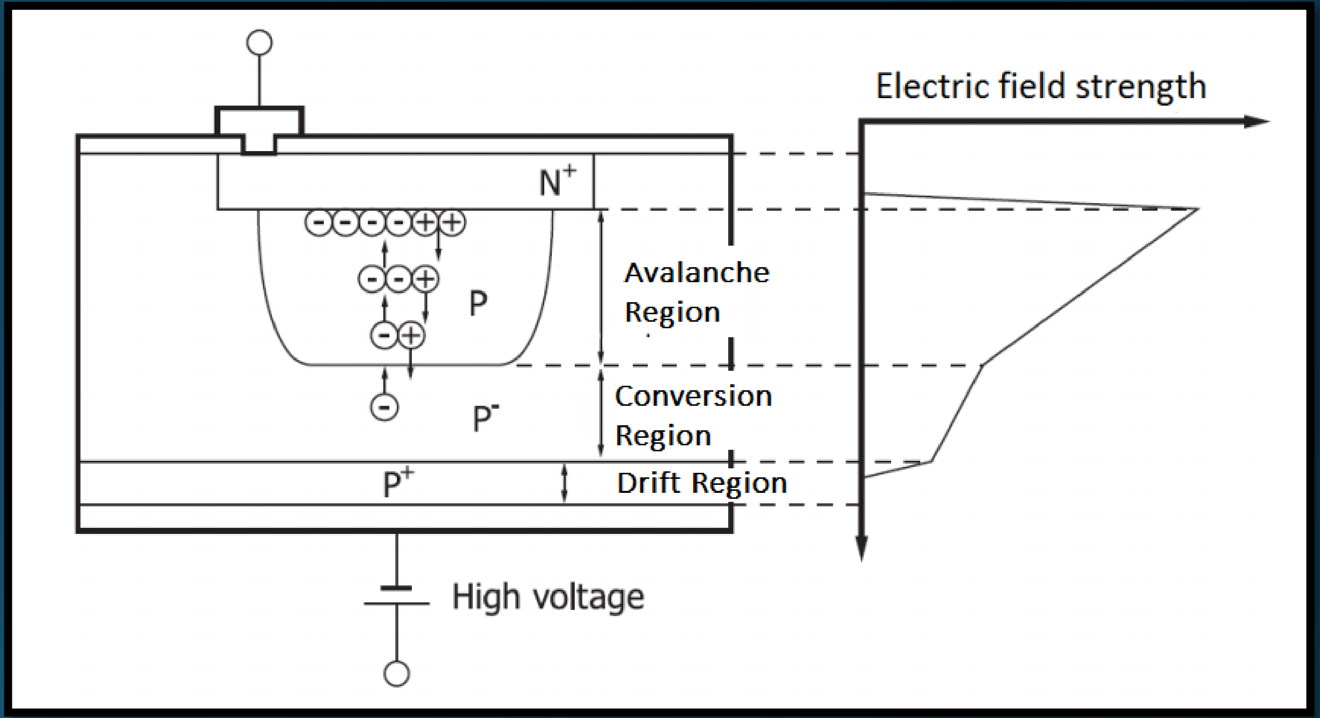


FIG 3: Basic Operating Principal of an APD[3]

[3]http://www.hamamatsu.com/resources/pdf/ssd/e03_handbook_si_apd_mppc.pdf

APD: Internal X-ray Detector

- Interior Detector Requirements
  - Ability to detect low energy x-rays between 1-10 keV
  - Small detector size (< 6cm) and ability to run in coincidence with MTAS
  - ^{40}K source must be visible to the detector
- We use a Large Area Avalanche Photodiode; 13mm x 13mm Active Area from RMD
- A liquid cooling system was set up in order to cool the APD to a target goal of -30^{o}C and increase its performance
- Electronics designed and provided by Paul Davis, U. Alberta MRS

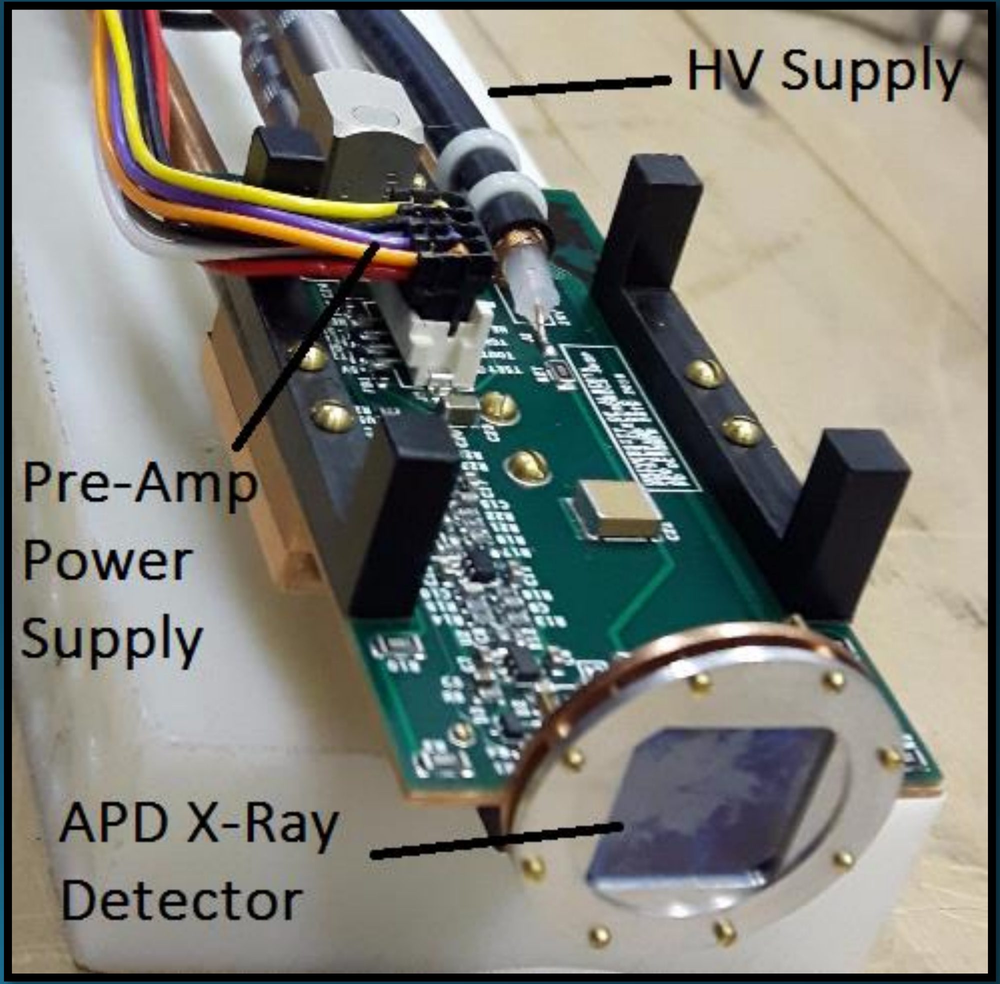


FIG 4: APD Setup for insertion into MTAS

APD Testing Setup

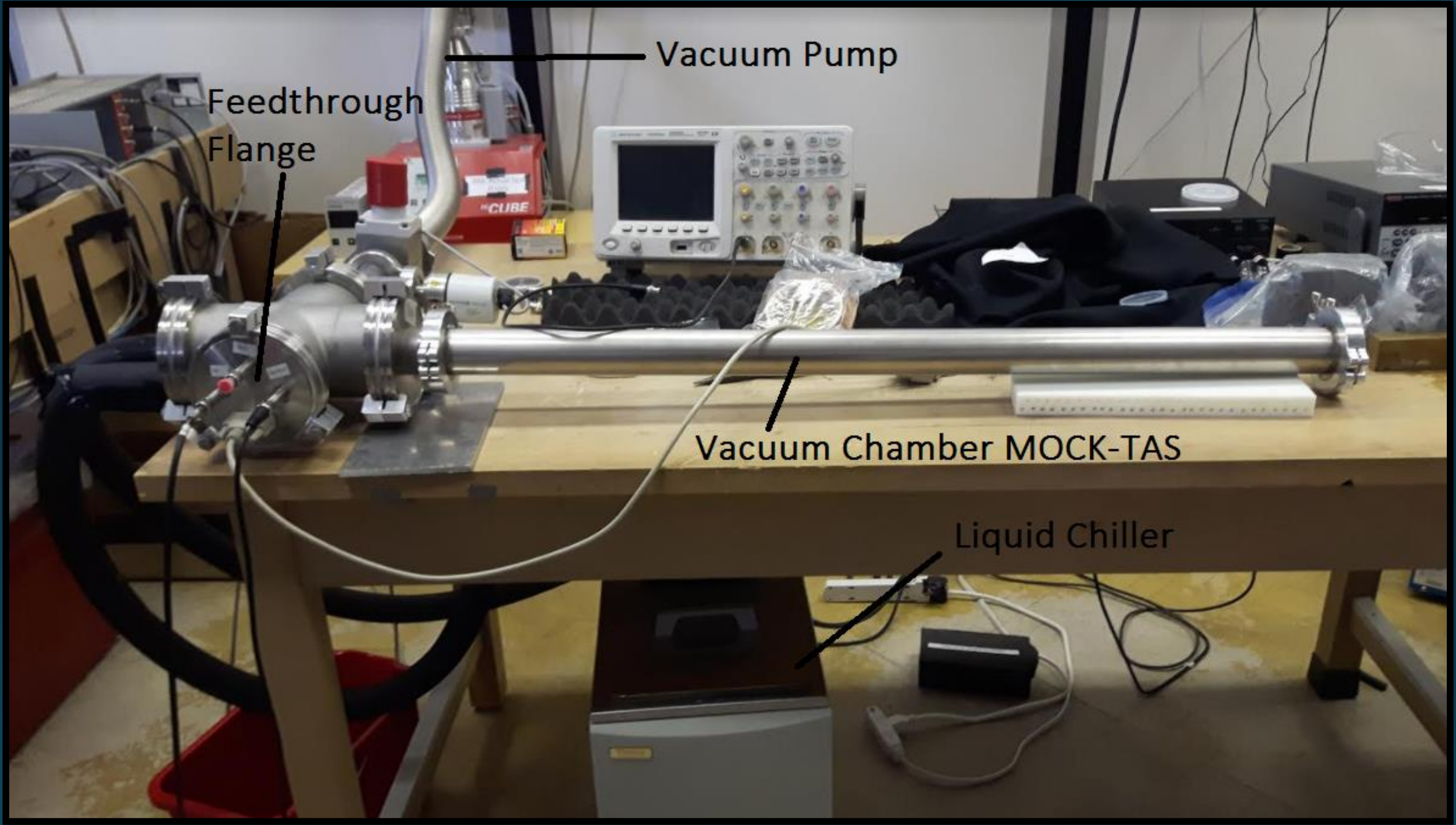
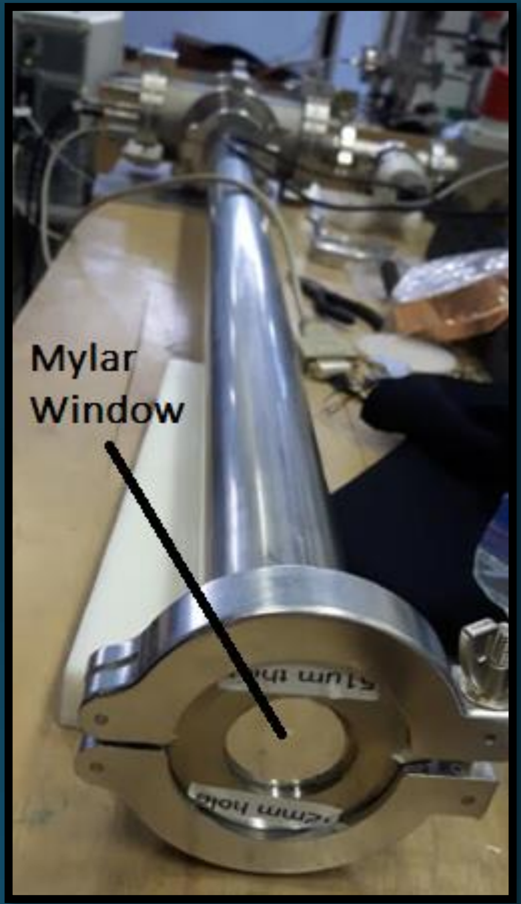
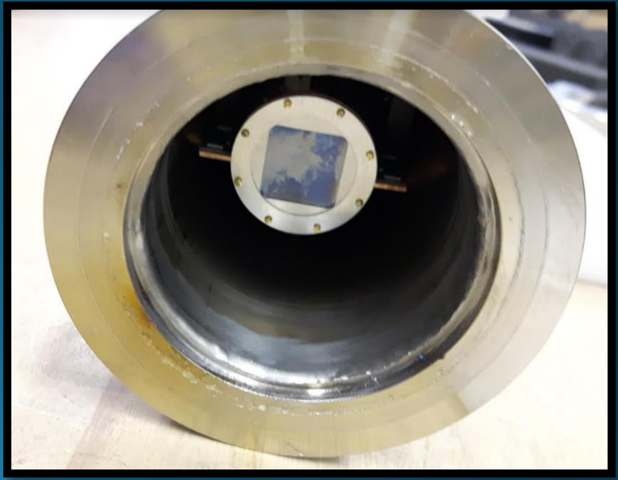


FIG 5: Queen's University APD Testing Setup





APD ^{55}Fe Characterization

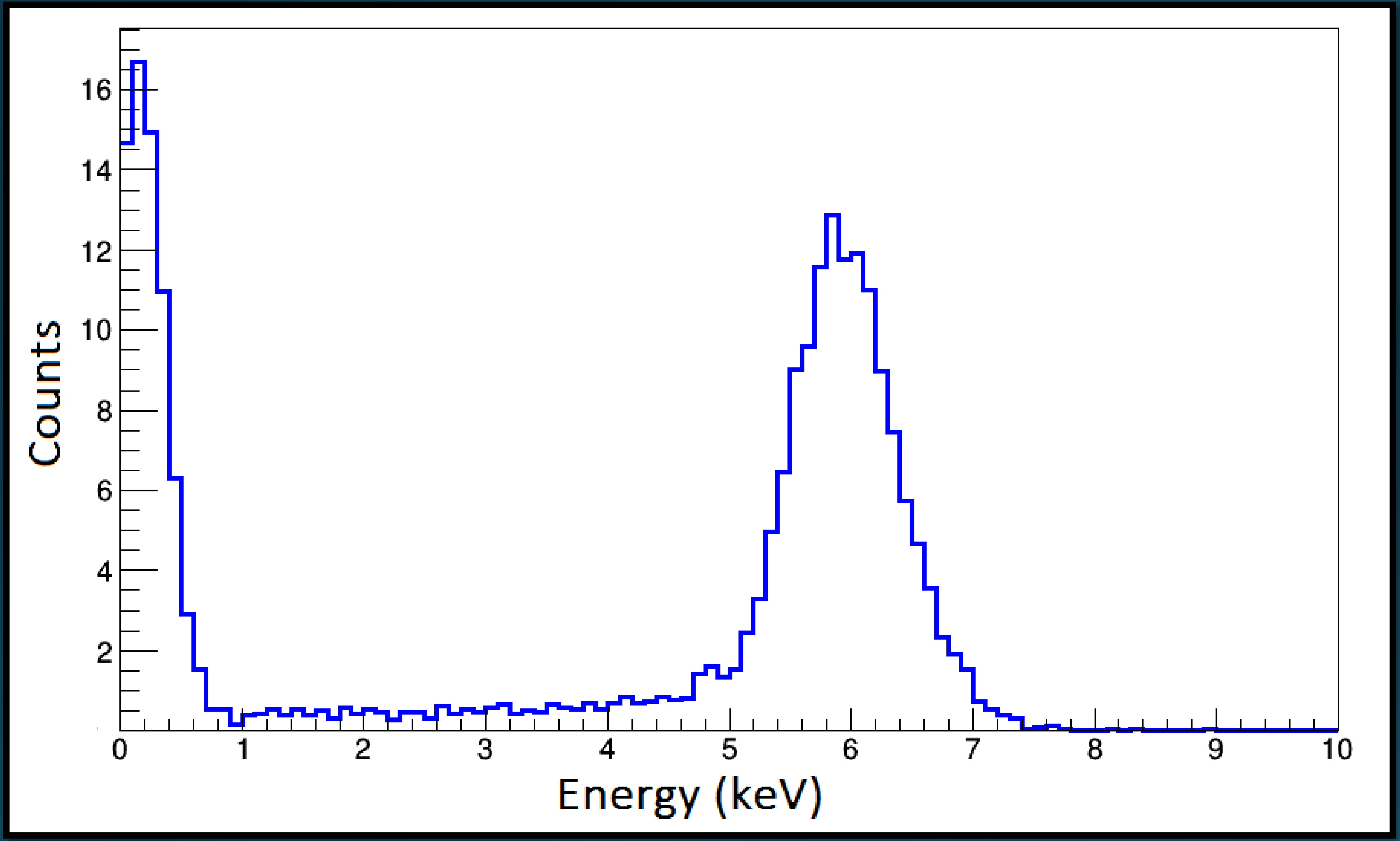


FIG 6: ^{55}Fe Spectrum from APD x-ray detector at Queen's University

- We use an ^{55}Fe (5.9 keV) source to perform our experiments at Queen's
- Typical resolution is ~8% (sigma/mean)
  - Low energy x-ray threshold measurements
  - Temperature Dependency
  - Voltage Dependency
  - MTAS feasibility

Low Energy X-Ray Threshold

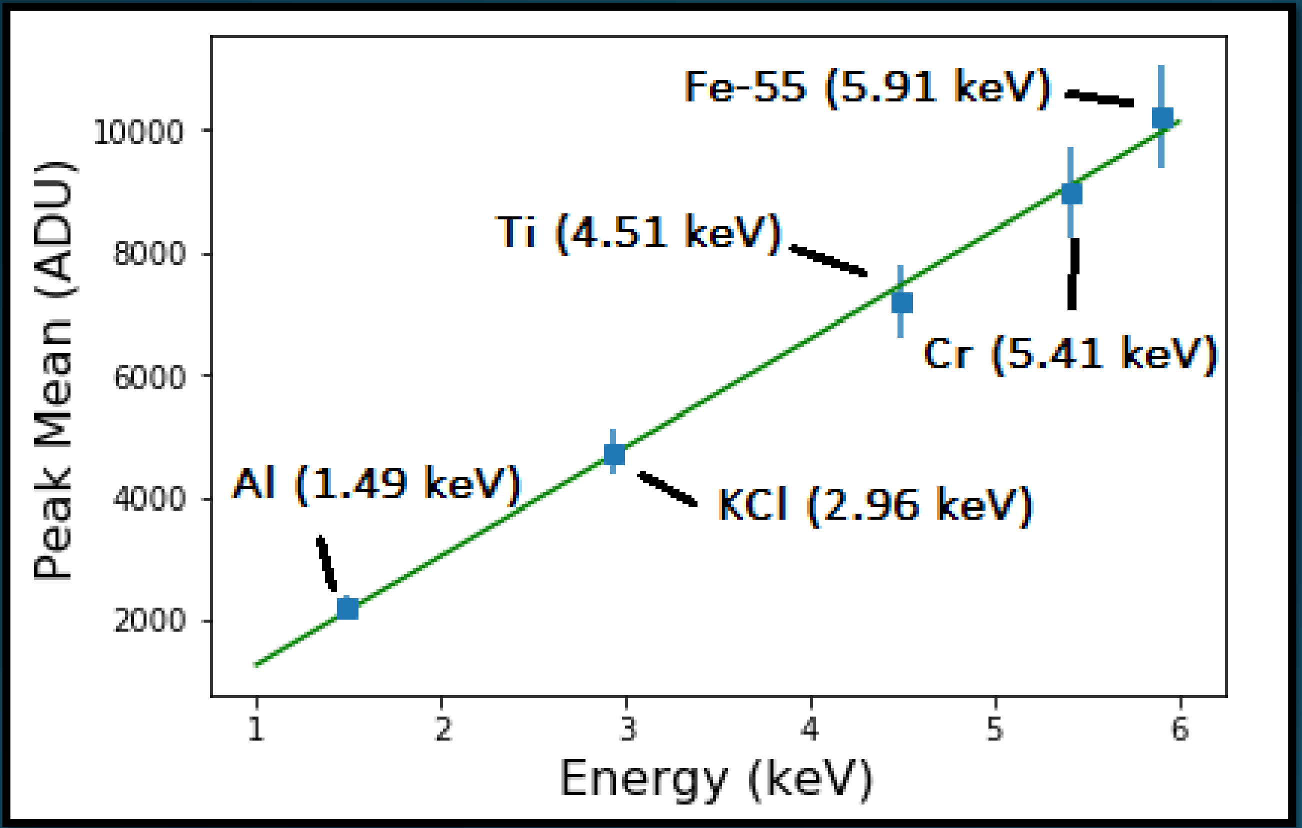


FIG 7: APD Fluorescence Calibration.

- APD must be able to detect low energy x-rays (~1.5 -10 keV)
- This is tested by Fluorescence. ^{55}Fe is used as the x-ray source
- Able to achieve our low threshold of 1.49 keV (Al). Difficult to go lower as we hit our noise threshold
- Calibration Targets Include:
    - Aluminum: 1.49 keV
    - KCl Window: 2.96 keV
    - Titanium: 4.51 keV
    - Chromium: 5.41 keV (from steel)

APD Gain Characterization

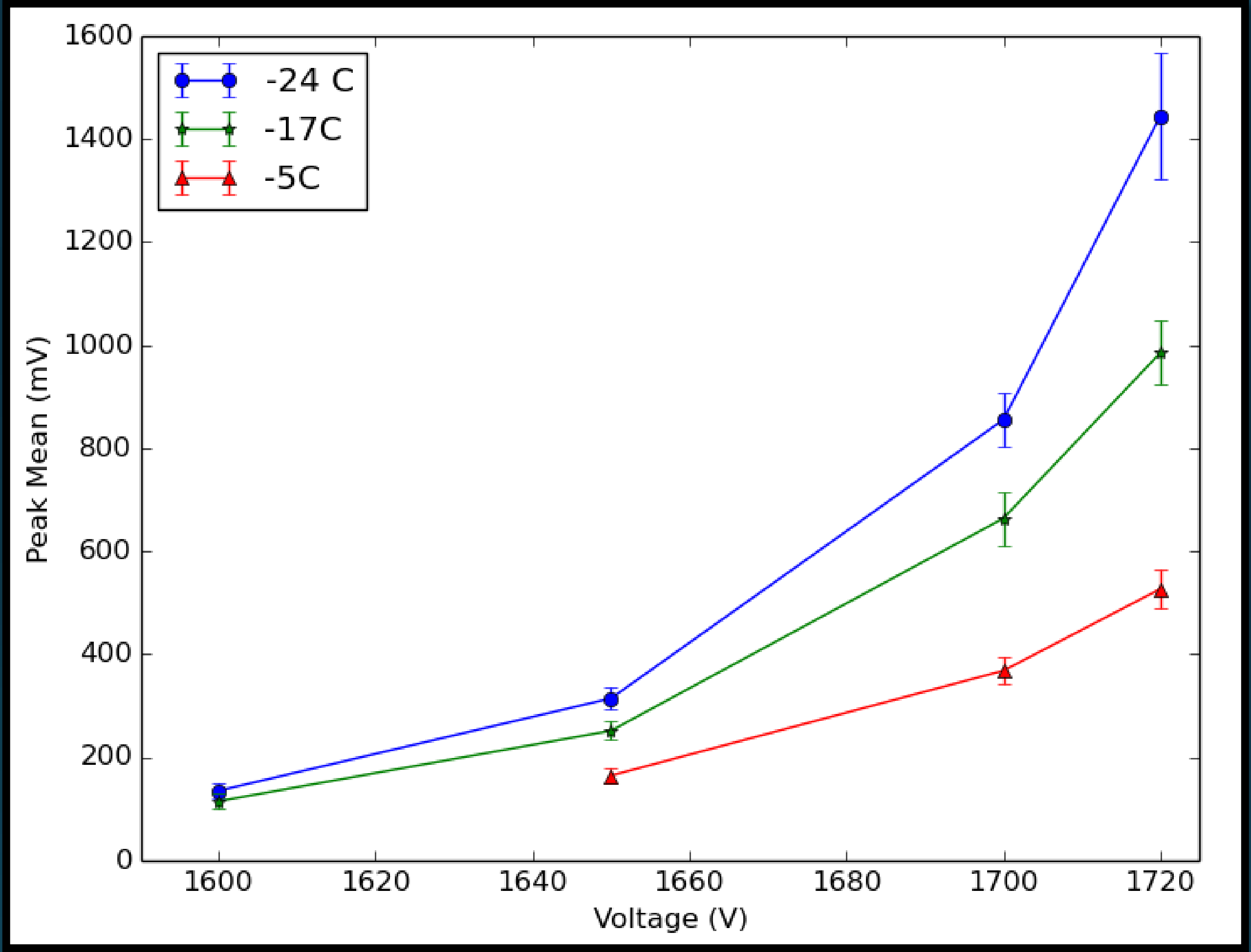
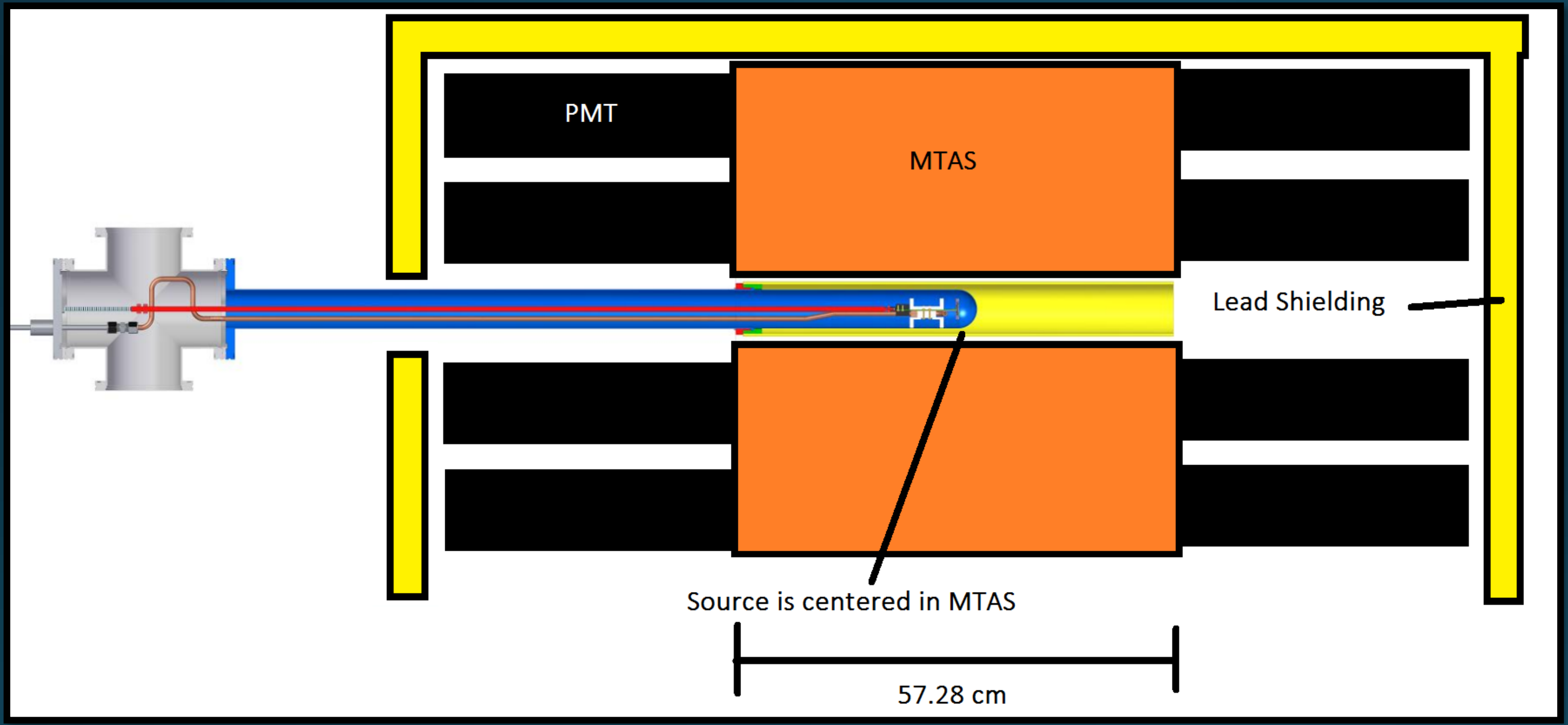
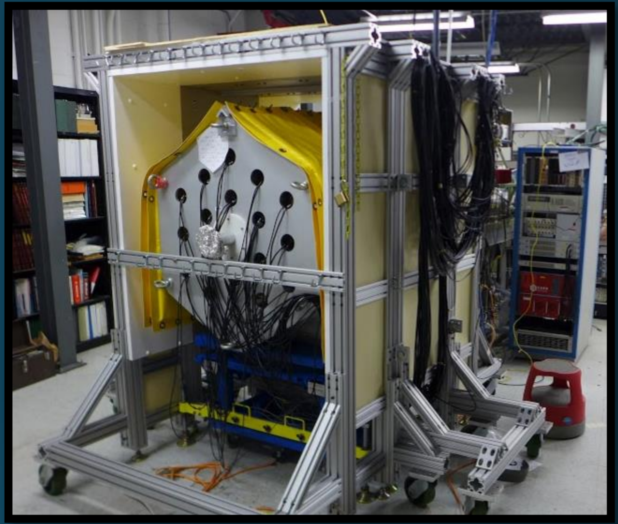


FIG 8: APD Characterization through Temperature and Voltage

- The gain factor of the APD can be controlled by the Voltage and Temperature
- Events blend into the noise below 1600 V and around 0°C
  - **Voltage:** By increasing the voltage you increase the electric field across the APD. This will induce a larger avalanche (per event) and produce a larger signal
  - **Temperature:** Higher temperatures increase the vibrations in the crystal lattice. Electron-hole pairs collide more keeping them from building energy and creating a new electron hole pair. Hindering the avalanche process and decreasing the signal

Complete KDK Setup





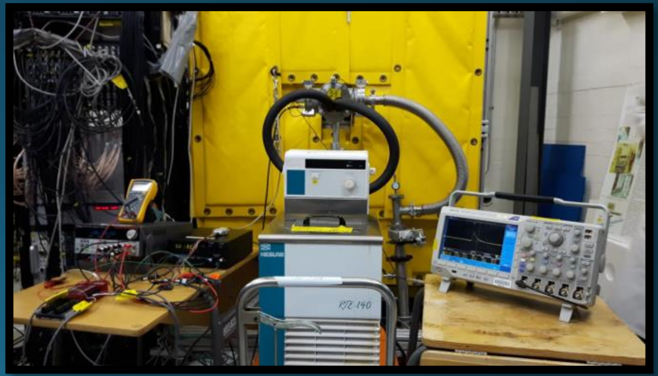


FIG 9: Complete KDK experimental setup (up). MTAS (upper right). Liquid Chiller, power supply and DAQ (Lower Right)

Can the APD detect ^{40}K x-rays?

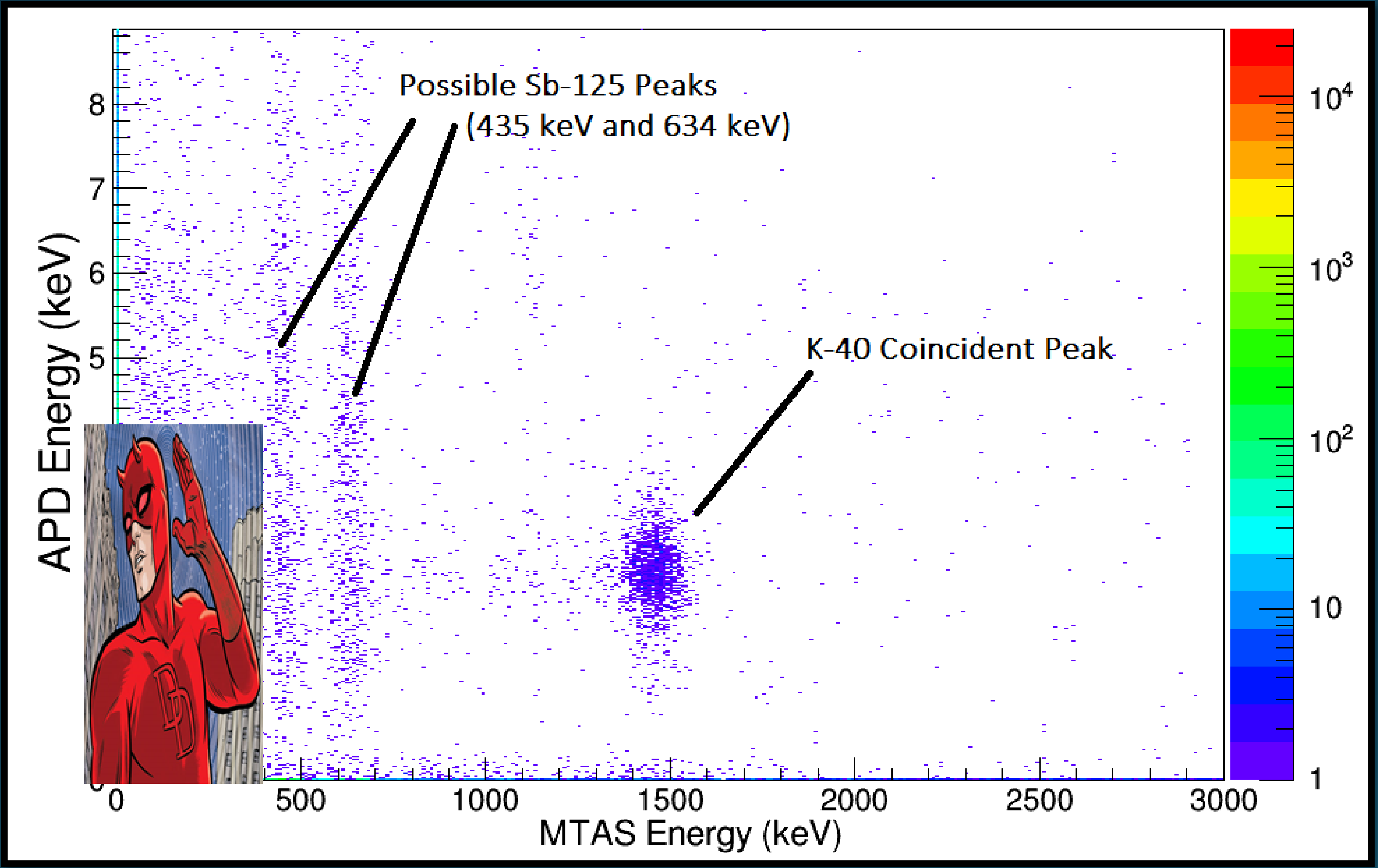


FIG 10: Blinded ^{40}K run.

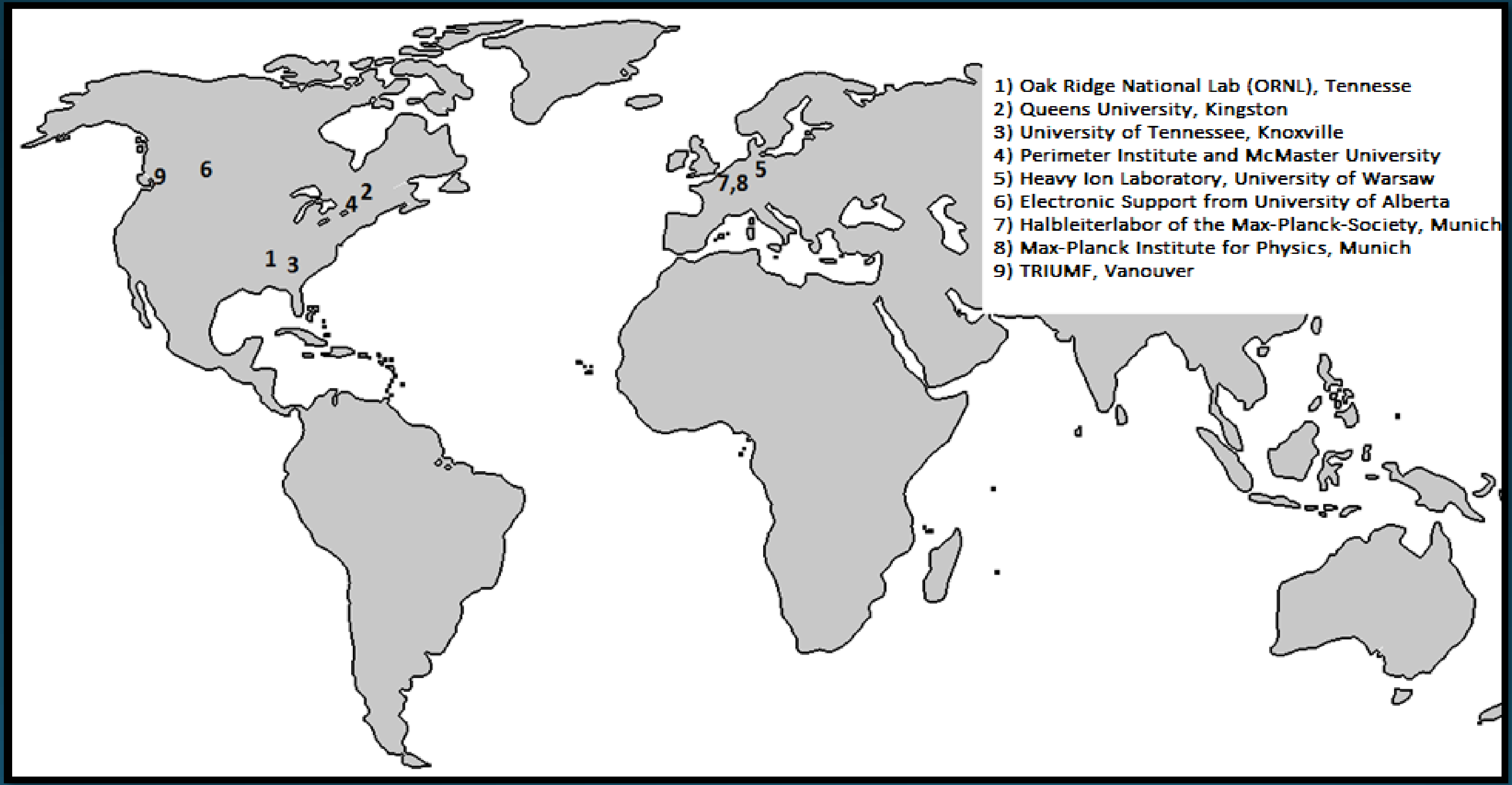
- Initial ^{40}K run was performed in March, 2017
- ^{40}K coincident peak was clearly visible
- Allows for branching ratio measurements to be performed by identifying coincident and anti-coincident regions
- Source contains a ^{125}Sb contamination
- Data is blinded in the anti-coincident region
- Analysis is being performed:
  - Understanding our background
  - Efficiency Measurements of system (MTAS + APD)
  - Effect of Auger electrons and β- from the decay

Summary/ Future Improvements

- The KDK collaboration is a group dedicated to the measurement of the branching ratio of the EC channel decay of ^{40}K.
- Current APD x-ray detector:
  - Detects low energy x-rays (Aluminum Fluorescence (1.49 keV))
  - Runs in coincidence with the MTAS gamma ray detector
  - Successfully see the ^{40}K coincident peak.
  - Has been characterized in terms of voltage and temperature
- APD is a successful candidate as the interior detector for the KDK experiment
- Current work is going to develop a better understanding of the APD detector (electron characterization), position measurements and into a new uncontaminated ^{40}K source

• KDK (Potassium-40 Decay) Team:

• Nathan Brewer[1],Philippe Di Stefano[2], Paul Davis[6],Robert Grzywacz[3], Daniel Hamm[3], Peter Lechner[7],Yuan Liu[1], Eric Daniel Lukosi[3], Chuck Melcher[3] ,Jelena Nikovic[7], Fredericca Petricca[8],Charlie Rasco[1],Fabrice Retiere[9] ,Krzysztof Piotr Rykaczewski[1],Luis Stand[3],Pierre Squillari[2] ,Matthew Stukel[2],Dan Stracener[1] ,Marzena Wolińska-Cichocka [1][3][5], Itay Yavin[4]



References

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.

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

3)http://www.hamamatsu.com/resources/pdf/ssd/e03_handbook_si_apd_mppc.pdf

4) Be, M.M., Chiste, V., Dulieu, C., Browne, E., Baglin, C., Chechev, V., Kuzmenco, N., Helmer, R., MACMAHON, D. and LEE, K., 2004. Table of Radionuclides (Comments on evaluation). *Monographie BIPM-5, 7*.

5) Bernabei, R., Belli, P., d'Angelo, S., Di Marco, A., Montecchia, F., Cappella, F., d'Angelo, A., Incicchitti, A., Caracciolo, V., Castellano, S. and Cerulli, R., 2013. Dark matter investigation by DAMA at Gran Sasso. *International Journal of Modern Physics A, 28*(16), p.1330022.

Extra Slides

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
- A high efficiency is needed to avoid false positives from the EC* channel and other background sources
- The centre of MTAS has a 63.5 mm through hole where the internal detector can be placed

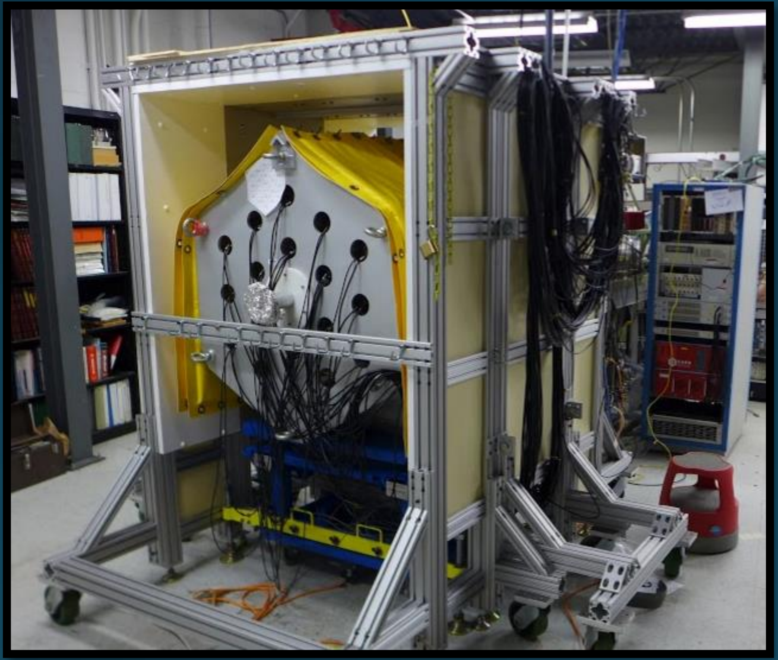


FIG 11: MTAS at ORNL[2]

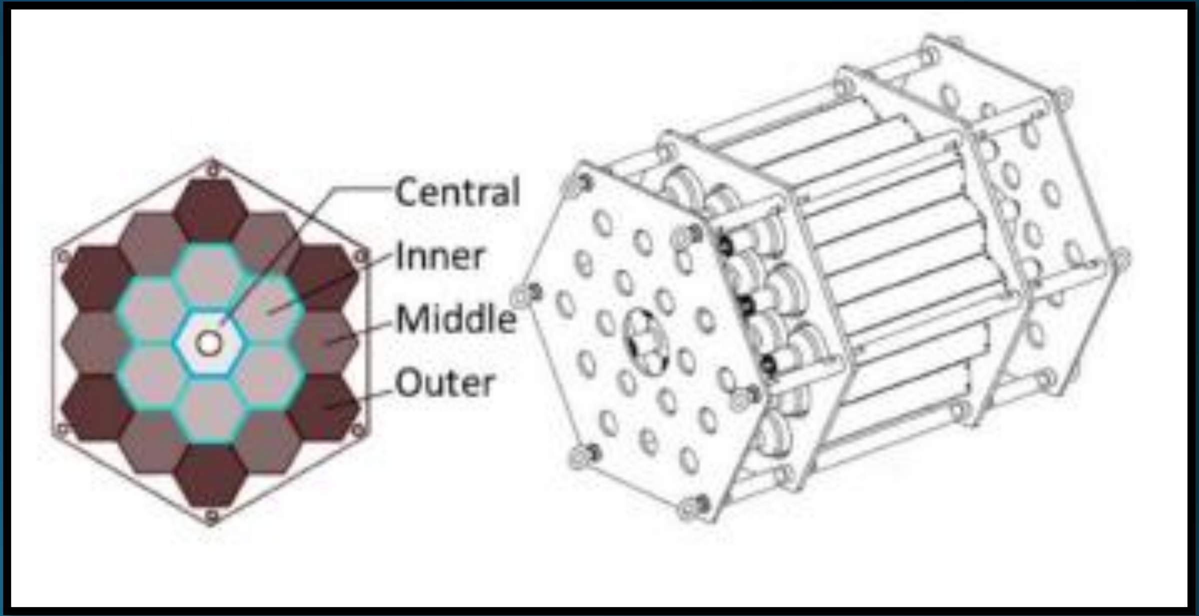


FIG 12: MTAS Schematic view[2]

[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 X-ray Detector Design

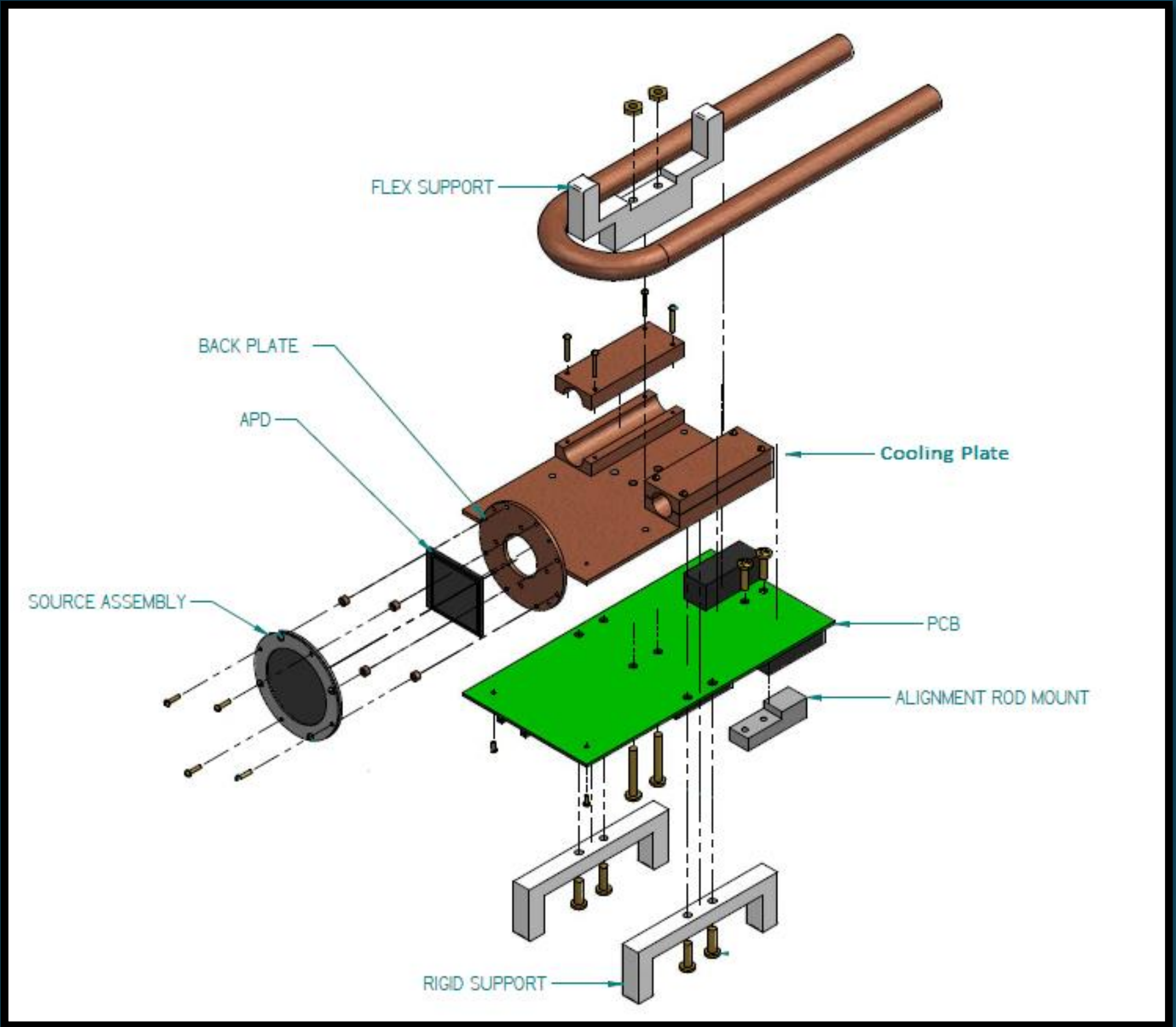


FIG 13: APD Assembly Setup

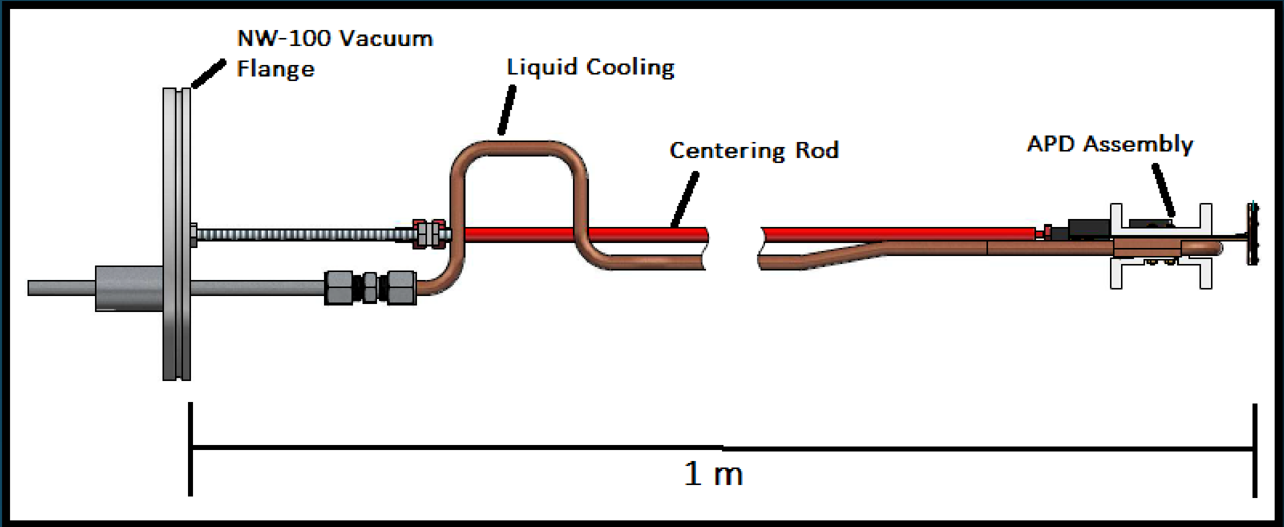


FIG 14: APD Cooling Setup

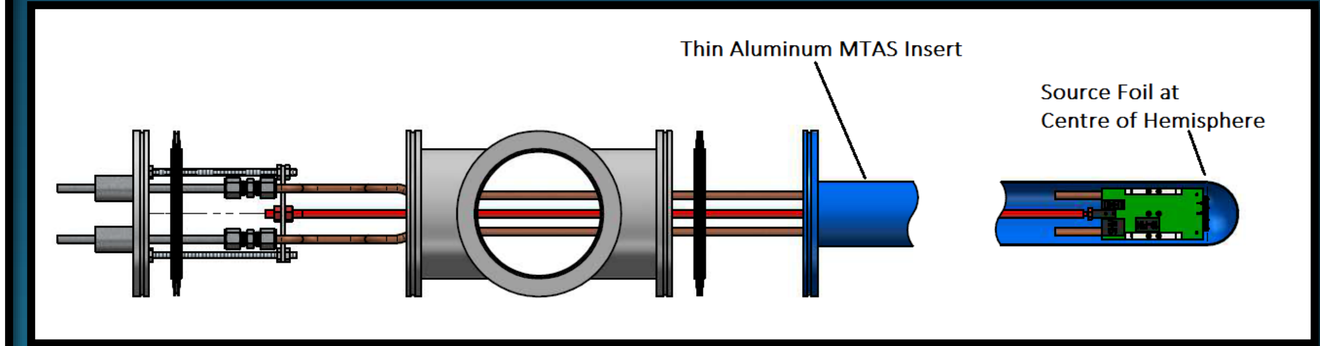


FIG 15: MTAS Insert Setup

KDK Experiment Flow Chart

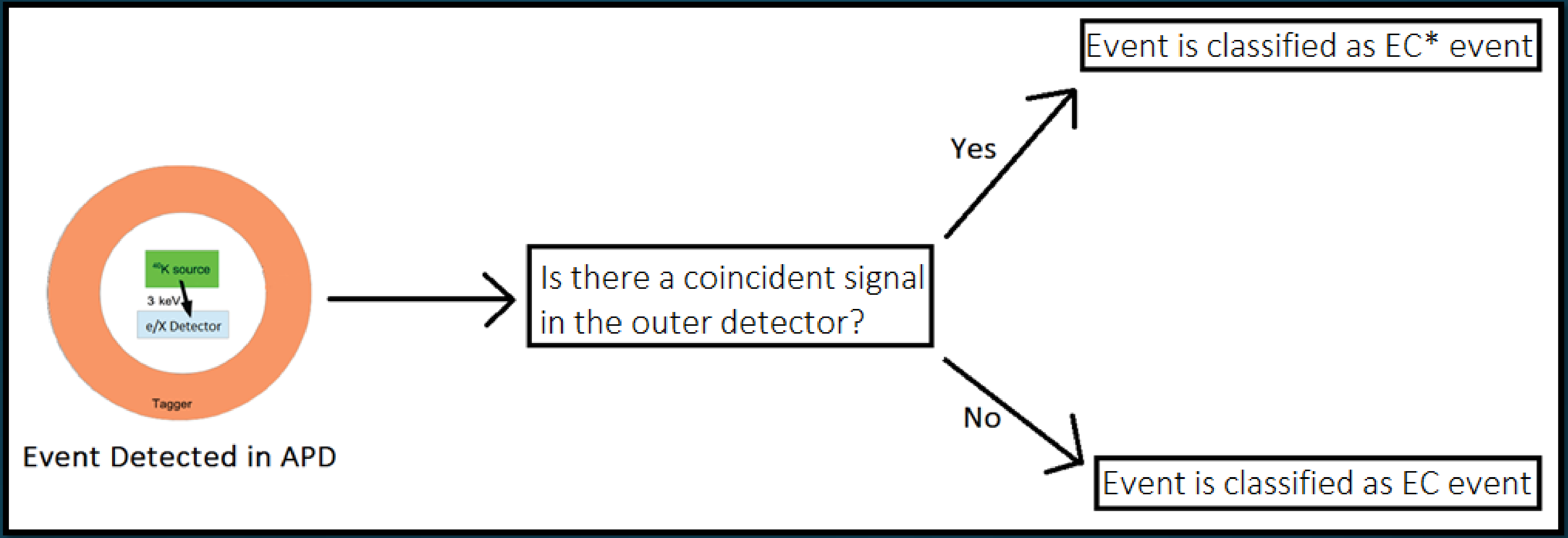
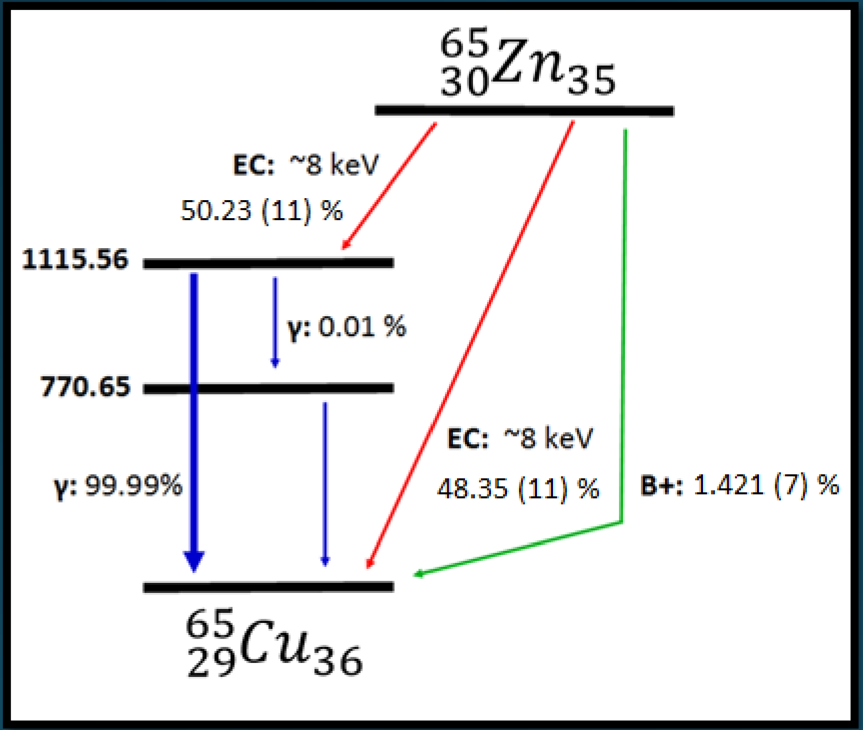


FIG 16: KDK Experimental Flow Chart

- By performing coincident measurements (250 ns window) we can separate the EC and EC* events from the radioactive source
- We can then determine the ratio between those events.
- Main concern becomes background events, False Positives and False Negatives

Calibration Sources

- Sources for testing are required in order for calibration of APD, MTAS veto efficiency and feasibility of experiment
- ^{65}Zn and ^{54}Mn provide excellent calibration sources.



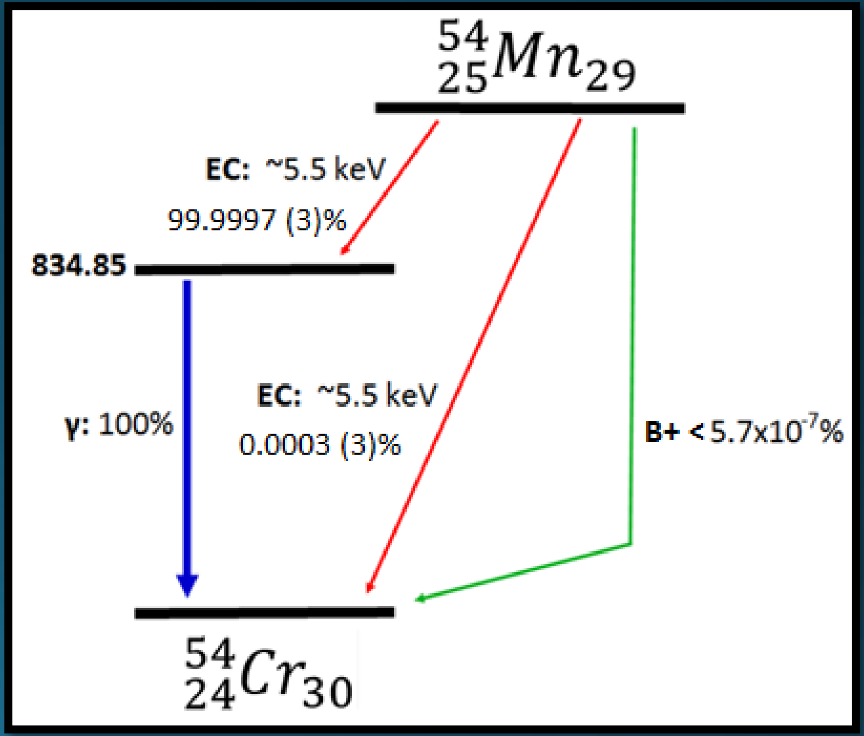
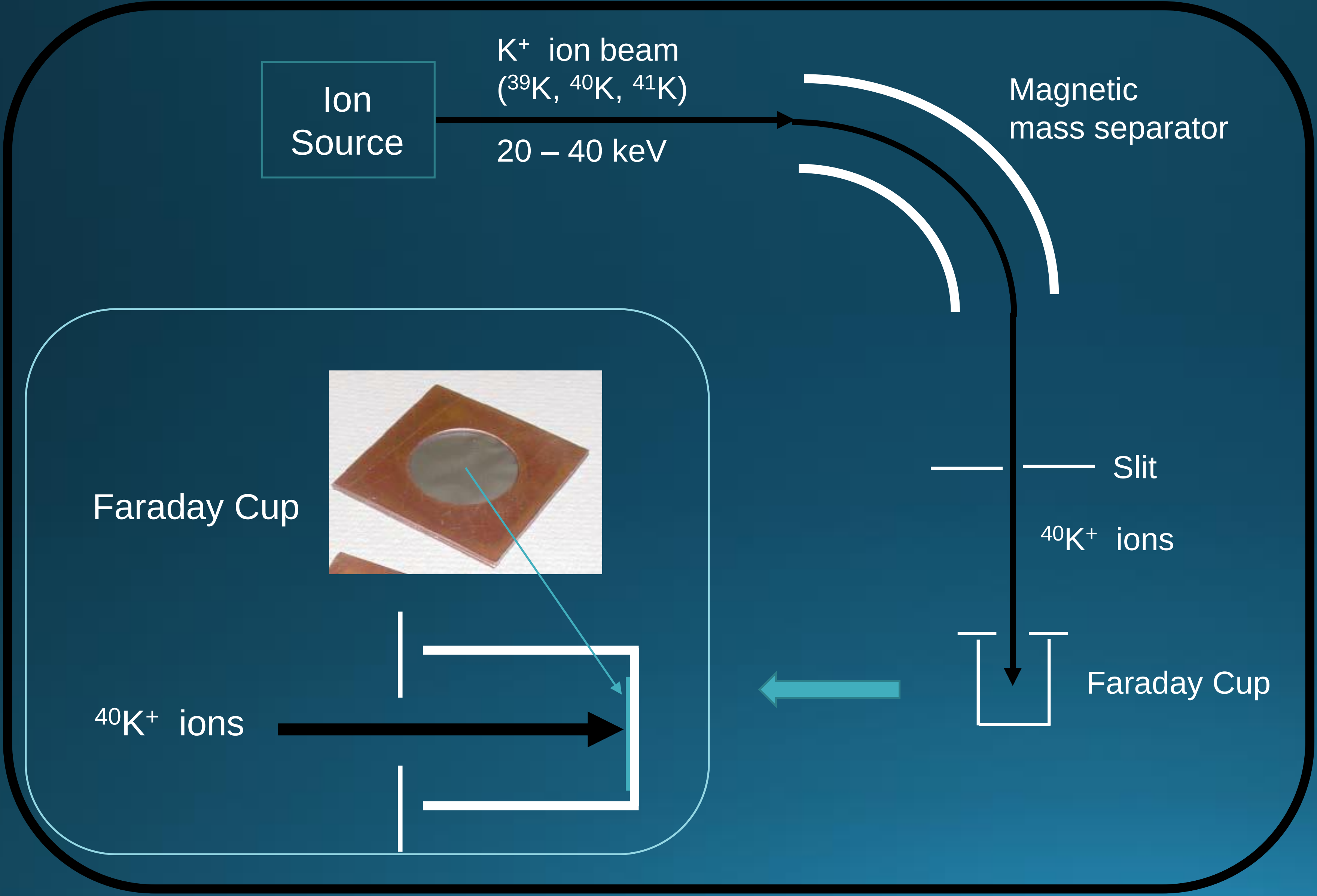


FIG 17: Decay Scheme for the calibration source ^{65}Zn[4] (Left) and ^{54}Mn[4] (Right).

[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*.

K-40 Source



- 0.1 mm Thin Carbon Foil (~1cm x1cm x 1µm) implanted with enriched with ^{40}K.
- KCL from American Instruments can be enriched with ^{40}K by 3%
- ORNL implanted the ^{40}K atoms onto a thin sheet of Carbon Foil

^{125}Sb

- ^{125}Sb adds a tricky background for a physics result from the run
- Beta-decay to excited states will contaminate the coincident sector (Seen on previous slide)
- Long lived isomers will contaminate the anti-coincident sector

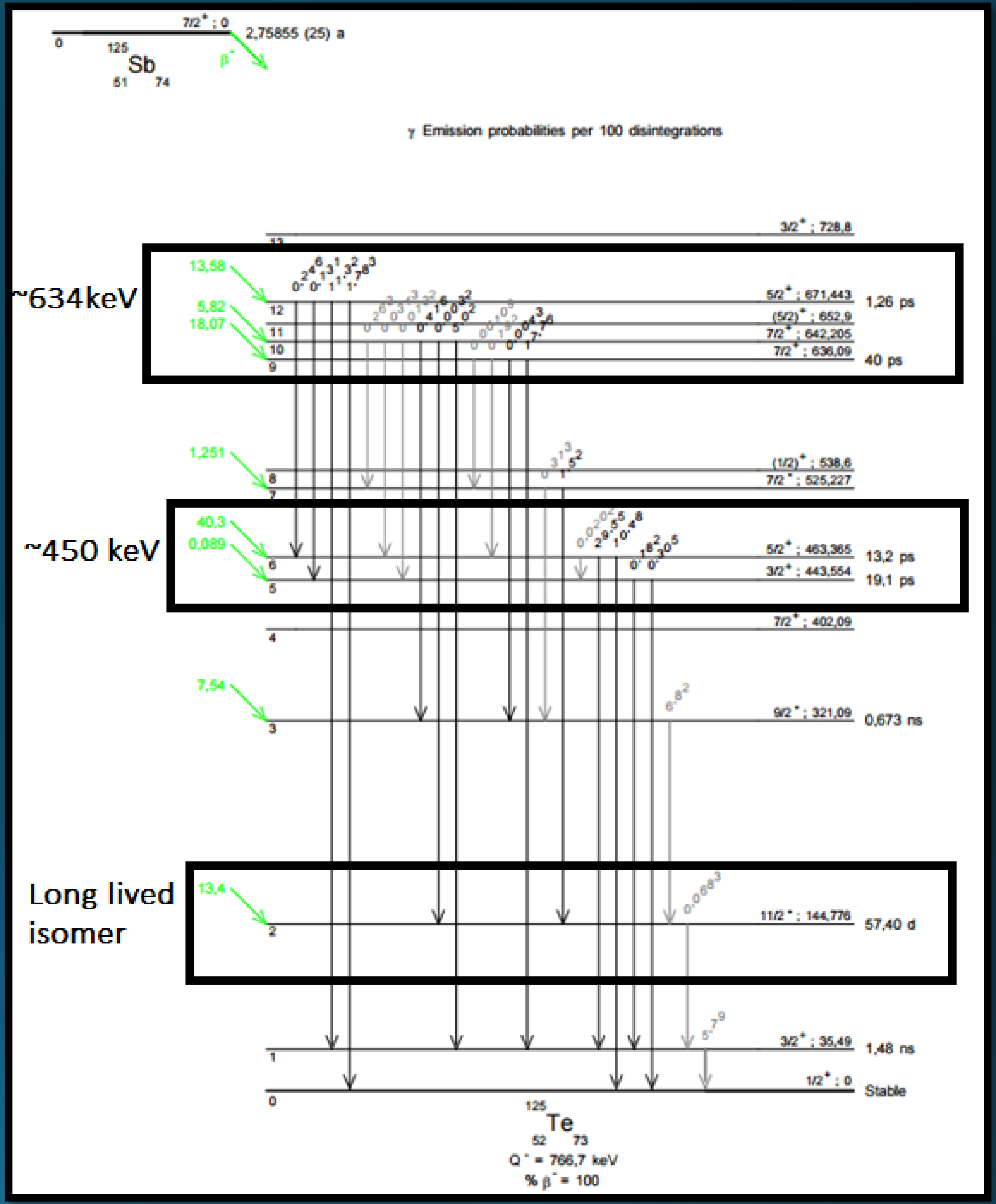


FIG 18: ^{125}Sb Decay Scheme[4]

[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*.

DAMA Experiment and Results

- 25 x 10 kg of NaI crystals registering energy depositions from 2 keV to tens of MeV, from almost any source: electrons, γ and X-rays, μ, α and nuclear recoils
- Uses the annual modulation of DM signals to interpret nuclear recoils as coming from WIMPs interacting with the crystals
- Event rates observed by DAMA: $R(E,t) = B_0(E) + S_0(E) + S_m(E)\cos(\omega(t - t_0))$

- R(E,t): Total Measured Event Rate
- $B_0(E)$: Background Rate
- $S_0(E)$: Time-independent Dark Matter Rate
- $S_m(E)$: Time-dependent Dark Matter Rate Amplitude

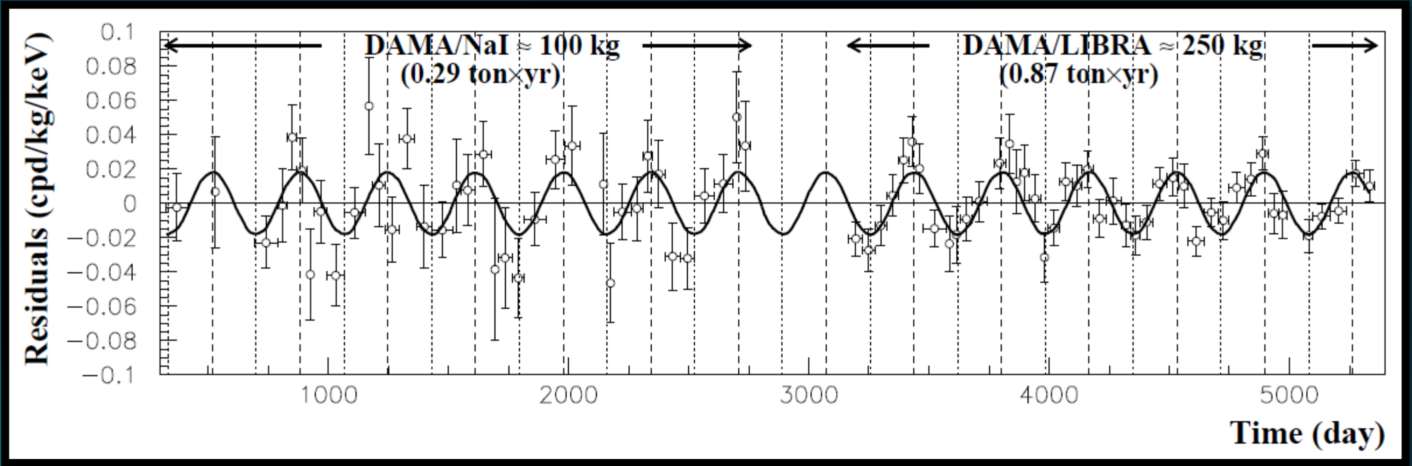


FIG 19: Single-hit event modulation rates measured by DAMA.[5]

[5] Bernabei, R., Belli, P., d'Angelo, S., Di Marco, A., Montecchia, F., Cappella, F., d'Angelo, A., Incicchitti, A., Caracciolo, V., Castellano, S. and Cerulli, R., 2013. Dark matter investigation by DAMA at Gran Sasso. *International Journal of Modern Physics A*, *28*(16), p.1330022.

Slide prepared by Pierre Squillari

Role of KDK in DAMA

- Dark Matter models predict different modulation fractions

$$\varsigma = \frac{S_m}{S_0} = \frac{S_m}{R_0 - B_0}$$

- Where the background is a function of the concentration of K^{40} ($[^{40}K]$) and the branching ratio.

$$B_0 = B_{other} + \alpha\,(1-\varepsilon)[^{40}K]BR_{EC*} + \alpha[^{40}K]BR_{EC} + \beta[^{40}K]$$

- The BR_{EC} is not precisely known which can lead to excluded modulation fraction regions

$$[^{40}\mathbf{K}] = \frac{R_0 - B_{other} - {}^{S_m}/_{\varsigma}}{\alpha(1+\rho-\varepsilon)+\beta} \quad \text{where} \;\; \rho = \frac{BR_{EC}}{BR_{EC*}}$$

Role of KDK in DAMA

$$[^{40}\mathbf{K}] = \frac{R_0 - B_{\text{other}} - {S_m}/{\varsigma}}{\alpha(1+\rho-\varepsilon)+\beta}$$

- A high branching ratio is unfavorable for DAMA and excludes the 7% and 10% modulation fractions

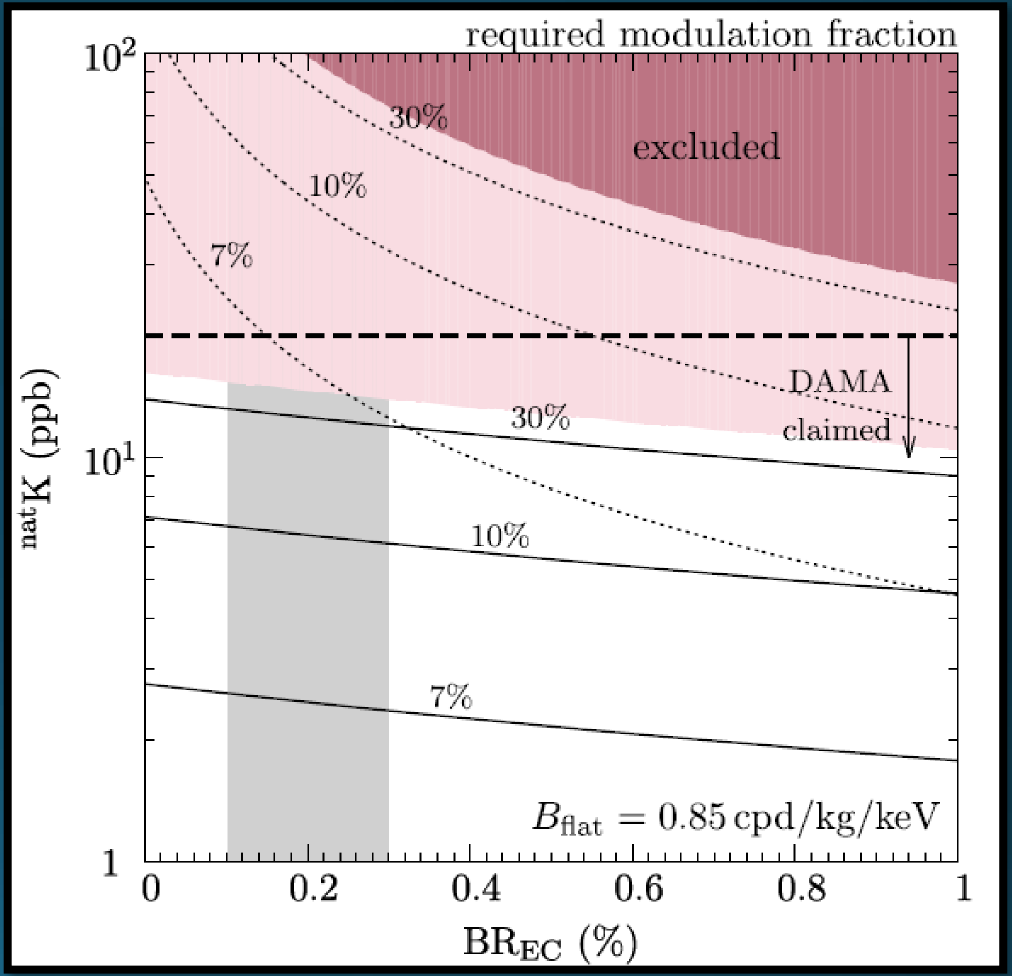


FIG 20: Required modulation fraction as a function of ^{nat}K contamination and BR_{EC}.

[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.

Electron Distance in APD

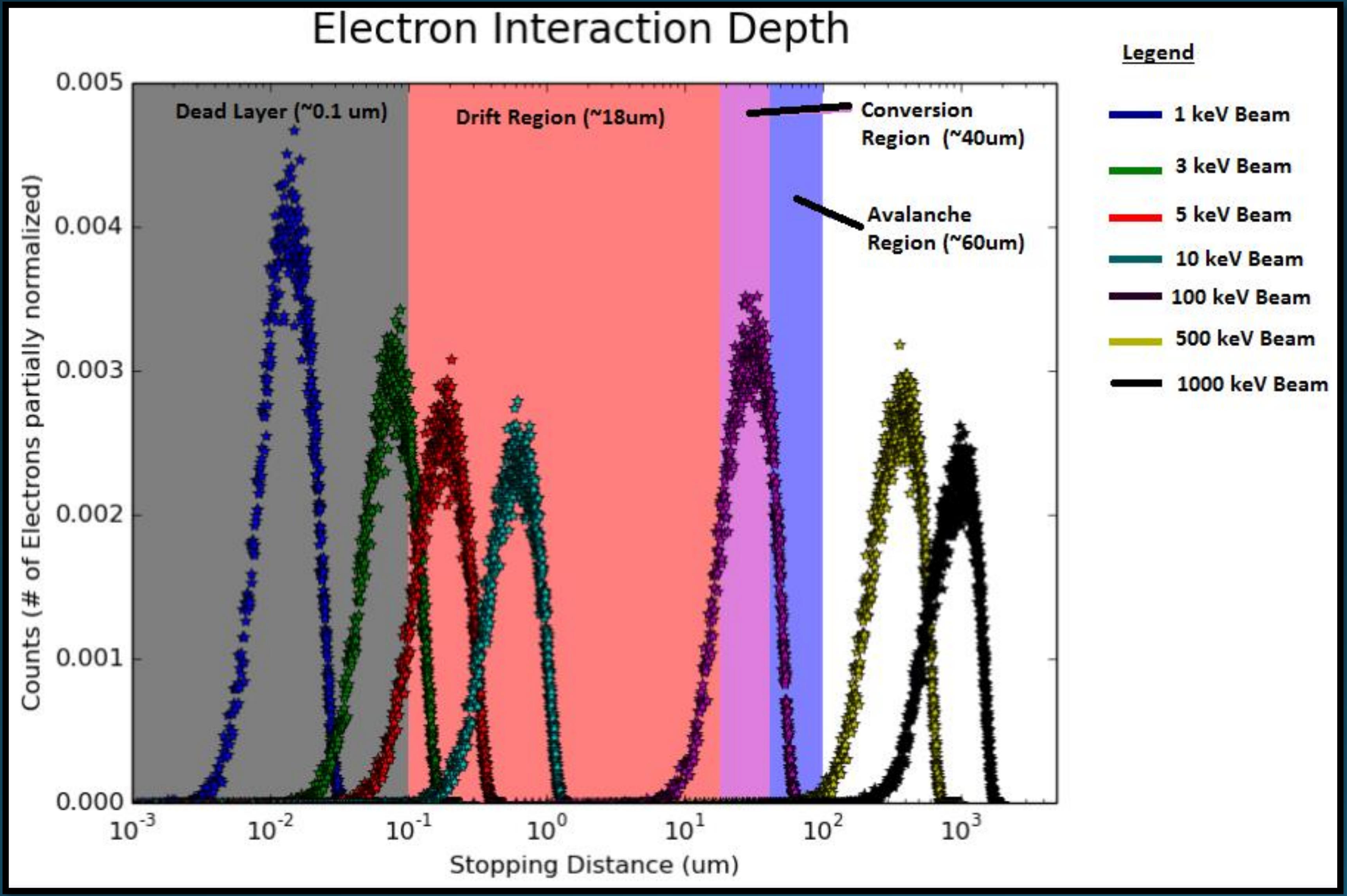
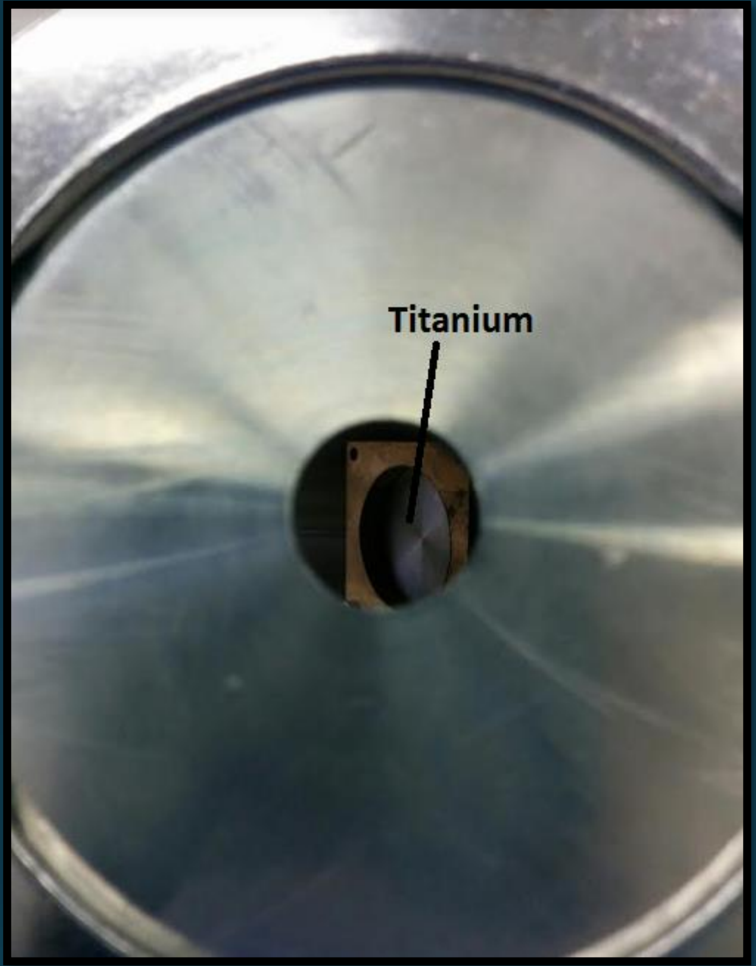
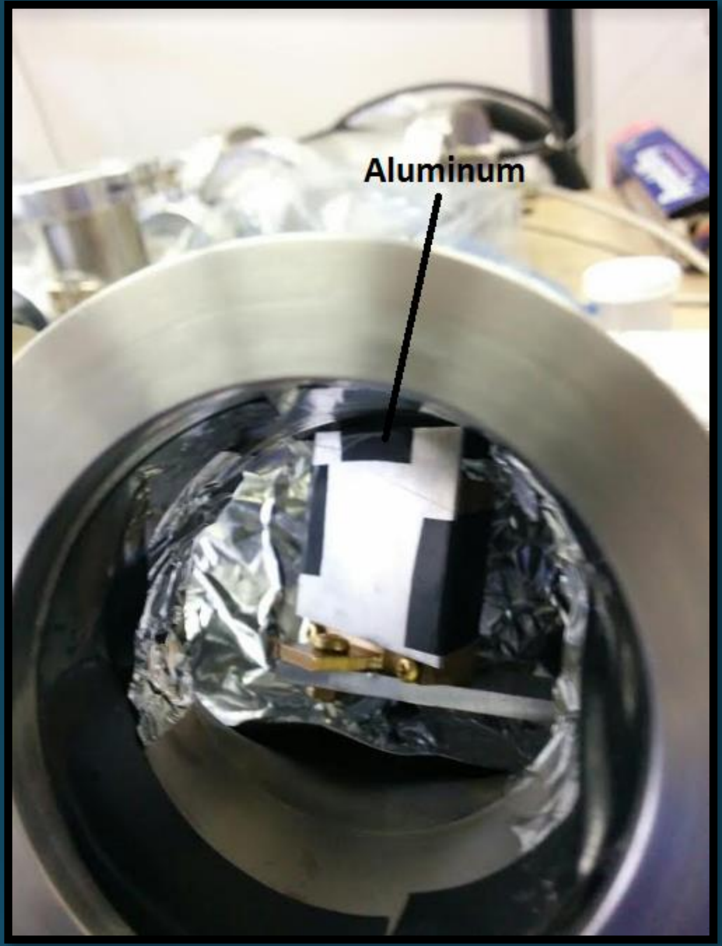
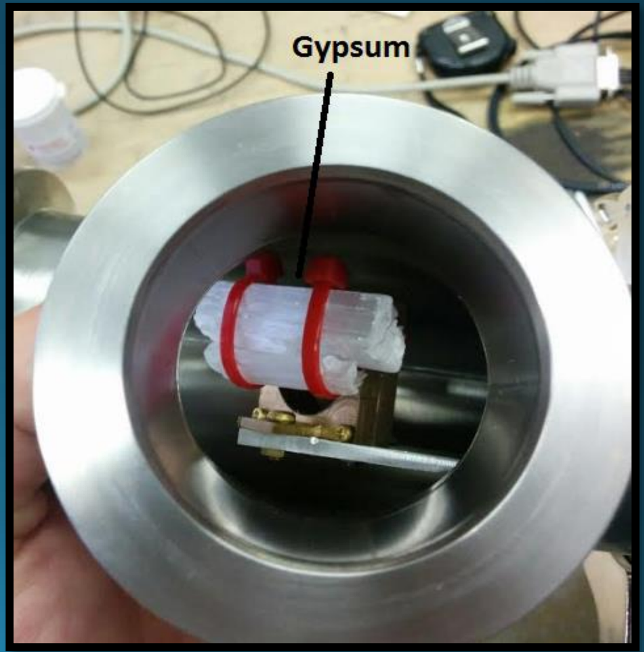


FIG 19: Multiple Energy Electron Stopping Distance in APD





Fluorescence Sources



Fluorescence Spectrum

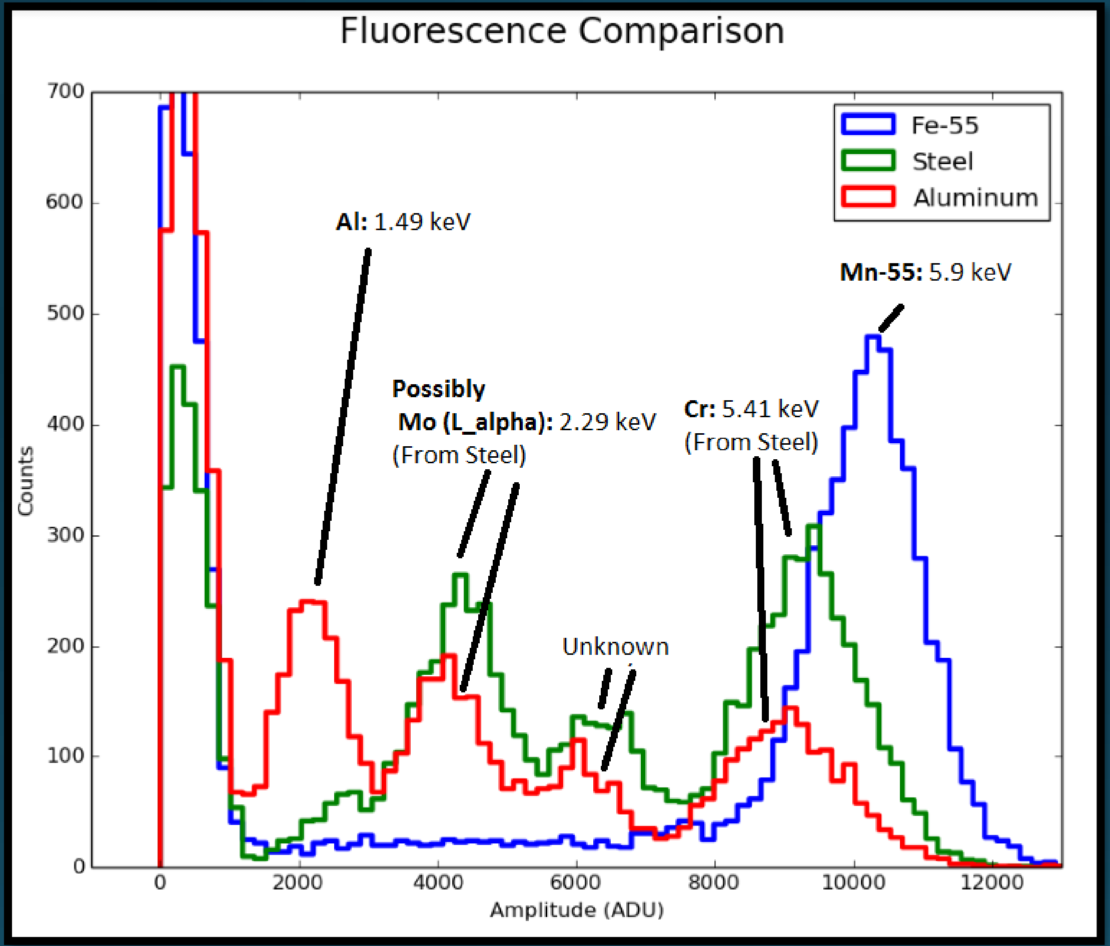


FIG 21: Flourescence Spectrum using a ^{55}Fe on a Steel and Aluminum target

- Not all spectrum are shown on left graph (to minimize clutter)
- Ability to see Aluminum Peak is great as it is much below 3 keV goal