# The KDK+ Experiment: Measuring the Rare Positron Emission of Potassium-40

June 9, 2025

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**Acknowledgements:**

**NEWS-G3:** Philippe Gros, Neha Panchal, Georgios Savvidis

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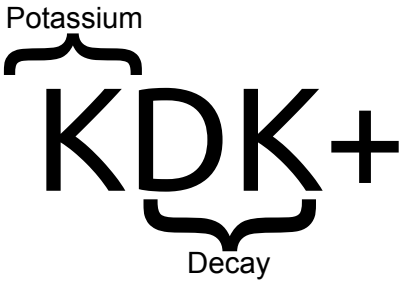
# Potassium Decay + (KDK+) Experiment




- follow up experiment to the original potassium decay (KDK) experiment which made the first detection of the rare electron capture to ground state decay of $^{40}$K.
- KDK+ is now looking for the rare $\beta+$ decay of $^{40}$K.

# Potassium-40

## Natural Occurrence

- Potassium-40 ($^{40}K$) is the largest contributor to radiation within the body.
- $^{40}K$ is frequently found in food we eat[1].

Table 2: Radioactive isotopes in the body (70 kg adult)

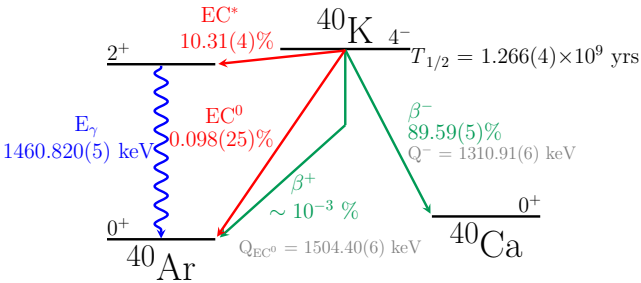
| Isotope | Amount of radioactivity in Bq |
|---|---|
| Uranium | 2.3 [1] [2] [3] |
| Thorium | 0.21 [2] |
| Potassium-40 | 4,000 [2] |
| Radium 226 | 1.1 [2] |
| Carbon-14 | 3,700 [2] |
| Tritium | 23 [4] |
| Polonium-210 | 40 [2] [3] |

## Scientific Application

- $^{40}K$ represents a background in many rare event search detectors, especially in scintillation detectors [2].
- $^{40}K$ has useful geochronological applications using K/Ar and $^{40}Ar/^{39}Ar$ dating techniques [3].

[1] https://www.cnsc-ccsn.gc.ca/eng/resources/radiation/types-and-sources-of-radiation/
[2] Hariasz et al., "Evidence for ground-state electron capture of K 40"
[3] Hames, "K/Ar and 40Ar/39Ar Dating Methods"

# $^{40}$K Decay Scheme




KDK+ is looking to measure the rare $\beta+$ decay mode.

## $^{40}$K decay modes

1. $\beta$-: Most common decay. BR = 89.25%
2. **EC***: Second most common decay. BR = 10.55%
3. **EC$^0$**: Rare decay first found by KDK. BR = 0.1% [4,5]
4. $\beta$**+**: Rarest decay previous measurements have inconsistencies. BR $\sim 10^{-3}$%

[4] Stukel et al., "Rare K 40 Decay with Implications for Fundamental Physics and Geochronology"
[5] Hariasz et al., "Evidence for ground-state electron capture of K 40"

# Motivation - Inconsistencies in $\lambda+$ calculations

Previous experimental measurements for the branching ratios have been conducted.

i **KDK (2023)**[6]**:** BR0/BR* $= 0.0095 \pm 0.0022 \pm 0.0010$

ii **Engelkemeir experiment (1962)**[7]**:** BR+/BR- $= (1.12 \pm 0.14)*10^{-5}$

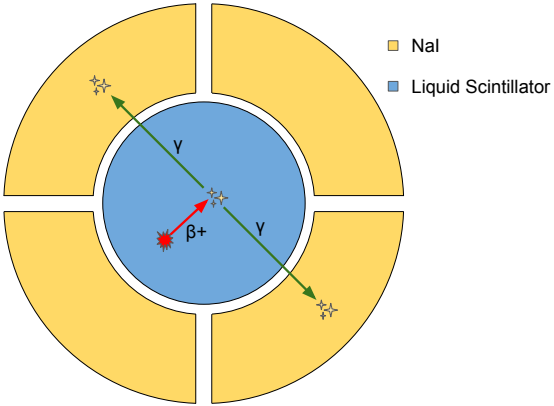
iii **Mougeot theory (2018)**[8]**:** BR0/BR+ $= 215.0 \pm 3.1$

If [i] is assumed to be correct, and taking the results from Kossert (2022)[9] for the partial decay constants, $\lambda$- and $\lambda$*, **we find inconsistent values for $\lambda+$**

1. i+ii) $\lambda+ = (5.5 \pm 0.7)*10^{-6}$ /Ga
2. i+iii) $\lambda+ = (2.5 \pm 0.6)*10^{-6}$ /Ga

[6] Stukel et al., "Rare K 40 Decay with Implications for Fundamental Physics and Geochronology".
[7] Engelkemeir, Flynn, and Glendenin, "Positron Emission in the Decay of K 40".
[8] Mougeot, "Improved calculations of electron capture transitions for decay data and radionuclide metrology".
[9] Kossert et al., "Activity standardization of two enriched 40K solutions for the determination of decay scheme parameters and the half-life".

# Experiment Overview




- KDK+ will measure the $\beta+$ decay by using a triple coincidence between a liquid scintillator and 4 segmented $\gamma$ detectors (possibility to have more segmentation with the Modular Total Absorption spectrometer (MTAS)).
- $\beta+$ particles will first interact in the liquid scintillator, before annihilating to produce two back-to-back 511 keV $\gamma$'s.
  1. $\beta+$ interaction in the liquid scintillator producing light.
  2. Two $\gamma$ detection in back to back NaI detectors.

# Experiment Overview - Duration

- The duration of the experiment is dependent on the enrichment of the potassium samples.
- The experiment currently will run using natural potassium.
  - Natural radioactivity of potassium: $r = 16.35$ Bq/g
  - $\beta+$ activity: 0.1635 mBq/g
- For 1000 $\beta+$ decays, it will take $\sim$24 days. In total, this will amount to $10^8$ events.

**Note:** These calculations are ignoring efficiencies within the detector itself.

# Liquid Scintillator

## Ultima Gold LLT - Primary choice

- Commercially available scintillator.
- Good potassium loading and high light yield.
- Poor stability over long durations.

## Linear Alkylbenzene - Alternative

- High potassium loading and high light yield.
- Long term stability to be tested soon.
- Difficult to buy in small quantities.

## Other Options

- Historically toluene has been used to detect $\beta+$ emissions. This will be considered if the above solutions do not work.
- A water-based LSC.
- Loaded plastic scintillators

# LSC Campaign - Potassium Salts

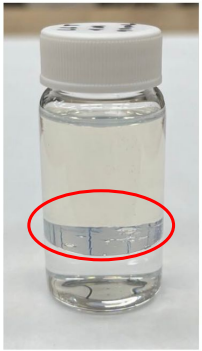
Basic ↓ Toxic ↓

| Potassium Salt | KCl | KOH | KI | K2CO3 | KNO3 | KF | KIO3 |
|---|---|---|---|---|---|---|---|
| Solubility in water $g \cdot L^{-1}$ | 360 | 1100 | 1430 | 1120 | 357 | 485 | 47 |
| K concentration $g \cdot L^{-1}$ | 188 | 766 | 336 | 632 | 138 | 326 | 9 |
| Natural 40K concentration $\mu g \cdot mL^{-1}$ | 22,0 | 89,6 | 39,3 | 73,9 | 16,1 | 38,1 | 1,0 |
| 3% enriched 40K concentration $mg \cdot mL^{-1}$ | 5,6 | 23,0 | 10,1 | 19,0 | 4,1 | 9,8 | 0,3 |

- Different potassium compounds that can be added to ultima gold LLT.
- Green compounds have been tested already, red are compounds that have been removed, and white are compounds that have yet to be tested.

# LSC Campaign - LSC solutions.

**Phase Separation**

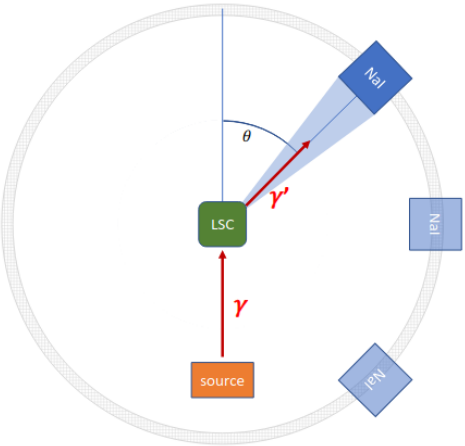


**Cloudy mixture**

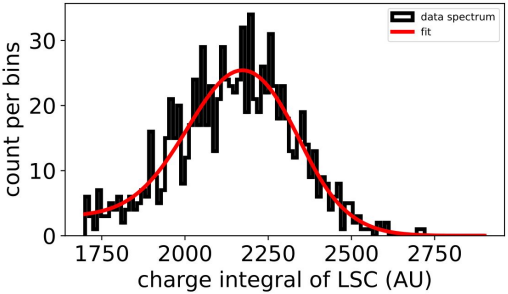
**Clear cocktail**

- Cocktail needs to show initial stability when loaded with salts.

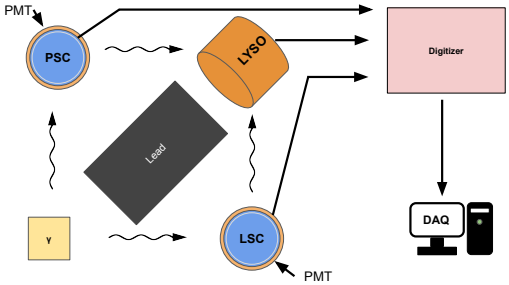
# LSC Campaign - Light Yield




- The light yield of each LSC cocktail is tested using a Compton scatter method using a secondary $\gamma$ detector.
- The light yield is determined from the Compton coincidence peak.



# LSC Long Term Stability

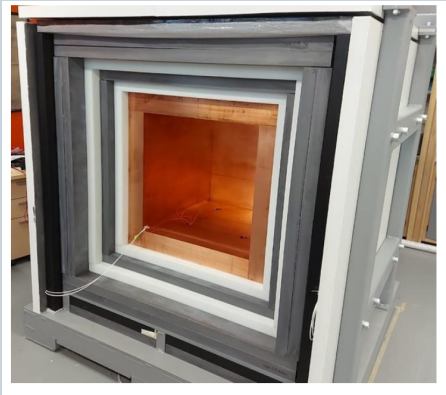



- PSC: Plastic Scintillator
- LYSO: Lutetium–yttrium oxyorthosilicate

- Long term stability of the LSC cocktails are compared to a reference sample to determine if they are stable over a long period of time.
- Reference sample used is a commercial plastic scintillator that has been made to be a similar volume to the LSC vessel.
- Compton scattering is done using a $^{65}$Zn source as well as a LYSO crystal as a secondary detector.

# LSC Long Term Stability Apparatus

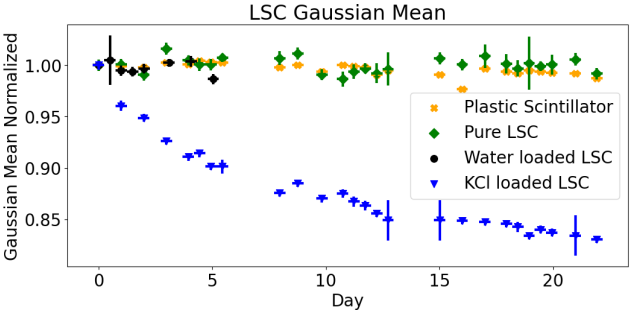
## G3 Shielding

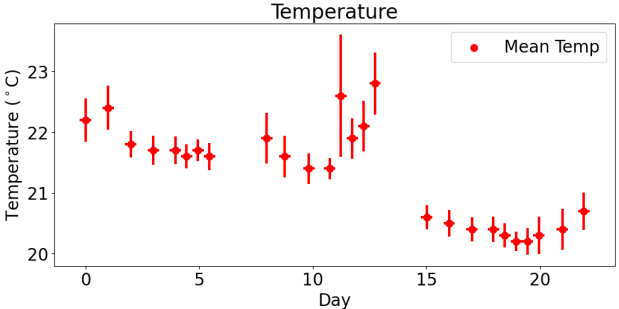


## Stability Experiment

- Apparatus used for the long term stability experiment.

# LSC Long Term Stability - Results




- Results show that the plastic scintillator has a constant light yield over time.
- A pure Ultima Gold LLT sample also shows a constant light yield.
- The loaded LSC with an aqueous potassium salt shows a decrease in light yield of ∼20%.

# LSC Vessel Calibration

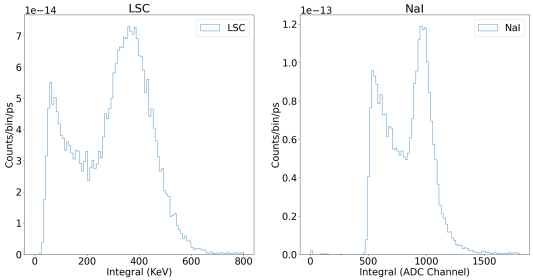
**Large 300 mL vessel**

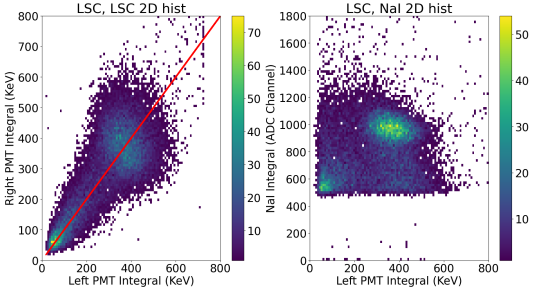
**Small 50 mL Vessel**

- Large vessel is for use in a NaI annulus located at Queen's University.
- Small vessel is for use in the Modular Total Absorption Spectrometer (MTAS) at Michigan State University.

# Large LSC Vessel - $^{137}$Cs uncollimated

- Calibration has begun on the large vessel using a Compton scattering technique.
- Compton scatter peak is used to calibrate the energy response of the scintillator.
- An uncollimated $\gamma$ source will produce events across the entire length of the detector.
- Soon tests will begin using a fine collimation to scan across the length of the detector.



# Conclusion

- KDK+ is follow-up experiment to KDK, looking for the rare $\beta+$ decay of $^{40}$K.
- Tests have been conducted to determine the best cocktail for the experiment, maximizing the amount of potassium loaded as well as the light yield.
- Long term stability experiments have been conducted that show that the loaded ultima gold LLT cocktail is currently not stable over a long period of time.
- Calibration for the two LSC vessels has begun. Position tests on the large vessel will begin soon.

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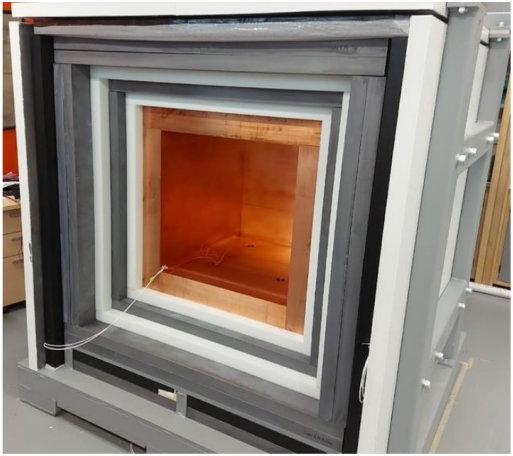
*Types and sources of radiation, howpublished* =. Accessed: 2025-06-07.

# G3 Shielding Layers

- G3 shielding is made up of polyethylene for neutron shielding, lead for $\gamma$ shielding, and active vetoes for muon shielding.



**Shielding Layers**

- 1 layer of 10 cm CP10100 copper
- 1 layer of 5 cm polyethylene
- 1 layer of 5 cm lead
- 1 layer of 5 cm polyethylene
- 2 layers of 5 cm lead
- 1 layer of active shielding consisting of 12.5 cm thick Eljen EJ-200 plastic scintillators

# Enriched Potassium Duration

**3% enriched potassium**

- Natural abundance of $^{40}$K is 0.0117%. A 3% enrichment is a 256 times increase in radioactivity.
- Following the same calculations with a 256 times increase to the radioactivity means that we find 1000 events, using 3g of potassium in 2.5 hours.
- With only 0.3 g of 3% enriched potassium, 1000 events occur in a single day.