

KDK⁺: remeasuring the β^+ decay of ^{40}K

P. Di Stefano^{1a} R. Arsenne¹ Y. Coudière¹ G. Croft¹ T. Domingo⁴
A. Erlandson⁴ P. Gros¹ L. Hariasz⁷ K. Hartling⁴ E. Heit¹
L. Hummel¹ C. Ingo¹ A. Lemaire¹ L. Lopez-Proville¹
D. Perez Loureiro C. Rasco² R. Rosero³ K. Rykaczewski²
P. Samuleev⁶ M. Stukel⁵ N. Swidinsky¹ M. Yeh³

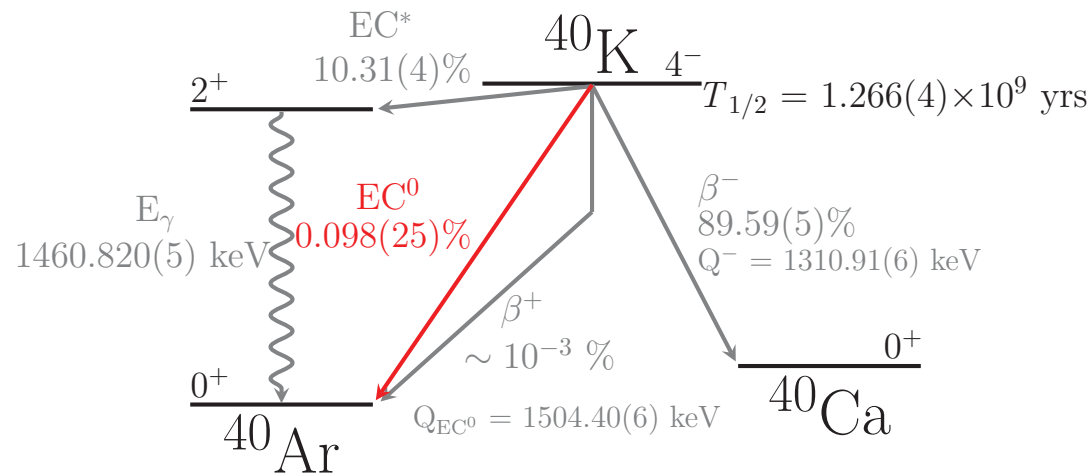
(Student/Postdoc/RA)

¹Queen's U, ²Oak Ridge Nat Lab, ³Brookhaven Nat Lab, ⁴Canadian Nuclear Lab, ⁵SNOLAB
⁶Royal Military College, ⁷Simon Fraser U

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^adistefan@queensu.ca, Queen's University, Kingston, Canada

Measuring the β^+ decay of ^{40}K in KDK+ I



Decays

$$\beta^- \quad ^{40}\text{K} \rightarrow ^{40}\text{Ca} + \beta^- + \bar{\nu}_e, \quad K_- \leq Q_- = 1.3 \text{ MeV},$$

$$P_- = 0.9$$

$$\beta^+ \quad ^{40}\text{K} \rightarrow ^{40}\text{Ar} + \beta^+ + \nu_e, \quad K_+ \leq Q_+ - 2m_e = 483 \text{ keV},$$

$$P_+ = O(10^{-5})$$

EC0/EC* See KDK

Measuring the β^+ decay of ^{40}K in KDK+ II

Tension

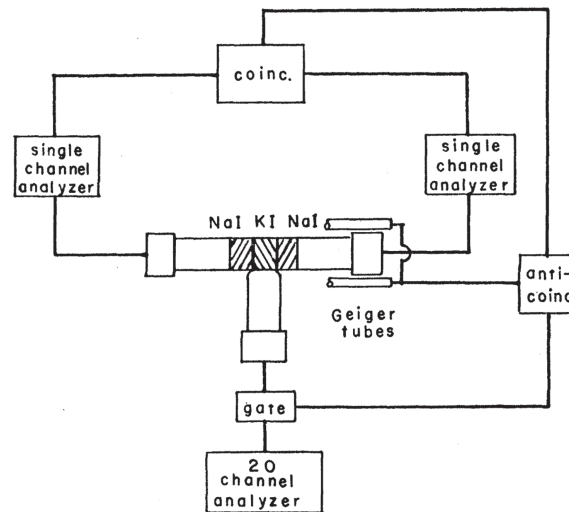
1. KDK expt 2023 [1]: $BR_0/BR_* = 0.0095 \pm 0.0022 \pm 0.0010$
2. Engelkemeir expt 1962 [2]:
 $BR_+ / BR_- = (1.12 \pm 0.14) \times 10^{-5}$
3. Mougeot theory 2018 [3]: $BR_0/BR_+ = 215.0 \pm 3.1$

Assuming 1. is correct, and taking Kossert 2022's evaluation [4] for λ_- and λ_* , we find tension between values for λ_+ :

- ▶ 1+2) $\lambda_+ = (5.5 \pm 0.7) \times 10^{-6} \text{ /Ga}$
- ▶ 1+3) $\lambda_+ = (2.5 \pm 0.6) \times 10^{-6} \text{ /Ga}$

Also interesting technique for other β^+ isotopes

Previous ^{40}K β^+ work



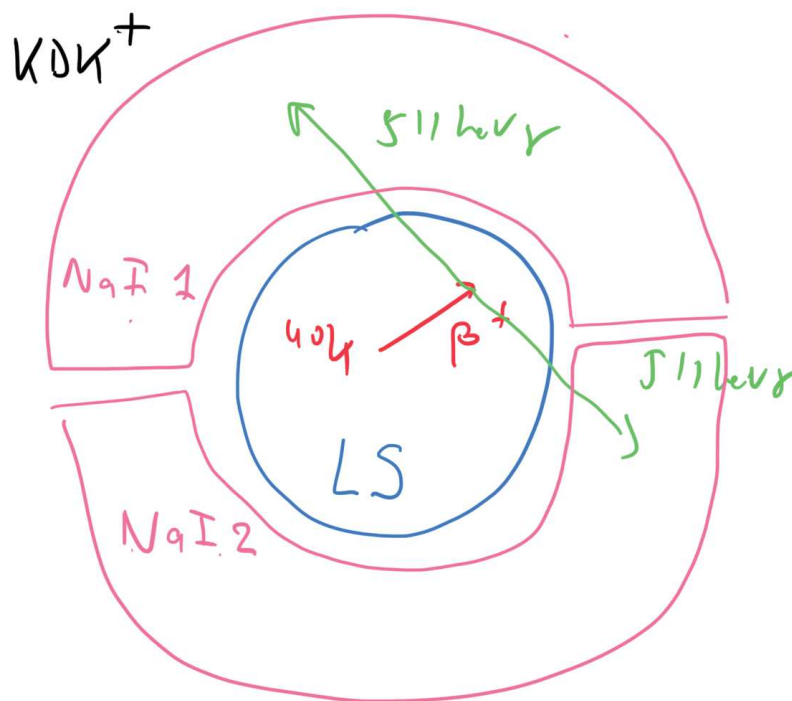
Tilley 1959 [5] First to use triple coinc for ^{40}K β^+ . Main detector KI. Find $P_+ / P_- < (1.3 \pm 0.7) \times 10^{-5}$.

Engelkemeir 1962 [2] Triple coin with liquid scint. Find $P_+ / P_- = (1.12 \pm 0.14) \times 10^{-5}$. Considered most credible by X. Mougeot as attention paid to pair creation from EC^* .

Leutz 1965 [6] Study of β^- , EC^* and β^+ . Triple coin with plastic scintillator. Find $P_+ / P_- = (1.5 \pm 0.5) \times 10^{-5}$. Presents Tilley's result as value instead of limit.

KDK+ technique

- ▶ Central liquid scintillator (LS) loaded with K to detect β^+
- ▶ Surrounding segmented NaI annulus to detect annihilation back-to-back 511 keV γ s
- ▶ Look for triple coincidence (β^+ /511/511)



- ▶ Goal: 10^3 β^+ from ~ 2 g natK, in ~ 1 month
- ▶ In 300 mL LS: K density 6 g/L ie 0.15 mol/L

K-loaded liquid scintillator requirements

Goal

- ▶ $10^3 \beta^+$
- ▶ eg 1 month with 2 g of natK (less if enriched)
- ▶ Baseline: 300 mL with 6 g/L of K

Requirements

Loading Cocktail should remain single-phase, transparent

Light yield (LY) Loading should not degrade LY compared to pure scintillator

Stability LY should be stable over many weeks

Solubility of salts in H₂O and in liquid scintillator

In H₂O

Salt	(g/L)	(moles/L)
LiCl	840	19.8
KCl	340	4.5

From wikipedia. Temperatures may not be same but are around room temperature.

In LS

Barrow 1976 [7] Scintillator = (toluene (1.6 L) Triton X100 (0.8 L) PPO (4 g/L) POPOP (120 mg/L)) then take 1 mL of KCl in H₂O at 1 mol/L, and add to 10 mL of the scintillator. Overall, 0.09 mol/L, less than our baseline

Ogawa 1999 [8] Many mixes including 1 mg K-propionate, 0.5 mL H₂O, 1 mL methanol, 10 mL Aquasol 2. Works out to density of K of 30 g/L or 0.8 mol/L

Kossert 2004 [9] 2 g KCl per 10 g H₂O (equivalent to 200 g/L). Added to various liquid scintillators including UGLLT, leading to 7 g/L of K in the mix. Samples shaken and centrifuged. **Stable for 60 days (in terms of detection efficiency).**

Frangville 2019 [10] Use Li α -valerate to reach 0.15% Li by weight, so about 1.5 g/L, in a plastic scintillator

Bergeron 2020 [11] 10 moles/L of LiCl in H₂O. Mixed with Ultima Gold AB to reach 1% mass fraction of Li, so about 10 g/L of Li.

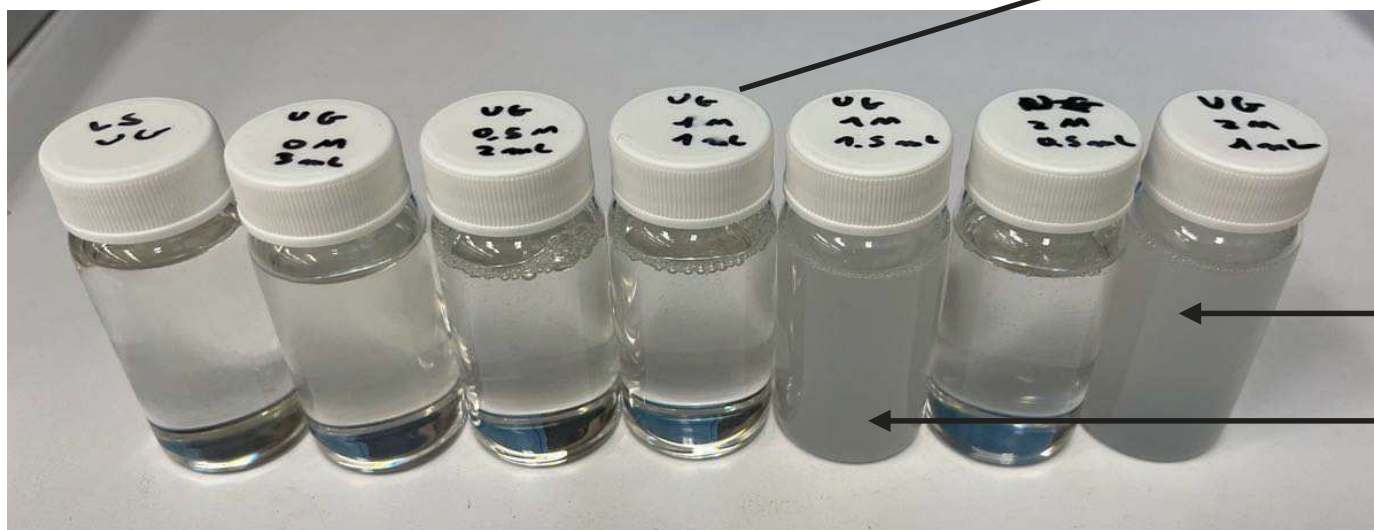
Our baseline mix **3 mL of (1 mol/L KCl in H₂O) + 17 mL UGLLT $\Rightarrow$ 0.15 mol/L or 6 g/L K**

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

Table 3. Sample capacity of selected cocktails for various ionic strength buffers (sample capacities are for 10 mL cocktail at 20 °C).

Ionic Strength	Ultima Gold XR	Hionic-Fluor	Pico-Fluor Plus	Ultima Gold	Ultima Gold MV	Opti-F
0.5 M NaCl	9.0 mL	1.4 mL	3.0 mL	1.5 mL	1.25 mL	1.1 mL
0.75 M NaCl	6.5 mL	2.25 mL	2.75 mL	0.75 mL	0.75 mL	0.75 mL
1.0 M NaCl	5.5 mL	8.5 mL	2.3 mL	0.5 mL	0.5 mL	0.5 mL

Source: PerkinElmer



Too much aqueous solution or KCl: cocktail separates in 2 phases and becomes cloudy when shaken

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer



✗



✗



✓

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

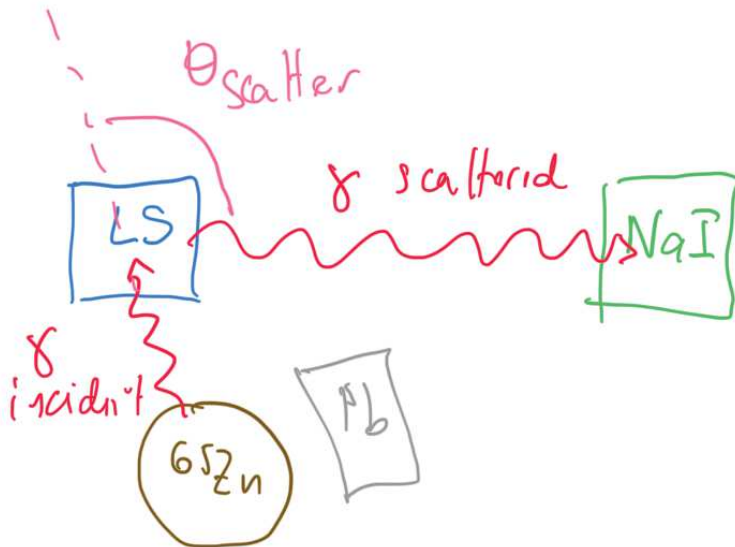
Results:

Cocktail in 20mL glass vial	Ultima Gold	Ultima Gold LLT
Quantity of dissolved K mmol	1	3
Mass of dissolved K mg	39	117
For natural potassium abundance		
Mass of 40K μg	4,6	13,8
Atoms of 40K	7E+16	2,1E+17
Activity of the source Bq	1,2	3,6
β^+ emitted in a month	32	96
For 3% enrichment		
Mass of 3% enriched 40K μg	1170	3510
Atoms of 40K	1,8E+19	5,4E+19
Activity of the source Bq	317	951
β^+ emitted in a month	8,3E+03	2,49E+04

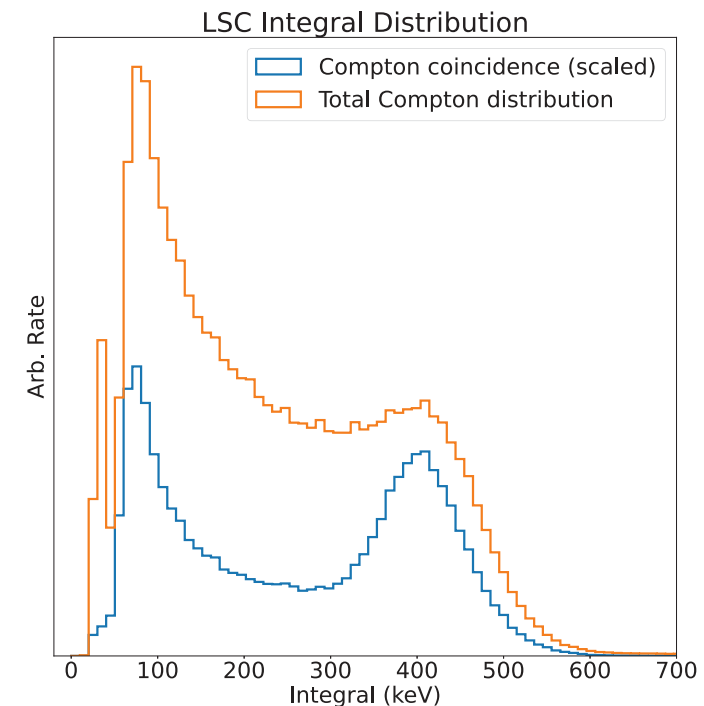
Characterizing liquid scintillators with Compton scattering

- Difficult to characterize LS with γ s because low Z, small size $\rightarrow$ **featureless Compton continuum**
- **Use coincidences:** fix Compton scattering angle to **fix deposited energy:**

$$E_{\gamma} \frac{1 - \cos \theta}{\frac{m_e c^2}{E_{\gamma}} + (1 - \cos \theta)}$$



^{137}Cs spectra of pulse integrals

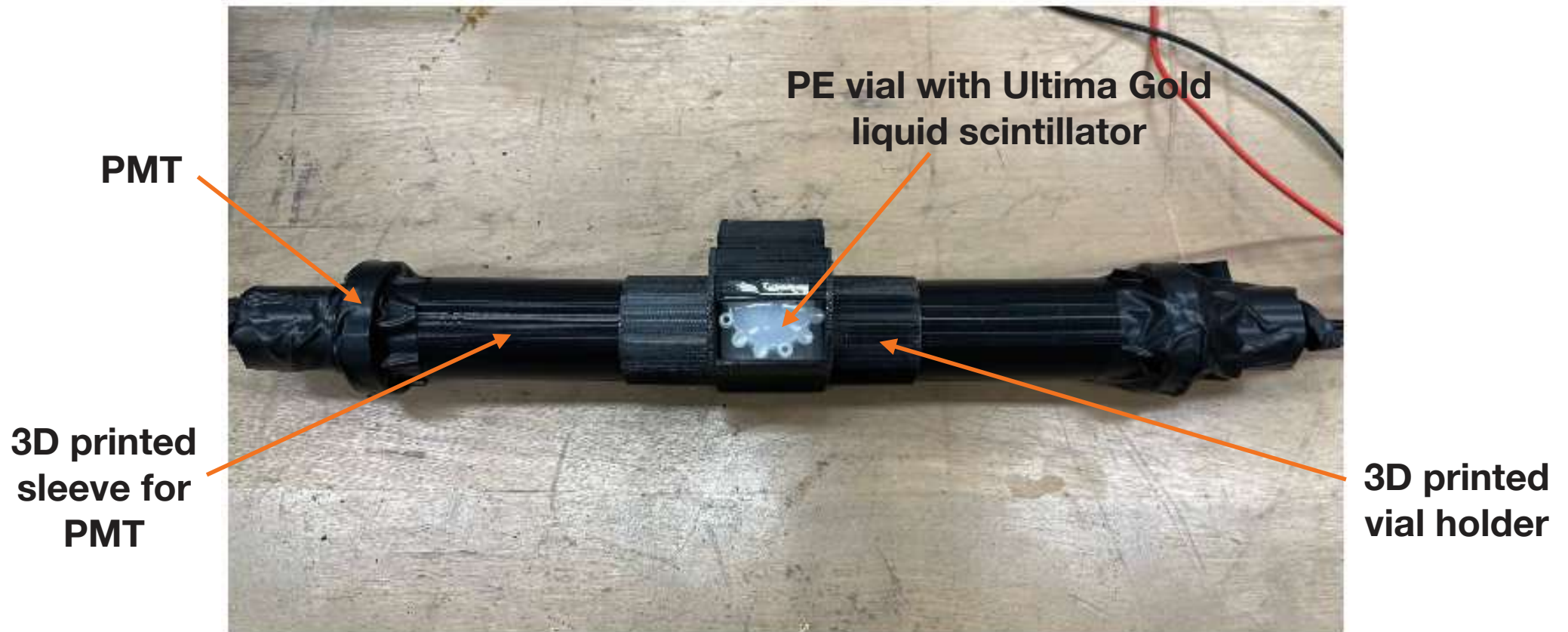


Well-defined line:

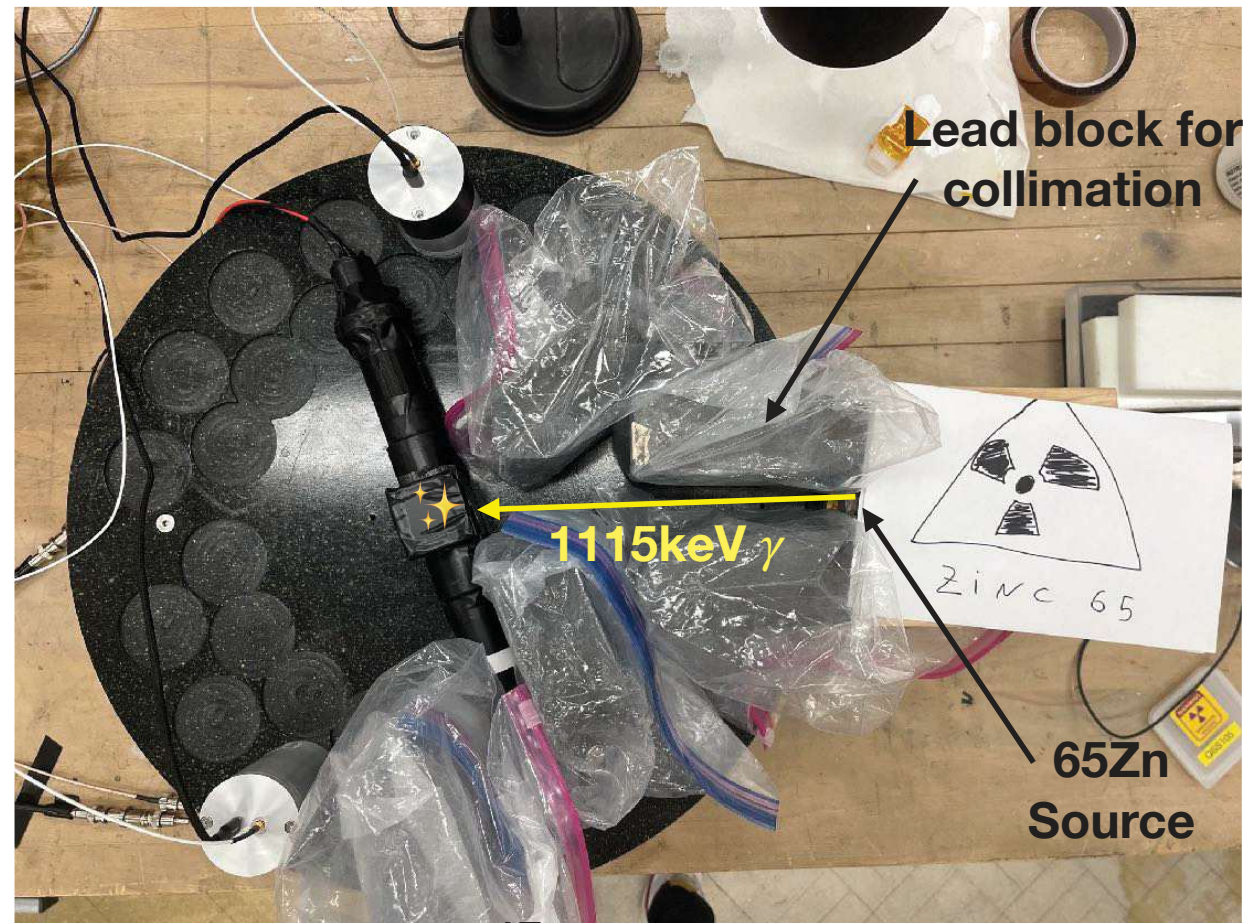
- Mean: light yield
- Integral: detection efficiency

Energy calibration of the liquid scintillator

Compton coincidence experiment - setup



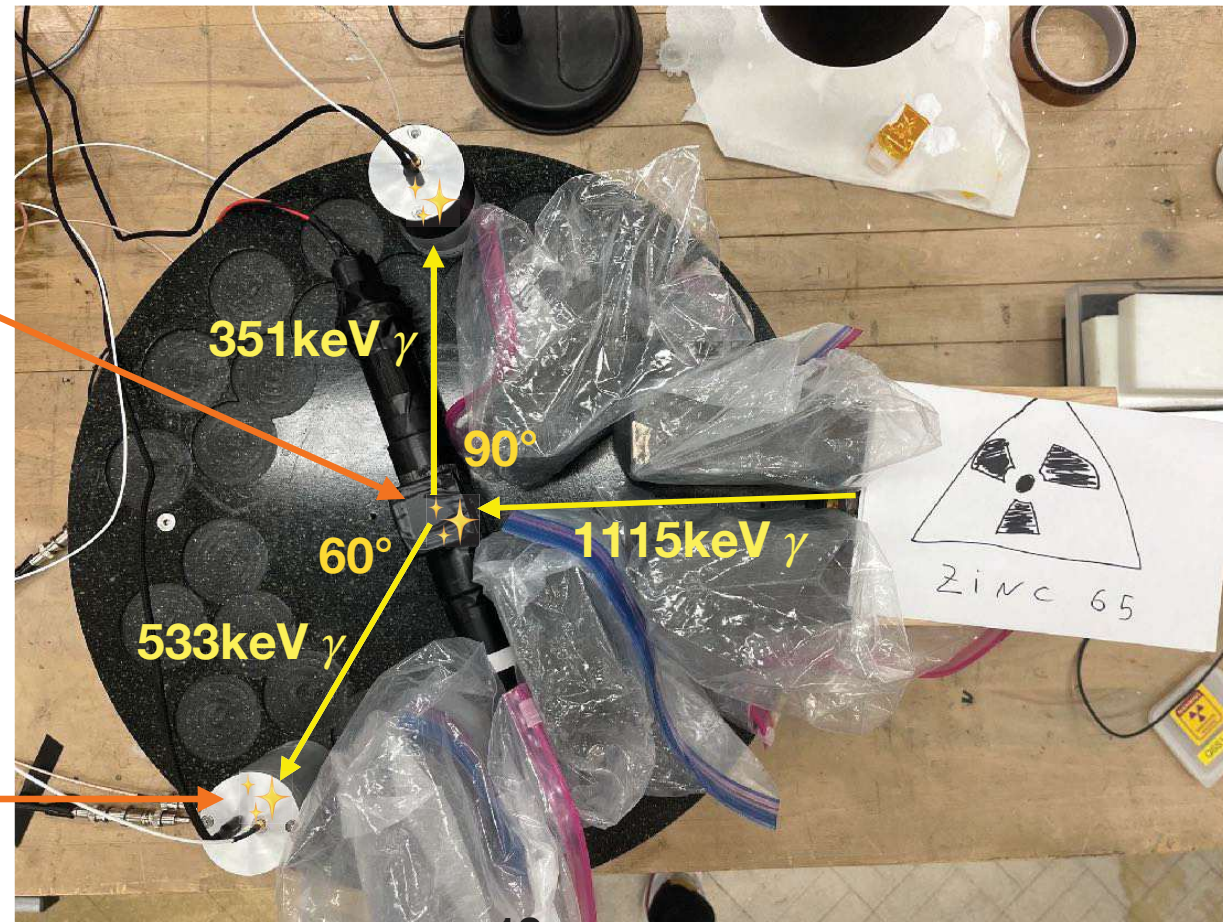
Energy calibration of the liquid scintillator



Energy calibration of the liquid scintillator

Incident gamma
scatters and deposits
energy in the liquid
scintillator

Scattered gamma
detected on NaI
crystal



Energy calibration of the liquid scintillator

60° - 90°, UltimaGold, 2 PMT Hamamatsu R6095

65Zn Source - 240ns Coincidence Window

400lsb LSC - 200lsb NaI - 1050V high voltage 15h

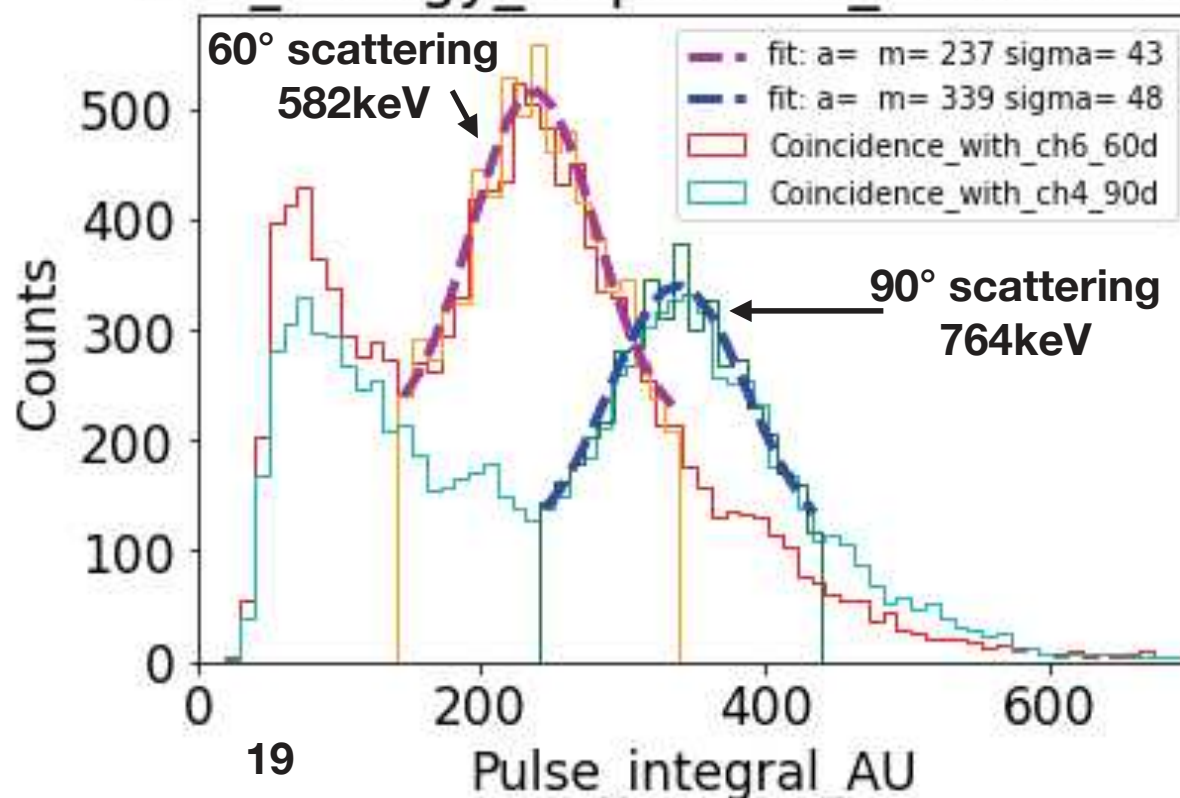
Kinetic energy of the electron after scattering with incident γ E_0 :

$$T_e = E_0 - E = E_0 - \frac{E_0}{1 + \alpha(1 - \cos \theta)}$$

$$\alpha = \frac{E_0}{m_e c^2}$$

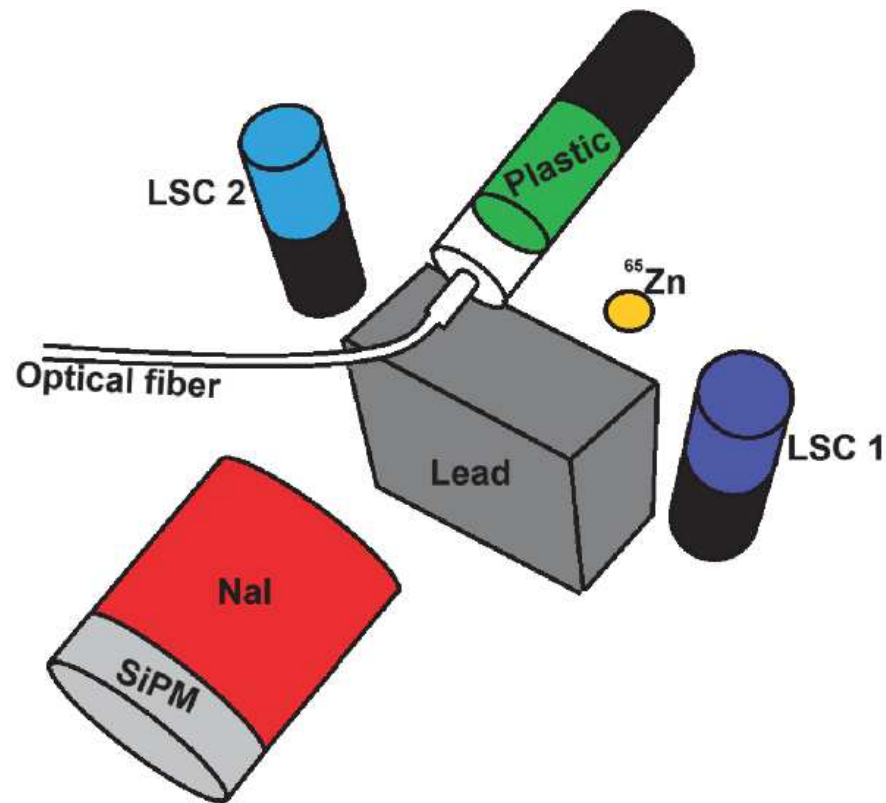
- ✓ Compare light yield of different cocktail
- ✓ Compare light collection of different setup
- ✓ Energy calibration of beta detector

LSC_Energy_Deposition_Coincidence

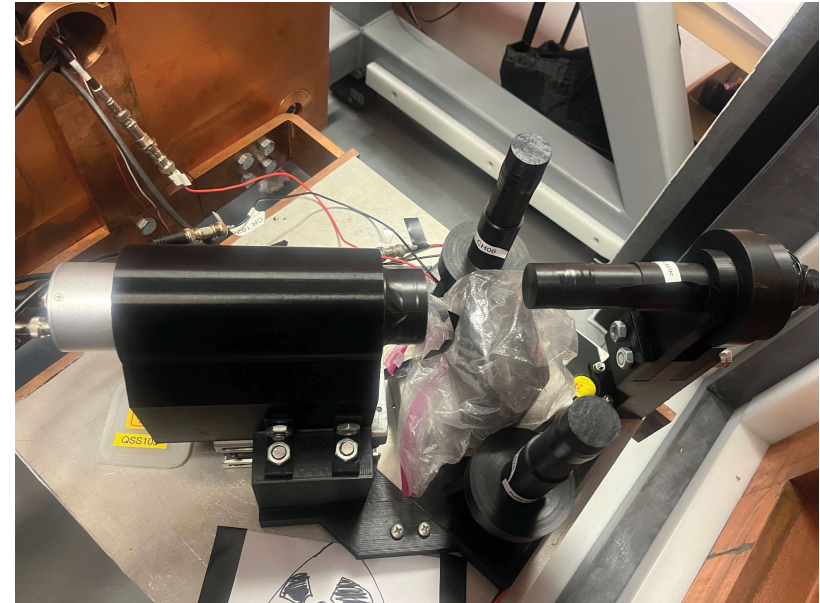


Stability of LY and efficiency over several weeks

Compton coincidences



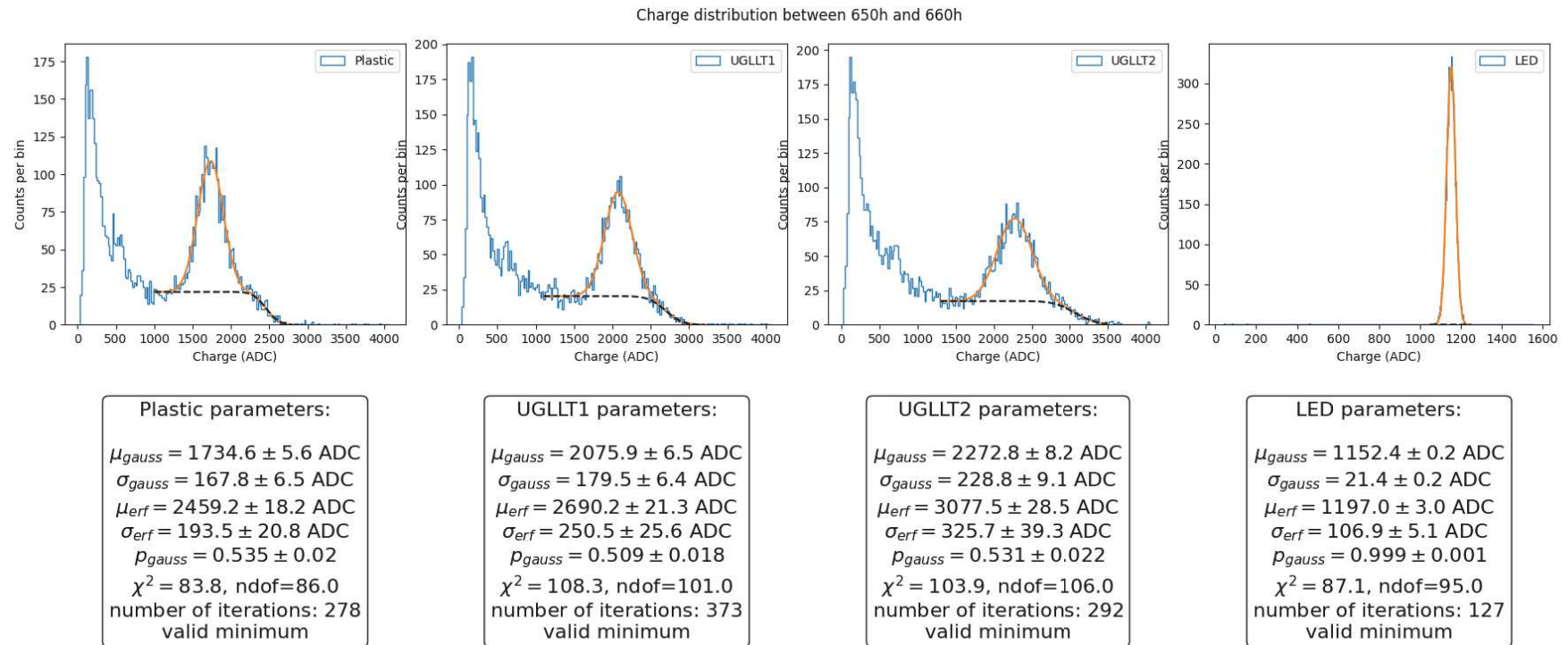
In NEWS-G shielding at Queen's



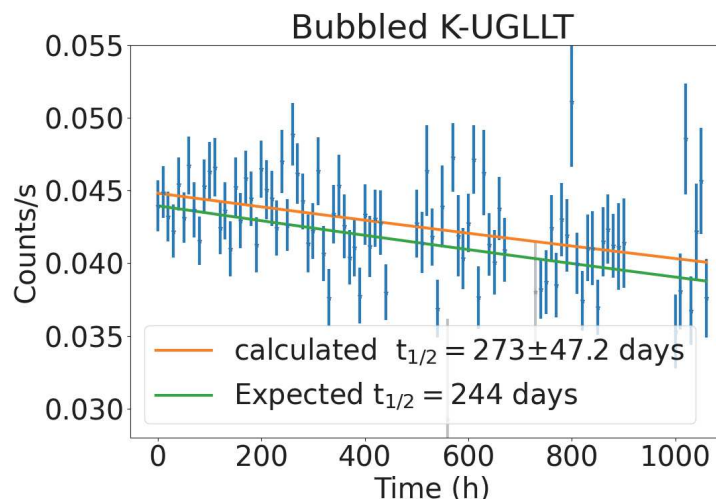
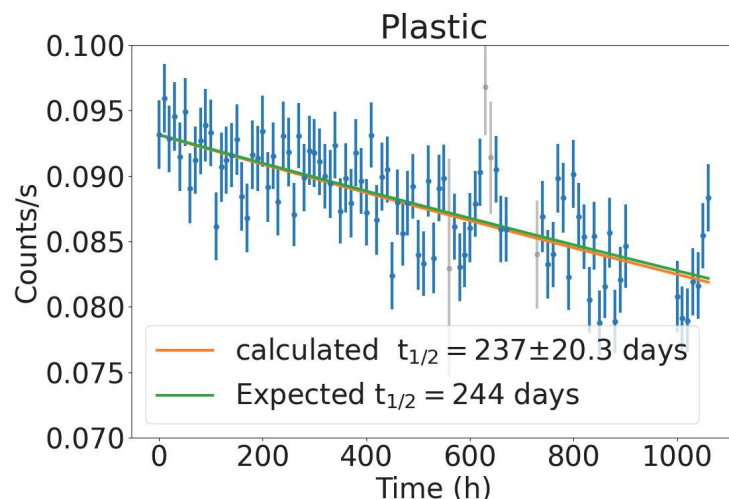
Monitor

- ▶ 2 LSC 20 mL vials
- ▶ References: plastic scintillator, LED and temperature

Examples of spectra (10 h of data)



Efficiency stability



Decay in count rate consistent with $T_{1/2}$ of ^{65}Zn source $\Rightarrow$
efficiencies constant

Consistent with literature [9] (only counts, not LY):

The total counting time for potassium and background samples including background measurements is more than 60 days plus additional test measurements. During this time the counting rates of all samples were stable.

N₂ bubbling

Currently investigating N₂ bubbling of LS to displace O₂, improve stability. In N₂ glovebox.



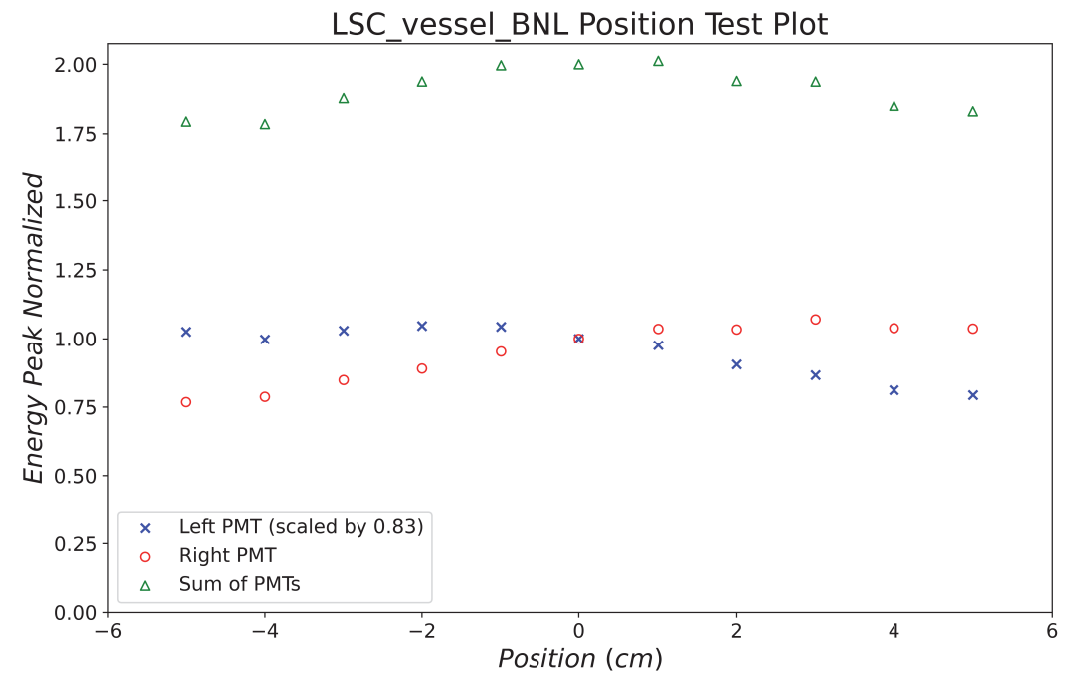
Liquid scintillator vessel

300 mL PTFE cylinder with PMMA windows & PMs on either end



Challenges include bubble when filling

Position response of LS vessel

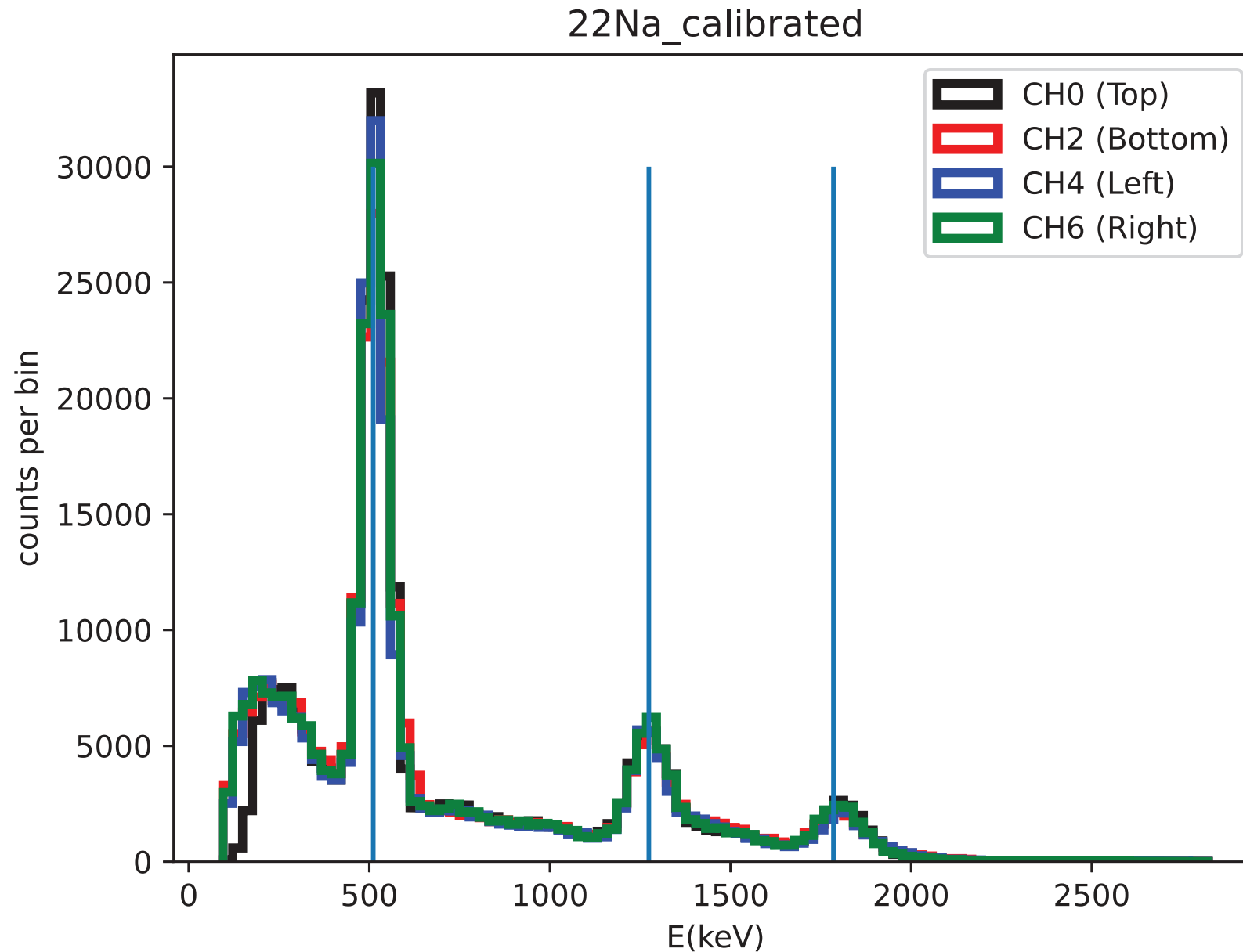


Tagging 511 keV γ s

- ▶ Medium-term option:
ORNL's MTAS (1 ton NaI array at Argonne?)
- ▶ Current tests with much smaller, early 1970s, NaI annulus at Queen's

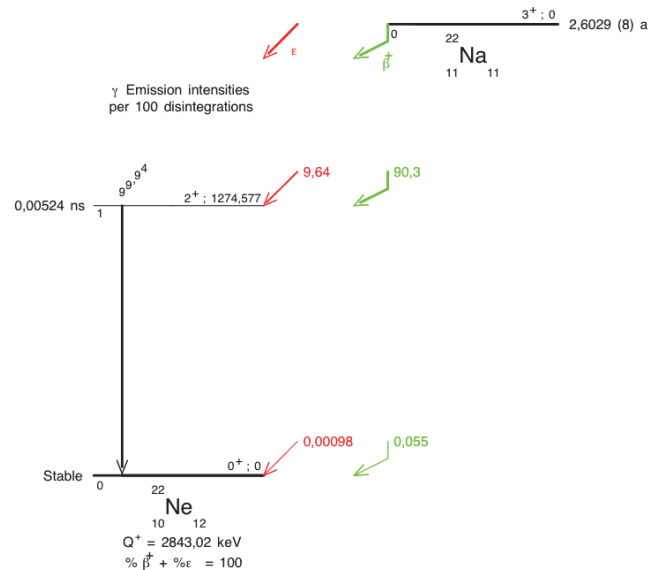


Response of NaI annulus to ^{22}Na



Overall efficiency calibration: ^{22}Na

- ▶ ^{22}Na decays 90% of time by β^+ to excited state of ^{22}Ne , also emitting 1.2 MeV γ



- ▶ Use ^{22}Na and additional tagger + sims to determine efficiency for detection of β^+ and 2×511 keV. Trigger on 1.275 MeV γ in extra detector, then look for β^+ in LS and 511 in detectors. Note ^{22}Na β^+ 90% of time to excited state there 10% of time, so would only give efficiency to precision of ^{22}Na BR.
- ▶ ^{22}Na : $Q=2843.02$ keV, so $E_+ \leq 2843 - 1275 - 1022 = 546$ keV. ^{40}K : $Q=1504.69$ keV, so $E_+ \leq 1504 - 1022 = 482$ keV. Sims may be necessary to account for difference in β^+ energies
- ▶ ^{22}Na chemically similar to ^{40}K .

Investigating pair-creation with ^{42}K

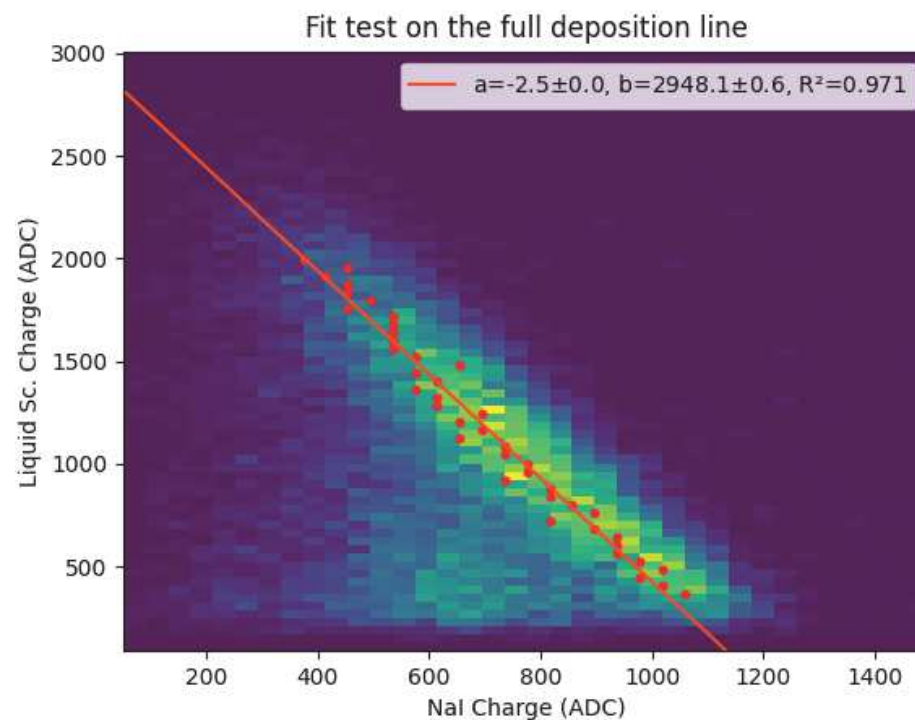
- ▶ Pair creation from 1.46 keV EC* γ s expected to be a background
- ▶ Challenges include:
 - Obtaining ^{42}K Neutron activation of KCl is messy. Instead, neutron activate natKOH, neutralize with HCl?
 - Regulations Need authorization to handle open sources

Moving ahead on liquid scintillator

Alternative LS Currently evaluating water-based LS from BNL —
better LY and stability expected

Shorter run time Use enriched ^{40}K ?

Calibration Track and correct evolution of LY in annulus using
Compton scattering



KDK+ status

- ▶ Goal: remeasure small β^+ branch of ^{40}K
- ▶ Converging on liquid scintillator cocktail loaded with K
- ▶ Expect to run 1 month with natK
- ▶ Pilot run ongoing at Queen's to integrate, understand overall experiment and γ tagging
- ▶ Option to move to MTAS