

Status of the KDK (^{40}K decay) project: Measuring a rare decay of ^{40}K with implications for dark matter claims

N. Brewer² P. Di Stefano^{1b} R. Grzywacz^{2,3,7} Y. Liu²
E. Lukosi³ C. Melcher³ C. Rasco² K. Rykaczewski²
L. Stand³ M. Stukel¹ M. Wolińska-Cichocka^{2,6,7}
I. Yavin^{4,5}

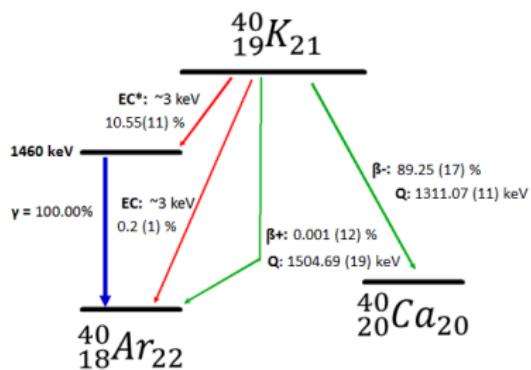
¹Queen's University, ²Oak Ridge National Laboratory, ³University of Tennessee,
⁴Perimeter Institute, ⁵McMaster University, ⁶University of Warsaw,
⁷Joint Institute for Nuclear Physics and Application

June 16, 2016

^bdistefan@queensu.ca

Decays of ^{40}K

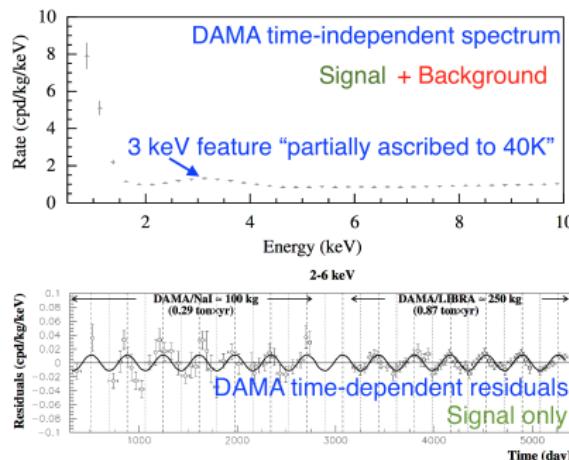
- ^{40}K : naturally occurring; 0.012% abundance
- $T_{1/2} = 1.2 \times 10^9$ years; main decay is β^- with branching ratio of 90%:



- Also electron capture (EC):
 - 3 keV X-rays and Auger electrons come from K-shell electron capture:
$$^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} + \nu_e.$$
 - Main contribution: EC* to excited state of ^{40}Ar , which then decays with $T_{1/2} = 1.6$ ps [1], emitting a 1.46 MeV γ . Branching ratio (BR*) is 10%. Can be tagged by 1.46 MeV γ .
 - Also contribution that can not be tagged, from direct EC to ground state. BR estimated from β^+ decay [2] of ^{40}K to ^{40}Ar as $0.2 \pm 0.1\%$ (theory dependent), and from total decay rate as $0.8 \pm 0.8\%$ (theory independent), but has never been measured [3]
 - EC to ground state would be the only known EC unique third-forbidden transition.

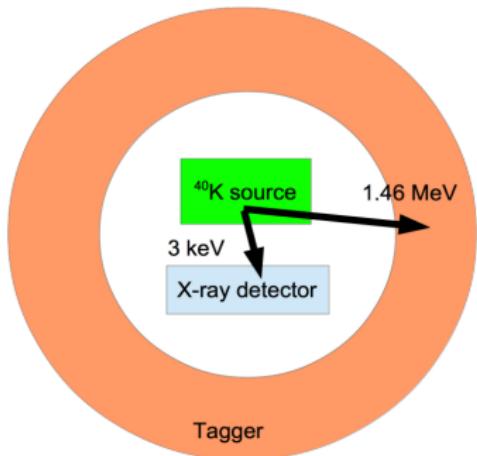
Dark matter, DAMA/LIBRA, and ^{40}K [3, 4]

- ▶ Exotic new dark particles may make up bulk of matter in universe.
- ▶ DAMA claims detection based on annual modulation caused by rotation of Earth around Sun, through particle halo of galaxy:



- signal**
modulation amplitude
time-independent amplitude $\approx \frac{1}{100}$
signal + background
- ▶ Average contaminations determined by EC* 3 keV/1.46 MeV coincidences between detectors: ^{nat}K : 13 ppb; ^{40}K : $\sim 10^{-12}$ g/g
 - ▶ ^{40}K 3 keV X-rays/Augers from EC
 - ▶ can't be tagged (unlike EC*)
 - ▶ contribute to time-independent component
 - ▶ constrain modulation fraction of signal and dark matter interpretation
 - ▶ Important to know EC branching ratio

Measuring direct EC with KDK: X-ray detector and tagger



- ▶ Trigger on small inner detector
 - ▶ Low threshold (~ 1 keV) and high efficiency to detect 3 keV X-rays (and Augers?)
 - ▶ Transparent to $E \gtrsim 10$ keV to reduce scattering, background
- ▶ Surround with 4π veto to tag 1.46 MeV γ with high efficiency (bonus if threshold low enough to measure 511 keV γ as cross check of BR_{EC} estimation from BR_{β^+}).
 - ▶ For a signal-to-noise of 1, need an efficiency of 98%
 - ▶ 98% absorption efficiency of 1.46 MeV γ requires 22 cm of NaI (or 77 cm of LAB, or 59 cm of LAr)
- ▶ Compare tagged to untagged triggers to figure out ratio of EC to EC*.

Modular Total Absorption Spectrometer (MTAS) tagger [6]

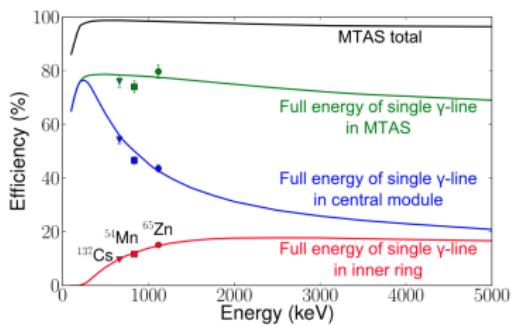
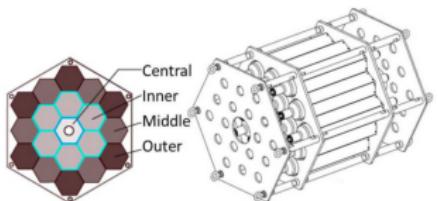
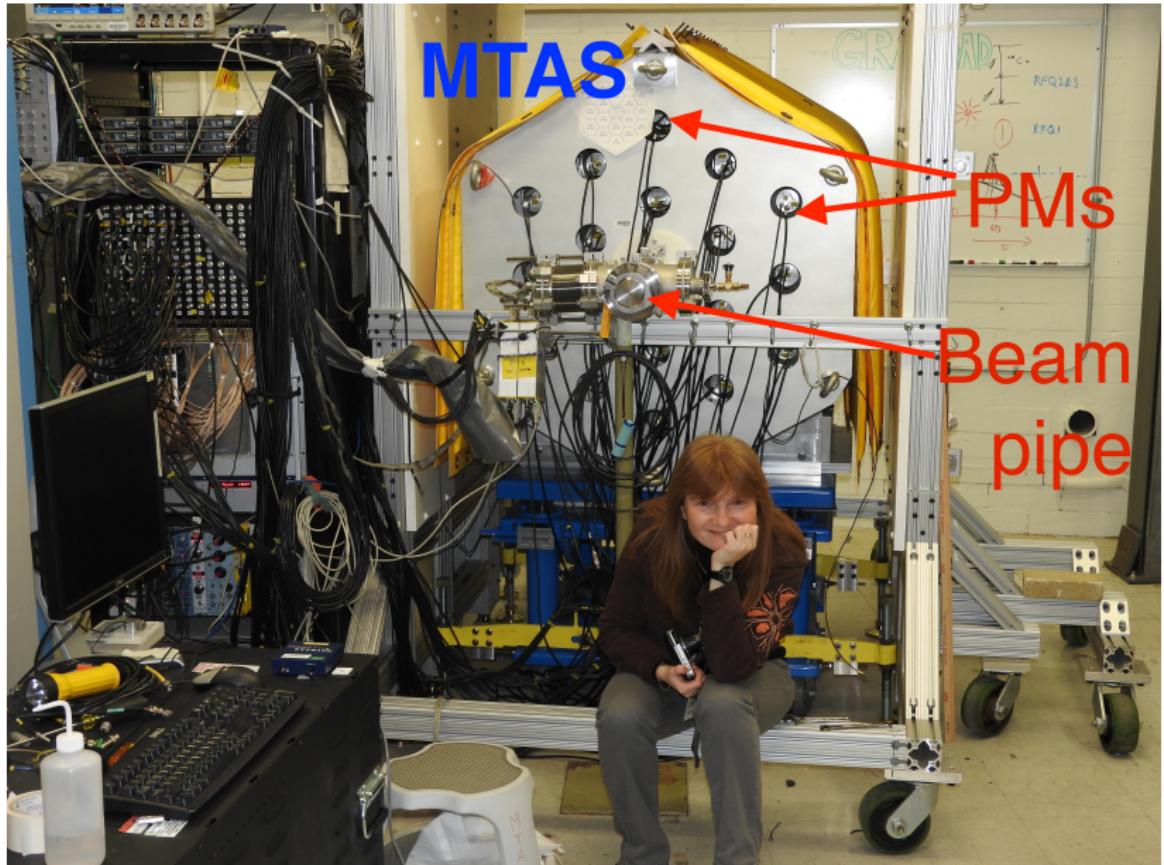


FIG. 3. The efficiencies of MTAS to detect single γ -ray transition are compared to GEANT4 simulations.

- ▶ At Oak Ridge, TN (ORNL), surface site
- ▶ Made up of 19 NaI(Tl) modules, ≈ 55 kg each, ~ 1 ton total (surrounded by 5 ton Pb shielding).
- ▶ 2.5" ≈ 6.5 cm diam hole through center: **source + small detector go here**
- ▶ Efficiency for tagging 1.46 MeV gammas from center is 98–99% (SNR: 1–2)
- ▶ BG rate < 1.46 MeV ≈ 240 Hz in each module (over all modules ≈ 4.5 kHz; this means the probability of one of these events arriving in a random $1\ \mu\text{s}$ window is 4.5×10^{-3}).
- ▶ 2 channels on a XIA Pixie 16 [5]
100 MS/s 12-16 bit ADC are available for small detector(s)

MTAS at ORNL



Options for X-ray detector and source

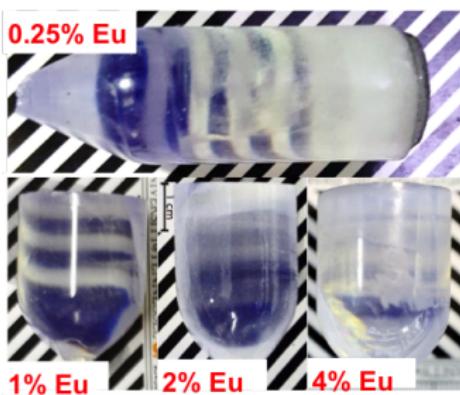
- ▶ **Composite (cf M. Stukel's talk last Tuesday)**: Small, sensitive detector, and removable source. Advantages:
 - ▶ source can be replaced to calibrate detector and tagging efficiency (eg with ^{54}Mn or ^{65}Zn), or removed to check backgrounds
 - ▶ good threshold and resolution
- ▶ **Homogeneous**: Source in bulk of small scintillator.
Advantages:
 - ▶ full absorption of X-rays/Augers
 - ▶ source supplied "free" with detector

Possibilities:

- ▶ Spiked NaI(Tl) scintillator: light yield sufficient ($\text{LY} = 40 \text{ photons/keV}$ [7]), but need much more K than usual contamination
- ▶ KI(Tl) scintillator: LY should be checked [8, 9, 10], may be hard to reach required threshold
- ▶ $\text{K}_2\text{La}_5\text{:Ce}$ and other exotics: can reach $\text{LY} = 55 \text{ photons/keV}$ [11], but mass of crystals?
- ▶ KSr_2I_5

KS_r₂I₅:Eu scintillator (E. Lukosi, C. Melcher, L. Stand^c)

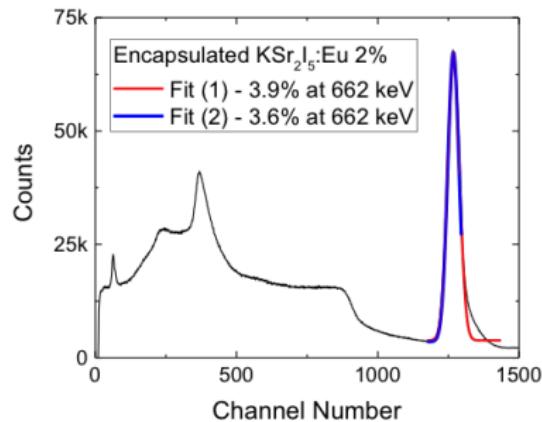
- ▶ Novel scintillator [12], high light yield ≈ 100 photons/keV, $\lambda \approx 450$ nm
- ▶ Density 4.4 g/cm³, total ⁴⁰K activity 6.6 Hz/cm³
- ▶ Available in several cm³
- ▶ 1" diameter crystals:



- ▶ Hygroscopic → encapsulate



- ▶ Excellent energy resolution (¹³⁷Cs):

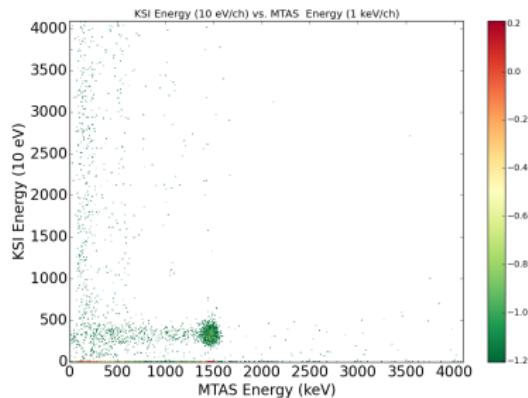


^cU. Tennessee

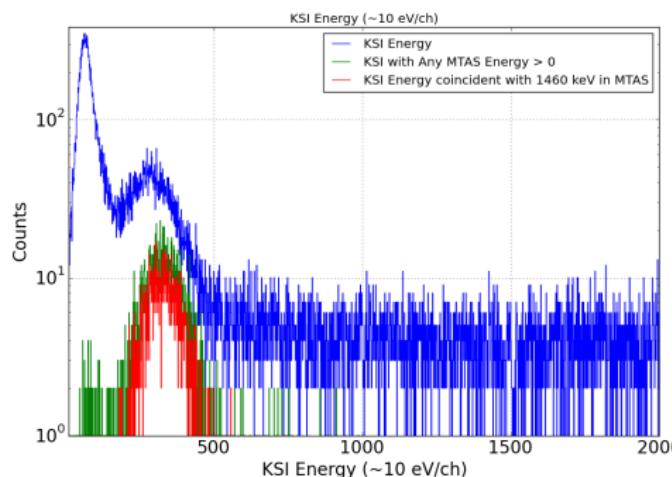
Preliminary tests of 4 g KSr_2I_5 in MTAS

*Unoptimized setup, single PM,
overnight*

KSI vs MTAS:



KSI spectra when cutting on MTAS
(doing things backwards):

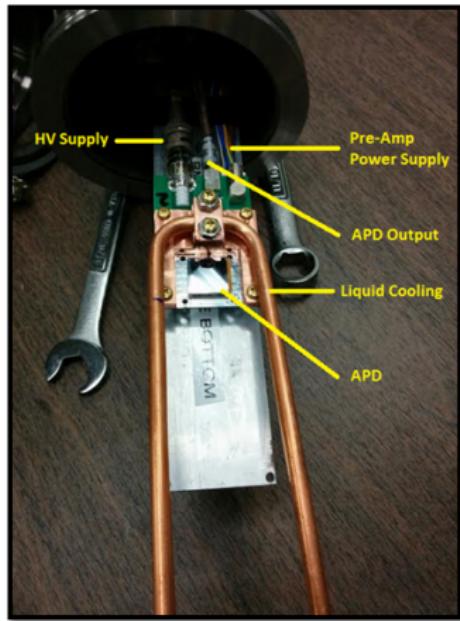


- ▶ ${}^{40}\text{K}$ coincidences!

- ▶ 3 keV X-rays/Augers visible
- ▶ Rates, backgrounds being studied

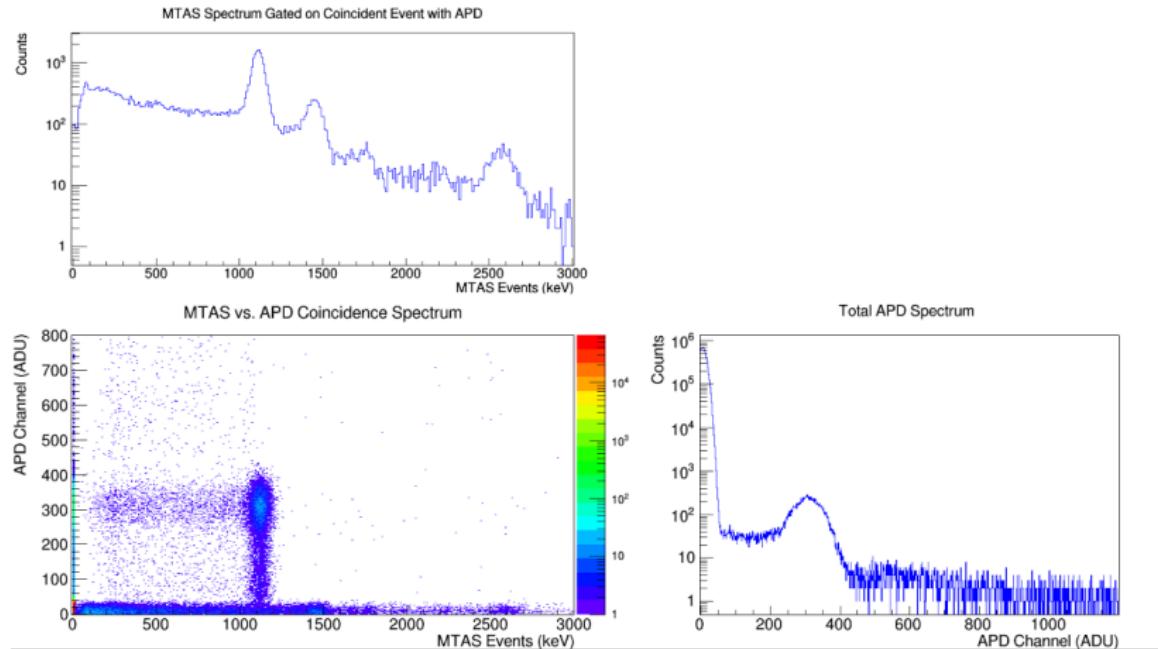
X-ray detector: large-area avalanche photodiode (LAAPD)

- ▶ LAAPD chosen for large surface area, and cost, rather than for resolution
- ▶ 1 keV threshold possible when cooled to -20° C → water/glycol mix, for now detector reaches $\sim -10^{\circ} \text{ C}$
- ▶ Device: RMD 1315, 1 cm^2
- ▶ Custom preamp supplied by P. Davis (U. Alberta MRS); pulse duration $\sim 200 \text{ ns}$



Preliminary ^{65}Zn calibration of LAAPD in MTAS

Mainly EC, EC*: $\sim 8 \text{ keV X-ray/Auger} (+ 1115 \text{ keV } \gamma \text{ EC}^*)$



Towards a ${}^{40}\text{K}$ source



Equivalent ${}^{40}\text{K}$ content

- ▶ Driver: $\sim 3 \times 10^4$ untagged 3 keV counts required to provide 10% stat error on ratio of EC/EC* branching ratios
- ▶ Source goals:
 - ▶ $10^{18} {}^{40}\text{K}$ nuclei (4×10^3 EC events per day)
 - ▶ Implanted in 1 cm^2 Al foil to depth of $1 \mu\text{m}$ (to reduced self-absorption and losses of efficiency)
- ▶ Production, including isotope separation and implantation, at ORNL
- ▶ Will start with K enriched to 3% ${}^{40}\text{K}$

Conclusions and prospects

- ▶ Measuring the branching ratio of electron capture of ^{40}K to ground state of ^{40}Ar will:
 - ▶ provide better understanding of the backgrounds in the longstanding DAMA claim for the discovery of dark matter, and in other dark matter searches
 - ▶ be the first observation of EC unique third-forbidden decay
 - ▶ inform nuclear shell models
- ▶ MTAS provides high-efficiency tagging
- ▶ 2 options being explored in parallel for X-rays
 - ▶ LAAPD and ^{40}K source
 - ▶ KSr_2I_5 scintillator which is also source
- ▶ Issues to be resolved:
 - ▶ determine **tagging efficiency** with high precision (suitable isotopes and Monte-Carlos)
 - ▶ understand **β^- background** and ways to mitigate it
 - ▶ produce **thin enriched ^{40}K source**
 - ▶ characterize **KSr_2I_5 at low energies** and its backgrounds
- ▶ Results expected in 2017

References |

- [1] Recommended data.
- [2] D. W. Engelkemeir, K. F. Flynn, and L. E. Glendenin.
Positron Emission in the Decay of K 40.
Physical Review, 126(5):1818, 1962.
- [3] Josef Pradler, Balraj Singh, and Itay Yavin.
On an unverified nuclear decay and its role in the DAMA experiment.
Physics Letters B, 720(4–5):399–404, March 2013.
- [4] R. Bernabei, P. Belli, S. d'ANGELO, A. Di Marco, F. Montecchia, F. Cappella, A. d'ANGELO, A. Incicchitti, V. Caracciolo, S. Castellano, R. Cerulli, C. J. Dai, H. L. He, X. H. Ma, X. D. Sheng, R. G. Wang, and Z. P. Ye.
DARK MATTER INVESTIGATION BY DAMA AT GRAN SASSO.
International Journal of Modern Physics A, 28(16):1330022, June 2013.
- [5] DGF Pixie-16 - 100mhz Multichannel Digital Gamma Finder in PXI format.
- [6] M. Wolińska-Cichocka, K. P. Rykaczewski, A. Fijałkowska, M. Karny, R. K. Grzywacz, C. J. Gross, J. W. Johnson, B. C. Rasco, and E. F. Zganjar.
Modular Total Absorption Spectrometer at the HRIBF (ORNL, Oak Ridge).
Nuclear Data Sheets, 120:22–25, June 2014.
- [7] Glenn F. Knoll.
Radiation Detection and Measurement.
Wiley, 3 edition, January 2000.
- [8] B. Smaller, J. May, and M. Freedman.
Scintillation studies on potassium iodide.
Physical Review, 79(6):940, 1950.

References II

- [9] J. Bonanomi and J. Rossel.
Scintillations de luminescence dans les iodures d'alcalins.
Helvetica Physica Acta, 25(VII):725–752, 1952.
- [10] H. V. Watts, L. Reiffel, and M. D. Oestreich.
Scintillation properties of pure alkali halides at low temperatures.
1962.
- [11] E. V. D. van Loef, P. Dorenbos, C. W. E. van Eijk, K. W. Krämer, and H. U. Güdel.
Scintillation properties of K₂lax5:Ce³⁺ (X=Cl, Br, I).
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 537(1–2):232–236, January 2005.
- [12] L. Stand, M. Zhuravleva, G. Camarda, A. Lindsey, J. Johnson, C. Hobbs, and C.L. Melcher.
Exploring growth conditions and Eu²⁺ concentration effects for KSr₂i₅:Eu scintillator crystals.
Journal of Crystal Growth, 439:93–98, April 2016.
- [13] X. Mougeot.
Reliability of usual assumptions in the calculation of β and ν spectra.
Physical Review C, 91(5), May 2015.

References III

- [14] Marc Diepold, Luis M. P. Fernandes, Jorge Machado, Pedro Amaro, Marwan Abdou-Ahmed, Fernando D. Amaro, Aldo Antognini, François Biraben, Tzu-Ling Chen, Daniel S. Covita, Andreas J. Dax, Beatrice Franke, Sandrine Galtier, Andrea L. Gouvea, Johannes Götzfried, Thomas Graf, Theodor W. Hänsch, Malte Hildebrandt, Paul Indelicato, Lucile Julien, Klaus Kirch, Andreas Knecht, Franz Kottmann, Julian J. Krauth, Yi-Wei Liu, Cristina M. B. Monteiro, Françoise Mulhauser, Boris Naar, Tobias Nebel, François Nez, José Paulo Santos, Joaquim M. F. dos Santos, Karsten Schuhmann, Csilla I. Szabo, David Taqqu, João F. C. A. Veloso, Andreas Voss, Birgit Weichelt, and Randolph Pohl.
Improved x-ray detection and particle identification with avalanche photodiodes.
Review of Scientific Instruments, 86(5):053102, May 2015.
- [15] SD197-70-72-661 Advanced Photonix Inc | SD197-70-72-661-ND | DigiKey.
- [16] L. M. P. Fernandes, F. D. Amaro, A. Antognini, J. M. R. Cardoso, C. a. N. Conde, O. Huot, P. E. Knowles, F. Kottmann, J. a. M. Lopes, L. Ludhova, C. M. B. Monteiro, F. Mulhauser, R. Pohl, J. M. F. dos Santos, L. A. Schaller, D. Taqqu, and J. F. C. A. Veloso.
Characterization of large area avalanche photodiodes in X-ray and VUV-light detection.
Journal of Instrumentation, 2(08):P08005, August 2007.
- [17] X-PIPS™ Detectors (integrated PA) - Series X - CANBERRA Industries.
- [18] Silicon Lithium Si(Li) Detectors - CANBERRA Industries.