Gamma-ray Source Detection with Coded-aperture Gamma Imager in a Complex Gamma-ray/Neutron Environment for Nuclear Safeguard

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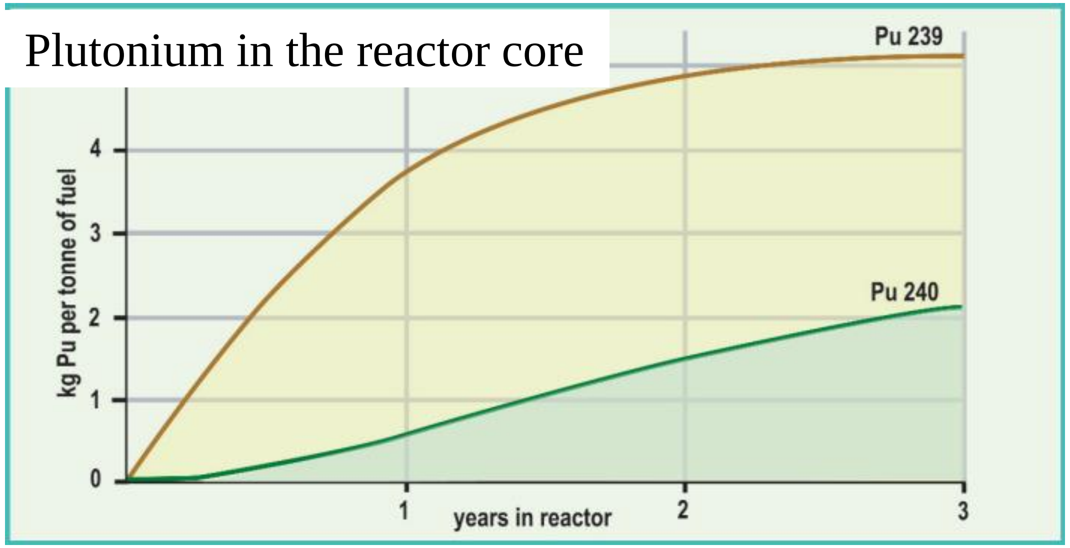
Introduction

Mixed gamma/neutron environments due to a severe nuclear accident

https://theconversation.com/fukushima-ten-years-on-from-the-disaster-was-japans-response-right-156554 (accessed May 2021).



Hore-Lacy, Ian. *Nuclear Energy in the 21st Century: World Nuclear University Press*. Elsevier, 2010.

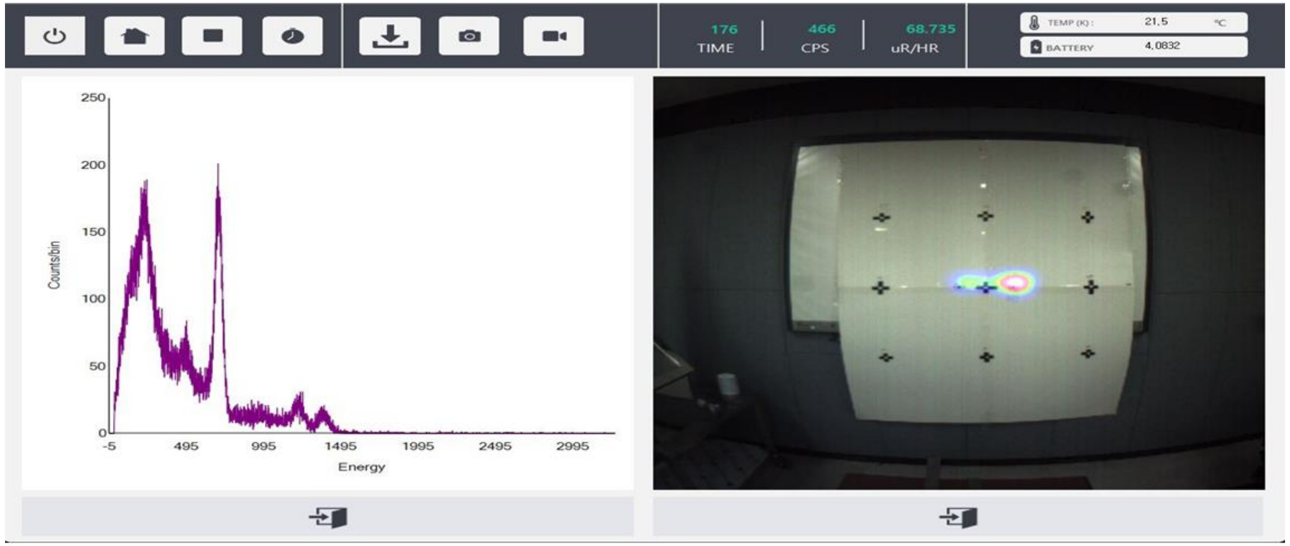
- ^{240}Pu (S.F) -> ^{151}Eu (n, γ) ^{152}Eu -> ^{59}Co (n, γ) ^{60}Co
- $^{137}Cs \xrightarrow{\beta^-} {}^{137m}Ba \xrightarrow{\gamma} {}^{137}Ba$

	$T_{1/2}$ (years)
^{152}Eu	13.52
^{60}Co	5.27
^{137}Cs	30.08

Methods

EPSILON-G

(**E**nergetic **P**article **S**ensor for the **I**dentification and **L**ocalization of **O**riginating **N**uclei)

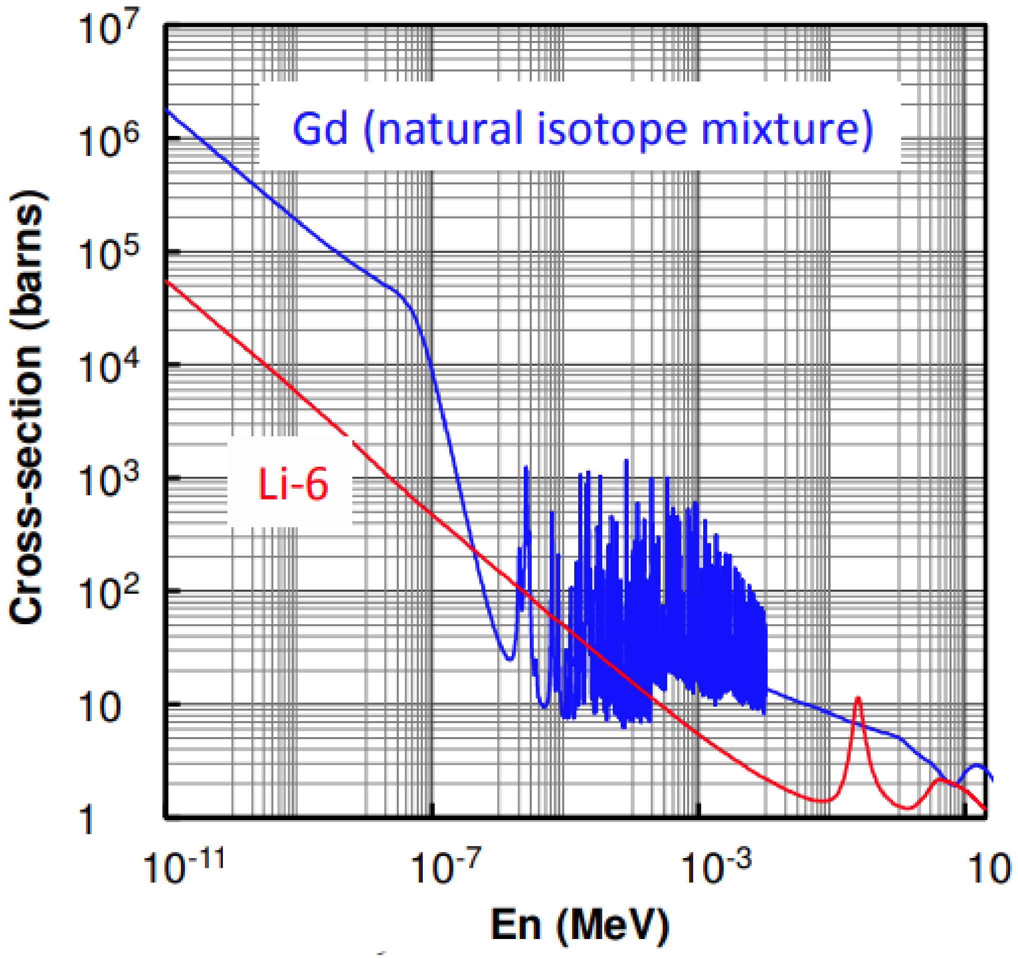


Specification

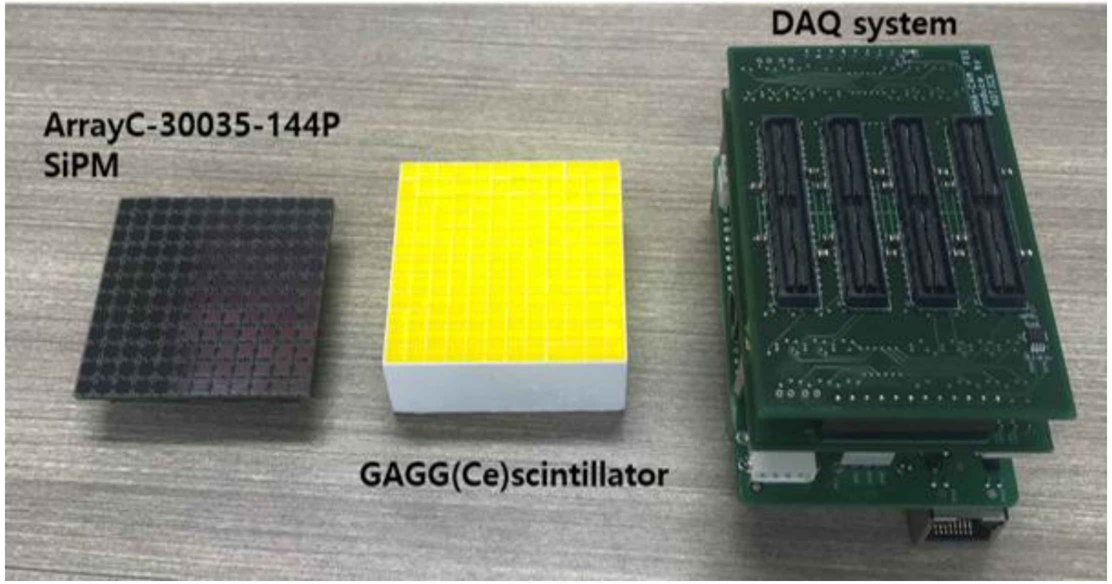
Technology	Coded-aperture
Field-of-view	45°
Energy Range	30 keV – 3 MeV
Energy Resolution	8% @ 662keV
Sensitivity	<2 sec. for 0.3 μSv/hr of ^{137}Cs
Dose rate range	0.08 μSv/hr (BKG) to 20 μSv/hr
Operational temperature range	-20°C to 60°C
Size (weight)	104 x 144 x 197 mm (5.1 kg)

Methods

- **Neutron total cross sections of ^{6}Li isotope and of natural mixture of Gd isotopes**



M. Korzhik, *et al*. "Ce-doped $Gd_3Al_2Ga_3O_{12}$ scintillator for compact, effective and high time resolution detector of the fast neutrons." arXiv preprint arXiv:1807.06390 (2018).



GAGG(Ce) ⇔ $Gd_3Al_2Ga_3O_{12}$(Ce)

Methods

Neutron total cross sections of ^{6}Li isotope and of natural mixture of Gd isotopes

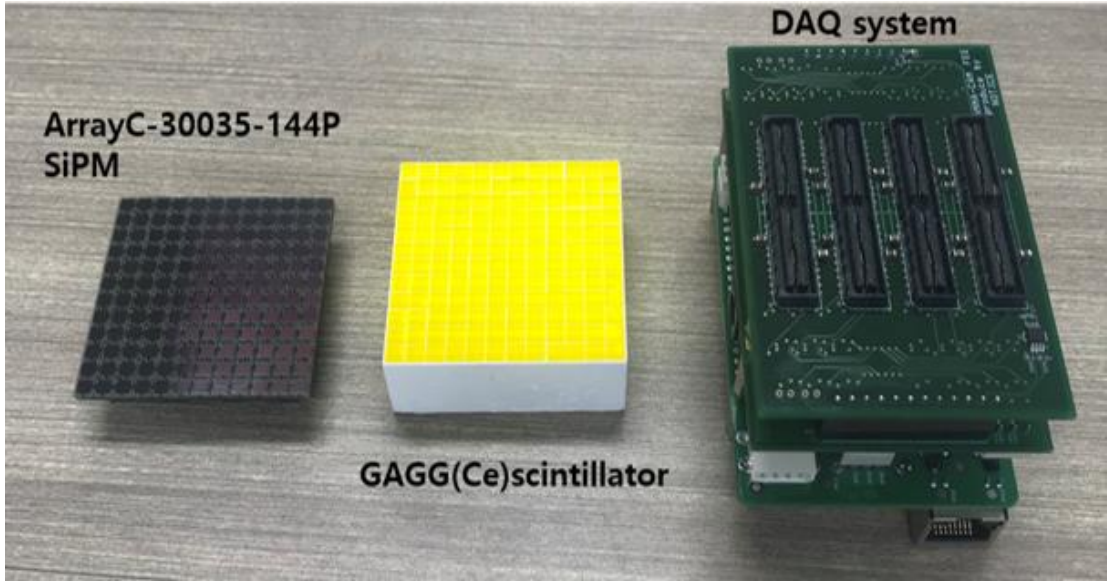
Table 1. Primary gamma-rays produced by $^{155}Gd(n, \gamma)^{156}Gd$, or $^{157}Gd(n, \gamma)^{158}Gd$

	γ-ray energy [keV]			Intensity %
	Primary	Secondary		$[10^{-2}]$
1	8448	–	–	1.8 ± 0.2
2	7382	1154	–	12.7 ± 1.4
		1065	–	10.6 ± 1.2
3	7288	1158	–	34.8 ± 2.4
		959	199	10.5 ± 1.1
4	6474	1964	–	35.2 ± 0.7
5	6430	2017	–	20.7 ± 2.2
		1818	199	11.7 ± 1.5
6	6348	2188	–	12.1 ± 1.7
		2097	199	9.8 ± 1.6
		1036	1154	4.6 ± 0.8
			1065	3.8 ± 0.7
7	6319	2127	–	9.4 ± 0.5
8	6034	2412	–	14.0 ± 1.7
		2213	199	6.4 ± 1.0
9	5885	2563	–	9.0 ± 2.1
		2364	199	8.4 ± 2.1
10	5779	2672	–	18.8 ± 0.8
11	5698	2749	–	28.6 ± 0.8
12	5661	2786	–	15.4 ± 0.7

T. Tanaka, *et al*. "Gamma-ray spectra from thermal neutron capture on gadolinium-155 and natural gadolinium." *Progress of Theoretical and Experimental Physics* 2020.4 (2020): 043D02.

Nuclear reactions	E_{γ} [keV]	Cross section (b)
$^{16}O(n, n'\gamma)^{16}O$	6,130	0.003-0.023

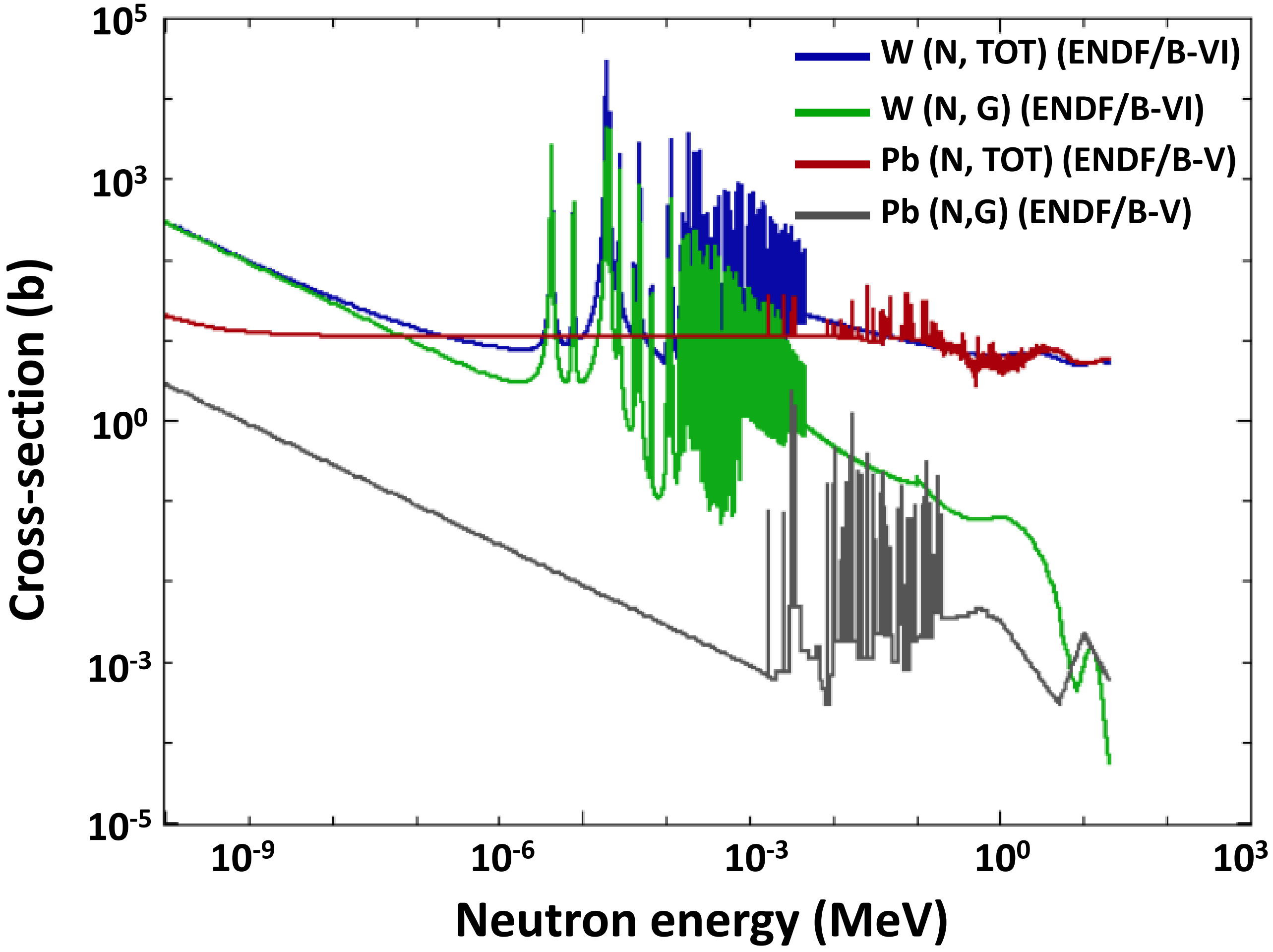
C. Nordborg, *et al*. "Gamma-ray production cross sections of neutron-induced reactions in oxygen." *Nuclear Science and Engineering* 66.1 (1978): 75-83.



GAGG(Ce) ⇔ $Gd_3Al_2Ga_3O_{12}(Ce)$

Methods

- **Neutron total cross sections of natural mixture of tungsten(W) and lead(Pb)**



MURA mask

Methods

Neutron total cross sections of natural mixture of tungsten(W) and lead(Pb)

Table 2. Primary gamma-rays produced by $^{A}W(n, \gamma)^{A+1}W$

Compound	E_γ [keV]
^{187}W	77.39(3)
^{187}W	145.79(3)
^{187}W	273.10(5)
^{187}W	5261.68(6)
^{183}W	6190.78(3)

Hurst, A. M., et al. "Investigation of the tungsten isotopes via thermal neutron capture." *Physical Review C* 89.1 (2014): 014606.

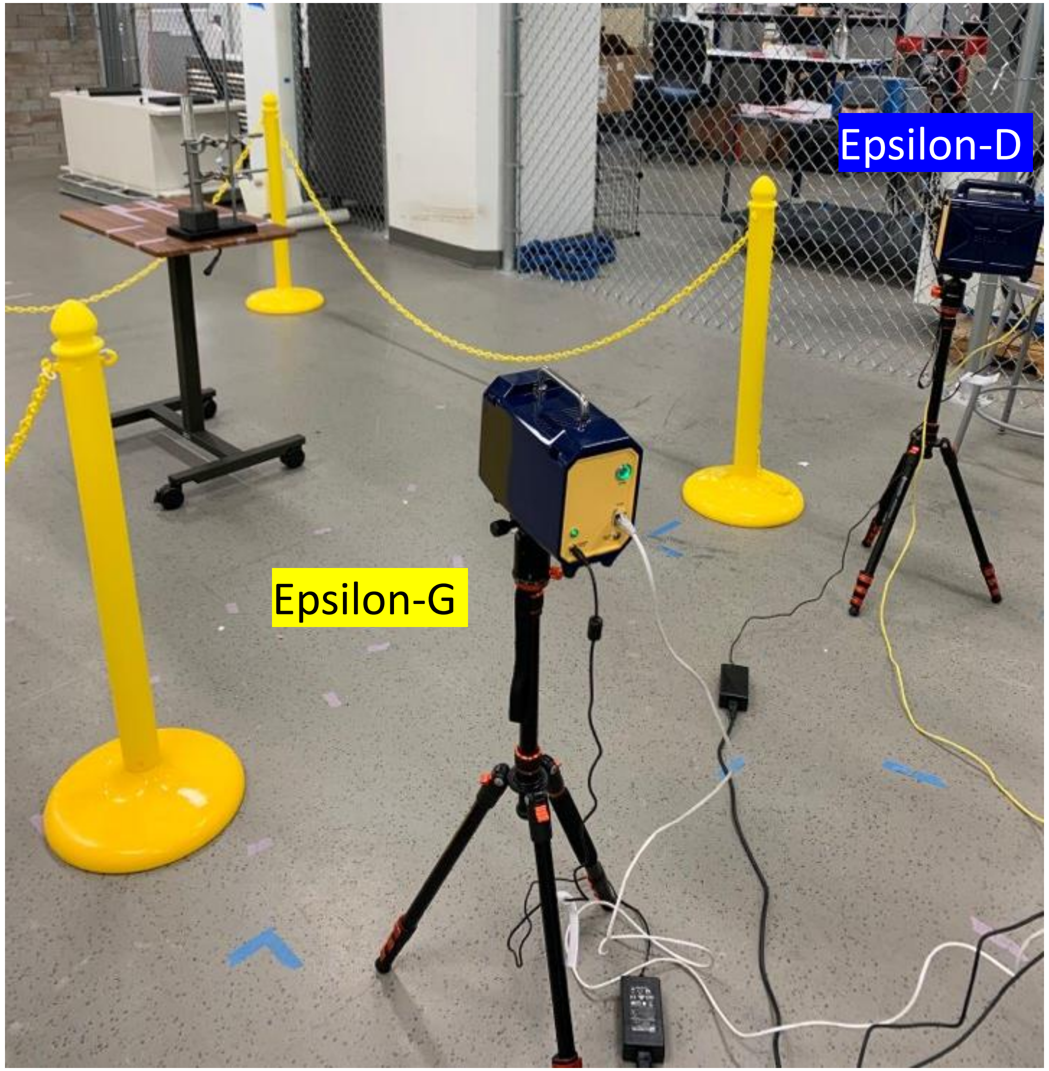
Table 3. Primary gamma-rays produced by $^{A}W(n, n'\gamma)^{A}W$

Compound	E_γ [keV]
^{182}W	100
	229
	1121
	1221
^{184}W	111
	253
	792
	903
^{186}W	112
	274
	615
	738

G. Henning, *et al*. "Measurement of (n, xnγ) reaction cross sections in W isotopes." *EPJ Web of Conferences*. Vol. 146. EDP Sciences, 2017.

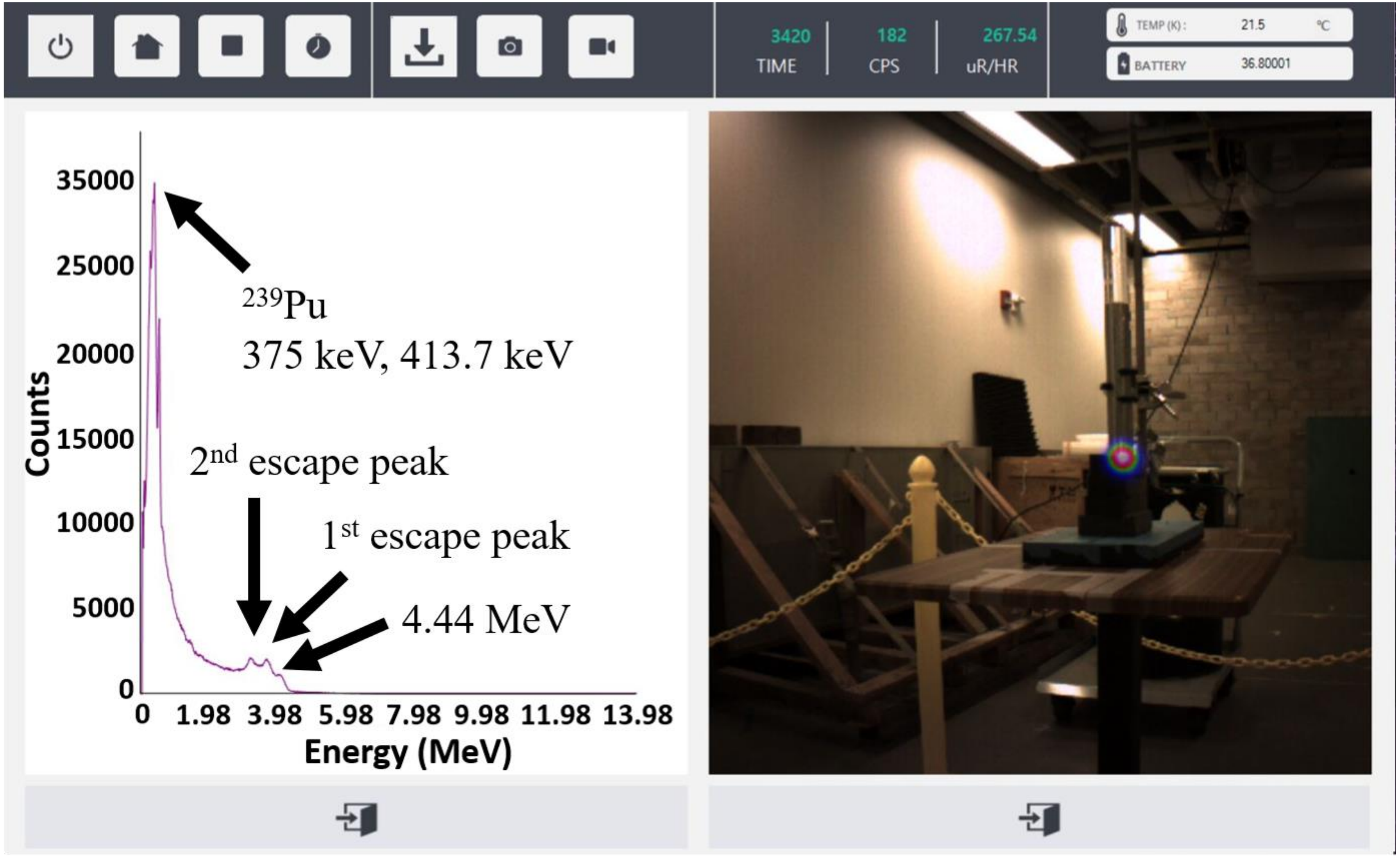
MURA mask

Methods



	^{239}PuBe	^{241}AmLi	^{252}Cf
Half-life	2.4×10^{30} yr	432 yr	2.65 yr
Decay mode(s)	^{9}Be(α, n)^{12}C	^{7}Li(α, n)^{10}B	α (96.9%) SF (3.09%)
Neutron Energy	0.5 - 11.5 MeV E_{ave}: 4.4 MeV	0.02 - 2 MeV E_{ave}: 0.54 MeV	0.2 - 7 MeV E_{ave}: 2.13 MeV
Average # emitted neutrons	1.7×10^{6} n/s-Ci	60,000 n/s-Ci	3.757 per SF
Gamma-ray Energy	4.4 MeV	59.5 keV 102.97 keV ($NpK_{\alpha 1}$: 101.66 keV)	0.14 - 10 MeV E_{ave}: 0.8 MeV

^{239}PuBe (1.7×10^{6} n/s)

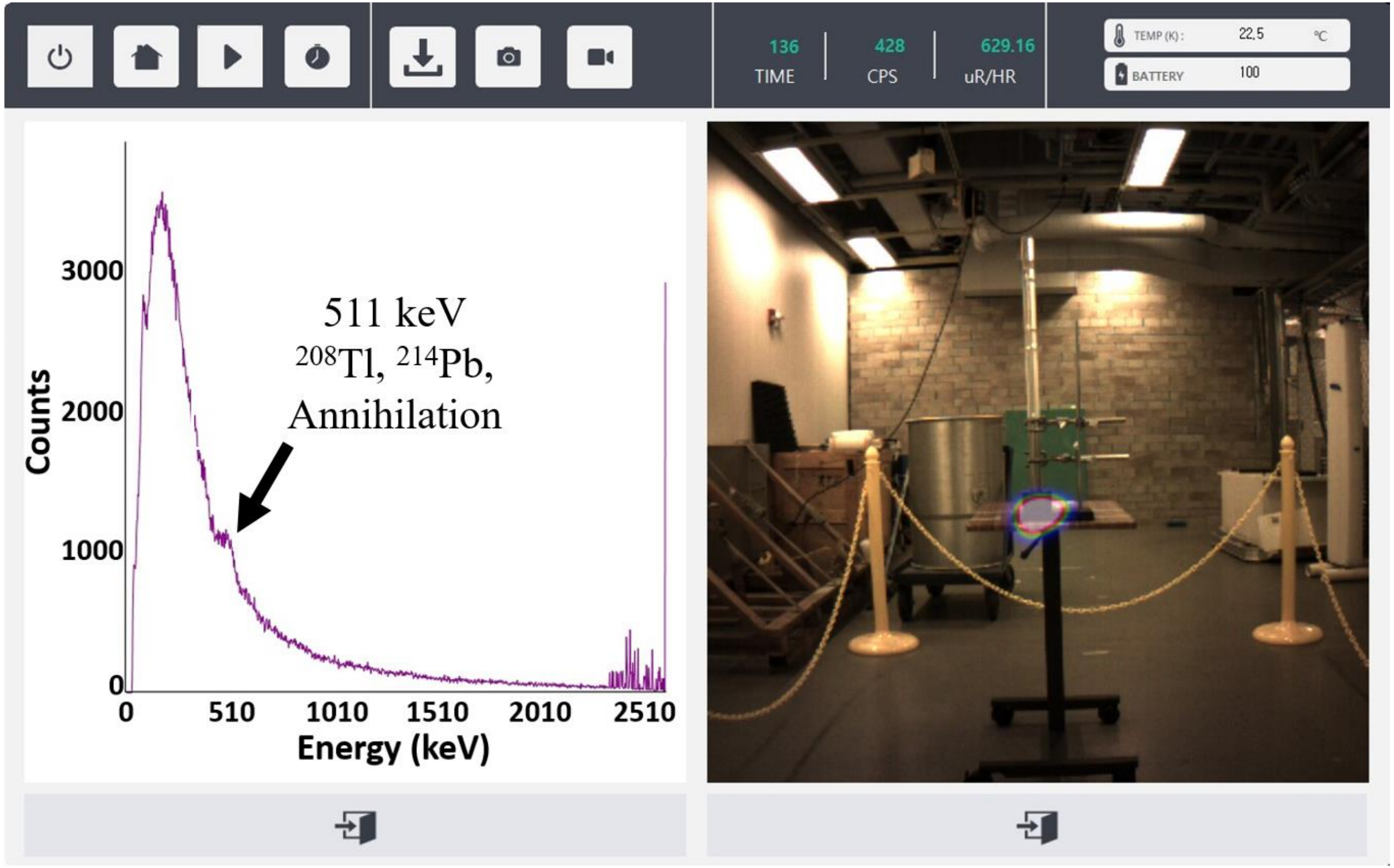


- Experiment Condition

- Source to detector distance: 1 m
- Initial source activity: 1 Ci
  (Sep, 30th, 1963)

^{252}Cf (5.37×10^6 n/s)

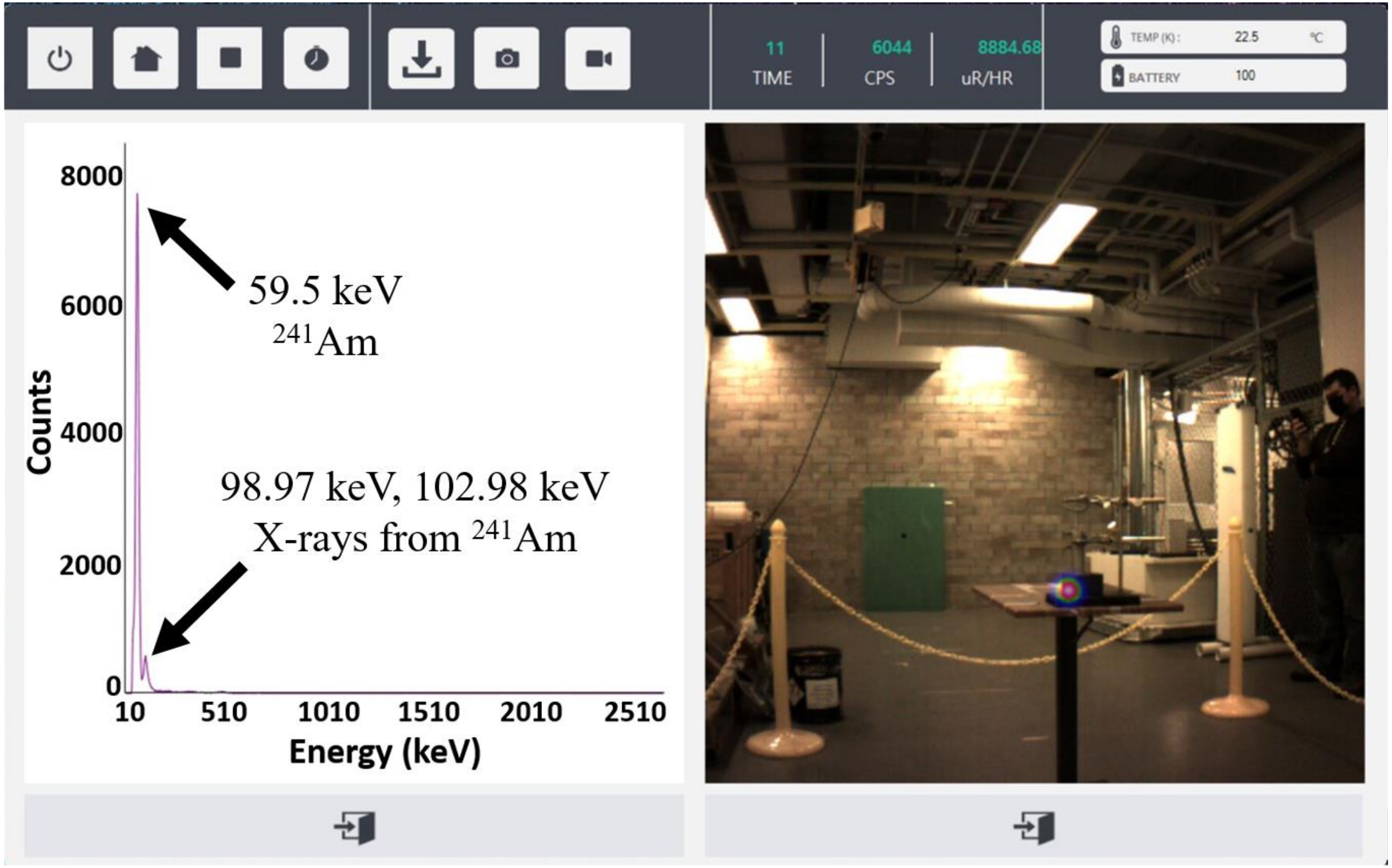
- Experiment Condition
- Source to detector distance: 2 m
- Initial source activity: 5.63 mCi (May, 8th, 2015)



^{241}AmLi (5.57 × 10^5 n/s)

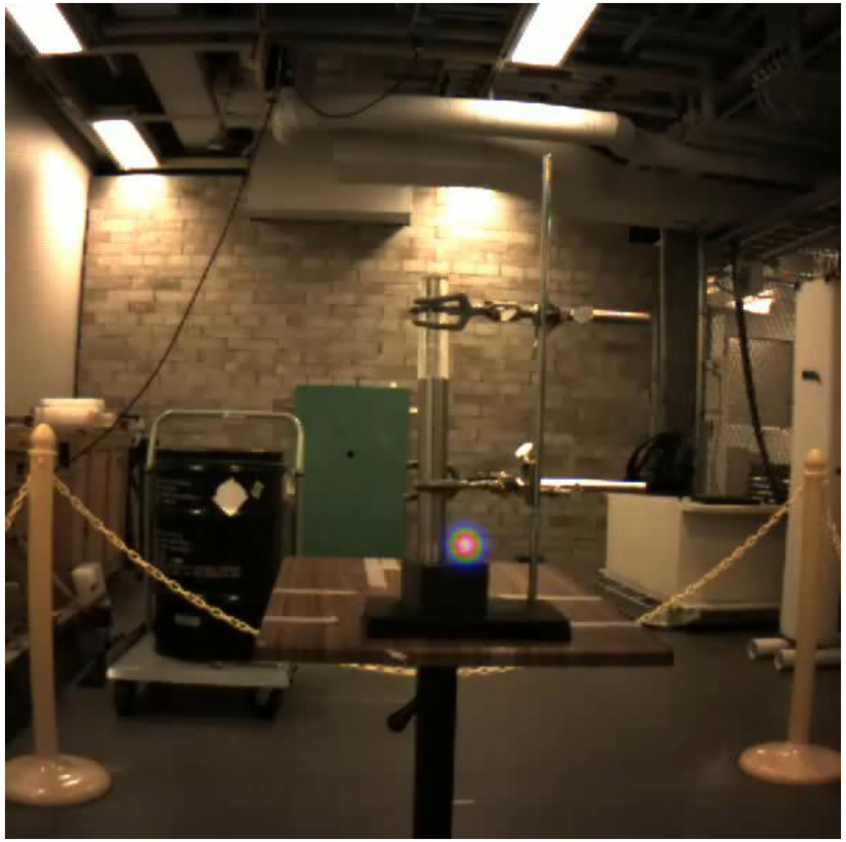
➢ Experiment Condition

- Source to detector distance: 2 m
- Initial source activity: 9.3 Ci
  (Dec, 10th, 2019)

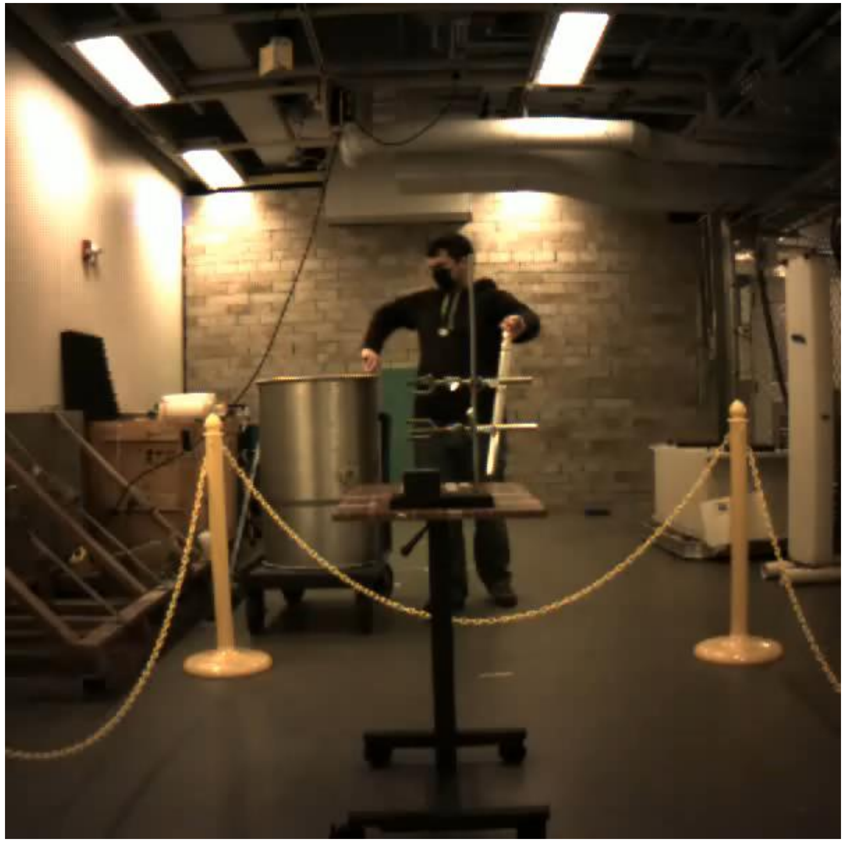


Real-time imaging of Epsilon-G

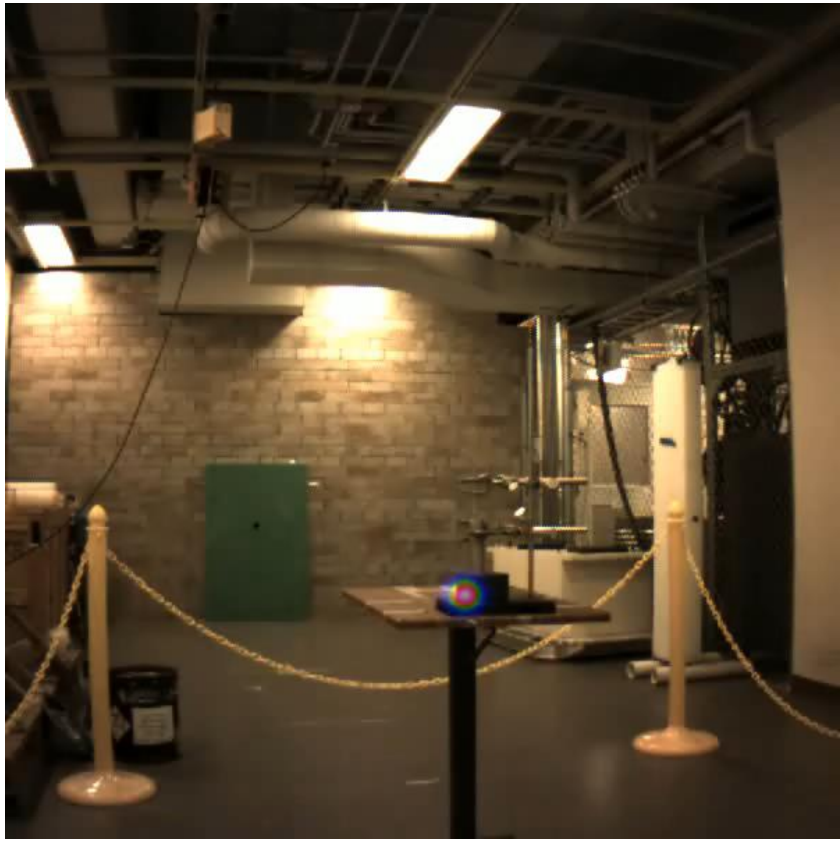
PuBe neutron source



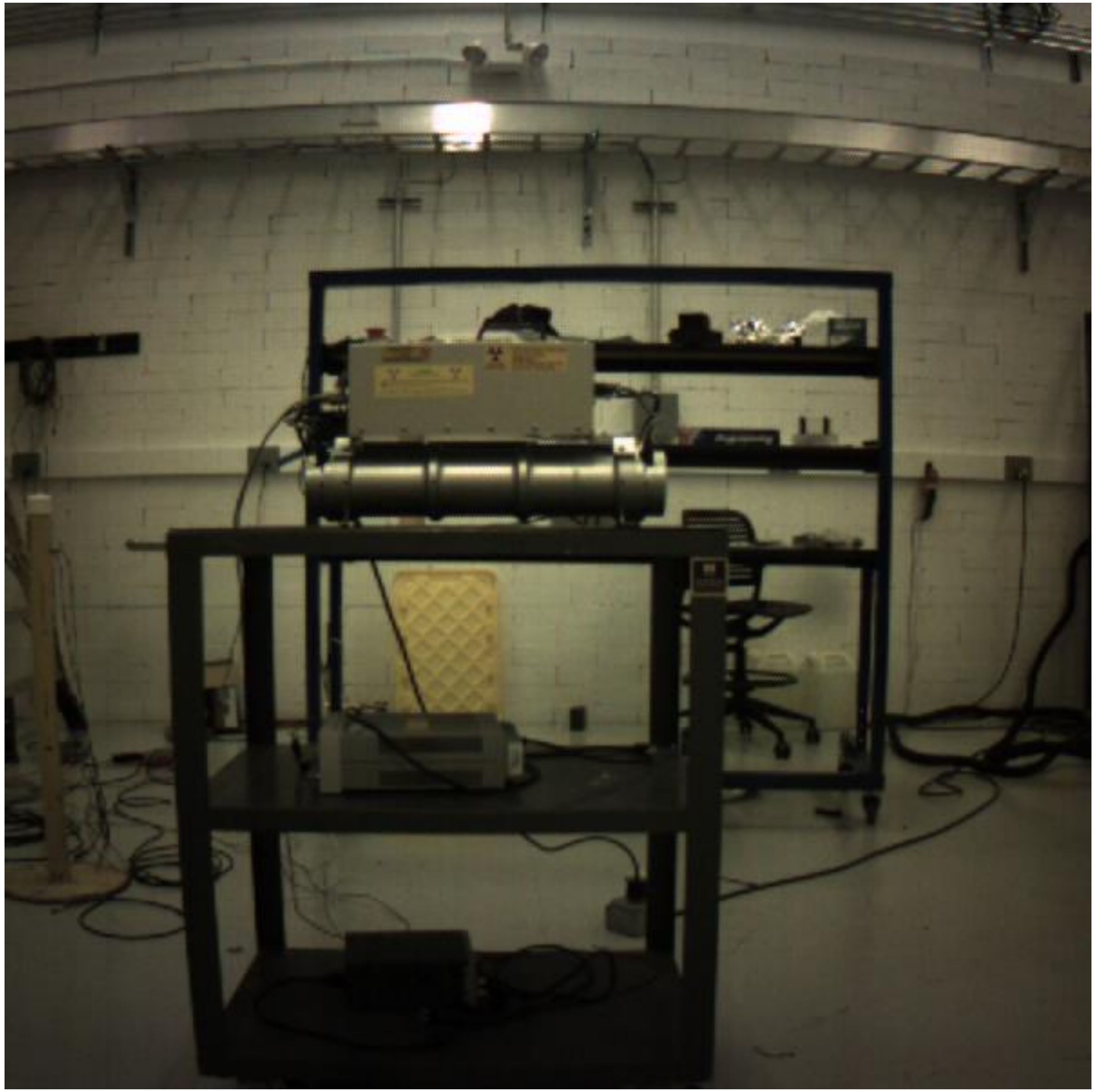
Cf-252



AmLi neutron source

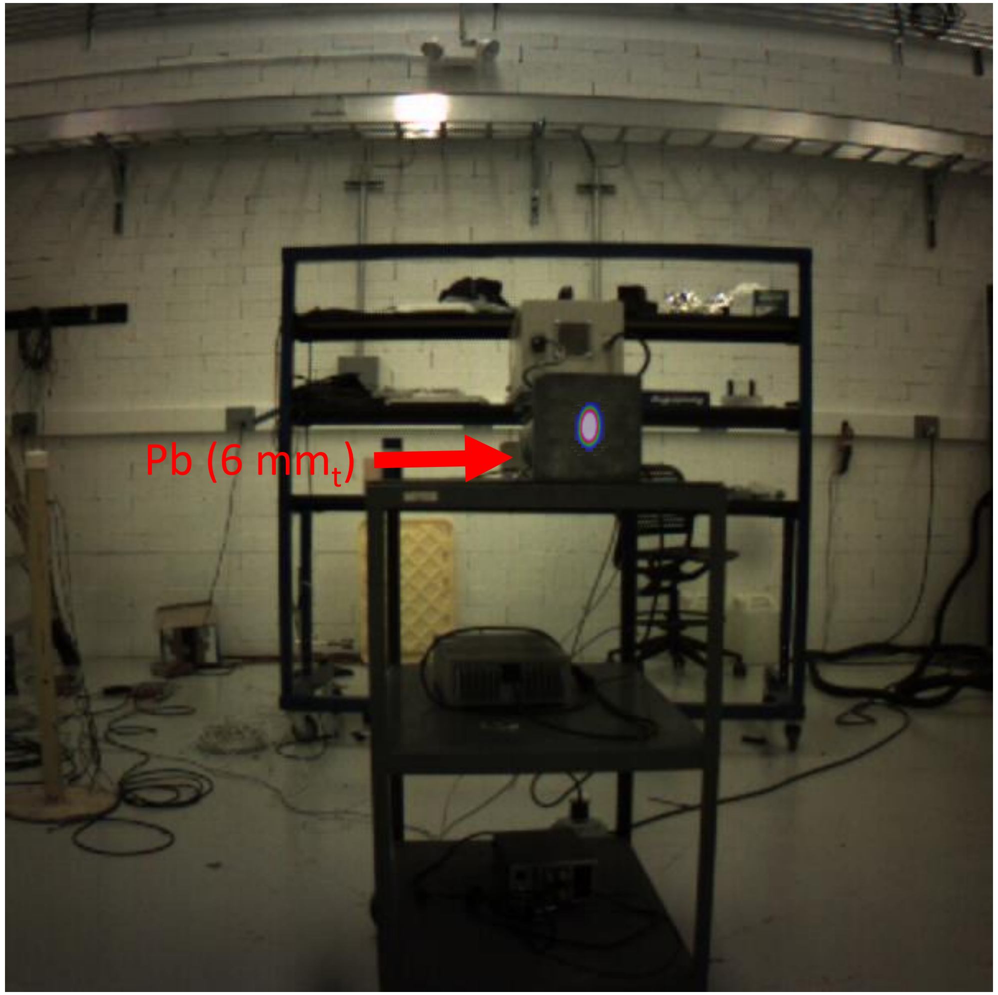


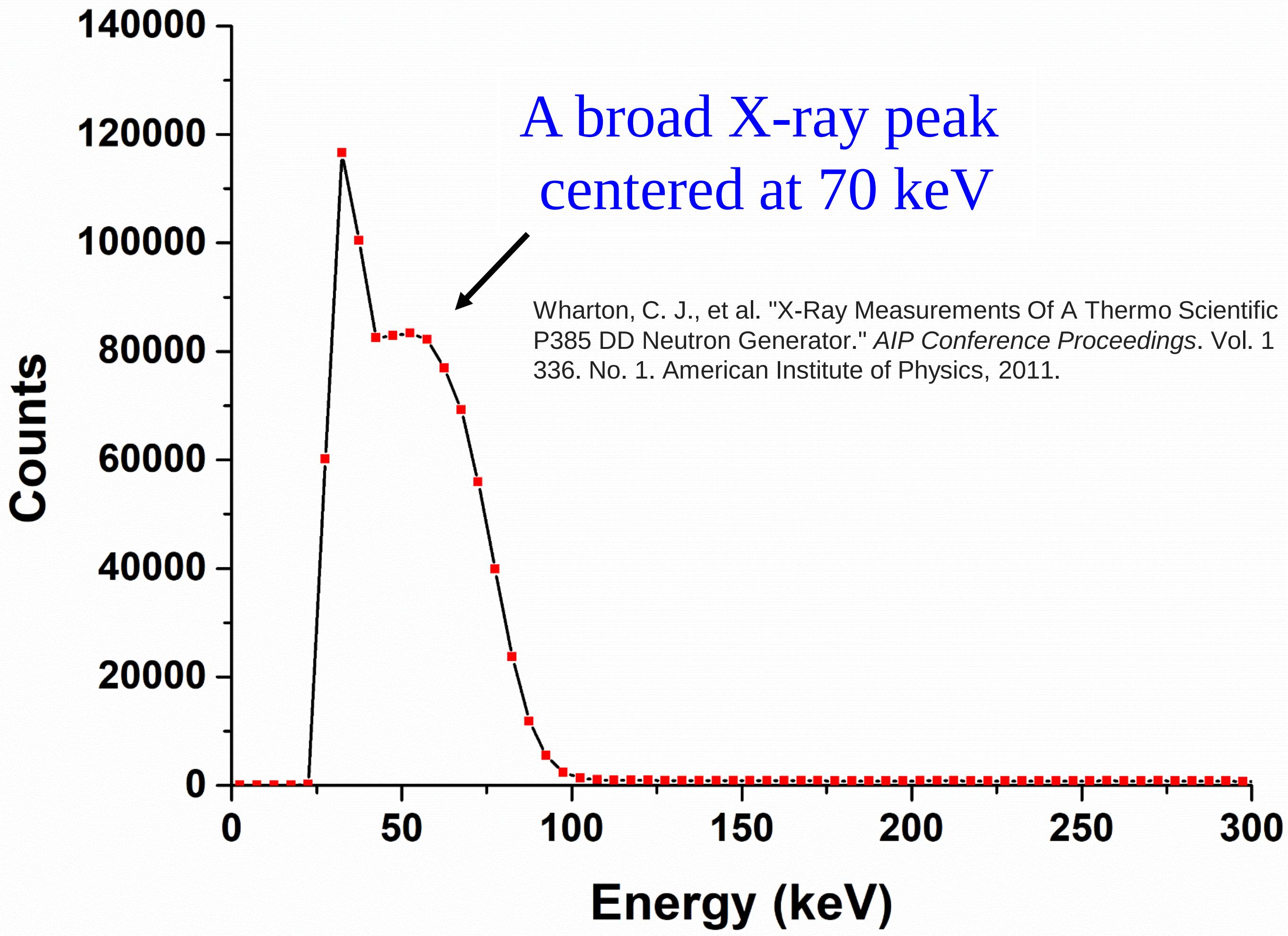
D-D neutron generator (2×10^6 n/s)



- Experiment Condition
- Source to detector distance: 2 m
- Fusion reaction: D(d, n)^{3}He (or D-D)
  (neutron energy about 2.4 MeV)

D-D neutron generator (2 ×10^6 n/s)





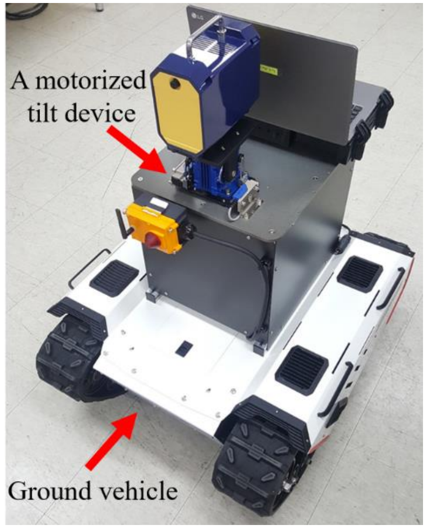
Wharton, C. J., et al. "X-Ray Measurements Of A Thermo Scientific P385 DD Neutron Generator." *AIP Conference Proceedings*. Vol. 1 336. No. 1. American Institute of Physics, 2011.

Conclusion and Future Works

- **Gamma-ray detection in mixed gamma/neutron environments**
  - ✓ Can provide a radionuclide distribution map in mixed gamma/neutron environments
  - ✓ Can maintain the gamma spectroscopy

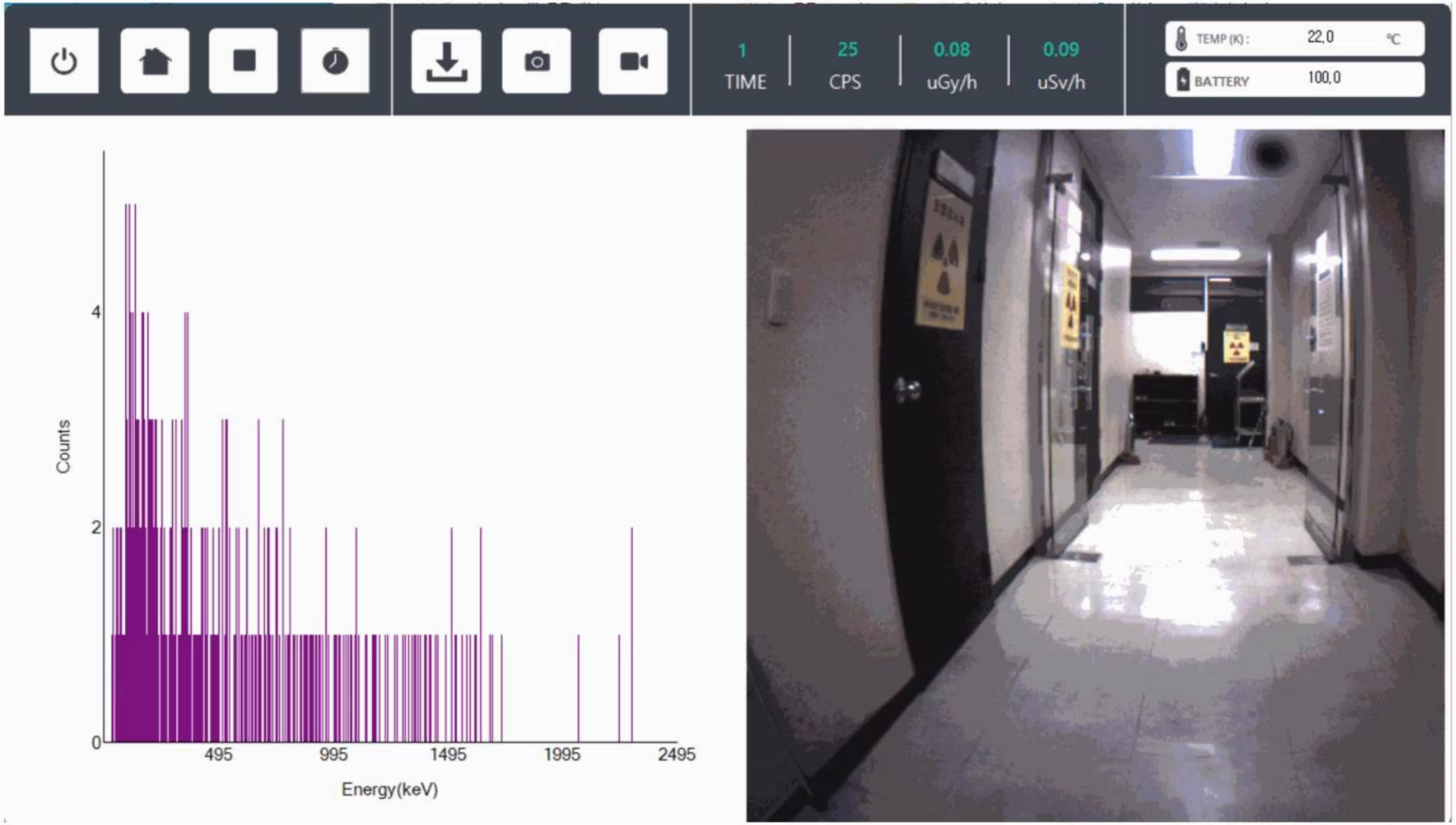
- **Future works**
  - ✓ Application of an unmanned robotic system with Epsilon-G in an area monitoring
  - ✓ Utilization of a Epsilon-D to verify the presence of gamma/neutron sources

Gamma-ray Source Detection with Coded-aperture Gamma Imager in a Complex Gamma-ray/Neutron Environment for Nuclear Safeguard



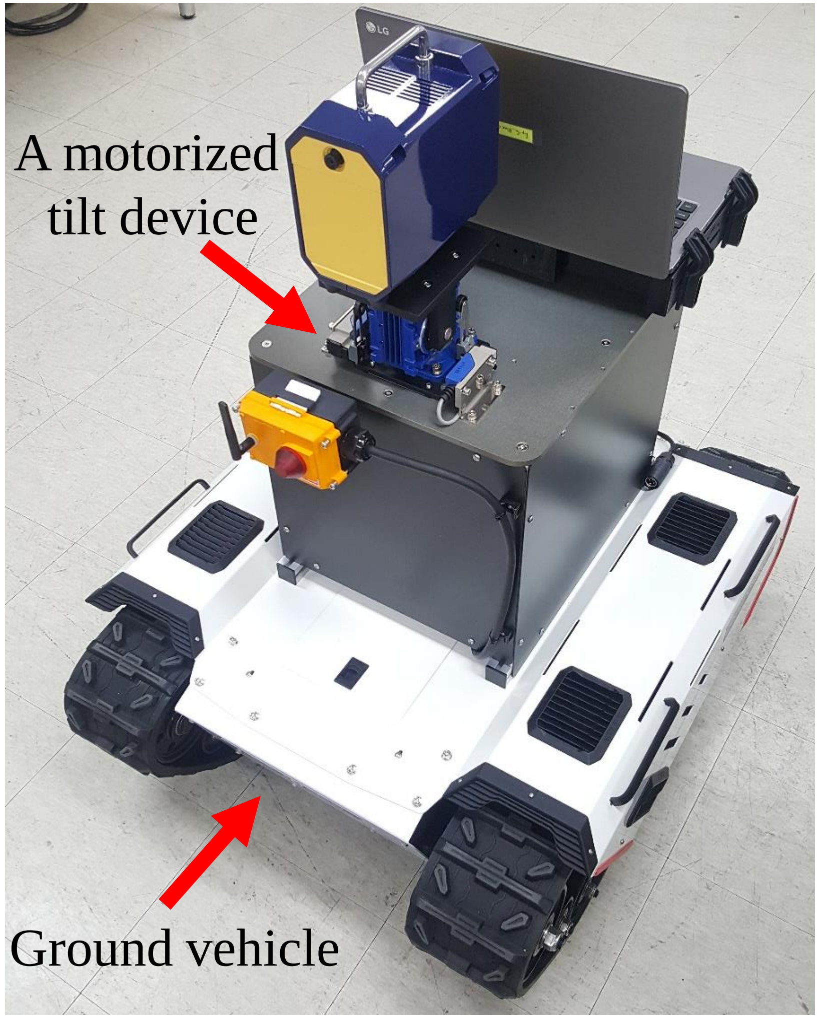
Thank you for your attention!

Application of Epsilon-G



Application of Epsilon-G

Illustration of use examples of an unmanned ground vehicle



Specification

Dimensions (W x H x D)	1023 mm × 780 mm × 900 mm
Vehicle Weight	130 kg
Battery	48V/30Ah
Max Travel (w/o loading)	10 km
Climbing Capacity	36° Can Climb Stairs
Horizontal Rotation Capacity	360°
Vertical Tilt Capacity of a Motor	± 30°