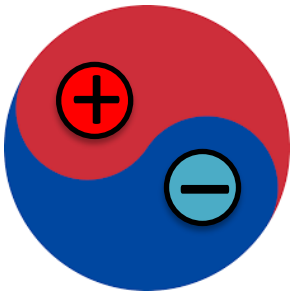
Fabrication and Data Acquisition of the KAPAE Phase II Detector for Investigating Invisible Decay in Positronium Annihilation



Dongwoo Jeong, Hongjoo Kim*, Hyeoung Woo Park

Kyungpook National University

ICHEP 2024, Prague

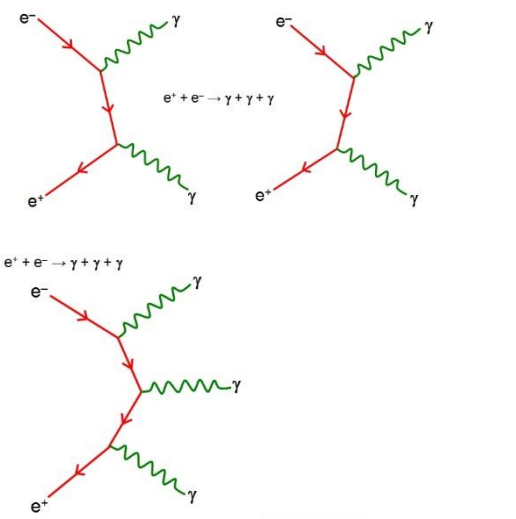
17 –24 July, 2024

KYUNGPOOK NATIONAL UNIVERSITY

Introduction

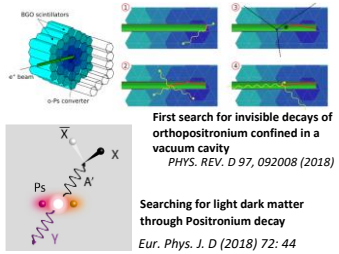
KAPAE

- KNU Advanced Positronium Annihilation Experiment (KAPAE)



Electron-Positron Pair

Physics



First search for invisible decays of orthopositronium confined in a vacuum cavity
PHYS. REV. D 97, 092008 (2018)

Searching for light dark matter through Positronium decay
Eur. Phys. J. D (2018) 72: 44

- Rare decay, QED verification
- New particle searches

Application

- **P**ositron **E**mission **T**omography (PET)

Introduction : Positronium annhilation

Positronium

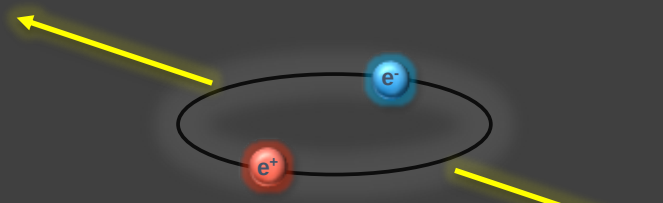
- Unstable hydrogen-like atoms ($M_p \longrightarrow m_{e^+}$)
- The spin state of Ps can be calculated using the hydrogen atomic model
- Positronium (Ps)

  - Singlet spin state (para-Positronium, p-Ps) : Lifetime = 125 ps

  - Triplet spin state (ortho-Positronium, o-Ps) : Lifetime = $142 \pm 0.02\ ns$

Singlet Spin State (p-Ps)

$[s = 0]$ $|0,0>=\frac{1}{\sqrt{2}}(\uparrow\downarrow-\downarrow\uparrow)$

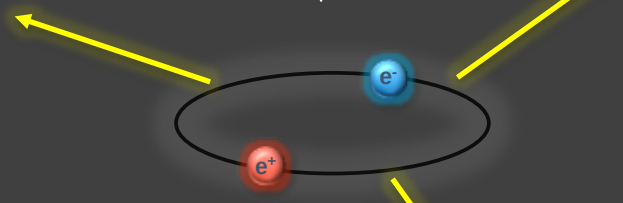


γ Energies = 511 keV

Triplet Spin State (o-Ps)

$[s = 1]$ $|1,1>=\uparrow\uparrow$, $|1,-1>=\downarrow\downarrow$

$|1,0>=\frac{1}{\sqrt{2}}(\uparrow\downarrow+\downarrow\uparrow)$



γ Energies < 511 keV

Introduction : KAPAE-II Physics

New Particle Searches

- Totally Invisible Exotic Decay (Mirror world, Extra dimensions, Mili-charged Particle, etc)

Milli-charged particles

- The grand unified theory (GUT) model
- Electric charge particles (”shadow” photon <<<< e^-)

$$\Gamma(o\text{–}Ps \rightarrow X\bar{X}) = \frac{\alpha^5 Q_X^2 m_e}{6} \cdot k \cdot F\left(\frac{m_X^2}{m_e^2}\right)$$

Extra dimensions

- k > 2.7 TeV

$$\mathrm{o}\text{–}Ps \rightarrow \gamma^* \rightarrow \text{additional dimension(s)}$$

$$\mathrm{Br} = \frac{9\pi}{4(\pi^2-9)} \cdot \frac{1}{\alpha^2} \cdot \frac{\pi}{16} \left(\frac{m_0 - Ps}{k}\right)^2 \approx 3 \times 10^4 \left(\frac{m_0 - Ps}{k}\right)^2$$

Mirror world

- The mirror universe model
- Vibration of o-Ps and mirror o-Ps

$$\mathrm{Br}(\mathrm{o}\text{–}Ps \rightarrow \text{ invisible}) = \frac{2(2\pi\varepsilon f)^2}{\Gamma^2 + 4(2\pi\varepsilon f)^2}$$

3×10^{-5} at 90% C.L.

A.Badertsher et. al,
PRL 124 101803 (2020)

Searching for Ps-> Invisible : 2×10^{-8}

A.Badertsher et. al,
PHYS. REV. D 95, 032004 (2007)

Introduction : KAPAE-II Physics

New Particle Searches

- Partially Invisible Exotic Decay (Axion Like Particle (ALP), Dark Photon, Dark Z, etc)

Axion Like Particle

PDG 2024: Best limit : ~10^{-4} - 10^{-6}

A^0 (Axion) Searches in Positronium Decays

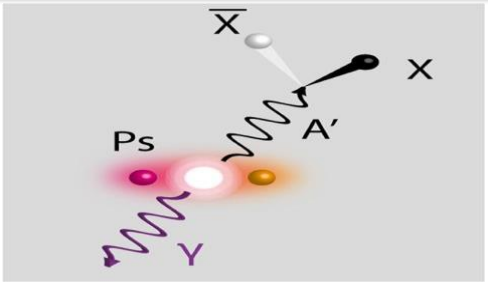
Decay or transition of positronium. Limits are for branching ratio.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4\times10^{-5}$	90	[1] BADERT...	02	CNTR	o-Ps → $\gamma X_1 X_2$, $m_{X_1}+m_{X_2} \leq$ 900 keV
$<2\times10^{-4}$	90	MAENO	95	CNTR	o-Ps → $A^0\gamma$ m_{A^0}=850–1013 keV
$<3.0\times10^{-4}$	90	[2] ASAI	94	CNTR	o-Ps → $A^0\gamma$ m_{A^0}=30–500 keV
$<2.8\times10^{-5}$	90	[3] AKOPYAN	91	CNTR	o-Ps → $A^0\gamma$ ($A^0 \to \gamma\gamma$), m_{A^0} < 30 keV
$<1.1\times10^{-6}$	90	[4] ASAI	91	CNTR	o-Ps → $A^0\gamma$, m_{A^0} < 800 keV
$<3.8\times10^{-4}$	90	GNINENKO	90	CNTR	o-Ps → $A^0\gamma$, m_{A^0} < 30 keV
$<(1–5)\times10^{-4}$	95	[5] TSUCHIAKI	90	CNTR	o-Ps → $A^0\gamma$, m_{A^0} = 300–900 keV
$<6.4\times10^{-5}$	90	[6] ORITO	89	CNTR	o-Ps → $A^0\gamma$, m_{A^0} < 30 keV
		[7] AMALDI	85	CNTR	Ortho-positronium
		[8] CARBONI	83	CNTR	Ortho-positronium

Dark Photon

- Light vector particle

p–Ps → γXX



J. Perez-Rıos, S. T. Love Eur. Phys. J. D (2018) 72: 44

Dark Z

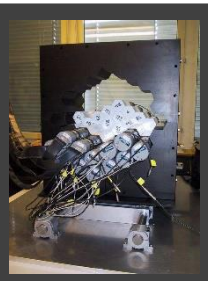
- Light vector particle

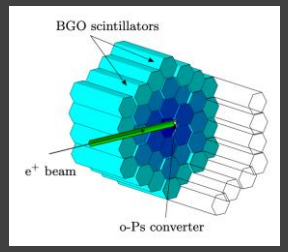
p–Ps, o–Ps → γZ

JUNG, LEE, and YU, *Phys. REV. D (2022)* 105, 095023

Introduction : Positronium experiments

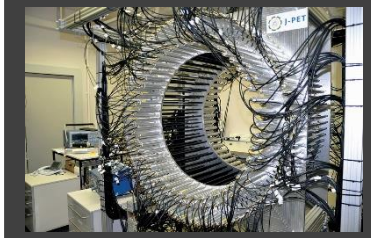
Positronium Experiments





- Invisible decay study
- Plastic + BGO + PMT
- o-Ps totally Invisible : 2.1×10^{-7}

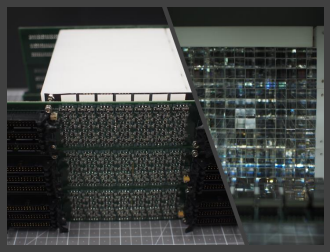
ETH Zurich (Switzerland)



- CP, CPT study
- Plastic + PMT

- Plastic + SiPM (ver. II)

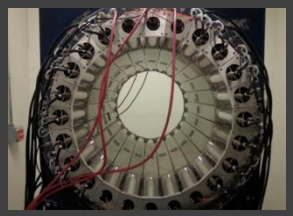
J-PET (Poland)
The Jagiellonian University



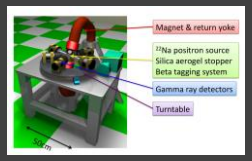
- BGO + SiPM
- Rare decay
- C, CP, CPT study
- Invisible decay search

KAPAE (Korea)
Kyungpook Nat'l Univ.

- CPT study
- NaI + PMT



APEX (U.S.A.)
Triangle Universities Nuclear Laboratory



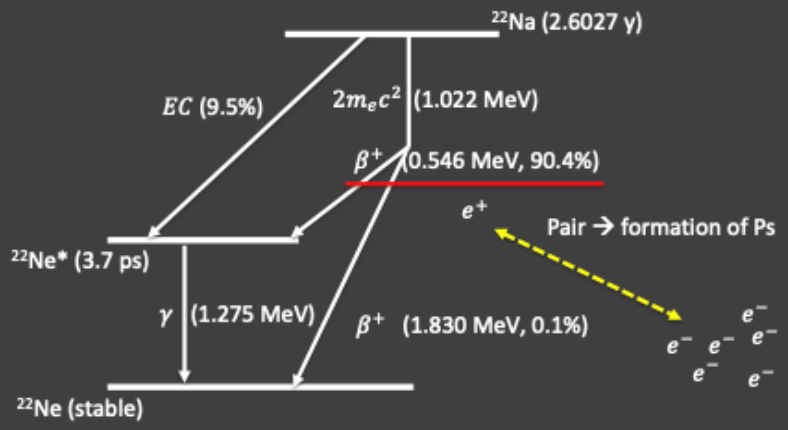
- CP & CPT study
- Plastic + NaI + PMT

ICEPP (Japan)
Univ. of Tokyo

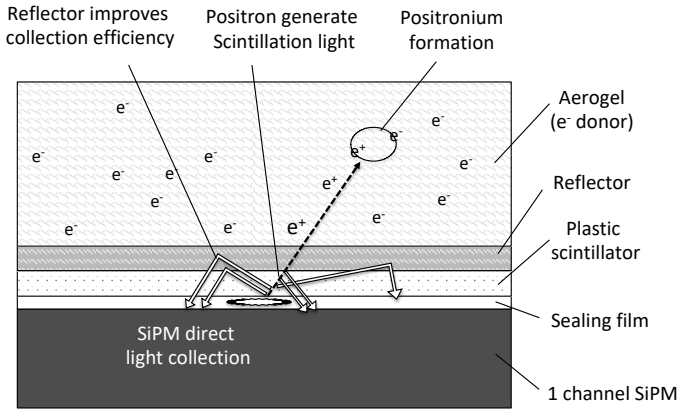
KAPAE new trigger concept

The concept of trigger for KAPAE

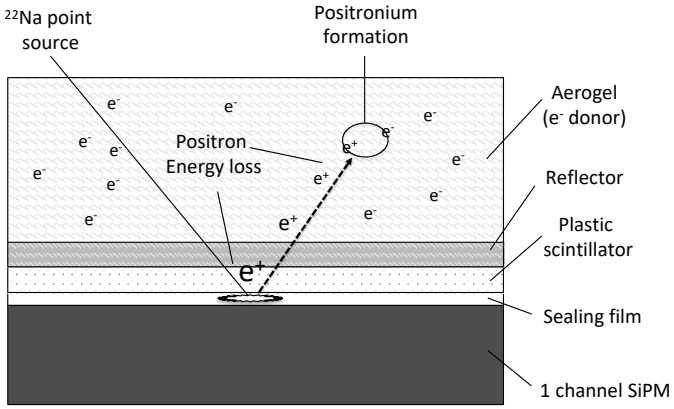
- Positronium = Electron + Positron
  - Positron → β^+ decay (^{22}Na)
  - Electron → aerogel
- Trigger signal
  → Plastic scintillator (PS)



Generation of trigger signal



Positronium formation in aerogel



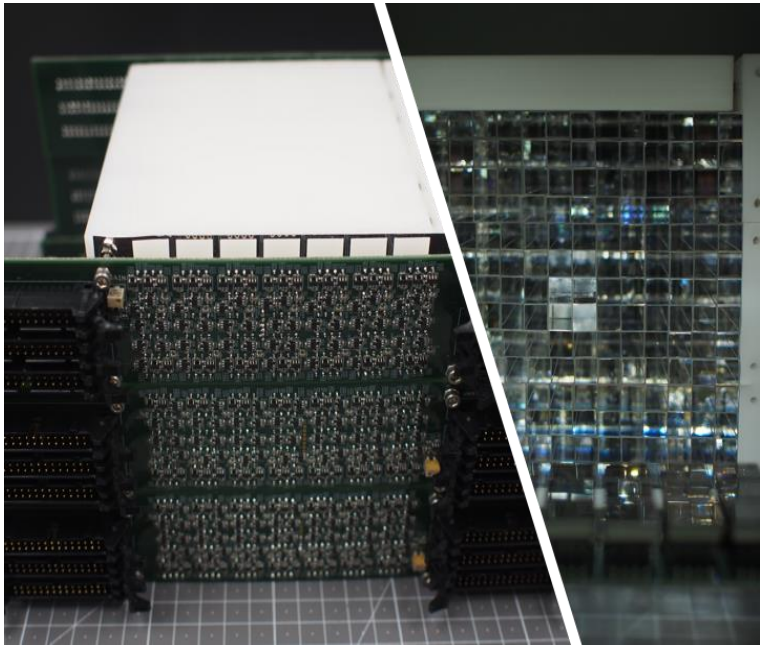
Trigger signal : PS + 1.275 MeV coincidence trigger

Concept of KAPAE-II Detector

KAPAE-II

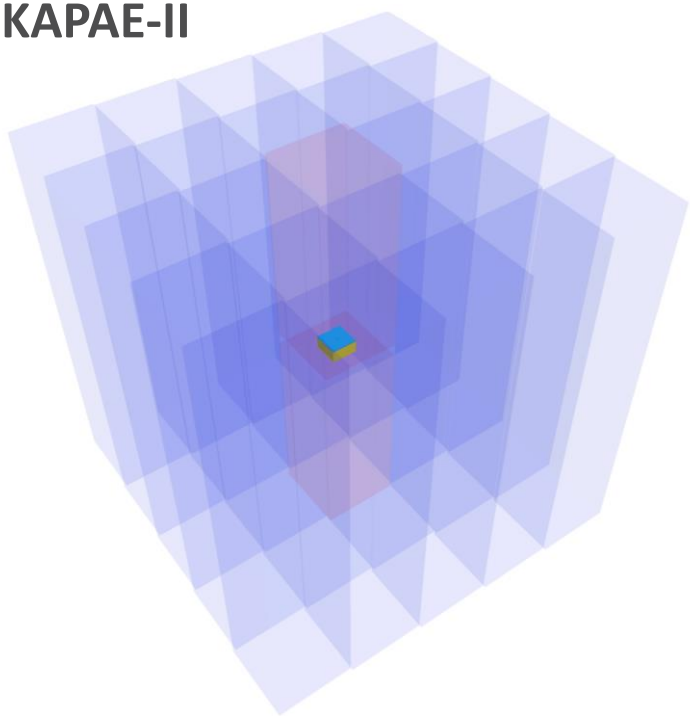
- Goal : Improvement of sensitivity of Invisible decay search
- Design : Minimization of dead area, thicker BGO system and minimize dead material of the trigger
- Sensitivity : KAPAE phase II → **3×10^{-9} at 90% CL**

KAPAE-I



0.75x0.75x15cm, 14x14 Array : 10.5x10.5 cm

KAPAE-II

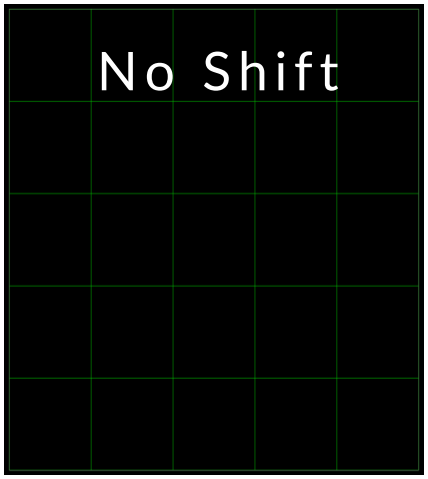


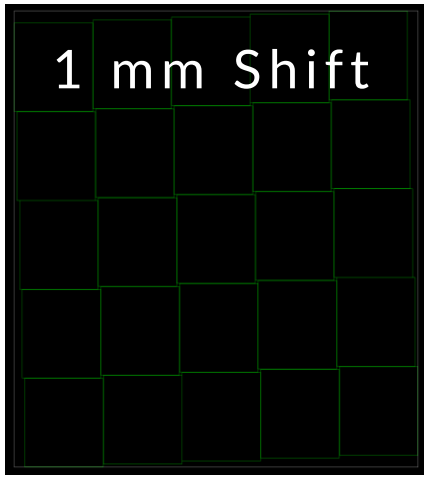
3x3x15cm, 5x5 Array : 15x15 cm

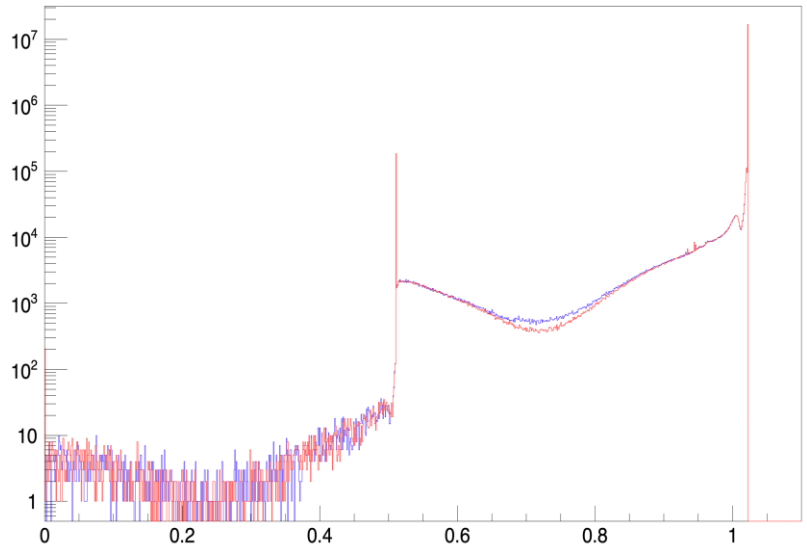
Simulation of KAPAE-II Detector

KAPAE-II

- GEANT4 with 100 million events with 2 gamma events
- The red line with no shift, the blue line with a 1 mm shift.
- With E< 60 keV, the sensitivity is 3×10^{-9} with 90% C.L.
- Maximum trigger rate: 100,000 Hz (Notice Korea KAPAE DAQ)







Optimization of KAPAE-II Detector

KAPAE-II

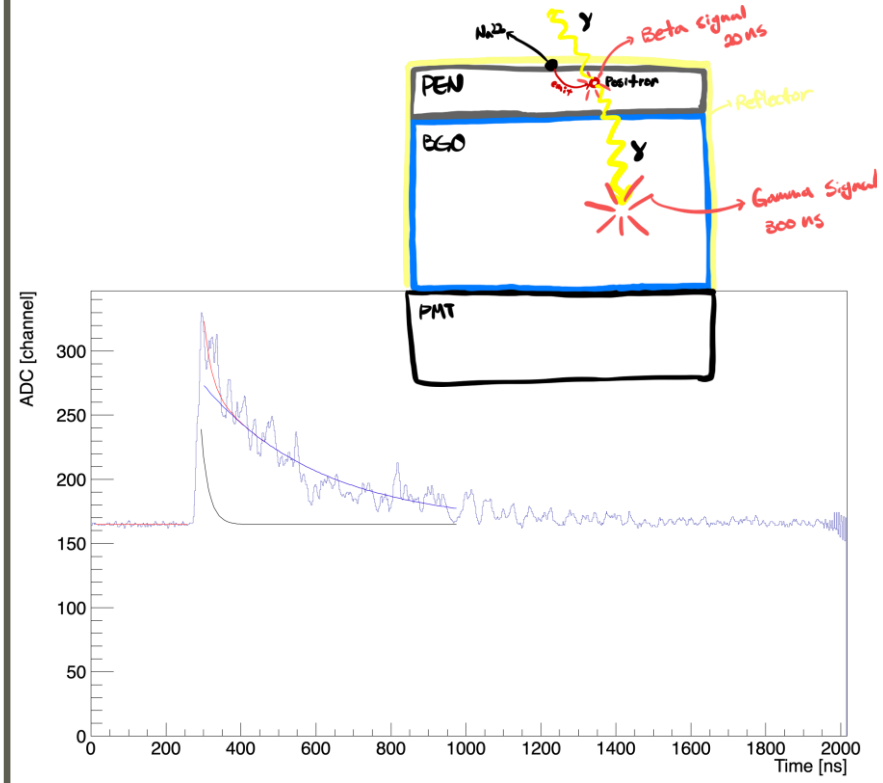
- Optimization for the KAPAE-II from KAPAE-I

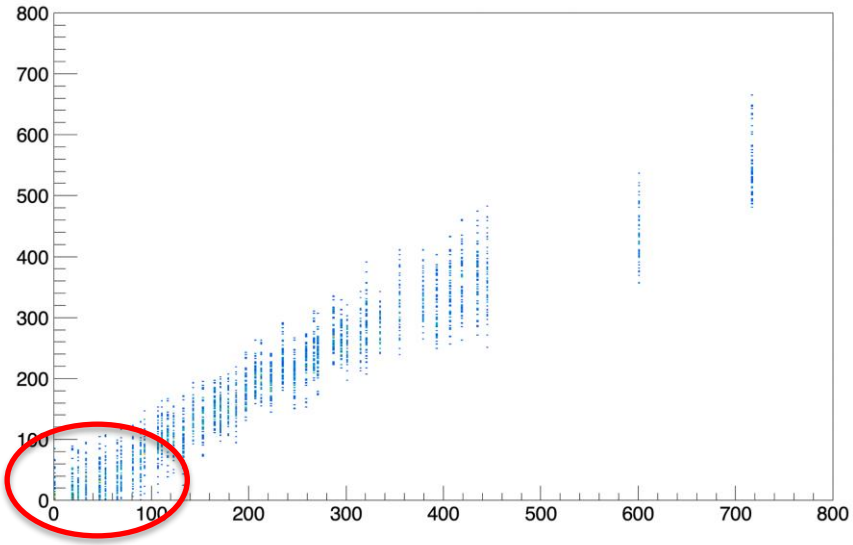
1) **Upgraded Trigger Setup : Phoswich vs SiPM without a board.**
2) **BGO surface treatment : Polishing vs Diffusing**
3) **Temperature dependence : RT vs -30 degree**
4) **Readout : Double vs Single side readout**
5) **Light sensor : 3x3 cm Metal package PMT vs 4x4 array of SiPM**

Optimization of KAPAE-II Detector

KAPAE-II

- BGO +PEN film phoswich can be used for the trigger
- Decay time of BGO is 300 ns while decay time of PEN is 18 ns
- Even if PEN energy is reconstructed good, there are still fake events that this option is abandoned.



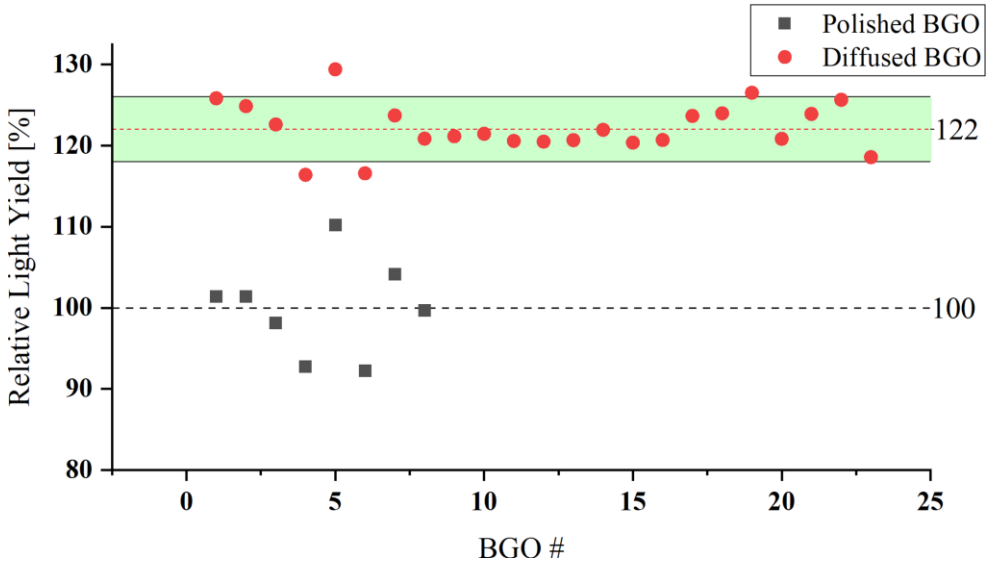


Optimization of KAPAE-II Detector

KAPAE-II

- All test crystals show 22% better light yield for the diffused BGO than polished ones.
- GEANT4 also confirm that about 20% better performance with diffused BGO
- We decide use diffused BGO for the KAPAE-II

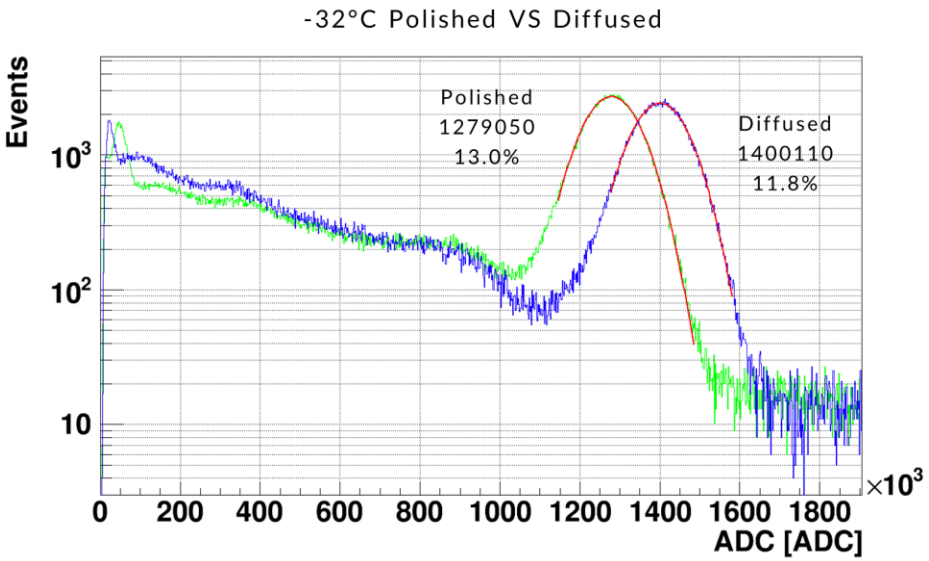
Absorption length	Light collection rate		Light improvement
[m]	Polished [%]	Diffused [%]	[%]
2	33	42	26
3	43	52	21
4	50	60	18
5	56	65	15
6	61	69	14

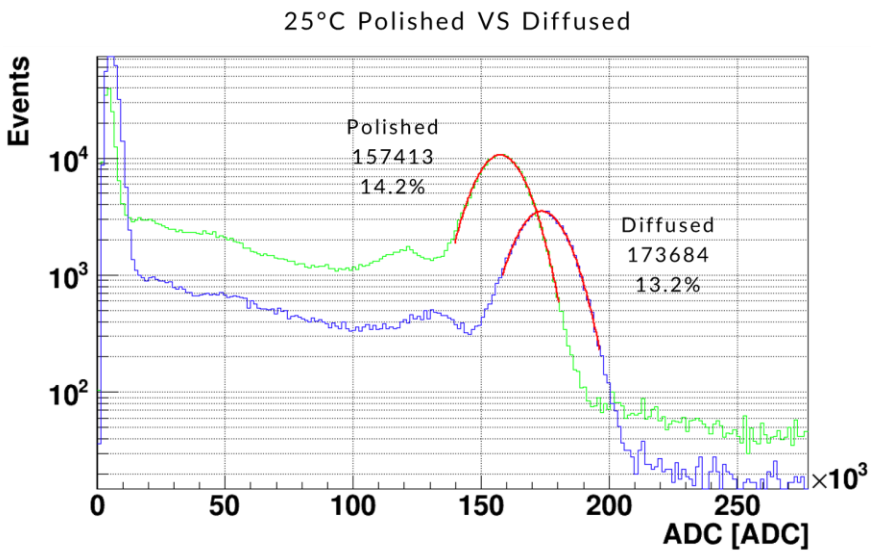


Optimization of KAPAE-II Detector

KAPAE-II

- At low temperature, the BGO light yield will be increased and SiPM noise will be decreased.
- Energy resolution of -32 deg. With diffused BGO is 11.8% while 13.2% at RT.
- We will setup our detector in the refrigerator that we can low the temperature to -30 deg.

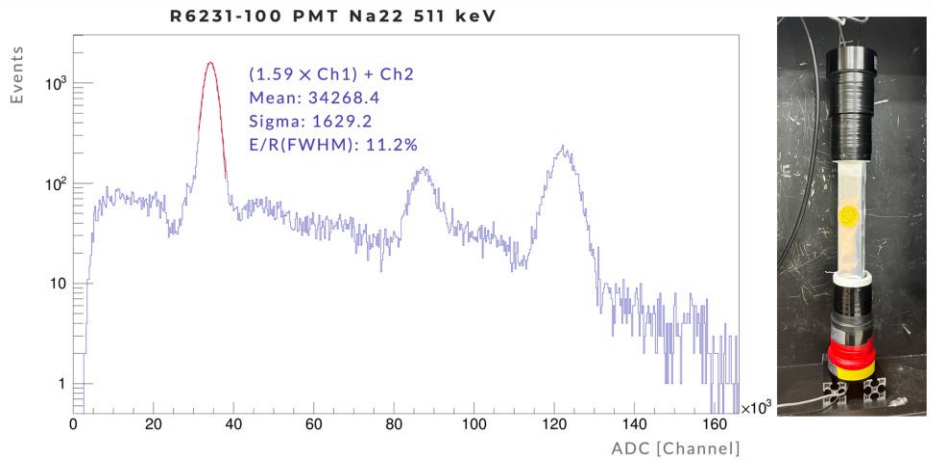


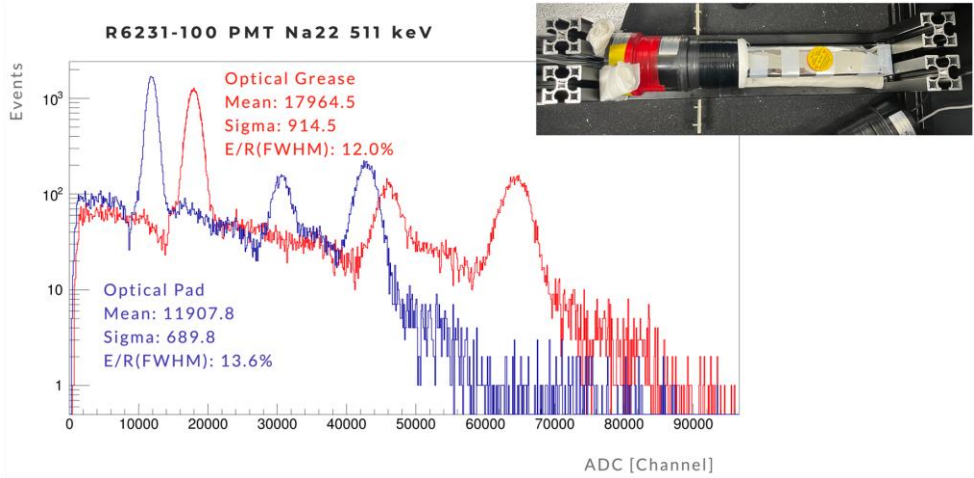


Optimization of KAPAE-II Detector

KAPAE-II

- A BGO crystal was tested with one side readout and both side readout
- Both side readout shows 11.2% energy resolution while 12% for single side readout
- We will used single side readout for the first stage and will be upgraded with both side readout.



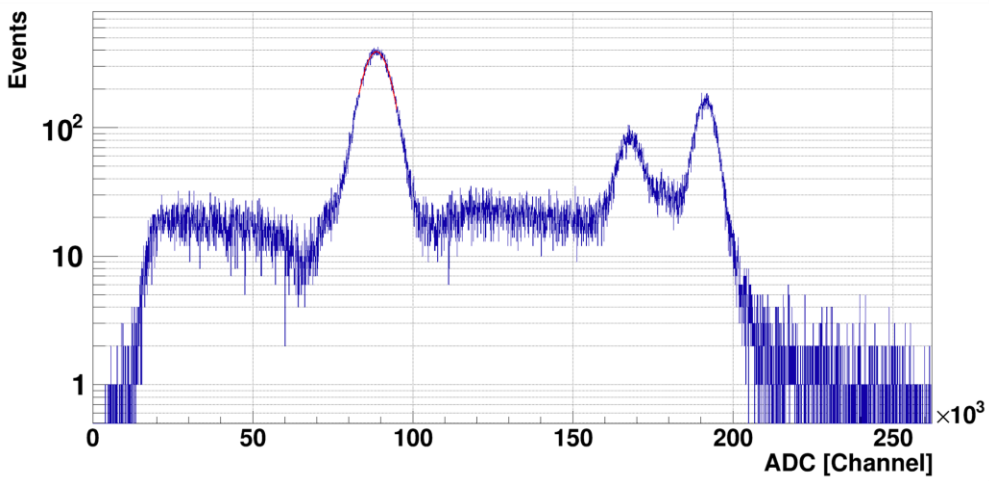


Optimization of KAPAE-II Detector

KAPAE-II

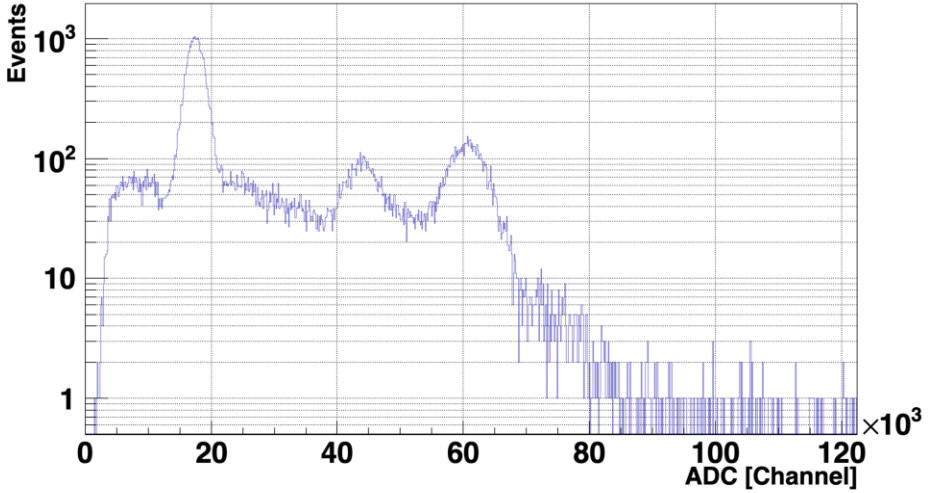
- 4x4 array of SiPM energy resolution is 11.8% while 18.2% for metal PMT.
- One of the reason for the worse energy resolution of PMT is active area of metal PMT (2x2cm)
- We will used SiPM array for the readout.

S13360-6075PE 4x4 array SiPM



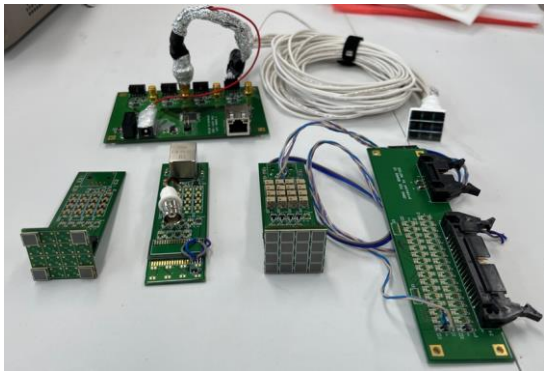
• 511 keV Energy resolution : 11.8 %

R11265U-300 PMT

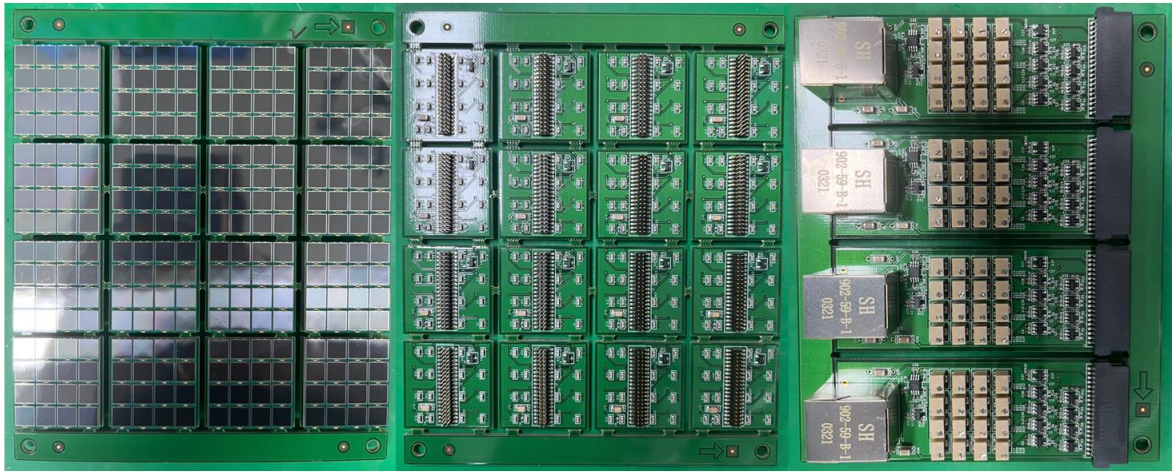


• 511 keV Energy resolution : 18.2 %

DAQ of KAPAE-II Detector



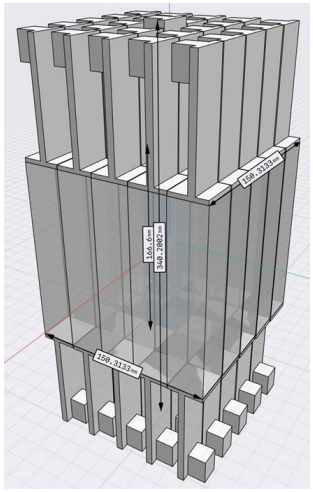
(a) (b) (c)



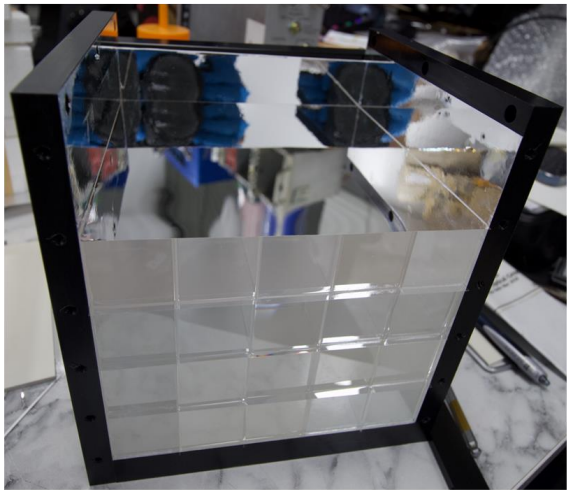
(d) (e)

Assembly of KAPAE-II Detector

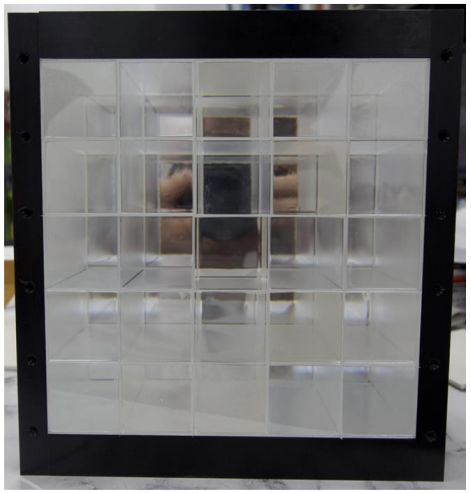
(a)



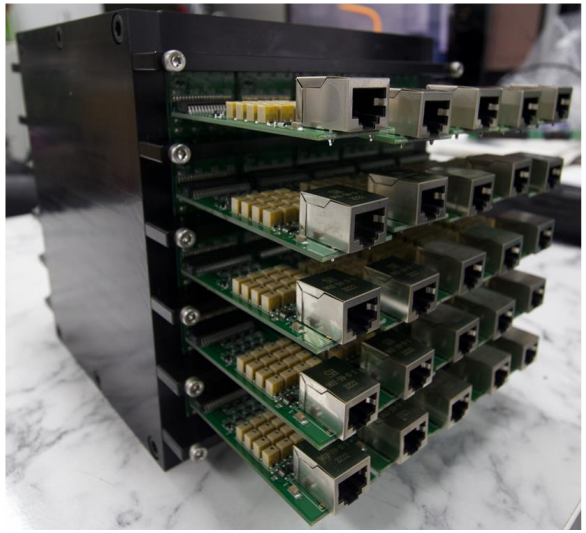
(b)



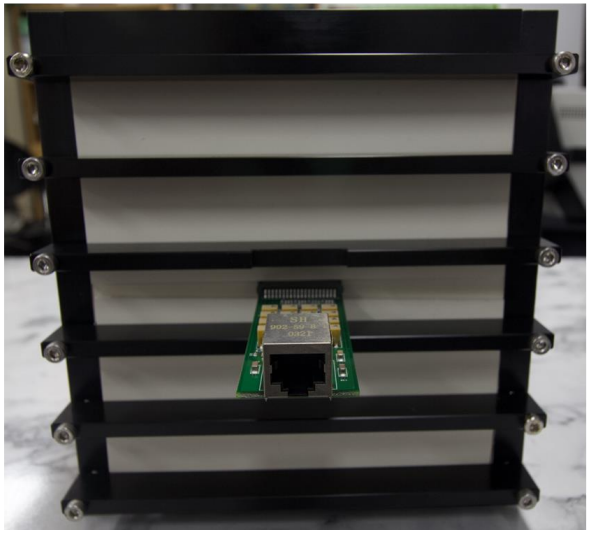
(c)



(d)



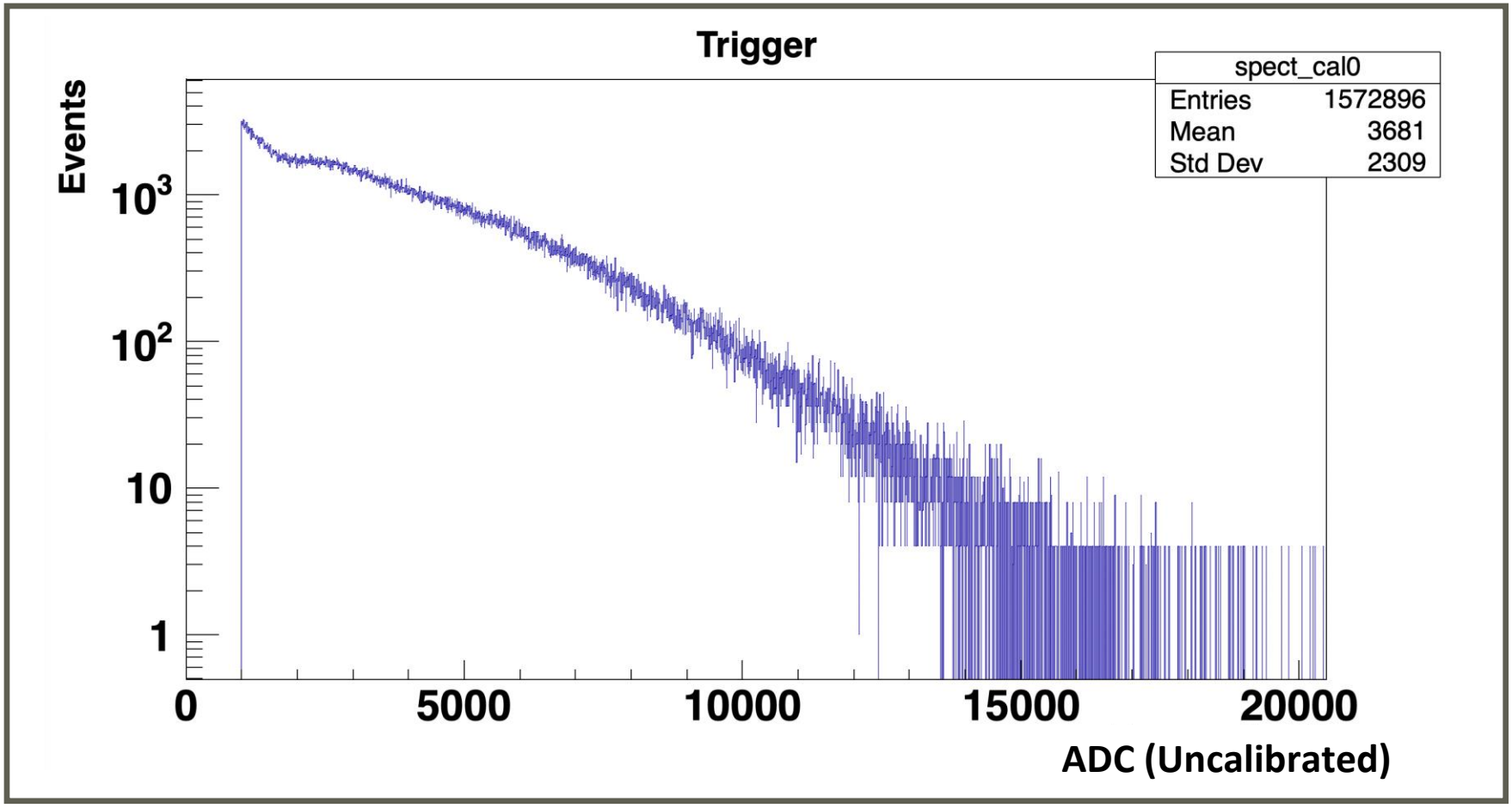
(e)



First data of KAPAE-II Detector

KAPAE-II

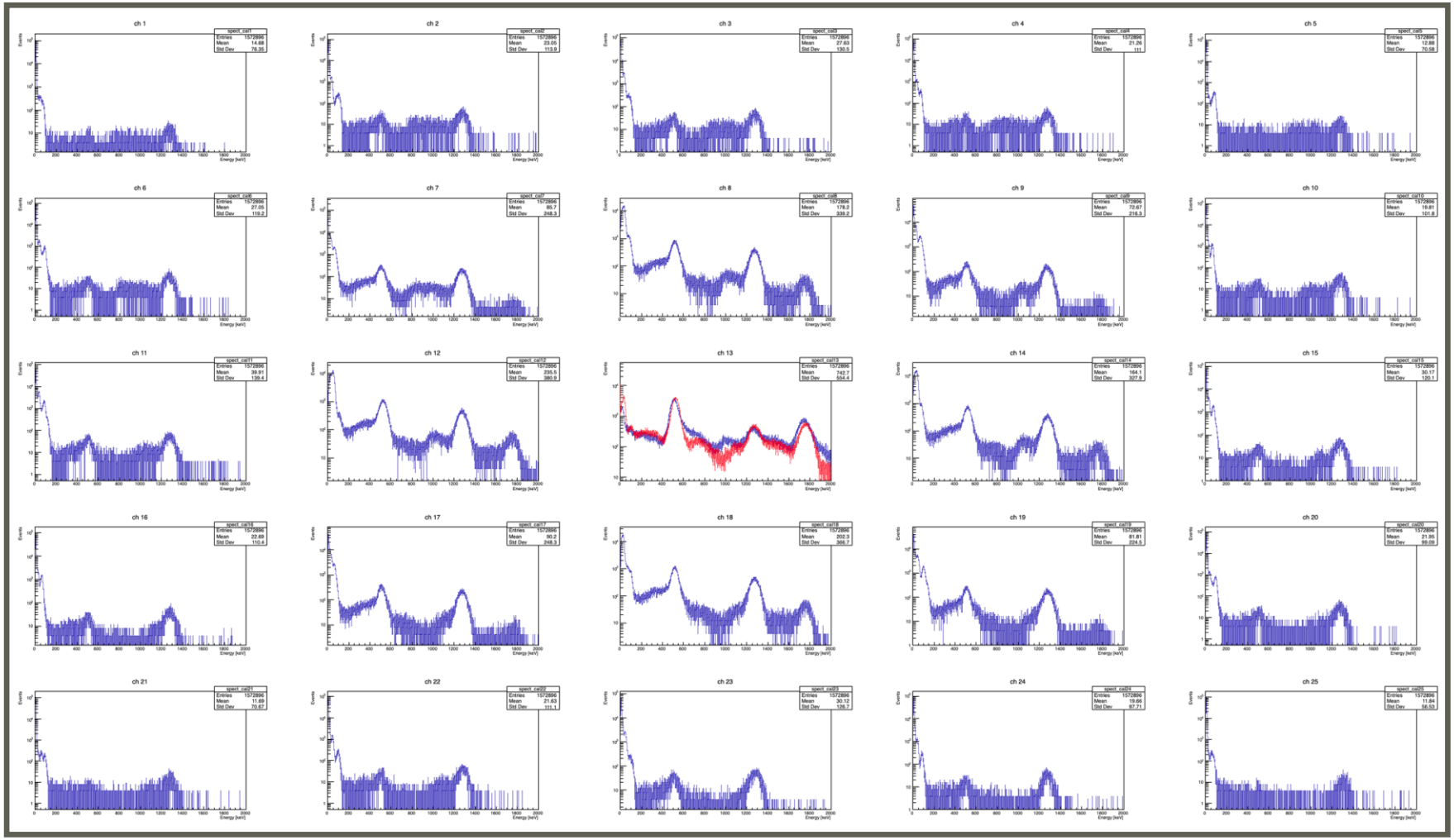
- Condition : Air, 27 degree
- Energy deposition in SiPM with PEN film by e+ energy



First data of KAPAE-II Detector

KAPAE-II

- Condition : Air, 27 ºC
- Energy distribution of 25 BGO crystals



Summary & Prospect

- **New particle searches such as mirror world, extra dimension, mili-charged particle, axion like particles, dark photon and dark Z can be performed through positronium invisible decay.**
- **KAPAE-II was constructed for the new particle searches and data taking is on-going in the Air for the p-Ps mode.**
- **In the 1st stage, dark photon search with p-Ps will be performed and the sensitivity could reach to 10^{-9} level with 3 month of data taking.**
- **KAPAE-II will be installed deep underground laboratory at Yemi underground laboratory if cosmic-ray background become a problem.**

Thank You !