Design of a Novel Compact Detector based on the BGO and SiPM for Ortho-Positronium Physics

3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

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Contents

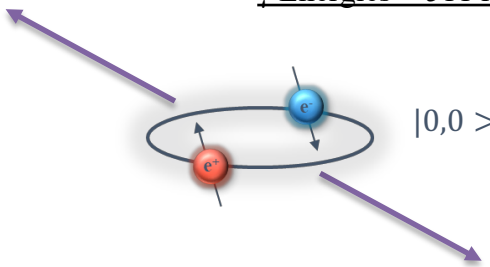
Introduction of ortho-Positronium

Introduction

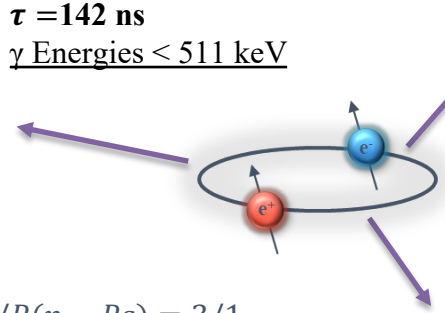
- Positronium = electron + positron system (Unstable hydrogen-like atom)
- Due to the unique properties of a particle-antiparticle system
  → Positronium is a sensitive probe
- Positronium can be divided according to spin state
  → Spin singlet state (para-positronium: p-Ps) or spin triplet state (ortho-positronium: o-Ps)

p-Ps → 2γ (, 4γ, …)
τ =125 ps
γ Energies = 511 keV

o-Ps 3γ (, 5γ, …)
τ =142 ns
γ Energies < 511 keV



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



$|1,1>=\uparrow\uparrow$

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

$|1,-1>=\downarrow\downarrow$

$P(o-Ps)/P(p-Ps)=3/1$

Spin singlet state

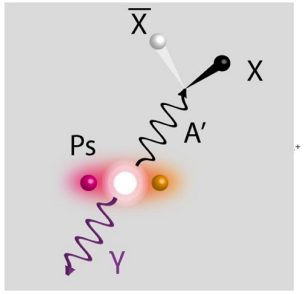
Spin triplet state

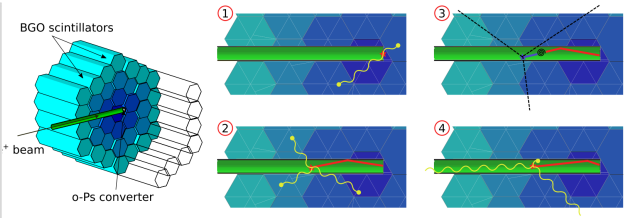
Introduction of ortho-Positronium

The Final Goal

- Positronium: C-violation & QED test & rare decay
- Invisible decay
  - → Experimentally interesting branching ratio of the order of 10^{-8}
  - → Extra-demensions
  - → Milli-Charged particles
  - → Darkmatter of a mirror particle type
  - → Axion
  - → Dark photon

Search of invisible decay





Searching for light dark matter through Positronium decay

Eur. Phys. J. D (2018) 72: 44

First search for invisible decays of orthopositronium confined in a vacuum cavity

PHYS. REV. D 97, 092008 (2018)

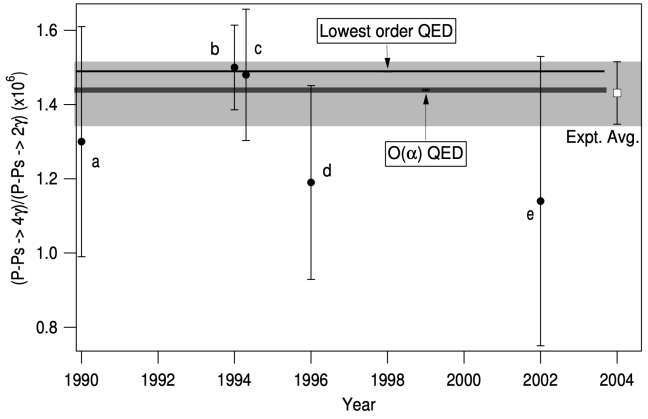
Search for C-violation

- C-violation
  - o-Ps → 4 γ search
  - o-Ps → 2 γ search

- Approximate calculation
  - 10^8 → ~10^{-7} (10^{-6}) : 10 times improvement

High order QED process Rare decay

- p-Ps → 4 γ search
- o-Ps → 5 γ search



SYMMETRY AND QED TESTS IN RARE ANNIHILATION MODES OF POSITRONIUM

Vol. 19, No. 12 (2004) 871–885

Design of a Novel Compact Detector

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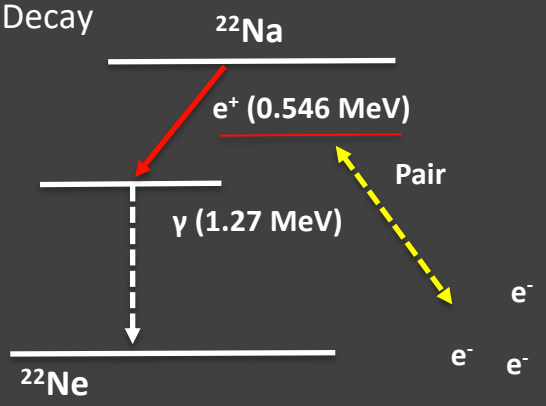
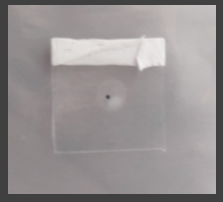
Positronium Source

β+ Decay



Customized radioactive sources

- KRISS (Korea Research Institute of Standards and Science)
- Film type
  → 1st ^{22}Na0.1 μCi
  → 2nd ^{22}Na 5 μCi



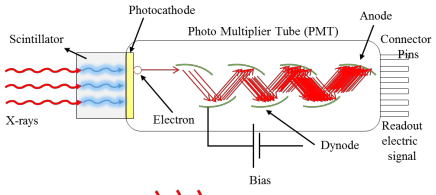
KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science

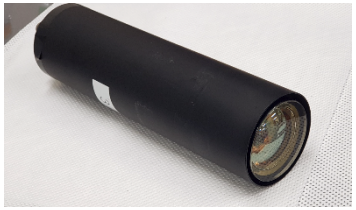
Main Elements of Detector

Photodetector

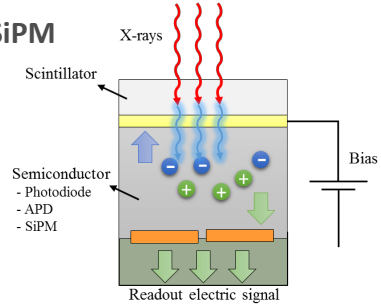
- The SiPM (silicon photomultiplier) is a photodetector replacing PMT (photomultiplier tube)
- The SiPM is Geiger mode avalanche photodiode
- high gain (~10^6) , low operating voltage (<100 V), and compact size.
- We were able to design a compact detector using SiPM

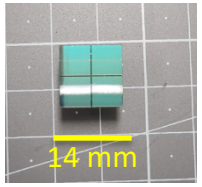
PMT

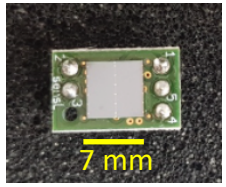




SiPM







Design of a Novel Compact Detector

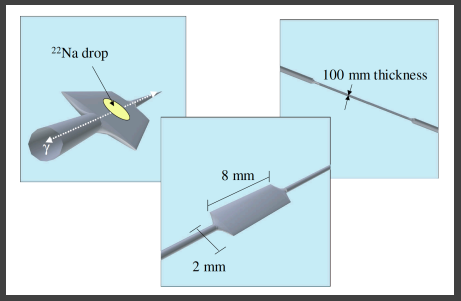
Design of Positron Trigger

- Tow major parts: Trigger part & Gamma detection part
  1) Trigger part
  - Positron passing measurement
  - o-Ps formation environment (silica aerogel and N_2 gas)

  ※ Other previous researchers used fiber triggers

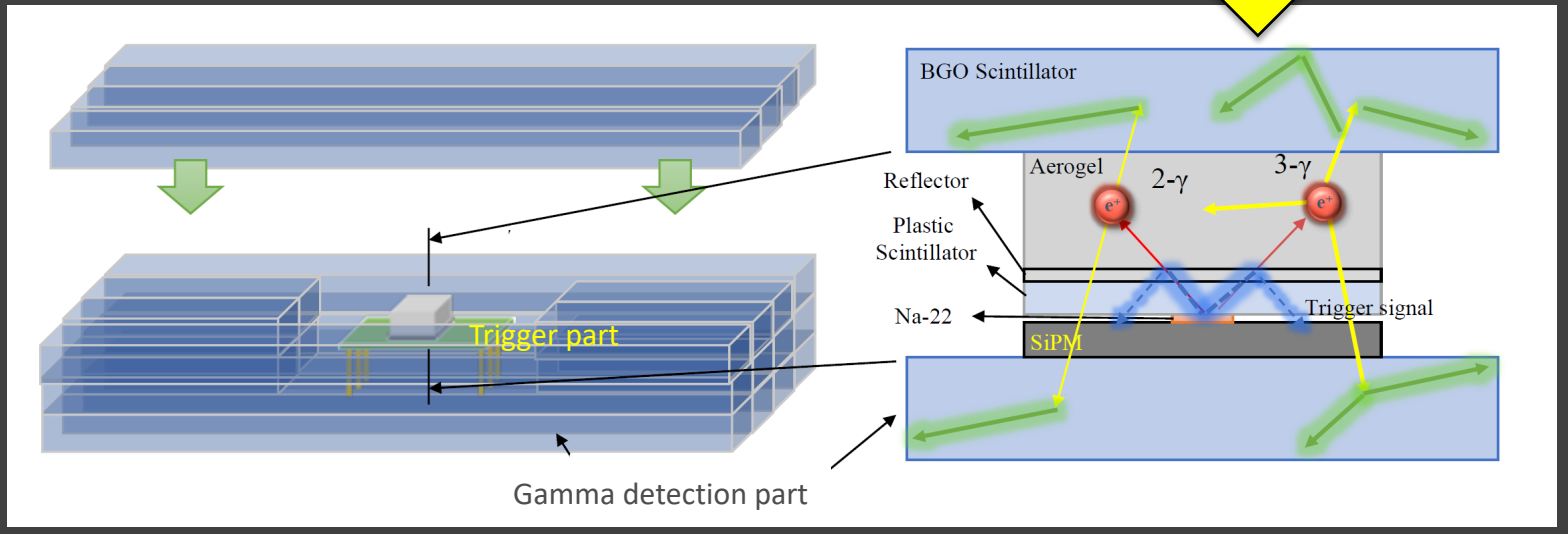
  → We improved the design by directly collecting light
  2) Gamma detection part
  - γ annihilation measurement → Consist of BGO and SiPM

New Search for Invisible Decays of Ortho–Positronium (2006)



Directly collects scintillation light → **Trigger efficiency improvement**

Schematic of ortho-Positronium detector



Design of a Novel Compact Detector

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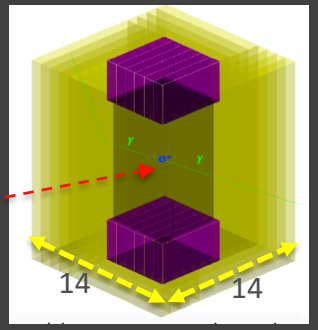
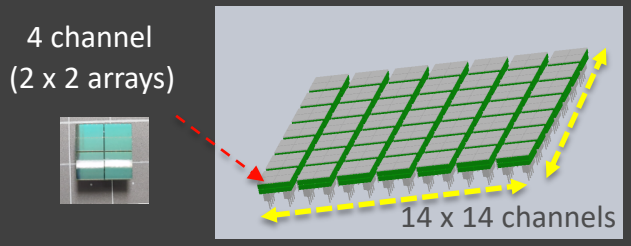
Full Design of Detector

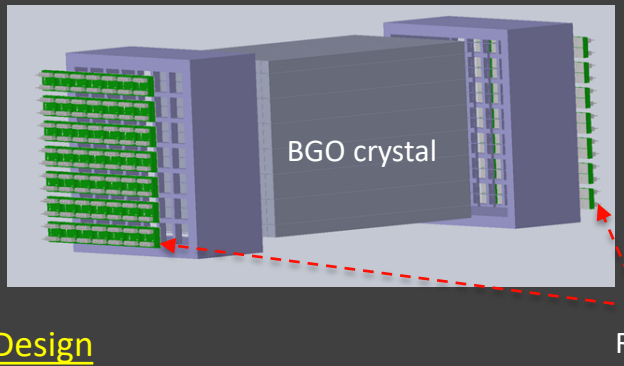
- The trigger part is surrounded by the gamma detection part with an array of 14 x 14 BGO scintillators (7.5 x 7.5 x 150 mm^3)



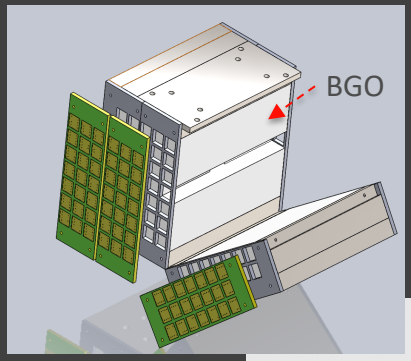
- For dual readout both sides of the BGO scintillators are coupled with 7 x 7 arrangement of 2 x 2 arrays for a total of 14 x 14 SiPMs

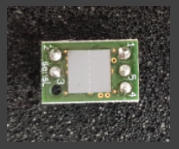


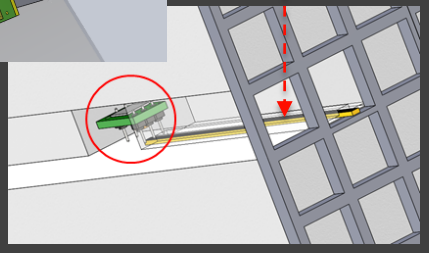
1st Design

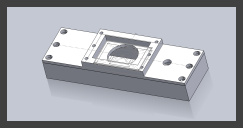


2nd Design





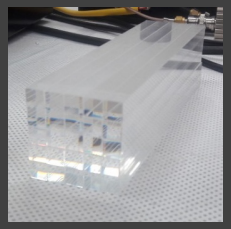




Pretest of Novel Compact Detector

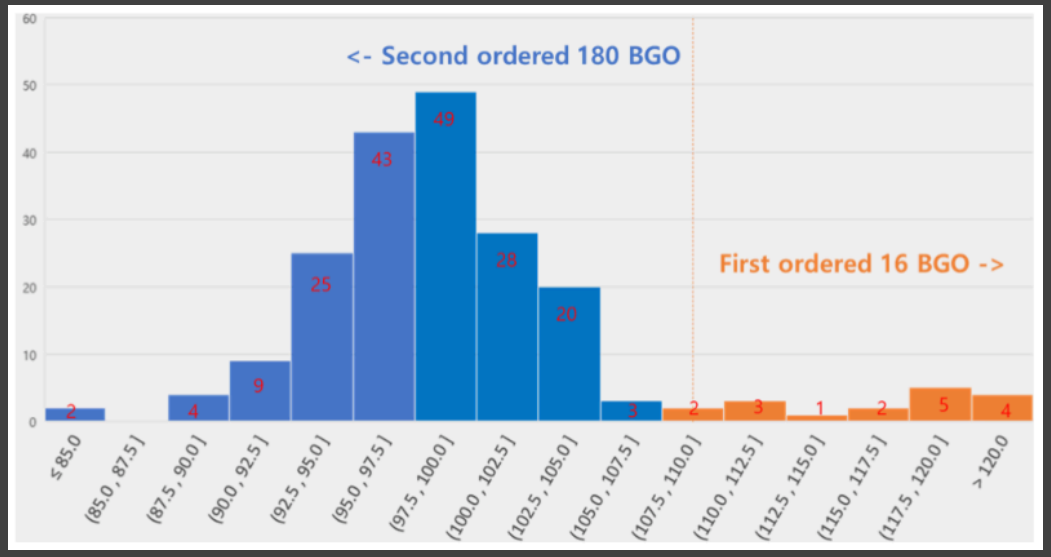
Inspection of BGO

- BGO has been customized from NIIC SB RAS
  (Nikolaev Institute of Inorganic Chemistry)
  → Inspection of 196 BGO scintillators coupled with PMT
- Radioactive source : Cs-137 (661 keV)
- To couple BGO with PMT, we designed holder

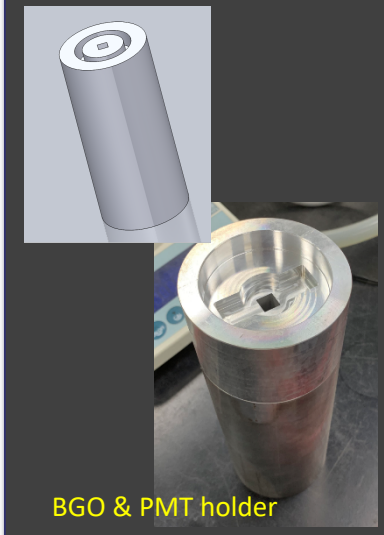


Inspection results of BGO scintillator

Light output variation



Experiment Setup



Pretest of Novel Compact Detector

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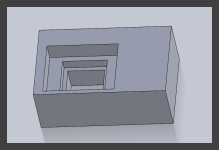
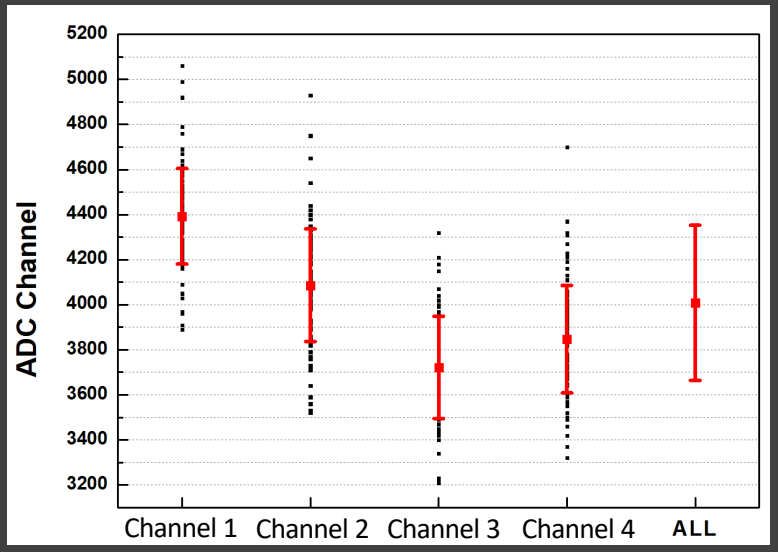
Inspection of SiPM

- Inspection of 100 SiPM coupled with small BGO scintillator
- SiPM (SensL ARRAYJ-60035-4P-PCB 22,292)
- Radioactive source : Cs-137 (661 keV)
- Operating voltage : 26 V

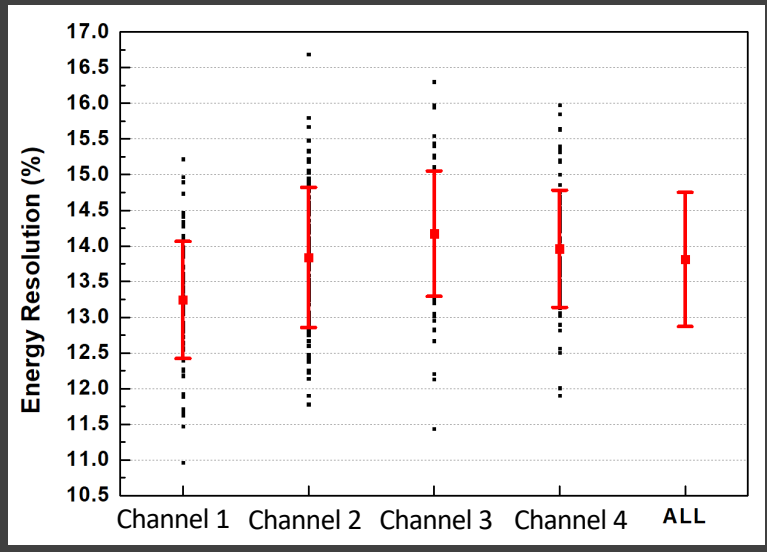


Inspection results of SiPM

Variation of light collection



Variation of energy resolution

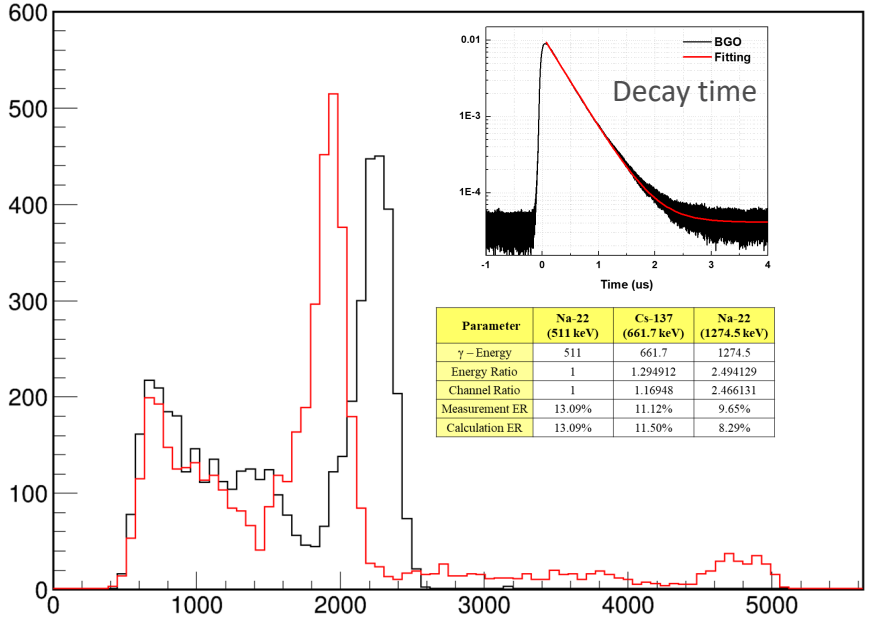


Pretest of Novel Compact Detector

Optimization of SiPM

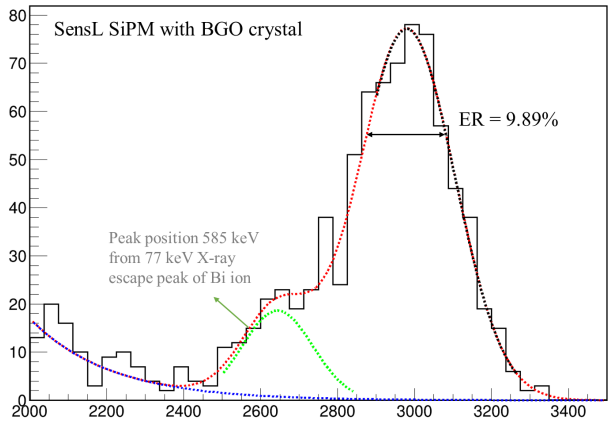
- Characterization of BGO scintillator coupled with SiPM
  → light output, energy resolution (ER), decay time
- Optimized energy resolution is 9.8% at 28 V bias
- The decay time is about 300 ns
- Light output linearity is well matched (0.511 ~ 1.27 MeV)

Source test (Cs-137: 661 keV & Na-22: 511 keV, 1.27 MeV)

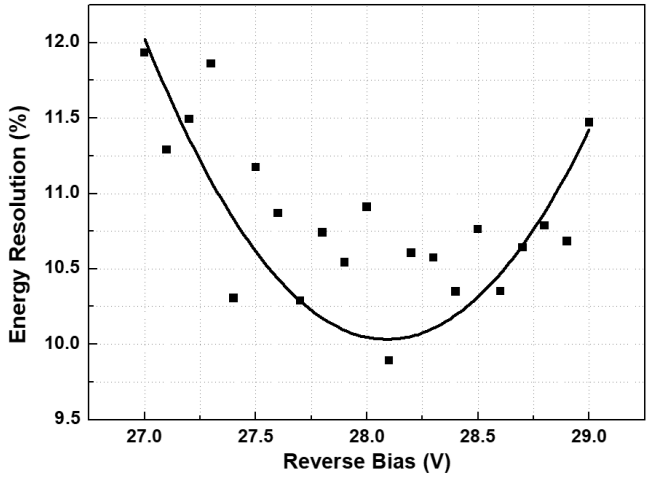


Parameter	Na-22 (511 keV)	Cs-137 (661.7 keV)	Na-22 (1274.5 keV)
γ – Energy	511	661.7	1274.5
Energy Ratio	1	1.294912	2.494129
Channel Ratio	1	1.16948	2.466131
Measurement ER	13.09%	11.12%	9.65%
Calculation ER	13.09%	11.50%	8.29%

Fitting of Cs-137 energy spectrum



Optimization of SiPM bias voltage

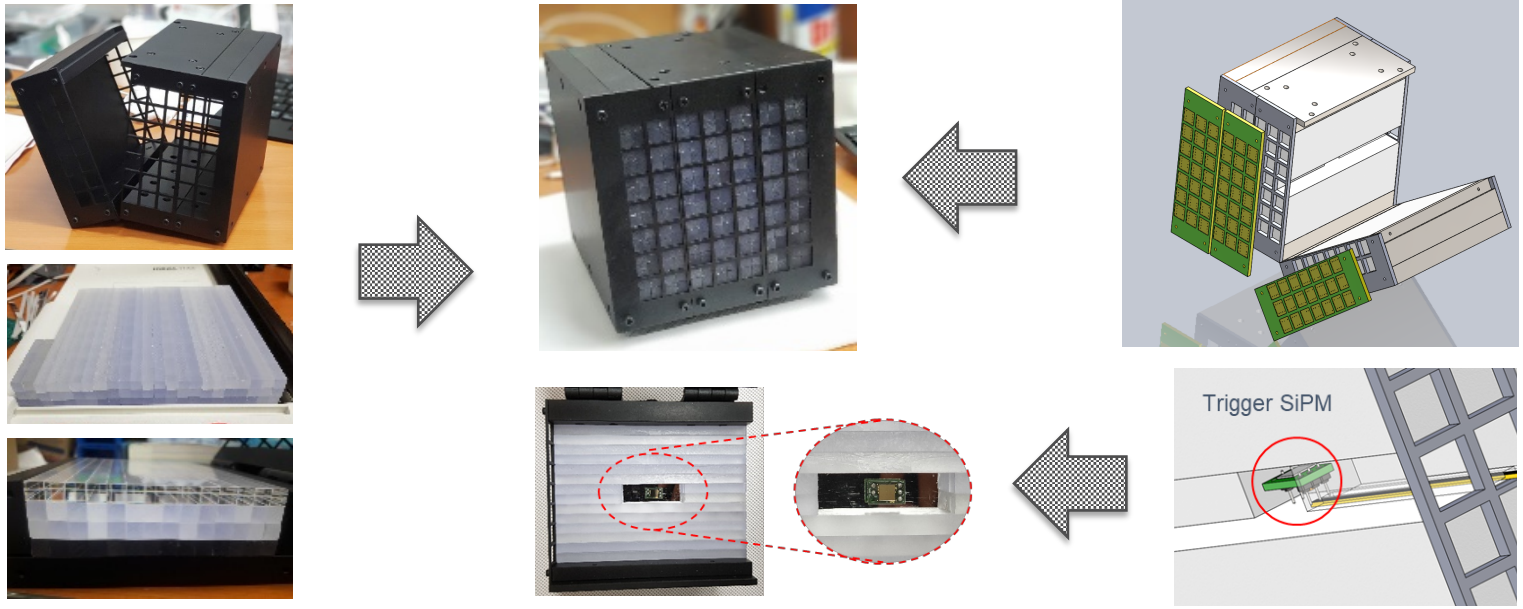


Pretest of Novel Compact Detector

Mock-up test

- Mock-up test of detector
  → Assemble test using 196 acrylic bar (7.5 x 7.5 x 150 mm^3)
- We modified design and material from mock-up results
  → add trigger chamber & Replacement of aluminum material with PP material

Mock-up

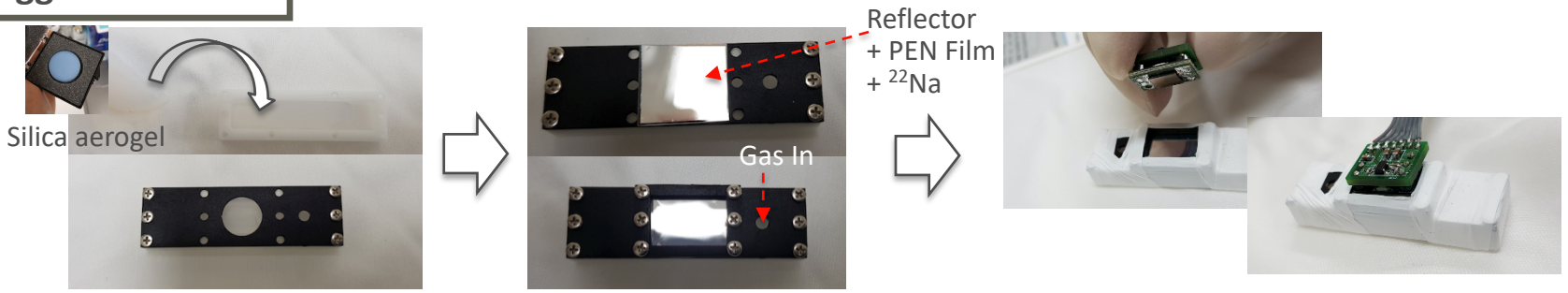


Partial Assembly Results

Partial assembly process

- Trigger chamber assemble
  → Consist of silica aerogel, reflector (3M VM2000), plastic scintillator(PEN 200 μm), positron source (^{22}Na)
- Partial assembly of 4 x 14 BGO array

Trigger Chamber



Partial assembly

IV Partial Assembly Results

DAQ system & Data transfer

- The DAQ system is provided by NOTICE corporation

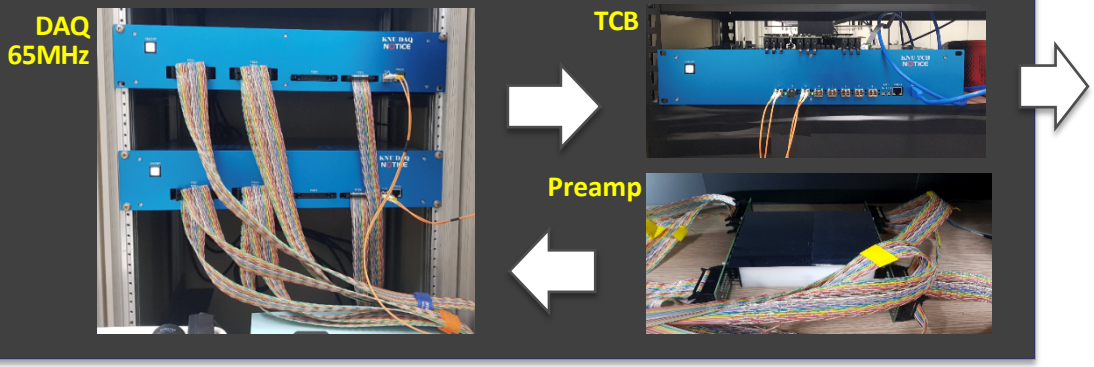
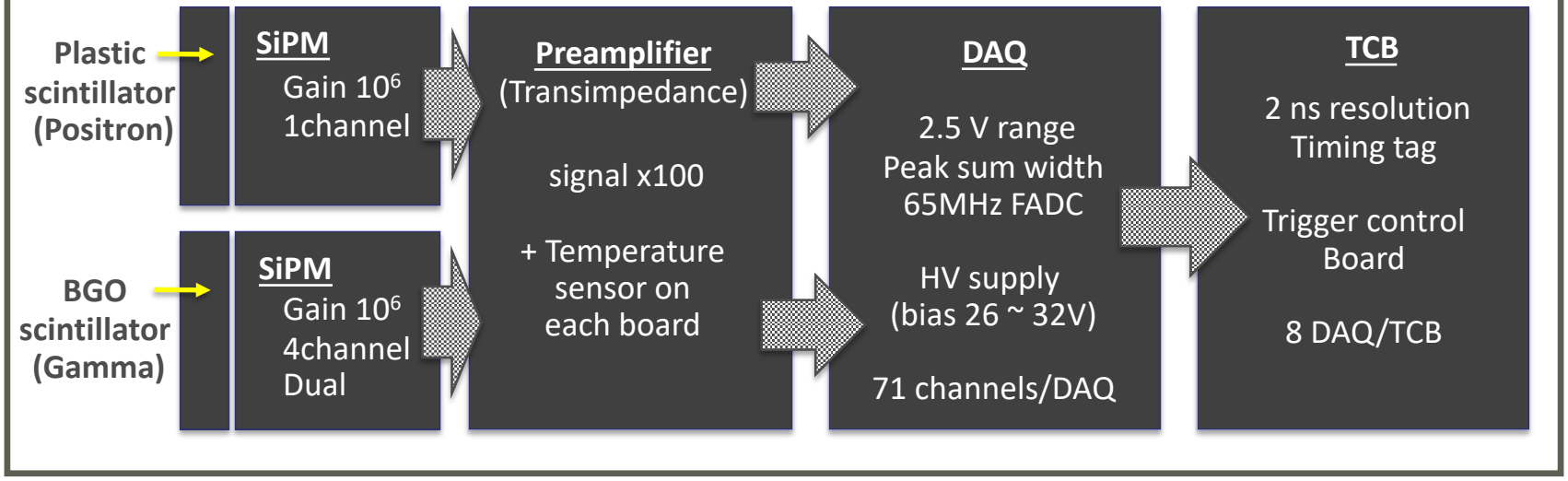


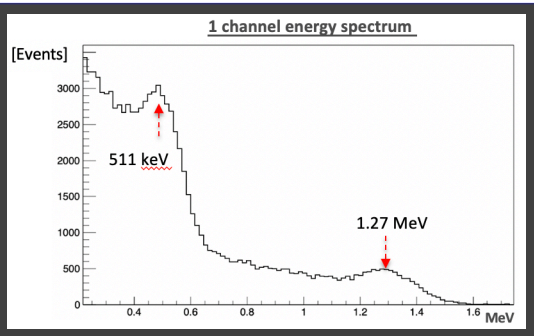
Diagram of Signal Processing



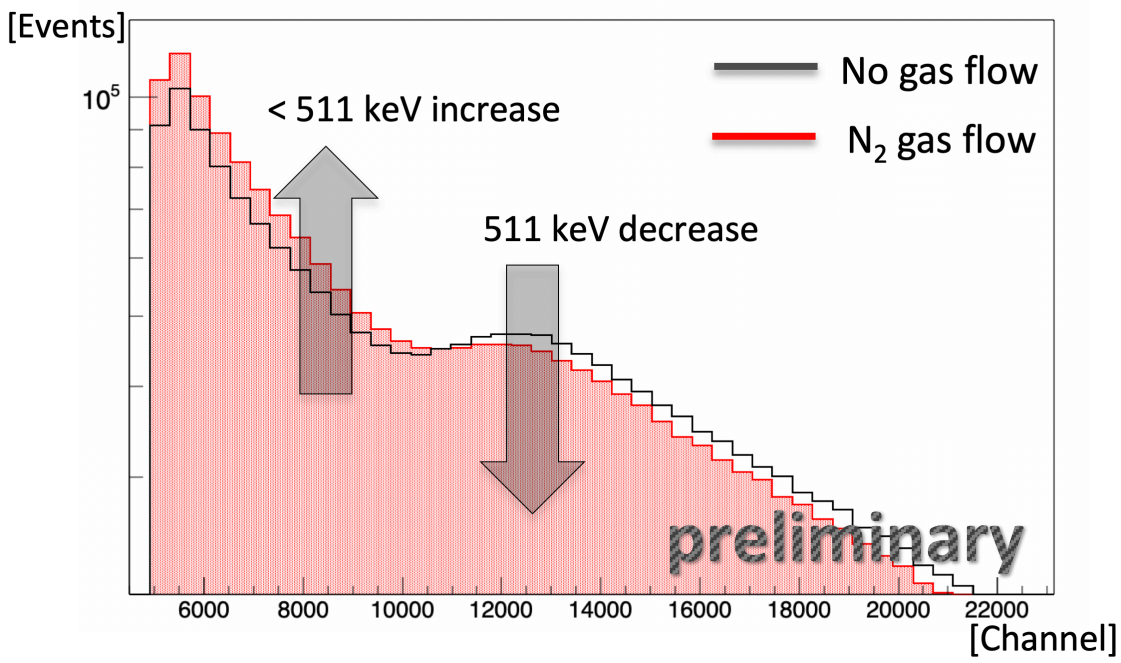
IV Partial Assembly Results

Gamma Parts Results

- Partial assembly not used optical coupling grease
  → Energy resolution is not optimized and the peak is not clear
- We could confirm 3 γ annihilation effect in N_2 gas (< 511 keV)



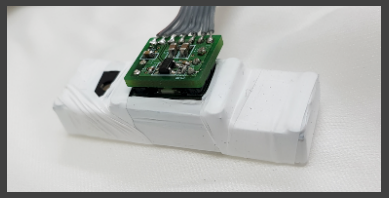
All BGO Signal SUM

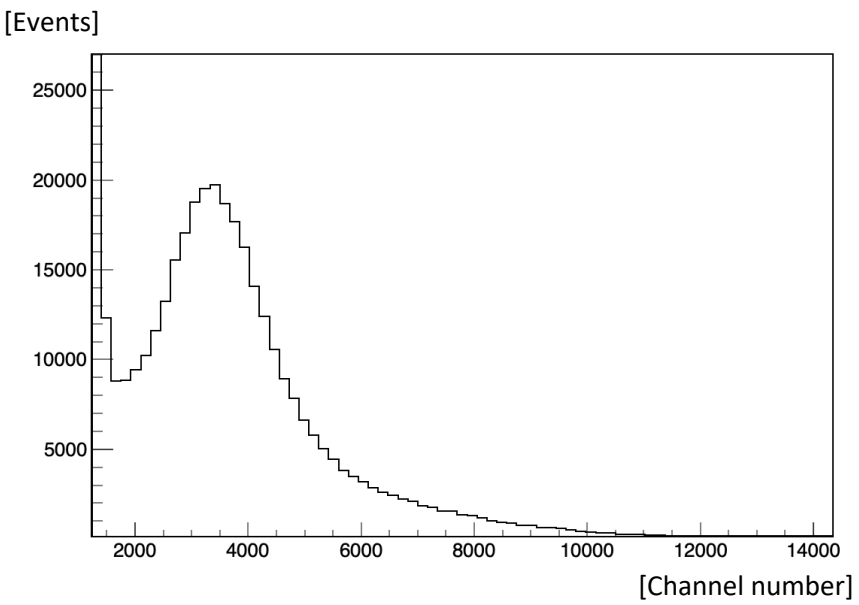


Partial Assembly Results

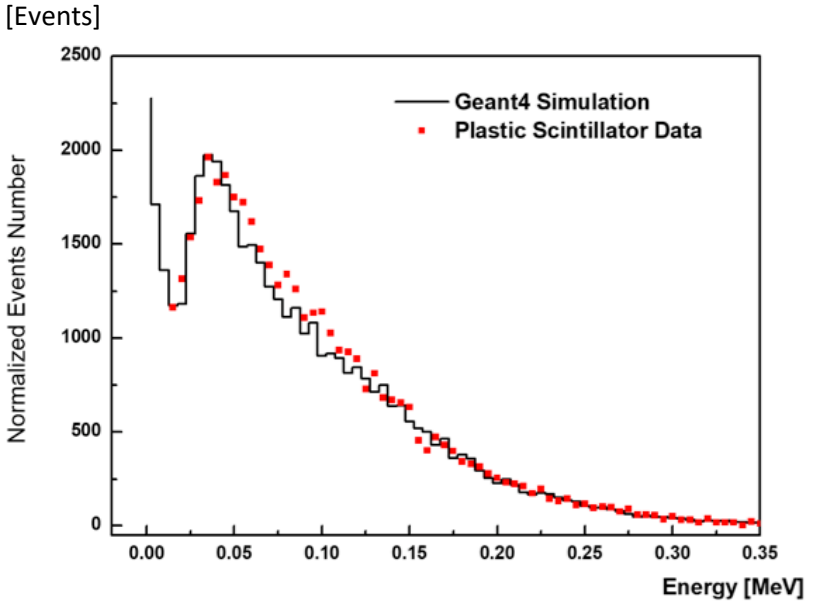
Trigger Part Results

- The positron trigger signal is in good agreement with the GEANT4 MC simulation result





Plastic scintillator signal (Trigger)



Compare MC simulation and experimental results

Summary

Summary

- We first designed SiPM & BGO based compact detector for positronium decay
- The novel compact detector offers high performance of positron trigger efficiency
- We have confirmed the possibility that the designed detector works well

Future plan

- Full detector assemble (14 x 14 BGO)
- Prepare of high activated ^{22}Na source
  → event number increasing
- Pile-up rejection and data analysis code
- Full GEANT4 MC simulation for efficiency calculation and background rejection
- We will study C-violation & QED test rare decay using novel compact detector

Thank You for your attention!

BACK UP

Pick-off

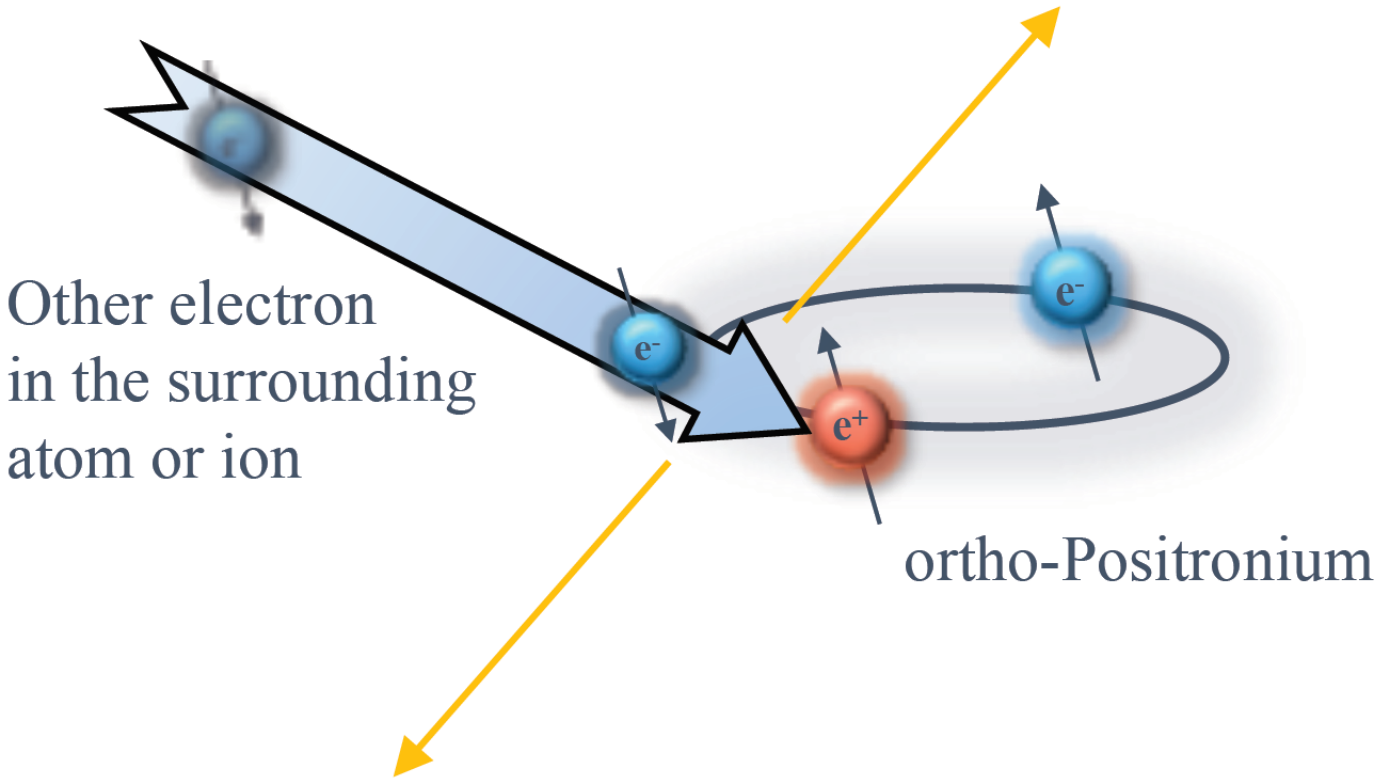
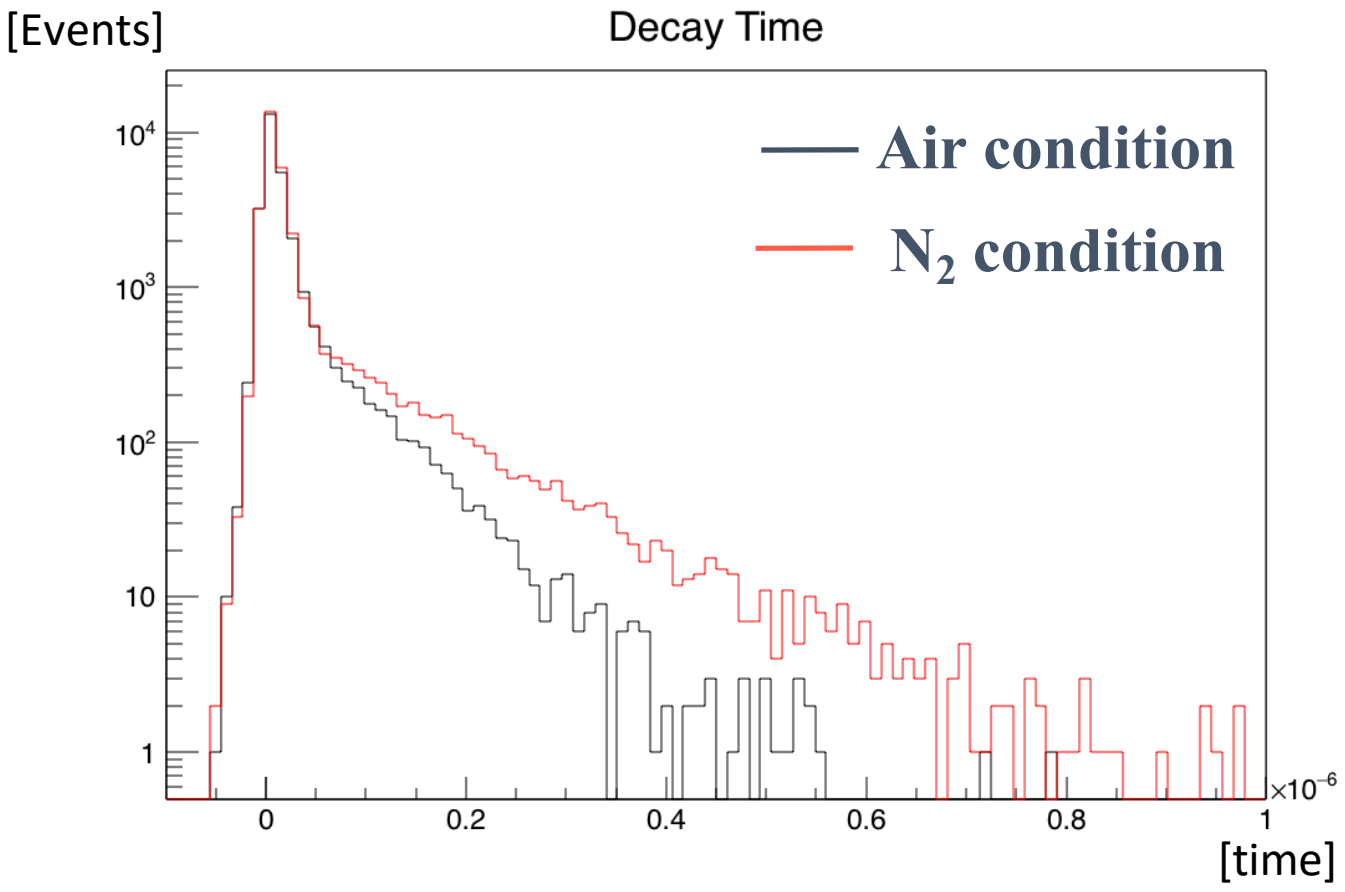


Figure 2. Pick-off process

BACK UP


[Events]
Decay Time
Air condition
N_2 condition
10^4
10^3
10^2
10
1
0
0.2
0.4
0.6
0.8
1
×10⁻⁶
[time]

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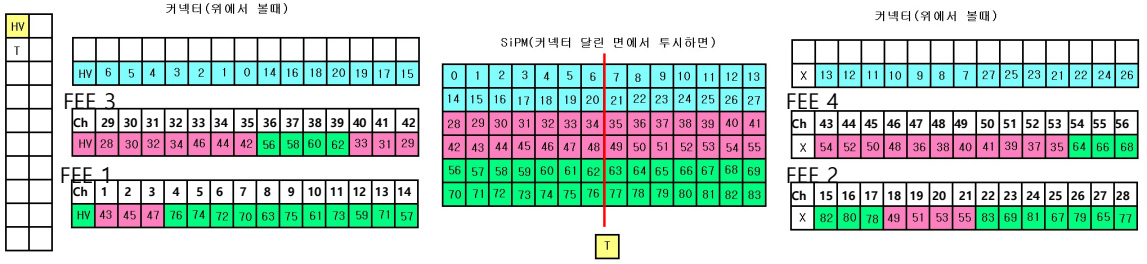
Channel matching



mid 1	pin	43	45	47	76	74	72	70	63	75	61	73	59	71	57
	ch	1	2	3	4	5	6	7	8	9	10	11	12	13	14
mid 2	ch	43	44	45	28	26	24	22	39	17	54	16	55	15	56
	pin	54	52	50	77	79	81	83	62	78	64	80	66	82	68

mid 1	pin	82	80	78	49	51	53	55	83	69	81	67	79	65	77
	ch	15	16	17	18	19	20	21	22	23	24	25	26	27	28
mid 2	ch	13	11	9	46	33	34	35	7	36	6	37	5	38	4
	pin	71	73	75	48	46	44	42	70	56	72	58	74	60	76

mid 1	pin	28	30	32	34	46	44	42	56	58	60	62	33	31	29
	ch	29	30	31	32	33	34	35	36	37	38	39	40	41	42
mid 2	ch	50	51	52	53	19	20	21	23	25	27	8	47	48	49
	pin	41	39	37	35	51	53	55	69	67	65	63	36	38	40

mid 1	pin	54	52	50	48	36	38	40	41	39	37	35	64	66	68
	ch	43	44	45	46	47	48	49	50	51	52	53	54	55	56
mid 2	ch	1	2	3	18	40	41	42	29	30	31	32	10	12	14
	pin	43	45	47	49	33	31	29	28	30	32	34	61	59	57

BACK UP

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1) sci. trigger efficiency = 10%
2) o-PS efficiency =5%
3) 511 keV gamma full peak 0.6, > 40% (GEANT4 simulation)

- CP,CPT and QED test:

40 kBq:40000 x 0.1 x 0.05 x 0.4 = 80 Hz , 14 days -> 10^8 evts
CP, CPT sensitivity : ~0.0001 (previous experiments ~0.001): 10 times improvement
C sensitivity : o-Ps -> 4g search, 10^8 -> ~10^{-7} (10-6):10 times improvement
o-Ps(5g/3g) ratio : 10^8 evt *10^{-6} Br = 100 evts (previous experiments 1-3 evt), 10% error

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C violation in lepton sector

$C = (-1)^{L+S}$

$\mathrm{BR}(o\text{-}Ps \to 4\gamma / o\text{-}Ps \to 3\gamma) < 2.6 \times 10^{-6}$ at 90% CL [22],

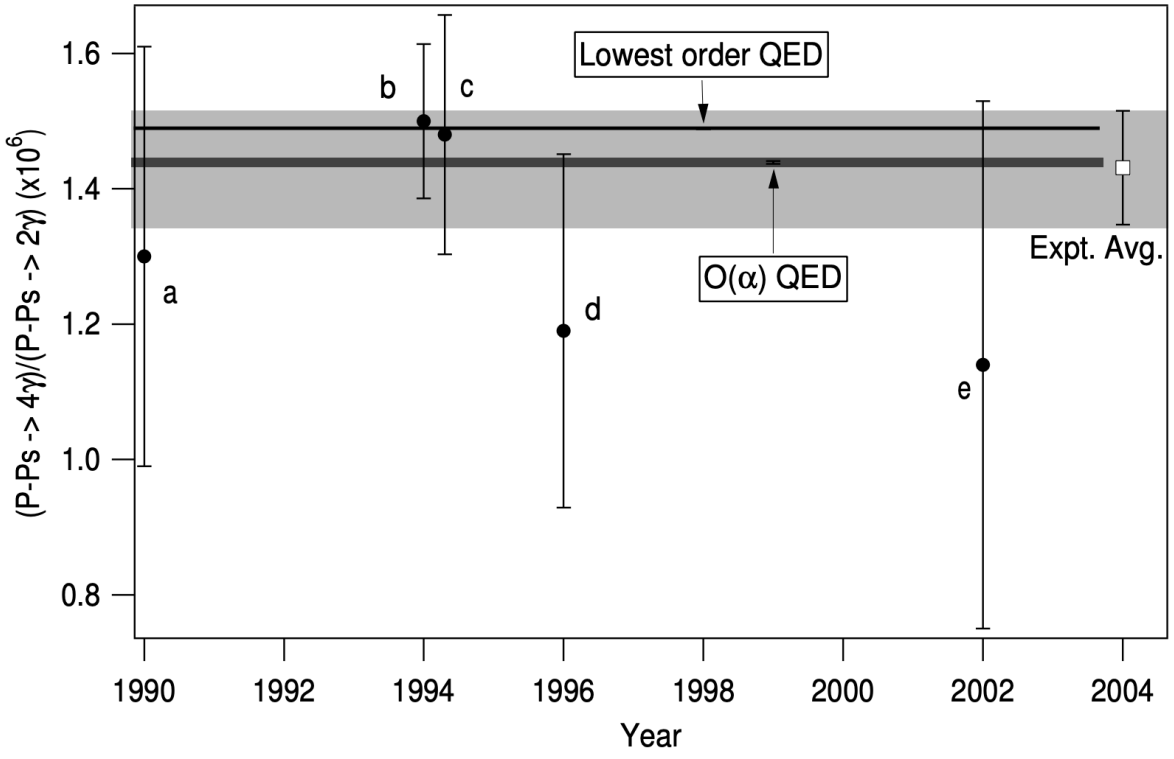
$\mathrm{BR}(p\text{-}Ps \to 3\gamma / p\text{-}Ps \to 2\gamma) < 2.8 \times 10^{-6}$ at 68% CL [23],

$\mathrm{BR}(p\text{-}Ps \to 5\gamma / p\text{-}Ps \to 2\gamma) < 2.7 \times 10^{-7}$ at 90% CL [24],

[22] J. Yang *et al.*, *Phys. Rev. A* **54**, 1952 (1996).

[23] A. P. Mills, S. Berko, *Phys. Rev. Lett.*, **18**, 420 (1967).

[24] P. A.Vetter, S. J. Freedman, *Phys. Rev. A* **66**, 052505 (2002).



$o\text{-Ps} \to 5\gamma$ to $o\text{-Ps} \to 3\gamma$ as $[2.2^{+2.6}_{-1.6}(\text{stat.}) \pm 0.5(\text{syst.})] \times 10^{-6}$

BACK UP (Reflector test)