Precision Measurement of the Hyper Fine Splitting of the Positronium (III)（γ-ray detectors）

A. Ishida, G. Akimoto, M. M. Hashimoto, T. Tagawa,
T. Suehara[A], T. Namba[A], S. Asai, T. Kobayashi[A], H. Saito[B],
M. Yoshida[C], I. Ogawa[D], S. Kobayashi[D] and T. Idehara[D]

Faculty of Science, University of Tokyo
ICEPP, Faculty of Science, University of Tokyo[A]
Graduate School of Arts and Sciences, University of Tokyo[B]
High Energy Accelerator Research Organization (KEK)[C]
FRI Center, University of Fukui[D]

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Outline

Two experimental plans for precision measurement of
hyper fine splitting (HFS) of the positronium (Ps)

(1) Indirect measurement using magnetic field
(Zeeman effect) (G. Akimoto and M. M. Hashimoto's talks)

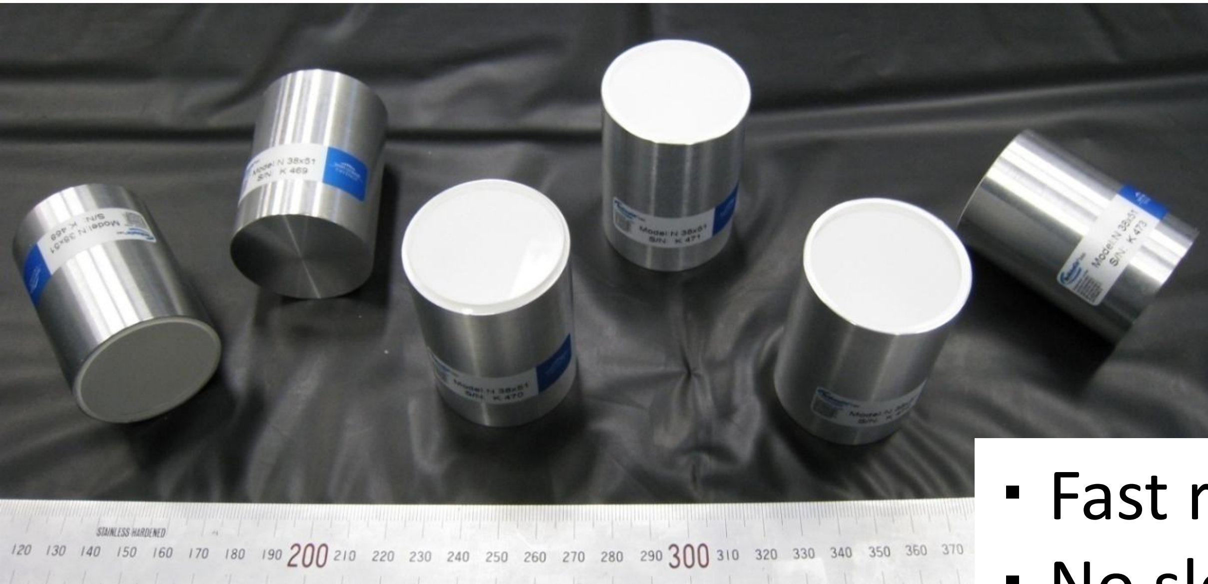
(2) Direct measurement with strong sub-terahertz Gyrotron
(Next talk by T. Suehara)

Research and Development of γ-ray detectors
for these two experiments

- Especially for (1) because the measurement will be performed in high magnetic field.

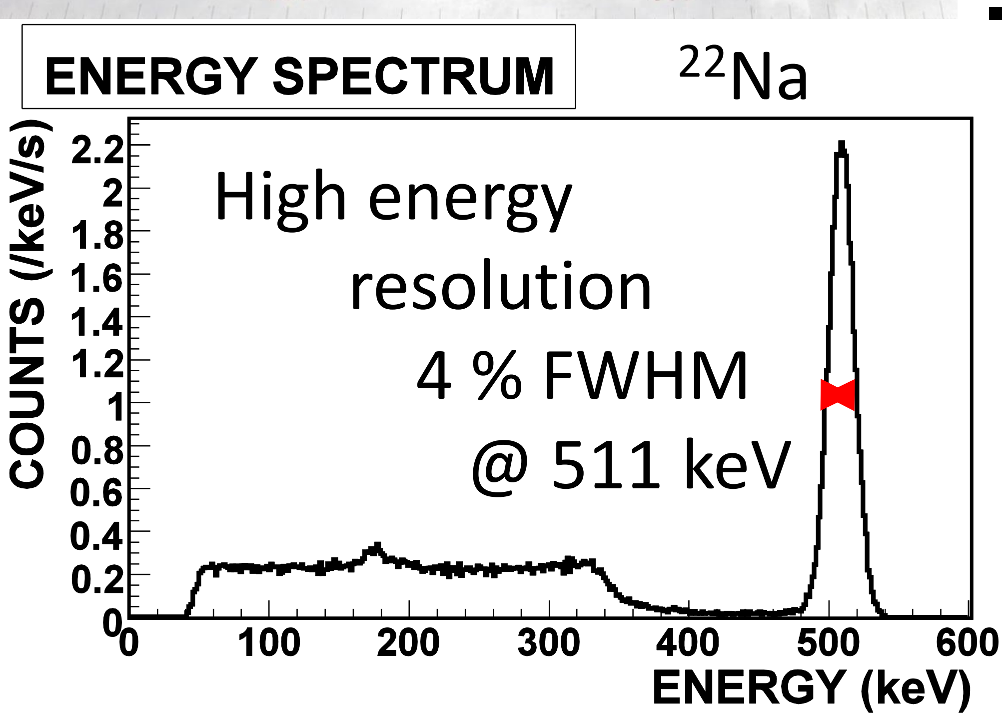
1. $LaBr_3$ scintillator
2. Fine mesh PMT in magnetic field
3. Overview of the detector design
4. Light guides
5. Tagging the 2γ decay
6. Simulation by Geant4

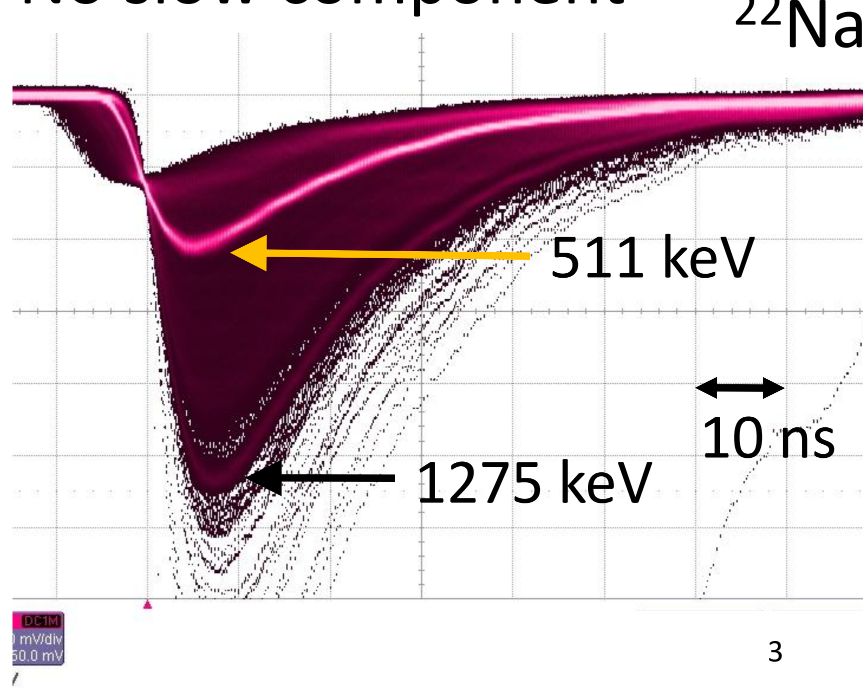
1. $LaBr_3$ Scintillator



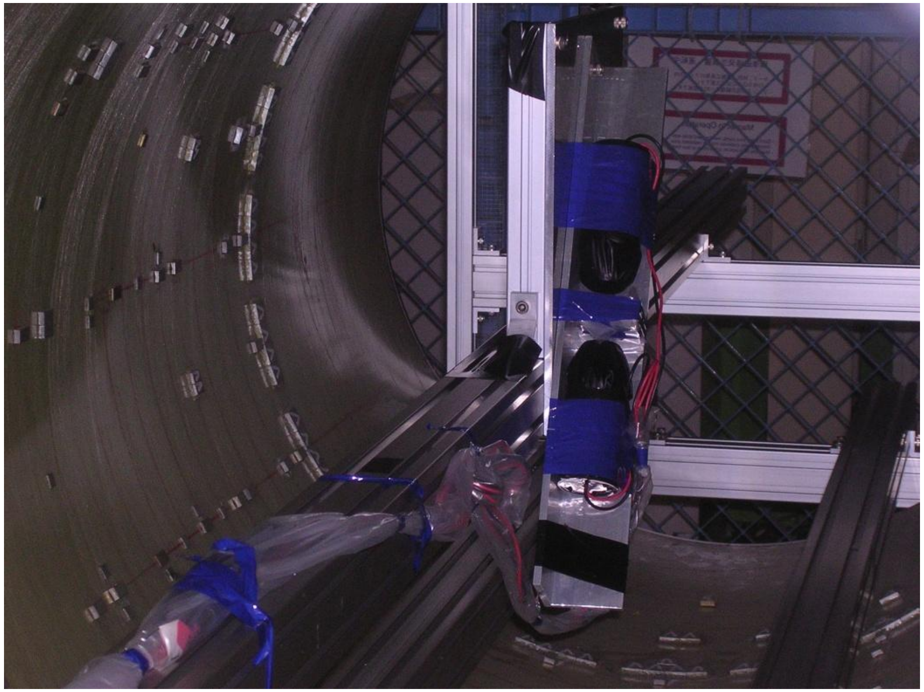
Diameter 1.5 inch
Length 2.0 inch
$LaBr_3(Ce) \times 6$
For experiments

- Fast rising time
- No slow component

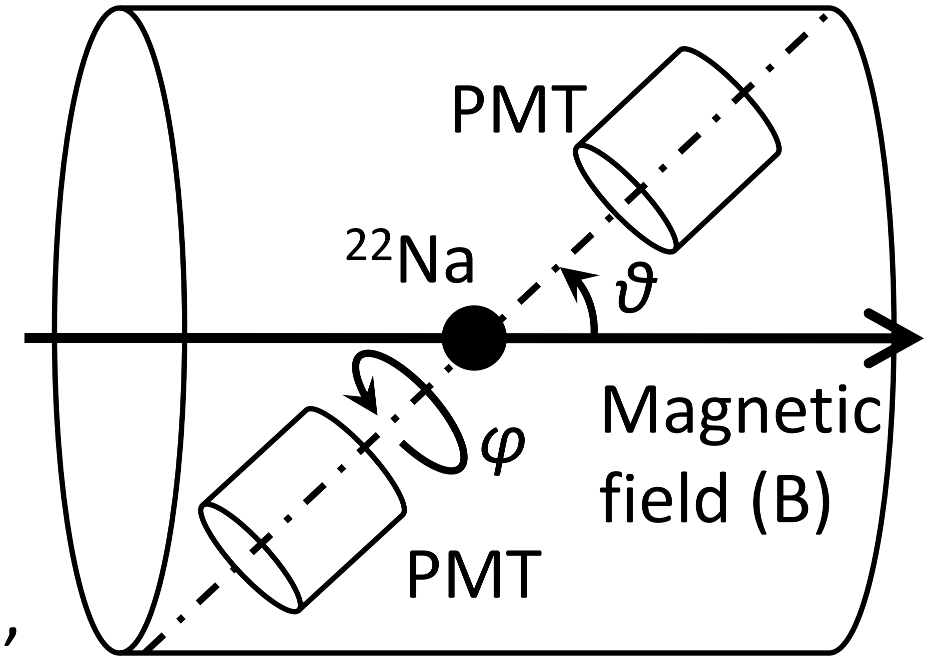




2. Fine Mesh PMT in Magnetic Field



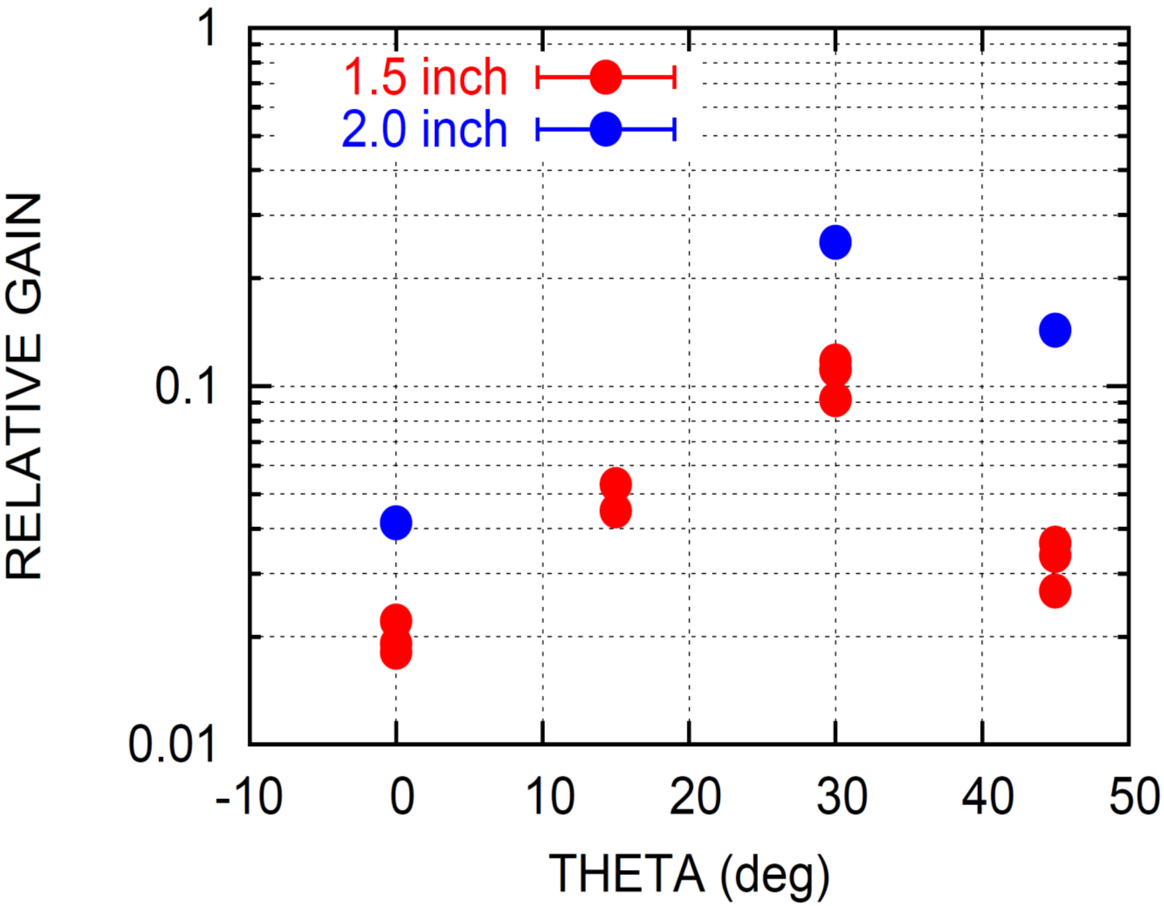
MRI Magnet (@ KEK)

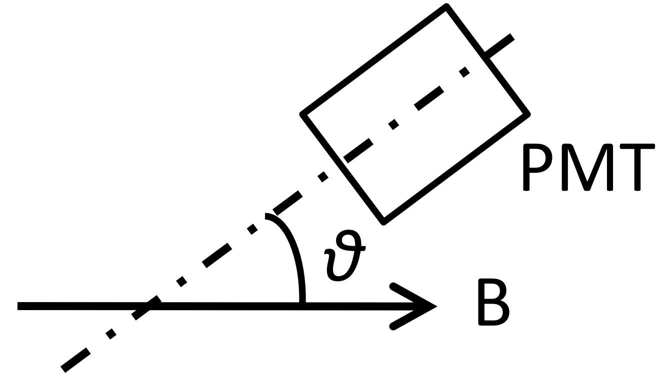


LaBr$_3$(Ce) scintillator (1 inch),
Fine mesh PMT
1.5 inch HAMAMATSU R7761 and
2.0 inch HAMAMATSU R5924
were set in back-to-back position.

Tested with ^{22}Na source
(511 keV 2γ back-to-back,
1275 keV γ)

Angle (ϑ) dependence of the PMT Gain

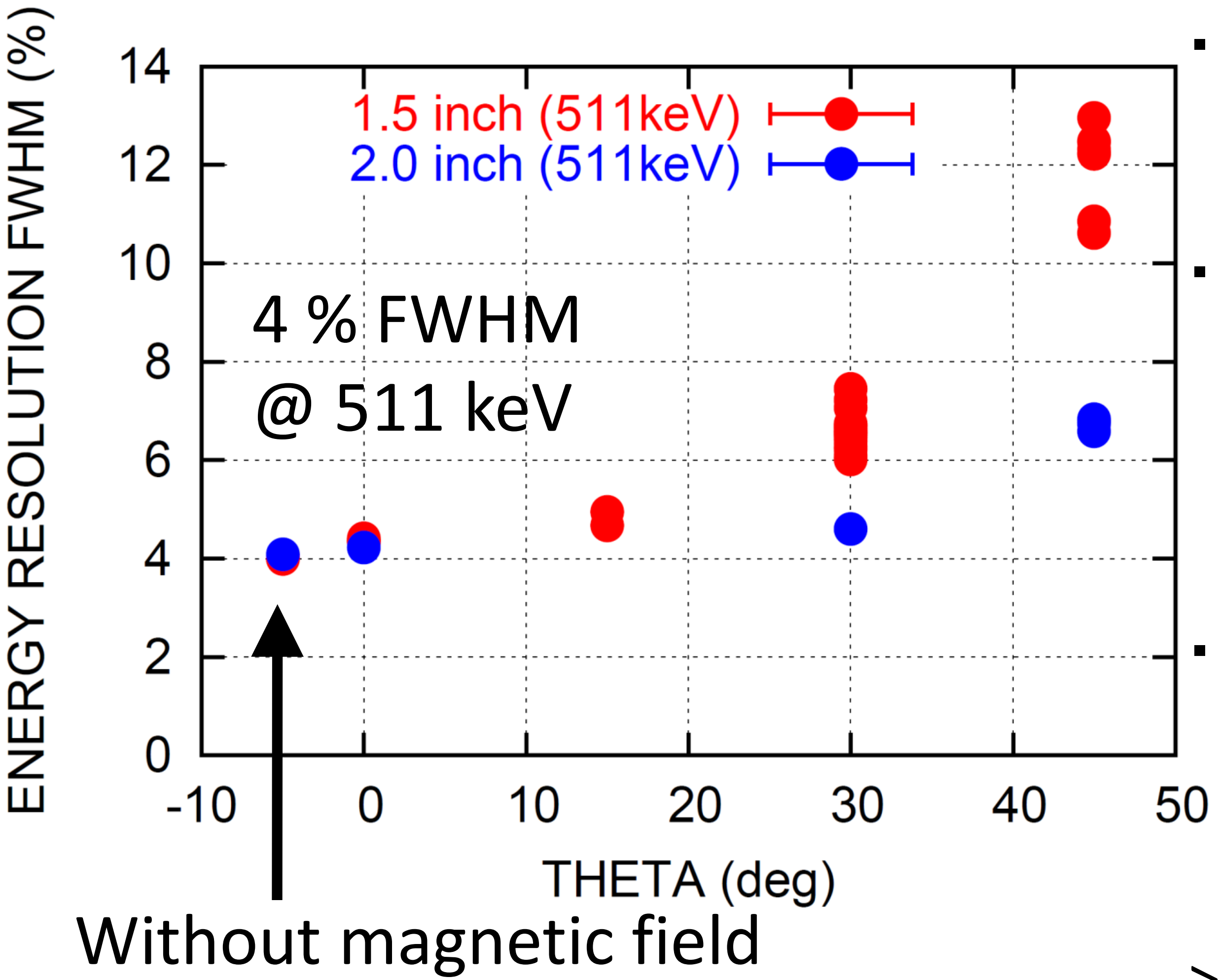




- 1.5 inch PMT is more sensitive to B.
- We get the least effect with 30 deg.
- 2 inch PMT has high gain even at 45 deg.

The gain was less than 10^{-4} with more than 60 deg angle. (Not measurable)

Angle (ϑ) dependence of Energy Resolution

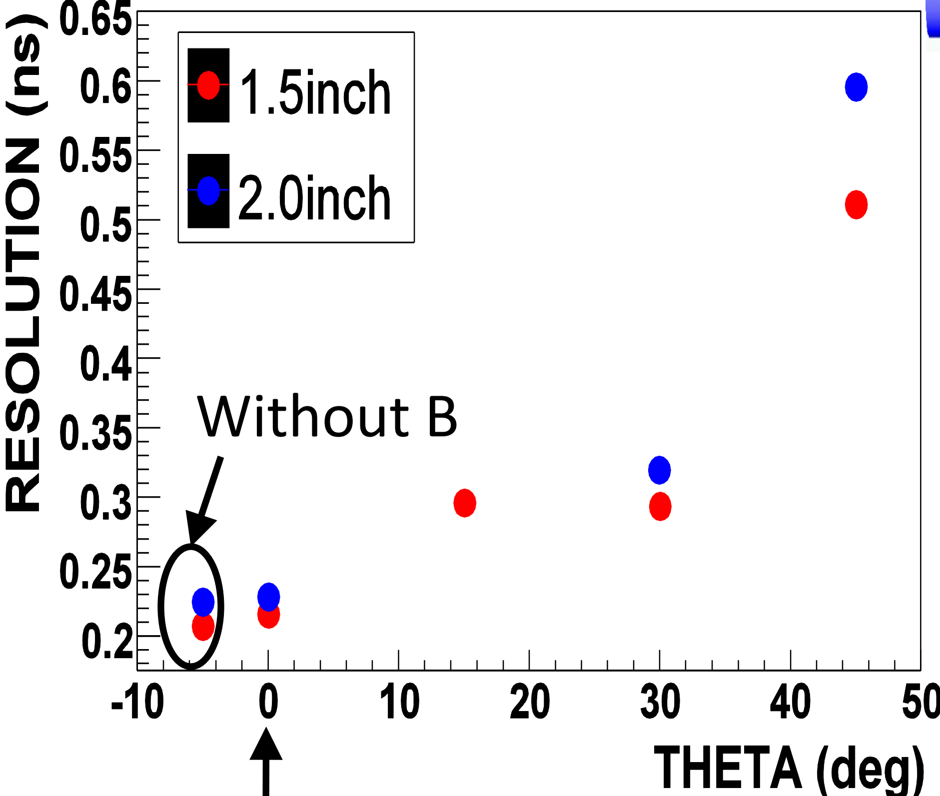


- Resolution at 0 deg is as high as that without magnetic field.
- Photoelectrons emitted from the cathode of the PMT go spiraling around magnetic field to the anode.
- Photoelectrons are collected most efficiently at the first dynode when the angle is 0 deg.

-> High energy resolution

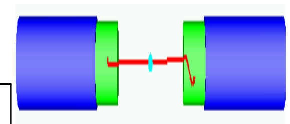
Angle (ϑ) dependence of Time Resolution

FWHM @ 511 keV



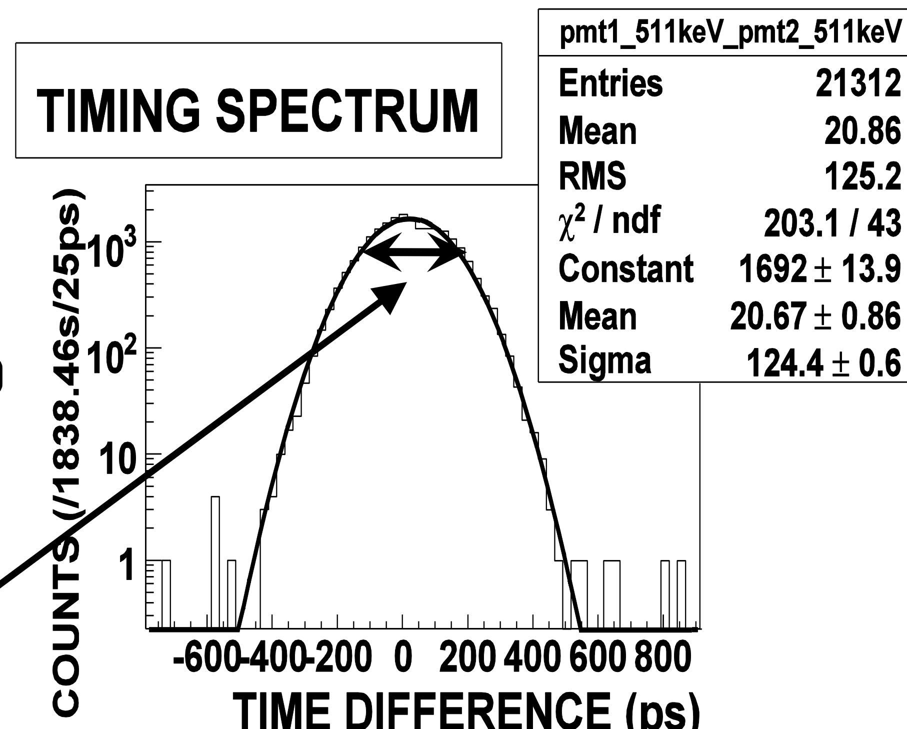
Not affected by B at 0 deg

FWHM 293 ps @ 511 keV

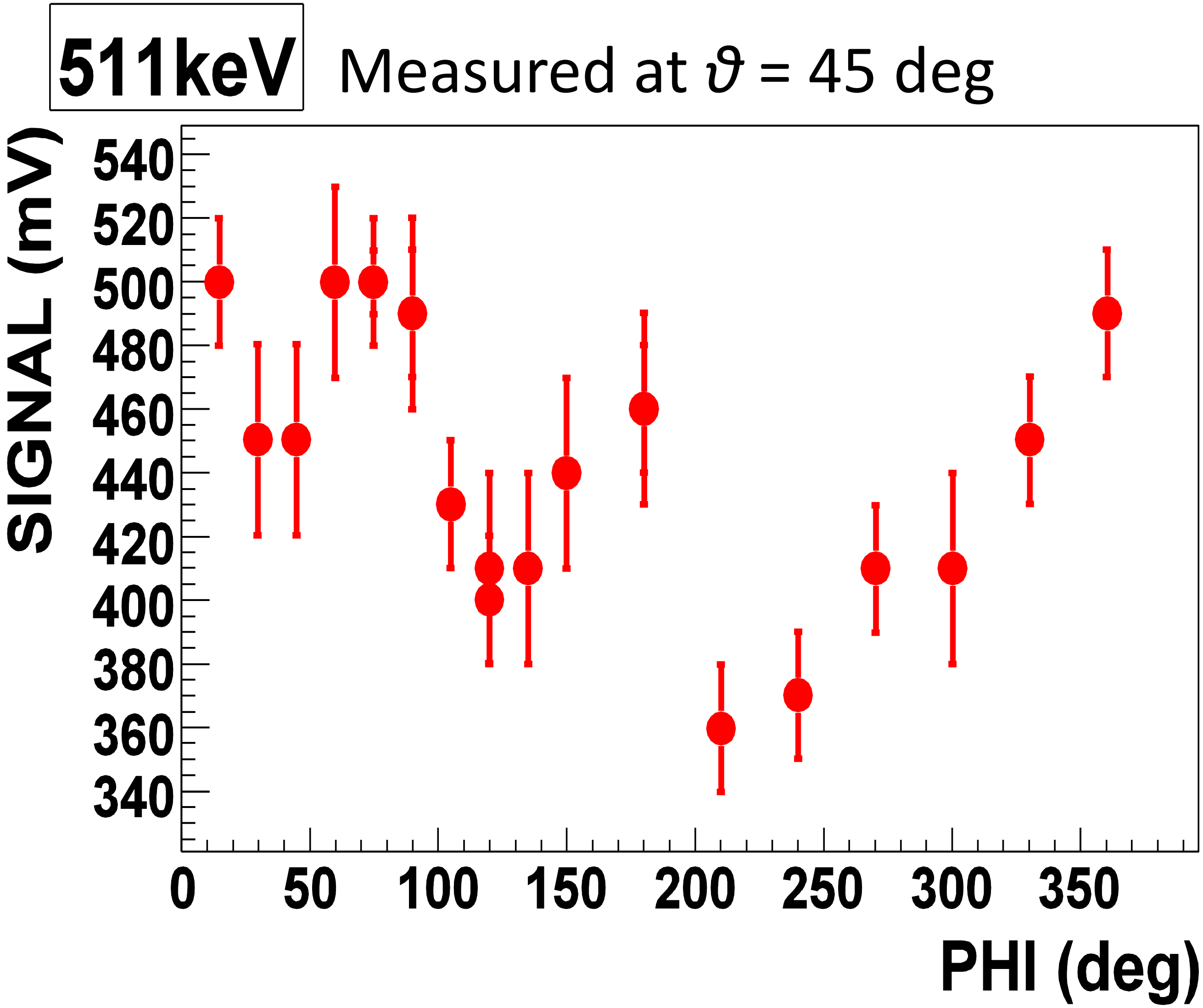


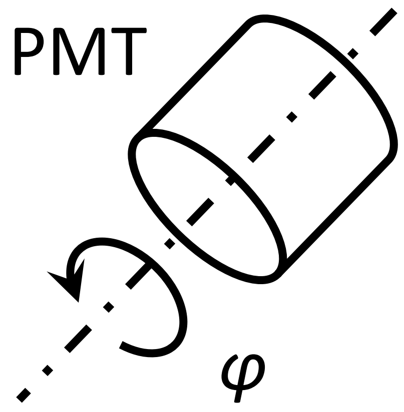
511 keV back-to-back

↓ ex.) The timing spectrum without magnetic field (1.5 inch + 2.0 inch coincidence)



Turning Angle (φ) dependence of the PMT Gain



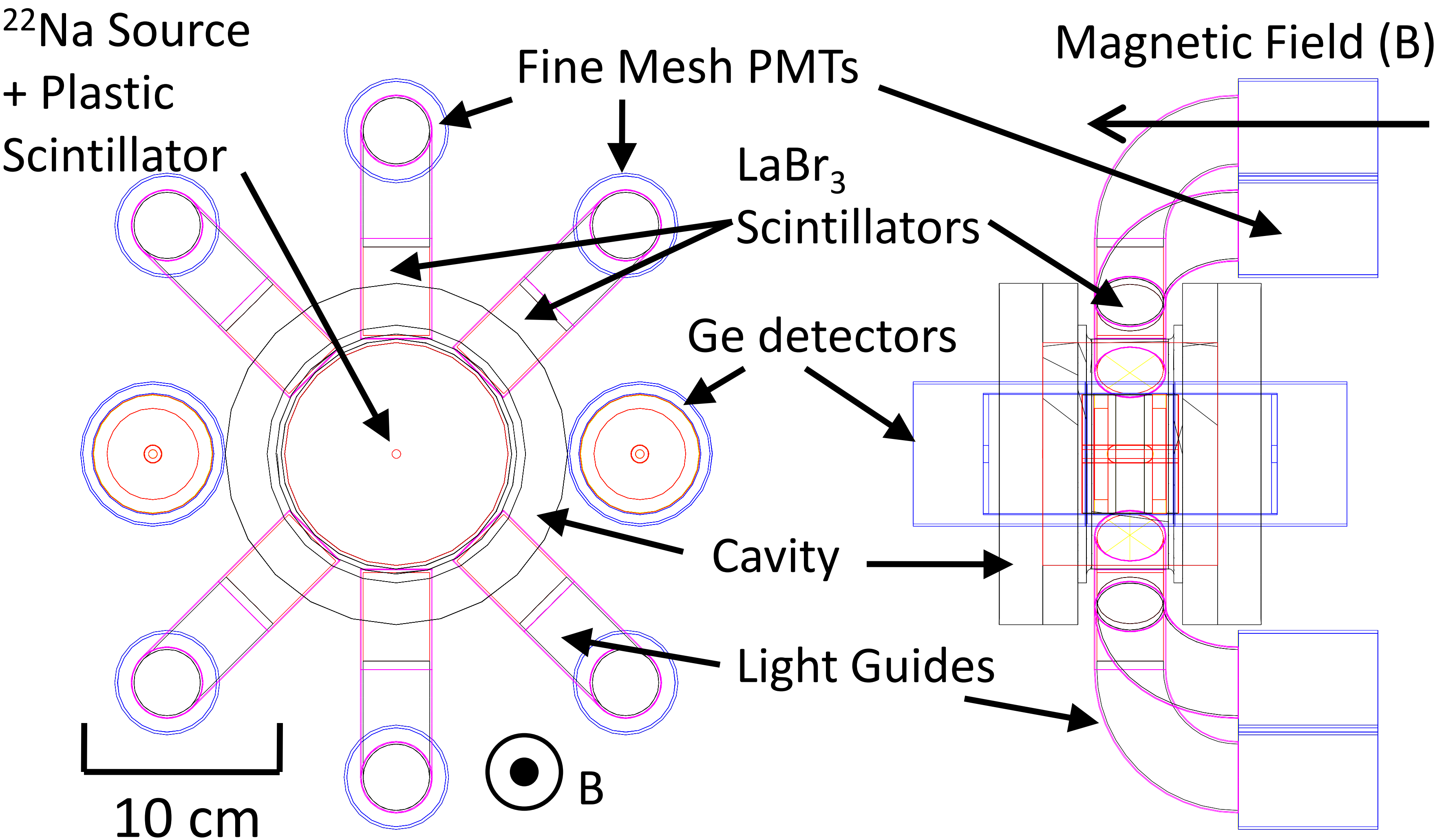


Effect ~ 25 %

3. Overview of the Detector Design

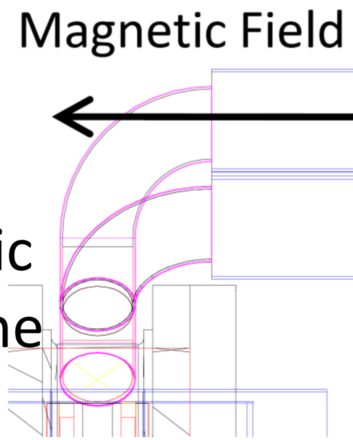
We can get the highest resolution at $\vartheta = 0$ deg, although the PMT gain is low.

-> Make the directions of the magnetic field and of the axes of the PMTs the same.



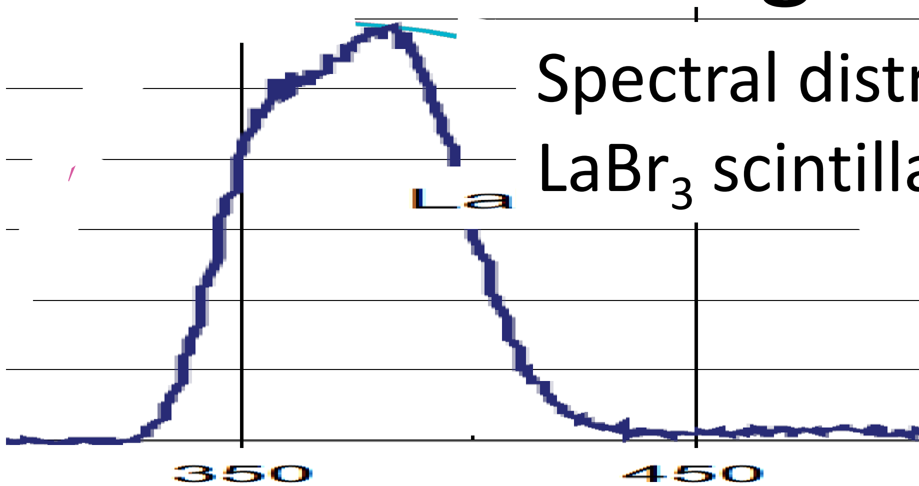
4. Light Guides

It's necessary to put PMTs far from the Cavity.
Bend light by 90 deg in order to make the directions of the magnetic field and of the axes of the PMTs the same.

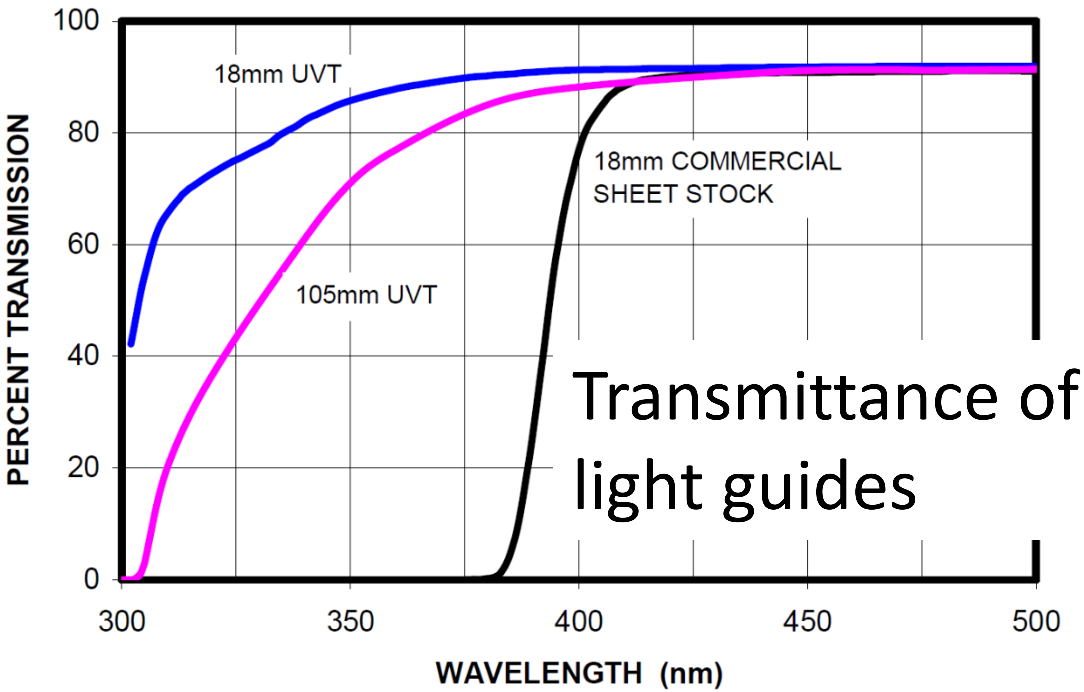


$LaBr_3$ scintillator 1 inch
Light guide 1.5 inch
  length 5/10/20/40 cm
  angle 45/90 deg
PMT 2 inch
Rolled by Gore-tex

UVT Light Guide



Spectral distribution of $LaBr_3$ scintillation light

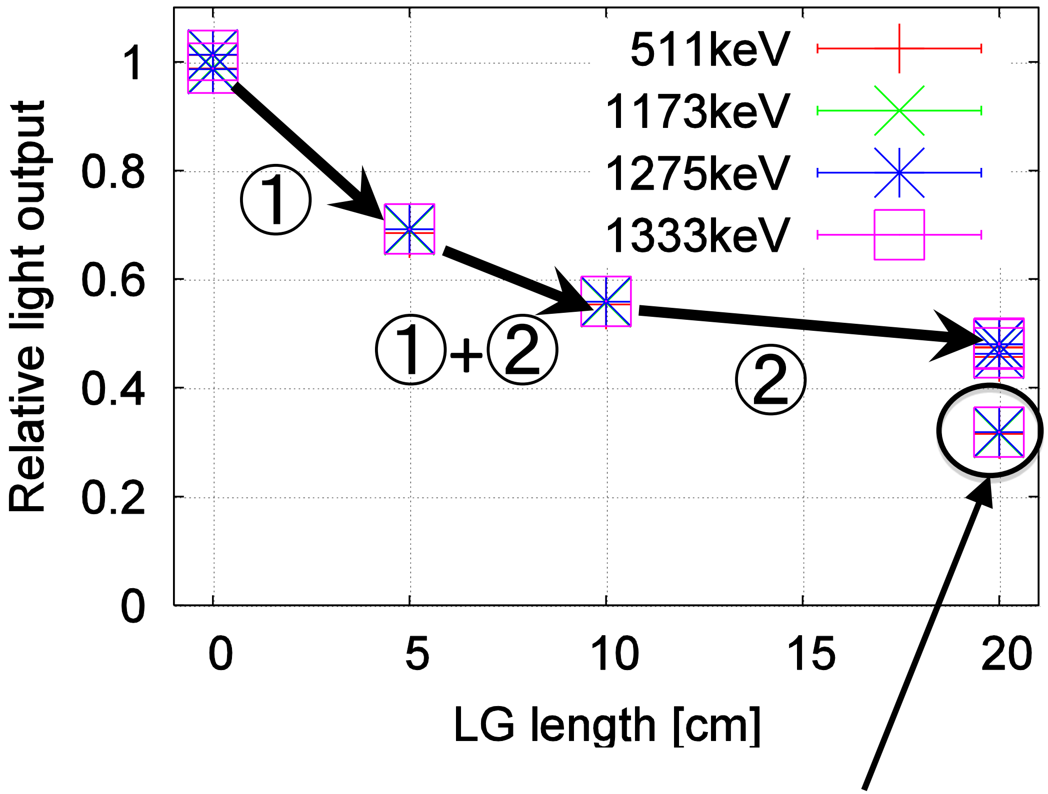


Transmittance of light guides

Because the typical wavelength of the $LaBr_3$ scintillation light is λ=380 nm,

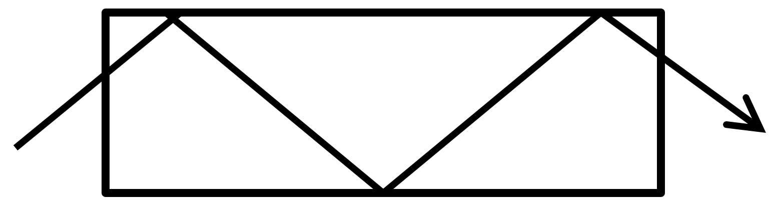
We have to use UVT (Ultra-Violet Transmitting) light guide.

Light guide length dependence of light output



LG was not on the surface of the PMT.

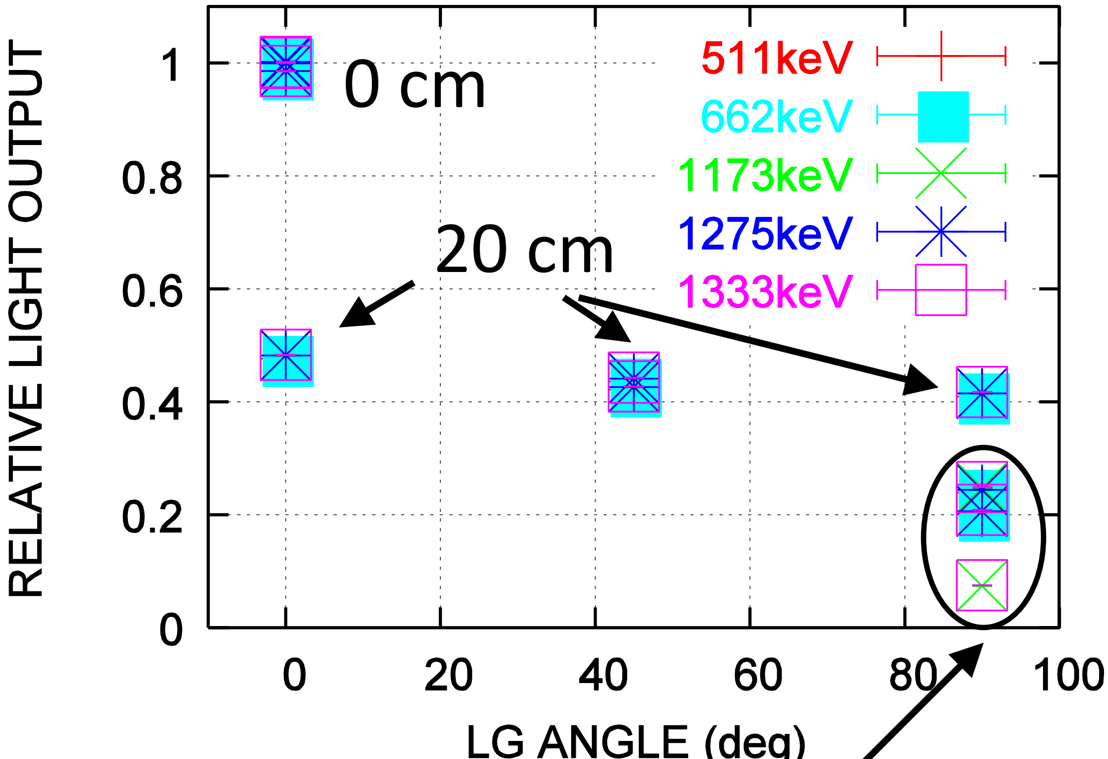
① Due to reflection condition



② Absorption (small effect)

A little less than a half at 20 cm, but it seems to have already got to be almost constant.

(Binding) Angle dependence

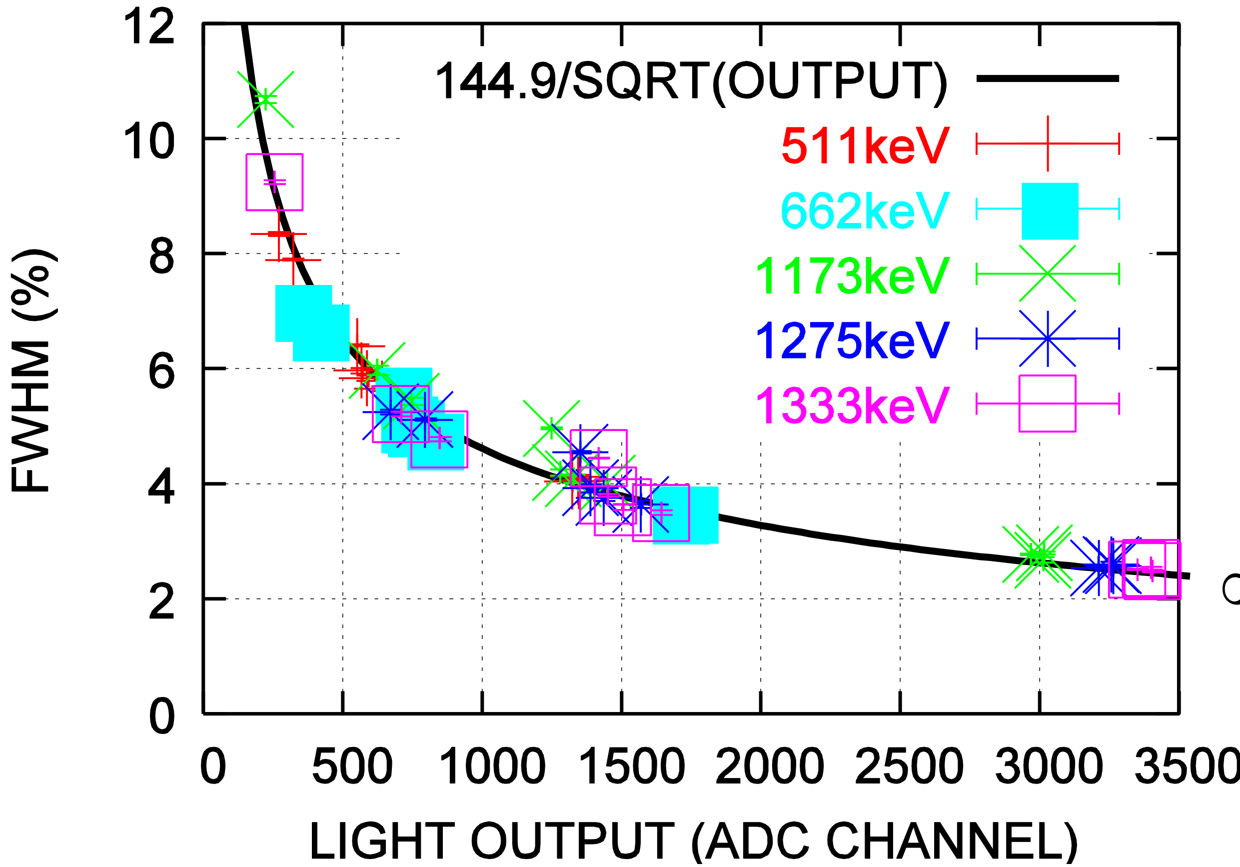


- It seems to be almost the same at 0, 45 and 90 deg (@ 20cm).
- Little effect of angle.

Bad design

The best design for 90 deg

Energy Resolution with Light Guides



$$\propto \frac{1}{\sqrt{OUTPUT}}$$

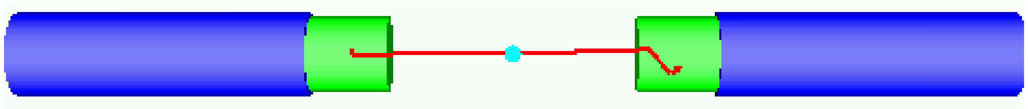
Energy resolutions only depend on the statistics of the light output.

5. Tagging the 2γ Decay

Calculate the HFS from the 2γ-3γ decay ratio

-> Necessary to tag the 2γ accurately We have 2 ways.

(1) Geometrical



Locate detectors in back-to-back position, and tag the gammas deposit 511 keV to both of the detectors.

(Advantage) High S/N (Disadvantage) Low collection efficiency

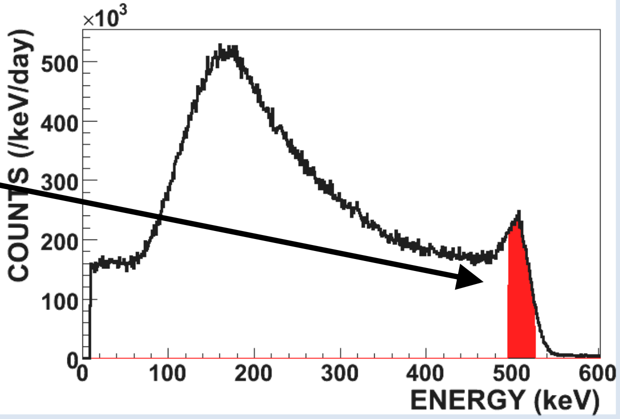
(2) Energy (Our new method)

Tag 511 keV using only energy information

(Advantage) High Collection efficiency

(Self-trigger counting)

(Disadvantage) Low S/N

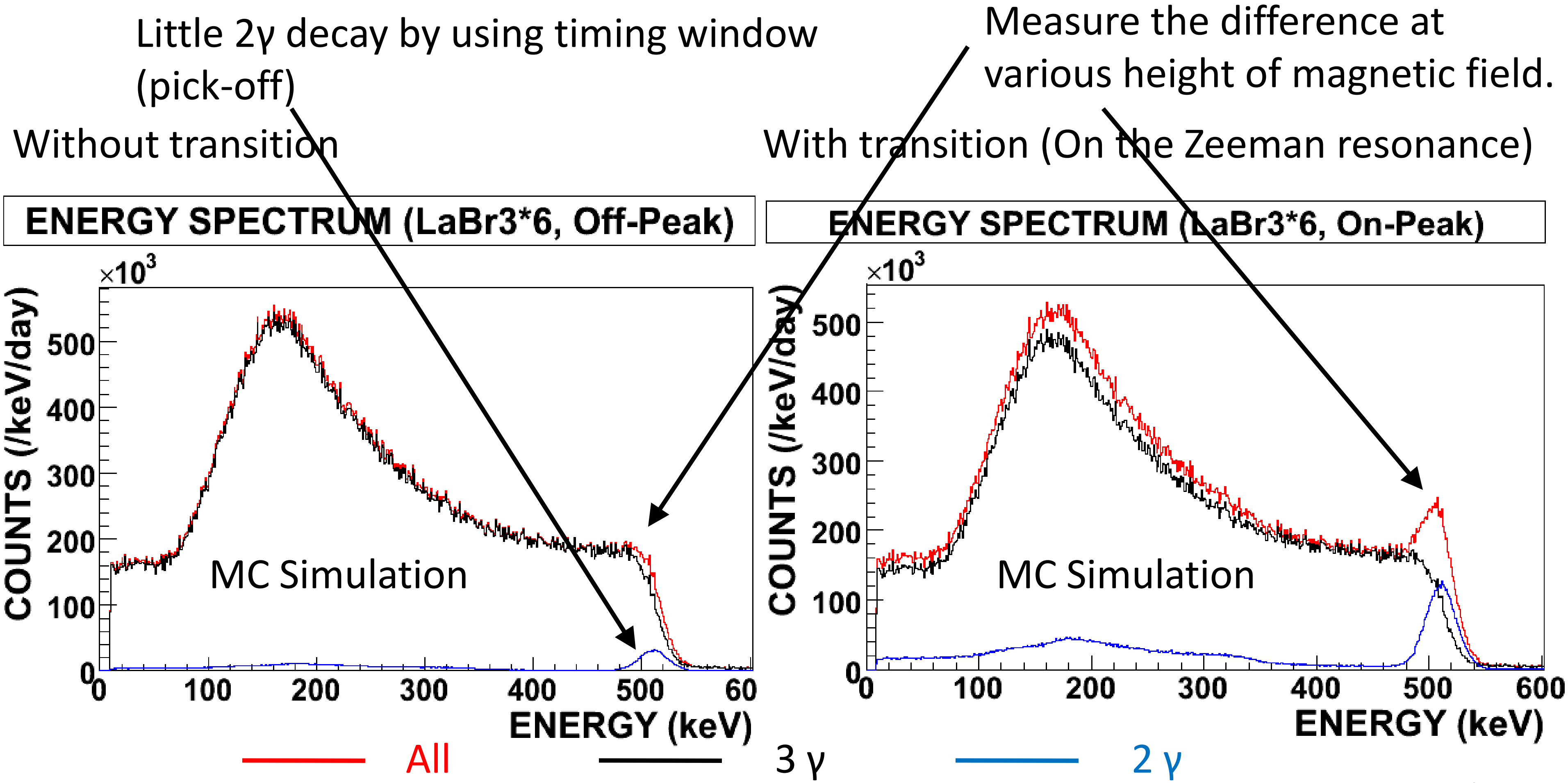


High energy resolution is recommended for energy tagging method.

-> Use $LaBr_3$ and Ge detectors.

6. Simulation by Geant4 (1)

According to the above measurement, $LaBr_3$ system has very high energy and time resolutions. We can distinguish between 2γ and 3γ decays with energy tagging method.



Simulation by Geant4 (2)

Expected numbers of events for one day run using 1MBq ^{22}Na

	Back-to-back		Energy	
	All	Detail	All	Detail
Without Transition	2.5×10^4	2 γ 1.4×10^4 3 γ 1.1×10^4	4.0×10^6	2 γ 8×10^5 3 γ 3.3×10^6
With Transition	6.4×10^4	2 γ 5.4×10^4 3 γ 1.0×10^4	6.0×10^6	2 γ 3.1×10^6 3 γ 2.9×10^6

(511 keV was cut by FWHM)

Back-to-back (geometrical information) -> Energy information

- 2 γ count x 57
- 3 γ count x 280

-> 50 times larger counts

S/N is only 5 times lower -> $LaBr_3$ + Energy tagging is very fine.

-> Measure with this new method.

Summary and Future Plan

- Design of the γ-ray detectors has been made for precision measurement of the Positronium hyper fine splitting.
- Measurement of the characteristics of fine mesh PMTs has been performed in 0.866 T magnetic field.
- Light guides were tested.
- According to the simulations by Geant4, we can get precise enough results with this design of the detectors.

- The first run will be performed from the end of this October.

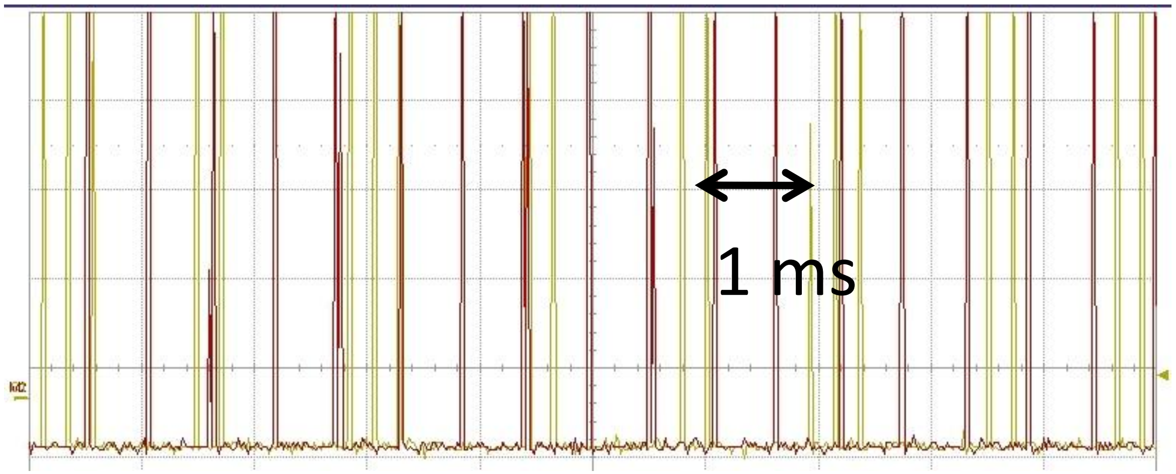
Backup

Ge Detectors in Magnetic Field

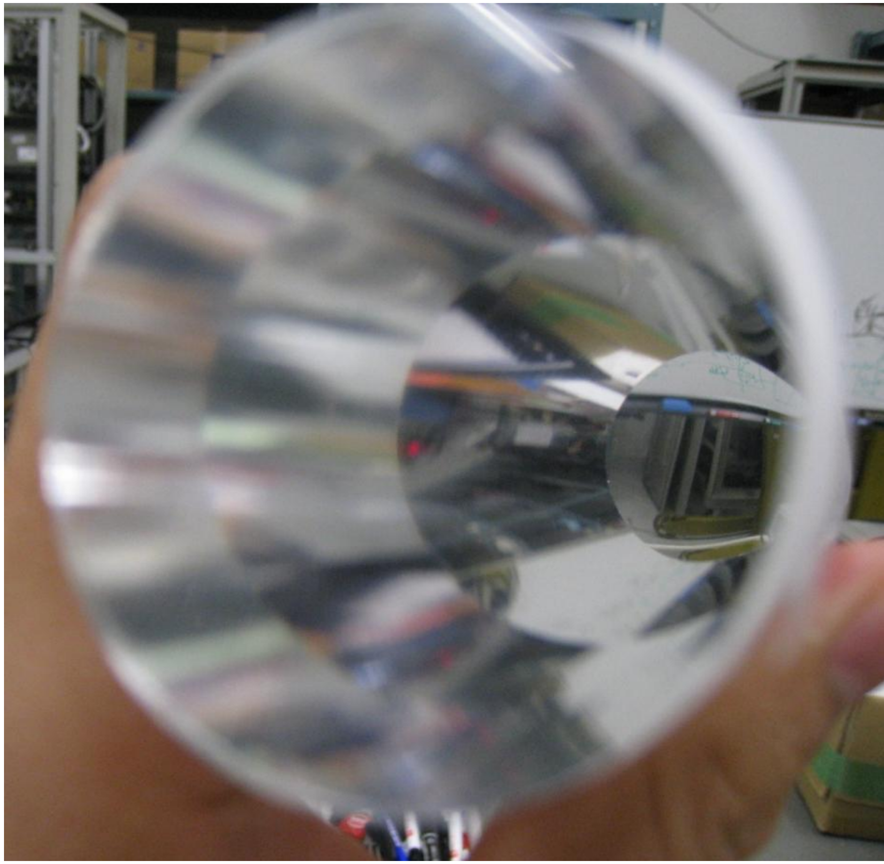
- Cannot use Ge detectors in high (> 500 Gauss) magnetic field.
- Limits of magnetic field in which Ge detectors work depend on the geometry (the angle between the axis of the Ge detector and the magnetic field).
- Penning discharge enhances the dark current.

(Thermalization may be measured without magnetic field)

Measured transistor reset (dark current) of the Ge (Ortec) in high magnetic field.



Light Guides



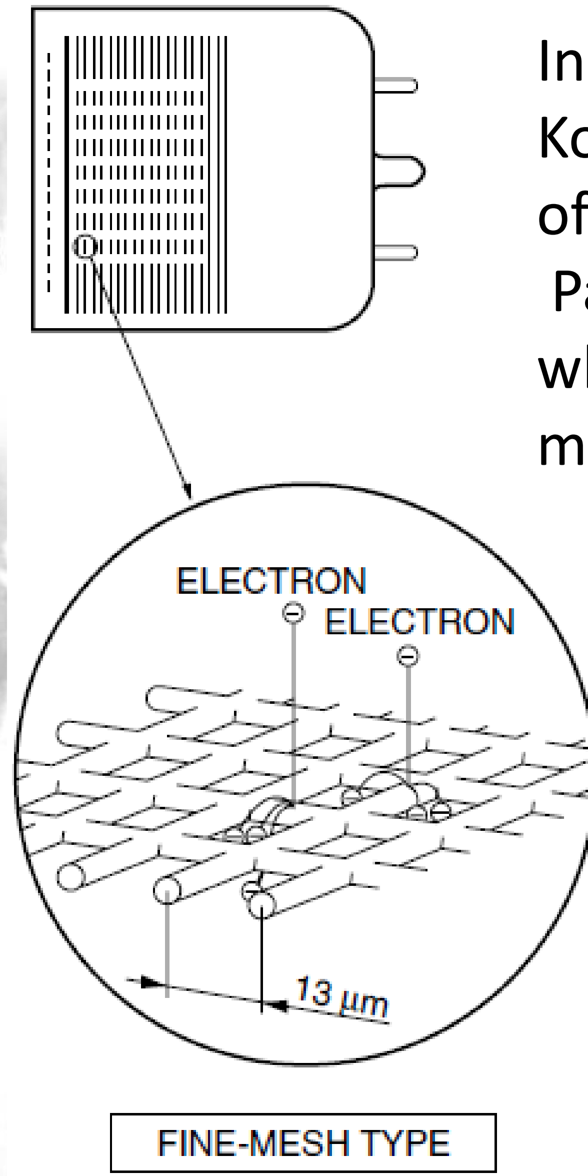
Total reflection condition

Acrylic refractive index 1.49

-> Critical angle 42.2˚

Bright at 90 deg binding

Fine Mesh PMT



Includes Kovar (Alloy mainly of Fe, Ni, and Co. Paramagnetism) which affect the magnetic field.

(Measurement at KEK)
A few cm from the center of the magnet
-> 100 ppm
10 cm
-> 10 ppm

Table of Scintillator Properties

Scintillator	Density	Refractive index	Photons per MeV	Emission Maximum	Decay Constant	Radiation Length
	g / cm^3			nm	ns	cm
NaI (Tl)	3.67	1.85	38000	415	230	2.59
CsI (Tl)	4.51	1.79	59000	565	1000	1.86
LYSO	7.25	1.81	32000	420	40	1.15
YAP (Ce)	5.55	1.93	19700	347	28	2.7
$LaBr_3$	5.29	1.9	63000	380	25.6	1.88

Estimation Factors

• Source	1 MBq	(^{22}Na)
• β^+ decay Intensity	89.89 %	Geant4 data
• Run Time	86400 s	(/day)
• Plastic Scintillator Tag (>60keV) & Stop In Cavity	2.55 %	Geant4 Simulation in N_2(1 atm) & 200 μm Plastic Scintillator
• Generation Prob. of Ps	50 %	M. M. Hashimoto's talk
• Spin Factor	50 %	(2/4)
• Expected events / day	5.0×10^8	
• Pick off ratio	3.4 %	Phys. Rev. A 18, 1426 (1978)
• Transition probability	10 %	Phys. Rev. A 2, 707 (1970)