Feasibility study on real-time γ-ray spectrum / dose measurement system

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Introduction

Background

Medical applications of radiation have been widely spread,
i.e., radiation therapy, production of radioactive drugs.

However

Priority is

treatment of patients > exposure of medical staffs

To decrease radiation exposure, the radiation measurement monitor is essential.

Present monitors : only dose or pulse height spectrum and dose

Necessary monitors : γ-ray energy spectrum and dose

Objectives

Develop a spectrometer system which can measure simultaneously γ-ray energy spectrum and dose in the medical application spot in real time.

Outline

1. Design of the spectrometer system
2. Check the detector performance
3. Spectral evaluation
   (pulse height spectrum →energy spectrum)
   a. By Spectrum type Bayesian estimation
   b. By Sequential Bayesian estimation
4. Spectrum & dose evaluation (energy spectrum →dose)
5. Future work & Conclusion

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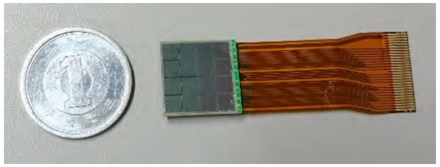
Design of the spectrometer system

Design condition

- Small and light for convenient use
- High detection efficiency
- Good energy resolution for spectrum estimation
- Energy range less than 3 MeV

CsI + MPPC (Multi-Pixel Photon Counter)



MPPC

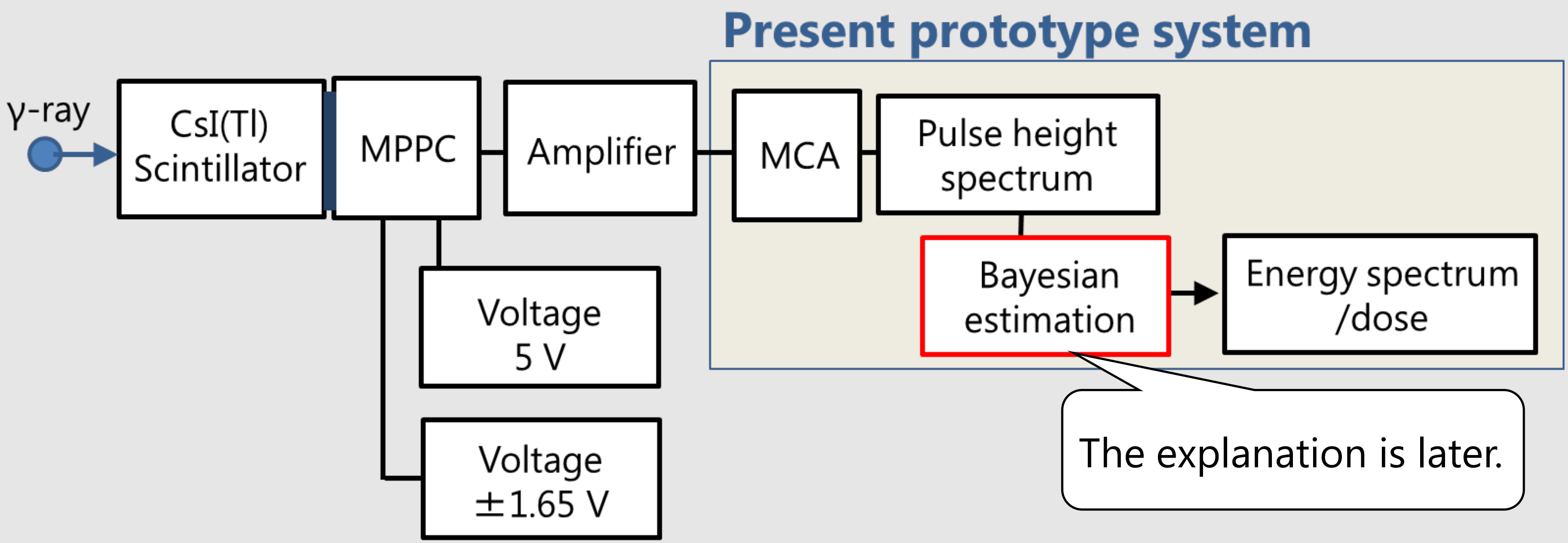
Features of CsI(Tl)

- Conformity of scintillation wavelength of CsI to MPPC
- No deliquescence
- High detection efficiency
- Good energy resolution

CsI(Tl) scintillator
(2.6 x 2.6 x 2.6 cm^3)

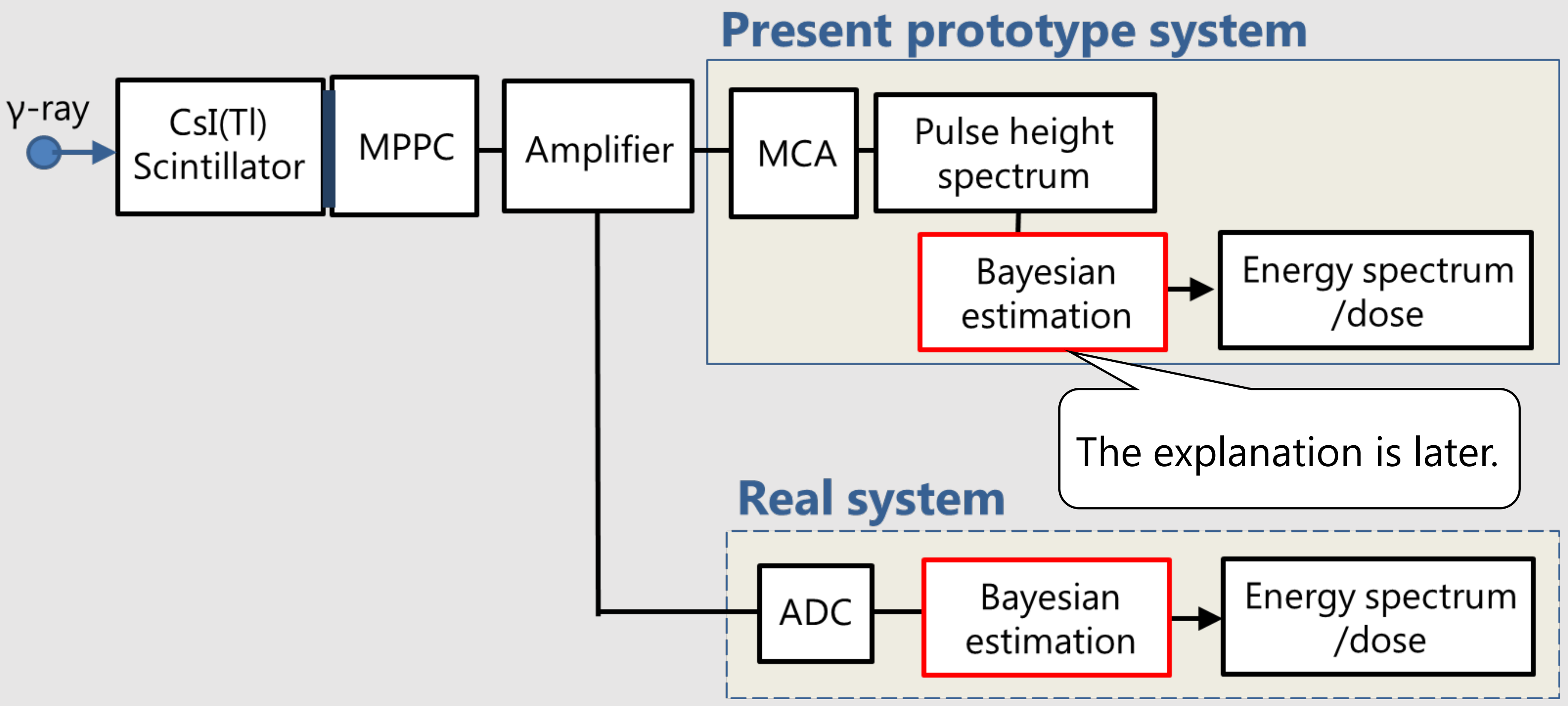
Design of the spectrometer system

Block diagram of the measuring system



Design of the spectrometer system

Block diagram of the measuring system



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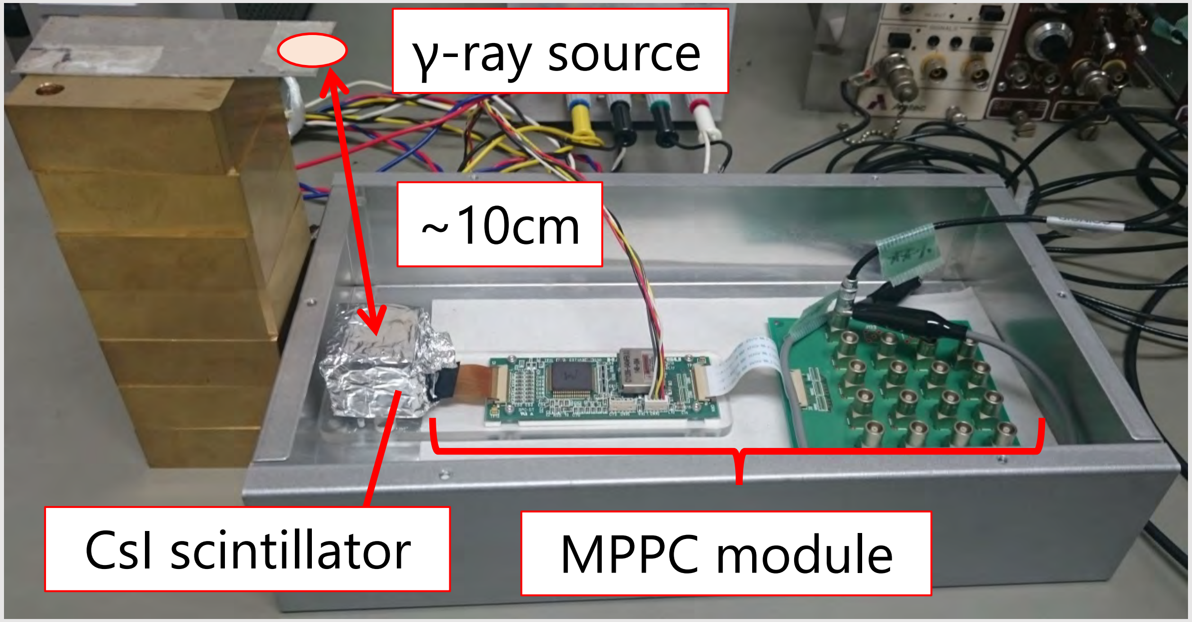
Experiment



Prototype detector system

Standard γ-ray sources

Nuclide	Energy (MeV)
^{22}Na	0.511
	1.274
^{60}Co	1.173
	1.332
^{133}Ba	0.356
^{137}Cs	0.662
^{241}Am	0.059

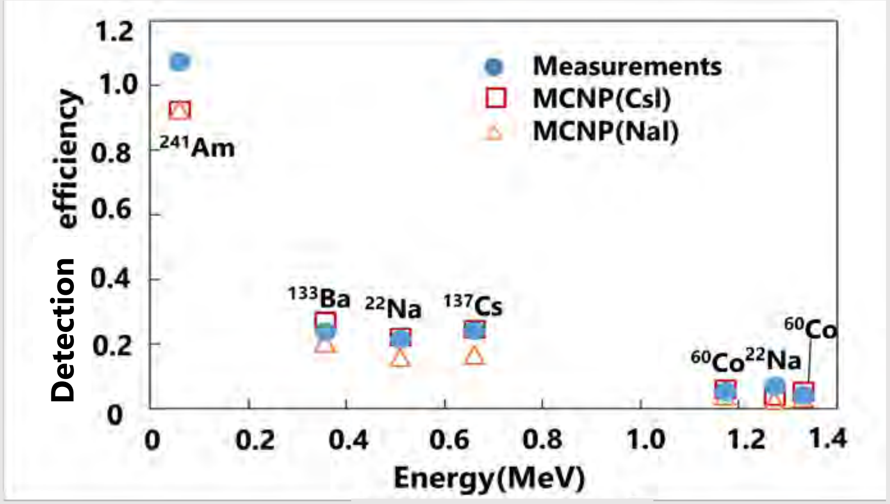
Pulse height spectra were measured with several γ-ray sources

①To compare the detection efficiency with calculation results by MCNP5(Monte Carlo N-Particle Transport Code)

②To check the energy resolution (to confirm energy spectrum reproduction possibility)

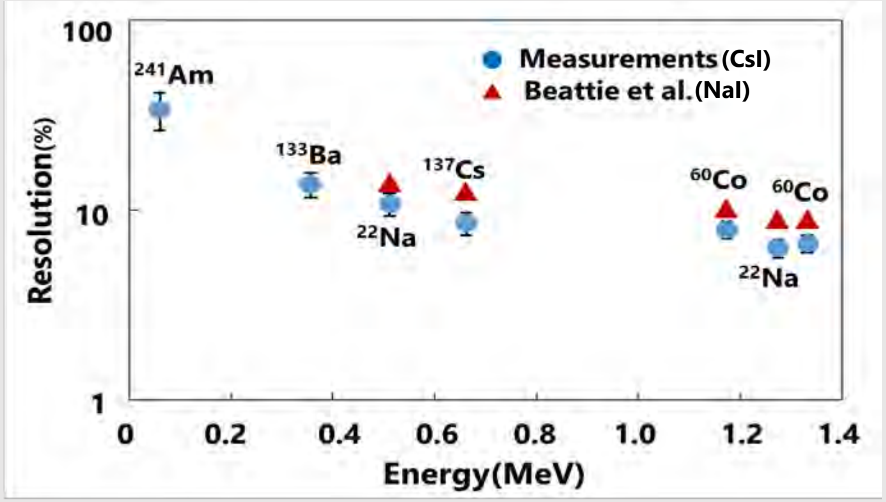
Basic performance of CsI(Tl)

① Detection efficiency



Measured detection efficiency of CsI (●) compared with the simulation result of NaI (△) and CsI (□) by MCNP5.

② Energy resolution



Measured energy resolution of CsI (●) compared with the measured value of NaI (▲).

① The agreement of measured and calculated values is excellent. The detection efficiency of CsI is higher than that of NaI.

② The energy resolution of CsI is better than that of NaI.

➡ CsI has suitable performance for present radiation measurement.

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What is the Bayesian estimation?

◆ Pulse height spectrum → Energy spectrum

We think of the following unfolding problem concerning radiation measurement.

$$\begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} R_{11} & \cdots & R_{1j} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{i1} & \cdots & R_{ij} & \cdots & R_{1m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mj} & \cdots & R_{mn} \end{bmatrix} \cdot \begin{bmatrix} \varphi_1 \\ \vdots \\ \varphi_j \\ \vdots \\ \varphi_n \end{bmatrix}$$

y_i : Pulse height spectrum (measurement)

R_{ij} : Response function (likelihood)

φ_j : Energy spectrum (prior probability)

According to the Bayes' theorem, we can derive the probability of the energy spectrum at $\boldsymbol{j}$, $\boldsymbol{P(j|i)}$, from a measured pulse height signal at pulse height $\boldsymbol{i}$ with the estimated response function of the detector, $\boldsymbol{R_{ij}}$, as in the following equation.

$$P(j|i) = \frac{R_{ij}\varphi_j}{\sum_{j=1}^{N} R_{ij}\varphi_j}$$

Bayesian estimation

a. Spectrum type Bayesian estimation
b. Sequential Bayesian estimation

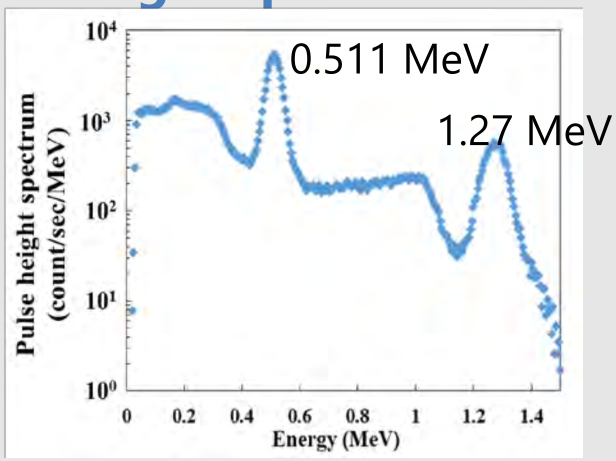
Spectrum type Bayesian estimation

Pulse height spectrum is measured in advance in this method.

$$\varphi'_j = \sum_{i=1} y_i \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

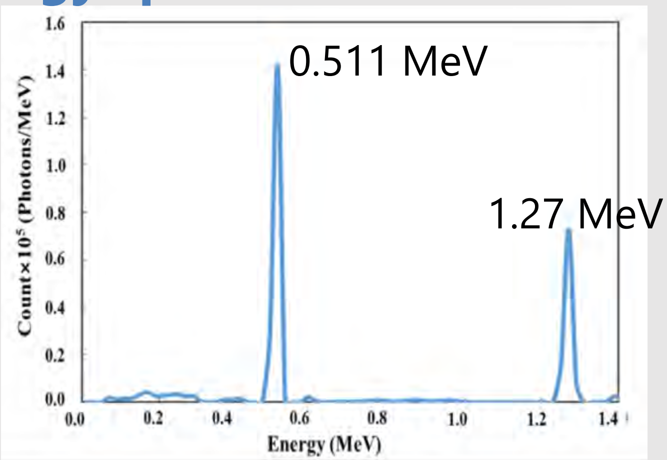
(φ'_j : posterior probability)

Pulse height spectrum



- Gamma-ray source : ^{22}Na
- Measuring time : 230 sec.
- Literature value of emission ratio :
  0.511 MeV :1.27 MeV=1.8:1.

Energy spectrum



- Converged in 1000 times iterations.
- Measured ratio of emitted γ-rays :
  0.511 MeV :1.27 MeV=1.73:1.

○ Proven through applications in the radiation measurement.

× Post-processing method ⇦ not suitable to real time measurement

Sequential Bayesian estimation

The energy spectrum is estimated sequentially for each count during measurement using the following equation.

$$\varphi'_j = (1-\alpha)\varphi_j + \alpha \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

(α is detailed later.)

○ Energy spectrum can be obtained in real time.

! No applications in the radiation measurement

Feasibility of the sequential Bayesian estimation is examined.

Sequential Bayesian estimation

At first, factor α is introduced to adjust the rate of correction to the energy spectrum(prior probability[1]).

$$\varphi'_j = (1-\alpha)\varphi_j + \alpha \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

Procedure to determine α value (for standard γ-rays source)

- ✓ Deviation between measured pulse height spectrum and folding spectrum of energy spectrum obtained by unfolding the measured pulse height spectrum
- ✓ Reproducibility of the emission rate of discrete γ-rays after unfolding

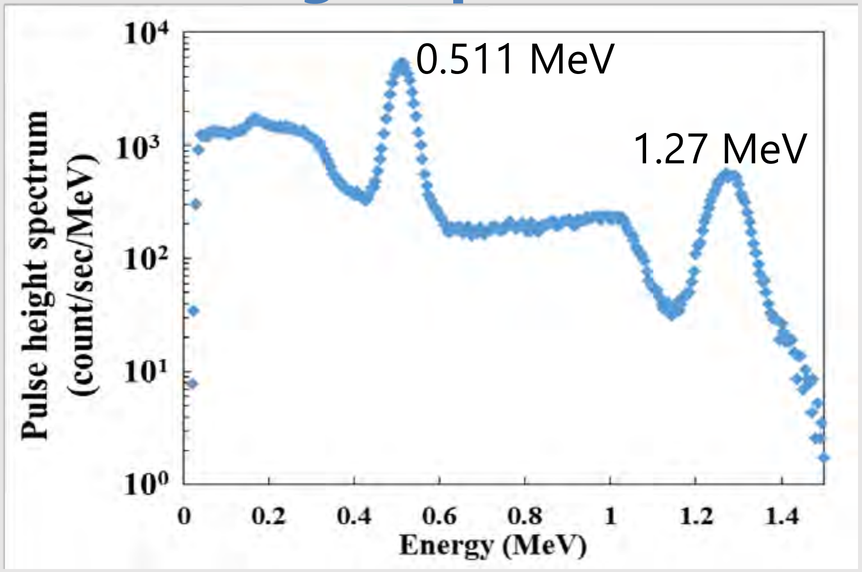
$\alpha \leqq 0.1$

(If α ＞0.1, deviation shows always larger for any number of measuring counts compared to cases for α≦0.1.)

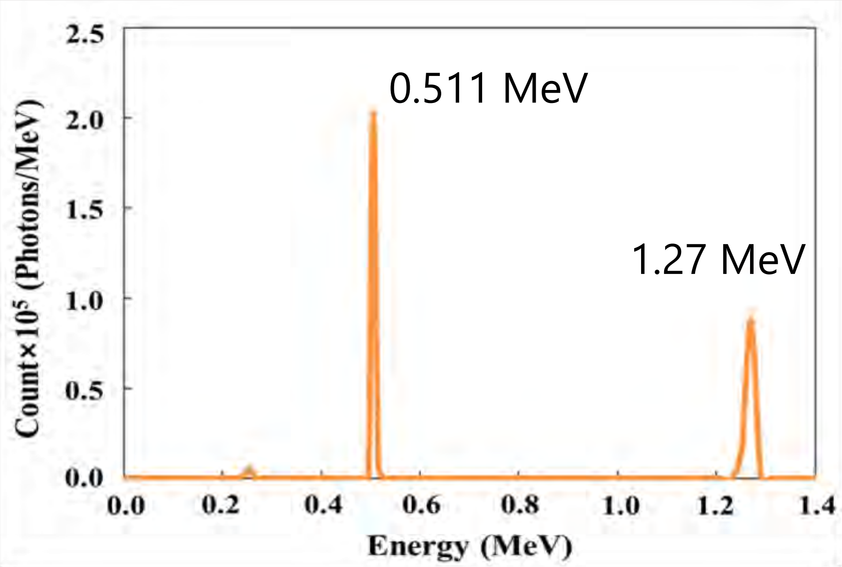
1) S. Iwasaki, *A new approach for unfolding problems based only on the Bayes' Theorem, Proceedings of the 9th International Symposium on Reactor Dosimetry*, pp. 245-252 (1996)

Sequential Bayesian estimation (example)

Pulse height spectrum



Energy spectrum



- Gamma-ray source : ^{22}Na
- Measuring time : 230 sec.
- Literature value of emission ratio : **0.511 MeV :1.27 MeV=1.8:1.**

- The α value is 0.05.
- Ratio converged at 5×10^4 counts.
- Measured ratio of emitted γ-rays : **0.511MeV :1.27MeV=1.99:1**.

It was confirmed that the sequential Bayesian estimation would have a potential ability to apply to spectrum estimation.

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Flow of Spectrum and Dose Evaluation Test

✔First step : Standard γ-ray source (^{22}Na)

- Spectrum (511 keV and 1.274 MeV γ-rays)
- Dose comparison with theory and survey meter

✔Second step : Nuclear fuel (UO_2) storage room

- Spectrum (continuously energetic γ-rays)
- Dose comparison with survey meter

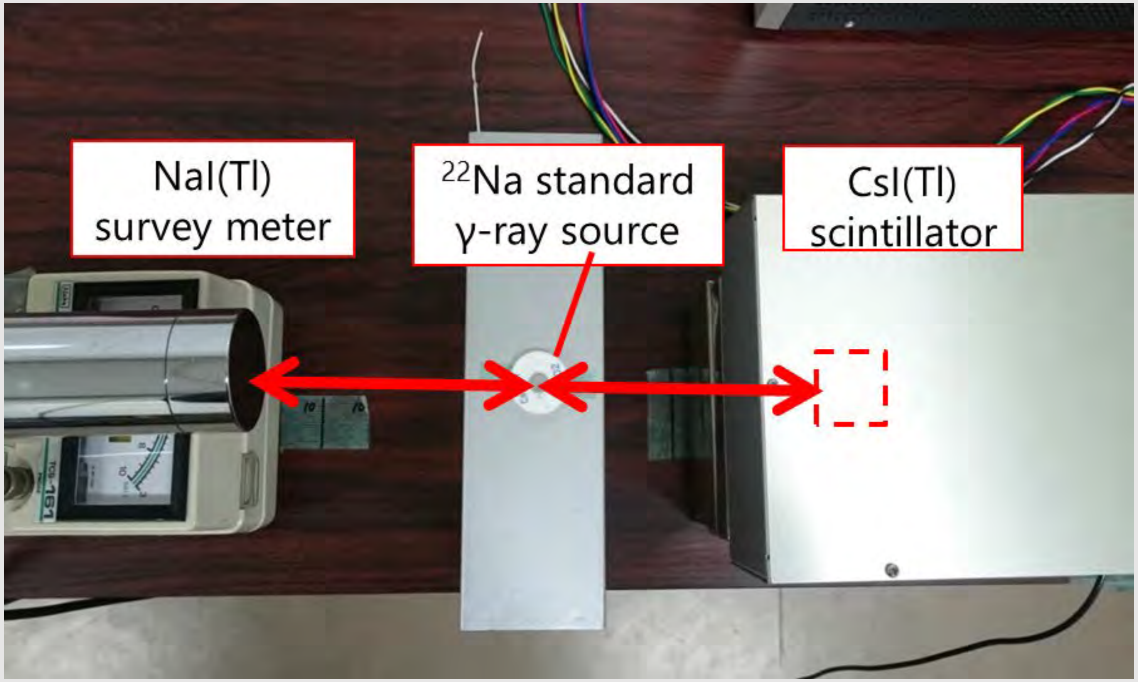
↓

Verification of the sequential Bayesian estimation method for spectrum & dose measurement system in real time.

Dose evaluation

◆ **Pulse height spectrum → Energy spectrum → Dose**

➢ First step : Standard γ-ray source



Measurement condition

- γ-ray source : ^{22}Na
- Distance : 20 cm
- Measuring time : every 60 sec.

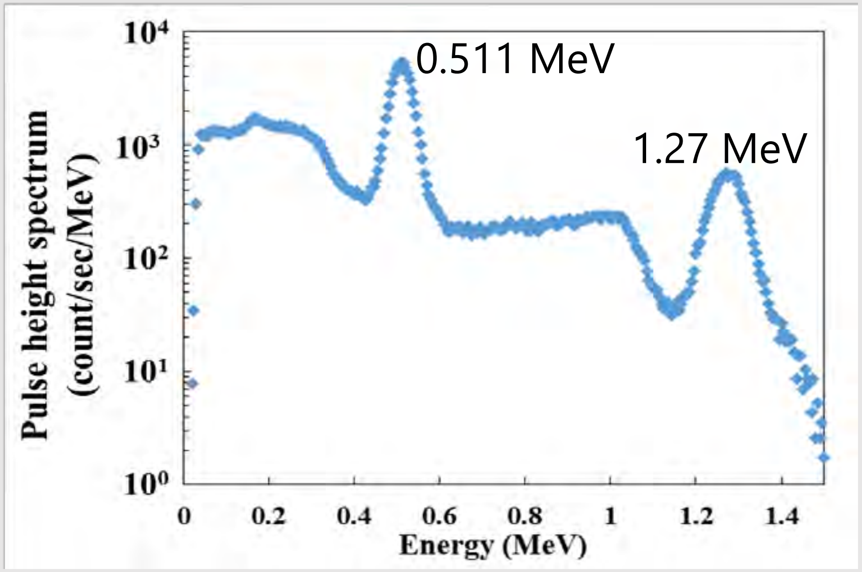
➢ Second step : Continuously energetic γ-rays (Nuclear fuel storage room in OKTAVIAN facility)

The dose was derived from the sequential Bayesian estimation with three kinds of α values (α=0.01, 0.05, 0.1).

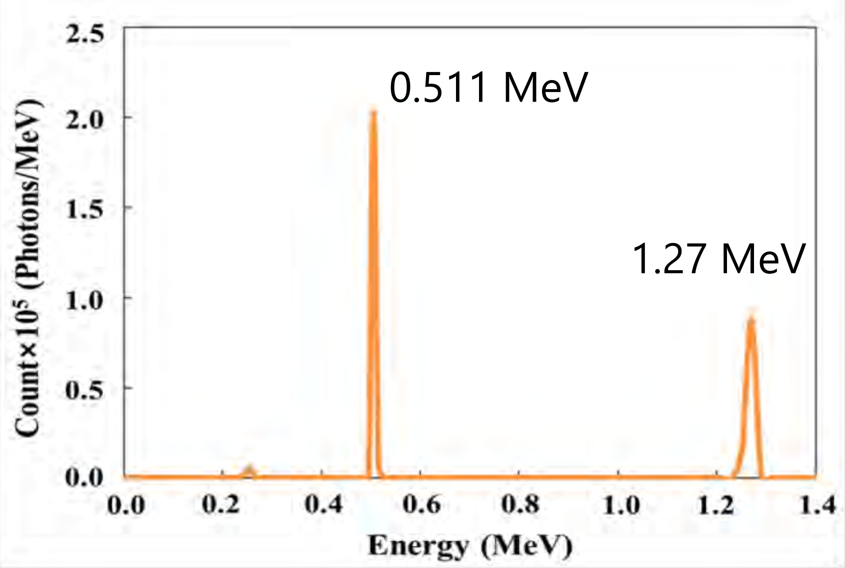
Pulse height spectrum → Energy spectrum ①

➢ First step : Standard γ-ray source (^{22}Na)

Pulse height spectrum



Energy spectrum

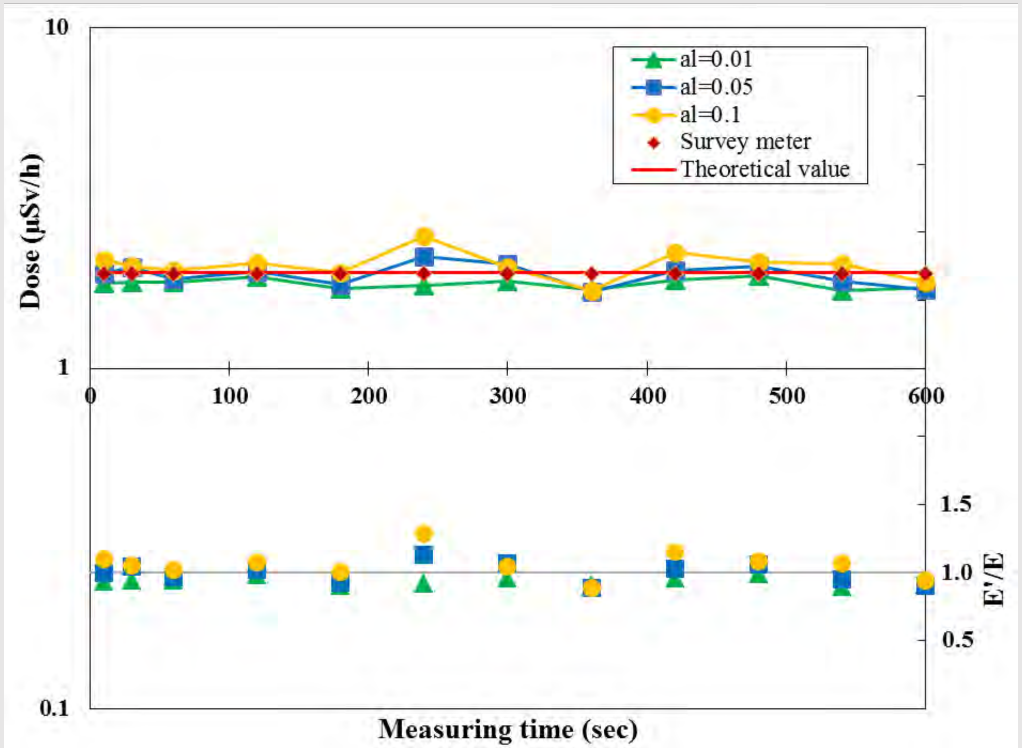


- Gamma-ray source : ^{22}Na
- Measuring time : 230 sec.

- The ***α*** value is 0.05.
- 1.5×10^4 counts.

Energy spectrum → Dose ①

➢ First step : Standard γ-ray source (^{22}Na)



Dose comparison between
① **the dose** derived from **the sequential Bayesian estimation** with three kinds of α values (α=0.01, 0.05, 0.1) (E')
and
② **survey meter value** (E).

The dose derived from the sequential Bayesian estimation was confirmed to be in good agreement with the survey meter value regardless of the α values less than 0.1.

Dose evaluation(Nuclear fuel storage room)

- Second step : Continuously energetic γ-rays

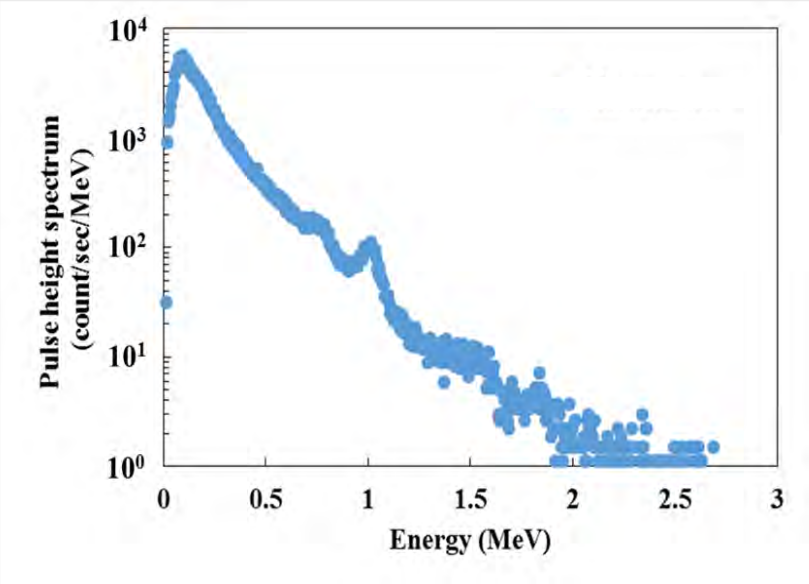
  Dose measurement was carried out in the nuclear storage room in OKTAVIAN facility of Osaka University.

Two tons natural uranium (UO_2) stored in this rack

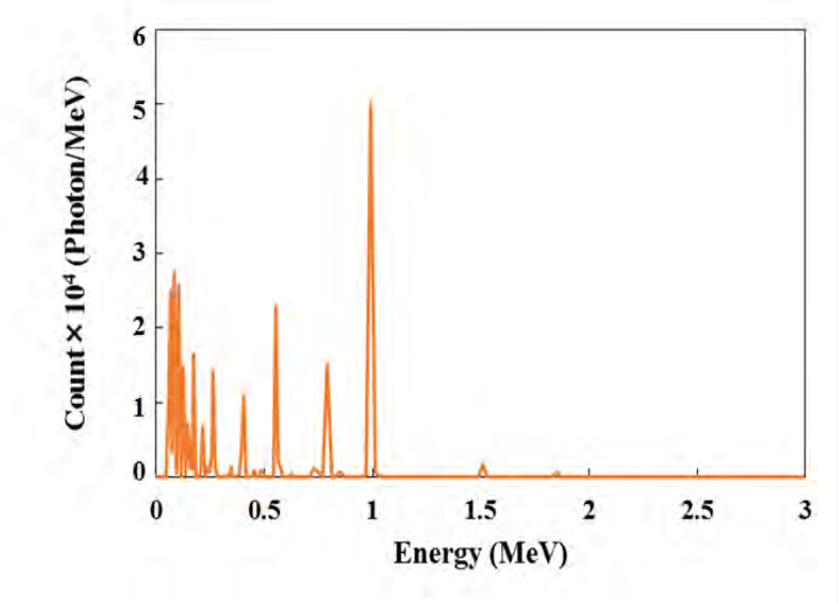
Pulse height spectrum → Energy spectrum ②

➢ Second step : Continuously energetic γ-rays

Pulse height spectrum



Energy spectrum



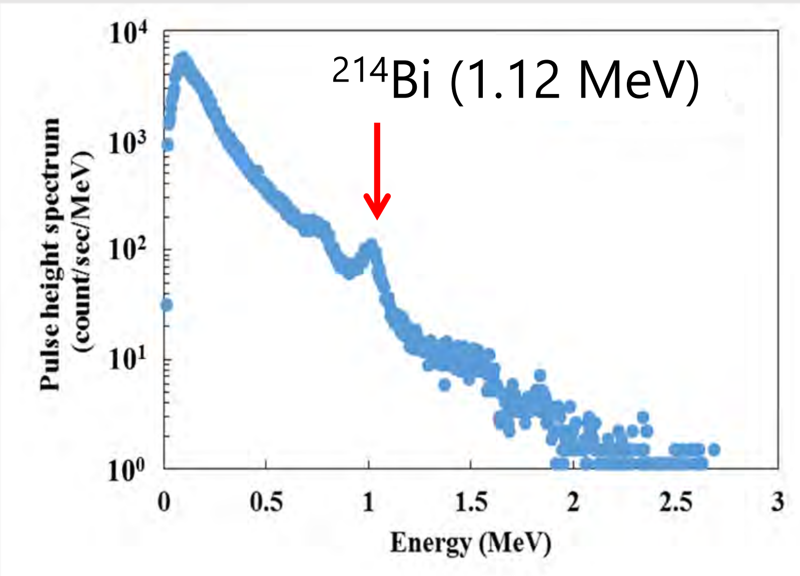
- Gamma-ray source
  : Nuclear fuel storage room
  (Natural uranium (UO_2), 2 tons)
- Distance : 3.25 m
- Measuring time : 540 sec.

- The ***α*** value is 0.05.
- 6.4×10^5 counts.

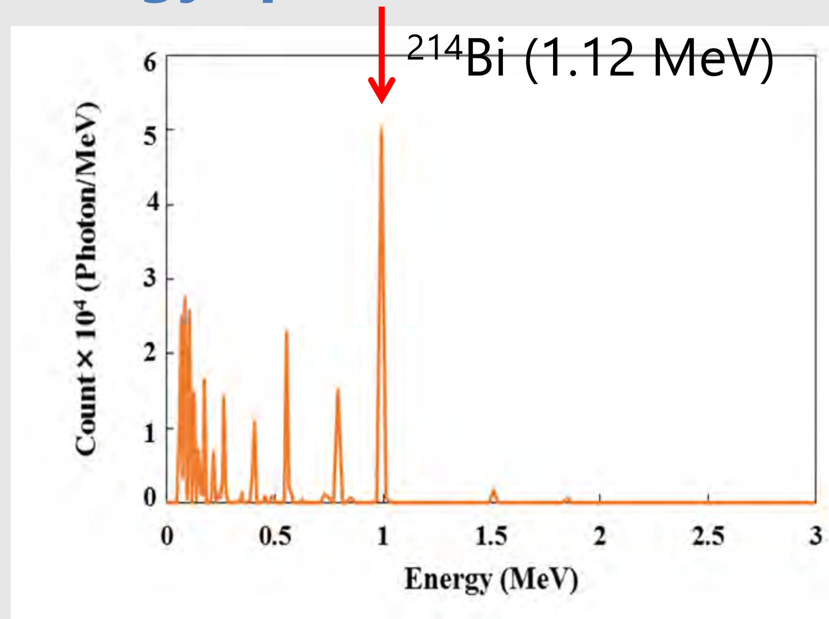
Pulse height spectrum → Energy spectrum ②

- Second step : Continuously energetic γ-rays

Pulse height spectrum



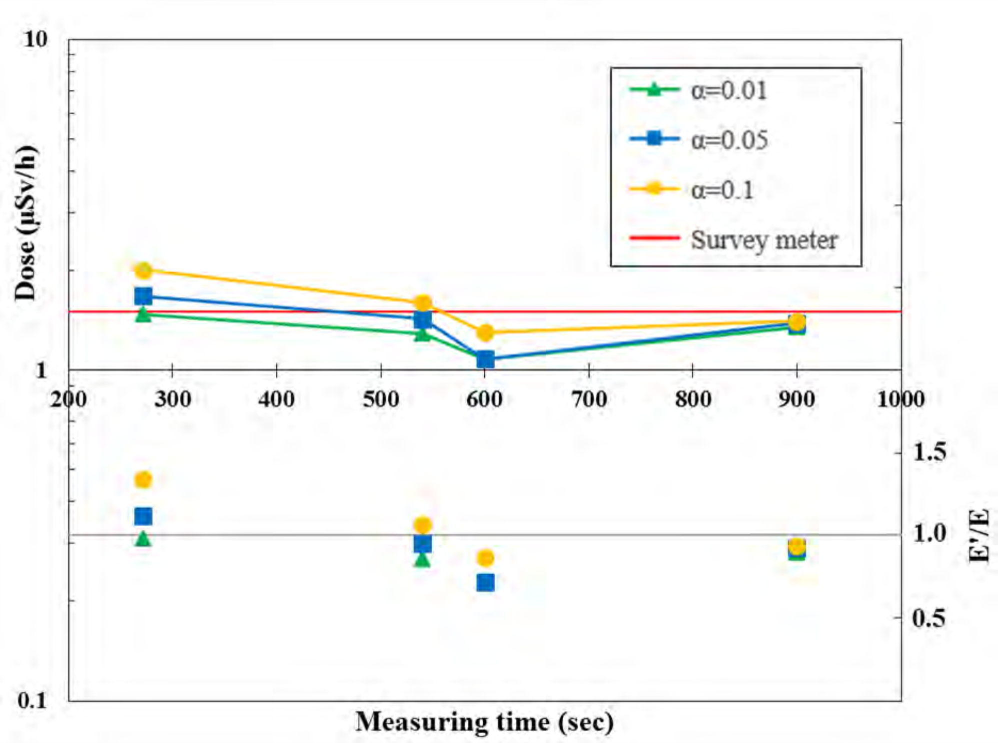
Energy spectrum



^{214}Bi(1.12MeV) peak in the pulse height spectrum is reproduced in the obtained energy spectrum. However the spectrum reproducibility of other peaks is not finally confirmed from this measurement. Nevertheless, we expect that dose could be evaluated from right figure.

Energy spectrum → Dose ②

➢ Second step : Continuously energetic γ-rays



Dose comparison between

① **the dose** derived from **the sequential Bayesian estimation** with three kinds of α values (α=0.01, 0.05, 0.1) (E')

and

② **survey meter value** (E).

The measured dose approaches the survey meter value regardless of the α values and with increase of the measuring time.

⇒This method has a potential ability to apply to γ-ray spectrum & dose estimation in real time with a suitable α value.

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Future work

- Optimize a suitable α value to make estimation convergence of energy spectrum and dose faster; with the number of counts as few as possible.
- Confirm the spectrum reproducibility with measurement in the nuclear fuel storage room by Germanium semiconductor detector.

After that

- Develop an actual spectrometer with real time data processing.
- Examine the minimum measuring time to be able to show an accurate energy spectrum.
- Compare the dose derived from the sequential Bayesian estimation with the dose estimated by G(E) function[2)].

2) S. Tsuda, M. Tsutsumi, *Calculation and Verification of the Spectrum – Dose Conversion Operator of Various CsI(Tl) Scintillation Counter for Gamma-ray, Japanese Journal of Health Physics,* ***47****(4)*, pp. 260-265 (2012)

Conclusion

- Basic characteristics of CsI(Tl) scintillator (2.6 x 2.6 x 2.6 cm^3) was examined.
  ⇒ CsI(Tl) can be utilized for the present spectrometer system.
- A prototype measuring system was designed and assembled.
- The possibility of data processing in real time was examined by application of the sequential Bayesian estimation.
  I. By comparison of the emission ratio of ^{22}Na γ-ray source with the literature value, it was confirmed that the system has an ability to estimate energy spectrum.
  II. The doses derived from ^{22}Na γ-ray source and nuclear fuel storage room were confirmed to be in good agreement with the survey meter values.

⇒ It was confirmed that <u>the present spectrometer system with the sequential Bayesian estimation has a potential ability to apply to real time and simultaneous γ-ray spectrum and dose estimation with a suitable α value.</u>

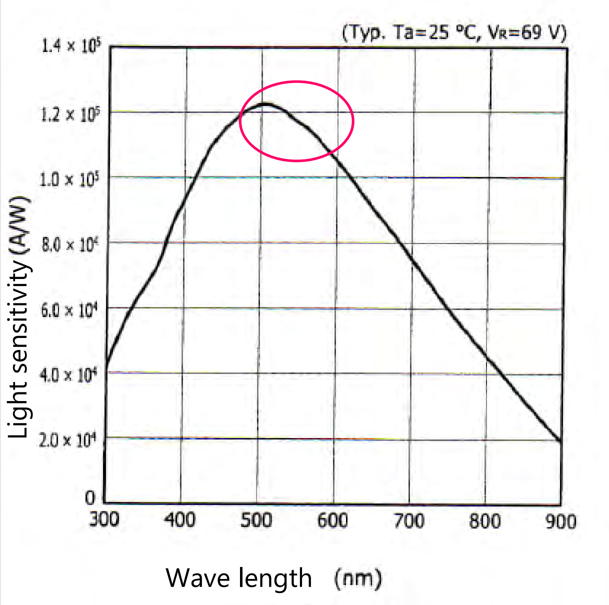
Appendix

CsI(Tl) & MPPC

Features of CsI(Tl)

- Conformity of scintillation wavelength of CsI to MPPC
- No deliquescence
- High detection efficiency
- Good energy resolution
- Scintillation wave length 500~600 nm

Characteristic of MPPC



Sequential Bayesian estimation (α method)

Factor α is introduced to adjust the rate of correction to the prior probability[1].

$$\varphi'_j = (1-\boldsymbol{\alpha})\varphi_j + \boldsymbol{\alpha}\frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

Initial spectrum of φ_j is arbitrary.

α =0.05

$$\varphi'_j = 0.95 \cdot \varphi_j + 0.05 \cdot \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

Before spectrum | New count

Contribution : 95 % | 5 %

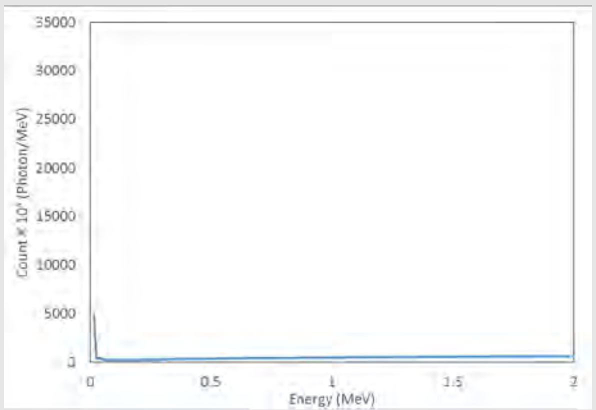
New counts always have a constant contribution (e.g. 5 %).

1) S. Iwasaki, *A new approach for unfolding problems based only on the Bayes' Theorem, Proceedings of the 9th International Symposium on Reactor Dosimetry*, pp. 245-252 (1996)

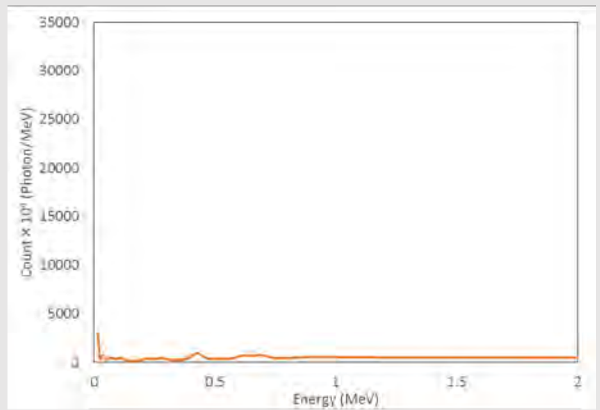
Sequential Bayesian estimation

- γ-ray source : ^{137}Cs
- Distance : 20 cm

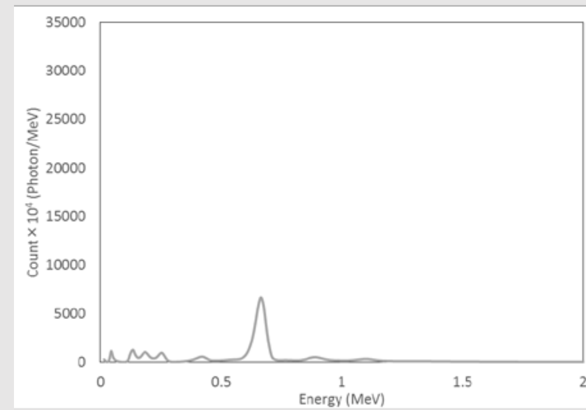
1 count



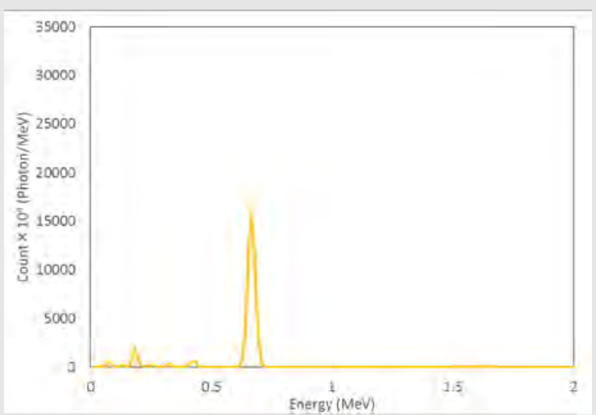
10 counts



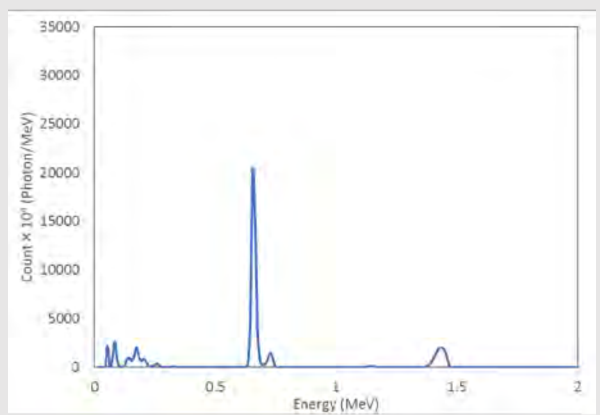
100 counts



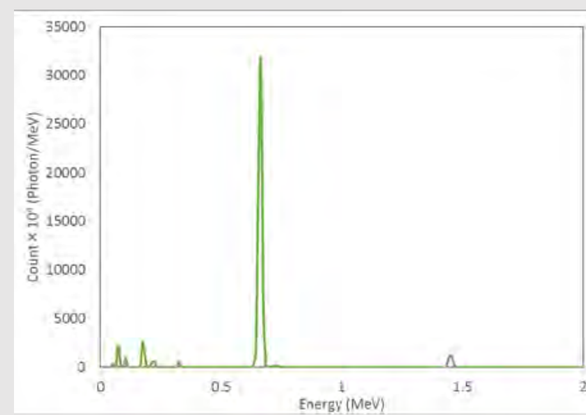
1000 counts



10000 counts



100000 counts



Sequential Bayesian estimation

Factor α is introduced to adjust the rate of correction to the prior probability[1].

$$\varphi'_j = (1-\alpha)\varphi_j + \alpha \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

Initial spectrum of φ_j *is* arbitrary.

Without α value

$$\varphi'_j = \varphi_j + \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

1 count

$$\varphi'_j = \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

2 counts

$$\varphi'_j = 0.5 \cdot \varphi_j + 0.5 \cdot \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

⋮

The contribution of new count decreases as the number of count increases.

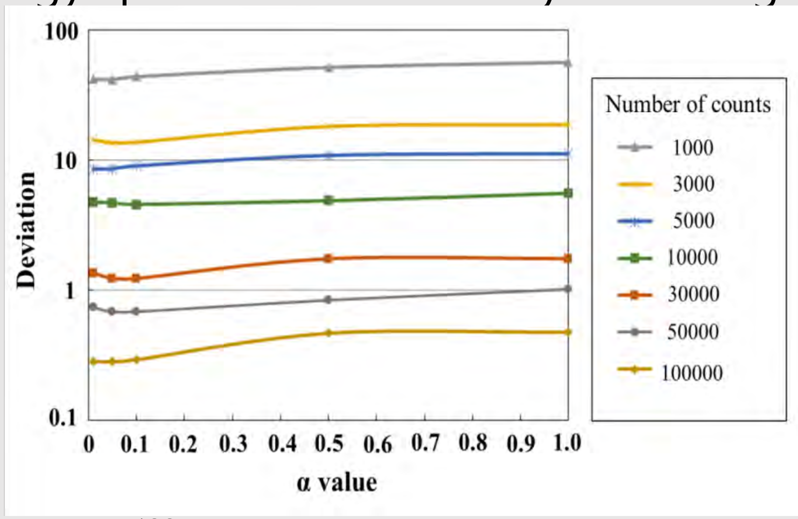
100 counts

$$\varphi'_j = 0.99 \cdot \varphi_j + 0.01 \cdot \frac{R_{ij}\varphi_j}{\sum_{j=1}^{n} R_{ij}\varphi_j}$$

1) S. Iwasaki, *A new approach for unfolding problems based only on the Bayes' Theorem, Proceedings of the 9th International Symposium on Reactor Dosimetry*, pp. 245-252 (1996)

The α value condition

- ✓ Deviation between measured pulse height spectrum(M_i) and folding spectrum(y_i) of energy spectrum obtained by unfolding the measured pulse height spectrum



Deviation for ^{133}Ba for various numbers of counts as a function of α.

Deviation

$$1/N\sqrt{\sum_i (M_i - y_i)^2}$$

N : the total number of counts

- ✓ Reproducibility of the emission rate of discrete γ-rays after unfolding

Nuclide	Energy (MeV)	The spectrum type Bayesian estimation (1000 times iterations)	The sequential Bayesian estimation (10000 counts)			The sequential Bayesian estimation (50000 counts)			The sequential Bayesian estimation (100000 counts)		
			α=0.01	α=0.05	α=0.1	α=0.01	α=0.05	α=0.1	α=0.01	α=0.05	α=0.1
^{22}Na	0.511	1.41	1.25	1.09	0.98	1.28	1.16	1.07	1.51	1.16	1.10
	1.274	1.36	1.55	1.61	1.74	1.46	1.28	1.27	1.10	1.06	1.10
^{60}Co	1.173	1.31	1.38	1.29	1.23	1.20	1.38	1.54	1.19	1.03	0.92
	1.332	1.28	1.32	1.36	1.25	1.40	1.06	0.87	1.27	1.15	1.20
^{133}Ba	0.356	0.72	0.80	0.77	0.60	0.76	0.68	0.48	0.65	0.54	0.49
^{137}Cs	0.662	0.81	0.82	0.75	0.73	0.80	0.71	0.68	0.77	0.69	0.68
Variance of C/E		0.10	0.11	0.12	0.15	0.10	0.07	0.13	0.09	0.06	0.07

Variance

$$1/N'\sum (C/E - 1)^2$$

N' : the number of data

Comparison of the number of emitted γ-rays (C/E) estimated by both Bayesian methods at 1×10^3 times iterations or 1×10^4, 5×10^4 and 1×10^5 counts and variance of C/E.

Dose evaluation (E'/E)

Dose comparison between the dose derived from the sequential Bayesian estimation with three kinds of α values (α=0.01, 0.05, 0.1) (E') and survey meter value (E).

➢ Monochromatic γ-ray source (^{137}Cs)

Measuring time (sec.)	α=0.01	α=0.05	α=0.1
10	0.89	0.95	1.07
30	0.93	1.05	1.14
60	0.96	1.06	1.15
120	0.89	1.02	1.12
180	0.97	1.27	1.47
240	0.91	1.12	1.25
300	0.90	0.94	0.98
360	0.91	1.04	1.20
420	0.85	0.92	1.01
480	0.89	0.87	0.96
540	0.97	1.11	1.18
600	0.82	0.88	0.99
Average	0.91	1.02	1.13

➢ Mixed field of various energetic γ-rays (Nuclear fuel storage room)

Measuring time (sec.)	α=0.01	α=0.05	α=0.1
271	0.99	1.12	1.34
540	0.86	0.95	1.07
600	0.72	0.72	0.87
900	0.90	0.92	0.94
Average	0.87	0.93	1.05

	Count rate	Dose
^{137}Cs (20 cm)	225 cps	1.7 μSv/h
Nuclear fuel storage room	1070 cps	1.5 μSv/h

$$\text{Dose [Sv]} = \sum_{j=1}^{N} \varphi_j \times D_j$$

D_j: Flux to dose conversion factor

Estimation of energy spectrum

By estimate energy spectrum,

- The energy information in the field is understood.
- The correct dose is evaluated.
- If the room becomes contaminated, it is possible to find the reason.

Uranium series

	Energy (MeV)	放出割合 (%)
^{214}Pb	0.0532	1.2
	0.242	7.43
	0.295	19.3
	0.352	37.6
^{214}Bi	0.609	46.1
	0.768	4.94
	1.12	15.1
	1.238	5.79
	1.765	15.4
	2.204	5.08

Nuclear fuel storage room(detail)

- Second step : Continuously energetic γ-rays

Dose measurement was carried out at the nuclear storage room in OKTAVIAN facility of Osaka University.

UO_2 (natural)

- 550 rods
- 37 compacts / rod

U amount:

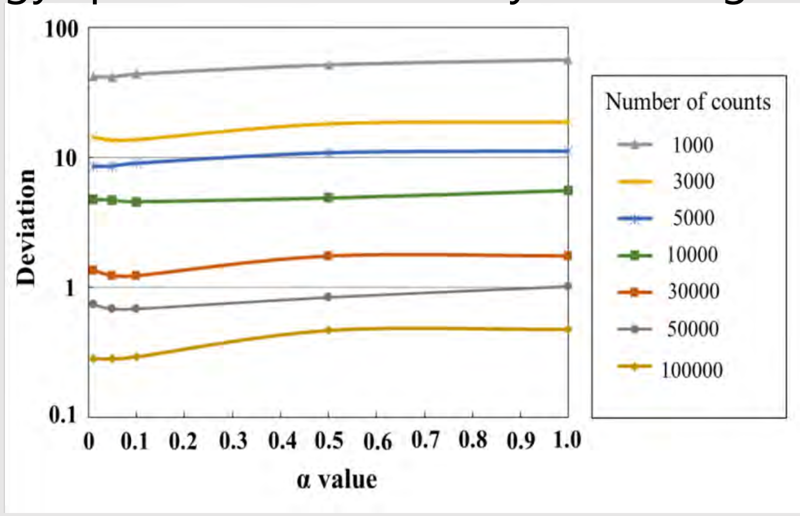
～104 g / compact

～3.8 kg / rod

～2.1 ton / 550 rods

The α value condition

- ✓ Deviation between measured pulse height spectrum and folding spectrum of energy spectrum obtained by unfolding the measured pulse height spectrum



- The deviation becomes less than 1% in 5×10[4] counts, moreover, large for α > 0.1.
- A similar tendency was seen for other nuclides as well.

⇒ **α** ≦0.1

Deviation for ^{133}Ba for various numbers of counts as a function of α.

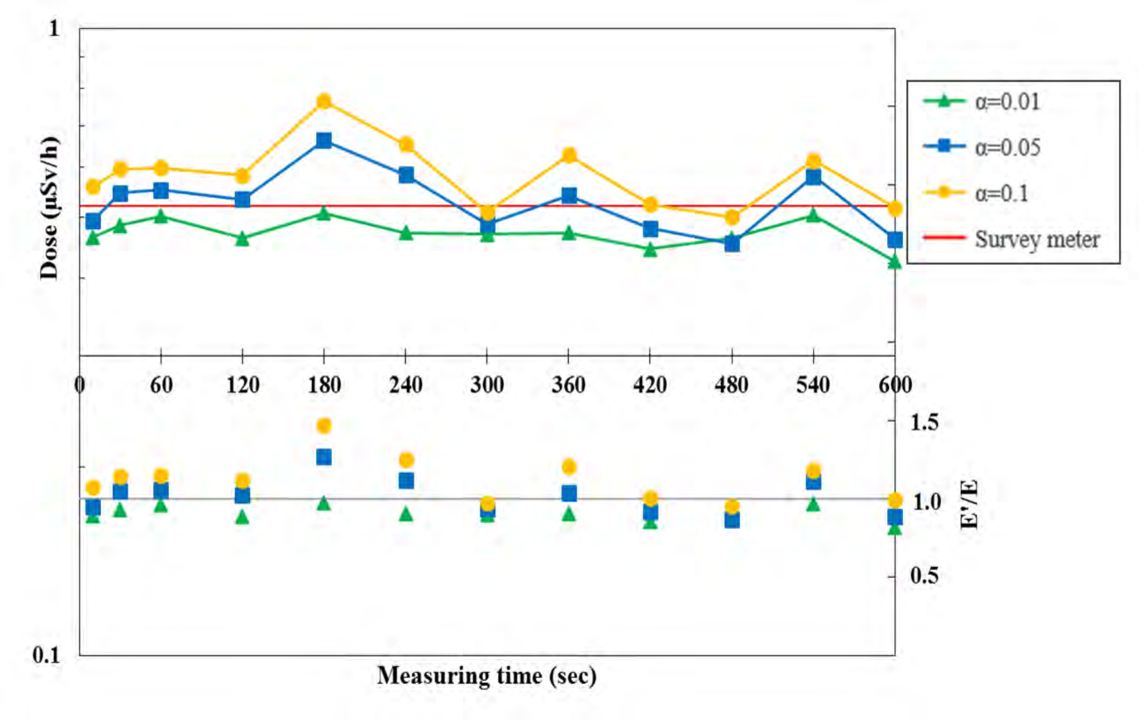
- ✓ Reproducibility of the emission rate of discrete γ-rays after unfolding

Nuclide	Energy (MeV)	The spectrum type Bayesian estimation (1000 times iterations)	The sequential Bayesian estimation (10000 counts)			The sequential Bayesian estimation (50000 counts)			The sequential Bayesian estimation (100000 counts)		
			α=0.01	α=0.05	α=0.1	α=0.01	α=0.05	α=0.1	α=0.01	α=0.05	α=0.1
^{22}Na	0.511	1.41	1.25	1.09	0.98	1.28	1.16	1.07	1.51	1.16	1.10
	1.274	1.36	1.55	1.61	1.74	1.46	1.28	1.27	1.10	1.06	1.10
^{60}Co	1.173	1.31	1.38	1.29	1.23	1.20	1.38	1.54	1.19	1.03	0.92
	1.332	1.28	1.32	1.36	1.25	1.40	1.05	0.87	1.27	1.15	1.20
^{133}Ba	0.356	0.72	0.80	0.77	0.60	0.76	0.68	0.48	0.65	0.54	0.49
^{137}Cs	0.662	0.81	0.82	0.75	0.73	0.80	0.71	0.68	0.77	0.69	0.68
Variance of C/E		0.10	0.11	0.12	0.15	0.10	0.07	0.13	0.09	0.06	0.07

Comparison of the number of emitted γ-rays (C/E) estimated by both Bayesian methods at 1×10^3 times iterations or 1×10^4, 5×10^4 and 1×10^5 counts and variance of C/E.

Dose evaluation ①

➢ First step : Monochromatic γ-ray source (^{137}Cs)



Dose comparison between
① **the dose** derived from **the sequential Bayesian estimation** with three kinds of α values (α=0.01, 0.05, 0.1) (E′)
and
② **survey meter value** (E).

The dose derived from the sequential Bayesian estimation was confirmed to be in good agreement with the survey meter value regardless of the α values and with increase of the measuring time.