

これまでの研究業績

1. ^{90}Sr Counter 開発研究
2. J-PARC E36 実験

千葉大学
2017. 08. 24
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1. ^{90}Sr Counter 開発研究

1. ^{90}Sr Counter 開発研究

背景

- 福島原発後、福島漁業が未だ再開しない、原因の一つは ^{90}Sr
- ^{90}Sr は骨に蓄積するため ^{137}Cs と比較して摂取は危険
- 新鮮な海産物の短時間での ^{90}Sr 放射能濃度測定が要求

目的

- 1時間で数十Bq/kgの ^{90}Sr を測定するために低バックグラウンド
- ^{40}K からの β 線や宇宙線 μ 由来の雑音を抑制
- 大面積の有効面積

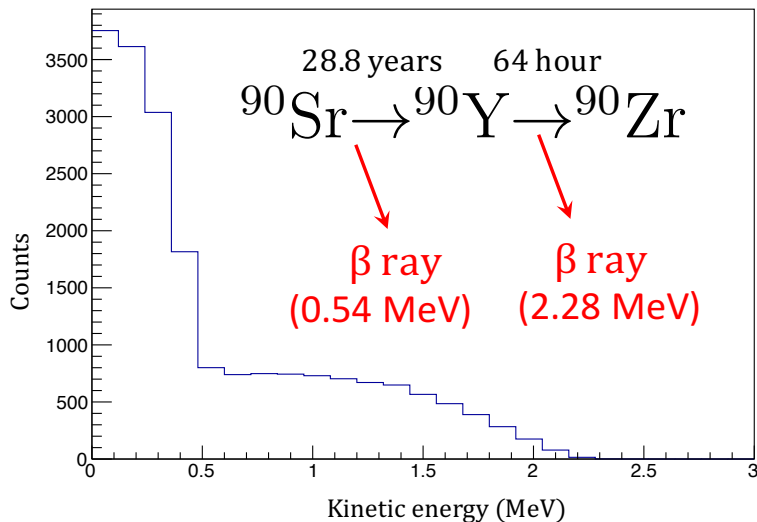


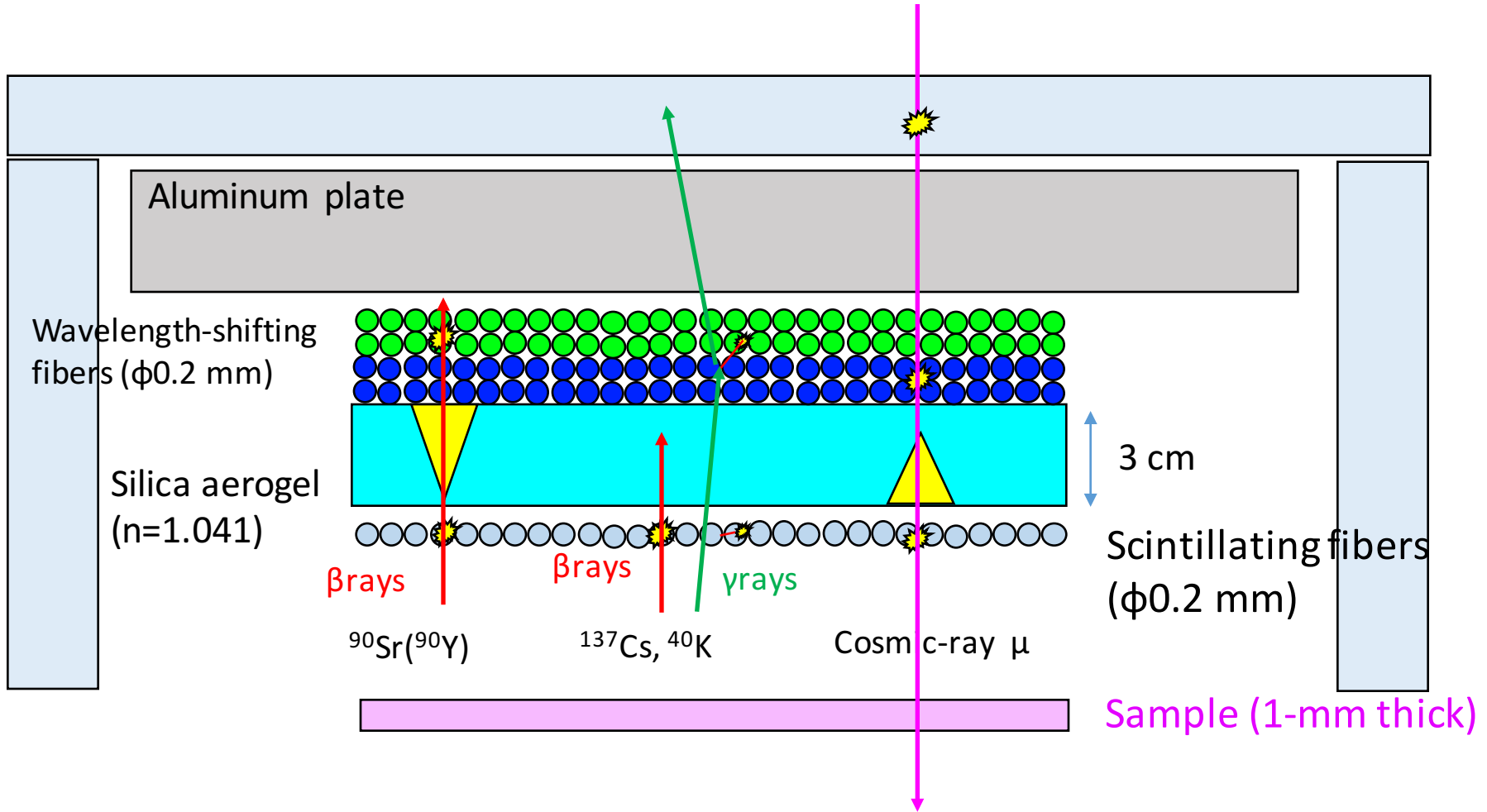
Fig. 1.1: Energy spectrum of β ray from ^{90}Sr and ^{90}Y .

Dose coefficient by ICRP publ.

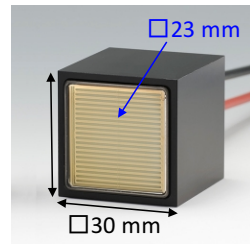
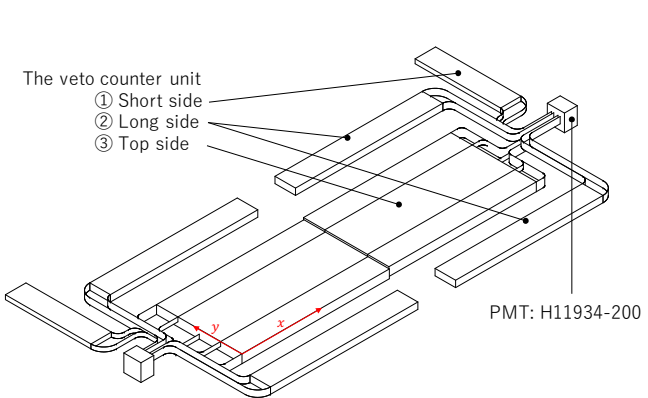
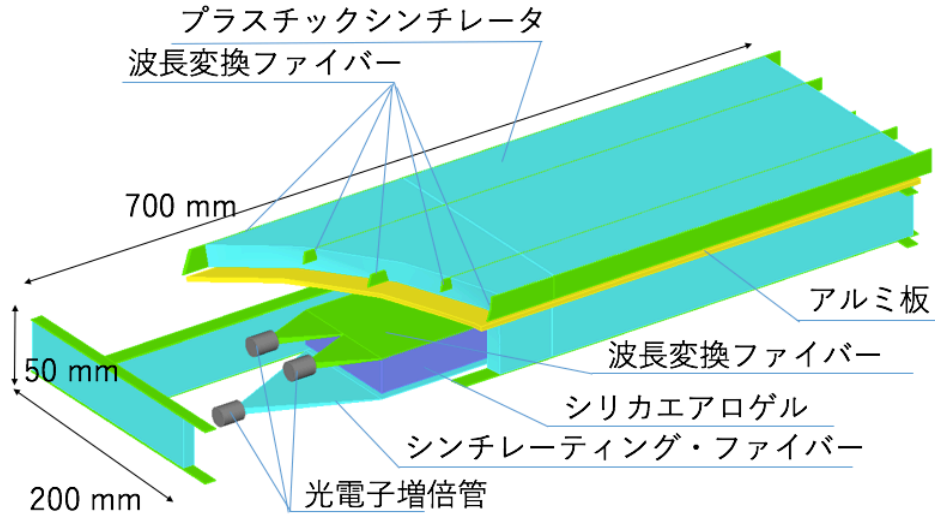
	^{90}Sr (^{90}Y)	^{137}Cs
Eff. Coeff. (Sv/Bq) (Adult)	2.4×10^{-8}	4.6×10^{-9}
Red Marrow		
Dose Coeff. (Sv/Bq) (Adult)	1.6×10^{-7}	4.4×10^{-9}
(Infant)	8.6×10^{-7}	6.8×10^{-9}

1. ^{90}Sr Counter 開発研究

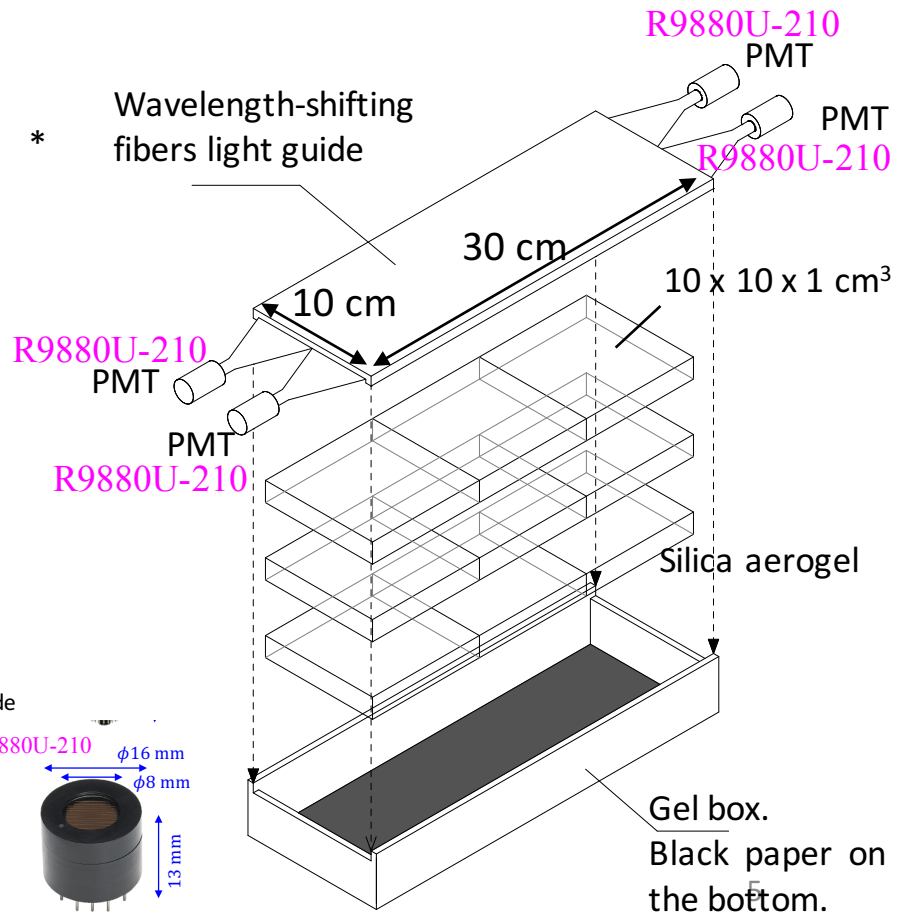
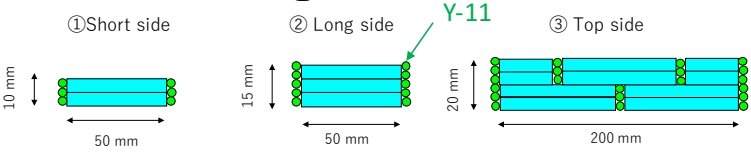
装置設計 概念図



1. ^{90}Sr Counter 開発研究

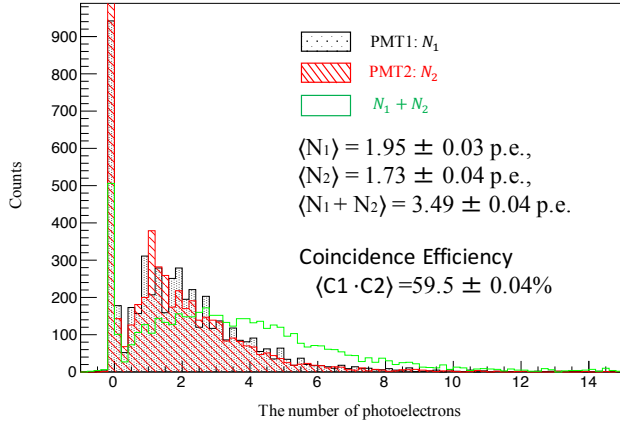


- Photocathode
 - □23 mm
 - Ultra Bialkali
- Metal Channel Dynode

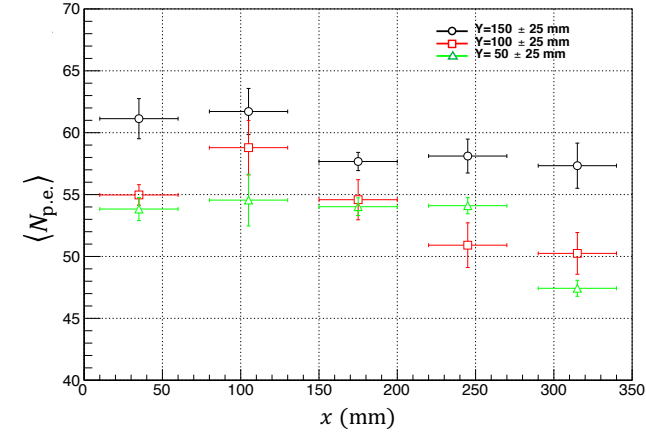
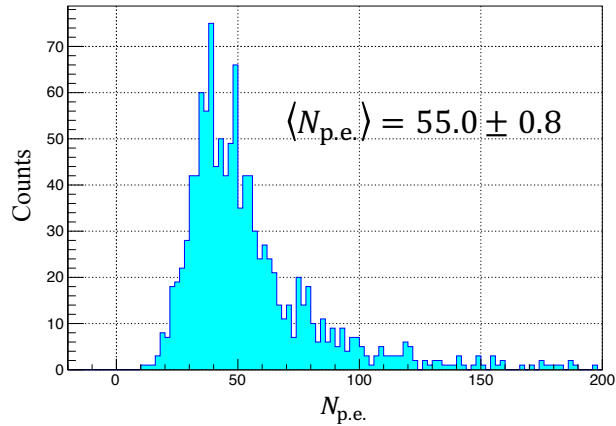


1. ^{90}Sr Counter 開発研究

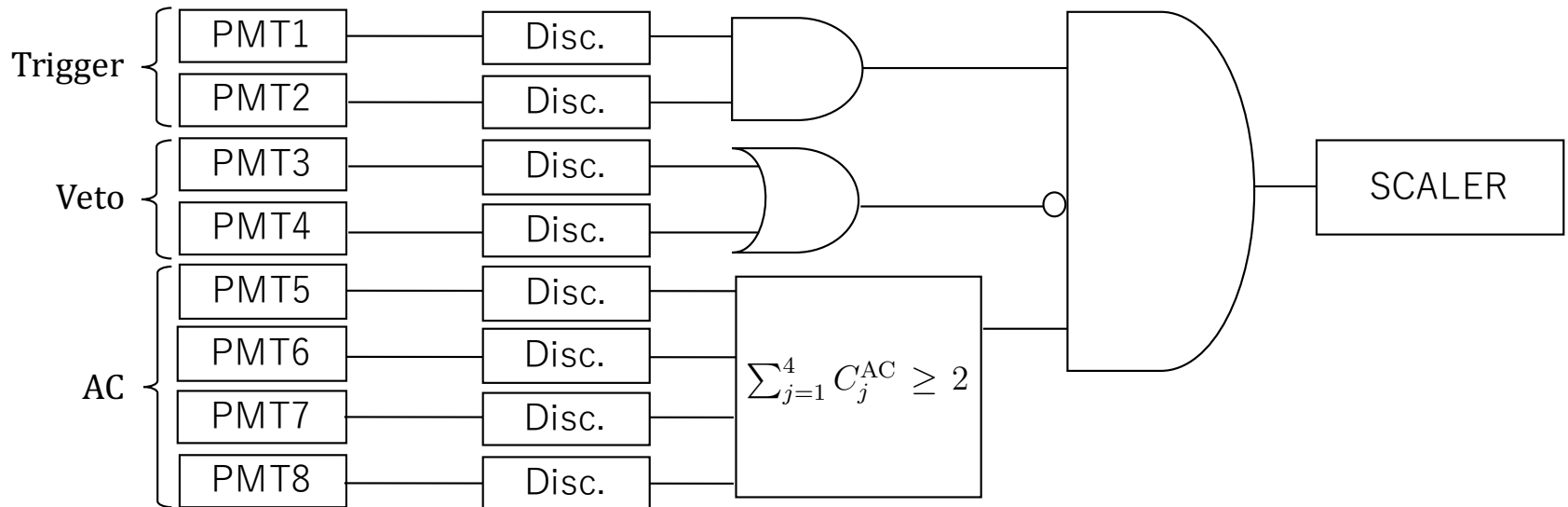
Trigger counter performance



Cosmic-ray veto counter performance



回路設計



1. ^{90}Sr Counter 開発研究

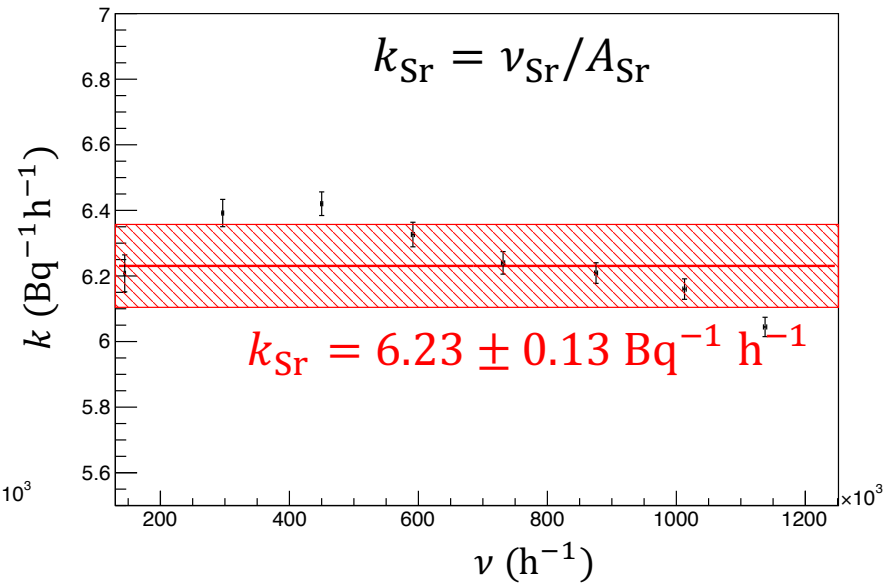
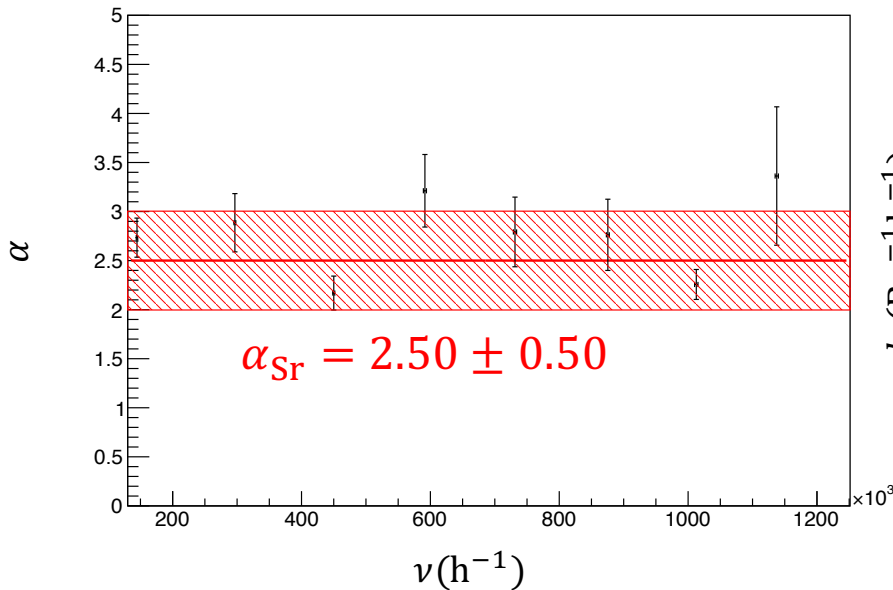
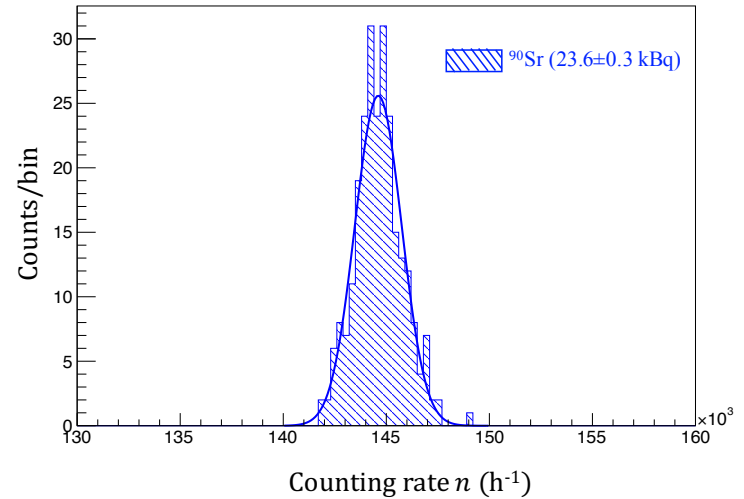
線源を用いた性能評価測定

$$\langle \Gamma_{\text{BG}}(n) \rangle \ll \langle \phi_{\text{Sr}}(n) \rangle \Rightarrow \Gamma_{\text{Sr}}(n) \approx \phi_{\text{Sr}}(n)$$

$$\Gamma_{\text{BG}}(n) = \frac{1}{\sqrt{2\pi\sigma_{\text{BG}}^2}} \exp\left\{-\frac{(n - \nu_{\text{BG}})^2}{2\sigma_{\text{BG}}^2}\right\},$$

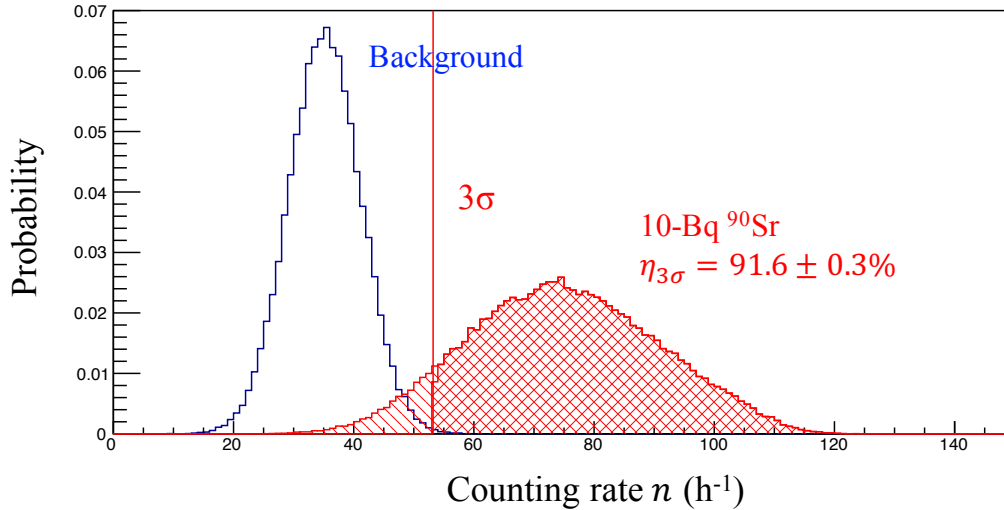
$$\phi_x(n) = \frac{e^{-\nu/\alpha^2} (\nu/\alpha^2)^{n/\alpha^2}}{\Gamma(n/\alpha^2 + 1)}, \quad (x = \text{Sr})$$

Source	α	k ($\text{Bq}^{-1} \text{h}^{-1}$)
^{90}Sr	2.50 ± 0.50	6.23 ± 0.13
^{137}Cs	0.532 ± 0.044	$(4.77 \pm 0.09) \times 10^{-3}$
^{40}K	1.067 ± 0.106	$(1.95 \pm 0.04) \times 10^{-2}$



1. ⁹⁰Sr Counter 開発研究

線源を用いた性能評価測定



- These curves show relations between ⁹⁰Sr radioactivity and the efficiency for 1, 2, 3σ threshold condition.
- Typical detection limit is determined to be $A_{3\sigma}^{50\%}$ satisfying $\langle \Gamma_{Sr}(n) \rangle > \langle \Gamma_{BG}(n) \rangle + 3\sigma$.
- $A_{3\sigma}^{50\%} = 4.6$ Bq at 1-hour measuring.

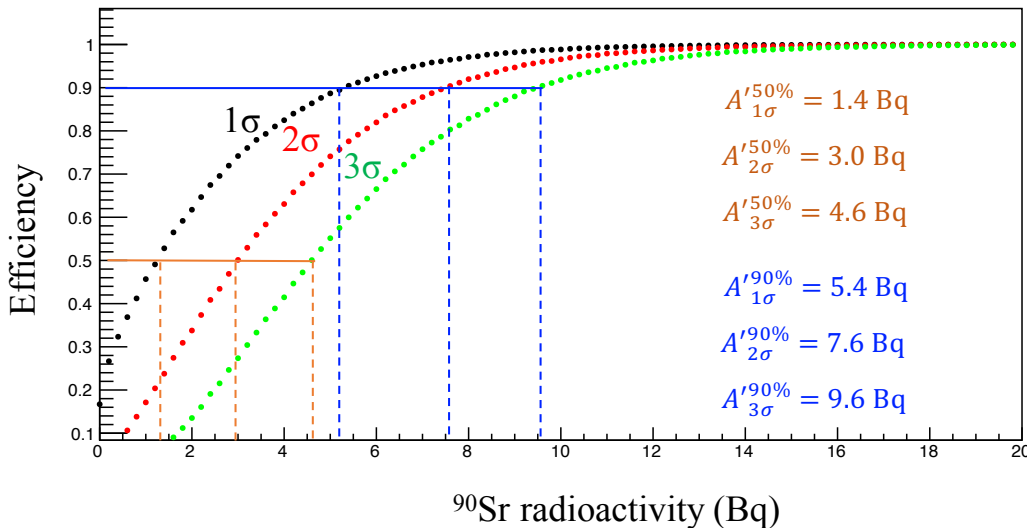
乾燥した海産物サンプルの密度 1 g/cm^3 、
体積圧縮率 $\varepsilon=0.3$ 、厚さ 1 mm 、質量 $m=30 \text{ g}$ とすると1時間測定における検出限界は、

$$A_{3\sigma}^{50\%} m \varepsilon^{-1} = 46 \text{ Bq/kg}$$

$A \propto S^{-1}$; it expected to be
 $8.4 \text{ Bq/kg @S=1 m}^2$

海水における検出限界は

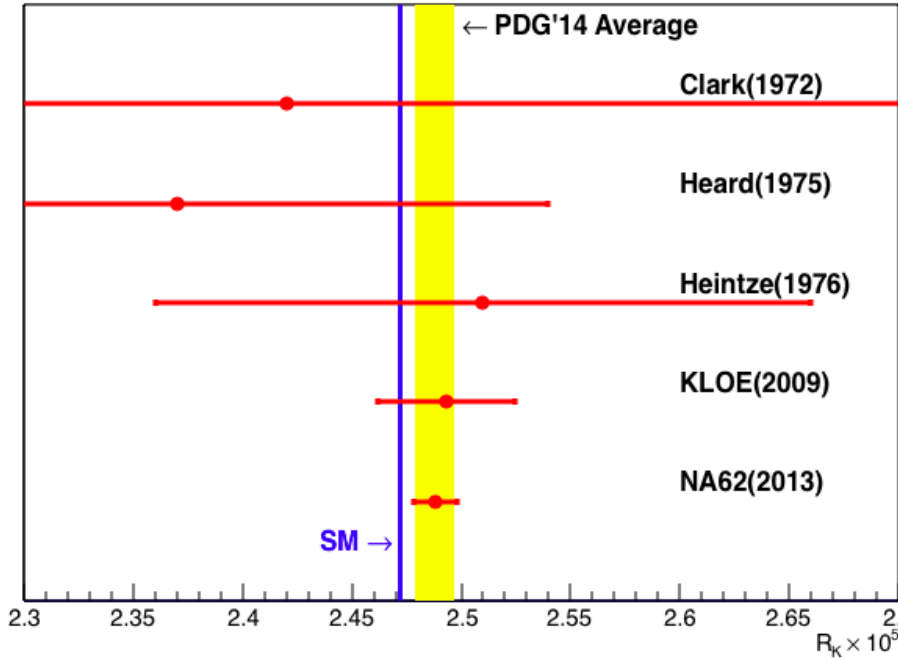
$$A_{3\sigma}^{50\%} m \varepsilon^{-1} = 1.5 \text{ Bq/L}$$



2. J-PARC E36 実験

2. J-PARC E36 実験

静止 K^+ を用いた $\Gamma(K^+ \rightarrow e^+ \nu_e) / \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$ の精密測定実験



	$R_K \times 10^5$	$\Delta R_K / R_K$
KLOE(2009)	$2.493 \pm 0.025 \pm 0.019$ (stat) (sys)	1.26%
NA62(2013)	$2.488 \pm 0.007 \pm 0.007$ (stat) (sys)	0.40%
SM	2.477 ± 0.001	0.04%

Initial goal of
E36

0.25%

$$R_K^{SM} = \frac{\Gamma(K^+ \rightarrow e^+ \nu_e)}{\Gamma(K^+ \rightarrow \mu^+ \nu_\mu)}$$

$$= \frac{m_e^2}{m_\mu^2} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 (1 + \delta_r)$$

radiative correction

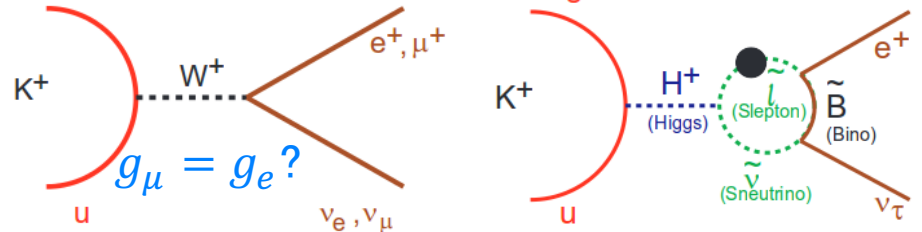
helicity suppression

$K^+ \rightarrow l^+ \nu_l$

$$\Gamma(K_{l2}) = g_l^2 (G^2 / 8\pi)$$

$$f_K^2 m_K m_l^2 \{1 - (m_l^2 / m_K^2)\}^2$$

Candidate Model:
MSSM with LFV



$$R_K^{LFV} = R_K^{SM} \left(1 + \frac{m_K^4}{M_{H^+}^4} \cdot \frac{m_\tau^2}{m_e^2} \Delta_{13}^2 \tan^6 \beta \right)$$

$$\sim R_K^{SM} (1 + 0.013_{\max})$$

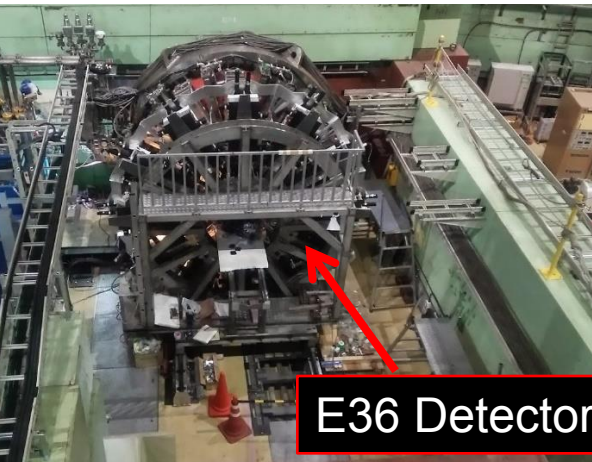
Phys. Rev. D **74**

2. J-PARC E36 実験

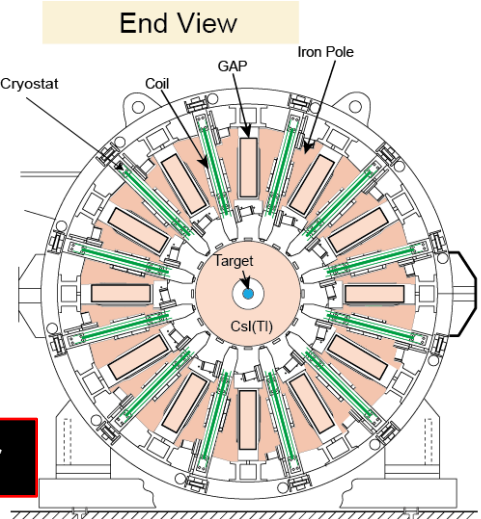
Phys. Run: October, 2015 – December, 2015



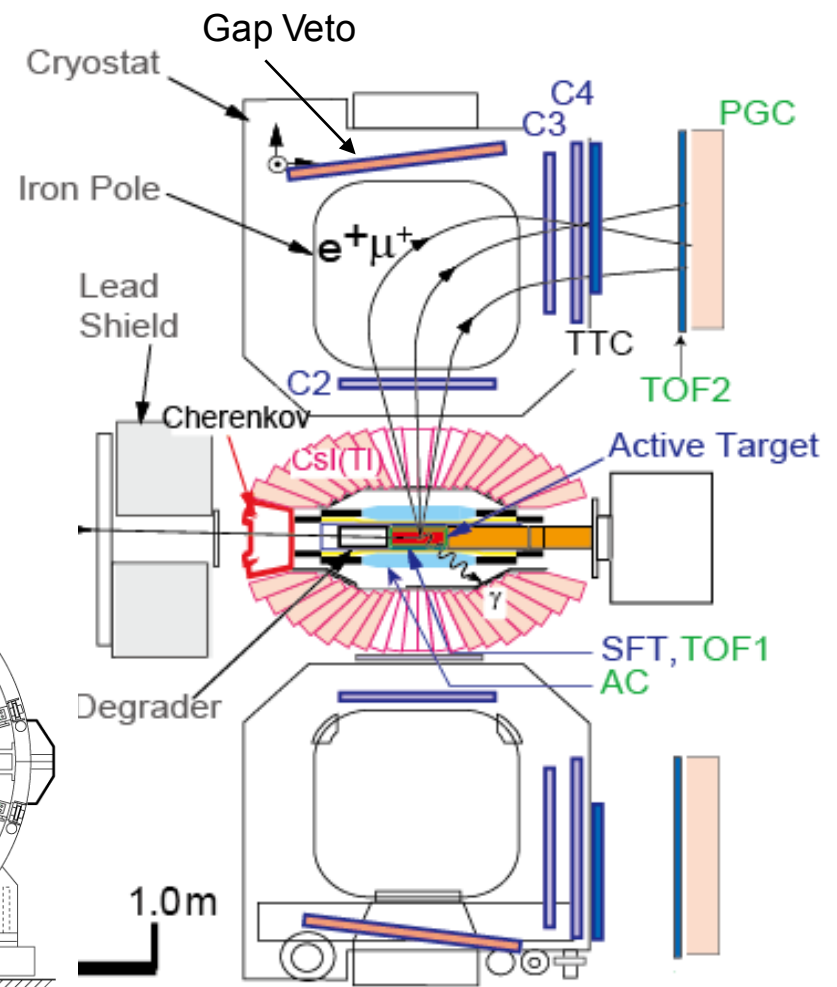
J-PARC Hadron Hall



E36 Detector



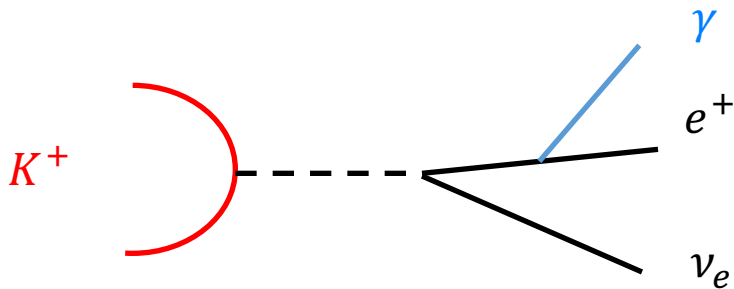
Side View



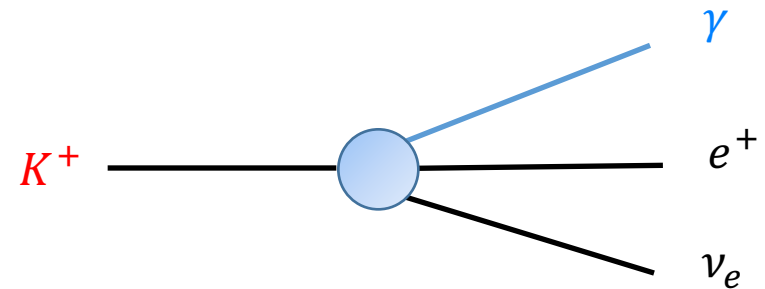
2. J-PARC E36 実験

$$R_K^{SM} = \frac{\Gamma(K_{e2}) + \Gamma(K_{e2\gamma}(IB))}{\Gamma(K_{\mu 2}) + \Gamma(K_{\mu 2\gamma}(IB))}$$

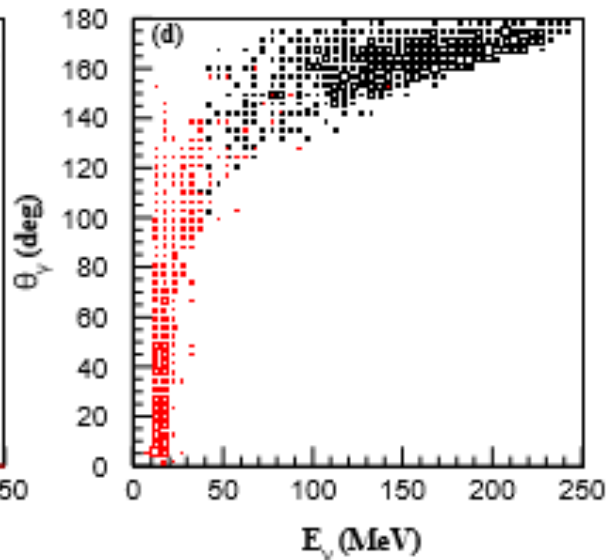
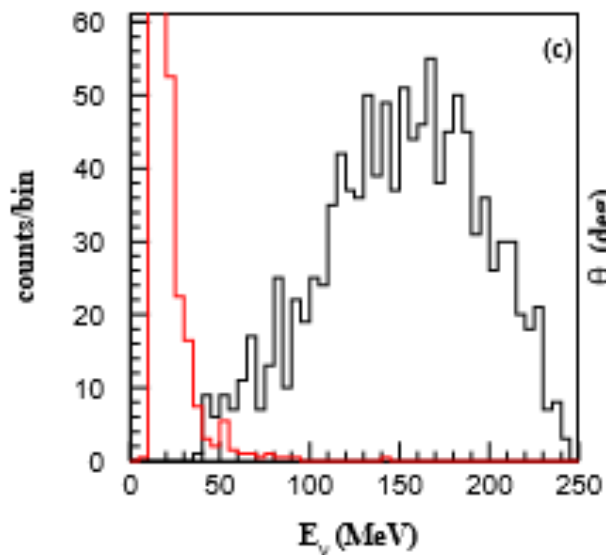
Background: $K_{e2\gamma}$ (SD)
 $K_{e2\gamma}: K^+ \rightarrow e^+ \nu_e \gamma$



Internal Bremsstrahlung (IB)



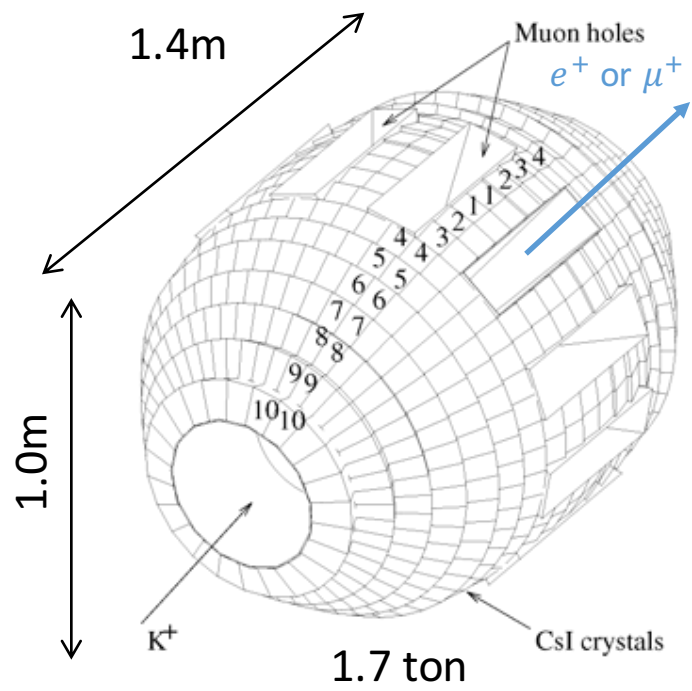
Structure Dependent (SD)



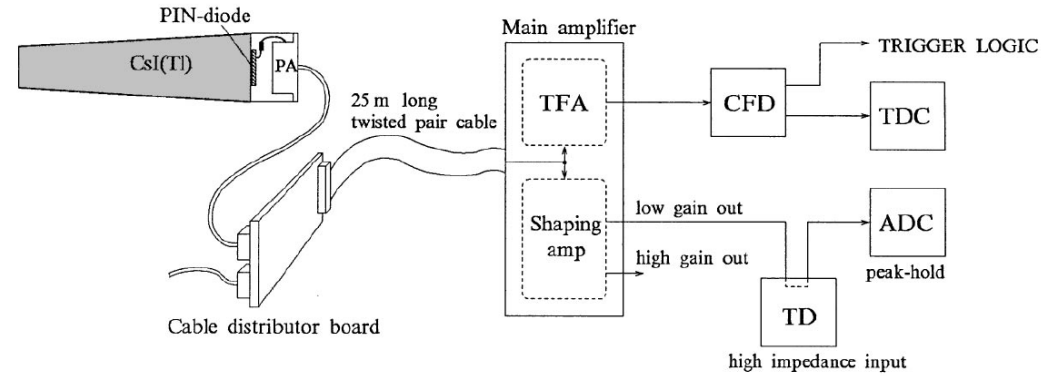
$$\Gamma(K_{e2\gamma}(SD)) \sim 9.4 \times 10^{-6}$$

2. J-PARC E36 実験

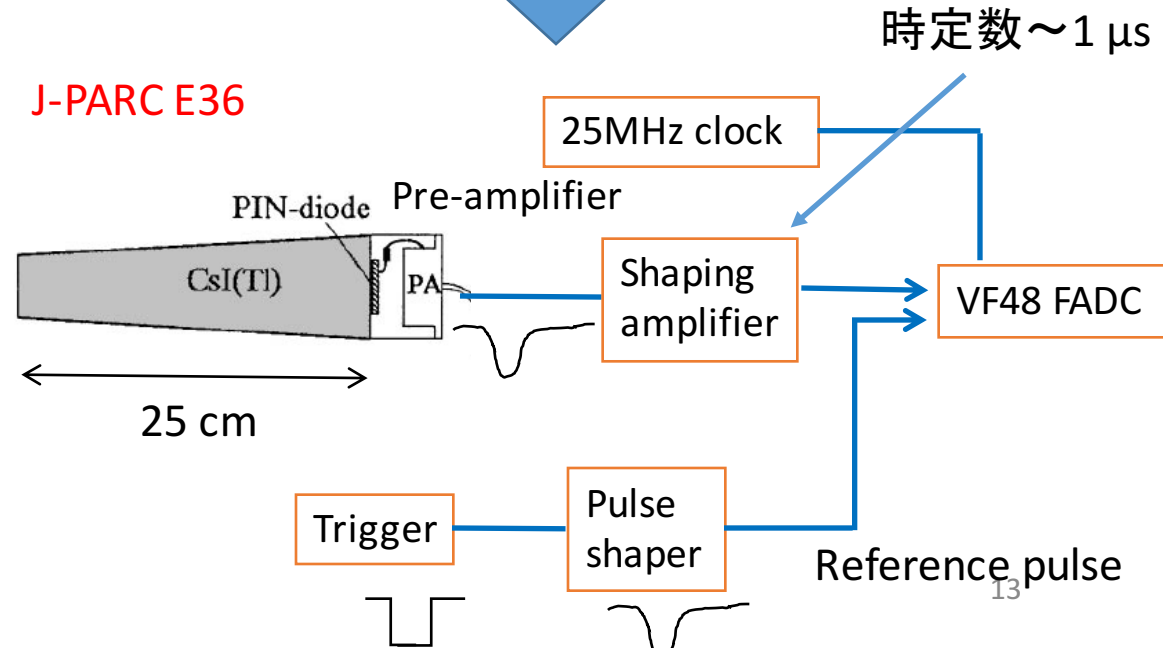
768 CsI(Tl) crystal modules



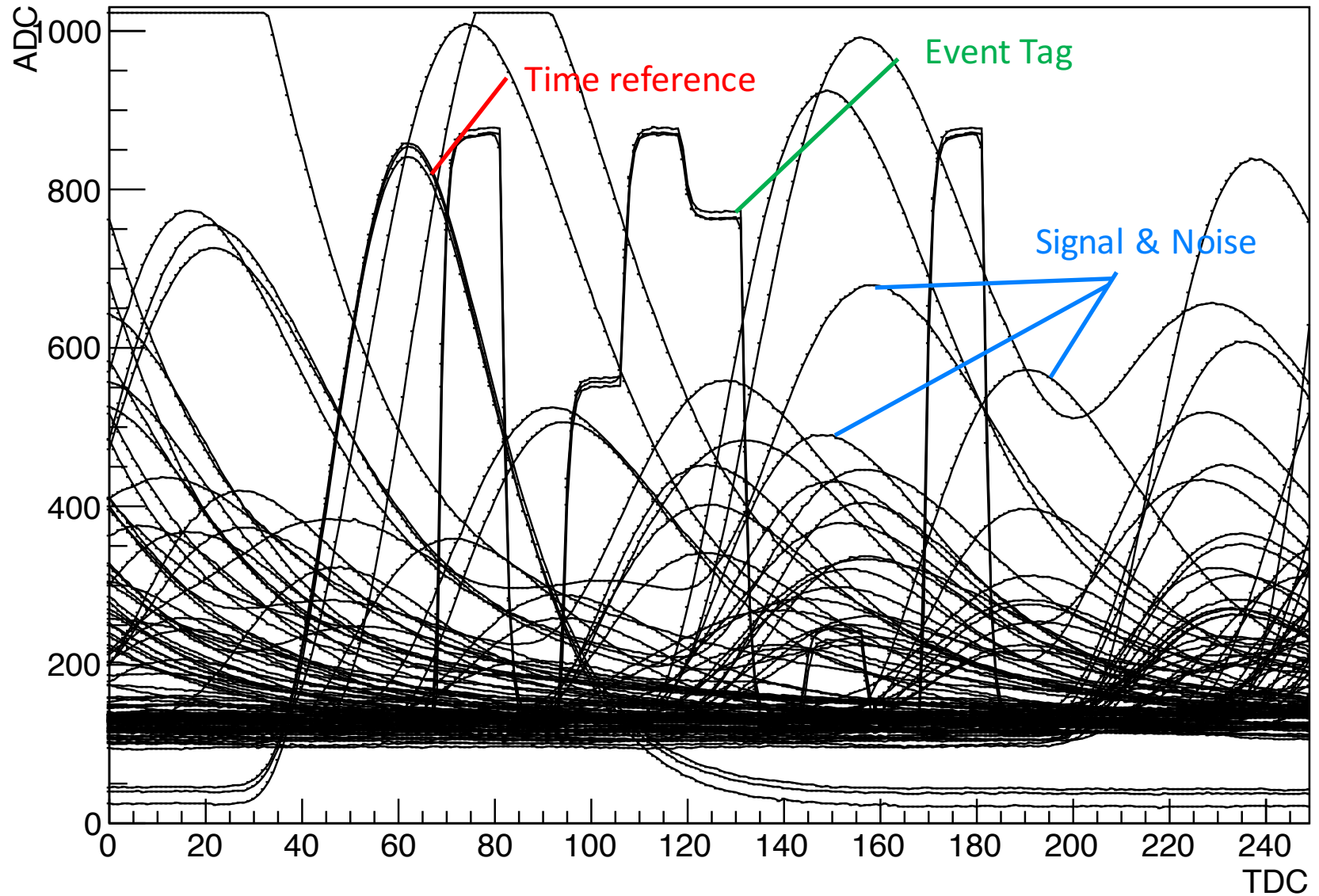
KEK-PS E246



J-PARC E36

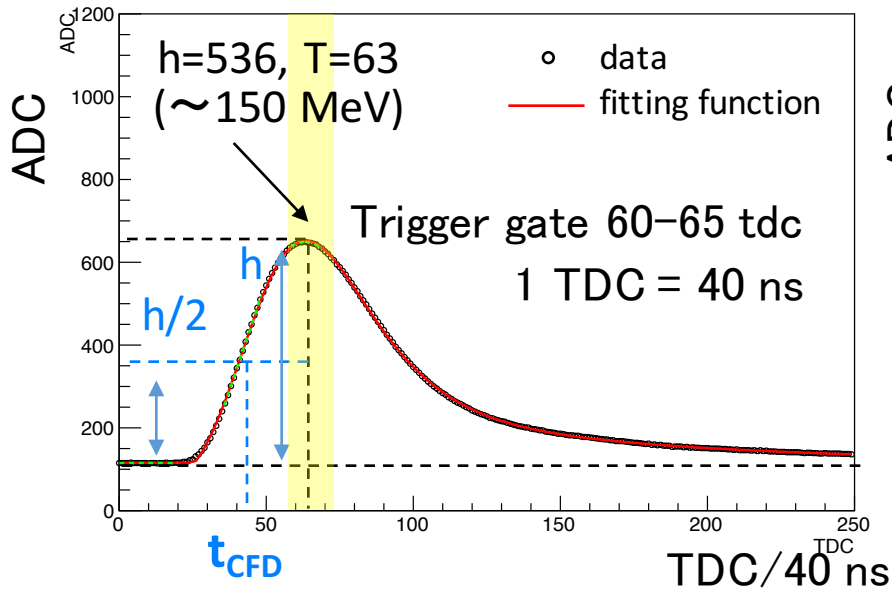


2. J-PARC E36 実験

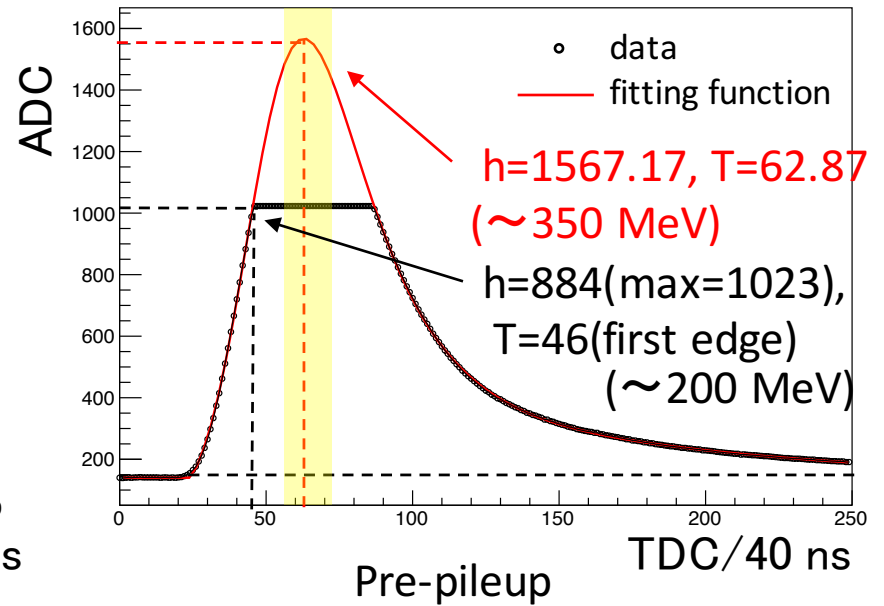


2. J-PARC E36 実験

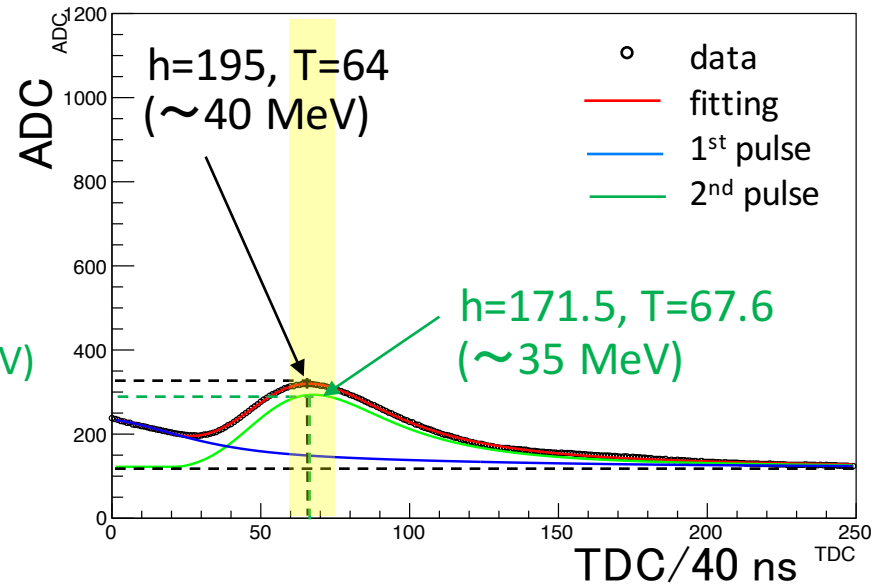
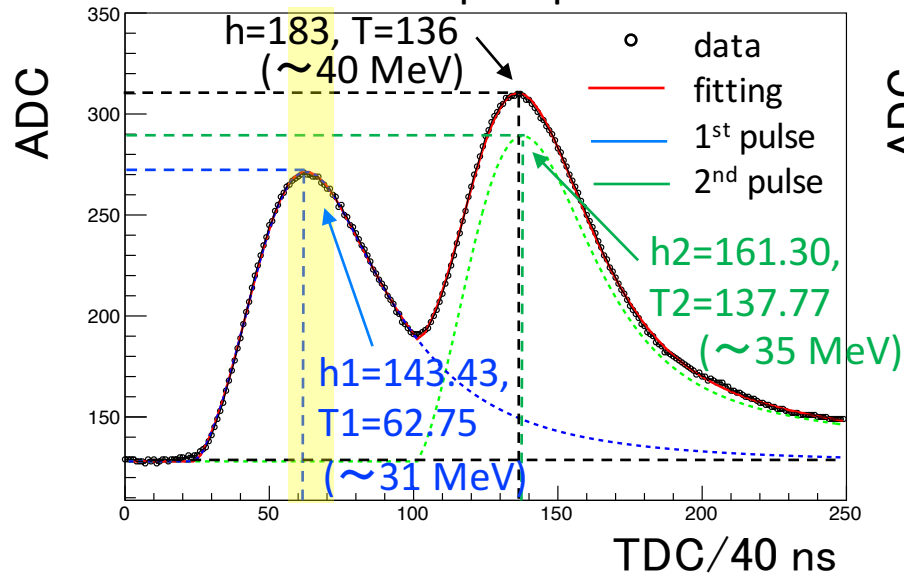
Typical pulse



Overflow pulse

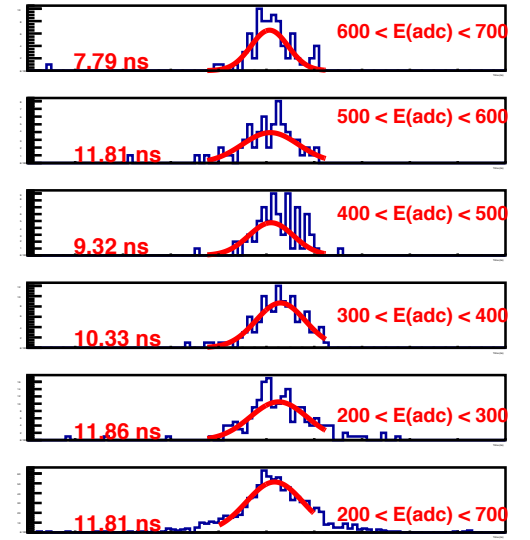
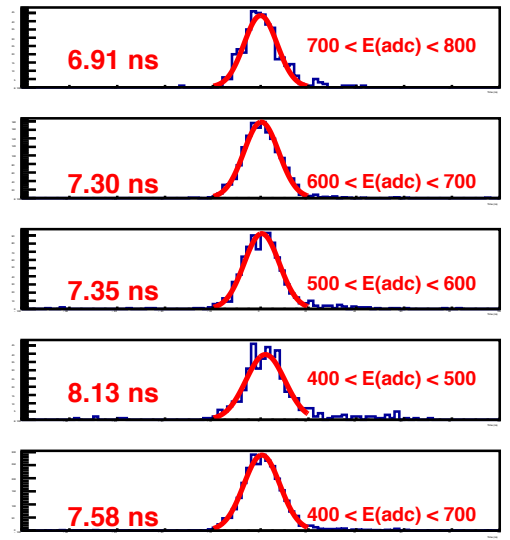
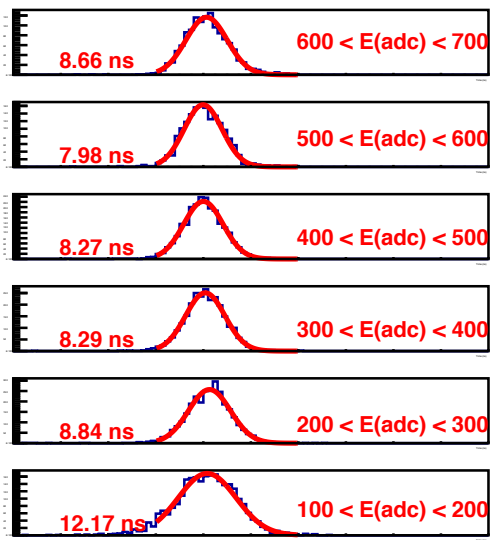
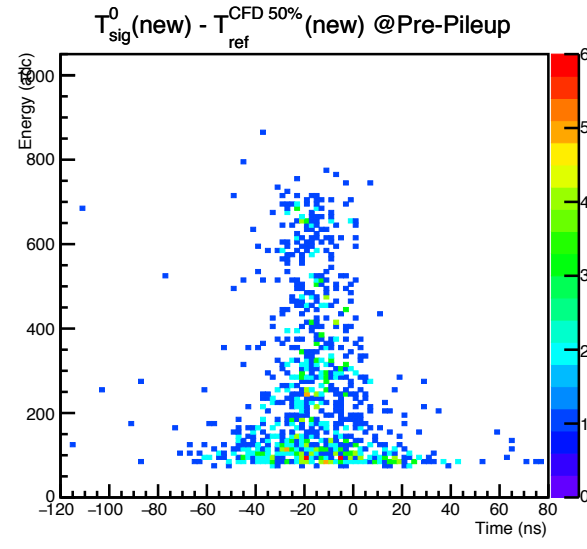
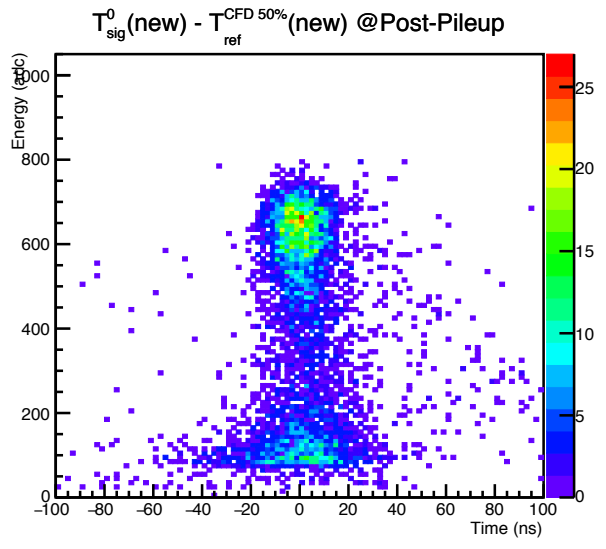
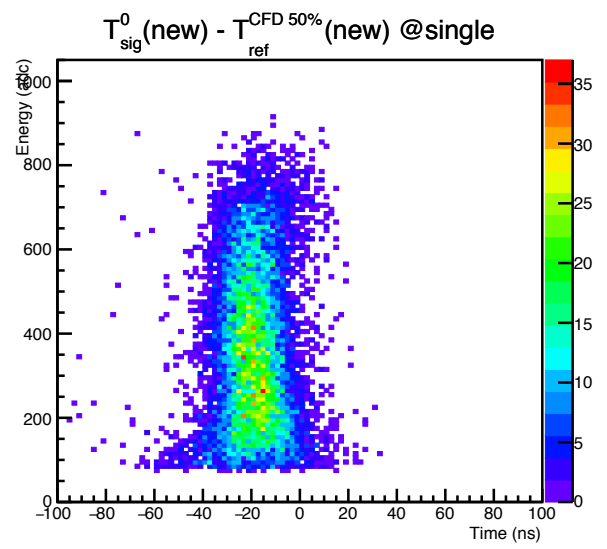


Post-pileup



2. J-PARC E36 実験

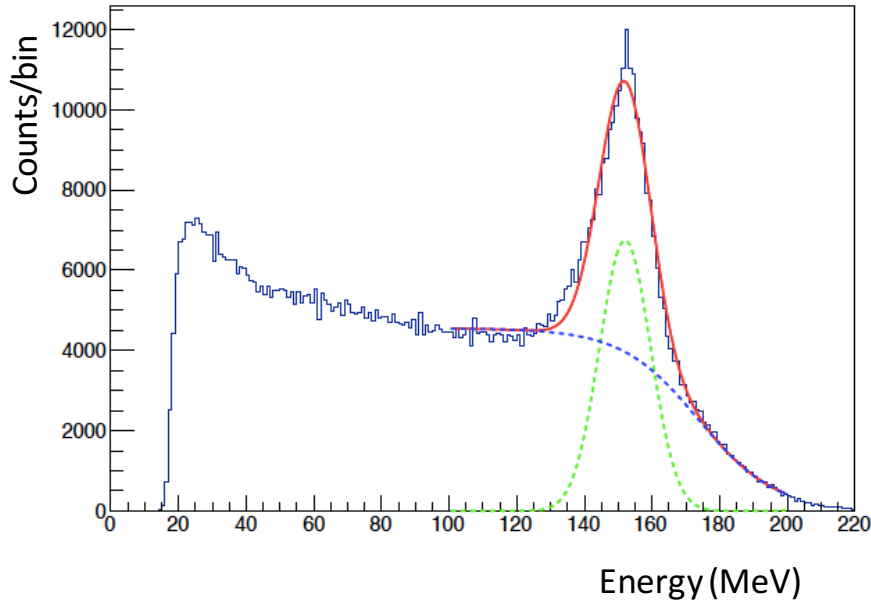
時間分解能評価



2. J-PARC E36 実験

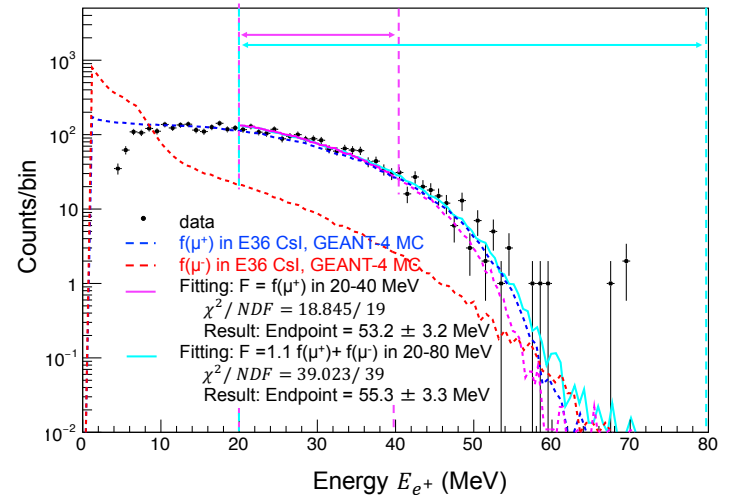
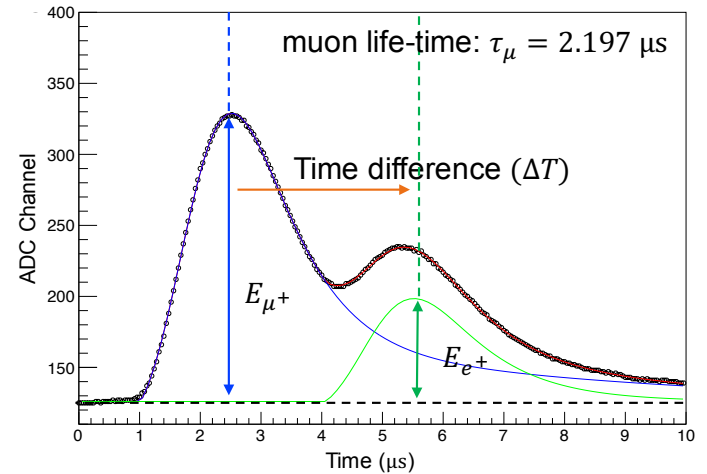
エネルギー較正

Stopped Kaon Beam
 $K^+ \rightarrow \mu^+ \nu: \mu^+$ ($K=153$ MeV)



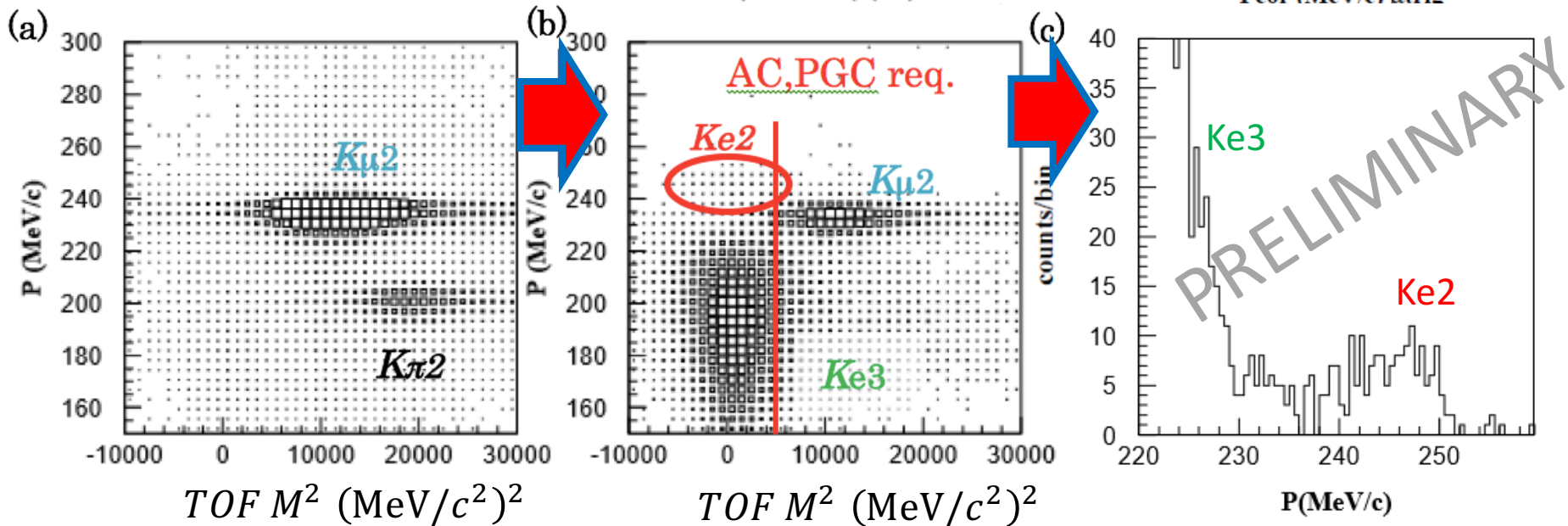
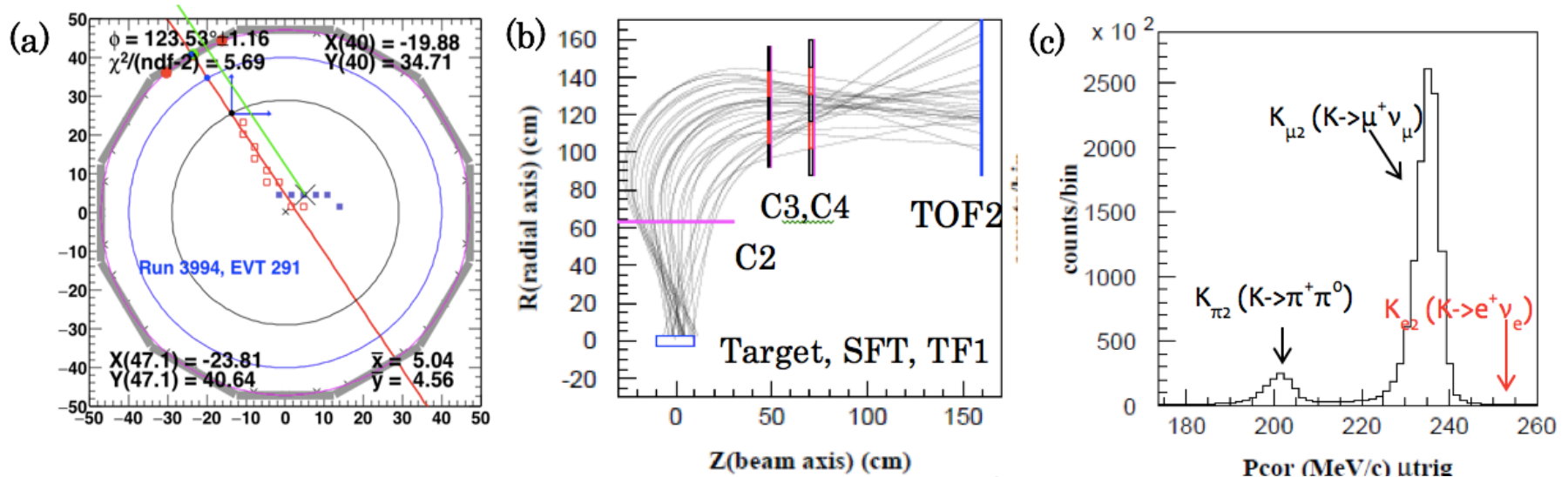
分解能: 4.96% (σ) @153 MeV
 ターゲット内損失エネルギー補正が必要

Cosmic-ray muon stop
 $\mu^+ \rightarrow e^+ \nu \bar{\nu}: e^+$ ($K_{\max}=53$ MeV)



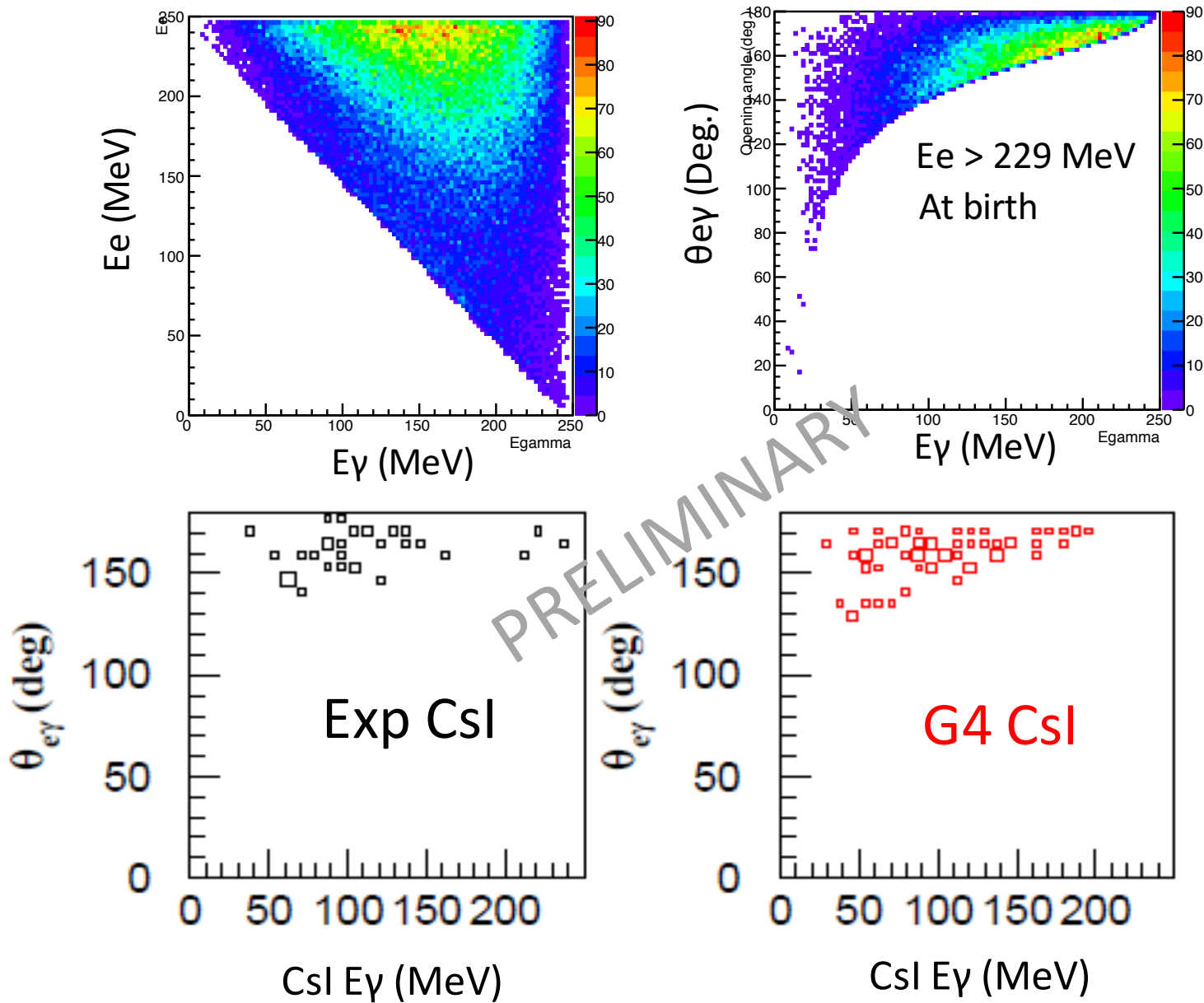
2. J-PARC E36 実験

Ke2 γ Background study



2. J-PARC E36 実験

Ke2 γ (SD) Background study comparing with MC



着任した場合の研究計画

- (1) 極低放射能測定システム構築・運用・データベース化・新技術開発
- (2) XMASS実験などの研究

(1) 極低放射能測定システム構築・運用・データベース化・新技術開発

運用・データベース化

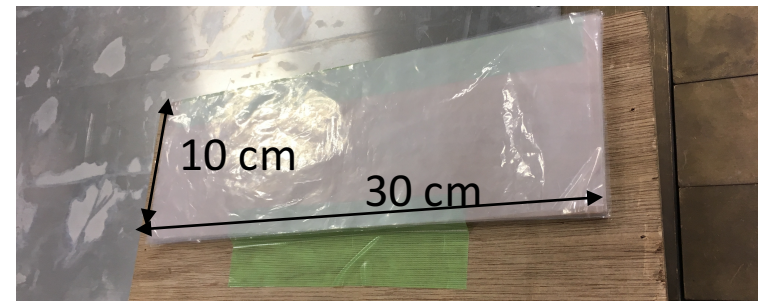
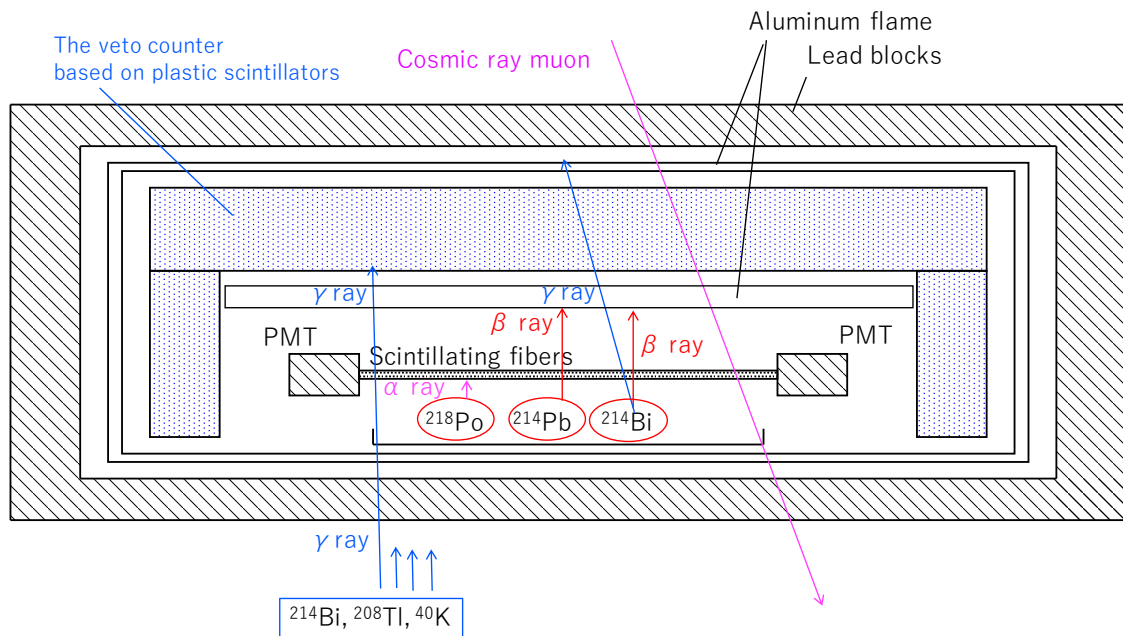
- 神岡地下で観測したデータを国際共同研究者が閲覧共有できるようなウェブプログラム・アルゴリズムの開発
- 神岡だけでなく様々な土地で収集したデータの
 - (1) 閲覧・検索機能、
 - (2) グラフによる可視化、
 - (3) 全国濃度分布など、毎時更新する環境ツールを構築
- また共同研究者の要望も取り入れて、ユーザビリティの向上
- 地下素核実験、地震予知、ラドンと肺がんの関係など

(1) 極低放射能測定システム構築・運用・データベース化・新技術開発

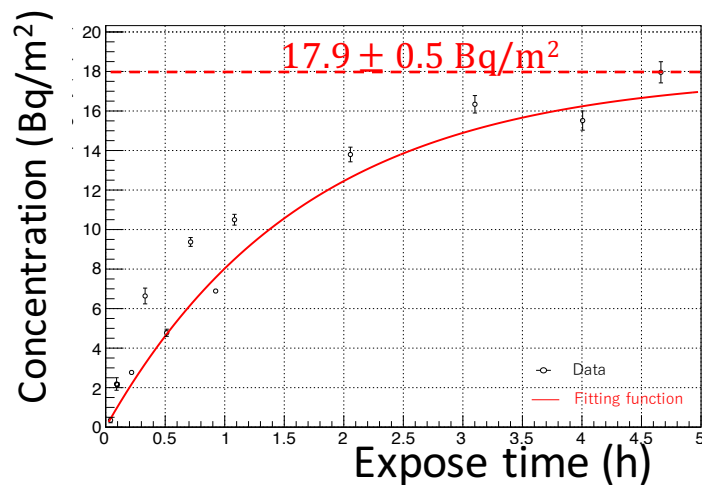
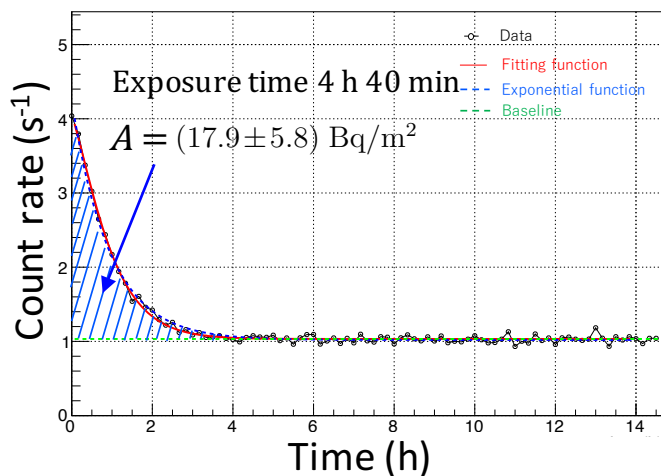
新技術開発

- α 線だけでなく β 線を測定することで空気中の ^{218}Po , ^{214}Pb , ^{214}Bi を観測する技術開発の研究
- 空気中のラドン崩壊後、サンプル表面に付着した ^{218}Po , ^{214}Pb , ^{214}Bi の放射能濃度を測定することで、間接的に空気中におけるこれら核種の存在を観測しました。
- この延長線上で空気中の濃度を間接的に推定する手法について研究する計画も持っています。

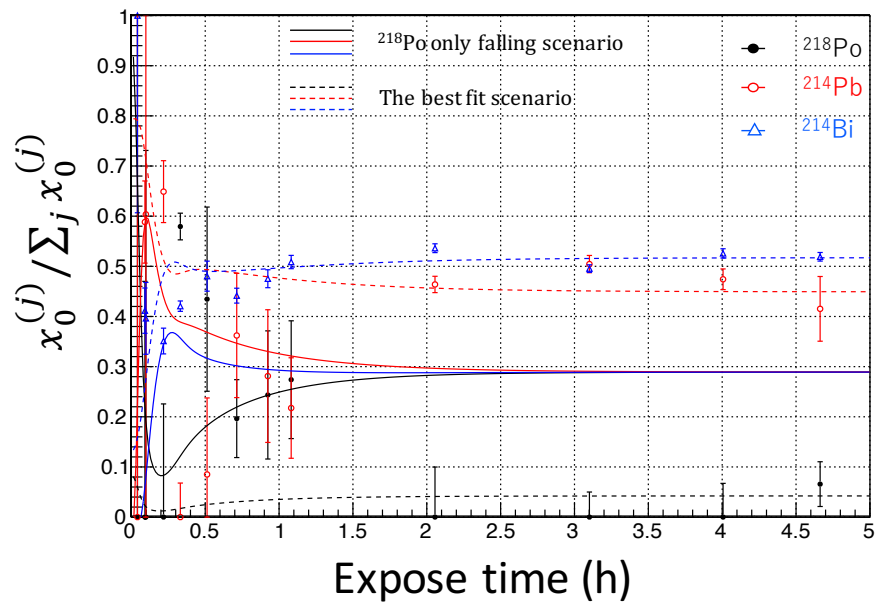
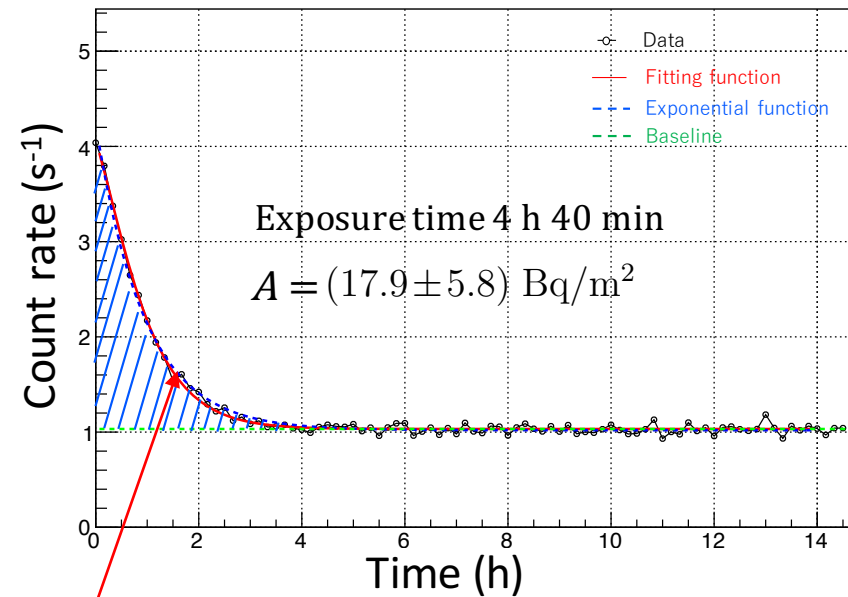
(1) 極低放射能測定システム構築・運用・データベース化・新技術開発



Polyethylene sample sheet (10枚)



(1) 極低放射能測定システム構築・運用・データベース化・新技術開発



$$f(t) = \frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)} \exp(-\lambda_1 t) + \left(\frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)} + \frac{\lambda_2 x_0^{(2)}}{\lambda_3 - \lambda_2} \right) \exp(-\lambda_2 t) + \left(\frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)} + \frac{\lambda_2 x_0^{(2)}}{\lambda_3 - \lambda_2} + x_0^{(3)} \right) \exp(-\lambda_3 t) + R_{BG},$$

free parameters

Isotope $j = 1, 2, 3$ are ^{218}Po , ^{214}Pb , ^{214}Bi , respectively.
 $\lambda_j = \tau_j^{-1}$: inverse of life time of isotope j
 $x_0^{(j)}$: initial intensity of isotope j
 R_{BG} : background rate

(2) XMASS実験

XMASS-I のデータ解析

- 解析コードの最適化：波形模型の開発、パイルアップ補正、時間分解能向上
- 宇宙線、環境放射能由来バックグラウンドの研究：パイルアップ補正・波形解析を改善したことによる影響、水中タンクに取り付けられたPMT情報、各センサー情報を駆使して解析する

(2) XMASS実験

XMASS-I.5, -II のモンテカルロシミュレーション

- 検出器模型の構築
- 不純物の放射性核種混同によるバックグラウンド推定評価
 - PMTを新調
- 検出器拡大による光学的な散乱計算、PMTで観測する信号模型
- 相互作用した点の再構成計算アルゴリズム

Buck up

これまでの研究業績

1. ^{90}Sr Counter 開発研究

閾値型チェレンコフ検出器

^{40}K からの β 線でチェレンコフ放射しない屈折率の閾値は

$$n_{\text{th}} = \frac{m_e c^2 + K}{\sqrt{(m_e c^2 + K)^2 - m_e^2 c^4}}$$

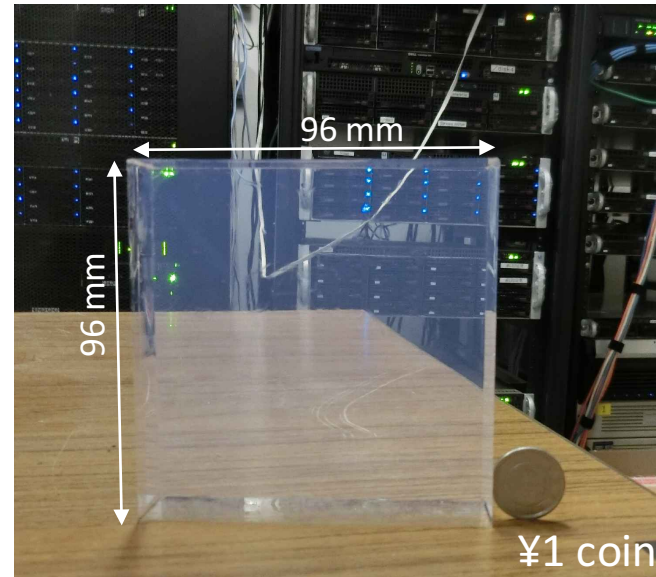
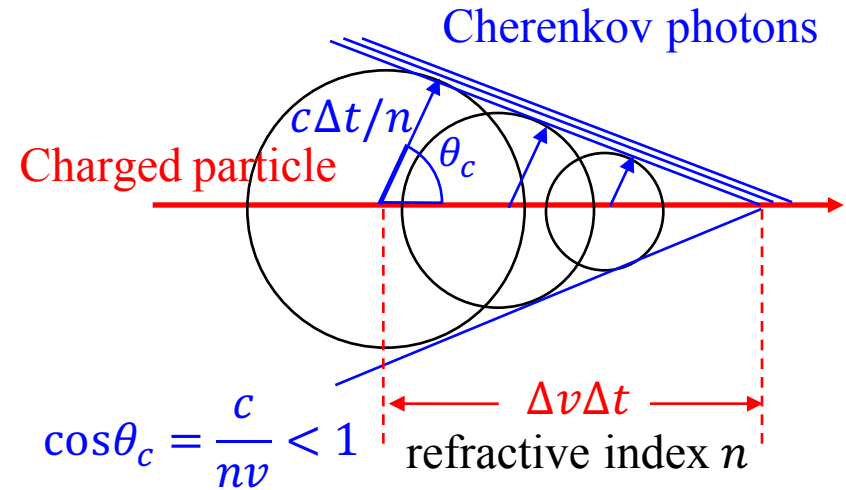
m_e は電子質量

$K = 1.31 \text{ MeV}$ なので $n_{\text{th}} = 1.041$

この屈折率では $E_\gamma = 1.53 \text{ MeV}$ 未満の γ 線がコンプトン散乱して反跳した電子もチェレンコフ放射しない。

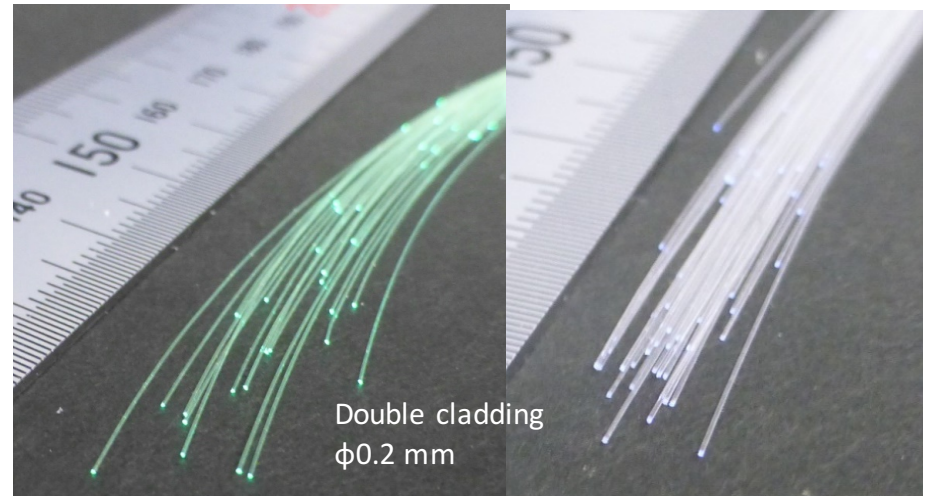
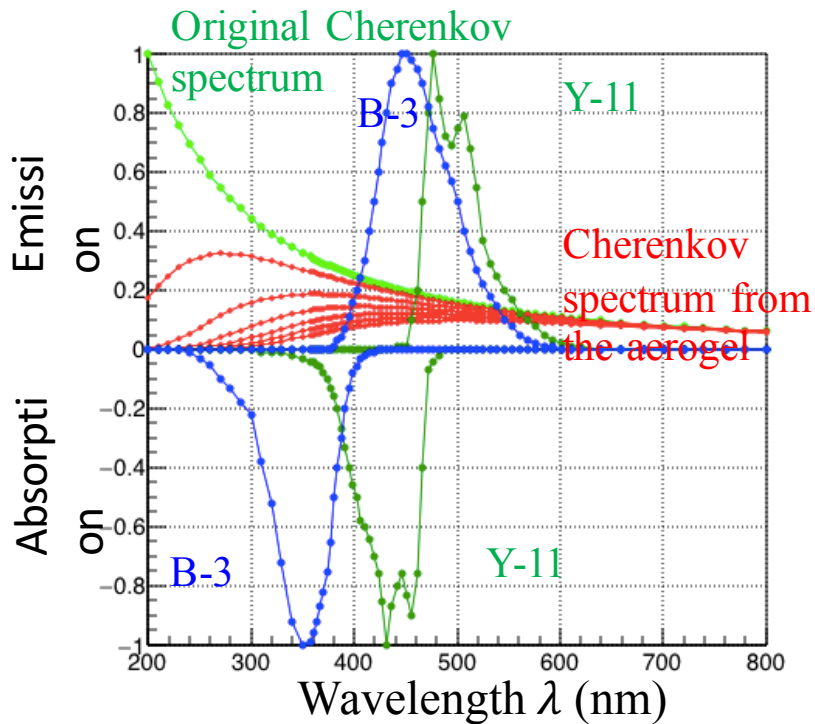
シリカエアロゲル

- SiO_2 と空気の混合体のように振る舞う個体
- 1.041のような屈折率を実現



これまでの研究業績

1. ^{90}Sr Counter 開発研究

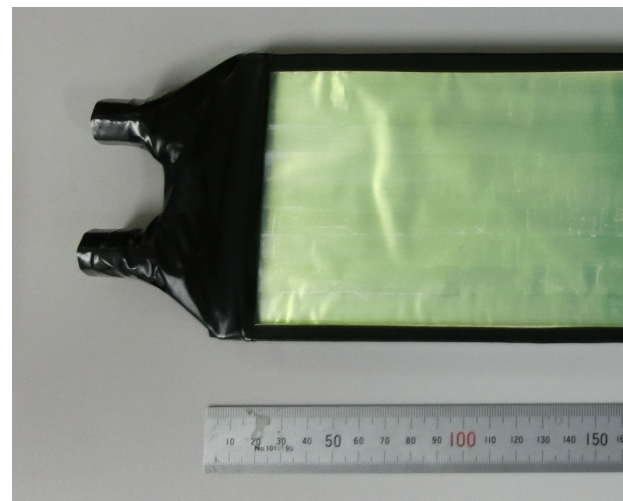
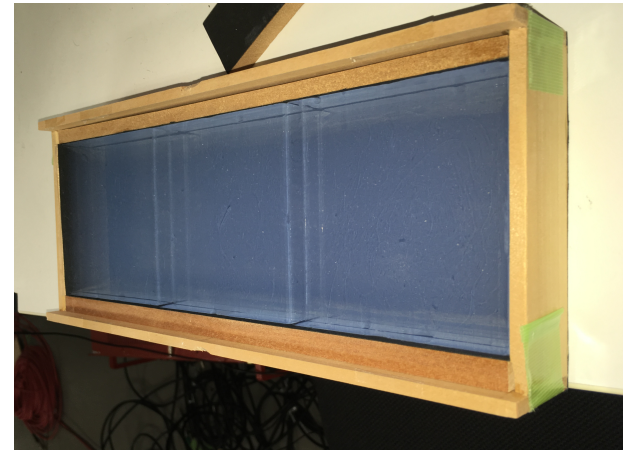
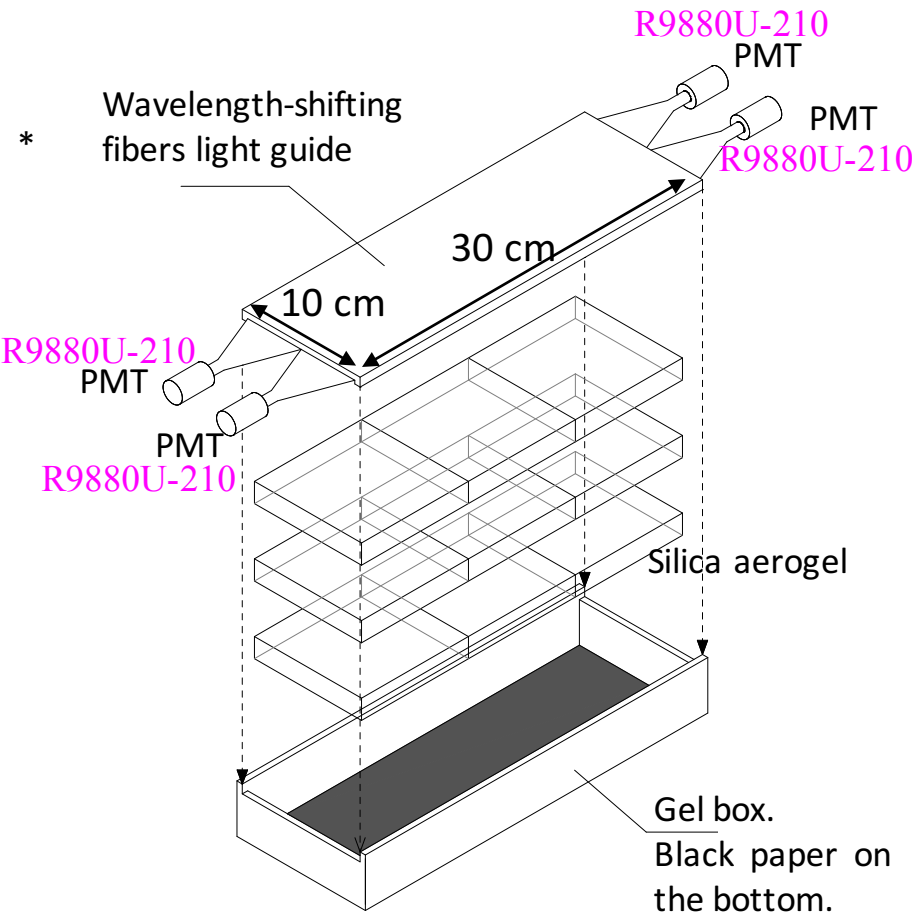


Kuraray Y-11(300)MJ

B-3(300)MJ

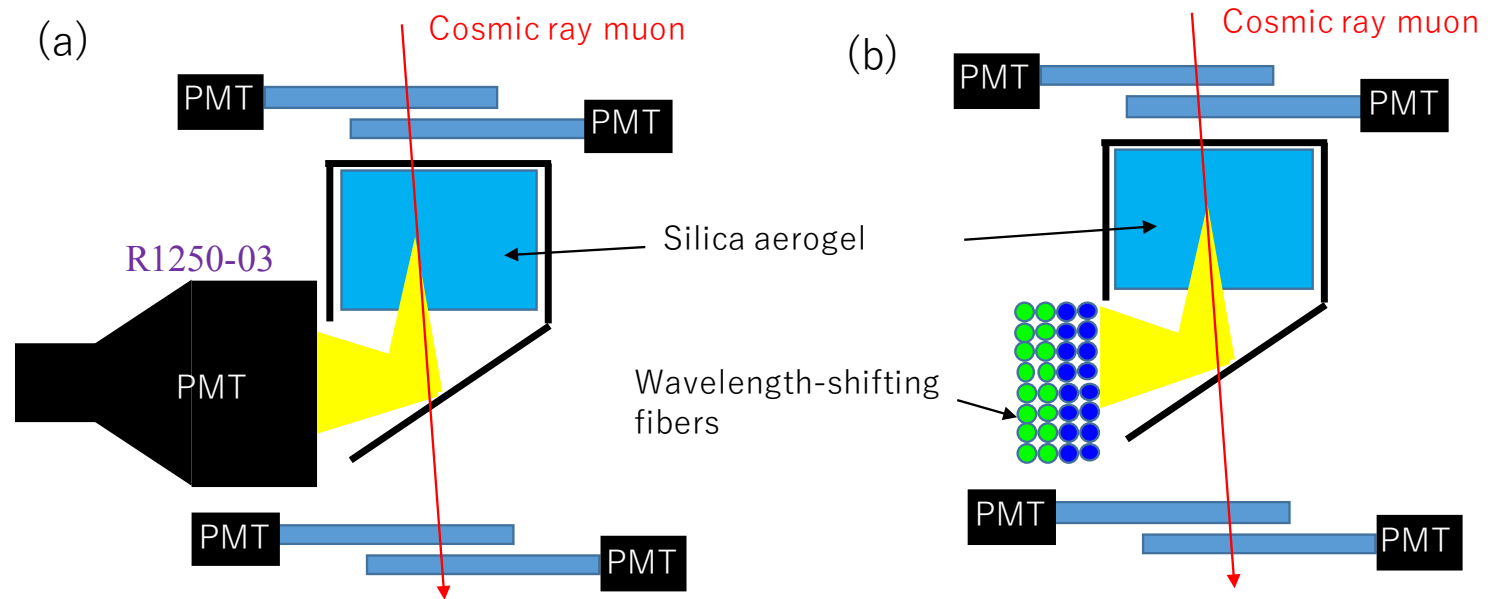
これまでの研究業績

1. ^{90}Sr Counter 開発研究



2. Basic concept an aerogel Cherenkov detector using wavelength-shifting fibers

Measurement of light collection efficiency



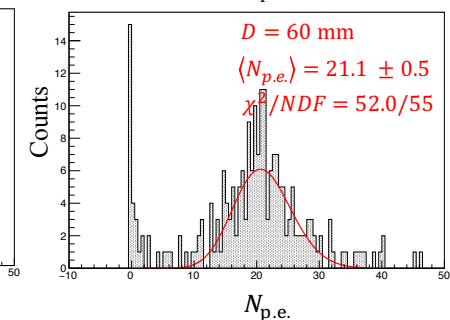
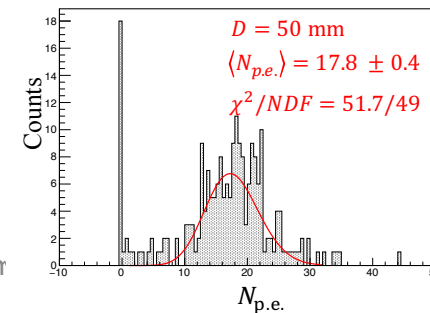
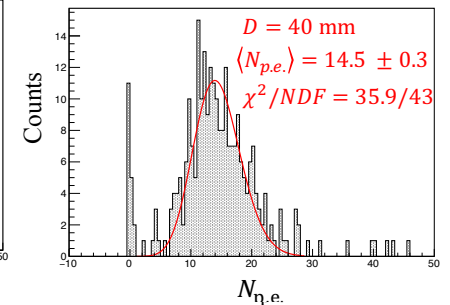
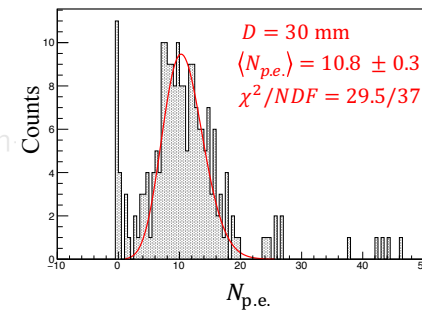
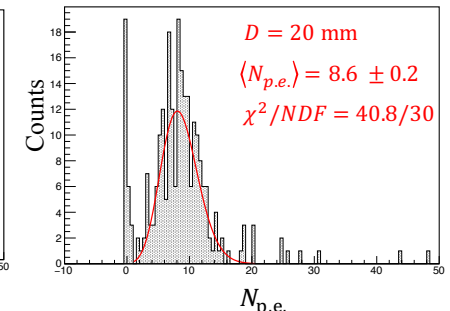
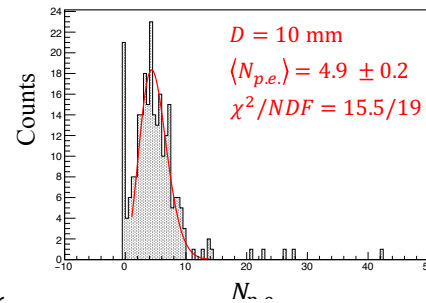
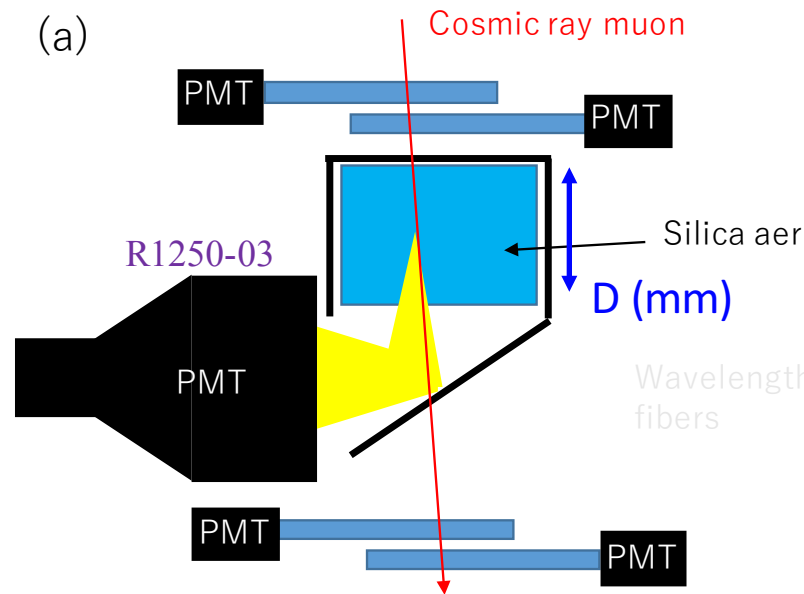
2. Basic concept an aerogel Cherenkov detector using wavelength-shifting fibers

Measurement of light collection efficiency

Poisson Function Fitting

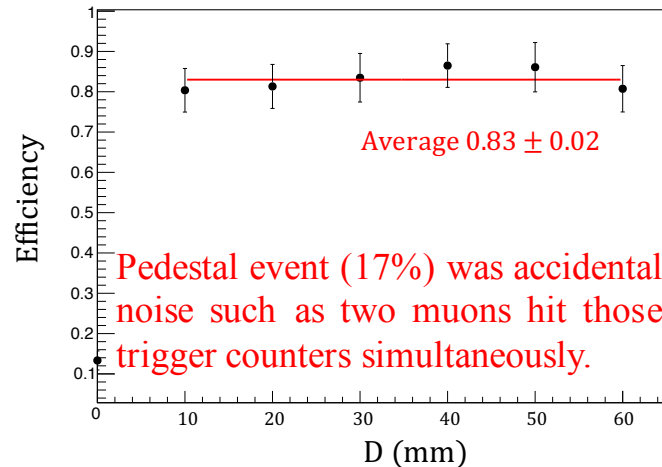
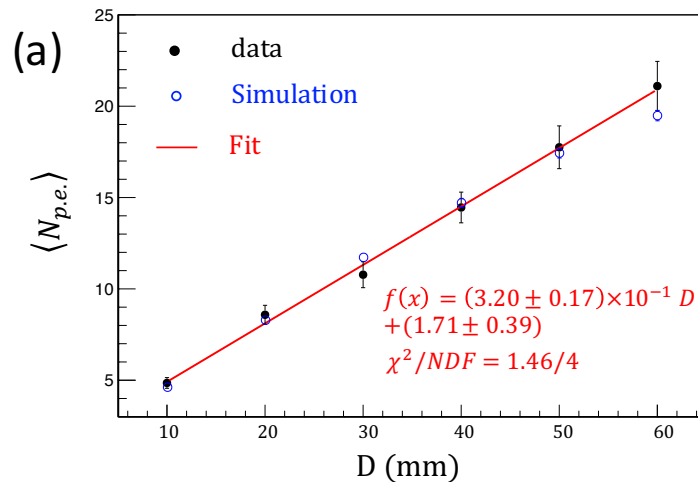
$$P(k, \nu) = e^{-\nu} \nu^k / k!$$

$$\langle N_{p.e.} \rangle (= \nu)$$



2. Basic concept an aerogel Cherenkov detector using wavelength-shifting fibers

Measurement of light collection efficiency



$$N_{p.e.} = 2\pi\alpha \int d\lambda dL \frac{\varepsilon_{QE}(\lambda) \cdot T(\lambda, L) \cdot \varepsilon_{ref}}{\lambda^2} + N_0$$

$$\varepsilon_{ref} = 0.466 \pm 0.004$$

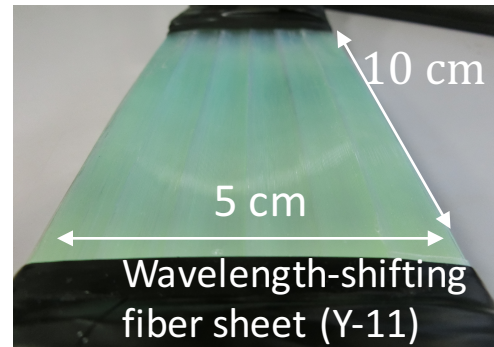
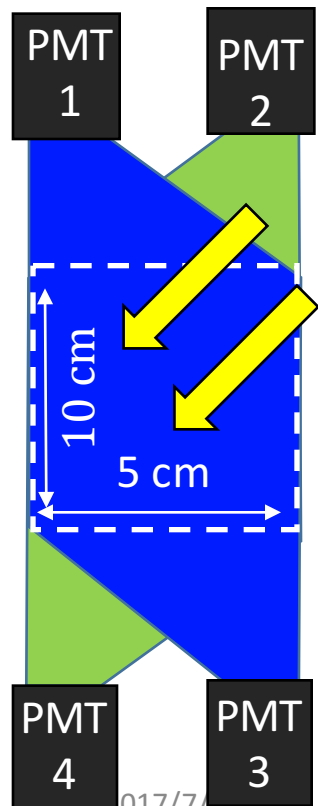
$$N_0 = 1.42 \pm 0.03$$

$$\text{with } \chi_{min}^2 = 30.7$$

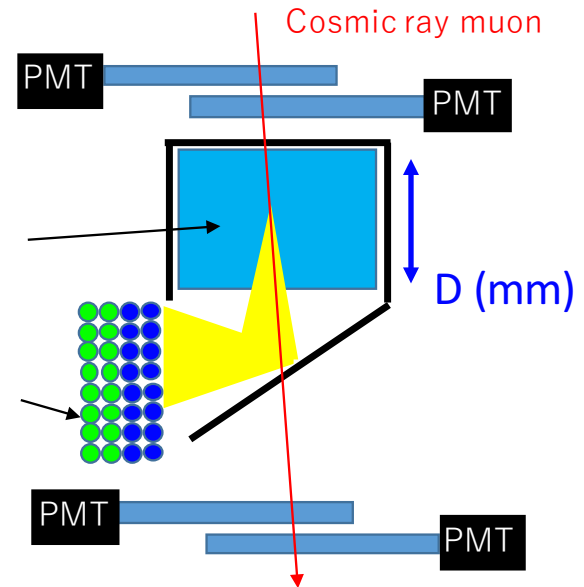
2. Basic concept an aerogel Cherenkov detector using wavelength-shifting fibers

Measurement of light collection efficiency

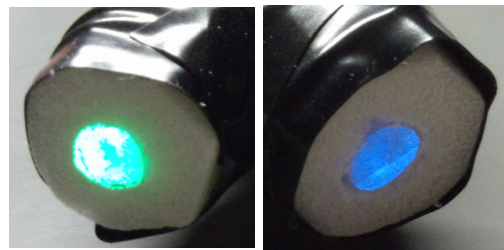
R9880U-210 R9880U-210



(b)



Wavelength-shifting fibers

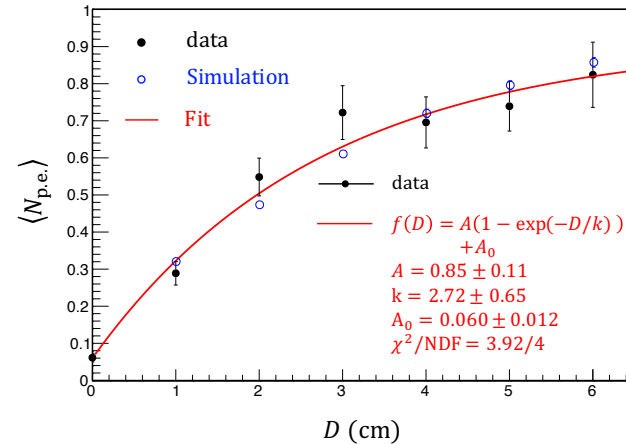
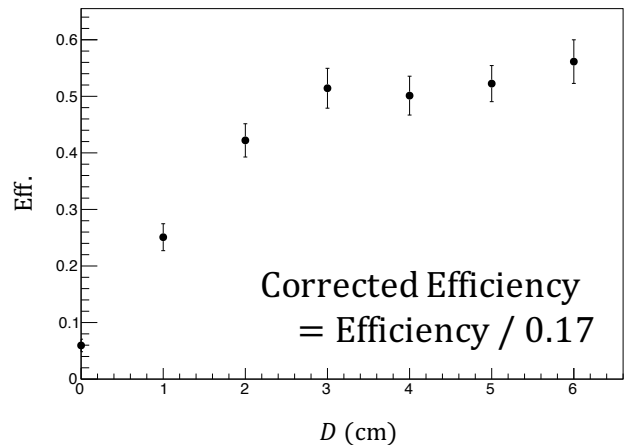


017/7/25
R9880U-210 R9880U-210

2. Basic concept an aerogel Cherenkov detector using wavelength-shifting fibers

Measurement of light collection efficiency

(b)



$$P(k = 0, \nu) = \exp(-\nu)$$

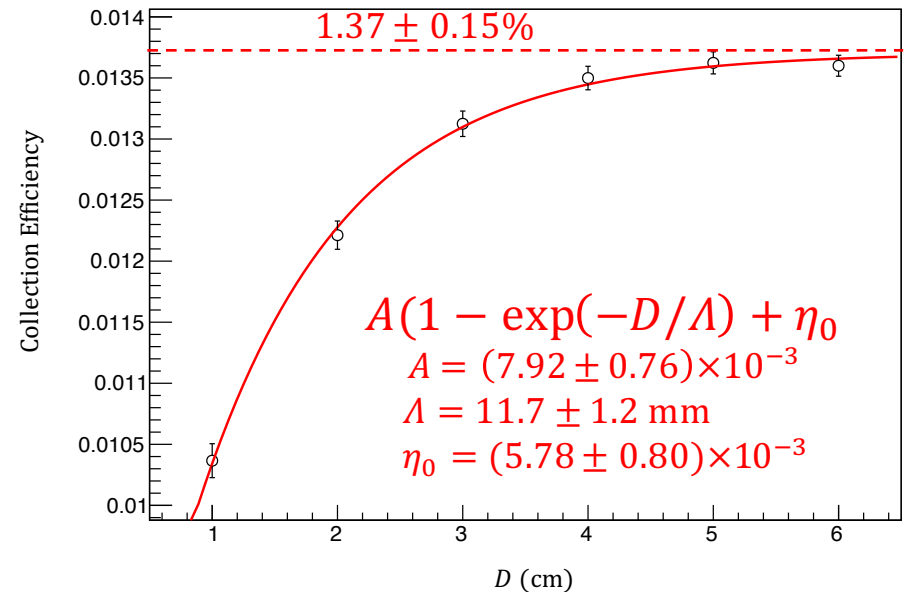
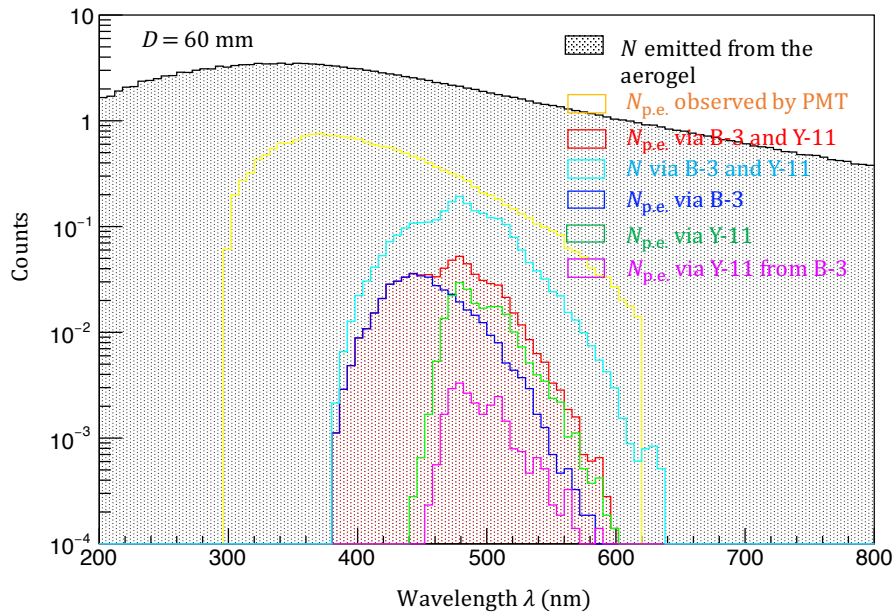
$$\langle N_{\text{p.e.}} \rangle \equiv \nu = -\ln(\text{inefficiency})$$

$$\begin{aligned}
 N_{\text{p.e.}} = & 2\pi\alpha \int d\lambda dL \frac{T(\lambda, L) \cdot \varepsilon_{\text{ref}}}{\lambda^2} \\
 & \left\{ \begin{aligned}
 & g_{\text{core}}^{\text{B-3}}(\lambda, \lambda') \varepsilon_{\text{trap}} \varepsilon_{\text{QE}}(\lambda') d\lambda' \\
 & + \frac{1}{2} g_{\text{core}}^{\text{B-3}}(\lambda, \lambda') g_{\text{core}}^{\text{Y-11}}(\lambda', \lambda'') (1 - \varepsilon_{\text{trap}}) \varepsilon_{\text{trap}} \varepsilon_{\text{QE}}(\lambda'') d\lambda'' \\
 & + (1 - g_{\text{core}}^{\text{B-3}}) g_{\text{core}}^{\text{Y-11}}(\lambda, \lambda'') \varepsilon_{\text{trap}} \varepsilon_{\text{QE}}(\lambda'') d\lambda'' \end{aligned} \right\} \\
 & + N_0,
 \end{aligned}$$

2. Basic concept an aerogel Cherenkov detector using wavelength-shifting fibers

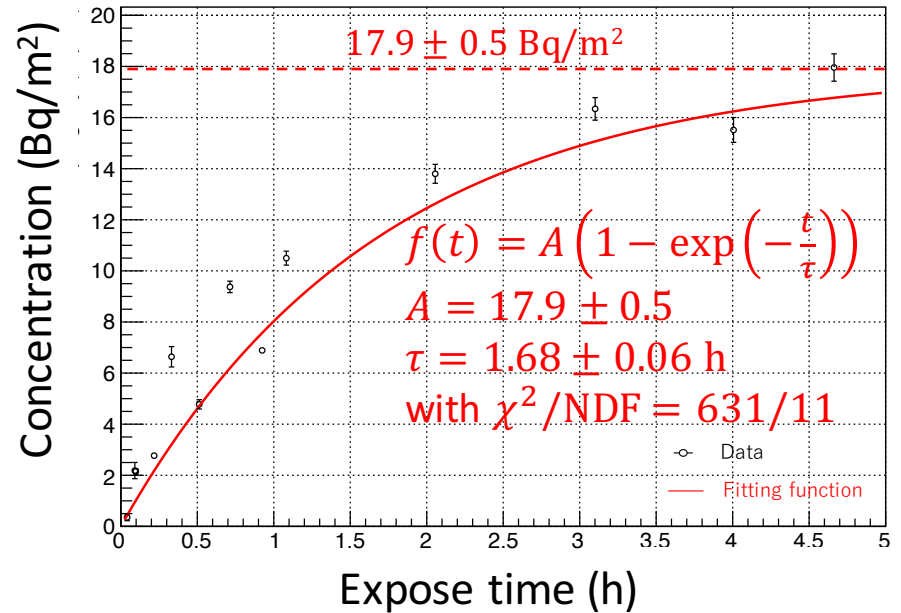
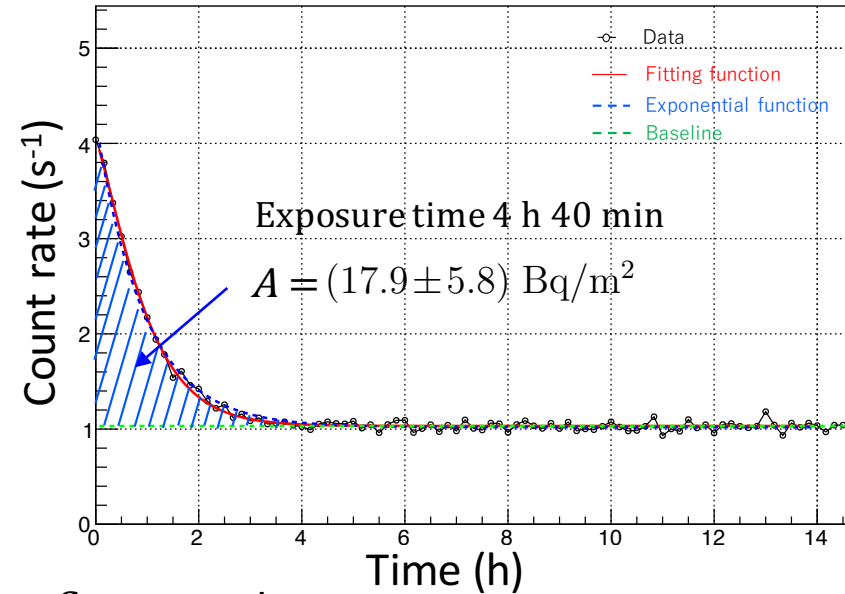
Measurement of light collection efficiency

(b)



3. Background study of environmental radiation

3.3. β rays surface inspection of sample sheets adsorbing radon progenies



Concentration

$$A = \sum_j (C(t_j) - R_{\text{BG}}) \Delta t_j \frac{\eta_\varepsilon k_\rho}{\varepsilon_{\text{Sr}} S}$$

$C(t_j)$: counting rate

R_{BG} : background rate

$\Delta t = 10 \text{ min}$

ε_{Sr} : ^{90}Sr eff. = $(8.68 \pm 0.01) \times 10^2 \text{ Bq}^{-1} \text{ h}^{-1}$

η_ε : ratio of ^{90}Sr eff. to radon prog. eff. = 0.37

k_ρ : correction coefficient = 1.15

S : 0.03 m^2

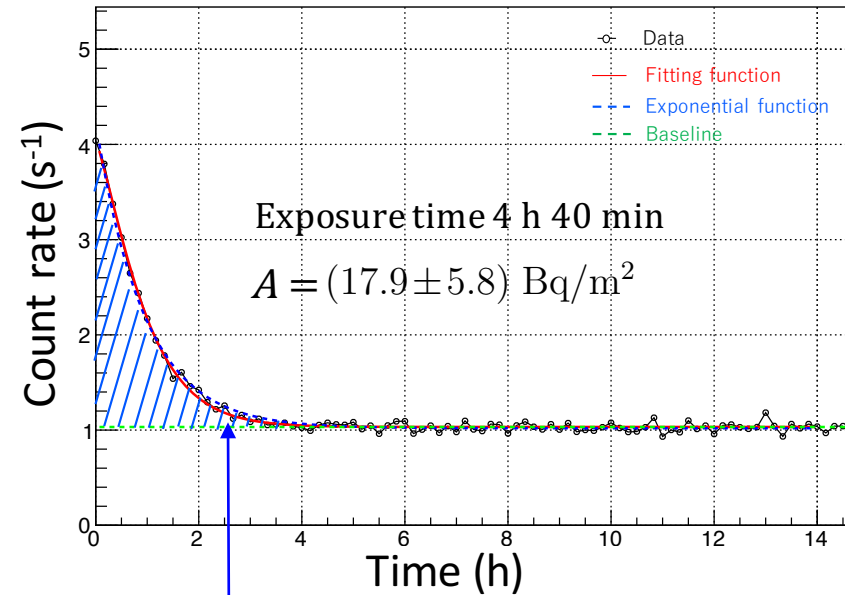
real-time stro

Interpretation

- (1) ^{218}Po only falls on the sample after the radon decay in the air. ^{214}Pb and ^{214}Bi produced at the sample.
- (2) ^{218}Po , ^{214}Pb , and ^{214}Bi in the air fall the sample after the radon decay in the air.

3. Background study of environmental radiation

3.3. β rays surface inspection of sample sheets adsorbing radon progenies



Simple exponential function fit

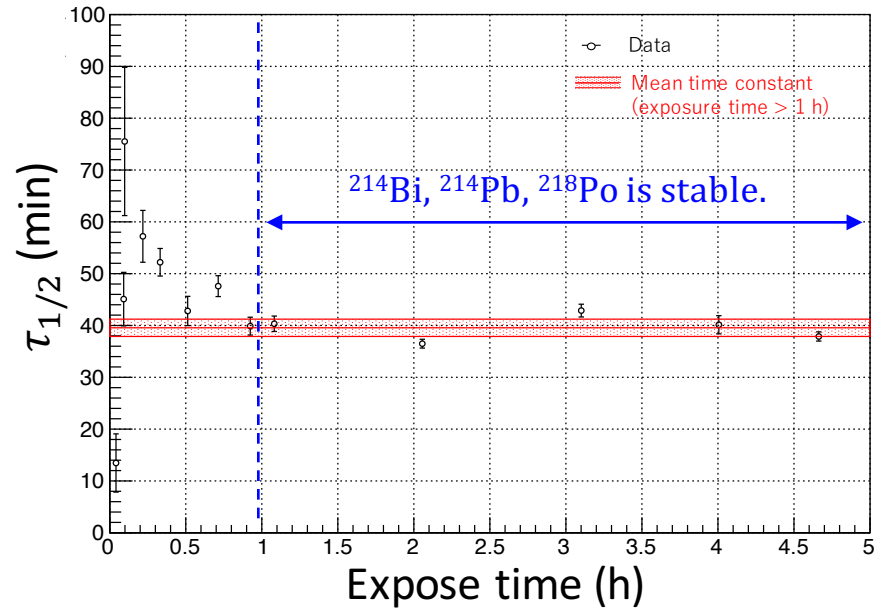
$$f(t) = A \exp(-t \ln 2 / \tau_{1/2}) + R_{BG}$$

$$A = 3.22 \pm 0.04$$

$$\tau_{1/2} = (0.95 \pm 0.02) \text{ h}$$

$$R_{BG} = (1.02 \pm 0.01) \text{ s}^{-1}$$

$$\text{with } \chi^2 / \text{NDF} = 0.32 / 69$$

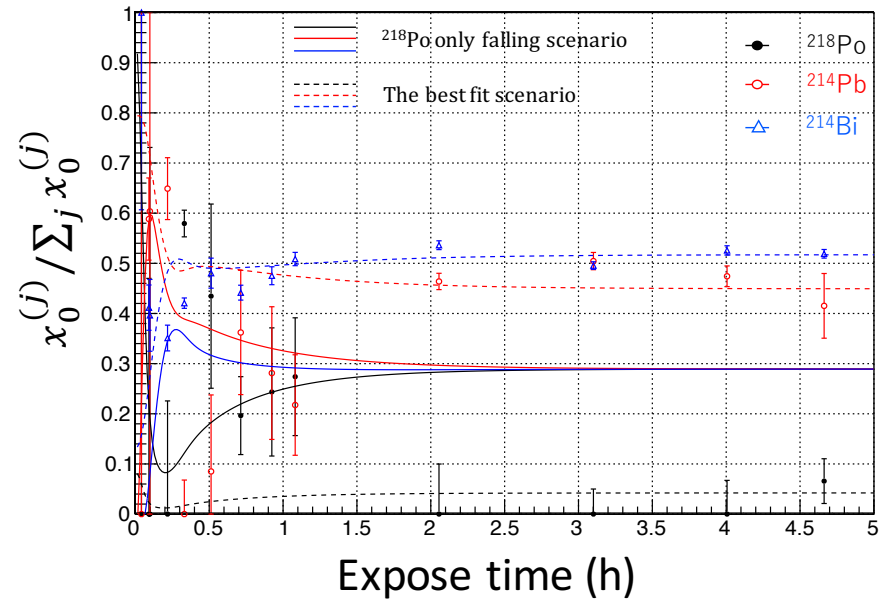
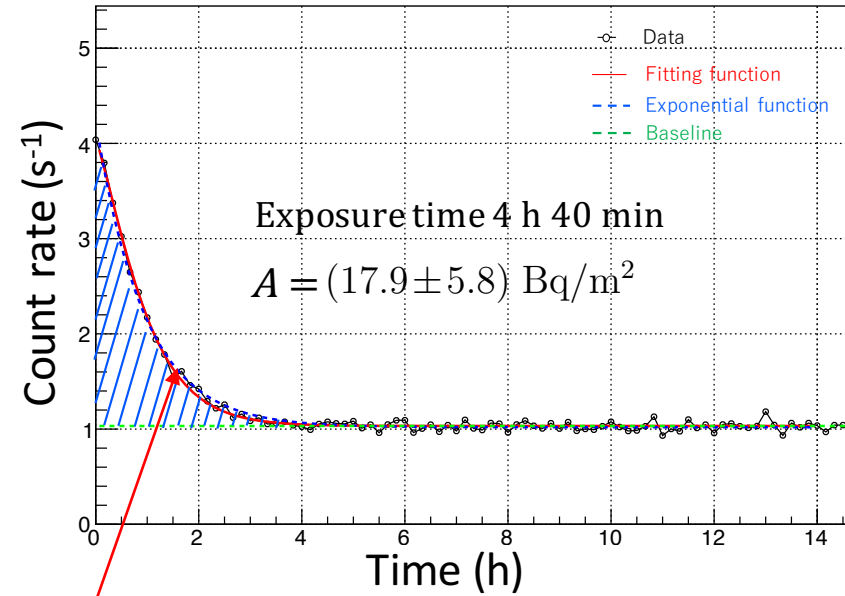


Interpretation

- (1) ^{218}Po only falls on the sample after the radon decay in the air. ^{214}Pb and ^{214}Bi produced at the sample.
- (2) ^{218}Po , ^{214}Pb , and ^{214}Bi in the air fall the sample after the radon decay in the air.

3. Background study of environmental radiation

3.3. β rays surface inspection of sample sheets adsorbing radon progenies



$$f(t) = \frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)} \exp(-\lambda_1 t) + \left(\frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)} + \frac{\lambda_2 x_0^{(2)}}{\lambda_3 - \lambda_2} \right) \exp(-\lambda_2 t) + \left(\frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)} + \frac{\lambda_2 x_0^{(2)}}{\lambda_3 - \lambda_2} + x_0^{(3)} \right) \exp(-\lambda_3 t) + R_{BG},$$

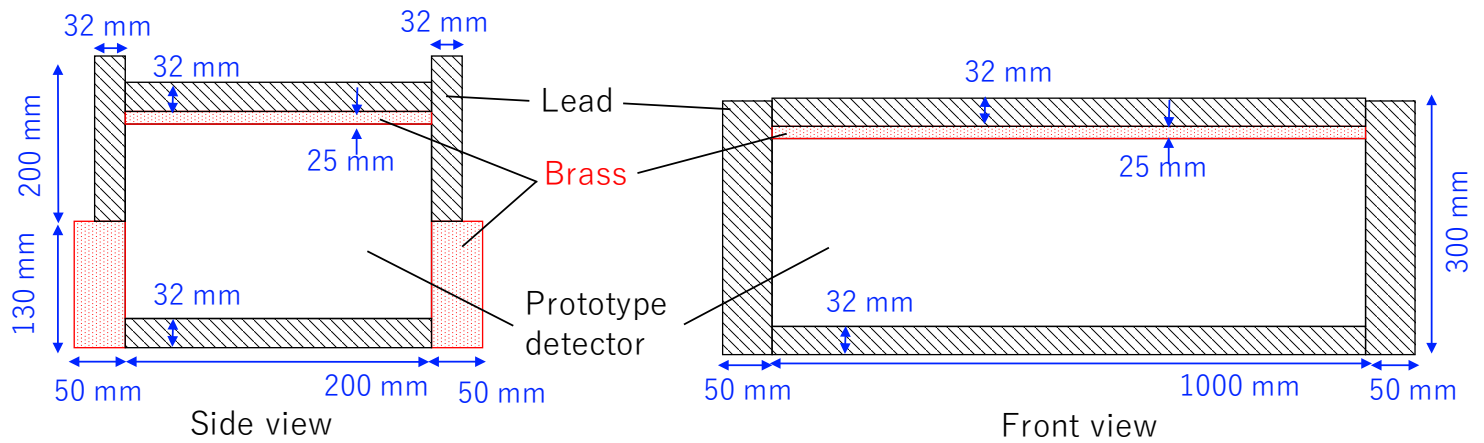
free parameters

Isotope $j = 1, 2, 3$ are ^{218}Po , ^{214}Pb , ^{214}Bi , respectively.

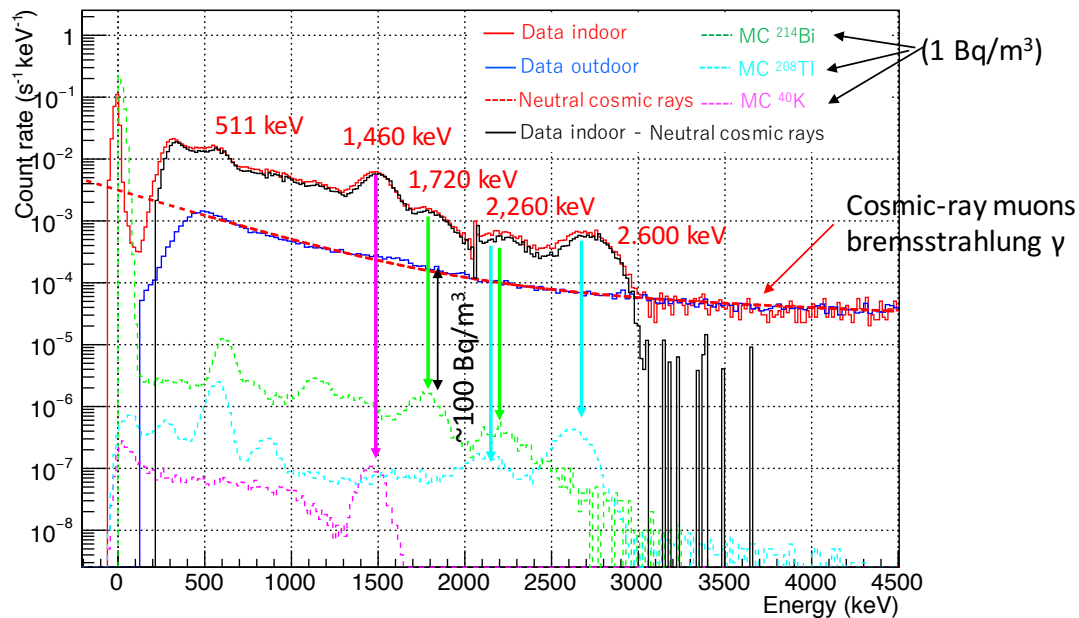
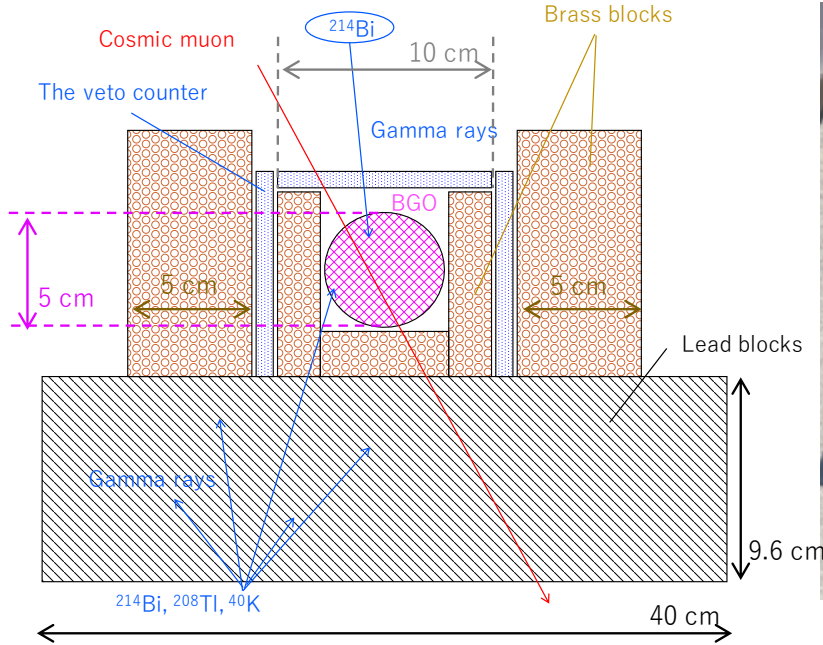
$\lambda_j = \tau_j^{-1}$: inverse of life time of isotope j

$x_0^{(j)}$: initial intensity of isotope j

R_{BG} : background rate

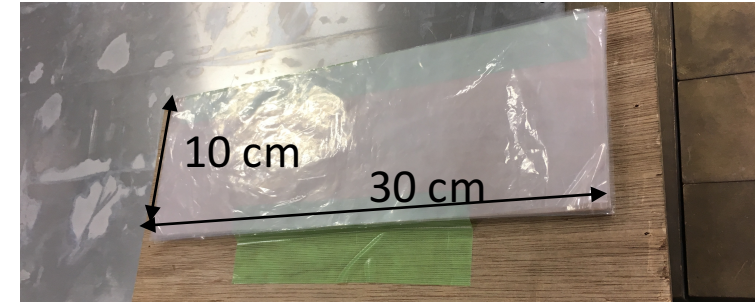
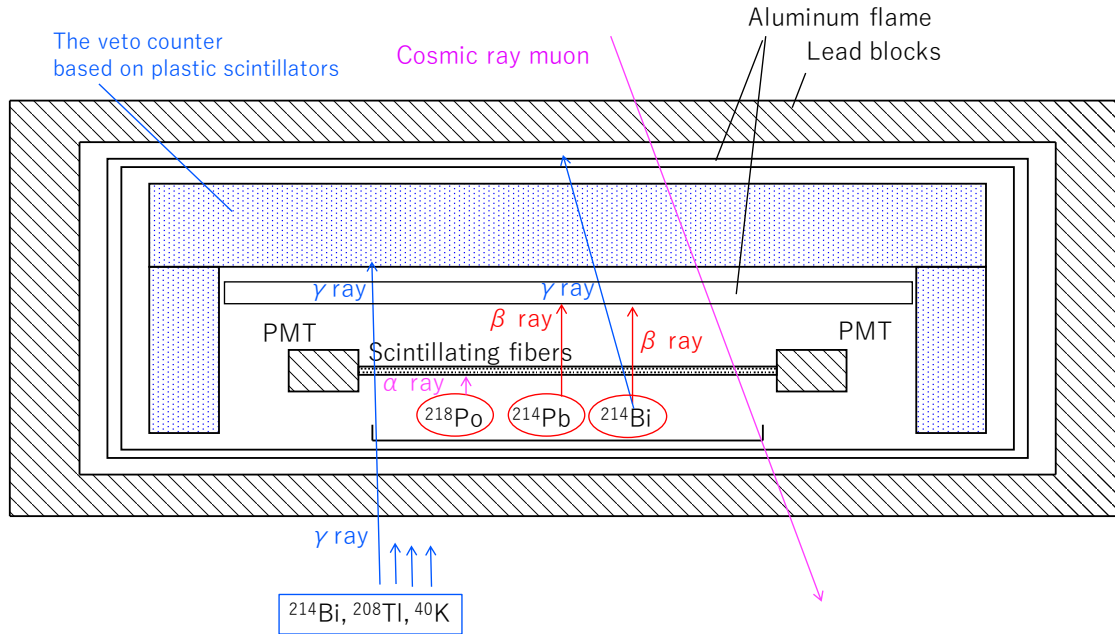


1. ^{90}Sr Counter 開発研究

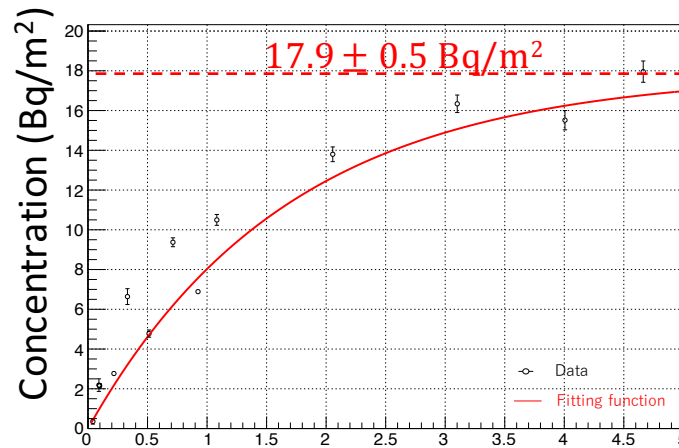
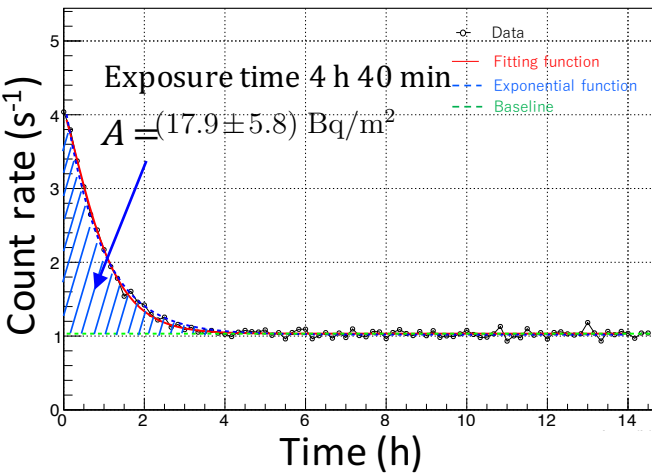


- 空气中 ^{214}Bi 濃度は 100 Bq/m^3 未満。
- コンクリート内部・表面に ^{214}Bi , ^{208}Tl , ^{40}K が存在している。
- 装置内部はできるだけ空間を減らすことを要請。

1. ^{90}Sr Counter 開発研究



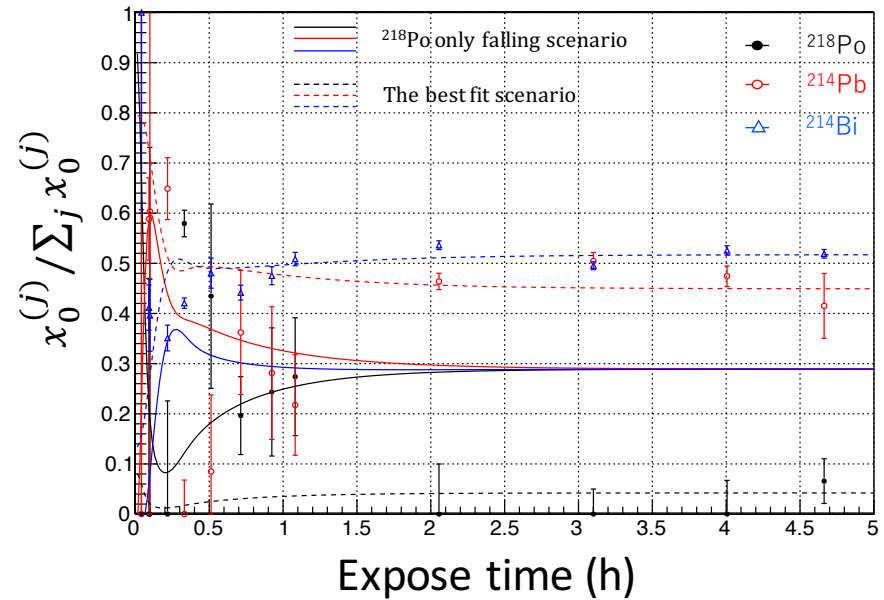
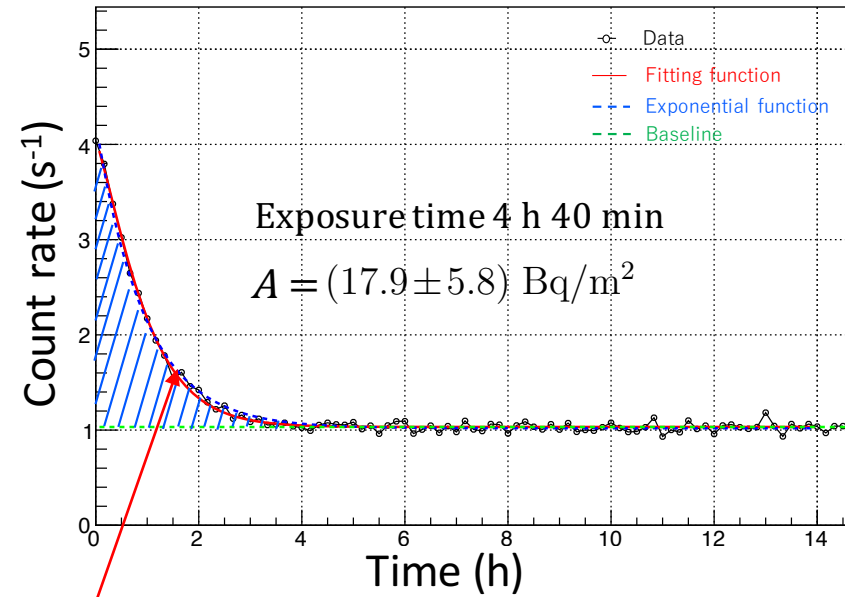
Polyethylene sample sheet (10枚)



- サンプル表面に 18 Bq/m^2 は無視できない。
- サンプルは空気に曝さないで測定する必要がある。

3. Background study of environmental radiation

3.3. β rays surface inspection of sample sheets adsorbing radon progenies



$$f(t) = \frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)} \exp(-\lambda_1 t) + \left(\frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)} + \frac{\lambda_2 x_0^{(2)}}{\lambda_3 - \lambda_2} \right) \exp(-\lambda_2 t) + \left(\frac{\lambda_1 \lambda_2 x_0^{(1)}}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)} + \frac{\lambda_2 x_0^{(2)}}{\lambda_3 - \lambda_2} + x_0^{(3)} \right) \exp(-\lambda_3 t) + R_{BG},$$

free parameters

Isotope $j = 1, 2, 3$ are ^{218}Po , ^{214}Pb , ^{214}Bi , respectively.

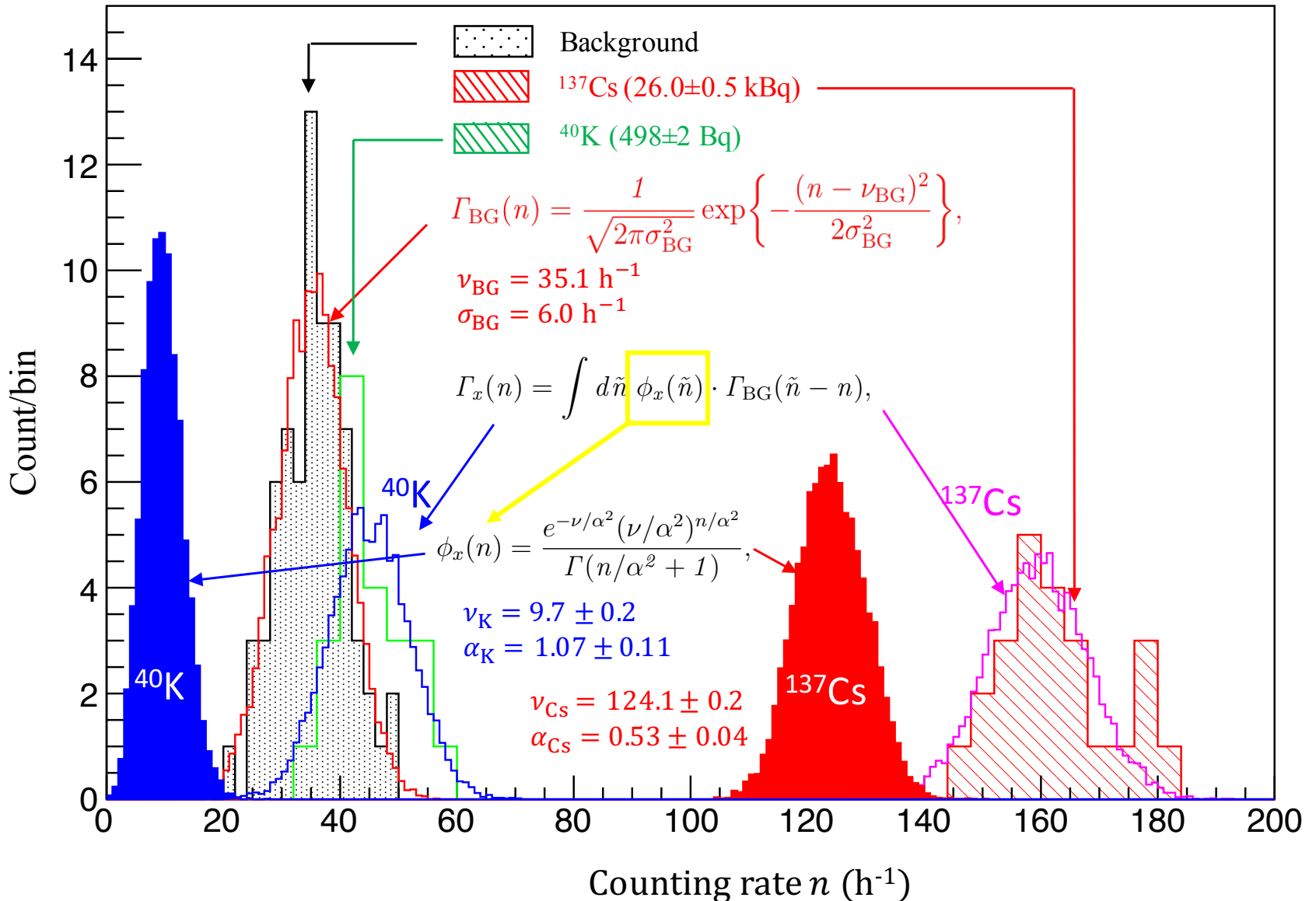
$\lambda_j = \tau_j^{-1}$: inverse of life time of isotope j

$x_0^{(j)}$: initial intensity of isotope j

R_{BG} : background rate

1. ⁹⁰Sr Counter 開発研究

線源を用いた性能評価測定



1. ^{90}Sr Counter 開発研究

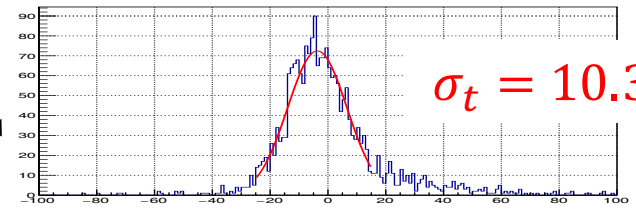
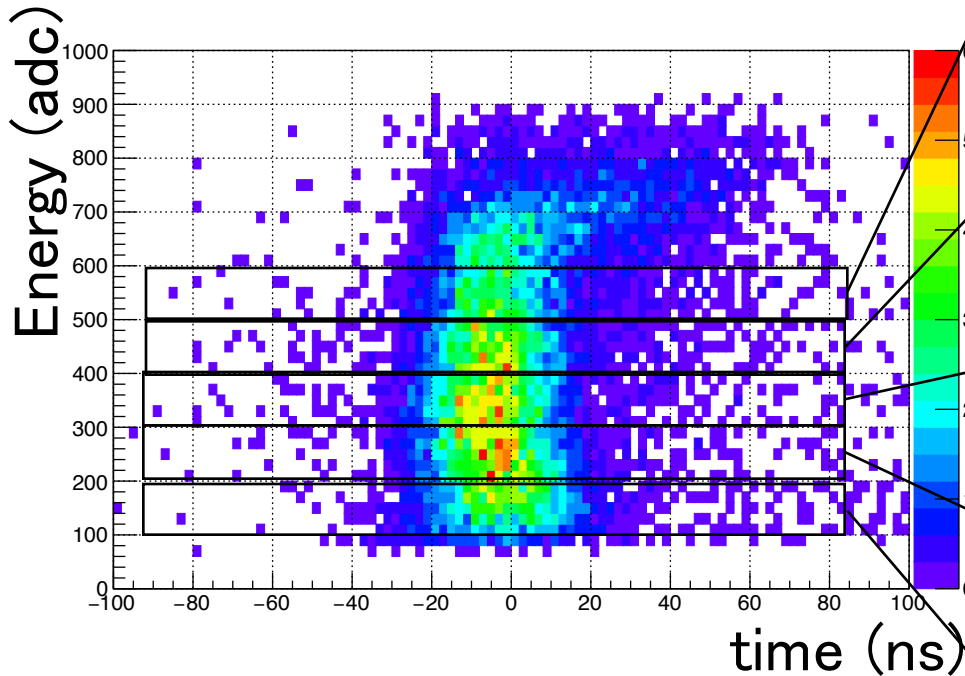
まとめ

- It is important to measure ^{90}Sr concentration in food because intake of ^{90}Sr is dangerous than ^{137}Cs , and the method of measuring ^{90}Sr rapidly is focused.
- Wavelength-shifting fiber system was adopted because it is not possible to inspect 10-Bq/kg ^{90}Sr by a large PMT reading Cherenkov photons directly.
- The light collection efficiency was estimated to be 1.0-1.4% for Cherenkov photons.
- The Cherenkov photons by ^{90}Y β rays was observed using the fibers.
- ^{214}Bi as the radon progenies in the air was not observed in the limit of 100 Bq/m³. The radon progenies on the sample sheets was not observed 18 Bq/m². It was found that the detector design should be performed the care for these ^{214}Bi .
- I produced a prototype detector with an effective area of 30×10 cm².
- The detection limit of weight concentration at 1-hour measurement was estimated to be 46 Bq/kg (seafood) and 1.5 Bq/kg (seawater). By extending to effective area of 1 m², it is expected to be 8.4 Bq/kg (seafood).

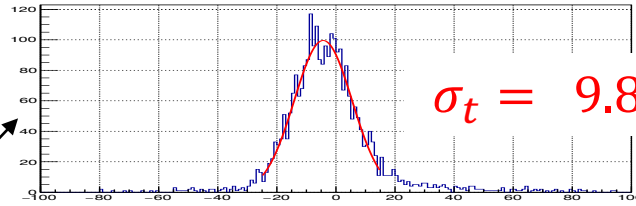
2. J-PARC E36 実験

時間分解能評価

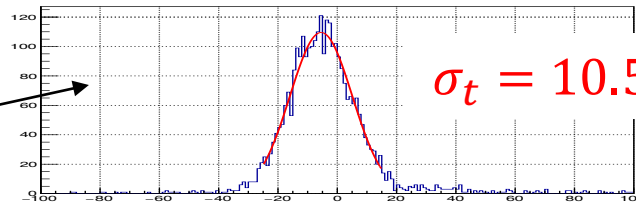
Muons stopped at CsI(Tl)



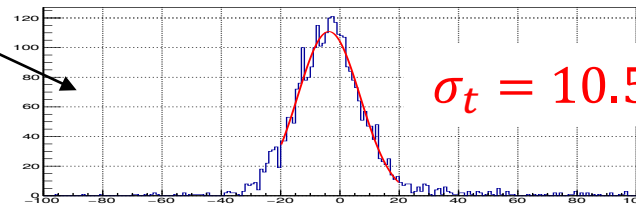
$$\sigma_t = 10.3 \pm 0.3 \text{ ns}$$



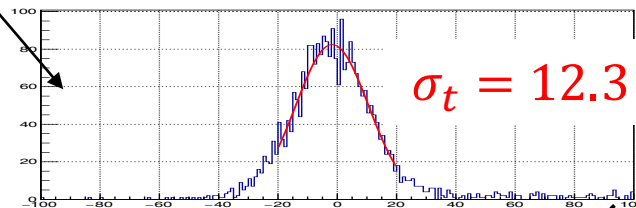
$$\sigma_t = 9.8 \pm 0.2 \text{ ns}$$



$$\sigma_t = 10.5 \pm 0.2 \text{ ns}$$



$$\sigma_t = 10.5 \pm 0.3 \text{ ns}$$



$$\sigma_t = 12.3 \pm 0.4 \text{ ns}$$

time (ns)

The timing resolution dose not depend on the photon energy strongly.

2. J-PARC E36 実験

時間分解能評価

Muon (K=153 MeV) stopped in CsI(Tl)

