宇核連研究会「宇宙核物理実験の現状と将来」
2014年8月7日、8日　　阪大RCNP

地上極低バックグラウンド測定による宇宙核物理

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1．ニュートリノ元素合成； Ba

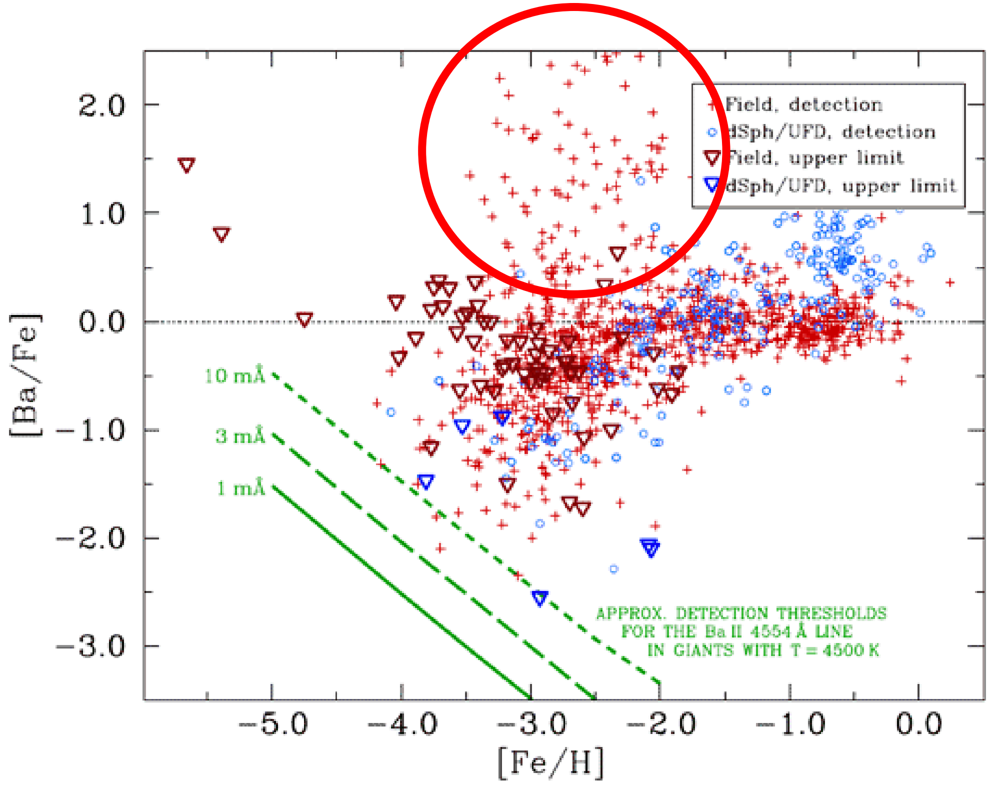
2．ニュートリノ原子核反応率をどうやって求めるか
－ 直接測定 vs 間接測定 －

3．同位体標的のミュオン捕獲測定

4．地上での極低バックグラウンド測定の可能性

5．まとめ

Barium in solar-system abundance is mainly from s-process, but is expected to be dominated by r-process in metal-poor stars.



I.U. Roederer, 2012 [2]

$$f_{odd} = \frac{N\left(^{135}Ba\right) + N\left(^{137}Ba\right)}{N\left(Ba\right)}$$

$= 0.11 \pm 0.01$ for s-only

0.46 ± 0.06 for r-only

0.17 in solar system

(Anders & Grevesse 1989 [1])

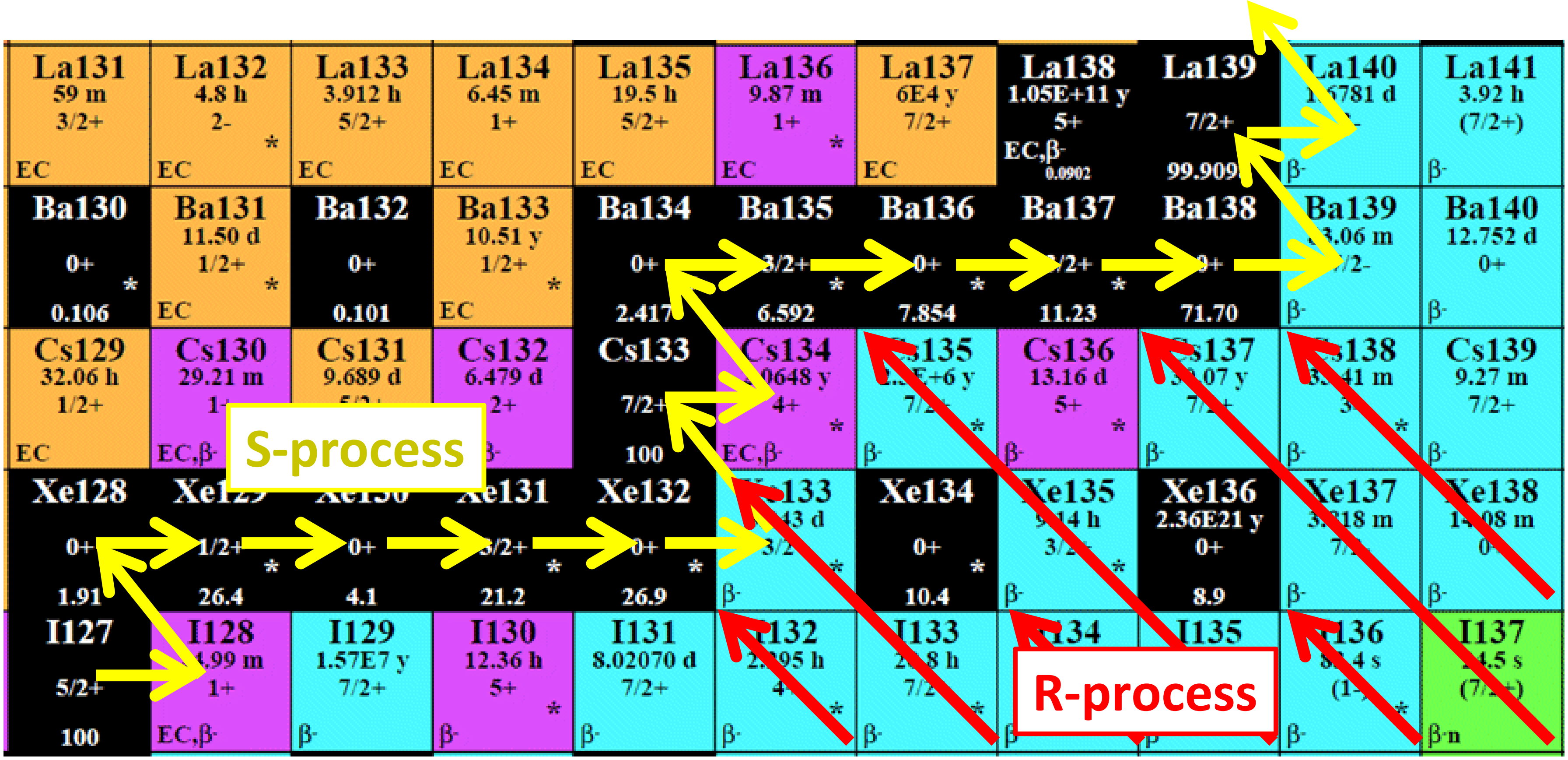
0.18 ± 0.08

Gallagher, Aoki, Honda et al. 2012

0.15 ± 0.12

Collet, Asplund, Nissen 2009

Another aspect of ββ nuclei

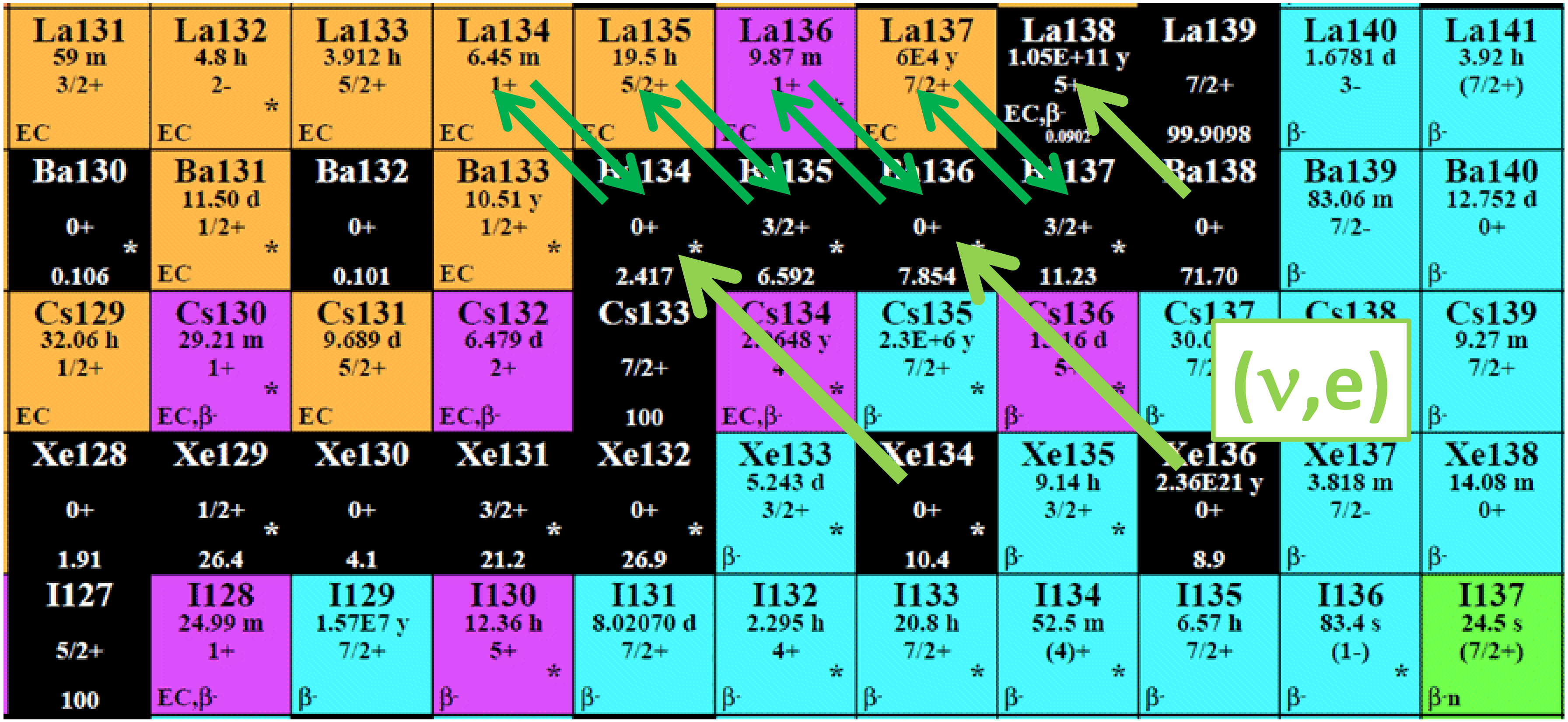


La131 59 m 3/2+ EC	La132 4.8 h 2- * EC	La133 3.912 h 5/2+ EC	La134 6.45 m 1+ EC	La135 19.5 h 5/2+ EC	La136 9.87 m 1+ * EC	La137 6E4 y 7/2+ EC	La138 1.05E+11 y 5+ EC,β- 0.0902	La139 7/2+ 99.909	La140 1.6781 d 3- β-	La141 3.92 h (7/2+) β-
Ba130 0+ * 0.106	Ba131 11.50 d 1/2+ * EC	Ba132 0+ 0.101	Ba133 10.51 y 1/2+ * EC	Ba134 0+ 2.417	Ba135 3/2+ * 6.592	Ba136 0+ * 7.854	Ba137 3/2+ * 11.23	Ba138 0+ 71.70	Ba139 83.06 m 7/2- β-	Ba140 12.752 d 0+ β-
Cs129 32.06 h 1/2+ EC	Cs130 29.21 m 1+ EC,β-	Cs131 9.689 d 5/2+	Cs132 6.479 d 2+ β-	Cs133 7/2+ 100	Cs134 2.0648 y 4+ * EC,β-	Cs135 2.3E+6 y 7/2+ * β-	Cs136 13.16 d 5+ * β-	Cs137 30.07 y 7/2+ β-	Cs138 33.41 m 3- * β-	Cs139 9.27 m 7/2+ β-
Xe128 0+ 1.91	Xe129 1/2+ * 26.4	Xe130 0+ 4.1	Xe131 3/2+ * 21.2	Xe132 0+ * 26.9	Xe133 5.243 d 3/2+ * β-	Xe134 0+ * 10.4	Xe135 9.14 h 3/2+ * β-	Xe136 2.36E21 y 0+ 8.9	Xe137 3.818 m 7/2- β-	Xe138 14.08 m 0+ β-
I127 5/2+ 100	I128 24.99 m 1+ EC,β-	I129 1.57E7 y 7/2+ β-	I130 12.36 h 5+ * β-	I131 8.02070 d 7/2+ β-	I132 2.295 h 4+ * β-	I133 20.8 h 7/2+ * β-	I134 [illegible] β-	I135 [illegible] β-	I136 83.4 s (1-) * β-	I137 24.5 s (7/2+) β-n

Parent of ββ decay = pure r-nuclei

Daughter of ββ decay = pure s-nuclei

ν-process



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Neutrino-induced double-beta decay of ^{134,136}Xe may play crucial roles in production of ^{134,136}Ba in r-process.

How to determine $\sigma_{\nu A}$ experimentally ?

1. Direct measurement

   Neutrino beam, muon-capture (inverse reaction)

2. Indirect measurement --- analogous interactions

   Neutral current --- photo- & Coulomb break up,

   (p,p′), etc.

   Charged current --- (p,n), (^{3}He,t), etc.

Muon-capture experiment at J-PARC/MLF/MUSE

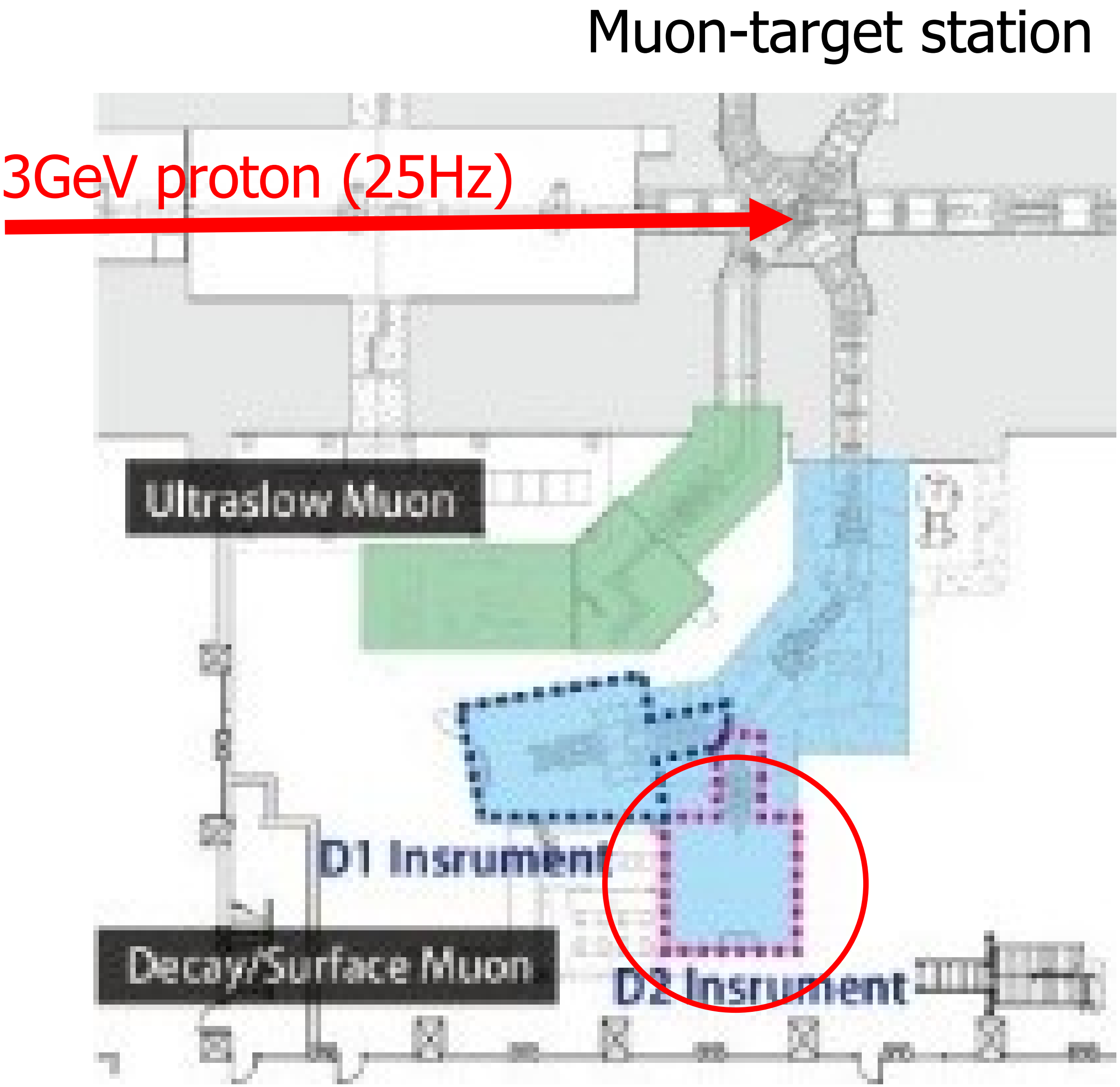
Method;

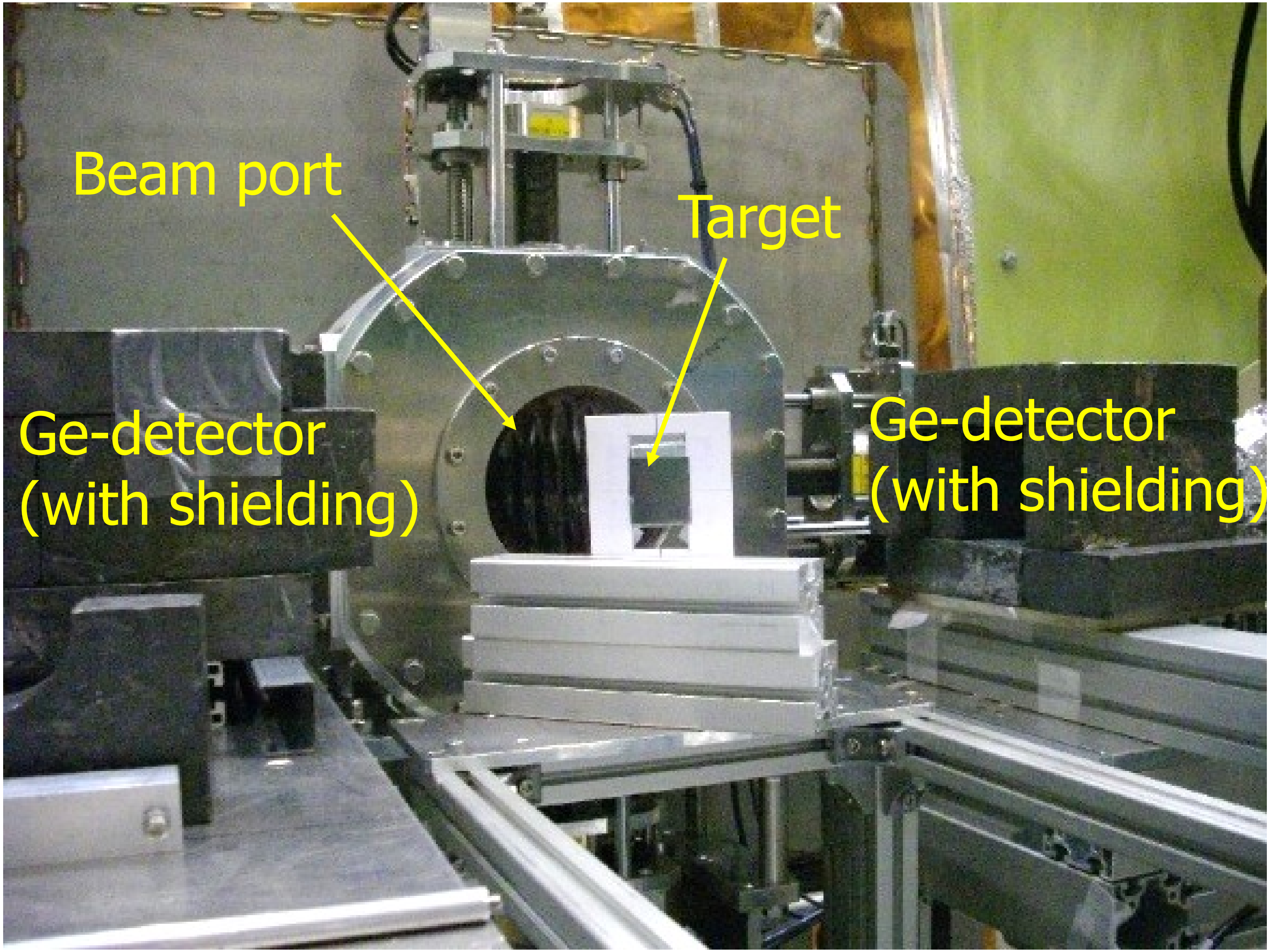
- prompt X-rays from muonic atoms
- prompt γ-rays from $(\mu^-,\nu_\mu xn)$ reactions
- β-delayed γ-rays from daughter nuclei

were measured with HP-Ge detectors

Target; ^{100}Mo (94.5% enriched, 80mg/cm^2)
^{nat}Nb (^{93}Nb 100%, 20mg/cm^2)
^{nat}Ta (^{181}Ta 99.99%, 167mg/cm^2)

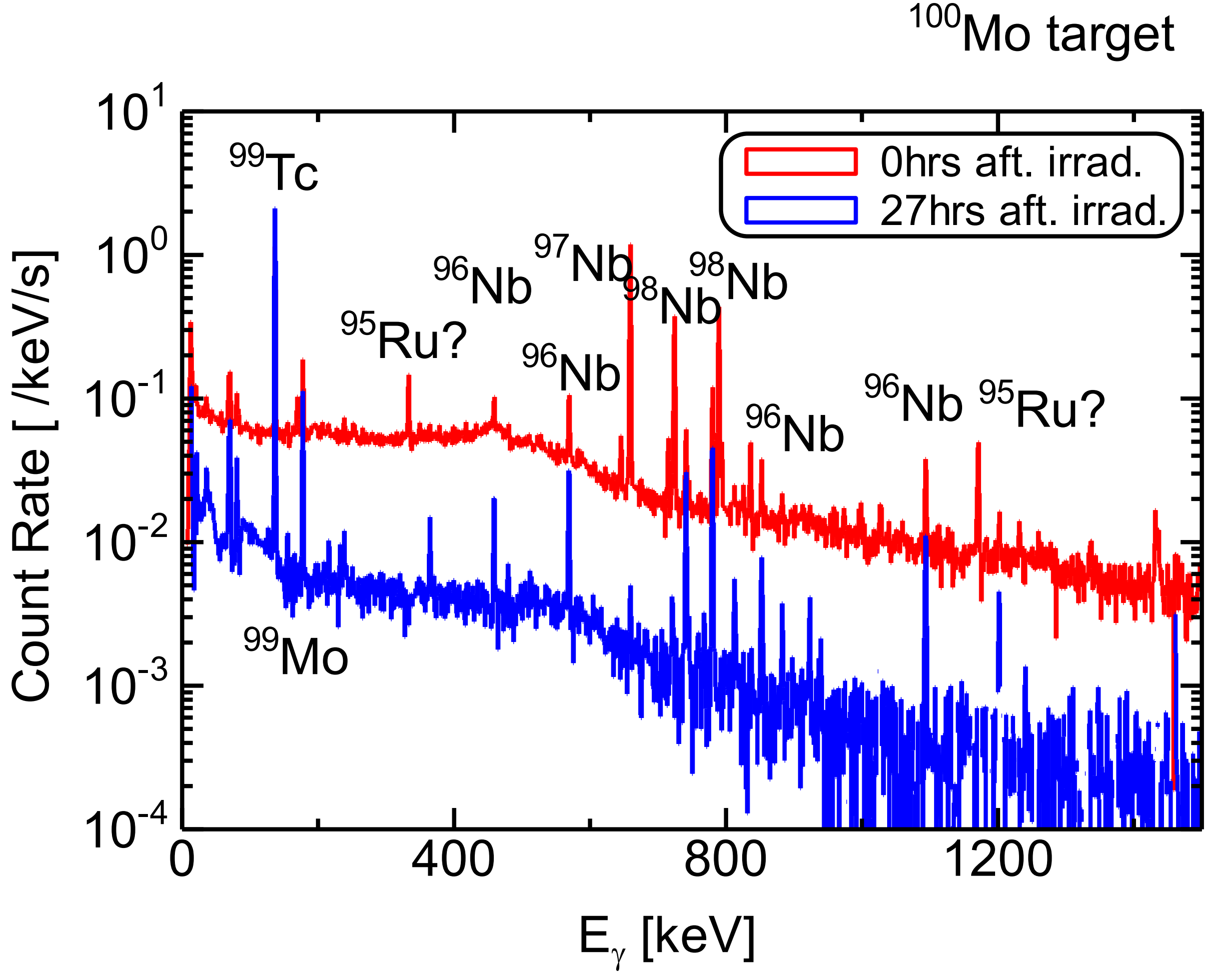
Muon-capture experiment at J-PARC/MLF/MUSE




Beam port
Target
Ge-detector (with shielding)
Ge-detector (with shielding)

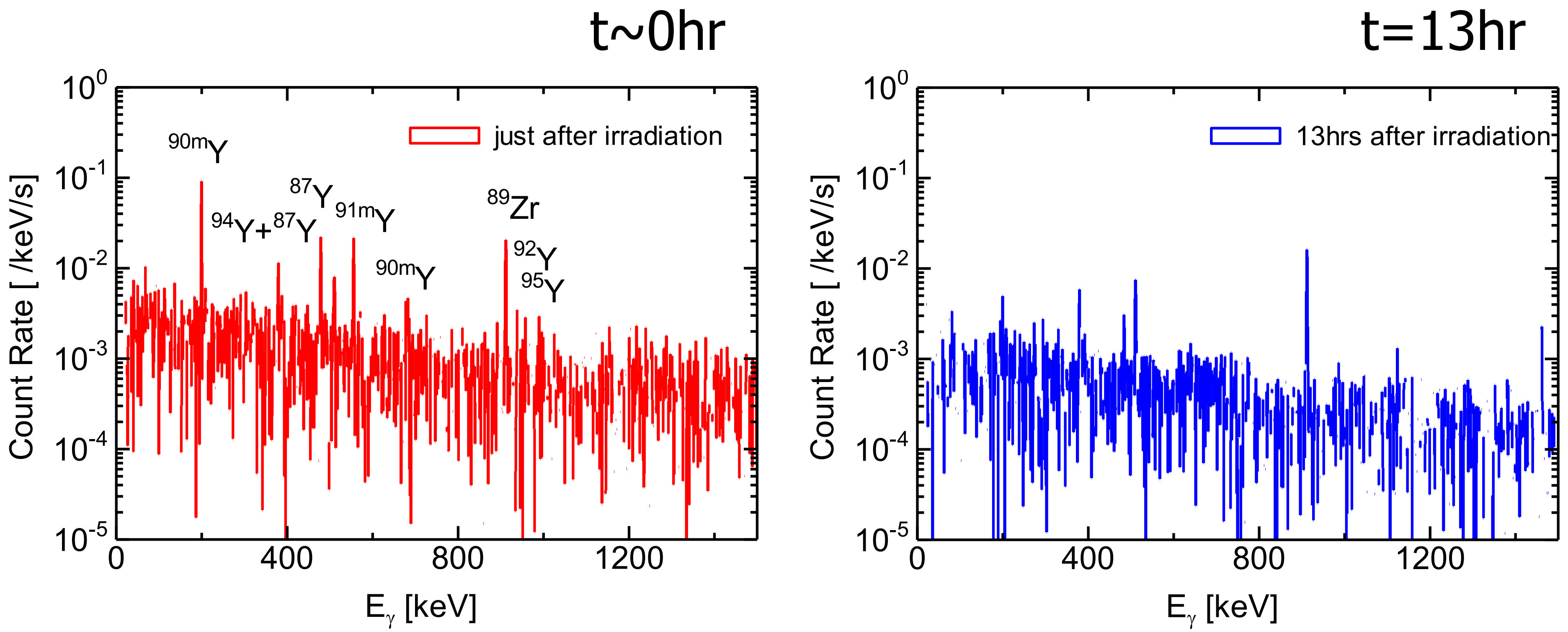
Net γ-ray spectra (^{100}Mo target, 80mg/cm^2)

$\Phi_{\mu^-} \sim 10^6$ /s, exposure time = 7 hrs



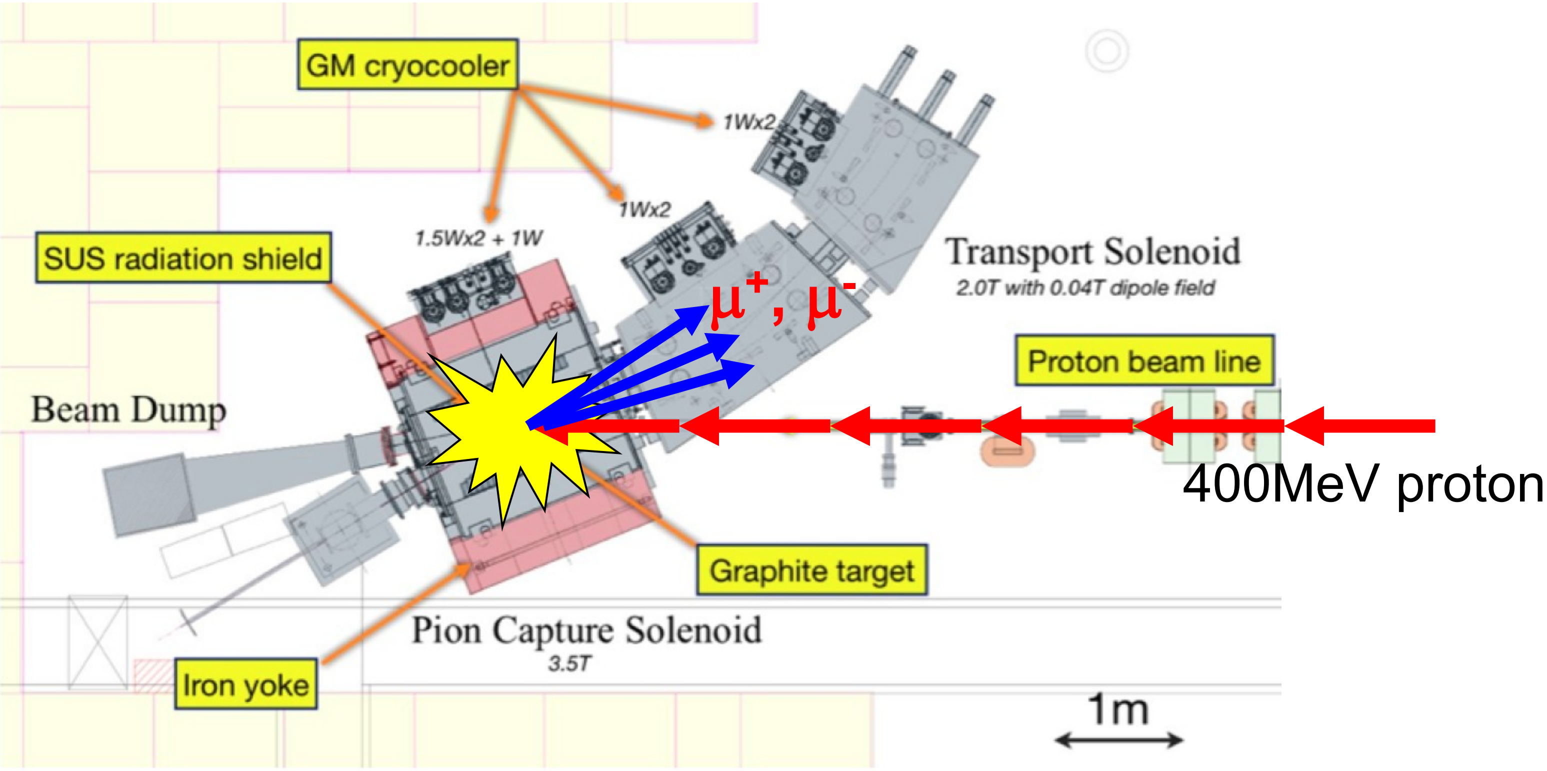
Net γ-ray spectra (^{nat}Nb target, 20mg/cm^2)

Φ_{μ^-} ~10^6 /s, exposure time = 50 min.


t~0hr

t=13hr

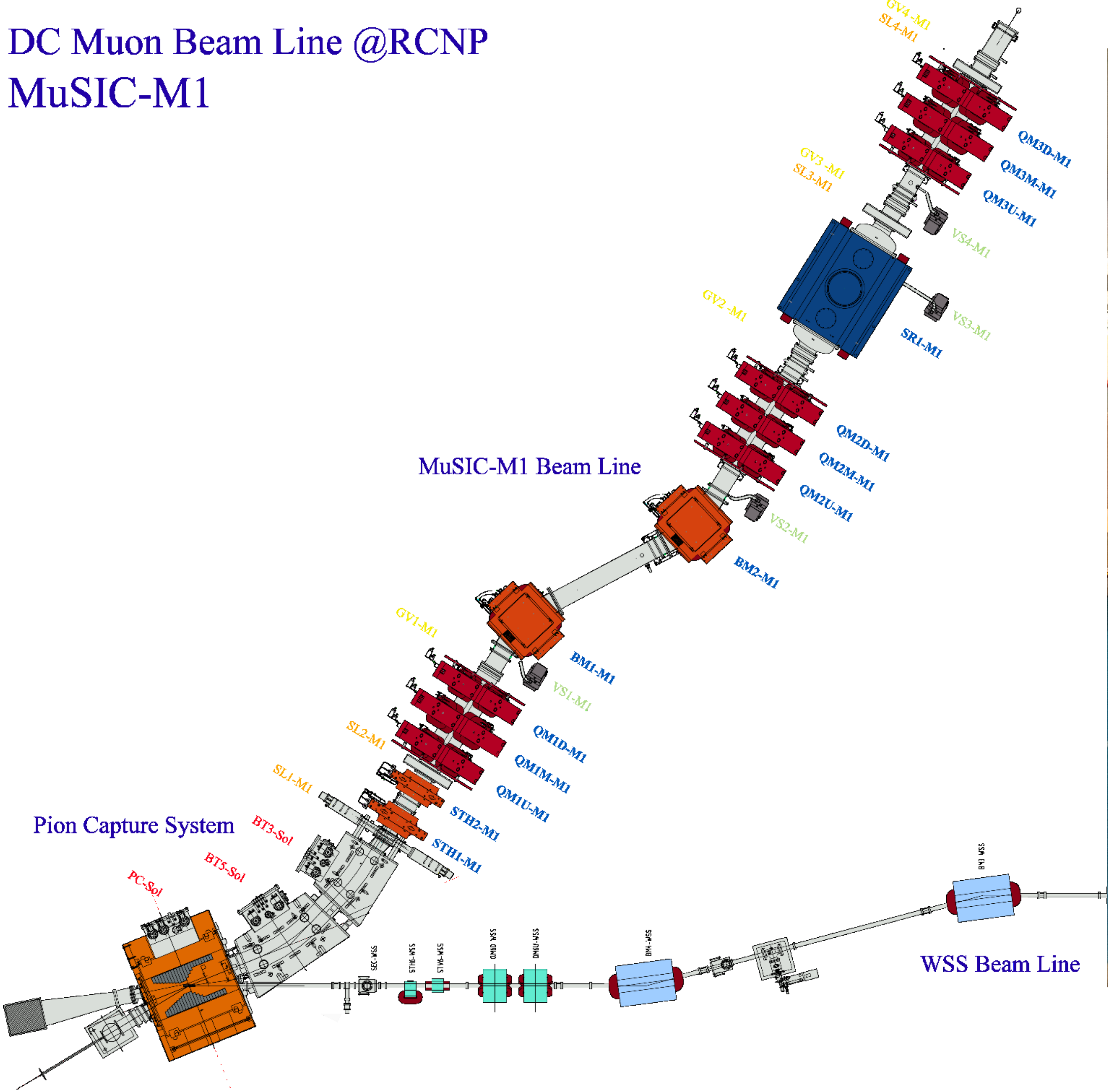
MuSIC High-intensity muon source at RCNP, Osaka



Stopped μ^- rate ~5×10^7 /s@400W (~10^5 /cm^2/s)

DC Muon Beam Line @RCNP

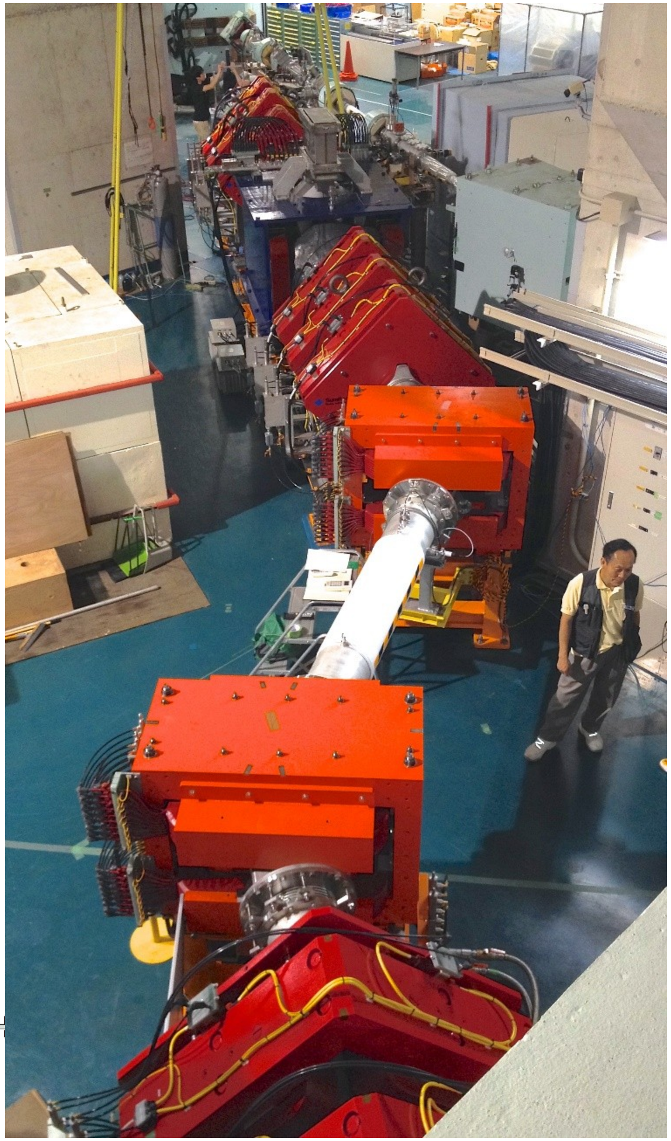
MuSIC-M1



MuSIC-M1 Beam Line

Pion Capture System

WSS Beam Line



不安定核標的実験の可能性

ミュオン原子生成率：

$$R_{Z\mu} \cong \left(\frac{Z \cdot N_Z}{10^{18}} \right) \cdot \Phi_\mu \cong \left(\frac{Z \cdot \Phi_Z \cdot t}{10^{18}} \right) \cdot \Phi_\mu$$

Φ_μ : incident muon intensity

Z : atomic number of unstable nuclei, Φ_Z : flux of unstable nuclei

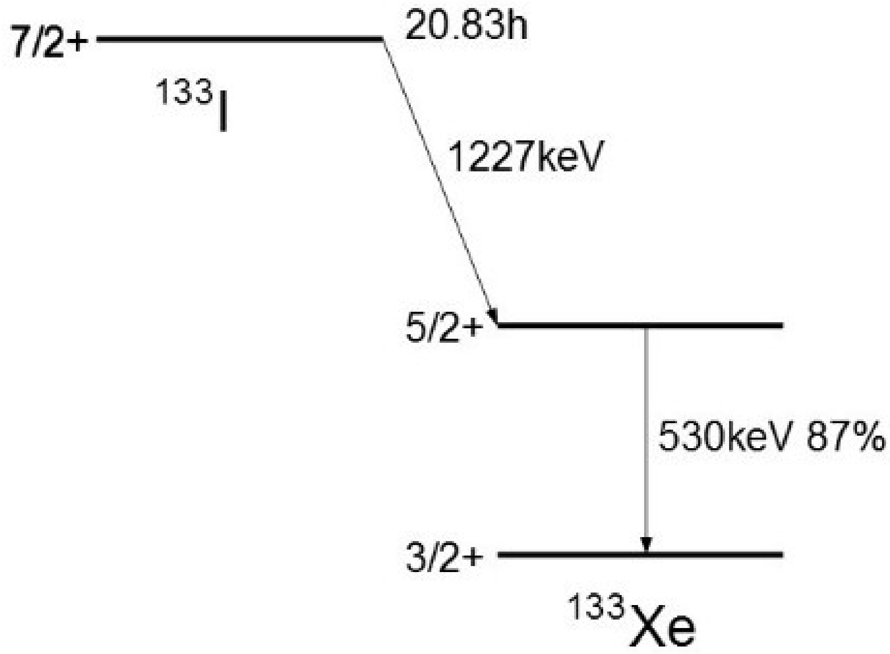
t : accumulation time

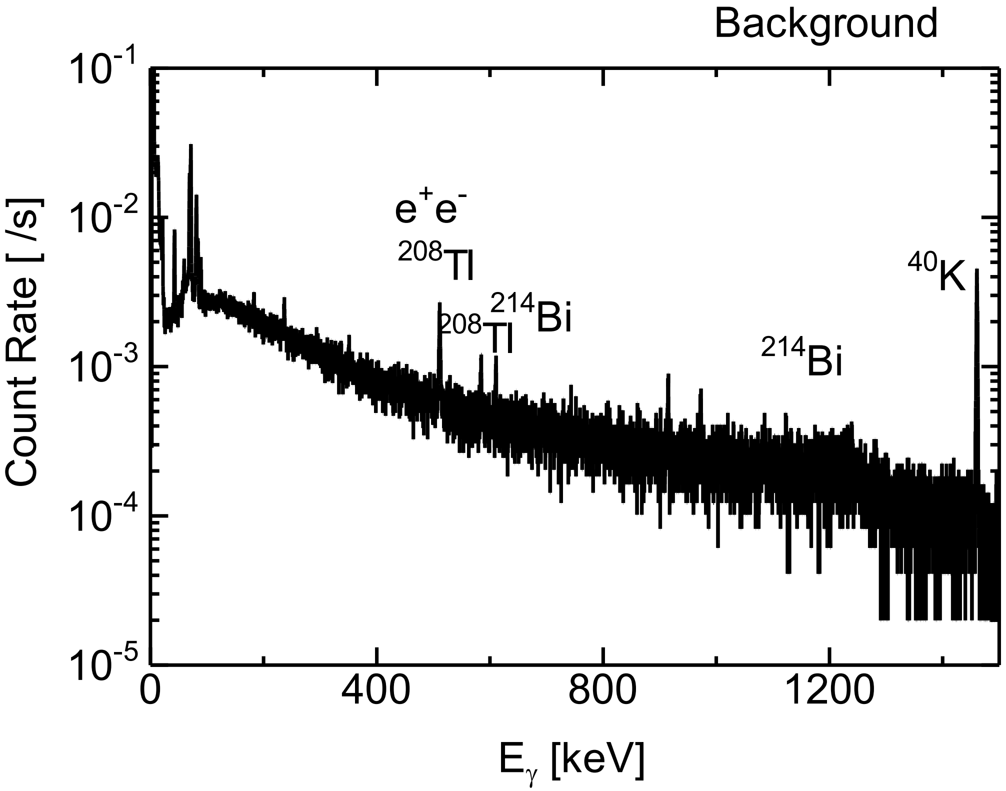
不安定核ビーム 10^5 個/cm^2/s (Z~40, t~10^5 s)

負ミュオン 10^5 /cm^2/s

⇒ 生成レート: *O(0.01)* /s、崩壊レート: *O(0.01)* /s

例: ^{133}Xe($T_{1/2}$=5.24d) (μ^-,ν_μ)^{133}I($T_{1/2}$=20.8h)





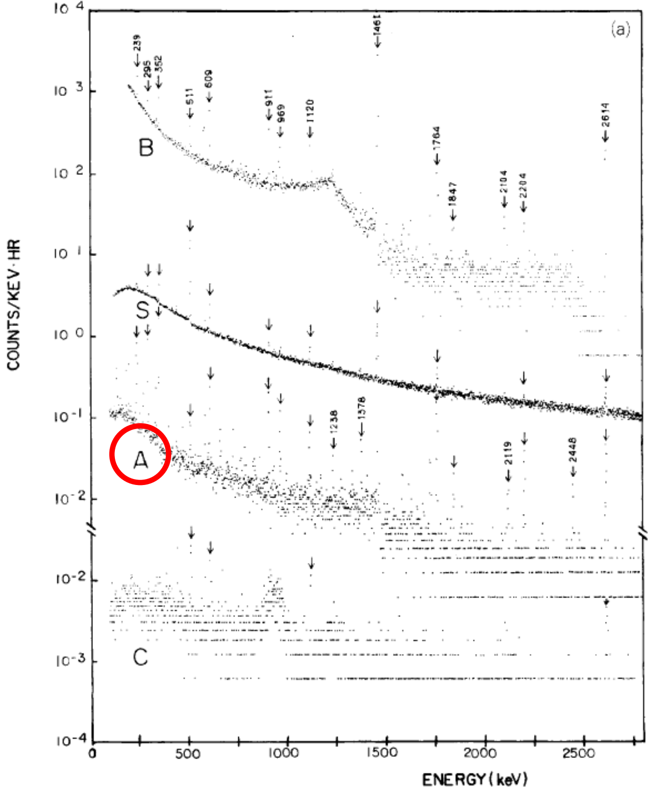
BG rate = 5×10^{-4} [/keV/s]

How deep can we go ?

ELEGANT-III BG rate

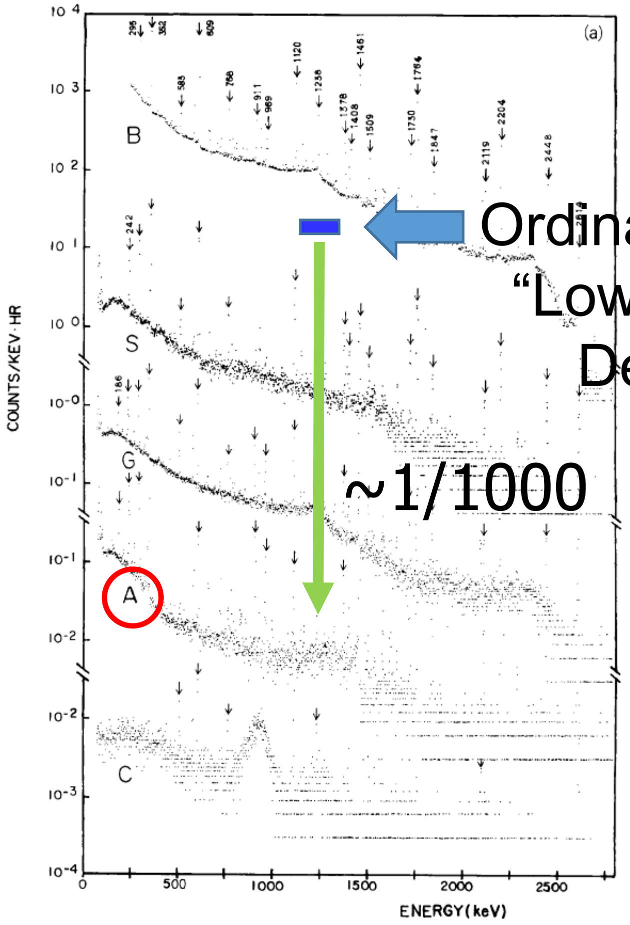
N. Kamikubota et al., NIM A245, 379 (1986)

Osaka (sea level)



Kamioka

(1000m underground, 2700m.w.e.)



Ordinary
"Low-BG"
Detector

~1/1000

B: not shielded S: shielded (15cm OFHC+15cm Pb)

G: shielded, with Rn rejection

A: anti-coincidence with NaI C: coincidence with NaI for ^{76}Se $2^+ \rightarrow 0^+$ (559keV)

まとめ

- ミュオン捕獲 --- ニュートリノ原子核反応に対する直接的な情報を与える

- 二次粒子ビーム (n, γ, μ, ν)×極低バックグラウンド放射化測定

  ⇒ 希少安定同位体、不安定核標的の (n,γ), (γ,n), μ-capture, etc. が測定可能に！

- ただし二次粒子ビーム源（≒加速器施設）で極限の低BG性能が実現すれば。

➡ 討論へ。