Real-time ^{90}Sr Counter

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Abstract*—Radioisotopes have been emitted around Japan due to a nuclear accident at the Fukushima daiichi nuclear power station in March 2011. A problem is the contaminated water including the atomic nucleus which relatively has a long half-life time and soluble such as ^{90}Sr, ^{137}Cs. Internal exposures by ^{90}Sr are more dangerous than ^{137}Cs's because Sr has effective half-life time of 18 years and property of accumulation in a born. We have developed real-time ^{90}Sr counter which is sensitive beta-ray of maximum kinematic energy of 2.28 MeV from ^{90}Sr and insensitive of beta-ray of maximum kinematic energy of 1.17 MeV and gamma-ray from ^{90}Sr by Cherenkov detection. This counter composes of Cerenkov counter, trigger scintillation counter and veto counter. Silica aerogel for Cherenkov counter can obtain refractive index between 1.017 and 1.049 easily. And wavelength shifting fiber (WLSF) is used as a light guide for extending effective area and producing lower cost. A mechanism of the identification of ^{90}Sr is explained in following. In case of ^{90}Sr, when the trigger counter reacts on the beta-ray from ^{90}Sr, aerogel emits the Cherenkov light and WLSF reacts and read the Cherenkov light. On the other hand, in case of ^{137}Cs, the trigger counter reacts on the beta-ray, aerogel stops the beta-ray and Cherenkov light is not emitted. Therefore, aerogel has a function as a radiator and shielding material. the gamma-ray is not reacted on the lower density detector. Cosmic rays would be also reacted by the veto counter. A prototype counter whose the effective area is 30 cm $\times$ 10 cm was obtained $(2.0 \pm 1.2)^3$ of mis-identification as ^{137}Cs/^{90}Sr. Detection limit in the surface contamination inspection depends on measurement time and effective area mainly. The sensitivity of wide range, $10^{-2} - 10^4$ Bq/cm^2, is obtained by adjustment of detection level in circuit of this counter. A lower radioactive sample ($< 10^{-2}$ Bq/cm^2) allows be detected significantly by heating treatment to evaporate water shielding the beta-rays.

I. Introduction

In march 2011, an accident at Fukushima daiichi Nuclear power station has been emitting about 900 PBq as a conversion of iodine with Internal Nuclear Event Scale (INES-estimation) of the radioisotope into the atmosphere, which is equivalent to one sixth of the nuclear accident at Chernobyl power plant. From the accident, a larger area (1800 km2) inside of Fukushima Prefecture in Japan has become to dangerous area when possible of emitting is 5 mSv/year or more [1].

Main radioisotope produced by nuclear reactor is known as ^{131}I, ^{129m}Te, ^{238}Pu, ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{133}Xe, ^{106}Ru and so on. Just after the accident occurred, we had been careful about internal exposure at the thyroid gland by accumulating ^{131}I through a breath, which has a short half-life (8 days). Currently in 2015, we are careful about exposure through the contamination water having ^{90}Sr, ^{137}Cs and so on, which have a long half-life.

A. The Risk of Contaminated Water

Atomic nuclear including in contaminated water by radioactivity are ^{90}Sr and ^{137}Cs mainly. ^{90}Sr is Alkali earth metal and has physical life-time of 29 years, biological life-time of 49 years and effective life-time of 18 years. On the other hands, ^{137}Cs is Alkali metal and has physical life-time of 30 years, biological life-time of 70 days and effective life-time of 70 days. When the nuclei is absorbed in the body, ^{90}Sr is accumulated into the born. In the case of ^{137}Cs, it is flowed out by the basal metabolism. The effective life-time τ_{eff} is defined as

$$\tau_{eff}^{-1} = \tau_{phys}^{-1} + \tau_{phys}^{-1}, \quad (1)$$

which τ_{phys} is physical life-time and τ_{bio} is biological life-time, and describes the incubation period in the body.

After the ^{90}Sr emitted into the sea, these accumulate into the sea foods. Therefore, we have dangerous to take them. Since of the ^{90}Sr's property accumulating into the born, they are accumulated ^{90}Sr depending on the period from the accident. A reference value of radioactivity which is included in the food has been defined as 100 Bq/kg by Health, Labour and Welfare phase, Japan in 2012.

B. Difficulty of Radioactivity Measurement

^{137}Cs has decay mode: (1) beta-ray of maximum 1.17 MeV and (2) beta-ray of maximum 0.51 MeV and gamma-ray of 0.662 MeV. Since of detection 0.662 MeV spectrum, ^{137}Cs is identifiable easily. In adding, since of gamma-ray's property of permeability, it is possible to suppress background from beta-ray of small energy by sheltering measurement. On the other hands, ^{90}Sr decays to ^{90}Y with beta-ray of maximum 0.55 MeV and ^{90}Y decays to ^{90}Zr with beta-ray of maximum 2.28 MeV. Beta-ray detection is only surface contamination inspection because it has less permeability. And in the case of environment existing ^{137}Cs, it is difficult to identify ^{90}Sr by background of ^{137}Cs's beta-ray.

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C. The inspection by chemical extraction

In conventional method, mount of ^{90}Sr in sample is estimated by chemical extraction. At first, pure strontiums are extracted from samples. Then, they are waited about a month to be a condition of radiative equilibrium. After becoming the condition, the mount of ^{90}Sr is estimated by measurement of ^{90}Y/^{90}Zr including the Strontiums. Therefore, this method has a long measurement time.

D. This study purpose

Since the above, a new device is required detection only ^{90}Sr, identifiable radiation over the limited 100 Bq/kg and measuring short-time. This article describes the design, construction, mechanism and performance estimation using radioactive source.

II. Real-time ^{90}Sr Counter

We have developed ^{90}Sr counter which measures at short-time or real-time ($\sim$ minutes) and identifiable ^{90}Sr in environment existing other radioation [2], [3]. This counter composes scintillating fibers trigger counter, Aerogel Cherenkov counter and cosmic ray veto counter. An event reacted only the trigger counter and the Cherenkov counter simultaneously is detected beta-ray from ^{90}Sr.

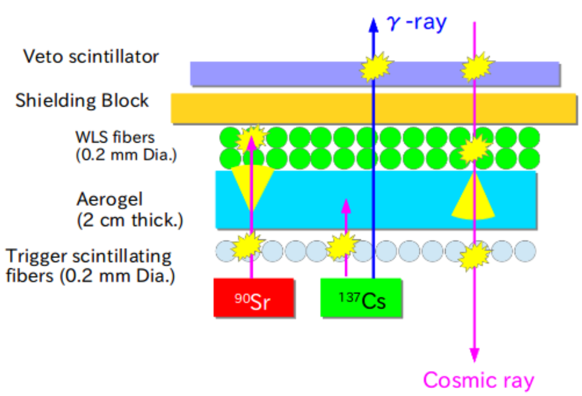

Fig. 1. Mechanism of real-time ^{90}Sr counter.

A. Scintillating fibers trigger counter

A trigger counter should have thinner type to loss energy of beta-ray for Cherenkov counter. The taking it is easy by using a sheet form of scintillating fibers than thinner scintillator crystal. The scintillating fibers trigger counter made from the fibers which size is 0.2 mm diameter is bundled and connected to photomultiplier tubes (PMTs) at the both ends. This counter was obtained detection efficiency of 54%. The thickness of the fiber sheet is depended to the efficiency and the energy loss. Therefore, the thinner type trigger counter is more important for ^{90}Sr counter.

B. Aerogel Cherenkov Counter

Relation between kinematic energy E_β and velocity $\beta = v/c$ of beta-ray is given as

$$\beta = \frac{\sqrt{(m_e + E_\beta)^2 - m_e^2}}{m_e + E_\beta}, \tag{2}$$

which m_e is mass of electron. Cherenekov counter makes yes or no decision based on Cherenkov threshold velocity $\beta_{th} = 1/n$ [4], when n is refreactive index. To not emission Cherenkov at beta-ray with maximum 1.174 MeV from ^{137}Cs, a refractive index of the radiator is required less than 1.0492 [2], [3], [5], [6]. Used radiator is a silica aerogel [7] with the index of 1.0485. A Cherenkov counter using silica aerogel as radiator is Aerogel Cherenkov counter. To extend effective area, wavelength shifting fiber sheet has been used instead of PMT cathode. This system has extending effective area, using small PMT and reducing production cost.

C. Cosmic ray veto counter

For suppression of background of cosmic ray, this system has been added veto counter. The veto counter composes plastic scintillator and WLS fibers and PMT. The Scintillator size is 200 mm $\times$ 100 mm $\times$ 5 mm. WLS fibers connected to four side faces of scintillator and bundled both end fibers in one. Then PMT is connected the bundled fibers and readouts scintillation light. When a muon as cosmic ray pass though center of the veto counter, mean number of photoelectrons is observed 6.6 by the PMT.

TABLE I
COMPONENT OF ^{90}SR COUNTER

the device	eff. area[mm^2]	components
SFT	300 $\times$ 100	scint. fiber sheet, PMT (x2), eff.: 54.4%
AC	300 $\times$ 100	aerogel, WLSF light guide, PMT (x4)
veto	400 $\times$ 200	scintillator, WLSF light guide, PMT (x1), mean num. of p.e.: 6.6

D. Electronics

All detection system based on NIM is given as

$$Count = C_{SFT} \cap C_{AC} \cap \overline{C_{veto}}, \tag{3}$$

which C_{SFT} is count of scintillating fibers trigger counter, C_{AC} is count of Cherenkov counter and C_{veto} is veto counter. C_{SFT} has coincidence logic of PMT signals. C_{AC} has OR logic of PMT signals.

E. Mechanism of identification of ^{90}Sr

The identification mechanism of ^{90}Sr is describes in following. In a case of ^{90}Sr, when the trigger counter reacts on the beta-ray, aerogel emits the Cherenkov light and WLS fiber reacts and read the Cherenkov light. On the other hand, in a case of ^{137}Cs, the trigger counter reacts on the beta-ray, aerogel stops the beta-ray and Cherenkov light is not emitted. Therefore, aerogel has a function as a radiator and shielding material. the gamma-ray is not reacted on the lower density detector. Therefore, the noise is reducible from other radiation. Cosmic ray is also reacted the veto counter.

III. Performance Estimation and Demonstration

We have produced real-time ^{90}Sr counter prototype. This effective area is 300 mm $\times$ 100 mm. We have estimated the performance using radioactivity sources default by isotope associate such as ^{90}Sr (25 kBq) and ^{137}Cs (25kBq).

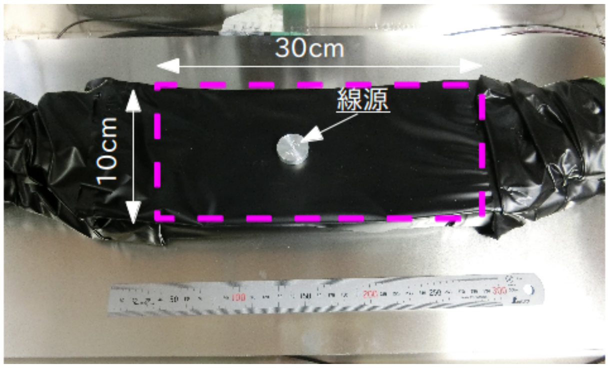

Fig. 2. The histogram which is number of count rate on each source

A. Performance estimation

We have made histograms which is number of counts N of putting source on a minute. A sensitive η of this counter for ^{90}Sr is default as

$$\eta(Sr) = \frac{R_{Sr} - R_{BG}}{A_{Sr}}, \tag{4}$$

which R is count rate calculated $R = N/t$, t is measurement time, R_{Sr} and R_{BG} are the count rate of ^{90}Sr and background event, respectively. A_{Sr} is radioactivity of about 25 kBq. A ratio Γ between sensitivity of ^{137}Cs and ^{90}Sr is given as

$$\begin{aligned} \Gamma(Cs/Sr) &= \frac{\eta(Cs)}{\eta(Sr)} \\ &= \frac{R_{Cs} - R_{BG}}{R_{Sr} - R_{BG}} \left(\frac{A_{Sr}}{A_{Cs}}\right), \end{aligned} \tag{5}$$

which R_{Cs}, R_{Sr} and R_{Cs} are count rate of ^{137}Cs, ^{90}Sr and background, respectively.

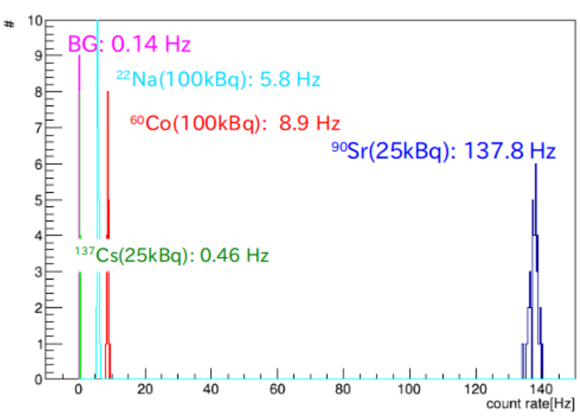

Fig. 3. The histogram which is number of count rate on each source

TABLE II
RESULT OF THE SENSITIVE AND THE RATIO [2]

performance	parameter
$\eta(^{90}Sr)$	$(5.49 \pm 0.06) \times 10^{-3}$ Hz/Bq
$\eta(^{137}Cs)$	$(1.12 \pm 0.66) \times 10^{-5}$ Hz/Bq
$\eta(^{60}Co)$	$(8.77 \pm 0.39) \times 10^{-5}$ Hz/Bq
$\eta(^{22}Na)$	$(5.65 \pm 0.33) \times 10^{-5}$ Hz/Bq
Background	$(1.48 \pm 0.46) \times 10^{-1}$ Hz
Γ(Cs/Sr)	$(2.0 \pm 1.2) \times 10^{-3}$

B. Demonstration in environment existing ^{137}Cs

This counter should be detected ^{90}Sr in environment existing a lot of ^{137}Cs. We have tried the demonstration using 10 ^{137}Cs sources as same as radioactivity. In the case of using a ^{137}Cs source, mean count rate is obtained 0.46 Hz. Then, in the case of using 10 sources, mean count rate is obtained 5.2 Hz. Therefore this counter has linearity on ^{137}Cs and lower sensitivity. Next, in the case of adding ^{90}Sr sources, mean count rate is obtained 165 Hz. This result is enough for detection ^{90}Sr in radioactive background.

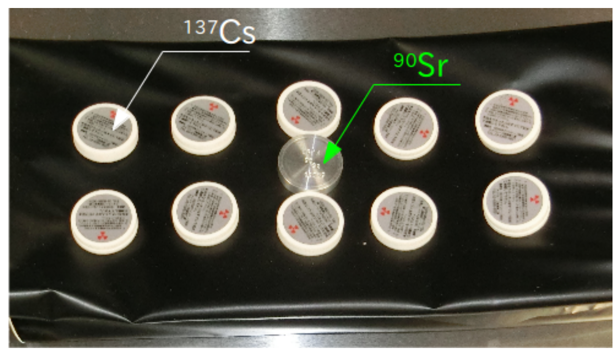

Fig. 4. demonstration of detection ^{90}Sr in radioactive background

C. Uniformity of the sensitivity

The previous tests have been measured at center of the incident position. We have check uniformity of this counter sensitivity with 11 points as same as making the histograms. As the result, the effective area with uniformity which default as fluctuation less than 10% is length of 21 cm and mean sensitivity is obtained 5.2 Hz/Bq.

IV. Consideration and Conclusion

A. Detection Limit of Bq/cm^2

From the results for prototype counter, we have a discussion about limit of detection for ^{90}Sr radioactivity. The limit of detection to identify between ^{90}Sr and ^{137}Cs at relativity of 99% or more is imported from

$$N_{Sr} = aSxt + cSt \tag{6}$$

$$N_{Cs} = bkSxt + cSt \tag{7}$$

$$N_{Sr} > N_{Cs} + 2.58\sqrt{N_{Cs}}, \tag{8}$$

where N_{Sr} is Number of count for ^{90}Sr, N_{Cs} is Number of count for ^{137}Cs, a is sensitivity of ^{90}Sr [Hz/Bq], b is sensitivity of ^{137}Cs [Hz/Bq], c is background rate per unit area [Hz/cm^2], S is effective area [cm^2], k is amounts ratio of ^{137}Cs/^{90}Sr at measurement environment, t is measurement time [sec], x is radioactivity of ^{90}Sr [Bq].

The value x satisfied Eq. (6), (7) and (8) means a limit of detection of ^{90}Sr and depends on effective area S, measurement time t and environment of the ratio of ^{137}Cs/^{90}Sr existence k. Then, By substitution the experimental values for them, the performance is achieved the limit of about 10^{-2} Bq/cm^2 at a minute of measurement time and the environment of $k = 100$ [2].

B. Detection Limit of Bq/kg

The detecting beta-ray is surface contamination inspection mainly. For radioactive contamination inspection of foods, radioactivity per unit of mass should be measured. The sample is thinned to thickness of about mm for the surface contamination inspection. For example, when a sample with density of 1 kg/L and thickness of 1 mm is 0.1 g/cm^2, detection limit is estimated 100 Bq/kg from the limit of the surface inspection. In adding, in a case of contamination water inspection, after a sample heated and evaporated, the limit would be able to be improved by the loss volume.

C. conclusion

We have developed real-time ^{90}Sr counter which detects only ^{90}Sr in radiation background and measures it at a short time. The prototype was produced and estimated performance. This counter has effective area 300 mm $\times$ 100 mm, ^{90}Sr sensitivity of $(5.49 \pm 0.06) \times 10^{-3}$ Hz/Bq and ^{137}Cs/^{90}Sr ratio of $(2.0 \pm 1.2) \times 10^{-3}$. The detection limit is satisfied enough 100 Bq/kg in environment of other radiation.

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