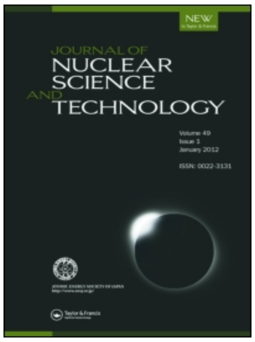

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Estimation of Absorbed Dose Rates in Air Based on Flux Densities of Cosmic Ray Muons and Electrons on the Ground Level in Japan

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Flux densities of cosmic ray muons and electrons were estimated from the pulse height spectra of cosmic ray charged particles observed using a spherical plastic scintillation detector. In order to obtain the pulse height spectrum of cosmic ray electrons separately from that of cosmic ray muons, the pulse height spectrum of cosmic ray electrons was derived by calculating the probability distribution of energy deposited in a plastic scintillator by electrons alone, utilizing the spectrum of cosmic ray electrons given in literature. Calculation was corroborated by measurement with spherical plastic scintillator detector of cosmic ray muons alone, obtained by passing the particles through a lead shield to eliminate electrons and photons. The aggregate absorbed dose rates in air imparted by cosmic ray muons and electrons thus derived proved upon further adding the contribution of cosmic ray photons to come quite close to the total absorbed dose rate given in literature from measurements performed in Japan.

KEYWORDS: absorbed dose rates, air, flux density, cosmic rays, cosmic ray muons, cosmic ray electrons, plastic scintillation detector, lower atmosphere, coincidence counting, Japan, ground level, dose rates

I. Introduction

In the field of health physics, many studies have been carried out for estimating the radiation dose imparted by the ionizing component of cosmic rays, which counts among the main sources of external exposure in the natural environment.[1–4]

For determining the cosmic ray dose at a point of interest from measurements of cosmic ray flux density, a simplified method has been developed for measuring the flux density of cosmic ray charged particles.[2,5] The method, which utilizes a spherical plastic scintillation detector, postulates that similar physical properties are presented by the detector crystal against cosmic ray muons as against electrons.

The method has proved applicable to determining cosmic ray doses at different locations measured at short intervals, and has been applied in practice to the evaluation of cosmic ray variations around nuclear facilities.[6]

While this method is conveniently adapted to cosmic ray determination in the natural environment, doubt has been raised on its accuracy, by reason of the postulate that the detector responds similarly to cosmic ray muons and electrons, despite the fact that they present different spectra, imputable to the disparity of their behavior in low-density media.

In the present study, in order to obtain the pulse height spectrum of cosmic ray electrons separately from that of muons, calculation of the pulse height spectrum of cosmic ray electrons alone was derived utilizing the spectrum of cosmic ray electrons given in literature. The above calculation was corroborated by measurement with spherical plastic scintillator detector of cosmic ray muons alone, obtained by passing the particles through a lead shield to eliminate electrons and photons.

Possible errors contained in the resulting flux density values of the two kinds of particle are discussed, leading to the conclusion that additionally taking into account the estimated contribution of cosmic ray photons should bring the present results quite close to what is given in literature for the total flux density of cosmic ray charged particles.

II. Principles Adopted for Estimating Flux Density

When measuring cosmic ray charged particles using a spherical detector, the flux density Φ ($\mathrm{cm^{-2}\cdot s^{-1}}$) is given by

$$\Phi = \frac{1}{\pi r^2}\int_0^{E_{\max}} \frac{dN}{dE}dE, \tag{1}$$

where dN/dE: Number of charged particles observed in unit time in the energy range between E and $E+\Delta E$
r: Radius of spherical detector
$E_{\max}$: Energy absorbed by spherical detector from cosmic ray charged particles passing through detector center.

The spherical detector alone will not be capable of correctly determining dN/dE over the entire range of absorbed energy between 0 and $E_{\max}$, on account of the involvement of environmental gamma rays in the low-energy region. Hence, in this instance, the flux density is determined empirically using the formula

$$\Phi_{\mathrm{measured}} = \frac{k}{\pi r^2}\int_{E_{dis}}^{E_{\max}} \left(\frac{dN}{dE}\right)_{\mathrm{measured}} dE, \tag{2}$$

where Φ_{measured}: Flux density derived from counting rate $(dN/dE)_{\mathrm{measured}}$ determined empirically
k: Conversion factor for deriving Φ_{measured} from counting rate in the range of absorbed energy above E_{dis}
E_{dis}: Lowest absorbed energy associable solely

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with cosmic ray event, and hence free from involvement of environmental gamma rays (around 3.5 MeV level).

In the lower atmosphere, $(dN/dE)_{\text{measured}}$ is considered to comprise $(dN/dE)_{\text{muons}}$, $(dN/dE)_{\text{electrons}}$ and $(dN/dE)_{\text{photons}}$, and hence the flux densities of muons and electrons can be derived using the equations

$$\Phi_{\text{muons}} = \frac{p_{\text{muons}} k_{\text{muons}}}{\pi r^2} \int_{E_{dis}}^{E_{\max}} \left(\frac{dN}{dE}\right)_{\text{measured}} dE, \quad (3)$$

$$\Phi_{\text{electrons}} = \frac{p_{\text{electrons}} k_{\text{electrons}}}{\pi r^2} \int_{E_{dis}}^{E_{\max}} \left(\frac{dN}{dE}\right)_{\text{measured}} dE, \quad (4)$$

where $p_{\text{muons}}, p_{\text{electrons}}$: Ratios to total counting rates presented by those of muons and of electrons, respectively, all in the range of energies above E_{dis}.

The value of p_{muons} can in principle be determined from the difference in spectrum pulse height between those obtained with the detector placed inside and outside a lead shield 10 cm thick, assuming that a shield of this thickness would absorb almost all cosmic ray electrons and photons.

Further details of the methods of measurement and calculation will be given in the next chapter.

The conversion factors k_{muons} and $k_{\text{electrons}}$ are derived using the formulas

$$k_{\text{muons}} = \frac{\int_{E_0}^{E_{\max}} \left\{ \left(\frac{dN}{dE}\right)_{\underline{\text{particles}}} - \left(\frac{dN}{dE}\right)_{\underline{\text{electrons}}} \right\} dE}{\int_{E_{dis}}^{E_{\max}} \left\{ \left(\frac{dN}{dE}\right)_{\underline{\text{particles}}} - \left(\frac{dN}{dE}\right)_{\underline{\text{electrons}}} \right\} dE}, \quad (5)$$

$$k_{\text{electrons}} = \frac{\int_{E_0}^{E_{\max}} \left(\frac{dN}{dE}\right)_{\text{electrons}} dE}{\int_{E_{dis}}^{E_{\max}} \left(\frac{dN}{dE}\right)_{\text{electrons}} dE}, \quad (6)$$

where Subscripts non-underlined: Measurements using spherical detector alone
Subscripts underlined: *Ditto* by coincidence counting using a combination of spherical and plane circular detectors
Subscript "particles": Measured pulse height spectrum of all charged particles
Subscript "electrons": Calculated pulse height spectrum of electrons alone.

For instance, $(dN/dE)_{\text{electrons}}$ would mean calculated pulse height spectrum of cosmic ray electrons alone, and $(dN/dE)_{\text{particles}}$ are corresponding spectrum determined by coincidence counting.

III. Calculation and Measurement

1. Muon/Electron Spectra

Cosmic ray spectra were derived using a spherical plastic scintillation detector NE102A—of 1.03 g·cm^{-3} density and measuring 7.6 cm in diameter—arranged as shown in **Fig. 1**.

For obtaining data on muon spectra, the detector was placed behind a 10 cm thick lead shield to eliminate lower energy cosmic rays including electrons.[7] Outside the shield, the cosmic ray intensity was simultaneously measured using a separate detector.

Along with cosmic ray particles, the scintillation detector used alone sensed also environmental gamma rays. Hence, for excluding gamma rays to obtain the total cosmic ray spectrum over the entire energy range including the region below E_{dis}, recourse was made to coincidence counting, with the spherical detector used together with a 20 cm-diameter 2 cm-thick plane circular detector, also shown in Fig. 1. This detector generated 5 μs-wide gate pulses upon passage through a pulse height discriminator set at a level above E_{dis}.

The foregoing measurements were carried out on the top of the No. 3 building in the campus of Fukuyama University, Hiroshima Prefecture, where the vertical cut-off rigidity is about 12 GV. The periods of test were September 1996 and December 1997, which roughly coincided with the period of minimum amplitude in the 11-year solar activity cycle.

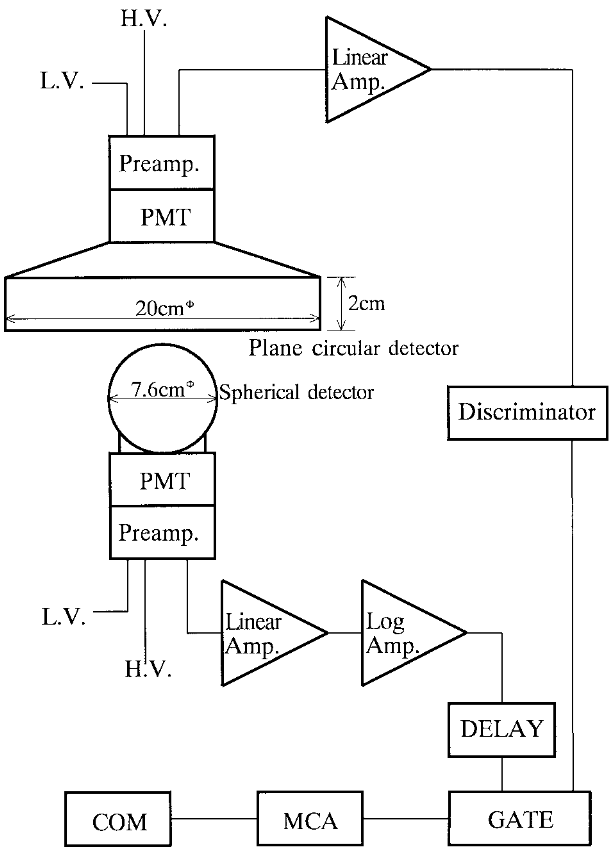

Fig. 1 System adopted for observing pulse height spectra of cosmic ray electrons and muons either using spherical detector singly or through coincidence counting in combination with plane circular detector

2. Model Used for Calculation

The spherical and plane circular detectors described in the preceding section are shown schematically in **Fig. 2** in longitudinal section.

For deriving the flux density from particle counting rates, the detector composition and physical quantities adopted were those of polystyrene resin $(CH(C_6H_5)CH_2)_n$. For calculations covering cases of spherical detector used alone, the resin of the plane scintillator was replaced by air.

3. Calculations

The probability distribution of electrons in the lower atmosphere was calculated by EGS4 Monte Carlo code[8] applied to the spectrum of cosmic ray electrons given graphically by Allkofer,[9] and assuming the electrons to be incident on the spherical detector with scalar flux proportional to $\cos^3\theta$ (θ: zenith angle).

More than 10^6 histories were calculated in the energy range below 10 GeV.

IV. Results and Comments Thereon

1. Results

Presented in **Fig. 3** are typical probability distribution spectra derived by Monte Carlo calculation based on data obtained with spherical detector used alone and with coincidence counting, for mono-energetic electrons carrying energies ranging from 1 to 100 MeV.

Scattering of the open square and round plots—for coincidence counting with incident energies in the range below 50 MeV—is ascribable to electron straggling in the plane detector, where the average energy loss per unit path length would appear to be around 2 MeV. Above 50 MeV incident energy, the presence of plane detector would appear not to have affected the rays reaching the spherical detector.

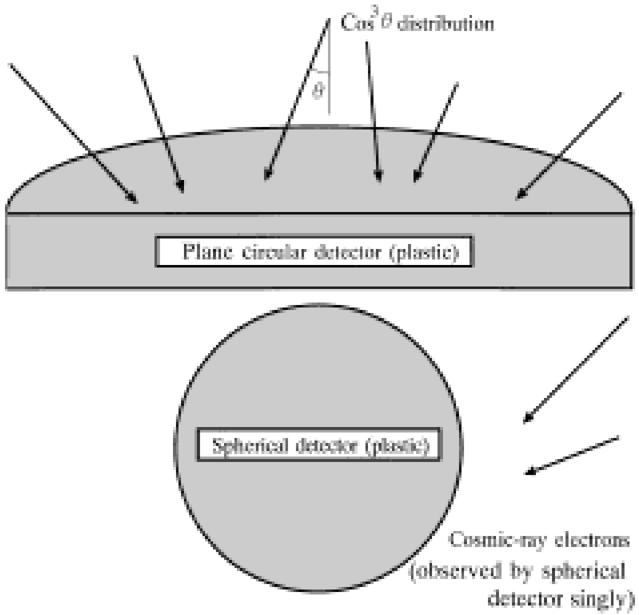

Fig. 2 Model used for the calculation of the energy deposition spectra of cosmic ray electrons in the spherical plastic scintillation detector

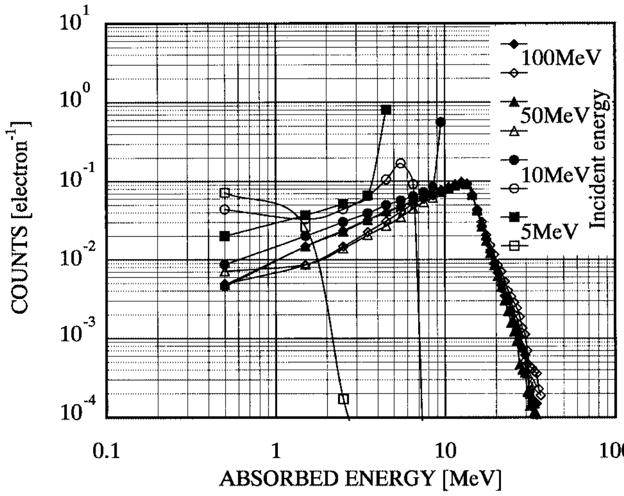

Fig. 3 Energy spectra of mono energetic electrons obtained with spherical detector used singly and with coincidence counting
Solid symbols: Spherical detector used singly
Open symbols: Coincidence counting with spherical and plane detectors

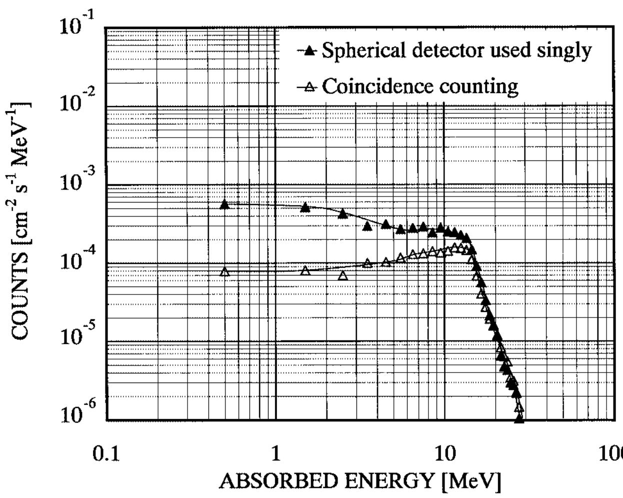

Fig. 4 Energy spectra of cosmic ray electrons obtained by Monte Carlo simulation applied to spectrum given in reference[9]

In **Fig. 4** are shown similarly calculated probability distributions of cosmic ray electrons in the range of incident energy from 1 to 10 GeV, compared between cases of spherical detector used alone and coincidence counting. The counting rate scale is adjusted to let the coincidence counting data agree with actually measured data using the coincidence counting system of Fig. 1.

Absorbed energy is noted to reach up to almost 30 MeV. The deviation of plots between calculations based on spherical detector used alone and on coincidence counting seen in the lower range of absorbed energy below 15 MeV can be ascribed to absorption of lower-energy electrons in the plane circular detector in the case of coincidence counting.

Shown in **Fig. 5** are spectra obtained of total cosmic ray charged particles, compared between cases of spherical de-

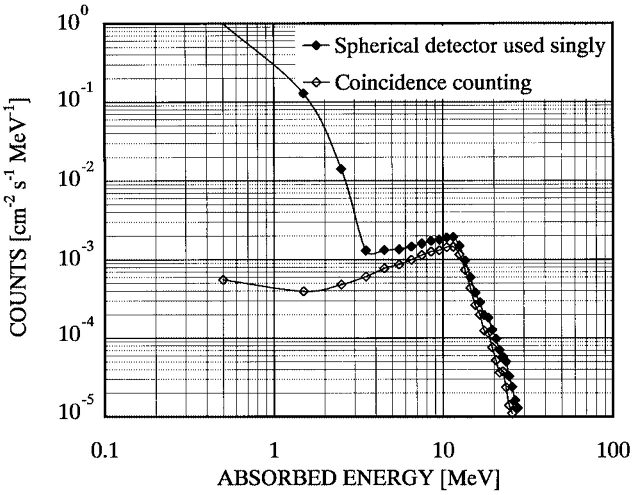

Fig. 5 Energy spectra of total cosmic ray charged particles
Conspicuous rise of plots in lower energy range are ascribable to involvement of environmental gamma rays.

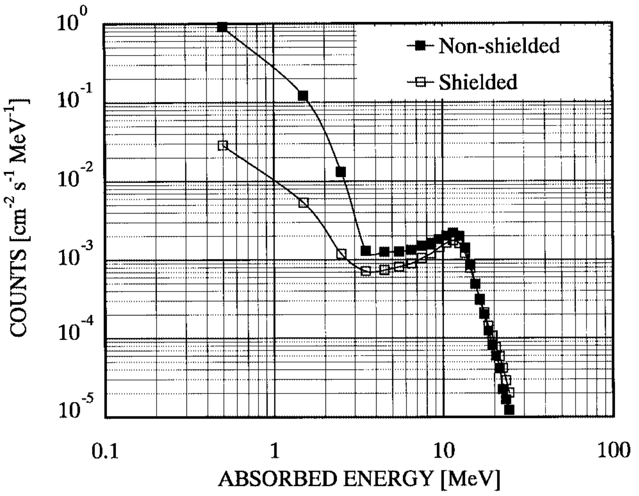

Fig. 6 Energy spectra of total cosmic ray charged particles with and without filtering through lead shield
Same cause as in Fig. 5 is assignable to conspicuous deviation in lower energy range.

tector used alone and coincidence counting. The conspicuous rise of the plots from measurements by spherical detector alone in the lower range of absorbed energy range is due to detection by the bare detector of environmental gamma rays along with muons and electrons, and is hence beyond the scope of discussion in the present study.

Apart from the above conspicuous deviation noted above, the minor deviation in the range below the peak of absorbed energy can be ascribed to scattering of cosmic ray photons and electrons within the plane detector in the case of coincidence counting, in which latter case also, the counting rate was circumscribed by the solid angle between the spherical and plane detectors. We will hence call "solid angle correction factor" the ratio of deviation between the plots of spectra measured by the spherical detector alone and by coincidence counting.

The solid angle correction factors are 1.19 and 1.29 respectively for electrons and muons, as determined from theoretical calculation performed with the scalar flux assumed proportional respectively to $\cos^3\theta$ and $\cos^2\theta$.

2. Effect of Shielding-Ratio *p*

Charged particle spectra are presented in **Fig. 6** separately for the cases of shielded measuring system to eliminate electrons/photons and of non-shielded system to cover all particles.

As in the case of Fig. 5, the large deviation between data from shielded and non-shielded counting rates seen in Fig. 6 in the range below E_{dis} absorbed energy is related to the presence of environmental gamma rays, and hence beyond the scope of discussion here. The corresponding deviation in the range above E_{dis} can on the other hand be ascribed to the cosmic rays that are lost in the lead shielding—photons and electrons that are absorbed, together with a trace of muons, while a part of the lower-energy muons would disintegrate and be detected as electrons.[7,10)] Ignoring the foregoing deviations, the shielded counting rate plots can be considered to derive mainly from high-energy cosmic ray muons, which the shield would only attenuate by less than a few percent.

Table 1 Counting rates observed above E_{dis} and values obtained of p_{muons} and $p_{\text{electrons}}$

	Counting rate (cm^{-2}·min^{-1})	p (%)
Muons	$(8.63\pm0.55)\times10^{-1}$	77.9±5
Electrons	$(1.90\pm0.55)\times10^{-1}$	17.2±5

Table 2 Counting rates obtained above and below E_{dis} and values of conversion factor k

	Counting rate below E_{dis} (cm^{-2}·min^{-1})	Counting rate above E_{dis} (cm^{-2}·min^{-1})	Conversion factor k
Muons	$(1.14\pm0.55)\times10^{-1}$	$(8.63\pm0.55)\times10^{-1}$	1.13±0.05
Electrons	$(1.01\pm0.55)\times10^{-1}$	$(1.90\pm0.55)\times10^{-1}$	1.53±0.01
Total	$(2.14\pm0.78)\times10^{-1}$	1.05±0.08	1.20±0.08

Given in **Table 1** is the ratio p_{muons} between the plots from non-shielded and shielded detectors derived from the plots in Fig. 6 in the absorbed energy above E_{dis}. The $p_{\text{electrons}}$, also given in Table 1, was similarly determined from relevant electron data—solid plots in Fig. 4 for bare detector used alone and solid plots in Fig. 6 for non-shielded detector. The ±5% uncertainty given for p_{muons} is to account for some lower energy muons failing to pass the lead shield[10)] and p_{muons} and $p_{\text{electrons}}$ comes to amount to 95.1%, and the remaining 4.9% can be assigned to the contribution of cosmic ray photons, this value being roughly equal to what has been given in literature.[6)]

3. Conversion Factor *k*

Given in **Table 2** are the values of the conversion factors $k_{\text{electrons}}$ and k_{muons} for deriving the flux densities from count-

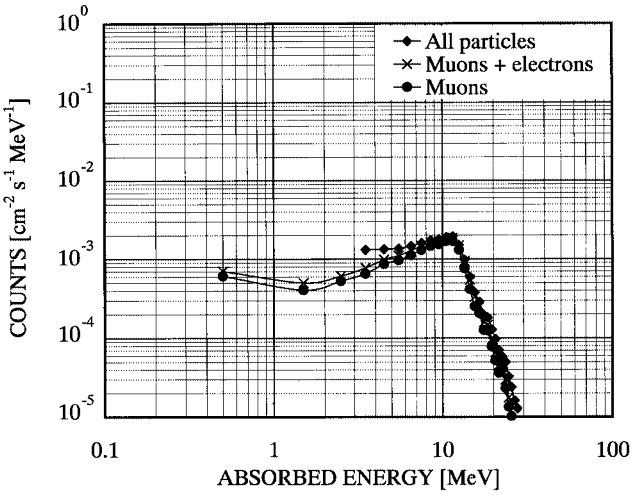

Fig. 7 Energy spectra of total cosmic ray charged particles measured in natural environment compared with present data on electrons and muons

ing rates in the range above E_{dis}.

The conversion factor $k_{\mathrm{electrons}}$ was determined from the plots in Fig. 4 for the case of calculation using spherical detector alone.

Shown in **Fig. 7** are spectra of total flux density measured in the natural environment and those derived in the present experiment. The slight deviation between the lozenge plots of measured total flux density and cross plots of the calculated aggregate muon+electron flux density can be ascribed, apart from possible error in the method of estimating cosmic ray flux density, to the contribution of cosmic ray photons, whose energy is distributed in the range of absorbed energy up to about 30 MeV.[11)]

The solid-circle muon plots in the same Fig. 7 have served to derive the value of k_{muons} in Table 2. In the same table, the distinctly larger value given for $k_{\mathrm{electrons}}$ compared with k_{muons} can be ascribed to the decisive contribution of lower-energy electrons present in cosmic rays. The value given for total k is somewhat larger than what is found in published literature.[6)]

V. Discussion

The data derived from the present study are summarized in **Table 3**, and compared with those given in published literature.[3,5)]

The generally lower values that have been obtained this time can be ascribed to difference in geomagnetic latitude. For electrons in particular,[5,6)] the smaller values obtained this time despite the adoption of a larger k factor could be due partly to errors incurred in data processing—notably in determining the constant p.

The values of absorbed dose in air given in the table were estimated by multiplying the flux density values obtained above by the ratios between flux density and average absorbed dose in air, which is 19.5 nGy·h^{-1} for muons and 5.7 nGy·h^{-1} for electrons, derived using as stopping power the values given in literature[5)] of 2.14 and 2.01 MeV·cm^2·g^{-1}, respectively.

Adding together the values of absorbed dose rate in air mentioned above for muons and electrons gives 25.2 nGy·h^{-1}, which is around 12% smaller than given by Wakasa[12)] from observations performed in Japan (15° N geomagnetic latitude), using ionization chamber and NaI(Tl) scintillation spectrometer. The discrepancy can be ascribed to the contribution of cosmic ray photons, which is around 2.8 nGy·h^{-1}.[11)] Further adding this contribution to the above sum for muons and electrons brings the total absorbed dose rate to 28.0 nGy·h^{-1}, which is quite close to what has been given by Wakasa.

It may be concluded from what precedes that the results obtained from the present study are applicable to independent evaluation of cosmic ray muons and electrons in the natural environment.

Further examination shall be made to substantiate this judgment.

VI. Conclusions

The following conclusions can be drawn from the present study:

(1) To derive energy absorption spectra separately for cosmic ray electrons and muons, that for electrons was derived from the probability distribution of energy absorbed by a spherical scintillator detector. The flux densities of cosmic ray electrons and muons were also determined from measurements of counting rate in the range of absorbed energy above involvement of environmental gamma rays.

(2) The spectrum for electrons in the range of energy below involvement of environmental gamma rays proved to be distinctly higher than that for muons, which is ascribed to the decisive contribution of lower-energy electrons.

(3) The sum of flux density values for muons and electrons proved to be around 12% lower than the value of

Table 3 Data compared between present study and others performed elsewhere

	Present study Flux density (cm^{-2}·min^{-1})	Present study Dose rate (nGy·h^{-1})	NCRP[3)a)] Flux density (cm^{-2}·min^{-1})	Nakashima and Furuta[5)] Flux density (cm^{-2}·min^{-1})
Muons	$(9.77\pm0.78)\times10^{-1}$	19.5 ± 1.6	1.08	—
Electrons	$(2.91\pm0.78)\times10^{-1}$	5.7 ± 1.5	4.2×10^{-1}	—
Total	1.27 ± 0.11	25.2 ± 2.2	1.50	1.41

[a)] Data obtained in period close to solar maximum at sea level at 50° N geomagnetic latitude.

flux density covering all cosmic ray particles reported from measurements performed in Japan using ionization chamber and NaI(Tl) scintillation spectrometer. This discrepancy is ascribed to the contribution of cosmic ray photons, which has not been taken into account in the present calculations and measurements.

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