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Atmospheric Effects on Cosmic-Ray Muon Intensities at Deep Underground Depths.

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Summary. — On the basis of the theoretical calculation of the atmospheric effect on the cosmic-ray muon intensity, it is demonstrated that the following two anomalous facts recently reported from muon observations at deep underground stations can be attributed to the atmospheric-temperature effect. One is the remarkable dependence of the muon intensity on the atmospheric pressure observed at Poatina (365 m w.e. in depth) and Matsushiro (250 m w.e. in depth), which is contradictory to theoretical expectations, and the other is the semi-annual variation in the muon intensity at Matsushiro, which exhibits a striking contrast to annual variations usually observed at underground stations shallower than Matsushiro. In the present paper, the barometer coefficient and the partial temperature coefficient are also provided for various combinations of parameters such as the muon threshold energy and the zenith angle to meet any requirement of observations.

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1. – Introduction.

Cosmic-ray muon intensities observed at ground-based stations are affected not only by the modulation of the primary cosmic-ray in space but also by the atmospheric effect (1,2). Recently, it was reported that muon intensities at

(1) *E.g.*, A. DUPERIER: *J. Atmos. Terr. Phys.*, **1**, 296 (1951); K. MAEDA and M. WADA: *J. Sci. Res. Inst. Tokyo*, **48**, 71 (1954); H. TREFALL: *Physica*, **23**, 65 (1957); G. CINI CASTAGNOLI and M. A. DODERO: *Nuovo Cimento B*, **51**, 525 (1967).
(2) L. I. DORMAN: *Cosmic Ray Variations* (Moscow, 1957).

deep underground stations show the following anomalous features. One consists in the large values of the barometer coefficient, that is, $-(0.047\pm0.002)$ %/mb at Poatina (365 m w.e. in depth) ([3]) and $-(0.027\pm0.004)$ %/mb at Matsushiro (250 m w.e. in depth) ([4,5]). From the theoretical point of view, the barometer coefficients for such deep underground depths are expected to be much smaller in magnitude (<0.017 %/mb) than those observed. Another anomalous feature is a semi-annual variation in the muon intensity observed at Matsushiro ([6]). This semi-annual variation exhibits a striking contrast to annual variations usually observed at shallower underground stations, such as Misato (34 m w.e. in depth) ([7]) and Sakashita (80 m w. e. in depth) ([8]).

To examine these observed phenomena, it is necessary to refer to the barometer coefficient and the partial temperature coefficient ([2]) for various observational conditions. These coefficients have been calculated by many researchers ([2,9]), and satisfactory values were already obtained for some observational conditions. Their calculations, however, were mostly made by assuming simplified models on the propagations of nucleons and pions in the atmosphere, and/or by assuming production spectra of muons deduced from ground-based experiments. These assumptions were made to cover insufficient information on the production cross-sections of secondary particles from hadronic collisions.

Recently such information has been much accumulated in virtue of the accelerator experiments and has been systematized by the aid of Feynman's scaling hypothesis ([10]) for the hadronic cascade. On the basis of such information and hypothesis, we have calculated the muon response function in a previous paper ([11]). This calculation gives more reliable values, for example, of the pion flux, the kaon flux and the muon production spectrum in the atmosphere.

([3]) A. G. Fenton and K. B. Fenton: *Proceedings of the XIV International Conference Cosmic Ray*, Vol. **4** (München, 1975), p. 1482; J. E. Humble, A. G. Fenton, K. B. Fenton and P. R. A. Lyons: *Proceedings of the XVI International Conference Cosmic Ray*, Vol. **4** (Kyoto, 1979), p. 258; P. R. A. Lyons, A. G. Fenton and K. B. Fenton: *Proceedings of the XVII International Conference Cosmic Ray*, Vol. **4** (Paris, 1981), p. 300.

([4]) S. Yasue, S. Mori and S. Sagisaka: *Proceedings of the XVII International Conference Cosmic Ray*, Vol. **4** (Paris, 1981), p. 308.

([5]) S. Sagisaka, S. Yasue, S. Mori, K. Chino and M. Ichinose: *Proceedings of the XVIII International Conference Cosmic Ray*, Vol. **10** (Bangalore, 1983), p. 237.

([6]) S. Yasue, S. Mori, S. Sagisaka and M. Ichinose: *International Symposium Cosmic Ray Modulation in Heliosphere* (Morioka, 1984), p. 355.

([7]) S. Mori: private communication.

([8]) H. Ueno, Z. Fujii, K. Fujimoto and K. Nagashima: *Proceedings of the XVI International Conference Cosmic Ray*, Vol. **12** (Kyoto, 1979), p. 228.

([9]) *E.g.*, M. Wada: *Scient. Papers Inst. Phys. Chem. Res.*, Vol. **54** (Japan, 1961), p. 335; K. Maeda: *J. Atmos. Terr. Phys.*, **19**, 184 (1960).

([10]) R. P. Feynman: *Phys. Rev. Lett.*, **23**, 1415 (1969).

([11]) K. Murakami, K. Nagashima, S. Sagisaka, Y. Mishima and A. Inoue: *Nuovo Cimento C*, **2**, 635 (1979).

In the present paper, the barometer coefficient and the partial temperature coefficient are calculated using the results in the above-mentioned paper [11], and are provided for various combinations of parameters, that is the muon threshold energy, the zenith angle and the atmospheric depth. On the basis of these results and also meteorological data, it is shown that the two anomalous phenomena observed at Matsushiro and Poatina mentioned above are attributed to the atmospheric-temperature effect. Some of these results have been briefly reported in our previous papers [4,5,12].

2. – Calculation of the barometer coefficient and the partial temperature coefficient.

With a change δP (mb) in the barometric pressure at the atmospheric depth x_0 (g/cm²) and with a change $\delta T(x)$ in the atmospheric temperature at x (g/cm²) ($x < x_0$), the integral muon intensity $I(\bar{E}_0, x_0, \theta)$ in the direction of a zenith angle θ at x_0 changes as

$$\delta\{\ln I(\bar{E}_0, x_0, \theta)\} = \beta(\bar{E}_0, x_0, \theta)\,\delta P + \int_0^{x_0} \alpha(x, \bar{E}_0, x_0, \theta)\,\delta T(x)\,\mathrm{d}x\,, \tag{1}$$

where E_0 is the total energy of muons at x_0, $\bar{E}_0$ is the threshold energy, and $\beta(\bar{E}_0, x_0, \theta)$ and $\alpha(x, \bar{E}_0, x_0, \theta)$ are called the barometer coefficient and the partial temperature coefficient, respectively [2]. Hereafter, these coefficients will be represented by β and $\alpha(x)$ for short, and they are defined as

$$\beta = \left[\frac{\partial\{\ln I(\bar{E}_0, x_0, \theta)\}}{\partial P}\right]_{\delta T=0}, \qquad P = g x_0, \tag{2}$$

and

$$\alpha(x) = D_{\mathrm{T}}[\ln I(\bar{E}_0, x_0, \theta)] \qquad \text{for } 0 < x \leqslant x_0\,. \tag{3}$$

In these equations, g is the gravitational acceleration and D_{T} is the operator by which we can obtain the variational amount of an operated function caused by the δ-functional change in the temperature T at x. Note that this operator has a dimension of $(°\mathrm{C})^{-1}\,\mathrm{g}^{-1}\,\mathrm{cm}^2$.

The formulae and the parameters used in the present calculation of the muon intensity are almost the same as those in our previous paper [11]. The integral muon intensity $I(\bar{E}_0, x_0, \theta)$ in the above equations can be expres-

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(12) S. SAGISAKA, K. MURAKAMI, A. INOUE, Y. MISHIMA and K. NAGASHIMA: *Proceedings of the XVI International Conference Cosmic Ray*, Vol. 4 (Kyoto, 1979), p. 235; S. SAGISAKA: *Proceedings of the International Symposium Cosmic Ray Modulation in Heliosphere* (Morioka, 1984), p. 360.

sed as

$$I(\bar{E}_0, x_0, \theta) = \int_0^{x_0} dx \int_{U(x,\bar{E}_0)}^{\infty} \sec\theta\, W(x, x_0, \theta; E)\, \Phi(E, x, \theta)\, dE\,, \tag{4}$$

where $\Phi(E, x, \theta)$ is the muon production spectrum at x with an energy E, and $W(x, x_0, \theta; E)$ is the survival probability at x_0 ($> x$) of muons generated at x with E. The lower limit of the energy integral is defined by

$$U(x, E_0) = E_0 + b \sec\theta \cdot (x_0 - x)\,, \tag{5}$$

that is, $U(x, E_0)$ is the muon energy at x before being reduced to E_0 at x_0 ($> x$) by the energy loss with the constant coefficient b for relativistic particles.

The muon production spectrum $\Phi(E, x, \theta)$ in eq. (4) is given as

$$\Phi(E, x, \theta) = \sum_{i=\pi,\mathrm{K}} \eta_i \frac{m_i^2}{m_i^2 - m_\mu^2} \int_{E_{i,l}}^{E_{i,u}} \frac{w_i(E_i, x)}{cp_i} J_i(E_i, x, \theta)\, dE_i\,, \tag{6}$$

where

$$\begin{cases} E_{i,u} = \dfrac{1}{2}\left\{\dfrac{m_i^2 + m_\mu^2}{m_\mu^2} E + \dfrac{m_i^2 - m_\mu^2}{m_\mu^2} cp_\mu\right\}, \\ E_{i,l} = \dfrac{1}{2}\left\{\dfrac{m_i^2 + m_\mu^2}{m_\mu^2} E - \dfrac{m_i^2 - m_\mu^2}{m_\mu^2} cp_\mu\right\}. \end{cases} \tag{7}$$

In these equations, the subscript i indicates a kind of particles, such as charged pions and kaons, m_i and m_μ are the rest masses, p_i and p_μ are the momenta, c is the velocity of light, $J_i(E_i, x, \theta)$ is the differential energy spectrum and $w_i(E_i, x)$ is the decay probability per unit path in $g^{-1}\,cm^2$. The factor η_i is the branching ratio of the decay production, and it is assumed in the present calculation that $\eta_\pi : \eta_K = 1 : 0.635$ [13].

The survival probability $W(x, x_0, \theta; E)$ in eq. (4) is given as

$$W(x, x_0, \theta; E) = \exp\left[-\int_x^{x_0} \sec\theta\, w_\mu(U(x', E_0), x')\, dx'\right], \tag{8}$$

and the decay probabilities in eqs. (6) and (8) are given as

$$w_i(E_i, x) = \frac{C_i T(x)}{p_i c x}\,, \qquad C_i = \frac{m_i c R}{\tau_i g M}\,, \qquad \text{for } i = \mu,\ \pi \text{ and K}, \tag{9}$$

([13]) A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Bostien, J. Kirz and M. Roos: UCRL-8030, Part I (1965).

where R is the gas constant, M is the mean molecular weight of the air and τ_i is the decay constant of the i-th particle.

Using these equations, we can express the barometer coefficient β defined by eq. (2) by the sum of three components, as

$$\beta = \beta_a + \beta_d + \beta_p \tag{10}$$

where

$$\begin{cases} \beta_a = -\dfrac{\sec\theta}{gI(\bar{E}_0, x_0, \theta)}\, bJ_\mu(\bar{E}_0, x_0, \theta)\,, \\ \beta_d = -\dfrac{\sec\theta}{gI(\bar{E}_0, x_0, \theta)} \displaystyle\int_{\bar{E}_0}^{\infty} w_\mu(E_0, x_0) J_\mu(E_0, x_0, \theta)\, dE_0\,, \\ \beta_p = \dfrac{\sec\theta}{gI(\bar{E}_0, x_0, \theta)} \displaystyle\int_{\bar{E}_0}^{\infty} \Phi(E_0, x_0, \theta)\, dE_0\,. \end{cases} \tag{11}$$

$J_\mu(E_0, x_0, \theta)$ is the differential energy spectrum of muons at x_0 and can be written for relativistic particles as

$$J_\mu(E_0, x_0, \theta) = \int_0^{x_0} \sec\theta\, W(x, x_0, \theta;\, U(x, E_0))\, \Phi\big(U(x, E_0), x, \theta\big)\, dx\,. \tag{12}$$

In eq. (11), β_a represents the effect of the absorption by the ionization loss, and β_d and β_p represent the effect due to the increases in the μ-e decay and in the muon production at x_0, respectively.

As for the partial temperature coefficient, eq. (3) is expressed by the sum of two terms, as

$$\alpha(x_1) = \alpha_d(x_1) + \alpha_p(x_1)\,, \tag{13}$$

where

$$\begin{cases} \alpha_d(x_1) = \{\cos\theta I(\bar{E}_0, x_0, \theta)\}^{-1} \displaystyle\int_0^{x_1} dx \int_{U(x,\bar{E}_0)}^{\infty} D_T[W(x, x_0, \theta; E)]\, \Phi(E, x, \theta)\, dE\,, \\ \alpha_p(x_1) = \{\cos\theta I(\bar{E}_0, x_0, \theta)\}^{-1} \displaystyle\int_{x_1}^{x_0} dx \int_{U(x,\bar{E}_0)}^{\infty} W(x, x_0, \theta; E)\, D_T[\Phi(E, x, \theta)]\, dE\,. \end{cases} \tag{14}$$

The term α_d represents the negative temperature effect due to the decrease in survival muons produced at $x\ (< x_1)$ as

$$D_T[W(x, x_0, \theta; E)] = -\frac{\sec\theta}{T(x_1)}\, w_\mu\big(U(x_1, E_0), x_1\big)\, W(x, x_0, \theta; E)\,. \tag{15}$$

The term α_p in eq. (14) represents the effect due to the variation in the muon production at x ($\geqslant x_1$) caused by the increase in the decay probability of pions and kaons at x_1, and using eq. (6), it is further expressed as

$$\alpha_p(x_1) = \alpha_p^+(x_1) + \alpha_p^-(x_1)\,, \tag{16}$$

where

$$\left\{\begin{aligned}
\alpha_p^+(x_1) &= \frac{\sec\theta}{I(\bar{E}_0, x_0, \theta)\, T(x_1)} \int\limits_{U(x_1,\bar{E}_0)}^{\infty} W(x_1, x_0, \theta; E)\, \Phi(E, x_1, \theta)\, \mathrm{d}E\,, \\
\alpha_p^-(x_1) &= \frac{\sec\theta}{I(\bar{E}_0, x_0, \theta)} \int\limits_{x_1}^{x_0} \mathrm{d}x \int\limits_{U(x,\bar{E}_0)}^{\infty} W(x, x_0, \theta; E)\cdot \\
&\quad \cdot \sum_{i=\pi,K} \left\{\eta_i \frac{m_i^2}{m_i^2 - m_\mu^2} \int\limits_{E_{i,l}}^{E_{i,u}} \frac{w_i(E_i, x)}{cp_i} D_T[J_i(E_i, x, \theta)]\, \mathrm{d}E_i\right\} \mathrm{d}E\,.
\end{aligned}\right. \tag{17}$$

The term α_p^+ expresses the positive temperature effect caused by the additional production of muons at x_1, while the term α_p^- expresses the negative temperature effect caused by the decrease in the flux of the parent pions and kaons at x ($> x_1$).

The differential energy spectrum J_i in eq. (6) and its variation $D_T[J_i]$ in eq. (17) are calculated by the following equations ([11]) representing the transitions of the hadronic intensity spectra J_i ($i = \mathcal{N}$, π and K, where $\mathcal{N}$ indicates nucleons):

$$\left\{\begin{aligned}
\frac{\partial J_{\mathcal{N}}(E_{\mathcal{N}}, x, \theta)}{\sec\theta\, \partial x} &= -\frac{1}{\lambda_{\mathcal{N}}} J_{\mathcal{N}}(E_{\mathcal{N}}, x, \theta) + \Psi_{\mathcal{N}\mathcal{N}}(E_{\mathcal{N}}, x, \theta)\,, \\
\frac{\partial J_\pi(E_\pi, x, \theta)}{\sec\theta\, \partial x} &= -\left\{\frac{1}{\lambda_\pi} + w_\pi(E_\pi, x)\right\} J_\pi(E_\pi, x, \theta) + \\
&\quad + \Psi_{\mathcal{N}\pi}(E_\pi, x, \theta) + \Psi_{\pi\pi}(E_\pi, x, \theta)\,, \\
\frac{\partial J_K(E_K, x, \theta)}{\sec\theta\, \partial x} &= -\left\{\frac{1}{\lambda_K} + w_K(E_K, x)\right\} J_K(E_K, x, \theta) + \\
&\quad + \Psi_{\mathcal{N}K}(E_K, x, \theta) + \Psi_{\pi K}(E_K, x, \theta)\,,
\end{aligned}\right. \tag{18}$$

where $\Psi_{ij}(E_j, x, \theta)$ represents the production spectrum of the j-th particle due to the interaction of the i-th particle with air nuclei. In these equations, the contribution of the secondary nucleon from the pion collision is neglected and the kaon flux is taken into account only for the first generation in their cascade.

The production spectrum is represented as

$$\Psi_{ij}(E_j, x, \theta) = \int_{E_j}^{\infty} \frac{F_{ij}(E_j, E_i)}{\lambda_i E_j} J_i(E_i, x, \theta)\, \mathrm{d}E_i \,, \tag{19}$$

where $F_{ij}(E_j, E_i)/E_j$ gives the number of the j-th particle per unit energy produced from the interaction of the i-th particle. The values of this F_{ij} are referred to the previous paper [11], in which they were calculated on the basis of the recent accelerator experiments [14] and Feynman's scaling hypothesis [10] for the hadronic interaction.

The interaction mean free paths λ_i ($i = \mathcal{N}$, π and K) in eqs. (18) and (19) are assumed to be independent of their energy [11], as

$$\lambda_{\mathcal{N}} = 80 \,, \qquad \lambda_\pi = 120 \,, \qquad \lambda_K = 140 \,, \qquad\qquad [\mathrm{g/cm^2}] \,.$$

Equation (18) is numerically solved by assuming the spectra of the incident primary cosmic rays [11,15] as

proton: $j_p(E_n)\, \mathrm{d}E_n = 1.74 \cdot 10^4 (E_n + 0.89)^{-2.75}\, \mathrm{d}E_n$;

heavy nucleus ($Z > 2$, He equivalent):

$$j_z(E_n)\, \mathrm{d}E_n = 1.27 \cdot 10^3 (E_n + 0.31)^{-2.75}\, \mathrm{d}E_n \,,$$

where j_p and j_z have a dimension of $\mathrm{m^{-2}\, sr^{-1}\, s^{-1} (GeV)^{-1}}$ and E_n is the total energy per nucleon in GeV. In the calculation, the contribution of the heavy primary cosmic-ray (He equivalent) to the hadron cascade is assumed to be four times as large as that of the single proton.

3. – Calculated results of the barometer coefficient and the temperature coefficient.

The barometer coefficient and the temperature coefficient are calculated under the assumption of the atmospheric-temperature distribution given in U.S.

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(14) F. C. Erne: National Laboratory High-Energy Physics, Japan, KEK-73-10 (1973), p. 1; D. C. Carey, J. R. Johnson, R. Kammerud, M. Peters, D. J. Ritchie, A. Roberts, J. R. Sauer, R. Shafer, D. Theriot and J. K. Walker: *Phys. Rev. Lett.*, **33**, 327 (1974); G. Giacomelli: NAL-PUB-73/74-EXP. (1973).

(15) E. Juliusson: *Proceedings of the XIV International Conference Cosmic Ray*, Vol. **8** (München, 1975), p. 2689.

Standard Atmosphere [16]. The resultant values are obtained for all the combinations of the following parameters for each of different atmospheric depths:

Muon threshold energy: 0.178 to 10^3 GeV; eight threshold energies are given for each decade of energy.

Zenith angle: 0°, 16°, 32°, 48° and 64°.

3'1. *Barometer coefficient.* – Figure 1 gives some examples of the barometer coefficient as a function of the muon threshold energy (multiplied by $\cos\theta$) for the atmospheric depths of 1000 and 600 g/cm². In the figure, the solid, dotted and dashed lines correspond to the zenith angles θ's of 0°, 32° and 64°, respectively. We can see that the coefficients for vertically and obliquely incident muons at 1000 g/cm² are almost equal to each other, whereas those at 600 g/cm² are different from each other.

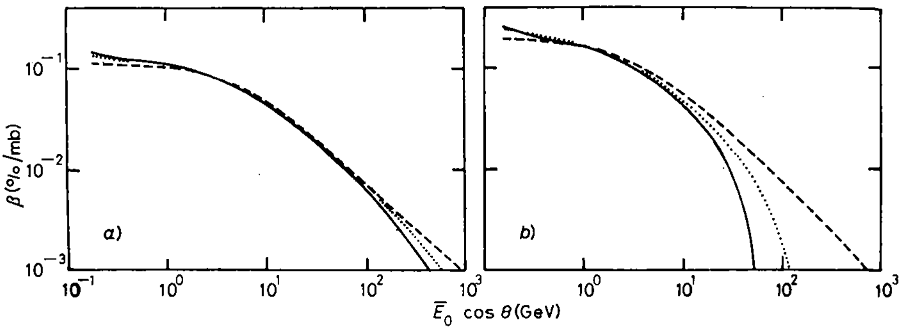

Fig. 1. – Barometer coefficients β represented as a function of $\bar{E}_0\cos\theta$ for $x_0 = 1000$ (a)) and 600 g/cm² (b)) and for $\theta = 0°$ (———), 32° (···) and 64° (– – –).

Figure 2 shows the barometer coefficient for each of the atmospheric depths from 500 to 1000 g/cm² at intervals of 100 g/cm². For a practical use, the coefficient is given by the contour lines on the polar co-ordinate in %/mb, where the amplitude of the radial direction gives the muon threshold energy and the angle from the vertical axis gives the zenith angle of incident muons.

3'2. *Partial temperature coefficient.* – Figure 3 shows the partial temperature coefficient of muons at sea-level, whose zenith angles are 0°, 32°, 48° and 64°, respectively. The coefficient (multiplied by $\cos\theta$) is shown as a function of the atmospheric depth, and the letters a)-h) in each individual figure indicate the muon threshold energies from 0.32 to 1000 GeV.

In fig. 4, the partial temperature coefficient at sea-level (the solid line,

[16] U. S. Standard Atmosphere, prepared under sponsorship of Environmental Science Services Administration, U.S.A. (1966).

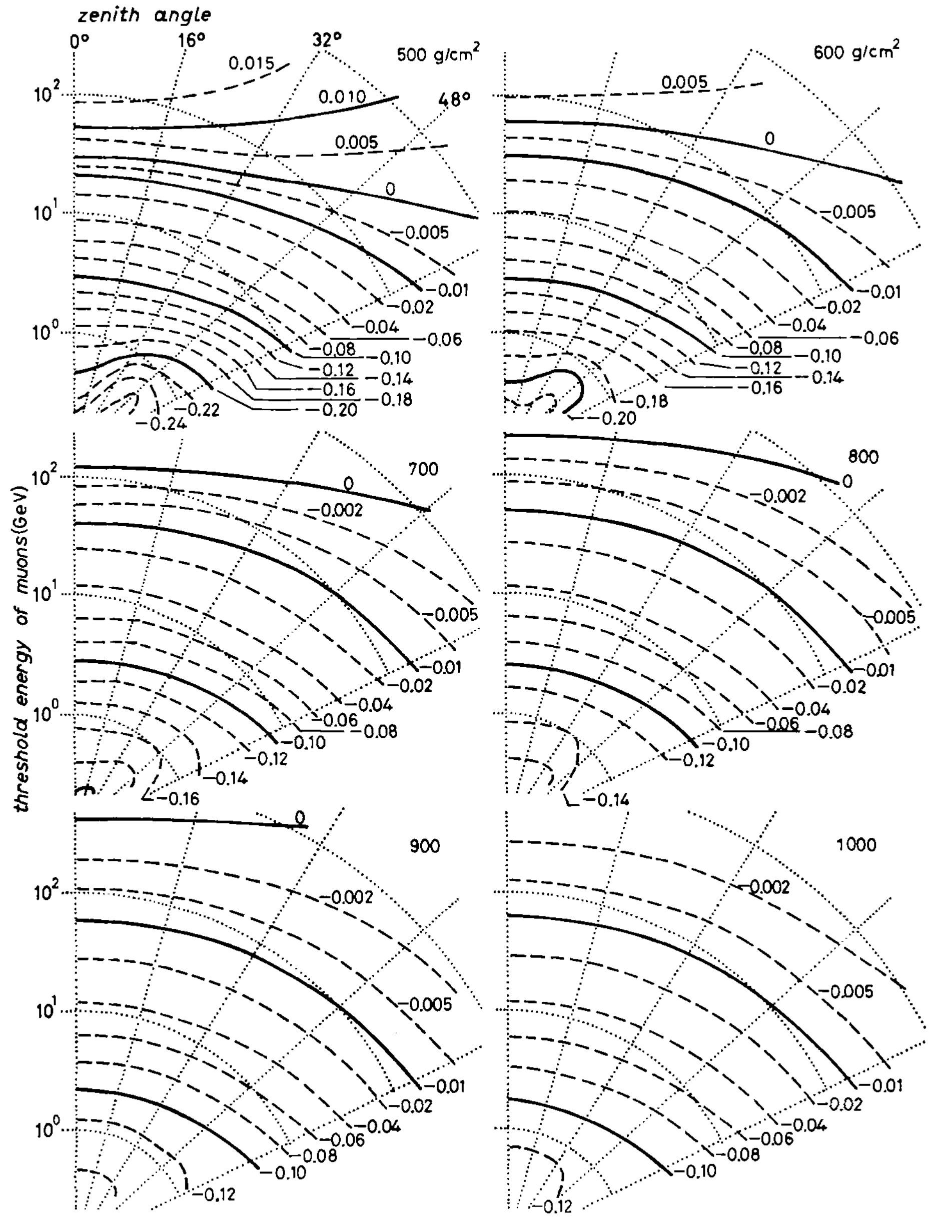

Fig. 2. – Barometer coefficients β [%/mb] for x_0's from 500 to 1000 g/cm² at intervals of 100 g/cm². The coefficients are given by the contour lines on the polar co-ordinate; its amplitude of the radial direction gives $\bar{E}_0$ and its angle from the vertical axis gives θ.

$x_0 = 1030\ \mathrm{g/cm^2}$) is compared with the one at high altitude (dotted line, $x_0 = 550\ \mathrm{g/cm^2}$) for two zenith angles of 0° and 64° and for three threshold energies of 1, 10 and 100 GeV, respectively. We can see that the coefficients at the two depths are almost equal to each other for high threshold energy of 100 GeV.

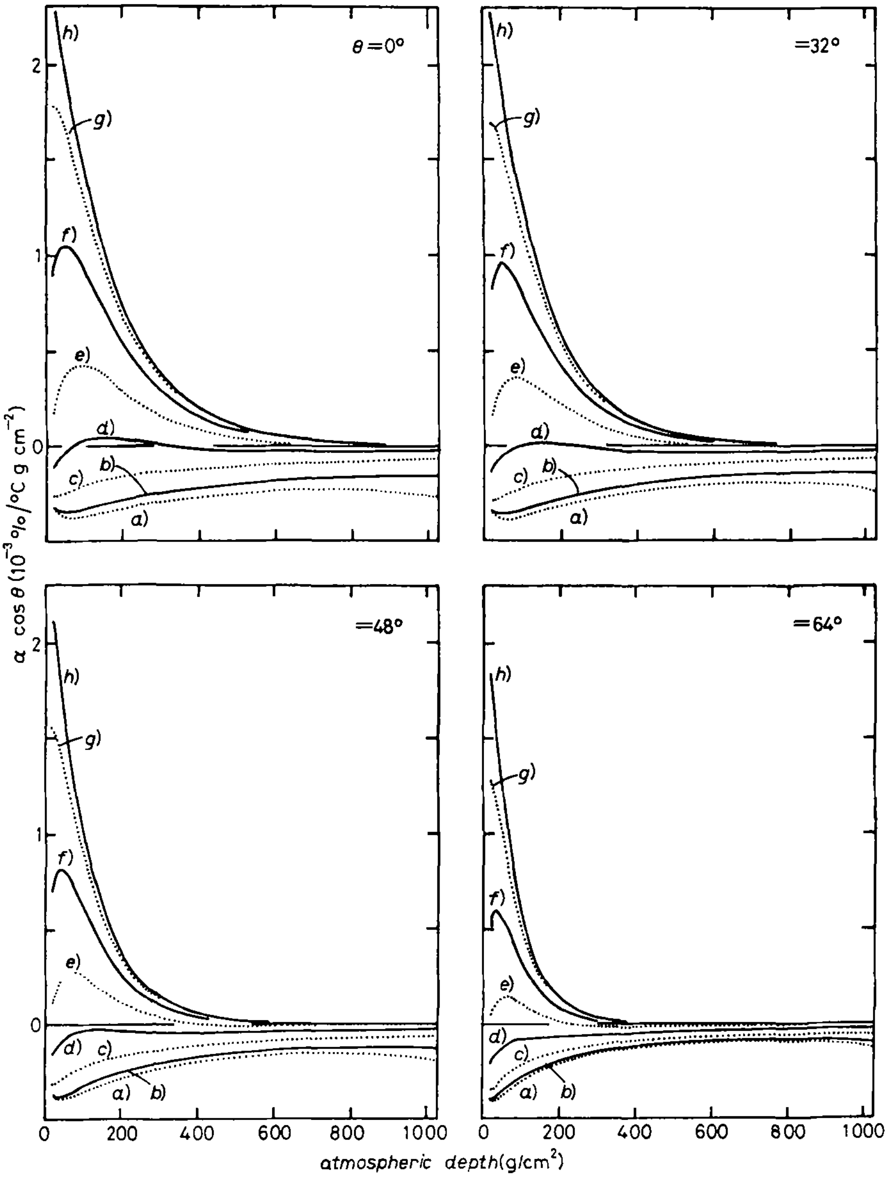

Fig. 3. – Partial temperature coefficients ($\alpha \cos\theta$) at sea-level for θ's of 0°, 32°, 48° and 64°, and for $\bar{E}_0 = 0.32$ (a)), 1.0 (b)), 3.2 (c)), 10 (d)), 32 (e)), 10^2 (f)), $3.2\cdot10^2$ (g)) and 10^3 GeV (h)).

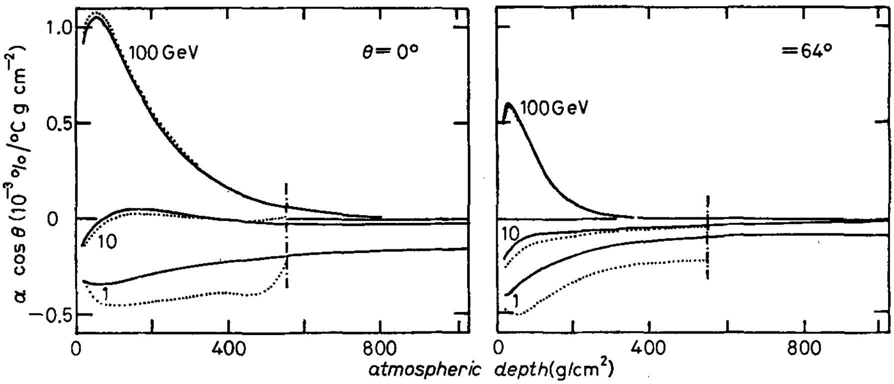

Fig. 4. – Comparison between the partial temperature coefficients α at sea-level (solid lines, $x_0 = 1030$ g/cm²) and those at high altitude (dotted lines, $x_0 = 550$ g/cm²) for θ's of 0° and 64° and for $\bar{E}_0 = 1$, 10 and 100 GeV.

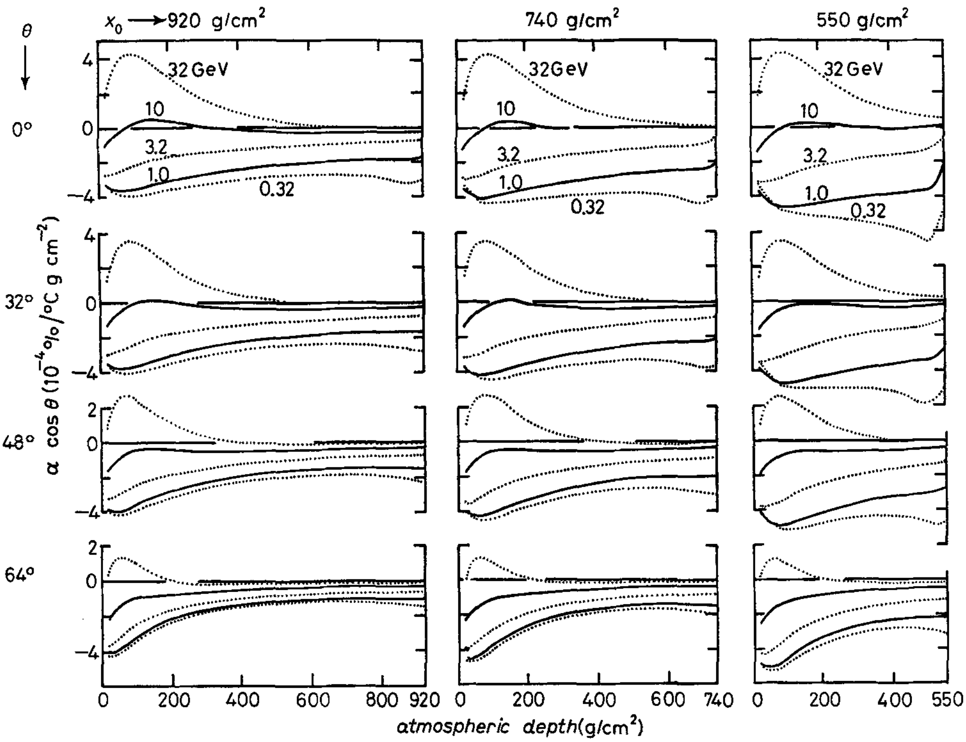

Fig. 5. – Partial temperature coefficients α for low threshold energies; five curves in each individual figure represent the coefficients for $\bar{E}_0 = 0.32$, 1.0, 3.2, 10 and 32 GeV. They are given for each combination of x_0 (920, 740 and 550 g/cm²) and θ (0°, 32°, 48° and 64°).

This is due to almost equal survival probabilities of high-energy muons at these depths. On the other hand, in the lower energy region including 1 and 10 GeV in the figure, the coefficients at the two depths are different from each other depending on their energies.

Figure 5 shows the partial temperature coefficients for low threshold energies, where the five curves in each individual figure represent the coefficients for the threshold energies of 0.32, 1, 3.2, 10 and 32 GeV, respectively. They are given for each combination of the observational atmospheric depths (550, 740 and 920 g/cm²) and the zenith angles (0°, 32°, 48° and 64°).

4. – Atmospheric effects on the muon intensity observed at deep underground stations.

4·1. *Apparent barometer coefficients.* – Figure 6 shows the barometer coefficients observed at various underground stations [3,5,17]. In the figure, the solid and open circles represent the coefficients at the stations whose altitudes

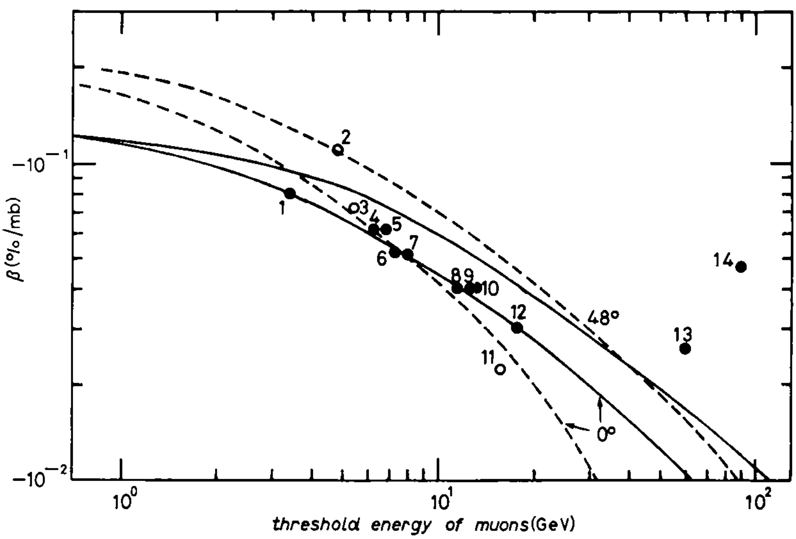

Fig. 6. – Barometer coefficients at various underground stations, together with the present coefficients β for $x_0 = 1000$ (———) and 600 g/cm² (– – –) and for $\theta = 0°$ and 48°. The solid and open circles represent the coefficients of the stations, whose altitudes are lower and higher than 1000 m, respectively, and are referred to No. 1-12 [17], 13 [5] and 14 [3]. Stations: 1) Yakutsk (20 m w.e. in depth), 2) Bolivia, 3) Embudo, 4) Mawson, 5) Misato, 6) Hobart, 7) Budapest, 8) Takeyama, 9) London, 10) Yakutsk (60 m w.e. in depth), 11) Socoro, 12) Sakashita, 13) Matushiro and 14) Poatina.

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[17] *Proceedings of the International Symposium High-Energy Cosmic Ray Modulation*, Appendix (Tokyo, 1976).

are lower and higher than 1000 metres, respectively. The present coefficients are also shown for the atmospheric depths of 1000 and 600 g/cm² and for the zenith angles of 0° and 48°, respectively. The observed coefficients seem to be consistent with the calculated coefficients for the threshold energy lower than several tens GeV if we take into account the difference of the observation altitudes, cut-off rigidities or aperture angles of the detectors among the stations. On the contrary, the observed values at the deep underground stations, that is, $-(0.027\pm0.004)$ %/mb at Matsushiro (250 m w. e. in depth) ([5]) and $-(0.047\pm0.002)$ %/mb at Poatina (365 m w.e. in depth) ([3]), are apparently larger in magnitude than the calculated ones (<0.017 %/mb). Such discrepancies might be due to the atmospheric temperature effect because the observed coefficients were obtained by a single correlation method between ΔI and ΔP neglecting the temperature variation ΔT. In the following, the influence of the temperature effect on the barometer coefficient will be estimated from the observed meteorological data.

The total amount of the variation in the muon intensity produced from the atmospheric effect can be expressed as

$$\Delta\{\ln I(\bar{E}_0, x_0, \theta)\} = \beta\Delta P + \Delta I_{\mathrm{T}}\,, \qquad \Delta I_{\mathrm{T}} = \int_0^{x_0} \alpha(x)\,\Delta T(x)\,\mathrm{d}x\,, \tag{20}$$

where Δ is used instead of δ in eq. (1) to indicate a finite variation. If ΔI_{T} has some correlation with ΔP, eq. (20) can be written in terms of ΔP as

$$\Delta\{\ln I(\bar{E}_0, x_0, \theta)\} = \beta_{\mathrm{A}}\Delta P + \text{the residue}\,, \tag{21}$$

where β_{A} is called the apparent barometer coefficient and given by

$$\beta_{\mathrm{A}} = \beta + \beta_{\mathrm{V}}\,. \tag{22}$$

In the equation, β represents the real barometer coefficient defined by eq. (20), and β_{V} is the virtual barometer coefficient caused by the temperature effect through its correlation with the barometric pressure. Note that the second term in eq. (21) represents the residual part of ΔI_{T} which has no correlation with the barometric pressure.

The calculations of the above β_{A} are made monthly for the period of July 1981-June 1982, during which the observed barometer coefficient at Matsushiro in fig. 6 was obtained. The meteorological data are referred to the radiosonde observation at Wajima Observatory (37.4°N, 136.9°E) ([18]), which is located about 160 km Northwest of Matsushiro. The daily values of $T(x)$ and P in the calculation are the averages of the observations at 9 h and 21 h

([18]) *Aerological Data of Japan*, edited by Japan Meteorological Agency (monthly issued).

(local time), and $T(x)$ are obtained at 21 isobaric levels from 20 to 1000 mb. The correlation coefficients are derived monthly between ΔP and ΔI_T in eq. (20) for various threshold energies. The averaged correlation coefficients over the one year are obtained, together with their standard deviations, as $+0.38\pm$ ± 0.22 for $\bar{E}_0 \leqslant 3.2$ GeV and -0.32 ± 0.23 for $\bar{E}_0 \geqslant 32$ GeV. These values indicate that the correlation at any $\bar{E}_0$ is not so large in magnitude and is changeable from month to month depending on atmospheric conditions. With an increase in the threshold energy, this correlation changes its sense from positive to negative due to the change in the sense of the temperature effect, and it follows that positive and negative virtual barometer coefficients are induced.

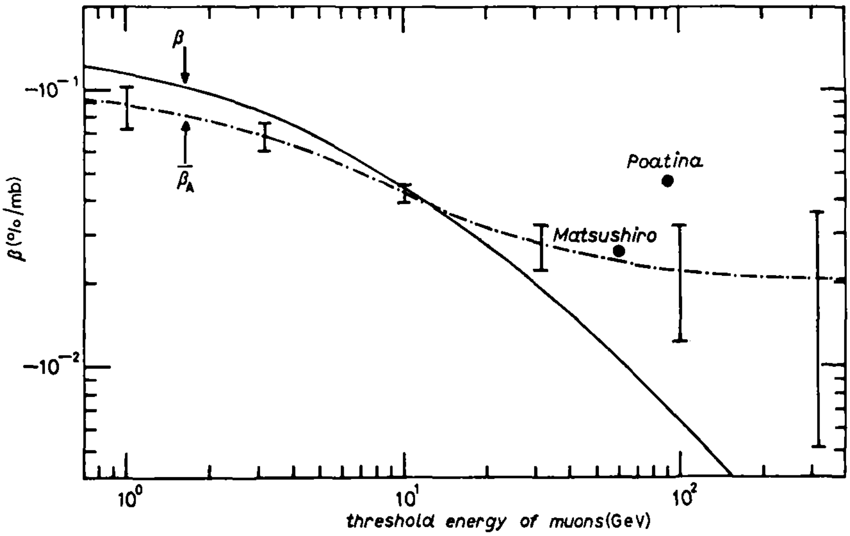

Fig. 7. – Real barometer coefficient β, averaged apparent barometer coefficient $\bar{\beta}_A$ at Wajima with its standard deviations, and observed coefficients at Matsushiro ([5]) and Poatina ([3]). Both β and $\bar{\beta}_A$ are the values for $\theta = 0°$ at sea-level, and $\bar{\beta}_A$ has been calculated in the period July 1981 - June 1982 during which the observed values at Matsushiro have been obtained.

Figure 7 shows the real barometer coefficient β and the averaged apparent barometer coefficient $\bar{\beta}_A$ with large standard deviations for the vertically incident muons at sea-level. In the figure, the deviation of $\bar{\beta}_A$ from β is equal to the average virtual barometer coefficient $\bar{\beta}_V$. We can see that this $\bar{\beta}_V$ is not so large in the energy region lower than about 30 GeV, indicating that the observed coefficients obtained by neglecting the temperature effect are in good agreement with the real coefficients (see fig. 6). With an increase in the threshold energy (> 30 GeV), however, $\bar{\beta}_V$ remarkably increases due to the temperature effect, and the observed coefficient at Matsushiro ($\bar{E}_0 = 62$ GeV for $\theta = 0°$) shows fairly a good agreement with $\bar{\beta}_A$. Although the coefficient at Poatina shows some discrepancy from $\bar{\beta}_A$, it may be due to the difference of the atmospheric conditions at Poatina from those used in the present analysis. On the basis of the above consideration, it is concluded that the anomalously large barometer coefficients observed at both Matsushiro and Poatina are attributed to the contribution of the large temperature effect on the cosmic-ray muon intensity at deep underground depths.

4'2. *Semi-annual intensity variation.* – Figure 8 shows the intensity variations of muons observed at three underground stations, that is, at Matsushiro (250 m w.e. in depth) [6], at Misato (34 m w.e. in depth) [7] and at Sakashita

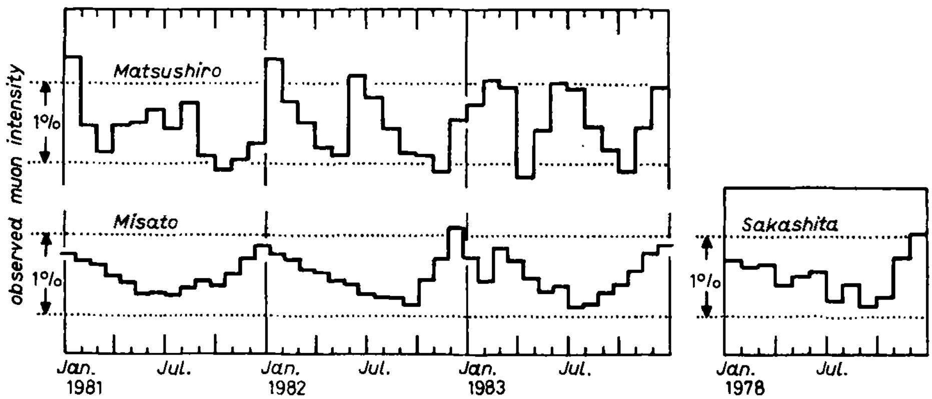

Fig. 8. – Observed intensity variations of muons at Matsushiro (250 m w.e. in depth) [6], at Misato (34 m w.e. in depth) [7] and at Sakashita (80 m w.e. in depth) [8].

(80 m w.e. in depth) [8]. In the intensity variation at Matsushiro, we can see a remarkable semi-annual variation every year, which shows a striking contrast to the annual variations at Misato and Sakashita. It will be shown in what follows that the difference in these variations can be attributed to the dependence on the muon threshold energy of the atmospheric temperature effect.

Figure 9 gives a schematic representation of the atmospheric partial temperature effects on muon intensity at shallow and deep underground depths, whose conditions are specified by ($\bar{E}_0 = 1$ GeV, $\theta = 0°$) and ($\bar{E}_0 = 100$ GeV, $\theta = 48°$), respectively. The latter condition is supposed to be approximately equivalent to that for the vertical telescope with a finite aperture angle at Matsushiro [19]. The partial temperature coefficients α_i ($i = 1, 2$) are shown

[19] S. Yasue, S. Mori, M. Ichinose, S. Sagisaka, T. Yokoyama, S. Akahane and K. Chino: *Proceedings of the XVI International Conference Cosmic Ray*, Vol. 4 (Kyoto 1979), p. 227.

on the top of the figure, where i indicates each of the above two cases. The seasonal deviations of the atmospheric temperature $(\Delta T)_j$ ($j = 1, 2, 3, 4$) from the yearly average at Wajima in 1982 ([18]) are shown on the left. We can see that the temperature deviation varies with the atmospheric depth in a complicated manner for each season, and the variation in the stratosphere is almost opposite in sign to that in the troposphere. The products $\alpha_i(\Delta T)_j$ are plotted in the middle of the figure for each combination of i and j. By inte-

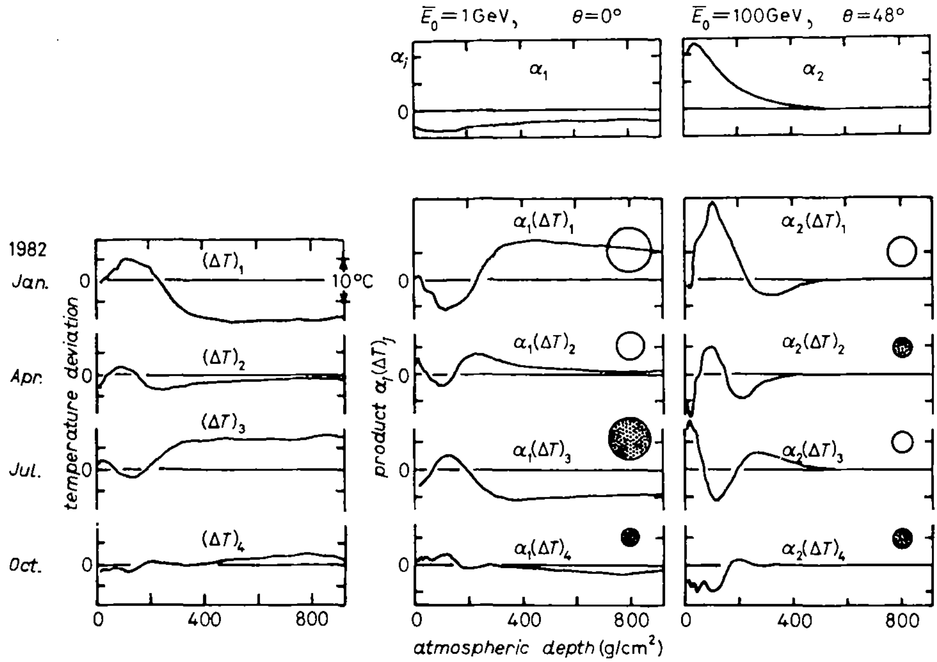

Fig. 9. – Schematic representation of the atmospheric partial temperature effect on the muon intensity observed at shallow and deep underground depths, whose conditions are equivalent to ($\bar{E}_0 = 1$ GeV, $\theta = 0°$) and ($\bar{E}_0 = 100$ GeV, $\theta = 48°$), respectively. α_i ($i = 1, 2$) are the partial temperature coefficients for the above two cases, and $(\Delta T)_j$ ($j = 1, 2, 3, 4$) are the seasonal deviations of the atmospheric temperature from the yearly average at Wajima in 1982 ([18]). The products $\alpha_i(\Delta T)_j$ are plotted for each combination of i and j, and the magnitude of each temperature effects is shown with the area of a circle; the open and shaded circles represent the positive and negative values, respectively.

grating each of these products from the top of the atmosphere to the ground, we can obtain the temperature effect $(\Delta I)_{ij}$ whose magnitude is shown with the area of the circle at the upper right-hand corner; the open and shaded circles represent the positive and negative values, respectively. The characteristic difference between the above two cases can be summarized as follows:

In the case of the shallow underground depth, α_1 is negative and almost independent of the atmospheric depth from the top to the ground. Then, the contribution of the product $\alpha_1\ (\Delta T)_j$ in the troposphere to the integral $(\Delta I)_{1j}$ is dominant compared with in the stratosphere, that is, the temperature effect is opposite in sense to the temperature itself near the ground surface showing an annual variation with its maximum in Winter.

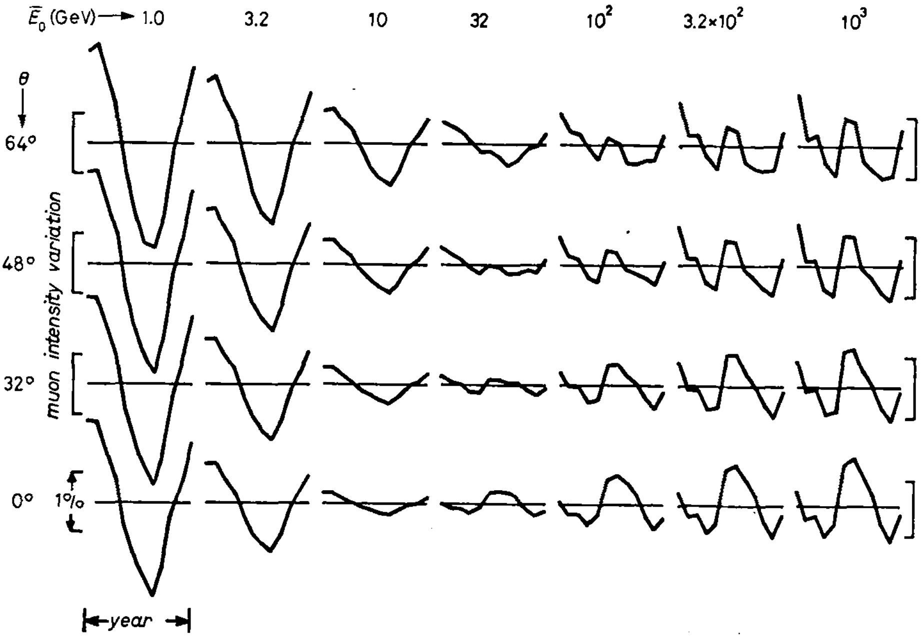

Fig. 10. – Intensity variations of muons at $x_0 = 920\ \text{g/cm}^2$ expected from the temperature variation at Wajima ([18]) in 1982. These are given for each combination of $\bar{E}_0$ and θ. $\bar{E}_0 = 1$, 3.2, 10, 32, 10^2, $3.2\cdot10^2$ and 10^3 GeV. $\theta = 0°$, 32°, 48° and 64°.

On the other hand, in the case of the deep underground depth such as Matsushiro, the contributions of the products $\alpha_2(\Delta T)_j$ to the integrals $(\Delta I)_{2j}$ in both stratosphere and troposphere are almost compensated each other for all seasons. The balance between the two contributions produces a semi-annual variation with maxima in Summer and Winter as is shown in the figure. This indicates that the above balance is very sensitive to the depth of the tropopause ($\approx 200\ \text{g/cm}^2$), the temperature distribution in the stratosphere, and also on the functional shape of the partial temperature coefficient.

The intensity variations caused by the temperature effect at $x_0 = 920\ \text{g/cm}^2$ are calculated monthly in 1982, and the resultant variations in the year are plotted in fig. 10 for each combination of the threshold energies (1.0, 3.2, 10, $3.2\cdot10$, 10^2, $3.2\cdot10^2$ and 10^3 GeV) and the zenith angles (0°, 32°, 48° and 64°). We can see that one maximum appears in Winter for any case, and in addition to this, another maximum appears in Summer at deep underground depths.

In order to compare the theoretical expectation with the observed variation at Matsushiro in 1981-1983, the variations caused by the temperature effect and also by the barometric pressure effect are calculated monthly from the meteorological data at Wajima ([18]). The resultant variations are plotted in fig. 11 for $\bar{E}_0 = 100$ GeV, $x_0 = 920$ g/cm^2 and $\theta = 48°$, together

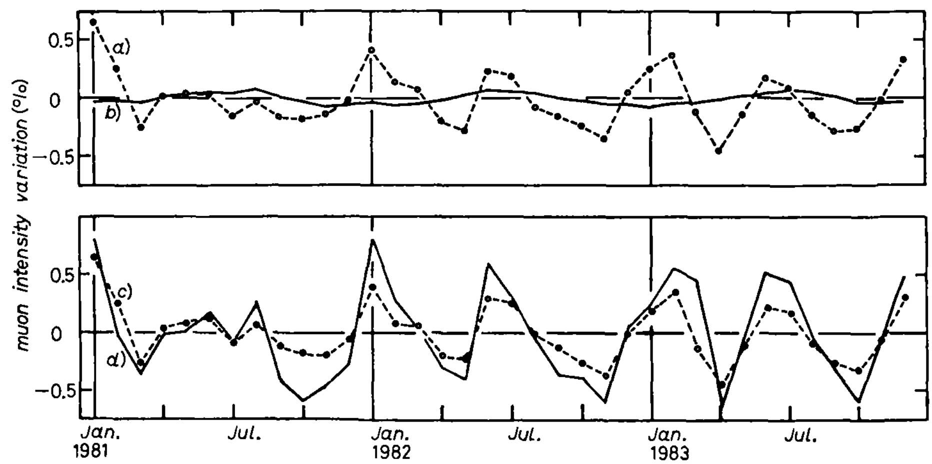

Fig. 11. – Intensity variations of muons for three years in 1981-1983; *a*) is the variation expected from the atmospheric temperature effect, *b*) from the barometric pressure effect, *c*) represents the sum of *a*) and *b*), and *d*) is the observation at Matsushiro (250 m w.e. in depth) ([6]). *a*), *b*) and *c*) are calculated for $x_0 = 920$ g/cm^2, $\bar{E}_0 = 100$ GeV and $\theta = 48°$, by referring to the meteorological data at Wajima ([18]).

with the intensity variation observed at Matsushiro ([6]). We can see that the theoretical variation is in good agreement with the observed one, particularly in time profile. Therefore, it is concluded that the semi-annual variation observed at Matsushiro can be mainly explained by the contribution of the atmospheric temperature effect.

5. – Discussions and conclusions.

On the basis of the theoretical calculation of the hadronic cascade and muon propagation in the atmosphere, the barometer coefficients and the partial temperature coefficients of cosmic-ray muons have been obtained for various combinations of parameters such as the muon threshold energy, the zenith angle and the atmospheric depth.

Using these results and also the meteorological data, we have shown that the anomalously large barometer coefficients observed at Poatina (365 m w.e. in depth) [3] and Matsushiro (250 m w.e. in depth) [4,5] are attributed to the apparent barometer coefficient β_A, which has been calculated by adding the term of the virtual barometer coefficient β_V (see fig. 7). This implies that the observed coefficients contain some errors. Therefore, it is strongly recommended to obtain the real barometer coefficient (β) from the observation by taking into account the variation in the atmospheric temperature, especially at deep underground stations where β_V is dominant. Otherwise, we get erroneous cosmic-ray data by the barometric correction. If the temperature data in the upper atmosphere are not available for this purpose, it would be better to leave the cosmic-ray data without applying any barometric correction since the barometric effect is negligibly small at such stations.

It has been also shown that the semi-annual variation in cosmic-ray intensity at Matsushiro [6], which exhibits a striking contrast to annual variations usually observed at underground depths shallower than Matsushiro, is explained by the temperature effect at deep underground depths, particularly in time profile (see fig. 11). The theoretical semi-annual variation, however, is a little smaller in amplitude than the observed one. This discrepancy might be due to the facts that the atmospheric condition at Matsushiro may differ from the one at Wajima, and that the radiosonde flight cannot sufficiently cover the altitudes where the temperature effect is effective for high-energy muons.

From the results shown in the present paper, it is concluded that the barometer coefficients and the partial temperature coefficients provided in the fig. 2, 3 and 5 are applicable to the analysis of the cosmic-ray data observed under various conditions. It is added to note that the present theoretical barometer coefficients (both β and β_A) for ground surface stations are somewhat small compared with observed ones [20]. This discrepancy arises only at the lower threshold energies below 3 GeV, and might be due to our insufficient expression of hadronic interaction at low energy.

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[20] *Cosmic-Ray Intensity During* IGY, No. 5, edited by National Committee for IGC Science Council of Japan (1961).

● RIASSUNTO (*)

Sulla base del calcolo teorico dell'effetto atmosferico sull'intensità dei muoni dei raggi cosmici, si dimostra che due fatti anomali riportati recentemente riguardanti osservazioni muoniche in stazioni a grande profondità si possono attribuire all'effetto della temperatura atmosferica. Uno è la notevole dipendenza dell'intensità muonica dalla pressione atmosferica osservata a Poatina (365 m w.e. di profondità) e Matsushiro (250 m w.e. di profondità), che è in contraddizione con previsioni teoriche, e l'altro è la variazione semiannuale nell'intensità muonica a Matsushiro, che mostra un contrasto stridente con le variazioni annuali osservate solitamente in stazioni sotterranee meno in profondità di Matsushiro. In questo lavoro si forniscono il coefficiente barometrico e il coefficiente parziale di temperatura per varie combinazioni di parametri come l'energia di soglia muonica e l'angolo zenitale per soddisfare ogni esigenza di osservazione.

(*) *Traduzione a cura della Redazione.*

Резюме не получено.