Discussion

Greisen, K.: I wish to describe Bollinger's Monte Carlo calculations since they are rather important to the present discussion. He used a mechanical computer to play the kind of game of chance described by Drs. Messel and Ogiline. At each value of meson energy, he followed the history of about 100 mesons, letting them lose energy by chance according to the theoretical formulae, until reaching the end of their ranges. The range distribution for mesons of a fixed high energy was found to be very wide. Then he assumed some incident spectrum and computed the number of mesons that would arrive at various depths underground. Within statistical fluctuation inherent in this method, the numbers were the same as would be computed by ignoring the fluctuations in the energy loss. This result is accident and depends on calculation of several factors. However, I want to emphasize that the conclusion is weak statistically-just as weak as the data now being compared on the assumption that Bollinger's conclusion is correct. It is quite important at this stage to repeat those Monte Carlo calculations with modern electronic methods that can permit much better statistical accuracy.

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III-5-12. Very Large Burst due to High Energy Muons

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It is very interesting to study electromagnetic interactions of muons with extremely high energies of order >1000 Bev because the question of whether or not the interaction would be affected by structure in the muon or nucleon will be answered. This question can at present only be studied in the cosmic radiation.

The large muon detectors at 20 mwe underground observing air showers[1] at Institute for Nuclear Study of Tokyo University was similarly used for this purpose. The experimental arrangement consist of four scintillation detectors each with an effective area of 2 m^2 and two neon hodoscope trays having its two layers which are placed under one half of the scintillation detectors (see Fig. 1). The detectors have a total area of 8 m^2 so that they can give an observation of very large number of bursts during a rather short time. About 11,000 bursts with sizes more than 100 ionizing particles initiated in rock were observed at 2,958.7 hours. The burst size S was given in terms of a sum of pulse heights in the 4 scintillation detectors that corresponds to numbers of ionizing particles only when the particles enter at vertical direction. Even bursts produced by very oblique incidence muon can trigger the detectors, so that their bursts give very larger false sizes than those caused by the same number of ionizing particles entered at vertical direction because of prolonging track length of passing particles in the scintillators. Thus it should be considered that burst sizes in this experiment do not correspond closely with transferred energies one by one.

A plot of the data, the differential frequential distribution of bursts as a function of size S from S=100 to 16,000 particles appears

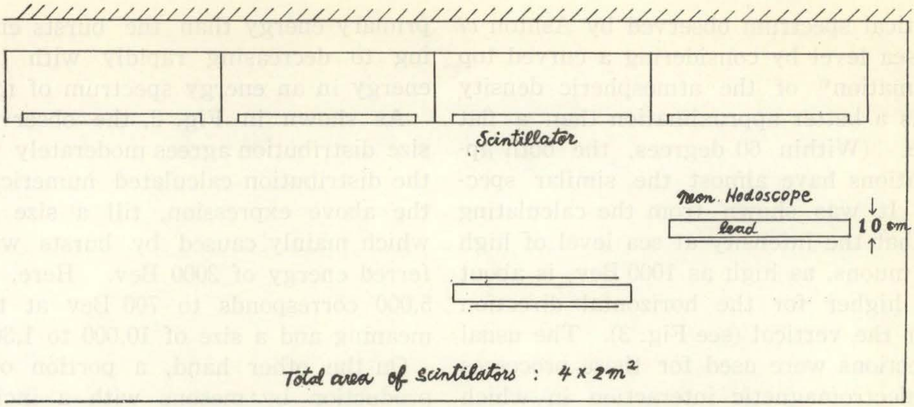

Fig. 1. Experimental arrangement.

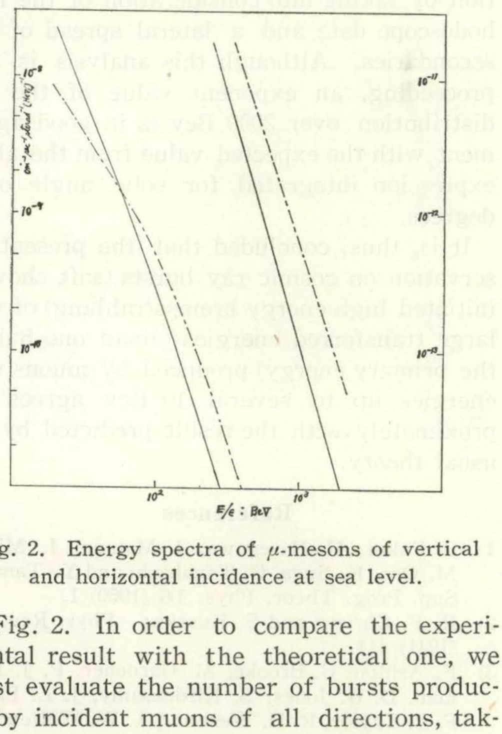

Fig. 2. Energy spectra of μ-mesons of vertical and horizontal incidence at sea level.

in Fig. 2. In order to compare the experimental result with the theoretical one, we must evaluate the number of bursts produced by incident muons of all directions, taking account of the effect of prolonging track lengths in each directions. Following the calculation of Christy and Kusaka[2)], number of bursts with size S_θ per cm² per sec produced by muon of a zenith angle θ is,

$$\frac{dn_i}{dS_\theta}=\frac{1}{dS_\theta}\bar{\varphi}N\int_0^\infty dE$$
$$\times\int_0^{\varepsilon_{\max}}\frac{dE}{\varepsilon}F(E/\varepsilon,\theta)\sigma_i(E/\varepsilon,\theta)P'''(E,S_\theta)\,. \quad (1)$$

Integrating for solid angle and considering the effective area of arrangement, the number of bursts with size S per cm² persec is given by

$$n_i(S)dS=dS\int\left(\frac{dn_i}{dS_\theta}\right)A(\theta,\varphi)d\Omega$$

where $\bar{\varphi}$: a unit of cross section $(e^2/\mu c^2)^2\alpha Z^2$

N: Avogadro number

E: the energy of the secondary (burst)

ε: a fraction of E to the primary energy of meson

E/ε: the energy of the primary meson

$F(E/\varepsilon,\theta)$: the number of mesons at 20 mwe per unit solid angle per unit energy per cm² per sec of energy E/ε at an angle θ with the vertical,

$\sigma_i(E/\varepsilon,\theta)$: a cross section, measured in unit $\bar{\varphi}$, for the creation of a secondary of energy E by a primary of energy E/ε in the absorber,

$P'''(E,S)$: the total probability of getting a burst greater than S from an initial ray of energy E taking account of a fluctuation effect with the approximation Furry Model,

$A(\theta,\phi)$: a total effective area of four scintillators as a function of a zenith angle θ and an azimuthal angle φ,

S_θ: a false burst size in terms of number of ionizing particles with vertical incidence as a function of a zenith angle θ.

Three distinct processes are important in the production of soft secondaries by muons; knock-on, bremsstrahlung and pair creation. We get, thus, the expected number of bursts to be compared with the experimental results by the following expression,

$$n(S)=n_{\mathrm{brems}}(S)+n_{\mathrm{knock}}(S)+n_{\mathrm{pair}}(S)\,. \quad (3)$$

In the above $F(E/\varepsilon,\theta)$, the spectrum of all zenith angles at 20 mwe was converted from the vertical spectrum observed by Ashton *et al*[3] at sea level by considering a curved top approximation[4] of the atmospheric density which is a better approximation than a flat top one. (Within 60 degrees, the both approximations have almost the similar spectrum.) It was shown from the calculating result that the intensity at sea level of high energy muons, as high as 1000 Bev, is about 6 time higher for the horizontal direction than for the vertical (see Fig. 3). The usual cross sections were used for these processes of the electromagnetic interaction in which bremsstrahlung is the most important process for bursts-production. For bremsstrahlung cross section incomplete screening one was employed, because bursts with a transferred energy produced by cosmic radiation would be mainly caused by muons of a little higher

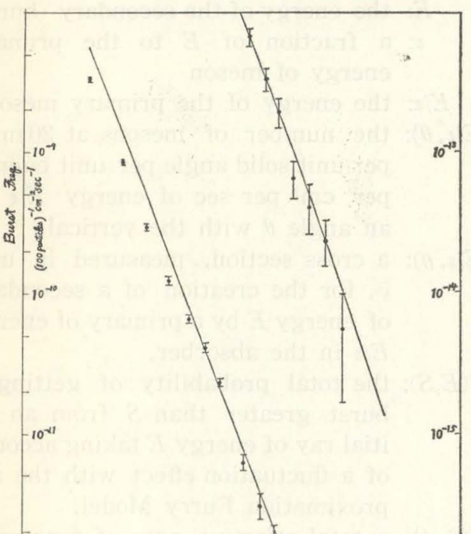

Fig. 3. Comparison of the observed burst size distribution with the expected one.

primary energy than the bursts energy owing to decreasing rapidly with increasing energy in an energy spectrum of muons.

As shown in Fig. 2, the observed bursts size distribution agrees moderately well with the distribution calculated numerically from the above expression, till a size of 16,000 which mainly caused by bursts with transferred energy of 2000 Bev. Here, a size of 5,000 corresponds to 700 Bev at the same meaning and a size of 10,000 to 1,300 Bev.

On the other hand, a portion of bursts-production by mesons with a incidence of smaller than about $\theta=60$ degrees could be distinguished from one near horizontal direction by taking into consideration of the neon hodoscope data and a lateral spread of soft secondaries. Although this analysis is now proceeding, an exponent value of the size distribution over 2000 Bev is in good agreement with the expected value from the above expression integrated for solid angle of 60 degrees.

It is, thus, concluded that the present observation on cosmic ray bursts (soft showers initiated high energy bremsstrahlung) of very large transferred energies (about one half of the primary energy) produced by muons with energies up to several 10^3 Bev agrees approximately with the result predicted by the usual theory.

References

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Discussion

Wolfendale, A. W.: There seems to be some disagreement between the horizontal spectrum computed by you and that of Allen and Apostolakis (Proc. Roy. Soc., in the press), at least for energies between a few hundred Gev.

Kitamura, T.: Yes, the disagreement would be based on a treatment of μ-e decay process. I will check. But, if the Allen and Apostolakis spectrum will be applied, the agreement between the observed and expected ones becomes better.

Menon, M. G. K.: In what angular regions are contributed to the present burst size distribution?

Kitamura: Near 100 Bev is about 70 degrees and near 1000 Bev is over 80 degrees.