ON THE FINE STRUCTURE OF THE CORE OF EXTENSIVE AIR SHOWERS

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Experimental data are presented which indicate the presence of well-collimated particle beams in the cores of extensive air showers. Various possible explanations of the observed phenomenon are considered.

A detailed study of the core structure of extensive air showers (EAS) by means of cloud chambers has been attempted in recent years in a number of experiments.[1,2] However, the lack of a sufficiently sensitive method for identifying the passage of a shower core through the array, and also the short time of exposure of the arrays, have made it impossible to obtain conclusive data on the structure of the shower in the core region.

We have previously reported on the observation of events of the passage of EAS cores through a diffusion chamber with an area of 0.6 m^2. The chamber was operated for 1800 hours simultaneously with an array consisting of counters and ionization chambers connected to a hodoscope, which made it possible to determine the core position in EAS.[3]

In the present article we wish to point to an important feature of the distribution of shower particles in the core region. This feature is the appearance, in this region, of a narrow (4 cm diameter) particle beam consisting of a large number (from 4 to 15) of particles with collinear trajectories. If we construct the lateral distribution of the particle flux with this beam as the axis, and extrapolate the lateral distribution observed at distances larger than the dimensions of the beam towards this axis in accordance with a power law, we find that the number of particles expected on the basis of such an extrapolation is much smaller than the one actually observed in the beam. The experimental data are given in the table. On the average, the number of particles in the beam is 7, while the number indicated by the extrapolation is 0.7. As can be seen from the table, it is very improbable that the observed particle beams can be due to Poissonian fluctuations in the lateral distribution of the trajectories of shower particles. In reality, fluctuations in the core region can be substantially different from Poissonian. However, for any type of fluctuations, one would expect a frequent appearance of a group consisting of a small number of particles in the diffusion chamber, and also a simultaneous appearance of several such groups, while this is, in fact, not observed. We shall discuss different possible explanations of the observed effect.

It is well known from the electromagnetic cascade theory[4,5] that the photon-flux density in the shower increases faster than the electron-flux density with decreasing distance from the axis of the electron-photon shower. Accordingly, we can assume that the observed feature of the lateral distribution of shower particles near the axis is related to the transition effect in the materials placed above the sensitive layer of the chamber. We shall estimate the value of the transition effect. According to Guzhavin and Ivanenko,[5] the lateral distribution of the electron flux at the maximum of the electron-photon shower is, at distances in the range of interest, of the form $\rho_e = C_e/r$, while that of the photon flux is of the form $\rho_f = C_f|\ln r|/r$, where C_e and C_f are constants and r is the distance from the shower axis in Molière units. For distances of the order of 1 cm ($r \sim 10^{-4}$) from the axis, $\rho_f/\rho_e \approx 3$. The ratio of the number of photons to the number of electrons in a circle with radius r ($r \sim 1$ cm) with its center at the shower axis $n_f/n_e = 3(1+1/9.2) \approx 3$.

The sensitive layer of the diffusion chamber was shielded by the glass cover of the chamber 1.5 g/cm^2 in thickness and the plastic room roof 1.5 g/cm^2 in thickness. Assuming that the radiation length for these materials is equal to ~ 25 g/cm^2, we obtain the value of ~ 0.1 for the probability of photon conversion.

Assuming that each photon produces a pair of charged particles, we find that, owing to the transition effect, the number of charged particles in a

r, m	N	n	r, m	N	n
4	$3.1 \cdot 10^4$	8	<1	$1.4 \cdot 10^4$	6
<1	$2.5 \cdot 10^4$	5	<1	$5.5 \cdot 10^4$	6
5	$8.8 \cdot 10^4$	5	2	$3.0 \cdot 10^4$	5
3	$2.1 \cdot 10^4$	5	<1	$1.8 \cdot 10^4$	4
<1	$4.5 \cdot 10^4$	8	<1	$2.7 \cdot 10^4$	4
<1	$3.5 \cdot 10^4$	15	9	$5.0 \cdot 10^4$	6
~1	$2.5 \cdot 10^4$	14	<1	$5.0 \cdot 10^4$	6
<1	$7.2 \cdot 10^4$	11	6	$9.0 \cdot 10^4$	6
2,5	$1.5 \cdot 10^4$	7	<1	$1.4 \cdot 10^4$	8
~1	$4.5 \cdot 10^3$	6	7	$1.0 \cdot 10^5$	6
~1	$3.5 \cdot 10^4$	5	<1	$7.0 \cdot 10^3$	8
<1	$2.9 \cdot 10^4$	12	2	$1.0 \cdot 10^4$	8
~1	$1.5 \cdot 10^4$	6	<1	$1.0 \cdot 10^4$	10
8	$1.5 \cdot 10^5$	10	<1	$8.5 \cdot 10^3$	5

Note: N is the number of particles in the EAS; n is the observed number of particles in the beam 4 cm in diameter; r is the distance of the beam from the shower axis as determined from hodoscope data.

circle with a radius of the order of a few centimeters can increase by a factor of 1.5. However, because of the small variation of the ratio ρ_e/ρ_f with r, we practically take the transition effect already into account when determining the number of charged particles in the circle with radius r (see table) from the distribution function of charged particles at distances larger than r. Thus, the observed effect cannot be explained by the transition effect.*

Let us now consider one possible explanation of the observed particle beams, namely that they are due to the nuclear-active component of EAS. High-energy nuclear-active particles interacting near the observation level can produce secondary particles of different nature, among them π^0 mesons.

The secondary particles produced in the interaction can form a beam, provided their energy is sufficiently high. Thus, for a nuclear interaction at the distance of the order of one nuclear mean free path (500 m), the particles which arrive at the observation level spread over a distance of $\sim 2 \times 10^{-2}$ m should have an energy $E \geq (5 \times 10^2 / 2 \times 10^{-2}) p_\perp \approx 2 \times 10^{12}$ ev, where $p_\perp \geq 10^8$ ev/c is the transverse momentum carried away in nuclear interactions by a secondary particle. Taking the number of particles in the beam into account, we find that the energy of the nuclear-active particles belonging to the beam is $\sim 10^{13}$ ev. According to reference 6, the number of nuclear-active particles with energy > E at sea level is given by the expression k/E (where E is given in ev, and $k = 2.5 \times 10^{11}$ ev for showers with a total number of particles $N \sim 10^4$). Hence it follows that the probability of a nuclear-active particle with energy $\geq 10^{13}$ ev near sea level appearing in a shower with a number of particles $N \sim 10^4$ is very small. At the same time, the expected number of showers with $N \geq 3 \times 10^4$ incident on the diffusion chamber during the observation time coincides with the number of beams accompanied by such showers, or is even smaller than it.[3]

It can easily be seen that, since the spectrum of the nuclear-active particles is of the form k/E, so that the number of nuclear-active particles does not increase greatly with decreasing energy, the probability of beams of low-energy nuclear-active particles appearing is also very small. It should also be noted that, if the beams were being produced by nuclear-active particles in the manner described above, we would obtain beams of different size.

It can be assumed that the observed particle beams represent the cores of electron-photon showers initiated by γ quanta originating in the decay of π^0 mesons produced in nuclear interactions. If the age of such an electron-photon shower is $s < 1$, then a sharp concentration near the axis is characteristic for the distribution of shower particles.

The electromagnetic cascade theory makes it possible to determine the energy of the π^0 mesons necessary for the production of the observed num-

*In reference 5, only electrons and photons with energy $E > \beta$ are considered. The number of electrons with energy $E < \beta$ in the distance range of interest amounts to only ~10% of the total number of electrons at these distances. The number of photons with energy $E < \beta$ can be considerably greater, since the high-energy electrons traveling near the shower axis can produce radiative photons of low energy. It is clear that the probability of radiating photons in the range from β to 0 decreases with increasing electron energy. Therefore, $\rho_f(>\beta, r)$ and $\rho_f(>0, r)$ should be identically equal for $r \to 0$. Hence it follows that, for $E > 0$, $\rho_f(r)$ will be still less dependent on the distance than for $E > \beta$, so that the ratio ρ_f/ρ_e will also be less dependent on the distance.

ber of beam particles in a circle with radius r. The number of particles in a circle with a given radius is determined by the degree of development of the electron-photon shower and by the lateral distribution of shower particles. Using the data of Ivanenko and Guzhavin on the lateral structure of an electron-photon shower produced by a particle with energy E_0, we find that, for an energy $E_0 = 10^{11} - 10^{12}$ ev, the maximum number of particles in a circle 2 cm in radius will be obtained for $s < 0.6$. If we set up the requirement that the number of particles in the circle be similar to that observed experimentally, then we find $E_0 \geq 10^{12}$ ev.

The point of origin of such a shower with $s < 0.6$ is located at an altitude of less than 150 g/cm^2 from the observation level. The flux of nuclear-active particles in an EAS is absorbed according to the law $e^{-x/\lambda}$, where $\lambda = 200$ g/cm^2, and, consequently, the number of nuclear-active particles of such a young shower is twice as large at the production level than at the observation level. Thus, not more than one particle with energy $\geq 10^{12}$ ev is contained in a shower with a number of particles $N = 3 \times 10^4$ at the observation level. Therefore, if the observed particle beams were the cores of young showers,* it would, at any rate, indicate a marked role of nuclear interactions in which the main part of the energy is concentrated in the π^0 meson.† It should be noted that Grigorov and Shestoperov[7] have indicated the possibility of an important role being played by such an energy concentration in the development of EAS.

Furthermore, it can be assumed that the observed beam of particles consists of high-energy μ mesons. The data on the energy of the nuclear-active component discussed above exclude the possibility of the production of such a beam in the lower layers of the atmosphere.

From the observed dimensions of the beam, and assuming an order of magnitude of the production height, we can estimate the energy of the μ mesons. We shall underestimate this energy, assuming that the transverse deviation of the μ mesons is due to Coulomb scattering only. The mean square deviation of particles with energy E is, neglecting the ionization loss in the atmosphere, given by the expression[8]

*We are indebted to I. P. Ivanenko for the discussion of this problem and his valuable remarks.

†This assumption is strengthened by the absence of the high-energy nuclear-active component in the region around the beam. From the data of the second row of ionization chambers of the core detectors,[3] nuclear-active particles with energy $\gtrsim 10^{11}$ ev were observed in none of the 28 cases given in the table.

$$\overline{r^2} = \left(\frac{E_s}{E}\right)^2 t_0 \alpha \int_0^H h^2 e^{-\alpha h}\, dh.$$

The notation and numerical values are the same as in reference 7. Assuming H to be of the order of 7×10^3 m, we obtain $\sqrt{\overline{r^2}} = 1.5 \times 10^{11}/E$. Hence, the minimum energy of μ mesons traveling in such a concentrated beam should be of the order of 10^{13} ev.*

For the production of beams of such μ mesons, the requirement is clearly either a direct production of μ mesons in nuclear interactions at energies $\geq 10^{14}$ ev, or their production through particles with a lifetime by one or two orders of magnitude shorter than the lifetime of π and K mesons. In fact, even assuming the maximum acceptable multiple production of particles with energy $E \sim 10^{13}$ ev, we find† their number to be of the order of 10 for $E_0 \sim 10^{14}$ ev. The probability of the decay of a μ meson with energy of the order of $\sim 10^{13}$ ev at an altitude corresponding to the mean height of shower production is not greater than $1/_{30}$. Thus, such an interpretation of the observed particle beams demands a basic revision of our ideas concerning the origin of the μ-meson component.

At present, it is impossible to make a final choice between the electron-photon and the μ-meson nature of the beam, and a further study of the effect is therefore necessary.

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*As can be seen from the formula given above, the estimate is not very sensitive to the altitude H. It should furthermore be noted that the taking into account of the transverse momentum obtained by particles in the $\pi \to \mu$ decay does not greatly influence the estimate.

†This follows from the energy and momentum conservation laws.