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170

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NUCLEAR INTERACTION IN PHOTOGRAPHIC EMULSION ACCOMPANIED BY LARGE ENERGY TRANSFER TO THE ELECTRON—PHOTON COMPONENT

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A nuclear interaction event with primary energy $E_0 = 250^{+250}_{-125}$ Bev in which about 200 Bev was carried away by one of the π^0-mesons is investigated in detail. The lower limit of energy transferred to the soft component is approximately 30% of the total shower energy.

DATA on interactions between particles with energy of the order of few hundred Bev and atomic nuclei obtained by means of a cloud chamber[1] indicate the existence of very large fluctuations of the fraction of energy carried away by photons. The minimum value of the energy transferred to photons was found to be equal to a few tenths of a percent of the primary energy. The problem of the maximum energy transfer to the soft component is also of considerable interest.

In a stack of stripped Ilford G-5 emulsions exposed at the altitude of 2.5 km during the Italian expedition of Prof. C. F. Powell in 1955, we found and studied in detail an interaction event of the type 1 + 12n characterized by an unusually large fraction of the energy carried away by the electron-photon component. The path length of particles in each emulsion layer was ~1.5 cm and the total

TABLE I. Angular distribution of penetrating particles

No. of particles	θ (first method)	θ (second method)	No. of particles	θ (first method)	θ (second method)
	$\theta_i \cdot 10^3$, radians	$\theta_i \cdot 10^3$, radians		$\theta_i \cdot 10^3$, radians	$\theta_i \cdot 10^3$, radians
1	40	2.5	9	245	235
2	40	11	10	280	265
3	40	32	11	430	420
4	80	67	12	510	525
5	104	95	$\theta_{1/2}^{-1}$	6	7
6	140	135	$1/\theta_{min}$	25	400
7	190	160	$\Sigma 1/\theta_i$	125	580
8	218	220			

length of the electronic cascade observed in the stack ~ 12 cm. A microprojection of the shower and the subsequent electronic cascade is shown in Fig. 1.

1. ANGULAR DISTRIBUTION OF PENETRATING PARTICLES AND MEASUREMENT OF THE ENERGY OF PRIMARY PARTICLE

In spite of the fact that the primary particle was neutral, it was possible to use two methods of measurement of the emission angles θ of penetrating particles with respect to the axis of the electron-nuclear shower. In the first method shower axis was identified with the center of circular symmetry of the angular distribution of penetrating particles. Such a procedure is based upon the assumption that the transverse momentum of all those particles is equal. Corresponding data are given in Table I. In the second method the shower axis was found from the direction of the first electron pair which initiated the large electronic cascade. Since that pair is situated in the same emulsion layer as the center of the star, and the energy of the electron cascade, according to estimates given below, is much greater than that of any penetrating particle we consider the second method to be much more accurate. The angular distribution of penetrating particles according to the second method is given in the third column of Table I, and has been adopted as the basis of subsequent considerations. The angle between the axes directions given by the two methods is small (~ 0.04) and, therefore, the estimates of energy of the primary particle given below for the different axes differ little (by not more than a factor of 1.5).

Analysis of the data of Table I indicates first of all that the angular distribution of penetrating particles is nearly isotropic in the coordinate system having a Lorentz factor $\gamma_c = 7$; e.g., about 85% of the particles should be emitted, for isotropic distribution, within the limits of the ten-fold range of values of θ_{lab} near $\theta = 90°$, which is in a good agreement with the experiment. However, the presence of an asymmetrically placed group of two penetrating particles emitted, in c.m.s., in the direction of the primary particle within a cone with opening angle $\theta_0 \leq 0.1$ radian, should be noted. It can be easily seen that the probability that any of those particles will be found in such a cone, for a random and isotropic emission, is less than 25%. Analysis of the angular and energy distribution of the particles of soft component* strengthens the

*It will be seen in the following that also 2–3 π^0-mesons are found in the cone.

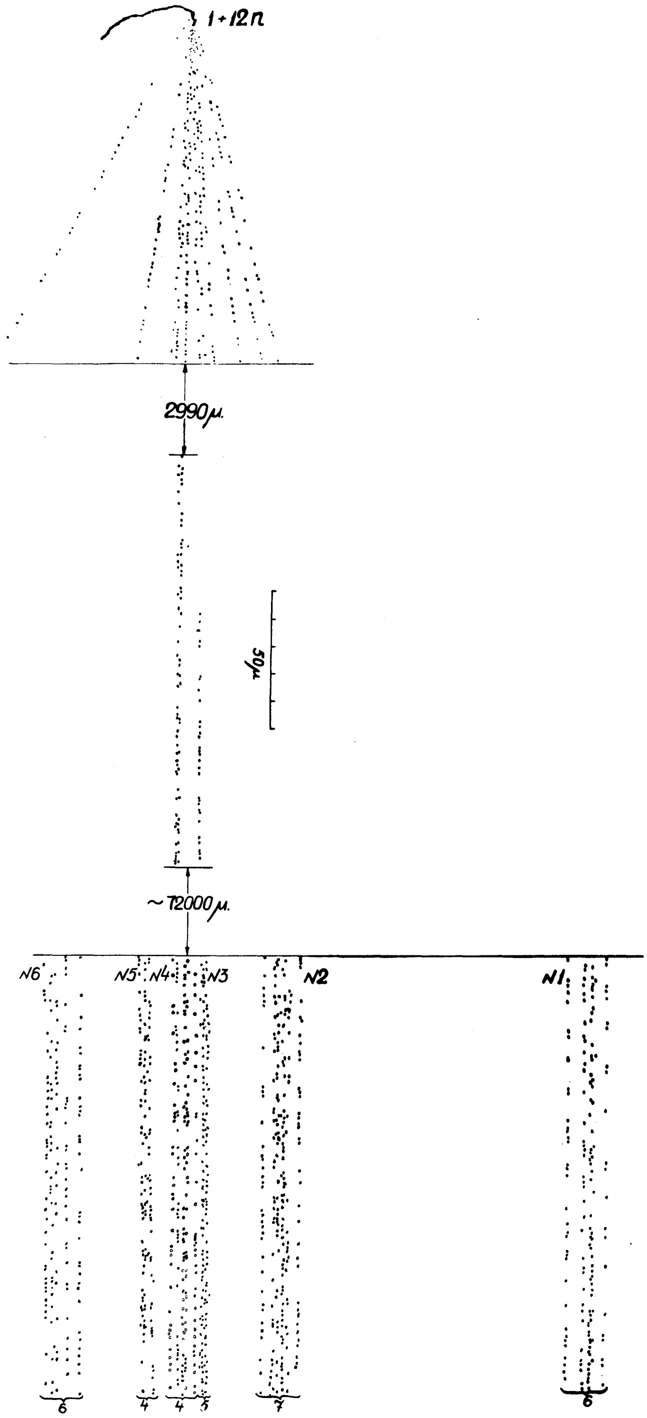

FIG. 1. Microprojection of star of the type 1 + 12n with subsequent electronic cascade.

conclusion about the existence of an anomalously narrow beam of secondary particles and, in consequence, about the absence of total isotropy of the angular distribution of secondary particles in c.m.s.

The probable relative error $\delta\gamma_c$ for isotropic distribution and for $n_s = 12$ amounts to ~ 30% (assuming that the fluctuations of the angular distribution are Poissonian). In determining the energy of the primary particle (a neutron, evidently), the tunnel effect should be taken into account.[2] The

TABLE II. Lateral distribution of electrons

R, μ		<25	25—50	50—100	100—200	Penetrating particle	ΣN_e
$N_e(R)$	$t = 1.6$	15	9	3	2	$R_{min} = 110\mu$	28
	$t = 3.1$	5	7	12	14	$R_{min} = 210\mu$	38
	$t = 4.5$	6	2	16	21	$R_{min} = 305\mu$	45

tunnel length found from the multiplicity of the event is $n_T = 2.5+1$. The primary energy, finally, is

$$E_0 = 250^{+250}_{-125}\ \text{Bev}. \quad (1)$$

The above value could be strongly underestimated if the angular distribution in c.m.s. were substantially asymmetric. In that case all usual methods of finding γ_c from the angular distribution would not be applicable and the only remaining possibility would be to assume that the transverse momentum $p_\perp$ of all particles is the same and known to us. C.m.s. can then be found from the condition that the total longitudinal momentum of all (relativistic) charged particles must vanish. Assuming that $p_\perp = 2\mu c$ (cf. Ref. 3) we obtain that $\gamma_c = 20^{+8}_{-5}$ and, consequently,*

$$E_0 = 2\gamma_c^2 n_T (n_s, \gamma_c) = 1300^{+700}_{-300}\ \text{Bev}. \quad (1a)$$

Adding the longitudinal momenta we find, however, that the total longitudinal momentum of charged particles of the backward cone amounts to $1/3\ Mc\gamma_c$, while the corresponding estimate of the tunnel length $n_T = 1.5$ calls for a value of 1.5 $Mc\gamma_c$. This means that among the particles of the backward cone there must be a number of slow nucleons (not mentioned by us) each with longitudinal momentum of $\sim Mc\gamma_c$ (in c.m.s.). The presence of even one such nucleon in the backward cone first, lowers immediately the estimated value of γ_c to 10 and the energy E_0 to 400 Bev and, second, renders improbable the hypothesis of substantial asymmetry of the angular distribution between the forward and backward cones.

In view of all that has been said above, we think that it is improbable that E_0 exceeds 800 Bev (taking into account both the fluctuations in the angular distribution and the errors of finding γ_c, assuming a symmetrical emission of particles in c.m.s.)

An estimate of the energy of the penetrating component, which is independent of the tunnel length and, in general, of the interaction mechanism, can be obtained from the following relation which is based upon the fact that the transverse momentum is approximately constant:

$$E_{pen} = \bar{p}_\perp \sum (1/\theta_i). \quad (2)$$

Assuming that $\bar{p}_\perp = 2\mu c$ (cf. Ref. 3), we find that $E_{pen} = 150$ Bev and, for the energy of the most energetic penetrating particle, we obtain $E_{max} = p_\perp/\theta_{min} = 110$ Bev.

*The given error of γ_c corresponds to twice the error of $p_\perp/\theta$ for the fastest particle. The influence of errors of $p_\perp$ and θ for the remaining particles is relatively small.

2. LATERAL AND ENERGY DISTRIBUTIONS OF THE PARTICLES OF SOFT COMPONENT

The distribution of particles in planes perpendicular to cascade axis at the depth $t = 1.6$, 3.1, and 4.5 cascade units is given in Table II. Only the particles within the cone with opening angle of 1° about the shower axis were taken into account, thus excluding practically all particles not connected with the shower. At the same time, for electrons of the core (at distances up to 0.01 cascade units from the axis) such a selection does not represent a serious limitation of the (lower) energies, especially at small depths ($t \leq 2$ cascade units). Linear deviations from the axis of the nearest penetrating particle calculated from the relation $R_{min} = t\theta_{min}2.5$ cm are given for comparison in the last column of the table. In all cases, the axis was chosen so as to pass through the center of circular

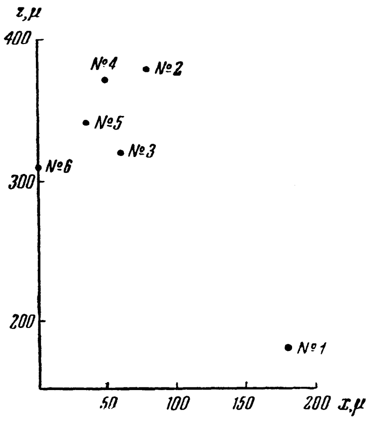

FIG. 2. Lateral distribution of cores of the electronic cascade at the depth of three cascade units.

symmetry of the lateral distribution of electrons in a given plane. In the mean, symmetry was conserved in spite of the presence of at least six

TABLE III.* Lateral and energy distributions of electron pairs

Opening angle $\alpha\cdot 10^3$	<0.32	0.32—2.2	0.83—2.2	2.2—6.2	>6.2	Number of photons with energy
Photon energy E_0, Bev	>32	32—10	10—3.2	3.2—1	<1	> 1 Bev
$t \leqslant 1$	2(a, b)	0	0	0	0	$2/0.77=3$
$1<t\leqslant 2$	3*	0	3	1	5	$7/0.77=9$
$2<t\leqslant 3$	0	1	2	4	5	$7/0.77=9$
$3<t\leqslant 4$	0	1	4	2	5	$7/0.77=9$

*Angular distances between adjacent pairs a—b: $\theta = (1.2 + 0.2)\cdot 10^{-3}$.
The three pairs denoted by * may possiblv be of bremsstrahlung origin.

sharply defined cores of the electronic cascade (cf. Figs. 1 and 2 where the positions of cores is shown in the plane perpendicular to the cascade axis at the depth t = 3.)

We also studied the lateral energy distribution of electron pairs (cf. Table III). The energies of corresponding photons were found from the opening angle of the corresponding pair (following Reference 4). In a few cases these estimates could be checked by direct energy measurements of the pair components from their scattering.

The width of energy intervals given in Table III were chosen so as to be equal to, or slightly narrower than, the mean relative errors of the energy of individual pairs.

Lateral and energy distributions of electrons and pairs given in Tables II and III permit us to estimate the total energy of soft component using one of the following four methods:

(a) by comparing the data of Table II* with cascade theory calculations[5] giving (for each section of the shower) the dependence of the total number of particles in the core on the universal parameter $Z_0 = E_0R$, where E_0 is the initial photon energy and R the radius of the core.

(b) by comparing the data of Tables II and III with the cascade curves N(y, t) for photons and electrons, where $y = \ln(E_0/E_{min})$ and E_{min} is the effective lower limit of energy of detectable particles.

(c) by adding the energies of all pairs of non-bremsstrahlung origin.†

(d) from the relation

$$\Delta\theta_{min} = 2\mu c^2 / E_{\pi^0} \qquad (3)$$

between the minimum angle of emission of photons in π^0-decay and the energy E_{π^0} of the pion (μ denotes the mass of π^0-meson). The required estimate of the π^0-meson energy follows after substituting in Eq. (3) the angular distances θ between adjacent pairs of non-bremsstrahlung origin given in Table III.

In general, the first method seems to us to be the most accurate. In this method random errors are due to uncertainty in the initial number of photons and statistical fluctuations of cascade processes, and systematic — to the omission of a certain number of particles because of angle limitation. In the second method, the error is, in addition to the above factors, substantially influenced by the indeterminacy of E_{min} increased by geometry effects which are not accounted for. Lastly, in the third method the inaccuracy of the measurement of the primary photon energy is most essential, since for a small number of those both the systematic and random errors may become very large.* It should be taken into account that the assumption of equipartition of energy between the primary photons,

TABLE IV. Estimates of the energy E_M of the central electronic cascade

Method of estimate*	E_M, Bev	E_M/E_0
Cascade curves with lateral limitations (table 2) (cf. ref. 5)	240	⩾50%
Cascade curves with energy limitations	~150	~30%
Total energy of pairs of non-bremstrahlung origin	225	~45%
Angle of emission of photons in π^0-decay	⩾200	⩾40%

*E_0 — probable energy of the primary particle (under the assumption of a symmetrical angular distribution).

*It should be borne in mind that only the particles of the central, most intensive cascade are included in Table II.

†Since the total observed length of the cascade is sufficiently large the correction for photon conversion can be neglected.

*The systematic error is connected here with the possibility of including photons of bremsstrahlung origin. We excluded the latter following the method of Ref. 6.

underlying the two first methods, can cause an apparent decrease of the total cascade energy. In actual experimental conditions this effect, however, is not large, corresponding roughly to the difference between the mean geometric and arithmetic value of the energies of primary photons, amounting to less than a factor of 1.5.

The number of photons n_0 produced in the nuclear interaction by means of π^0-mesons was found comparing the various methods of estimating the electronic cascade energy; for $n_0 = 2$ the agreement is satisfactory, for $n_0 = 4$ there is a marked discrepancy with the results of cascade theory.

Final estimates of the energy of the main core of soft component E_M by means of all four methods are given in Table IV where the values of the ratio E_M/E_0 are also given. Roughly similar estimates (smaller by a factor of 1.5 — 2) were obtained for the additional cascade (core 1 in Fig. 2) which started to develop at a greater depth.

It must be concluded therefore that at any rate not less than 30% of the total energy of the star is carried away by the soft component (accounting even for the errors mentioned at the end of section 1). At the same time, attention is drawn to the distinct concentration of high-energy photons near shower axis as compared with the angular distribution of penetrating particles. The bulk of energy of the electronic cascade is emitted within a cone with opening angle $\theta_{max} \approx 1/500$ while the deviation of the penetrating particle closest to the axis of the same cone is $\theta_{min} \approx 1/400$.

Referring to the result of Ref. 1 mentioned earlier, our results indicate that the energy fraction carried away by the soft component may fluctuate by a factor of ten or more. It should be noted also that the energy estimates given above confirm again (cf. Ref. 2) the inadequacy of the explanation of all jets (i.e., high-energy interactions with a small number of slow charged particles) by the n — n collision model.

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171