γ-RAYS FROM VERY HIGH ENERGY INTERACTIONS

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(presented by P. H. Fowler)

For the last two years we have been working with emulsion-heavy metal sandwich stacks on high energy nuclear disintegrations and γ-rays. The purpose of interweaving the emulsion with the metal sheets (which were Pb in some cases, and a tungsten nickel alloy in others) is to reduce both the interaction length λ_I and radiation length λ_R.

In our tungsten stacks 600μ emulsion sheets were interleaved with tungsten alloy sheets which were 1.6 mm thick to form an assembly with density $\rho \sim 12$ gm/cm^2, $\lambda_I \approx 12$ cm and $\lambda_R \sim 6$ mm. With this short value for the radiation length λ_R, electromagnetic cascades develop rapidly with little lateral spread, so that they can readily be detected, and more easily and accurately measured.

Most of our work has been done with stacks of volume ~ 20 litres exposed on Comet aircraft at ~ 220 gm/cm^2 atmospheric depth, where the majority of events found are of course secondary to other interactions in the overlying air. The total time at high altitude was $\sim 2{,}000$ hours. In all we detected $\sim 3{,}000$ cascades, of which roughly one half were produced by nuclear interactions within the assembly (normally in the metal between neighboring emulsion sheets). The other half resulted from the incidence of a γ-ray or electron on the stack. It is a special feature of stacks with high Z that discrimination between γ-rays or electrons and nuclear interactions is good, since λ_I/λ_R is large. Cascades produced by γ-rays originate, and will be located under the microscope at points close to the edge of the stack, while those initiated by nuclear interactions within the stack will originate fairly uniformly throughout the volume. In addition there is the appearance of the cascade under the microscope.

Figs. 1 and 2 illustrate the nature of the material. One of the main measurements we make on the cascades is a measurement of the energy content of the electromagnetic component. This we do by photometric measurement rather than by track counting. We find a simple relation between the maximum value of the photometric density as the cascade develops D_{max} and the cascade energy E. For γ-ray cascades,

$$E = \frac{3 \times 10^5 \lambda_R D_{max}}{A} (\text{BeV}) ,$$

where A is the grain area produced by each electron (including contributions due to δ-rays) measured in μ^2/mm. λ_R is the radiation length as before, measured in cm.

We have been able to check this formula in a few cases, where for example a single π^0-meson is responsible for the cascade. The angle between the two γ-rays then gives us the energy. Fig. 3 shows such an example.

For cascades produced by nuclear interactions, conditions are complicated by effects due to the transverse momenta $P_\perp$ with which the various γ-rays are emitted relative to each other. At high energies ($\gtrsim 1500$ BeV) the γ-rays are effectively collinear and the measurement of the density gives a measure of the total energy of all the γ-rays, using the same formula as that for γ-ray cascades. At lower energies the angles of emission will in general be larger (since $P_\perp$ is nearly constant), and straightforward application of the formula will lead to a progressive underestimation of the cascade energy. No correction has been made. An experimental check is being made on this correction factor now. We believe it will be ~ 1.3 at 400 BeV.

The main result of these measurements, which have been made in four separate exposures, has been the determination of the energy spectrum of the two classes of cascade. These are shown in Fig. 4. First results were reported in the Moscow Cosmic Ray Conference 1959. A similar spectrum above 1000 BeV was reported by the Tokyo group at the same conference, but for $E_\gamma < 1000$ BeV the spectrum flattened off. The experiment was performed at mountain altitudes. The γ-ray flux has been determined to lie between 400 and 6000 BeV, and is well represented by $N_\gamma \propto E^{-2.8}$. This may be compared, both to the estimate of the cosmic ray primary flux, which is $N_{(CR)} \propto E^{-1.8}$, and to the π-meson flux as estimated from the flux of high energy μ-mesons, determined at sea-level or underground, which is $N_{(\pi\mu)} \propto E^{-1.8}$.

If charge independence is to hold, then clearly the π^0 and $\pi^\pm$ energy spectra must be the same at any given atmospheric depth. μ-mesons at sea level come predominantly from $\sim$25 gm/cm^2 depth. γ-rays at jet aircraft level come from $\sim$170 gm/cm^2 depth. These are similar. I assume for the moment, that the γ-rays result from π^0 decays.

If we have a beam of unstable relativistic particles with an energy spectrum $dN = E^{-(\beta+1)}dE$, which decay, it is readily shown that the ratio of the number of secondaries with energy exceeding E to that of their parent (the " spectrum factor ") is given by,

$$R = \frac{f}{\beta+1} \frac{(\varepsilon_{max})^{\beta+1} - (\varepsilon_{min})^{\beta+1}}{\varepsilon_{max} - \varepsilon_{min}}$$

where f is the number of secondaries per parent particle, and ε_{min} and ε_{max} are the minimum and maximum values for the ratio of the secondary to primary energy.

Table I shows the relative efficiency with which various elementary particles transform into μ and γ-ray beams, using accepted values for branching ratio in decay, and decay probability at high energy, and the spectrum factor as given above.

If we consider pions we have the number of

$$\left.\begin{aligned} \mu\text{'s} &= 0.63 f_\pi N_\pi^{\pm} \\ \gamma\text{'s} &= 0.33 N_\pi^{\pm} \end{aligned}\right\} \text{hence } \mu/\gamma = 1.9 f_\pi \text{ for pions;}$$

for K-mesons $\mu/\gamma = 25 f_\pi$
for Λ^0 hyperons $\mu/\gamma = 2 f_\pi$
for Σ-hyperons $\mu/\gamma = 2.2 f_\pi$
for Ξ hyperons $\mu/\gamma = 1.0 f_\pi$

Only K-mesons give a ratio of μ to γ flux appreciably different from that of the pions. They produce considerably more μ-mesons. *A possible* explanation of the difference between the γ-ray and μ meson energy suggests itself, namely that the sea level μ-mesons at high energy are produced predominantly from K-mesons which have a flatter energy spectrum than the pions. If this is so it follows that K-mesons take away more energy than pions, which might well explain the low figure for the proportion of primary energy transformed into this soft component in nuclear interactions that is obtained in emulsion work. It also follows that $P_\perp$ for K mesons should be appreciably greater than that for pions, unless they are appreciably more peaked in the forward direction. This is not so at 30 BeV from the CERN results reported here, but their K mesons are not $K^\pm$ pairs. At still higher energies $\gtrsim$6000 BeV the γ spectrum should flatten out, so as to reflect the K spectrum; more measurements should elucidate this point readily. I must mention however that a K-meson origin for the high energy sea-level muons is contrary to the conclusion of the authors on the zenith angle dependence of the underground mesons.[1)]

Next I will discuss the cascades due to nuclear interactions in the stack. The feature to which I wish to draw attention is the " elbow " in the spectrum at about 4000 BeV. For higher energies the spectrum is given by $E^{-1.9\pm0.2}$; for lower energies it is certainly steeper, with an index of about -2.5 or becoming ~ -2.8 if a correction of 30% to the energy is applied at the lowest energy points. I do not feel that this is a manifestation of the cosmic ray energy spectrum; rather I feel that it is a feature of high energy collisions that the proportion of energy transformed into γ-rays in a collision no longer falls with increasing energy. We feel we have entered a ne wregime, and hope in future experiments to see if other parameters also change their character. The primary energy for this transition is $\sim 10^{14}$ eV.

I would now like to break away from these energy spectra and consider our highest energy events. We have six examples of nuclear interactions where more than 50,000 BeV was given to the soft cascade.

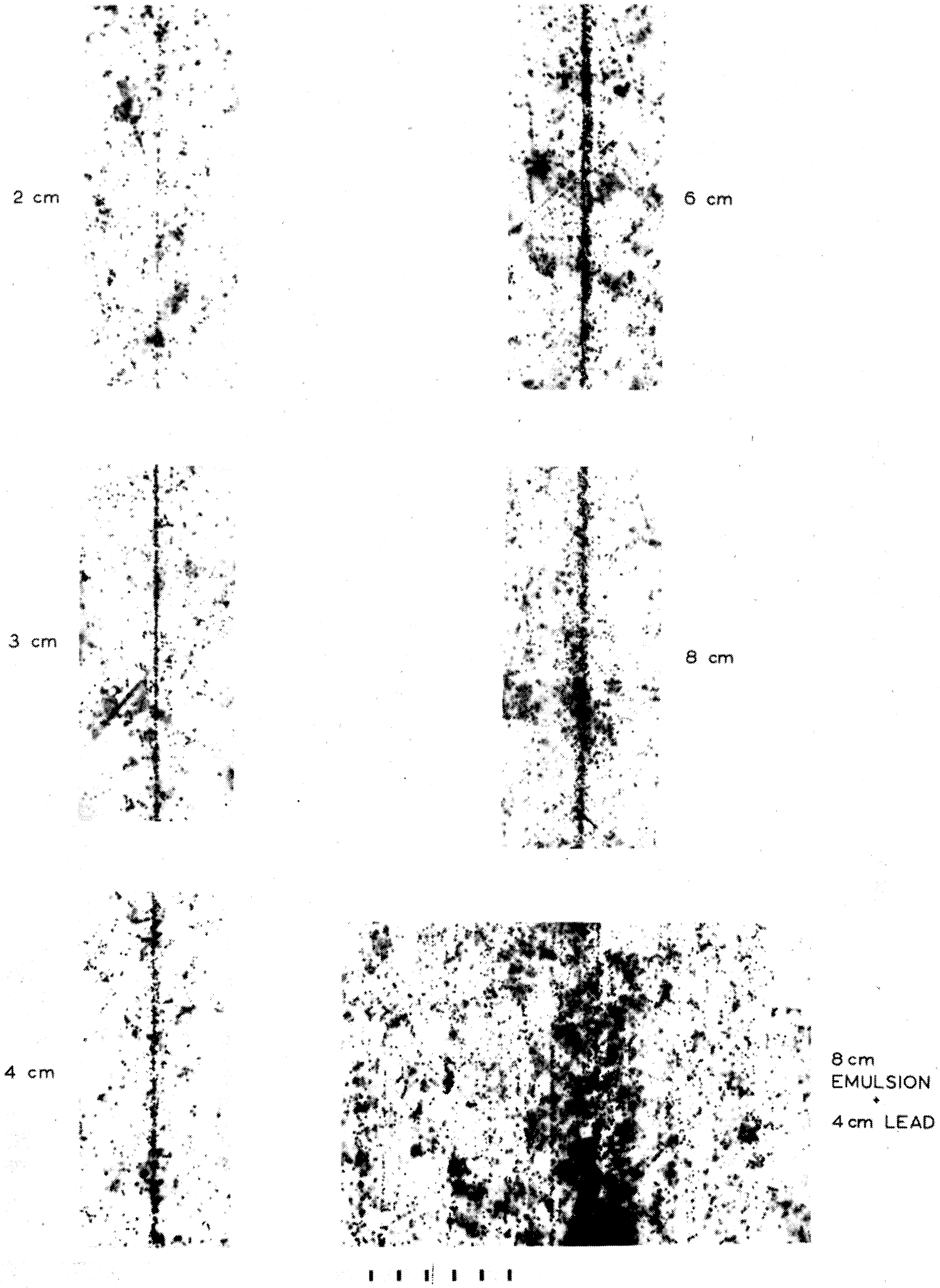

Fig. 1 Photon-initiated cascade ($E \sim 15{,}000$ BeV) in the first Comet stack.

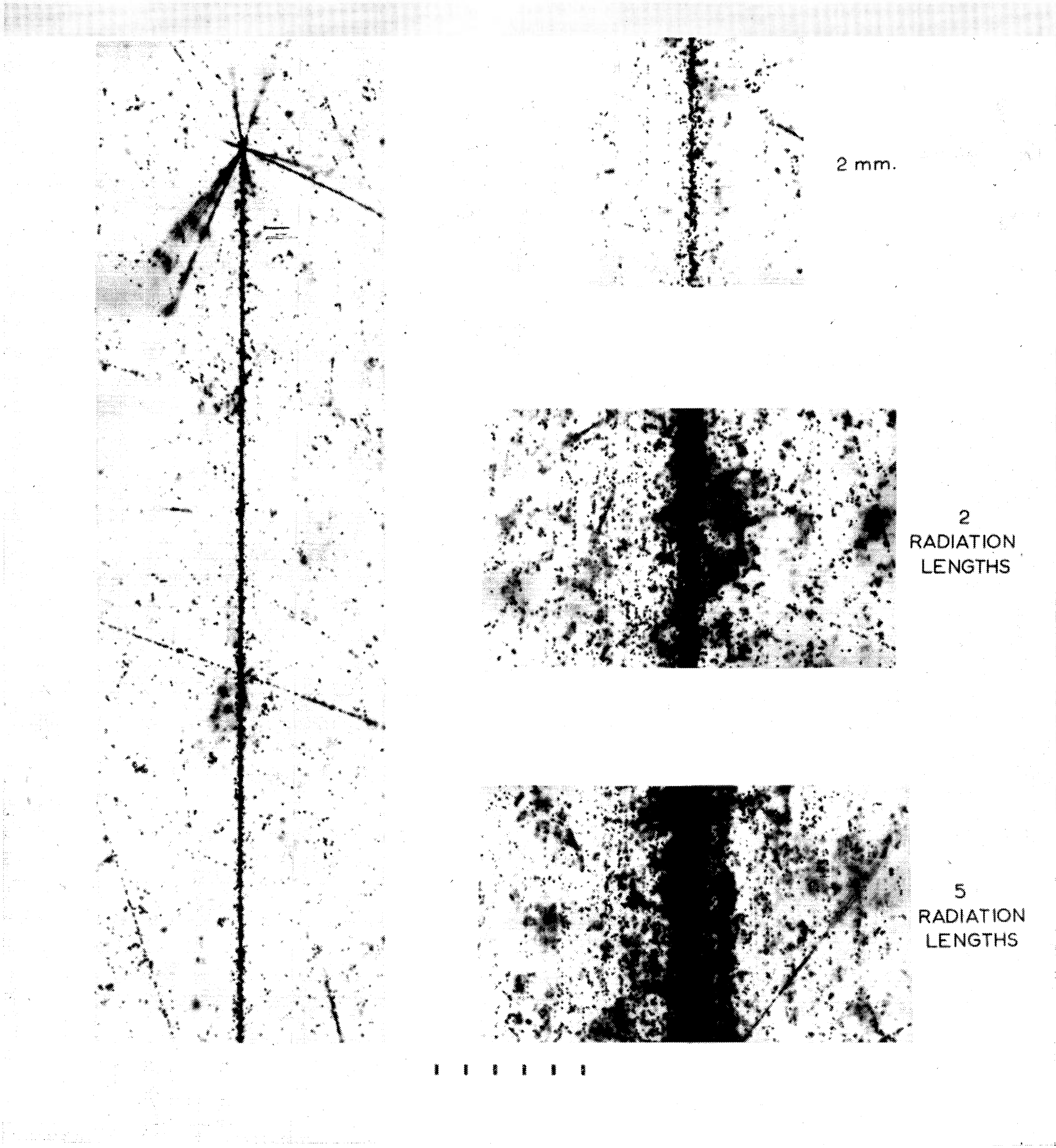

Fig. 2 A component of an extensive air shower, nuclear disintegration type, 15+110 p, $E \sim 200{,}000$ BeV. This shows the development of the ensuing electromagnetic cascade.

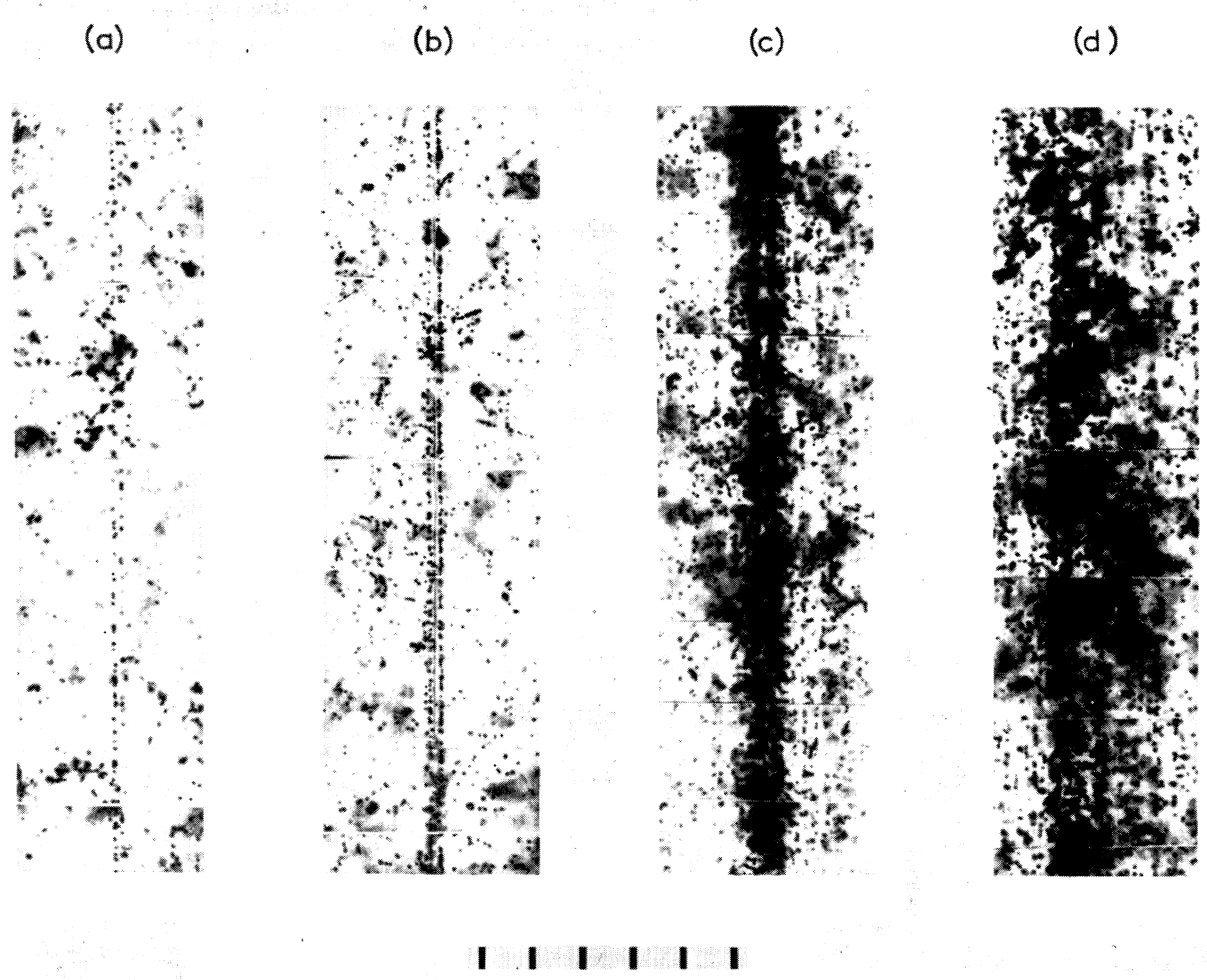

Fig. 3 Cascade resulting from a single π^0 meson of energy 4000 BeV. *(a)* Just after the materialization of both γ-rays; *(b)* 1 radiation length from *(a)*; *(c)* 4 radiation lengths from *(a)*; *(d)* 6 radiation lengths from *(a)*. In *(a)*, *(b)* and *(c)* the two cores can be distinguished; in *(d)* they have merged.

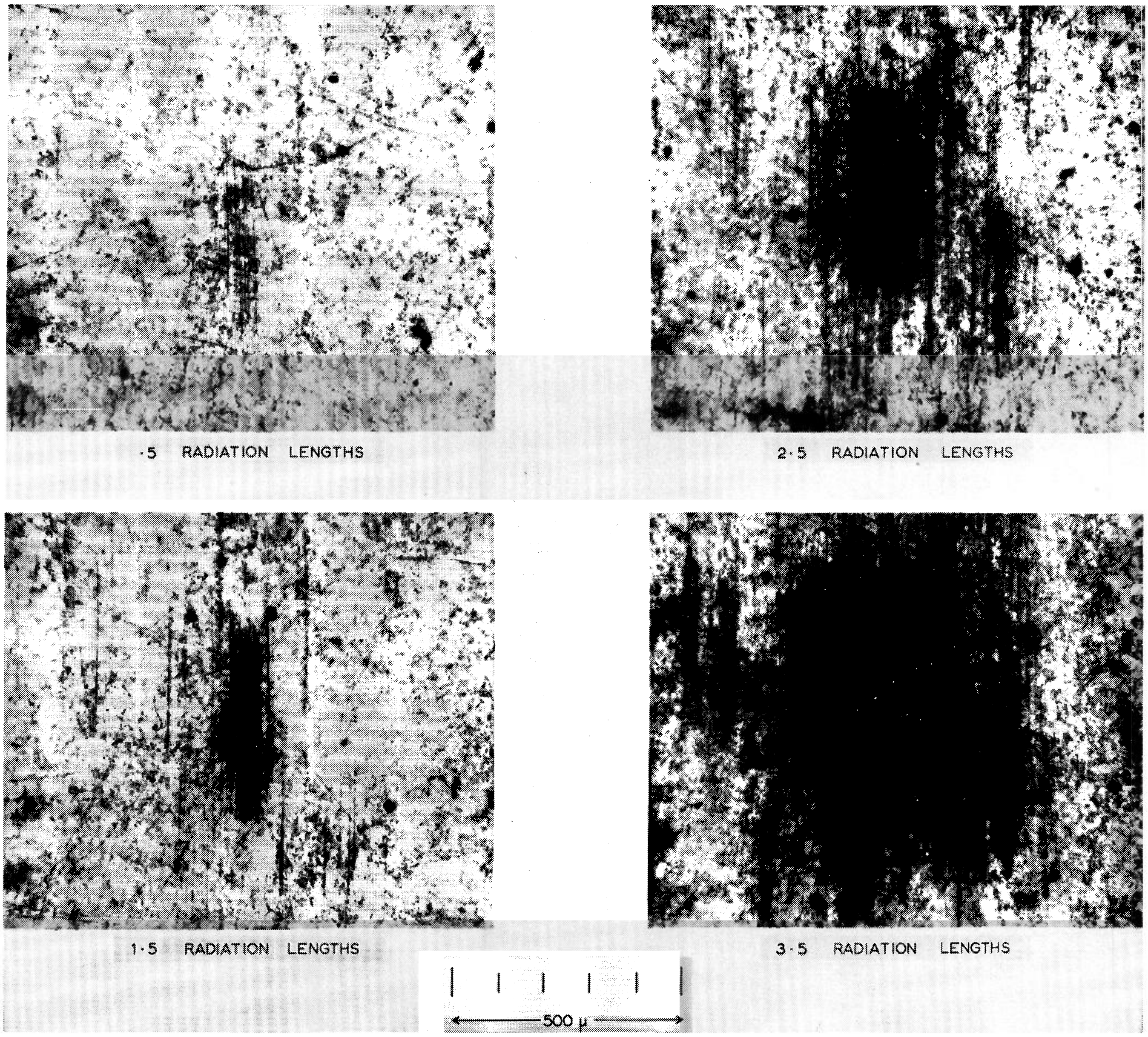

Fig. 6 Stages of development of a large shower.

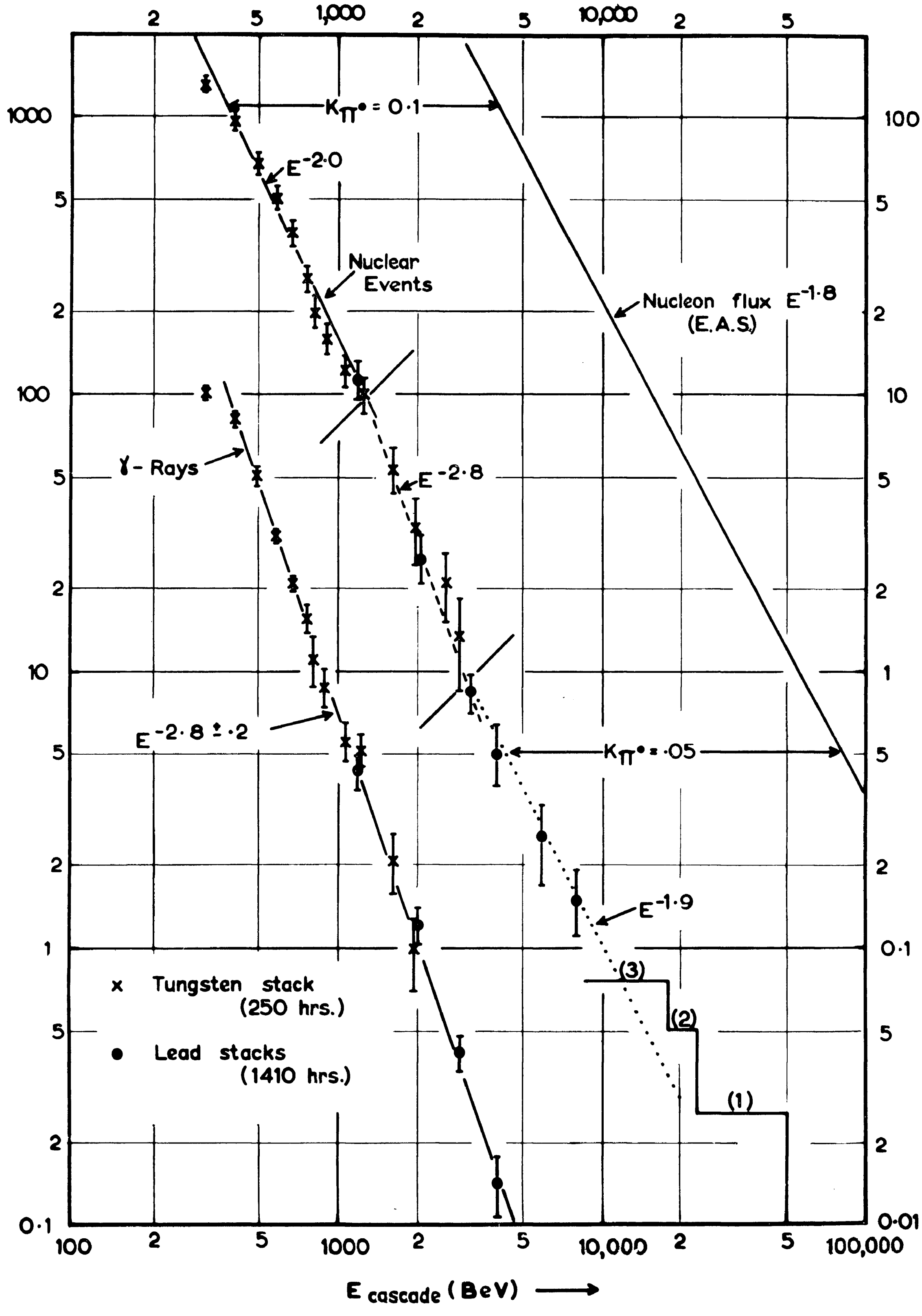

Fig. 4 Integral spectrum of cascades in Comet stacks (depth of 220 g/cm^2). The abscissa on the left indicates (vertical γ ray flux)$\times 10^8$ cm^{-2} sec^{-1} ster^{-1}; on the right, the vertical flux of nuclear particles (in the same units) capable of giving cascades of energy greater than E.

Table I. Relative efficiency of transformation into muons and γ-rays for various particles

Decay mode	Weighting factor	Decay prob.	$\frac{E_{max}}{E}$	$\frac{E_{min}}{E}$	Spectrum factor	Contribution to flux for $\beta=2$
$\pi^\pm\to\mu^\pm+\nu$	$N_{\pi^\pm}$	f_π	1	0.57	$\frac{1.9}{\beta+1}$	$0.63 f_\pi N_{\pi^\pm}$
$K^\pm\to\mu^\pm+\nu$	$\sim{}^2/_3 N_{K^\pm}$	$f_K \sim 7 f_\pi$	1	0.05	$\frac{1.05}{\beta+1}$	$1.61 f_\pi N_{K^\pm}$
$K^0{}_1\to 2\pi\to 2\mu$	${}^1/_3 N_{K^\pm}$	f_π	0.92	0.08	$\frac{3.8}{(\beta+1)^2}$	$0.13 f_\pi N_{K^\pm}$
$\pi^0\to 2\gamma$	${}^1/_2 N_{\pi^\pm}$	1	1	0	$\frac{2}{\beta+1}$	$0.33 N_{\pi^\pm}$
$K^0{}_1\to 2\pi^0\to 4\gamma$	${}^1/_6 N_{K^\pm}$	1	0.92	0.08	$\frac{3.8}{(\beta+1)^2}$	$0.070 N_{K^\pm}$
$\Lambda^0\to\pi^-+p$ ↓ μ^-	${}^2/_3 N_{\Lambda^0}$	f_π	0.24	0.06	$2.5\frac{(0.24)^\beta}{(\beta+1)^2}$	$0.011 f_\pi[N_{\Lambda^0}+0.88N_{\Sigma^0}+1.47N_{\Xi^0}]$
$\Sigma^+\to\pi^++n$ ↓ μ^+	${}^1/_2 N_{\Sigma^0}$	f_π	0.35	0.04	$2.1\frac{(0.35)^\beta}{(\beta+1)^2}$	$0.015 f_\pi N_{\Sigma^0}$
$\Sigma^-\to\pi^-+n$ ↓ μ^-	N_{Σ^0}	f_π	0.36	0.04	$2.1\frac{(0.36)^\beta}{(\beta+1)^2}$	$0.031 f_\pi N_{\Sigma^0}$
$\Xi^-\to\pi^-+\Lambda^0$ ↓ μ^-	N_{Ξ^0}	f_π	0.25	0.04	$2.4\frac{(0.25)^\beta}{(\beta+1)^2}$	$0.016 f_\pi N_{\Xi^0}$
$\Lambda^0\to\pi^0+n$ ↓ 2γ	${}^1/_3 N_{\Lambda^0}$	1	0.24	0.06	$2.6\frac{(0.24)^\beta}{(\beta+1)^2}$	$0.0056[N_{\Lambda^0}+0.88N_{\Sigma^0}+1.47N_{\Xi^0}]$
$\Sigma\to\gamma+\Lambda^0$	N_{Σ^0}	1	0.12	0	$\frac{(0.12)^\beta}{\beta+1}$	$0.0048 N_{\Sigma^0}$
$\Sigma^+\to\pi^0+p$ ↓ 2γ	${}^1/_2 N_{\Sigma^0}$	1	0.35	0.04	$2.3\frac{(0.35)^\beta}{(\beta+1)^2}$	$0.015 N_{\Sigma^0}$
$\Xi^0\to\pi^0+\Lambda^0$ ↓ 2γ	N_{Ξ^0}	1	0.26	0.04	$2.4\frac{(0.26)^\beta}{(\beta+1)^2}$	$0.018 N_{\Xi^0}$

In three of these, the disintegration was one km away, so that $\sim$30 gm/cm^2 or 0.6 radiation lengths of air intervened. In each case the stack was peppered by the secondaries. Two of the other cases occurred in the packing material, and one in the emulsion itself. Fig. 5 shows a plan of the stack; both structure and fine structure are observed. The very close multiplets of γ-rays or electrons can be attributed to electromagnetic processes, since $P_\perp$ relative to each other is $\sim$1 MeV/c. Such subdivision is often to be expected. In those three cases the energy spectrum of the γ-rays has been measured, over a factor of 10 in energy, and the result can be expressed for each star as

$$dN \approx \frac{2d\varepsilon}{\varepsilon^{1.5}}, \text{ where } \varepsilon = E/E_{max}$$

and E_{max} is the energy of the highest energy γ-ray. Integration of this expression gives an average value of eight, for the number of γ-rays for which $0.1<\varepsilon<1$. There is some selection bias towards high multiplicity in these families, which is difficult to evaluate, but an approximate fraction of all high energy γ-rays were to be found in these three showers. We will use this formula in trying to determine the nature of the primary of the next event I wish to discuss.

This last event was found, very recently, in a balloon flight exposure—it caused us great excitement. It appears that 600 particles were created in the disintegration. Fig. 6 (see plate following p. 830) shows four views of the early stages of development. The large multiplicity of γ-rays is readily visible.

We can measure the convergence of these γ-ray cascades and the shower particles readily. It is

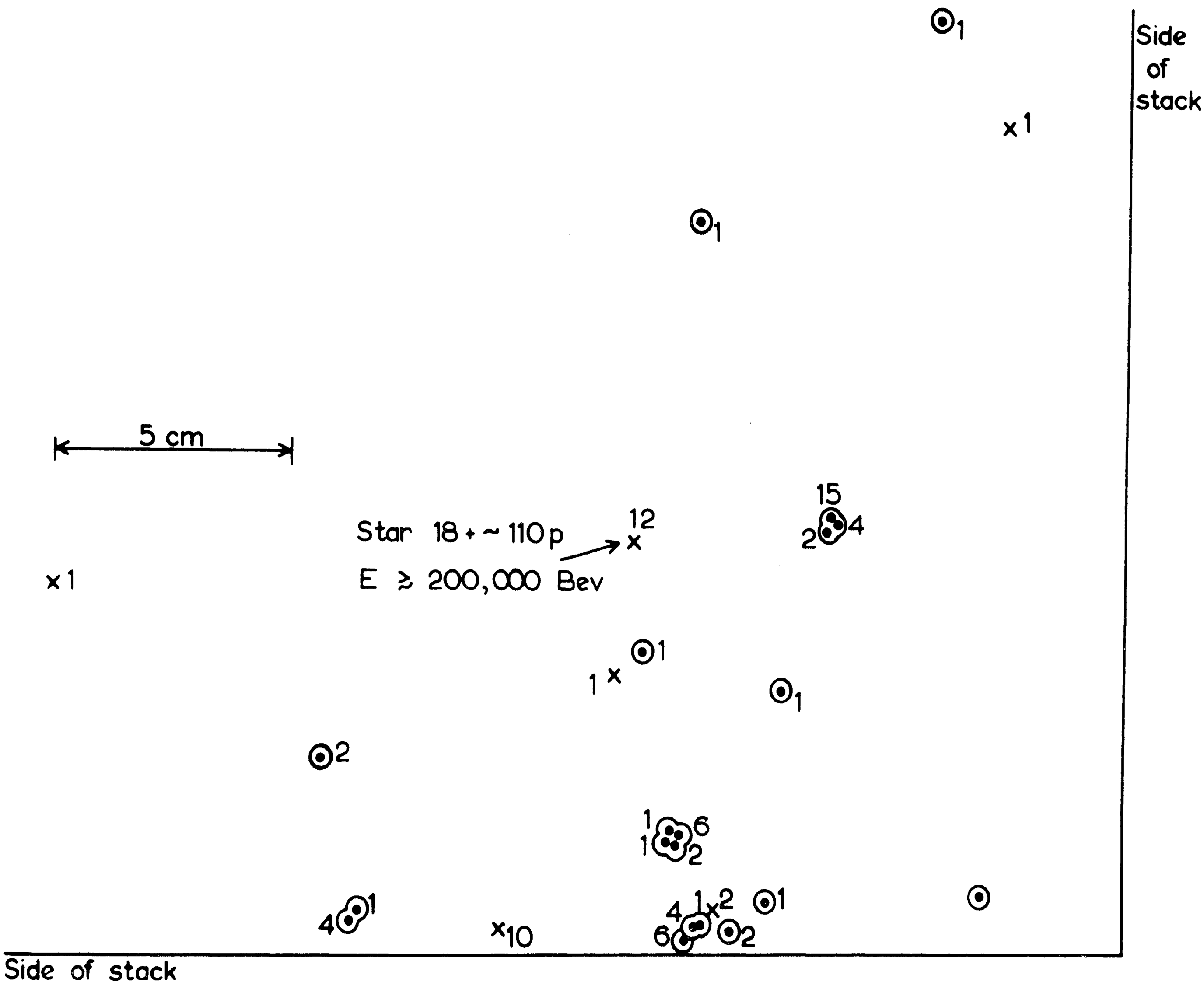

Fig. 5 Structure of " family " in Comet I. The crosses indicate nuclear events, circles electromagnetic cascades. The energy of the cascades is given in units of 10^3 BeV. The total energy in electromagnetic cascades intercepted by the stack is about 90,000 BeV.

clear that they all—or nearly all— had a common origin at a point ~35 cm from the edge of the stack in the aluminum sphere which surrounded the plate assembly which was ~ 1 mm thick!

We have measured the track density photometrically 300 microns off axis and so obtain a figure of ~250,000 BeV for E_γ. We scanned for shower particles and individual γ-rays to a depth of 1.9 conversion lengths, out to an angle of 2.5×10^{-3} radians. We found 137 γ rays, (which upon correction for the depth to which we carried the scan becomes 155), and 202 shower particles. Fig. 7 gives their angular distributions.

There are several deductions we can make:

(1) The number of $K^\pm$, $p^\pm$ etc. was $202-155=47\pm20$ in the forward hemisphere of the c.m. system. That is 20% of all particles, a figure which agrees with that obtained before in emulsion work at the lower primary energies of ~10^{12}-10^{13} eV. In this case, though, it is clear that these particles must be " created " particles since the target nucleus was only aluminum.

(2) $P_\perp$ for the γ-rays was ~300 MeV/c, again a figure very similar to the 30 BeV and 10^3 BeV data. This figure is obtained from a comparison of the

angular distribution of the γ-rays to the estimate of their total energy content.

(3) Taking 600 MeV/c for $P_\perp$ for the shower particles, we estimate their energy content as $\sim 8 \times 10^5$ BeV, and have that the total energy radiated was $\sim 10^6$ BeV.

(4) The value for $\gamma_{c.m.}$ is not very certain, but appears $< 10^3$, as that $E_p < (2 \times 10^6)$ BeV/c. We may get a coarse estimate of the number of primary nucleons that might have been involved in the collision from comparison with the " family's " spectra, taken at $\ll 220$ gms/cm^2 where heavy primaries are not present. In these cases ~ 8 γ-rays are found for which $0.1 < \varepsilon < 1$; here we have 13, for which $1 < \theta/\theta_{min} < 0.1$, which suggests that few primary nucleons were involved. Further if a heavy primary ($Z \geq 6$) were involved, the protons would have to have received values for $P_\perp \gtrsim 10$ BeV/c, since no central core of unresolved tracks was found.

On balance we feel that the primary was most probably an α-particle with an energy $\sim 5 \times 10^5$ BeV/c, which produced in all about 600 secondary particles, and the collision was very inelastic.

(5) We see that the angular distribution agrees very well with Heisenberg's theory, and in particular it shows no double hump for either γ-rays or shower particles in spite of its large energy. The full curve is a Gaussian curve with $\sigma \approx 0.8$. For such a value of σ pronounced double humping with a peak to valley ratio ~ 3 is expected on the two-center model.[2]

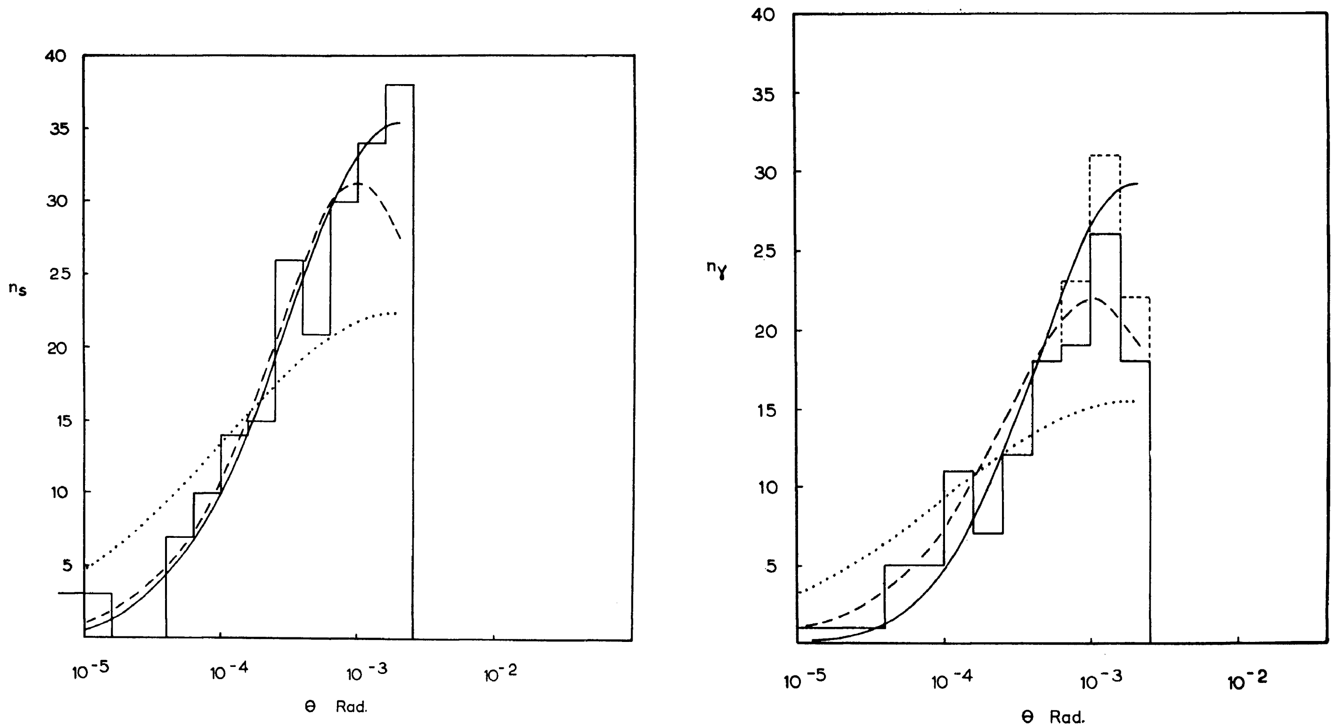

Fig. 7 " Texas Lone Star ". At left is shown the distribution of shower particles with angles less than $10^{-2.6}$ radians, and at right similar distributions for γ-rays. The dashes indicate the distributions predicted by Heisenberg's theory, the dots the distributions predicted by Landau's theory for n-n collisions.

LIST OF REFERENCES AND NOTES

1. Greisen, K. " Progress in Cosmic Ray Physics ", Vol. III (North Holland Publishing Company, Amsterdam), (1956).
2. Gierula, J. (This Session.)

DISCUSSION

VEKSLER: The Dubna group at Kiev and also at this conference noticed that there is a very steep rise in the K production cross section which appears to begin in the region of several BeV. There may be an apparent difficulty in explaining these results because if the steep rise of the cross section takes place at very high energies, one of the main channels would be this high energy K-pair production. So the question I would like to ask is the following: is there any possibility of getting some idea about that part of the cross section which is due to K-pair production at these very high energies?

FOWLER: In our experiment I cannot think of any way, but I would make this point, that in this analysis we assume that the gamma rays all come from π^0 mesons and if this is not true, then whatever follows from it is unlikely to be tιue.

TICHO: I wonder if Fowler would like to comment on the relative amounts of π's and K's on the basis of the high energy muon spectrum.

FOWLER: If the measurements are taken at their face value we do not ιequire an immense number of K's; we just require that their energy content be large, say about twice that of the π's, and then, because of the more favorable decay probabilities for the K's at a given energy, this contribution will be sufficient. That is to say, peιhaps only twice as many K's as π's above a given energy when you fold in the whole cosmic ray primary energy spectrum, would give at sea level a predominance of muons formed from K decay as compared to π decay which is the usual accepted mode of origin.

VON DARDEL: I just want to remind you that already at 25 BeV the K production cross section is about 25% of the corresponding π cross section and it could well be that at the high energies of Fowler it could be even more comparable with the π production cross section.

FOWLER: I am very encouraged by that, but I still repeat that you have to fold in the cosmic ray energy spectrum and what determines the K meson energy spectrum predominantly is the manner in which the cross sections change with energy.

APPENDIX TO SESSION P2

Papers contributed to the Conference but not presented

PARTICLE ABUNDANCES IN INTERACTIONS WITH 25 GeV PROTONS

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The 25 GeV internal proton beam of the CERN proton synchrotron is, at the end of the acceleration cycle, made to interact with a thin aluminum flip target. The strong focusing property of the machine will keep the protons in orbit in spite of multiple scattering and energy loss in the foil until a major fraction, about 50%, of the protons have interacted with the aluminum nuclei. Secondary particles will be emitted from the foil. The energy and angular distribution of these particles is of importance for planning further experiments with the machine. Several exploratory investigations [1, 5] have been made, during the initial operation period of the machine, on the secondary beams at various angles of emission.

A detailed theory of the production process, even for the simpler case of a *p-p* collision, does not exist at present. Statistical theory [2] can however be used as a guide for the energy distributions and composition of the secondary particles from this interaction. Von Behr and Hagedorn [3] have carried out calculations with this model for 25 GeV *p-p* collisions, and have given the laboratory production spectra at various angles for the different secondary particles.

The present measurements have been done on secondary beams leaving the synchrotron at angles of 6° and 3° with respect to the internal beam. Due to the deflection of the particles in the fringing field the angles of emission in the " 6° " beam, range from 6.1° to 6.3° for positive particles and from 5.9° to 4.8° for negative particles between 24 and 5 GeV/c. The " 3° " beam contains only positive particles with an angle of emission increasing from 3.4° at 24 GeV/c to 5° at 6 GeV/c. For the present discussion we will neglect these small variations in emission angle.

The beams were momentum analyzed by a 2.4 meter bending magnet and the velocity determined with a velocity selective gas Čerenkov counter of high resolution [4]. Since the Čerenkov counter has very nearly 100 per cent efficiency the ratio between quadruple coincidences $S_1S_2S_3C$ with a triple counter telescope and the triple coincidences in this telescope $S_1S_2S_3$ gives directly the abundance of particles of the selected velocity in the beam.

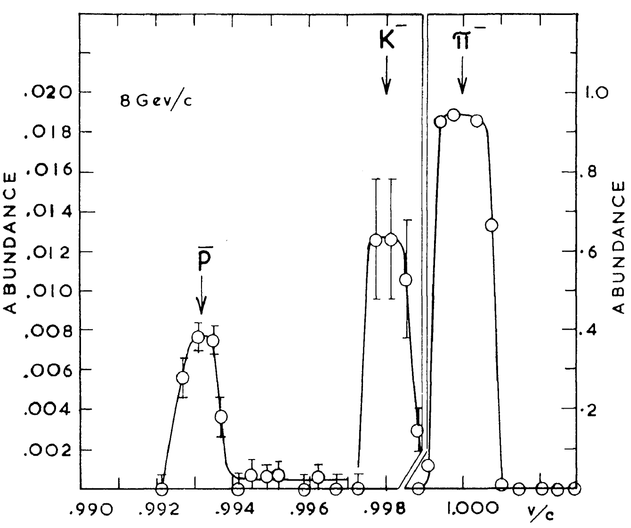

Fig. 1 Velocity spectrum of 8 GeV/c negative particles emitted at 6° from the CERN proton synchrotron.

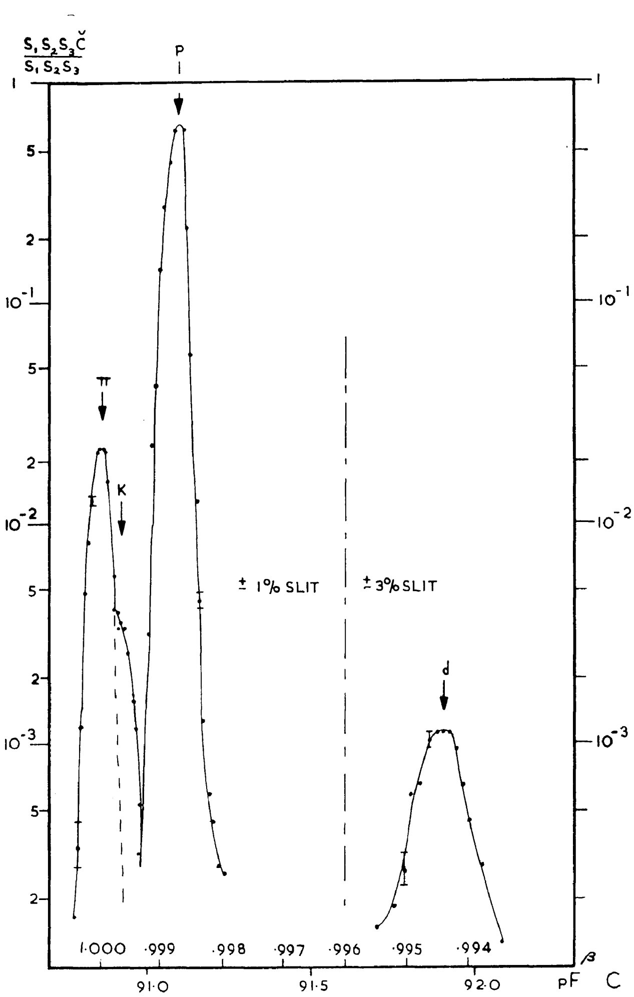

Fig. 2 Velocity spectrum of 18 GeV/c positive particles emitted at 3°.

Typical velocity spectra are shown in Fig. 1 for an 8 GeV/c negative beam and in Fig. 2 for an 18 GeV/c positive beam. *K*-mesons and heavier particles are completely resolved while pions, muons and electrons merge together into a single peak.

The momentum band defined by the magnet and geometry is associated with a velocity spread of the particles. As long as the velocity band selected by the Čerenkov counter is wider than the velocity spread the peak in the velocity spectrum will have a flat top, which directly indicates the abundance of the particle in the beam. For heavy particles the velocity spread is often wider than the resolution curve and the peak will be lower and broader. The abundance may then be determined by comparing the area of the peak with the corresponding area for a particle of known abundance.

The abundance measured in this way refers to the beam at the last counter of the experimental set-up. To obtain the beam composition at the target the data were corrected for decay of *K*-mesons along the beam. No correction for interactions in the counters and in the air along the path were made. The pion abundance was not corrected for decays, since the decay angles are so small that most of the decay muons will stay in the beam and be recorded as if they were pions.

The momentum spectrum of the positive pion component in the 3° beam is shown on an arbitrary scale by the crosses in Fig. 3. The trend of the experimental points agrees well with the prediction of statistical theory [3] normalized to the experimental value at 10.2 GeV/c. A comparison not only of the trend but also of the absolute intensity would neces-

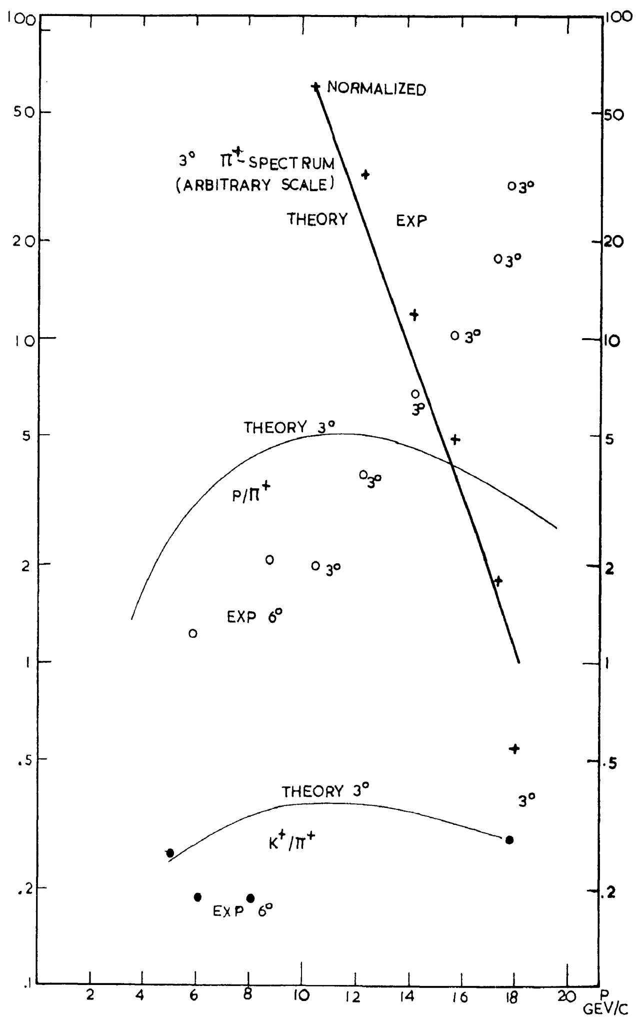

Fig. 3 Crosses: the measured π^+ momentum spectrum; the full curve is the theoretical spectrum, normalized to the experimental point at 10.2 GeV/c.
Open circles: measured p/π^+ ratio in beams at 6° and 3°.
Full circles: measured K^+/π^+ ratio. The curves are the predictions of the statistical theory for 3° laboratory angle.

sitate an accurate knowledge of the number of circulating protons in the synchrotron, of the target efficiency and of the solid angle and momentum band of the channel. Other investigations [5] also show that the pion production is fairly accurately accounted for by the statistical theory.

The measured proton-pion ratio, (Fig. 3, open circles) indicates a large excess of protons above 14 GeV/c and a smaller deficiency of protons below this energy, compared to the statistical theory. We believe this discrepancy to be due to the protons which suffer peripheral collisions, not accounted for by the usual statistical theory, and which lose less than half of their initial energy.

The measured K^+/π^+ ratio (Fig. 3, full circles) is 0.2-0.3, almost independent of the momentum, in the range 5 to 18 GeV/c. In the negative 6° beam the K^-/π^- ratio was measured as 0.066 ± 0.020 at 5 GeV/c, 0.054 ± 0.007 at 6 GeV/c and 0.039 ± 0.007 at 8 GeV/c. For *K*-mesons of both signs the predictions of the statistical theory are in fair agreement with these results, if the interaction volume for processes involving *K*-mesons is taken as 1/5 of the ordinary pion-nucleon interaction volume. If the K^+/K^- ratios of 3-5 measured at 6° between 5 and 8 GeV/c are representative, most of the K^+ production is associated with hyperons and only a smaller fraction is due to pair production of *K*-mesons, even at 25 GeV.

The antiproton to pion ratio at 6° was measured as 0.014 ± 0.002 at 6 GeV/c, 0.0075 ± 0.0008 at 8 GeV/c, 0.0028 ± 0.0006 at 11 GeV/c and 0.0028 ± 0.001 at 16 GeV/c. The statistical theory predicts much higher $\bar{p}/\pi^-$ ratios, ranging between 0.4 at 16 GeV/c and a maximum of 0.8 at 10 GeV/c, in direct production of antiprotons. In addition the decay antiprotons from antihyperons for which the statistical theory predicts a copious production will increase these values by a factor of two over most of the momentum range. Von Behr and Hagedorn [3] discuss factors which may decrease the high predicted antiproton production. Reannihilation of antibaryons in a final state interaction after the *p-p* collision has already been taken into account in the calculations. For interactions in nuclei the probability for annihilation with other nucleons in the nucleus should be strongly dependent on the atomic weight of the target nucleus. Since no difference in antiproton abundance at 7 GeV/c was measured between an aluminum and beryllium target, we believe the annihilation in the target nucleus to be small at our energies.

The measurements at 18 GeV/c, Fig. 2, and at 10 GeV/c, show deuterons to be present at these higher energies as well as in the lower energy beams investigated previously [1] by Cocconi et al. The d/π^+ ratio is 0.05 at 18 GeV/c in good agreement with the prediction of a statistical theory in which the deuteron is regarded as an elementary particle, synthesized directly in the *p-p* interaction.

We wish to express our gratitude in particular to the machine group of the CERN proton synchrotron, which by its wholehearted cooperation made the measurements possible.

LIST OF REFERENCES AND NOTES

1. Cocconi, V. T., Fazzini, T., Fidecaro, G., Legros, M., Lipman, N. H. and Harrison, A. W. Phys. Rev. Letters **5**, p. 19 (1960).
2. Milburn, R. Rev. Mod. Phys. **27**, p. 1 (1955); Hagedorn, R. Nuovo Cimento **15**, p. 434 (1960).
3. von Behr, J. and Hagedorn, R. CERN Report 60-20 (1960).
4. Mermod, R., von Dardel, G., Weber, G. and Winter, K. (Submitted for publication in Nuclear Instr. and Meth.)
5. Cocconi, G. (Session P2.)

PION CLOUD EFFECTS IN HIGH ENERGY MESON PRODUCTION

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A rather general point of view as to the mechanism of high energy meson production has emerged out of the following experimental data obtained in our laboratory and in collaborations. High energy nuclear collisions were recorded in five emulsion stacks. (A) irradiated by the internal 9 BeV proton beam at Dubna, (B) irradiated by a 7.3 BeV negative pion beam, (C), (D) and (E) exposed in the stratosphere over Italy.

In stack (A), 500 and stack (B), 152 meson showers of at least three shower particles from light nuclei were recorded by area scanning and their angular distribution was analyzed in Duller-Walker coordinates. The same analysis was performed on 78 high energy nuclear jets recorded in Prague by cascade scanning in stack (C) and on 53 jets produced by heavy primaries found in our laboratory by re-scan for alphas and along the track scan for heavier primary nuclei in stacks (C), (D) and (E). In (A) and (E) individual estimates for the c.m.s. Lorentz factor were obtained. Their spectra yielded the range of effective target masses and proved the occurence of collisions involving individual pions in the meson clouds of the collision partners. Individual dispersions estimated for the showers demonstrate the occurrence of significantly non-isotropic angular distributions with a bimodal shape typical for two-center jets. The same bimodal structure appears in the high energy nucleon jets and in 22 beam-induced jets also. The following simple model accounts for most of the regularities of the two-center structure. A considerable fraction of nucleon-nucleon interaction can be reduced effectively to a pair of quasi-independent nucleon-pion collisions. Each of these collisions gives rise to a highly excited emitting center. The Lorentz factors of the two centers in the laboratory frame and the Lorentz factor of relative motion in their common c.m.s. are then increasing functions of the primary energy. This implies increasing anisotropy of meson showers as a function of energy with saturation above several hundred BeV. An additional spurious increase of anisotropy beyond this saturation limit comes from the non-monoenergetic spectrum of secondaries in the rest system of the emitting centers. Expected and observed values of the ratio of laboratory frame Lorentz factors of the two centers are as follows: for 9 BeV protons expected ratio 4.0, observed 3.8 ± 1.2. Heavy primary nuclei, average energy about 700 BeV, ranging up to 10,000 BeV, expected ratio 6.67, observed 6.61 ± 0.7. In interactions with complex nuclei central collisions lead to additional maxima in the angular distribution. These maxima have been observed at the correct location in nine jets induced by heavy primary nuclei of relatively high charge in heavy emulsion nuclei. No such events were observed above 1,000 BeV. It appears that in high energy interactions leading to multiple meson production, nuclear matter does not behave in a continous manner, but that the individual nucleons play a major role. The unambiguous two center collisions at very high energies imply very small dimensions for the nuclear core.