a preponderance of secondary radiation, and that very few interactions at stratosphere elevations result in the formation of τ-mesons.

ACKNOWLEDGMENTS

Opportunity is taken to thank the ONR and the aeronautical staff of General Mills for the exposure and recovery of the several emulsion preparations. The casting of emulsion disks of adequate sensitivity was greatly facilitated by Dr. C. Waller of Ilford Limited through provision of a supply of G5 gel. Appreciation is expressed to Dr. M. M. Shapiro for many helpful discussions of meson production mechanisms, and for providing space in the gondola on several balloon flights.

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Emulsion Cloud-Chamber Study of a High Energy Interaction in the Cosmic Radiation*

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A new technique is described for studying high energy interactions utilizing photographic emulsions as detectors. A detailed study has been made with this technique of one very high energy mixed shower. Evidence is obtained for the multicore structure of the soft component at depths of several radiation lengths in this mixed shower, along with the existence of a finite lifetime for the decay of the neutral π-meson into two photons of the order of 1×10^{-14} sec.

High energy nuclear interactions lead to the production of mixed showers of mesons, nucleons, and electronic components. Such interactions with energies above 10^{12} ev have been previously studied both by observing the resultant electronic and nucleonic cascades in Auger showers and by directly observing the primary interactions in the photographic emulsions. Observations on Auger showers are necessarily indirect. While on the other hand the photographic plate allows a detailed study of the primary interaction to be made as to distribution and multiplicity, the energies of the products cannot be determined, and the primary energy can only be approximately estimated from kinematic considerations. Hitherto, such events have very rarely been found and only in the course of random surveys.

We have made observations with a technique which allows a much more detailed study to be made of the interactions, and at the same time permits the events to be found with relative ease. The events are observed in a so-called emulsion cloud chamber consisting of alternate layers of photographic emulsions and absorber. An interaction in the stack starts a mixed shower. The plates near the interaction show just the charged mesons and nucleons formed in the primary interaction. Later in the stack the electronic component begins to multiply and form well-marked electronic cores. From these cores and their degree of multiplication can be determined the numbers, and energies of the neutral mesons resulting from the initial interaction. It is further possible to measure the lifetime of the neutral mesons from the finite path lengths they transverse at high energies. To find such an event, one of the emulsions in the emulsion cloud chamber is scanned for high energy electronic cores. If the plates are well aligned it is possible to predict the position of a core in succeeding and preceding plates and thus trace the event back to the first plate in which it appears; this plate is usually near the origin of the shower and the tracks reproject back to the point of origin.

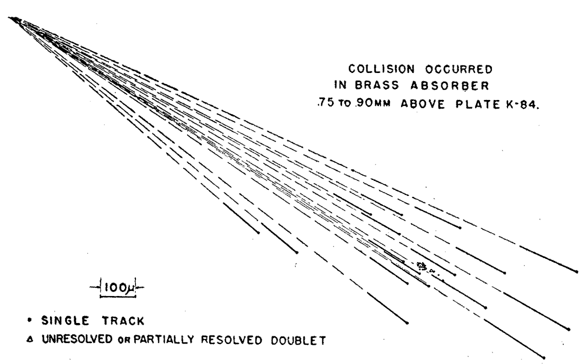

Fig. 1. Target diagram of hard shower in first plate (plate 8) showing reprojection of tracks to a common origin.

One important advantage of this technique over cloud-chamber techniques is the high resolution of the photographic plate in which tracks are resolved within $\frac{1}{2}\mu$ and cores of electronic showers can be resolved which would completely "swamp" a cloud chamber and permit no detailed structure to be discernible.

The energy range for which the technique is applicable depends on the material of which the stack is constructed. The core of an electronic shower does not show above the background of random tracks in the experiment described below unless its energy is in excess of 10^{11} ev. If we had used a stack exclusively of photographic plates, this limit would have been about 5×10^{12} ev; with high Z materials the limit would have been as low as 10^{10} ev.

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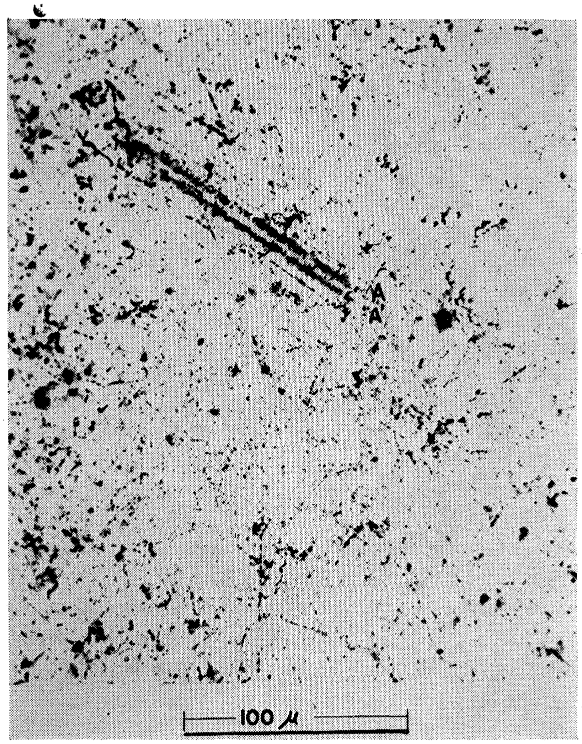


FIG. 2. Microphotograph of main target area in plate 15, 2.7 radiation lengths from origin of shower. The two resolved electronic cores AA' are believed to originate from the decay of a neutral meson into two photons. The photograph is a single shot in one focal plane taken with a ×20 objective.

We describe in the following section the application of this technique to measurements of a high energy interaction, the so-called T-star.

EXPERIMENTAL

The apparatus used has been described previously.[1] It consisted of a stack of twenty 6 in.×4 in. 100-μ Ilford G5 emulsions each separated by a 3-mm brass plate. The effective radiation length from emulsion to emulsion in this stack calculated for the mixture of materials used was 2.4 cm. The T-star started in the brass plate above plate 8 and was inclined at such an angle that it traversed 0.94 cm or 0.39 radiation lengths, from one plate to the next. The cores can be followed through to plate 20, thus covering a total of 4.7 radiation lengths in the stack.

Figure 1 shows the target diagram of the first plate on which the event is found. The coordinates of the entrance and exit points of the tracks into the emulsion were found from the stage motions of the microscope, and are plotted on the diagram. Figure 1 thus shows the projections of the tracks in the emulsion on the plane of the glass. It will be noted that there are 36 minimum ionization tracks about half of which are in a wide core, and half in a narrow core, and that the tracks clearly project back to a single origin. The origin lies about 0.1 cm back in the brass or 0.06 of a radiation unit. Further down in the stack rapid cascade multiplication occurs and various cores become visible. Later these cores begin to "wash" one into the other, and resolution between the cores is lost.

Plate 7 was scanned for the primary which caused the interaction. One track of minimum ionization with the right length, direction, and position was found, but no tracks of greater ionization were found. With the background of random minimum tracks, we are not certain that the interaction was caused by a charged primary, but we can be sure that the charge of the primary was less than two.

Figure 2 is a microphotograph of part of the target area of plate 15, 2.7 cascade units from the origin of the shower; the most striking feature is the two very close electronic cores marked A and A'. These cores which under higher magnification consist of bundles of minimum ionization tracks can first be seen resolved on plate 14 and can be traced through to plate 18. On plates 19 and 20 the cores are no longer resolved. Figure 3 shows a microphotograph of plate 20. The region of high density marked AA' corresponds to the double cored structure on plate 15, now no longer resolved. In addition a new barely resolved double-cored structure

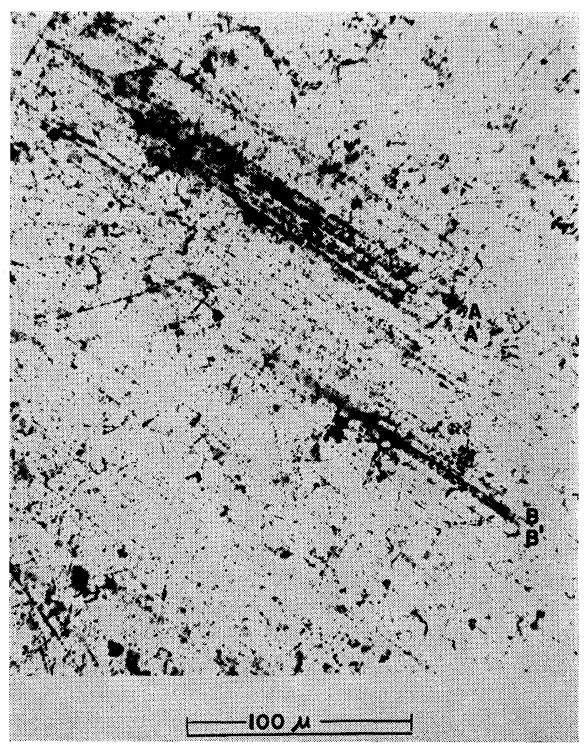


FIG. 3. Microphotograph of main target area in plate 20, 4.7 radiation lengths from origin of shower. The region AA' represents the now unresolved cores AA' of plate 15 and the barely resolved cores BB' represent the soft showers from the decay of a more energetic neutral meson. The photograph is a single shot in one focal plane taken with a ×20 objective.

[1] M. F. Kaplon *et al.*, Phys. Rev. **85**, 295 (1952).

can be seen to the left of the main core. This second double core BB' is first visible on plate 17 and is unresolved on plates 17, 18, and 19.

In addition to these well-marked cores we can distinguish eight other cores of smaller density which are resolved on three or more plates. In order to make energy estimates, we made counts of the numbers of tracks within 25μ and 50μ of the shower axis on each core.

Most of the cores are not resolved from the over-all background. After plate 15, AA' and BB' are resolved from other cores down to plate 20 and another core is resolved until plate 17. The cores only resolved to plate 15 contained about ten tracks in a twenty-five micron radius on plate 15. The core resolved down to plate 17 contained twenty-six tracks. AA' contained forty tracks on plate 20, and BB' contained thirty-four tracks on plate 20 within a twenty-five micron radius.

INTERPRETATION

a. Lifetime of the Neutral Meson

In the previous section two double-scored showers, AA' and BB', were described. These showers are of higher energy and appear to start later in the stack than the other γ-rays that materialize. We interpret these showers as a result of neutral mesons that have decayed after a finite path length each into two photons.

Shower AA' first appears on plate 12, and is resolved on plates 14–18. The separations on the various plates can be measured and the cores reprojected back to the point of the origin. The origin appears to be between plates 10 and 11, about 2.5 cm from the primary interaction. The energy of the shower can be estimated in two ways. The angle between the two photons emitted by a neutral π-meson of mass μc^2 and energy $\mu c^2\gamma_0$ is given by

$$\sin\tfrac{1}{2}\theta = (1/2\gamma_0)(r^{\frac{1}{2}}+r^{-\frac{1}{2}}),$$

where r is the ratio of the energies of the two γ-rays. θ can be directly measured and r estimated from the ratio of the numbers of electrons in the two cores: r is from 2:1 to 5:1 and $\theta = 2.1\times10^{-4}$ radian. This gives an energy for AA' of $1.4-1.8\times10^{12}$ ev.

A less reliable estimate can be made from cascade theory. We have calculated on the basis of the structure function of Fernbach and Eyges[2] and the electron spectra,[3] the expected number of particles for various depths and primary energies. On this basis, the shower has an energy of 4×10^{12} ev. The behavior of the structure function is not well known at the origin, and we therefore believe that the value of 1.5×10^{12} ev is more reliable and that the cascade calculations should be changed by a factor of the order of two to give agreement with experiment. The path length of 2.5 cm and the energy of 1.6×10^{12} ev leads to a lifetime in the rest frame of the neutral meson of $\tau_0 = 7\times10^{-15}$ sec.

Shower BB' is only resolved on one plate and cannot therefore be projected back. It is first seen on plate 17. An estimate from cascade theory leads to a higher energy for this shower relative to AA' of the order of two. The most probable point of decay of the neutral meson is half a cascade unit from plate 17. Using this value, the opening angle is 1.35×10^{-4} radian and hence the energy is 2.4×10^{12} ev. The distance traversed by the neutral meson is 7 cm before decaying, leading to a lifetime of 13×10^{-15} sec.

Other explanations are possible: (1) The two photons arising from the neutral meson decay at the point of interaction failed to convert until plate 17. The probability for this is $1:10^3$. (2) The BB' neutral meson was formed in a second interaction. This neutral meson is the highest energy observed in the shower. It would seem difficult for a secondary interaction to produce higher energies than the primary. The primary produces besides AA', eight other cores. No cores other than BB' start after plate 17. We therefore believe that we are observing the delayed decay of a neutral meson with lifetime 1×10^{-14} sec.[4,5]

b. The Energy Balance and Spectrum of Neutron Mesons in the Core

In Sec. a, we have given energies for showers AA' of 1.6×10^{12} ev and BB' of 2.4×10^{12} ev. Using the cascade theory modified by the factor of two (see preceding section) a shower core of 5×10^{11} ev can be recognized and about seven cores with energies of the order of 10^{11} ev-3×10^{11} ev. The neutral meson spectrum is thus consistent with one neutral meson of 2.4×10^{12} ev, one of 1.6×10^{12} ev, one of $6-8\times10^{11}$ ev, and about four of energies $2-4\times10^{11}$ ev. An examination of isolated pairs outside the core within an opening angle of 0.03 radian on plate 9 (average separations 5μ) leads to an average energy of 2.5×10^{10} ev for the photons[6] and thus an average energy of 5×10^{10} ev for the neutral mesons outside the core. Adding this contribution for ten neutral mesons outside the core to the previous energies in the core we find the total energy in the soft component is thus 6×10^{12} ev. Using a 2:1 partition between the charged and neutral meson component (see Sec. c) the total energy is 1.8×10^{13} ev.[7]

[2] S. Fernbach, Phys. Rev. **82**, 288 (1951).

[3] L. Janossy and H. Messel, Proc. Roy. Irish Acad. **54**, 31 (1951).

[4] H. L. Bradt *et al.*, Helv. Phys. Acta **23**, 24 (1950); A. G. Carlson *et al.*, Phil. Mag. **41**, 701 (1940); and J. J. Lord *et al.*, Phys. Rev. **80**, 970 (1950). Bradt gives $\tau_0 \leq 3\times10^{-13}$; Carlson gives $\tau_0 \leq 5\times10^{-14}$ and Lord gives $\tau_0 \leq 2\times10^{-15}$.

[5] This is to be contrasted with the theoretical prediction for the *PS-PV* theory which gives $\tau_0 = 0.3\times10^{-17}/(g^2/\hbar c)\cdot(g^2/\hbar c \sim \frac{1}{4})$. J. Schwinger, Phys. Rev. **82**, 664 (1951).

[6] H. L. Bradt *et al.*, Helv. Phys. Acta **23**, 24 (1950). See definitions and formula 2a.

[7] If nucleons and antinucleons are also produced in the interaction, this energy estimate could be raised as a result of the presence of non-ionizing nucleonic component.

The energy of the star can also be estimated from kinematic considerations. If the mesons and nucleons are formed in a single collision symmetric about the 90° line in the c.m. system, we have the following relation between the laboratory angles θ_f containing a fraction f of the particles, θ_{1-f} containing a fraction $1-f$ and $\bar{\gamma}$ the energy in units of the rest mass of a nucleon in the c.m. system.[6]

$$\bar{\gamma}^2 = 1/\theta_f \theta_{1-f}.$$

The approximation is made that the particles in the c.m. system have moderate velocities. Figure 4 shows θ_f plotted against f. The curve appears symmetric about $f=0.5$. Taking the value corresponding to $\theta_{0.5}$, which has the highest statistical weight, gives $\bar{\gamma}=50$ or an energy of 6.5×10^{12} ev. The accuracy of such a determination depends on two assumptions, the validity of assuming a single nucleon-nucleon collision, and the statistical accuracy inherent in determining $\theta_{0.5}$ with thirty-six tracks. By assuming a Poissonian fluctuation. the experimental value of $\theta_{0.5}$ can correspond to theoretical values of $\theta_{0.5\pm0.08}$, thus giving an error in the energy determination of a factor of 4. The opening angle is thus consistent with energies from $1.6\times10^{12}-2.6\times10^{13}$ ev.

We assume that the estimate from the energy balance 1.8×10^{13} ev is correct. If the angular distribution was the result of plural processes, and energetic neutral mesons had escaped detection by decaying outside the stack the energy might be higher.

c. Charged Particles to Neutral Meson Rate

In plate 8, any γ-rays formed directly in the primary interaction[8] and from the decay photons from slow neutral mesons have not as yet materialized, the shower starting 0.06 radiation units back. A count on this plate gives a total number of thirty-six charged particles. We considered an area enclosing the primary core containing twenty-five tracks in plate 8 and scanned the corresponding area on plate 9 for minimum ionization tracks satisfying our length and angle criteria. The number of tracks found was forty-five, an increase of twenty tracks in 0.39 cascade unit. An estimate taking into account cascade multiplication gave a total of twenty-four γ-rays at the start of the shower corresponding to twelve neutral mesons. Allowing for the finite lifetime of the neutral meson, we have to add four neutral mesons decaying further down in the stack. Thus we obtain a neutral to charged ratio of 0.6 ± 0.2.[9]

[8] R. E. Marshak, Phys. Rev. **74**, 1736 (1949). Marshak shows that the contribution of directly produced γ-rays should be negligible in such an event.

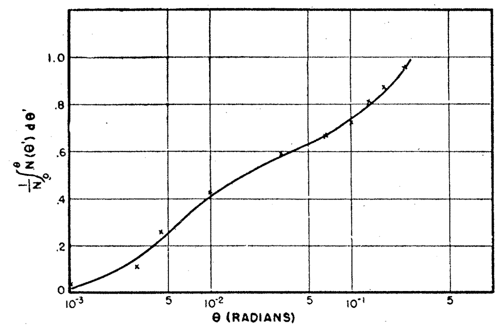


FIG. 4. Integral angular distribution in the laboratory system of the hard shower in the first plate.

DISCUSSION

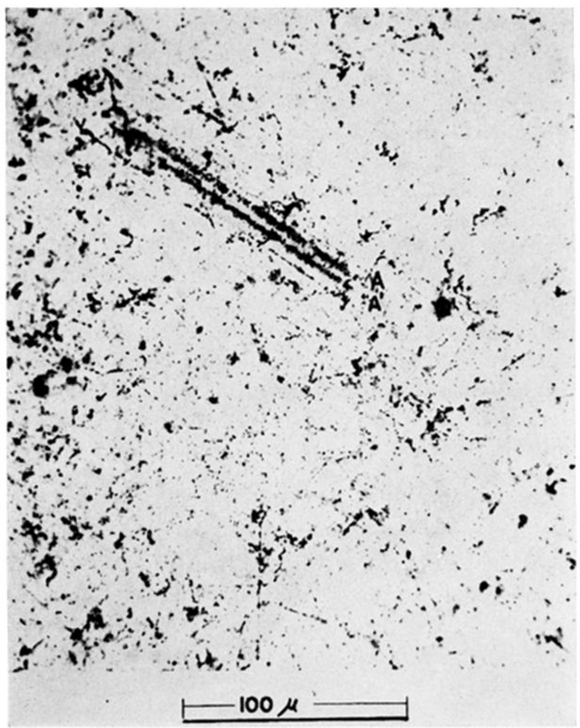
The total multiplicity of thirty-six charged particles plus approximately eighteen neutral mesons giving a total of fifty-four particles cannot be interpreted in terms of pure plural processes, even though the collision occurs in brass. An estimate based on a simple three generation model indicates multiplicities of at least four if the mesons are assumed to be interacting, and of seven if the mesons are assumed to be noninteracting.

We intend, in a later publication, to give a fuller account of our results and to compare them in detail with other experimental results available and with theoretical predictions.

We wish to thank Dr. H. L. Reynolds for his assistance in the early stages of this work and Professor R. E. Marshak for many valuable discussions.

[9] The ratio of 0.6 ± 0.2 strictly speaking, is the ratio of neutral mesons to total number of charged particles. As the charged particle beam must contain some nucleons (and possibly anti-nucleons), the ratio

$$p = N(\pi^0)/[N(\pi^+)+N(\pi^-)] > 0.6\pm0.2.$$



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