It has usually been assumed in the past that one can neglect the interaction between an electron beam, moving at a speed small compared with c, and the magnetic components of an electromagnetic wave propagating with a phase velocity near to or greater than c. We have shown that this is not always justified and that in some circumstances such as propagation in an attenuating medium, the interaction with the magnetic components is more important than the interaction with the electric components in some particulars at least.

This analysis has served once again to stress the importance of taking initial and boundary conditions into account in a discussion of propagation in an active medium.

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A High Energy Proton-Proton Collision with Associated Events

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An event observed in a nuclear emulsion is interpreted as an incident proton of energy 1000 Bev colliding with a hydrogen nucleus and producing a cone of six charged mesons. The presence of three neutral mesons is deduced from two electron pairs and one triplet in the region of the cone. The triplet is due to an electron pair produced by a gamma-ray of energy 24 Bev in the field of an electron. An additional electron pair is produced by bremsstrahlung. The kinetic energies of several particles are deduced from scattering measurements and these range from 800 Mev to 17 Bev. The total energy of the shower is estimated as 100 Bev. In the center-of-mass system the mesons have energies of the order of 400 Mev and an almost isotropic distribution. It is concluded that most of the energy is carried by two neutrons, and only one-tenth of the energy of the primary particle goes to meson production. The results are compared with the theories of multiple meson production.

I. INTRODUCTION

Most of the data published on very high energy collisions with nuclei deal with the interaction of protons, neutrons, or heavier nuclei with the light (C, N, O) and heavy (Ag, Br) groups of nuclei present in photographic emulsions, and in these cases as many as thirty minimum ionization tracks have been produced, which have been shown[1] to be mainly mesons. Some of these mesons arise from the interaction of the primary particle with a single nucleon (multiple production), but if the energy of the primary particle is distributed over a part of the nucleus plural production of mesons by interactions between many pairs of nucleons is possible. It is clear that it is of fundamental importance to the theory of meson production to study collisions of protons or neutrons with hydrogen nuclei—events which are likely to be missed in nuclear emulsions as all tracks are at minimum ionization. Very few examples of these collisions have been published. An event described by Camerini *et al.*[2] occurred near the edge of the plate, so no detailed measurements could be made. Pickup and Voyvodic[3] have found four such events, but the energies of only a few particles could be measured because the lengths of tracks in the emulsion were short. A collision of a very energetic singly charged particle with a nucleus heavier than hydrogen has been observed by Lord, Fainberg, and Schein,[4] in which, however, the mesons are most probably produced by a single nucleon-nucleon encounter.

This paper describes an event in which a singly-charged particle with an estimated energy of the order of 1000 Bev collides with a nucleus to produce a shower of seven particles at minimum ionization one of which, however, is an electron. The event was observed in an Ilford G-5 emulsion, 400μ thick, which was exposed to cosmic radiation at 70,000 ft. Since no tracks of ionization above the minimum were observed, it is most likely that the atom struck was hydrogen. The event fortunately occurred near the center of the plate, and the primary particle was traveling almost parallel to the emulsion surface, so very long tracks of most of the secondary particles are visible, allowing detailed study. The region around the event was carefully scanned, and three electron pairs and one triplet associated with the event were found. The triplet is due to production of an electron pair in the field of an electron by a photon of energy about 24 Bev.

II. DESCRIPTION OF THE EVENT

The primary collision consists of a singly-charged particle at minimum ionization producing seven secondary particles, also at minimum ionization, within a cone of half-angle about 11°. One of the secondaries is an electron of energy 60 Mev, and is probably a knock-on

[1] P. H. Fowler, Phil. Mag. 41, 169 (1950).
[2] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. 41, 413 (1950).
[3] E. Pickup and L. Voyvodic, Phys. Rev. 82, 265 (1951).
[4] Lord, Fainberg, and Schein, Phys. Rev. 80, 970 (1950).

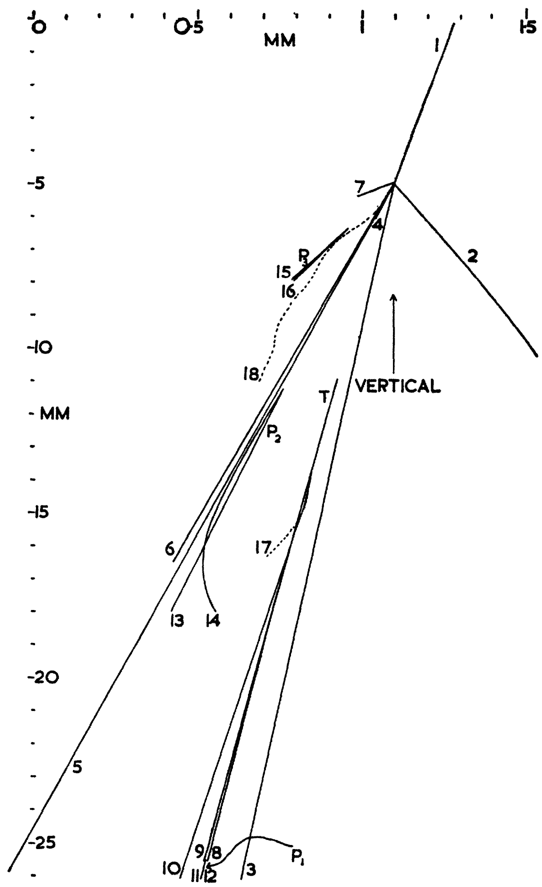

FIG. 1. Diagram of the tracks of the high energy collision including the triplet T_1 and three electron pairs, P_1, P_2, and P_3. The lateral scale is ten times the vertical so as to separate the close tracks. High energy knock-on electron tracks are shown as dotted lines.

electron produced near the point of collision; the others are protons or mesons.

The distribution of the secondary charged particles is shown in Fig. 1, and a mosaic of the primary collision in Fig. 2. Track 1 is the primary which has a length in the emulsion of 8 mm. Tracks 2, 3, and 5 are about 20 mm and track 6 about 10 mm long, so detailed scattering measurements of these could be made.

The energies of the particles were obtained from scattering measurements by the method given by Fowler.[1] For these particles the small angle scattering is of the order of 0.003° per 100μ and to obtain an accurate value of the scattering, cell lengths from 1000 to 4000μ were used; then the "noise-level" is less than the mean deviation of the chord per 100μ, and a correction is made for it in the following way.

Let D_n' represent the measured mean deviation for cell length n, where the unit of cell length is 100μ, and D_n the true deviation due to scattering alone.

Assume $D_n'^2 = D_n^2 + D_0^2$, where D_0 is the noise-level The angular deviation per unit cell length, $\alpha(100)$, is

$$\alpha(100) = D_n/n^{\frac{3}{2}},$$

and

$$D_n'^2 = n^3\alpha^2(100) + D_0^2.$$

A plot of $D_n'^2$ against n^3 should give a straight line of slope $\alpha^2(100)$ and of intercept D_0^2 at $n=0$. The value of $\alpha'(100) = D_n'/n^{\frac{3}{2}}$ tends to the limit $\alpha(100)$ as n is increased. This procedure was followed for the more energetic tracks of length greater than 12 mm. Results for tracks 3 and 5 are given in Table I.

From the value of $\alpha(100)$, the momentum p of a fast particle was obtained from[5]

$$p\beta \simeq 40/\alpha(100) \text{ Mev}/c.$$

and of a slow particle from Fig. 3 of reference 1.

The values of $\alpha(100)$, kinetic energies and other relevant data for all tracks are listed in Table II.

For track 2 the value of $\alpha(100)$ is large and the noise-level unimportant. Track 6 is not long enough to treat in the same way as Nos. 3 and 5, so the mean value of the noise found for them was combined with the measured mean deviation in a cell 2000μ long to give the energy of the particle. For particles 4 and 7 the lengths in the emulsion are too short to allow any scattering measurements to be made. Track 18 has a length of 6.2 mm in the emulsion at minimum grain density which, combined with the large value of $\alpha(100)$, 0.5°, shows that it is an electron.

Associated with the star are one triplet and three electron pairs; their positions and orientations are shown in Fig. 1. A mosaic of the triplet is given in Fig. 3 and a drawing in Fig. 4. The grain density at the start is nearly three times minimum, indicating that the three tracks start at one point. Track 10 separates from the other two after 1300μ and tracks 8 and 9 can be separated after 4000μ.

Track 9 shows a marked difference of mean deviation between the two portions of its length from 4 to 8 mm and from 8 to 13 mm, indicating a large energy loss near 8 mm. The first part (4–8 mm) is too short to give a corrected value of $\alpha(100)$, but the comparison of the measured values of $\alpha'(100)$ for cell length 1000μ for this part of track 9 with that for track 8 indicates that probably both were initially of about the same order of energy, namely, 12 Bev. The second part of track 9 (8–13 mm) has a mean scattering of 0.031° per 100μ, corresponding to an electron energy of about 1 Bev. The angle between tracks 8 and 9 is very small, being of order 0.004°.

At a distance of 13.3 mm from the origin of the triplet there is an electron pair (P_1, tracks 11 and 12, Figs. 3 and 4) between tracks 8 and 9. The pair tracks pass through the edge of the emulsion after 600μ, so their energies cannot be estimated. Track 17, also at minimum ionization, begins 4 mm from the origin of the triplet; scattering measurements give $\alpha(100) = 1.24°$, corresponding to a knock-on electron of energy 24 Mev.

[5] Dilworth, Goldsack, Goldschmidt-Clermont, and Levy, Phil. Mag. **41**, 1032 (1950).

An electron pair P_2 (tracks 13 and 14) begins 6.2 mm from the center of the star, the angle between the tracks being 0.43°. Mean scattering angle for track 13 is 0.02° and its energy is 2 Bev, the corresponding figures for the first 3.5 mm of track 14 being 0.093° and 300 Mev. For the remaining 3.5 mm of track 14, $\alpha(100)$ is 0.385° and the energy is 85 Mev, indicating that a large energy loss has occurred at about 3.5 mm from its origin. The electron pair P_3, originating 1.5 mm from the star, consists of tracks 15 and 16 at 0.05° to one another. As the track lengths are short only the lower limits of energy can be given as 1.25 Bev and 800 Mev, respectively.

The grain densities of all the long tracks were measured and it was found that the grain density of a track increased gradually from the surface to a depth of 40μ, after which it reached a constant value. The grain densities of tracks which are more than 40μ below the surface are given in Table II. It may be noted that the grain densities of the electron tracks over a range of energies from 60 Mev to 12 Bev do not show any significant increase with energy, although ionization loss is expected to increase over this energy range.

III. DISCUSSION OF THE TRIPLET AND PAIRS

It has been assumed in the preceding description that the three particles forming the triplet are electrons. From the measurements of scattering and grain density it is not possible to distinguish electrons, mesons and protons at these high energies. However, the fact that there is a knock-on electron (track 17) of energy 24 Mev produced by one of the particles, 8 or 9 indicates that one at least of these is not a proton, as the maximum energy of an electron knocked on by a 12-Bev proton is 6 Mev. Further, if the event were a neutron-proton collision the incident neutron producing the event T_1 must originate from the main star. Thus, it should have only a fraction of the energy of the incident proton (track 1), and consequently, the angular spread of the secondary particles in T_1 should be several times larger than that of the main star. But the observed angular spread of the particles in T_1 is extremely small ($\sim$0.004°) compared with the half-angle of the cone of the main star of 11°.

The result is consistent with the assumption of the production of an electron pair by a gamma-quantum in the field of an electron. This type of event has been observed by Gaerttner and Yeater[6] in a cloud chamber with γ-rays of energies between 5 and 100 Mev. They found a triplet-pair ratio of 1 to 12 and a maximum energy for the recoil of 3 Mev. The γ-ray energy required to produce the triplet which we observe is of the order of 24 Bev and a recoil electron energy of 400 Mev (track 10) is reasonable.

The average angle ϕ between a pair electron and the γ-ray is approximately given by[7]

$$\phi = m_0c^2/E,$$

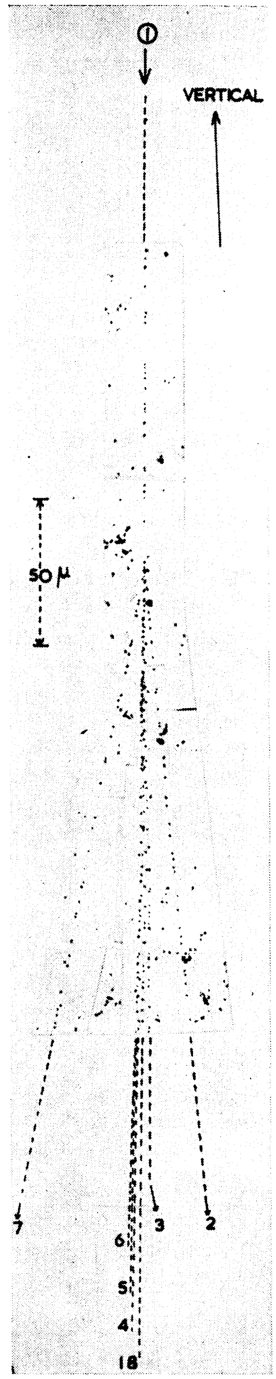

FIG. 2. Mosaic showing the primary particle and the charged secondary particles resulting from the nucleon-nucleon collision.

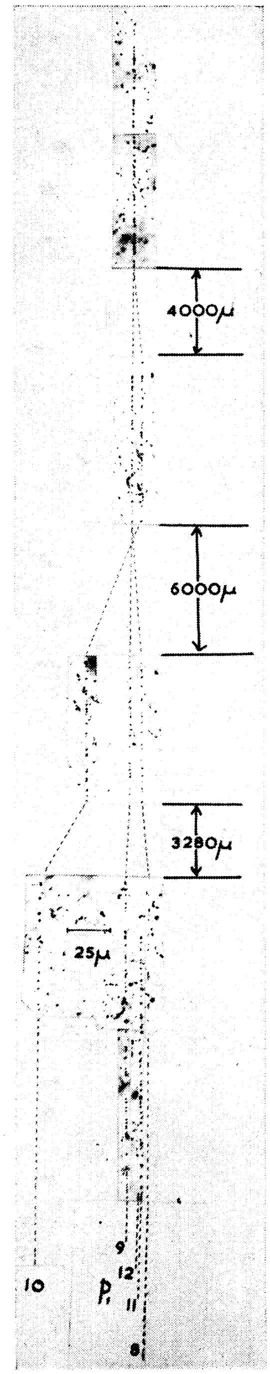

FIG. 3. Mosaic showing sections of the three electron tracks 8, 9, and 10 forming the triplet produced by the photon of energy 24 Bev. The beginning of the electron pair P_1 (tracks 11 and 12) is shown between tracks 8 and 9.

[6] E. R. Gaerttner and M. L. Yeater, Phys. Rev. 78, 621 (1950).

[7] B. Rossi and K. Greisen, Revs. Modern Phys. 13, 258 (1941).

TABLE I. Scattering measurements for two long tracks using various cell lengths.

Cell lengths (μ)	Track 3 D_n' (μ)	Track 3 $\alpha'(100\mu)$ (degrees)	Track 5 D_n' (μ)	Track 5 $\alpha'(100\mu)$ (degrees)
1000	0.49	0.0084	0.51	0.0092
1600	0.74	0.0066	0.64	0.0058
2000	0.87	0.0056	0.78	0.0050
2600	0.88	0.0038	0.88	0.0038
3000	0.94	0.0032	0.93	0.0022
4000	1.19	0.0027	1.31	0.0030
Corrected $\alpha(100\mu)$		0.0022		0.0025
"Noise-level" D_0	0.71		0.63	

where E is the energy of the electron. For tracks 8, 9, and 10 the angles calculated from this relation are 0.0017°, 0.0017°, and 0.07°, respectively. The observed angle between tracks 8 and 9 is less than 0.004° which is in agreement with this result.

It is unlikely that pair P_1 (Fig. 1) is directly associated with the main star as the perpendicular distance from the star to the bisector of the pair of tracks is 40μ. If, however, the recoil track is in such a direction that the bisector does not coincide with the γ-ray then this pair could be associated with the main star, and be produced by the second photon from the neutral meson, the first photon from which produced the triplet. Alternatively, the pair might be produced by a photon of bremsstrahlung from either of the electrons 9 or 10, each of which suffers a large energy loss along its measured path.

As the three tracks of the triplet are highly collimated, it is possible to obtain the direction of the incident gamma-ray to a high degree of accuracy. This is not possible when a gamma-ray produces an electron in the field of a nucleus owing to the uncertainty in the direction of recoil of the nucleus. In the present case the direction of the γ-ray passes within 1μ of the star and it has an energy of 24 Bev. Comparing the values of the energies of the charged mesons and their angular distribution (see Fig. 5), it seems unlikely that the neutral meson N_1, producing this γ-ray had an energy much higher than 30 Bev. If we assume that the neutral meson had this energy and gave rise to one photon of 24 Bev and a second photon of 6 Bev, then the rest lifetime T_0 of the neutral meson is less than 10^{-14} sec. This estimated limit T_0 does not vary greatly with the energy assumed for the second photon. For example, for a neutral meson of energy 50 Bev the value of T_0 is less than 3.6×10^{-15} sec. From a study of pair production, Carlson, Hooper, and King[8] obtained a value of T_0 less than 5×10^{-14} sec and Lord, Fainberg, and Schein,[4] from a single pair, a value less than 2×10^{-15} sec.

The ratio of the energies of the electrons in pair P_2 is 6:1 and a line drawn dividing the angle subtended by the electrons in the ratio 1:6 passes within 5μ of the star center. For pair P_3 where the angle between the electrons is only 0.05° the bisector of this angle passes within 0.25μ of the center of the star. It is clear that both these pairs are associated with this event. The energy of the γ-ray producing the pair P_2 is 2.3 Bev and that producing P_3 is greater than 2 Bev. From Fig. 5, assuming that the direction of the neutral meson is approximately coincident with the γ-ray, the energies of the neutral mesons, N_2 and N_3, producing pairs P_2 and P_3 are estimated to be 18 Bev and 3.0 Bev, respectively.

IV. DISCUSSION OF THE HIGH ENERGY STAR

The energies of four of the secondary particles 2, 6, 5, and 3 are plotted in Fig. 5 against the angles between the directions of the secondary and primary particles.

TABLE II. Summary of grain densities, mean scattering angles, directions, and energies of all tracks. Estimated energies of neutral mesons are also given.

	No. of track	Length (mm)	Grain density /50μ	α(100) degrees	Assumed nature of particle	Kinetic energy (Bev)	Angle with primary in l-system	Kinetic energy of neutral mesons (Bev)
	1	8	min		proton	1000		
	2	20	min	0.045	meson	0.80	6.80°	
	3	20	min	0.0022	meson	17	0.88°	
	4	1	min		meson	(~4)	2.9°	
	5	20	min	0.0025	meson	15	1.0°	
	6	11	12.24±0.20	0.0062	meson	6	2.1°	
	7	0.45	min		meson	(~0.2)	11.5°	
T_1	8	14	12.65±0.20	0.0029	electron	12	0.51°	(30)
T_1	9	14	12.16±0.20	<0.008	electron	~12		
T_1	10	14	12.65±0.20	0.076	electron	0.40		
P_1	11	0.6	min		electron			
P_1	12	0.6	min		electron			
P_2	13	6.8	12.84±0.30	0.02	electron	2.0	0.94°	(18)
P_2	14	13.0	12.23±0.20	0.093	electron	0.3		
P_3	15	1.4	min	<0.026	electron	>1.25	3.42°	(3)
P_3	16	1.4	min	<0.041	electron	>0.80		
	17	1.4	min	1.24	electron	0.024		
	18	6.2	12.70±0.4	0.496	electron	0.060	3.0°	

[8] Carlson, Hooper, and King, Phil. Mag. **41**, 701 (1950).

Assuming that a smooth curve connects energy and angle, the energies for particles 4 and 7 are estimated (see Table II). The energies and angles of the two pairs P_2 and P_3 and triplet T_1 are also shown on the figure. The energies given in Table II for the neutral mesons producing them are estimated from the curve, assuming the same distribution in energy with angle for neutral mesons as for charged mesons.

Camerini *et al.*,[2] and Pickup and Voyvodic[3] found similar events some of which contained odd numbers of shower particles, and the latter authors suggested that to conserve charge a collision with a heavy nucleus must be assumed. In the present event, although it first appeared that there were seven charged shower particles, one of these was later identified as an electron of much lower energy than any of the others. This is most probably a knock-on electron. The event can, therefore, be explained as a proton-proton collision producing six charged and three or more neutral mesons and this satisfies the conservation of charge. If a heavy nucleus were involved one would expect some evaporation particles of low energy to be emitted.

If it is assumed that the six charged and three neutral particles represent all the mesons produced in the event, then the energy of the meson shower is about 100 Bev. For these nine particles the value of β and the resolved component $\beta_x = \beta \cos\theta$ in the direction of the incident particle are tabulated in Table III.

If we convert the velocities of the particles from the laboratory system (l-system) to a system where the center of mass of these particles is at rest (c-system), the resultant momentum will be zero. The momentum p_x' of a particle in the c-system is given by

$$cp_x' = B_c w(\beta_x - \beta_c),$$

where $c\beta_c$ is the velocity of the c-system, $B_c = 1/(1-\beta_c^2)^{\frac{1}{2}}$, and w is the total energy of the particle in the l-system. Since $\Sigma p_x'$ for all particles is zero in the c-system, then

$$\beta_c = \Sigma w\beta_x / \Sigma w.$$

The energy w' and angle θ' of a particle in the c-system are calculated from the relations:

$$w' = B_c w(1-\beta_c\beta_x),$$
$$\tan\theta' = \tan\theta\beta_x / B_c(\beta_x - \beta_c)$$

and are given in Table III.

In this system the particles have about the same order of energy and the sum of the energies is 4.04 Bev. The particles are not confined to a forward and backward cone.

If the process is assumed to be a proton-proton collision, where the velocity of the incident proton before collision in the c-system is $c\beta_c$, the total energy W' of the two protons in the c-system is

$$W' = 2M_0c^2B_c = 44.2 \text{ Bev},$$

where M_0 is the rest mass of a proton.

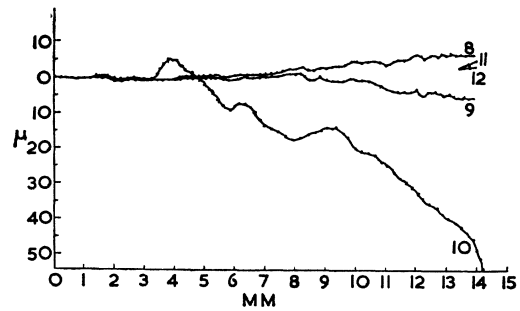

FIG. 4. Enlarged drawing of the electron tracks forming the triplet showing multiple scattering and the position of the electron pair.

Thus only one-tenth of the available energy is taken by the meson shower. In this case the excess must be ascribed to additional neutral particles. If we assume two neutrons are produced, each of these must have energies of 20 Bev in the c-system and about equal and opposite momenta.

In the l-system the energy of the primary proton is given by the relation

$$W = M_0c^2B \simeq 2M_0c^2B_c^2$$

which gives $W = 1000$ Bev. The total energy of the neutrons is of the order of 900 Bev and the sum of the energies of the observed particles is 100 Bev. If this

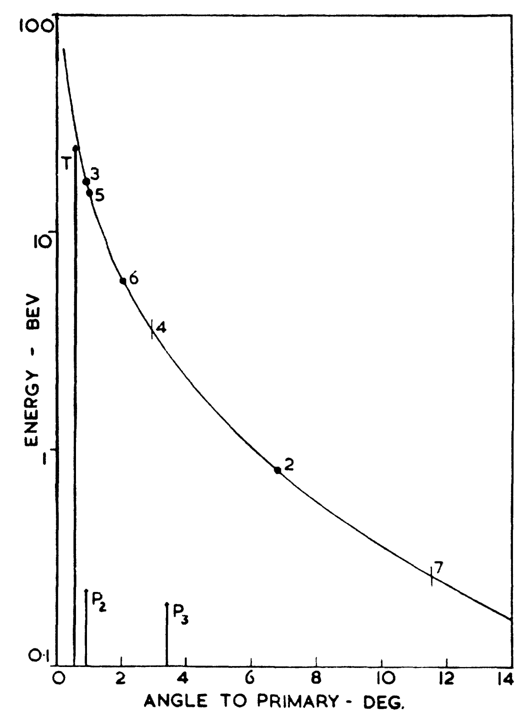

FIG. 5. Energies of four secondary particles, 3, 5, 6, and 2 plotted against their angles relative to the primary particle direction in the laboratory system. Energies of photons producing triplet T_1 and pairs P_2 and P_3 are represented on the diagram at their corresponding angles. Estimated values for tracks 4 and 7 are indicated.

TABLE III. Velocities of mesons in the laboratory system, and energies and angular distribution in the center-of-mass system.

	l-system		c-system	
Meson	β	β_x	Angle θ°	Energy (Bev) w'
2	0.988895	0.981973	164	0.42
3	0.999967	0.999839	42	0.43
4	0.999429	0.998130	114	0.27
5	0.999957	0.999757	49	0.41
6	0.999740	0.999140	88	0.25
7	0.9112	0.8929	176	0.86
N_1	0.999989	0.999952	23	0.67
N_2	0.999970	0.999825	39	0.46
N_3	0.999007	0.99721	127	0.27

excess energy of 900 Bev is carried instead by two unobserved neutral mesons, these will have a total energy of 40 Bev in the c-system which is ten times as great as the sum of the energies of the other nine mesons, which is unlikely.

Another alternative that might be considered is that two of the charged particles in the shower are protons. The grain densities of protons having kinetic energies less than 1 Bev are significantly above the minimum value and so track 2 cannot be a proton. Track 7, which is at minimum ionization, would correspond to a proton of total energy >1.94 Bev, a value much higher than was estimated from Fig. 5. If, however, we assume that track 7 is due to a proton of energy 1.94 Bev and that one of the other fast tracks is also due to a proton, we still find that the observed energy of the shower ($\sim$100 Bev) is much less than the energy of the incident proton ($\sim$400 Bev). This assumption will reduce the number of charged mesons to four and additional neutral mesons of much higher energy than the ones observed must be postulated to balance the energy. This gives, in addition, an excess of neutral to charged mesons. For these reasons the former assumption of the excess energy being taken by two neutrons seems the more plausible.

V. COMPARISON WITH THEORY

These results may be compared with the theories of multiple meson production, developed by Fermi[9] and Heisenberg.[10] Assuming the energy W' of the incident protons in the c-system is 44.2 Bev, the expected number of charged mesons (n) from Fermi's theory is given by the following relation for the intermediate range of energy.

$$n=1.34(\epsilon'-2)^{3/4}/\epsilon'$$

where $\epsilon'=W'/M_0c^2$ and M_0 is the mass of the proton. This gives the number of charged mesons produced as 8 or 9. Alternatively, if the formula for the extremely high energy case

$$n=1.2(W/M_0c^2)^{1/4}$$

is considered where W is the energy of the incident proton in the l-system we get a value of n of 7. Our observed number is 6.

On the Heisenberg theory the average number N of charged and uncharged mesons produced is given by

$$N=W'/m_0c^2 \ln(W'/m_0c^2),$$

where m_0c^2 is the meson rest mass. This gives a value of n of 55 against an observed number of approximately 9.

Both of these results have been obtained on the assumption that practically all the energy in the c-system goes to the meson production. In the present event only one-tenth of the energy has been used in this way. Assuming $W'=4$ Bev, Fermi's formula for the intermediate energy ranges gives $n=1$ and the Heisenberg formula $N=8.5$.

In the theory of meson production by Fujimoto *et al.*,[11] it has been assumed that a fraction of the incident energy may go to meson production and the angular distribution should be isotropic in the c-system. Also Freir and Ney[12] observed a collision of a carbon nucleus with a proton and estimated that one-third of the energy of one of the protons of the carbon nucleus went to meson production. In the present event it is concluded that one-tenth of the energy of the primary proton is used in meson production and the mesons are isotropically distributed in the c-system.

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[9] E. Fermi, Phys. Rev. **82**, 683 (1951).
[10] W. Heisenberg, Nature **164**, 65 (1949).
[11] Fujimoto, Fukuda, Hayakawa, and Yamaguchi, Prog. Theor. Phys. **5**, 669 (1950).
[12] P. Freir and E. P. Ney, Phys. Rev. **77**, 337 (1950).

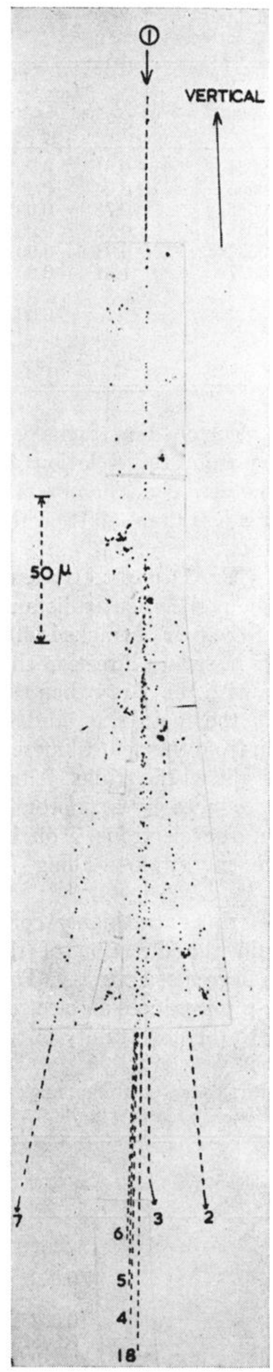

FIG. 2. Mosaic showing the primary particle and the charged secondary particles resulting from the nucleon-nucleon collision.

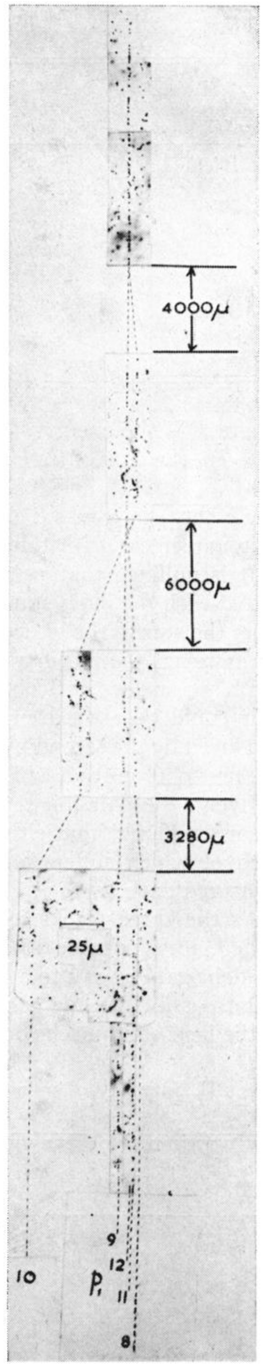

FIG. 3. Mosaic showing sections of the three electron tracks 8, 9, and 10 forming the triplet produced by the photon of energy 24 Bev. The beginning of the electron pair P_1 (tracks 11 and 12) is shown between tracks 8 and 9.