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Some Experimental Results Concerning Mesotrons

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In the first part of the article cross sections for anomalous, non-Coulombian single scattering of mesotrons are determined by a comparison of the scattering observed in two different lead thicknesses, a method partly described in a previous paper. For mesotrons with energies above $\sim 5\times 10^8$ ev it is found that the scattering through angles ranging from less than 5° up to 90° is predominantly anomalous. The second section concerns itself with showers of mesotrons. The phenomenon of saturation for the production of mesotron showers in lead as reported by Jánossy and Sinha is not confirmed. Some special photographs of mesotron and electron showers are reproduced and discussed. In the last section an analysis of the number of slow, heavily ionizing mesotrons and protons gives only slight and not conclusive evidence that mesotrons of very low energies (<20 Mev) disappear by a process other than any known so far.

1. APPARATUS

THE present article is intended to give a summary of results obtained from an analysis of about 40,000 cloud-chamber photographs taken several years ago by means of the apparatus described previously on several occasions.[1,2] The cloud chamber is 60 cm in diameter and 15 cm deep, and it contained argon at a pressure of 1.3 atmospheres saturated with a mixture of water and *n*-propyl alcohol vapors. Throughout the experiments to be described, three lead plates, 1 cm, 5 cm, and 1 cm thick, respectively, spaced 13 cm apart, were mounted horizontally inside the chamber. Expansions were controlled by coincidences of two counters located above the cloud chamber. All the photographs were stereoscopic.

The apparatus was operated in a sub-basement room under an estimated 60 cm of concrete. The position and amount of additional lead absorbers will be given in the course of the discussion.

For nearly half of the pictures, a homogeneous magnetic field of 1150 oersteds was maintained in the cloud chamber.

The photographs have been analyzed with particular regard to the effects of scattering and showers of cosmic-ray mesotrons, and to the number of mesotrons and protons of low energies.

2. ANOMALOUS SCATTERING

The angles α through which the rays were deflected while traversing one of the three lead plates were measured in the photograph taken along the axis of the cloud chamber. Distributions in α of the rays with the thicknesses t of the lead plates as parameters have thus been obtained. Since the magnetic field of 1150 oersteds is not sufficient to measure the energy of individual fast mesotrons, the distributions in

[1] T. H. Johnson, J. G. Barry, and R. P. Shutt, Phys. Rev. 59, 470A (1941).
[2] R. P. Shutt, Phys. Rev. 61, 6 (1942).

α involve the energy distribution of the particles inside the cloud chamber.

Mesotrons can be scattered by electrical forces as expressed by Coulomb's law or by short range nuclear and spin forces. When the deflections of the individual particles occur in one single act, the scattering is called single, while one speaks of multiple scattering when a large number of very small deflections is involved. Williams[3] has shown that the Coulomb scattering is predominantly multiple. For a given energy the distribution in α is Gaussian for multiple scattering, with only the mean value $\bar{\alpha}$ of the Gaussian depending on assumptions made concerning the kind and range of the scattering force. $\bar{\alpha}$ is of the form $kt^{\frac{1}{2}}$ where k is independent of the thickness t. The approximations involved are good as long as α is not too large. As discussed in a previous paper[2] introduction of the transformation $u=\alpha t^{-\frac{1}{2}}$ into the Gaussian distribution in α results in a function of u which is independent of t. It has also been shown[2] that even if the electrical scattering were single, the particular form of Coulomb's law would lead to an expression transformable in the same manner, provided the α are not too large. The following conclusions can be drawn. Provided the energy distributions of the particles in two lead plates of different thicknesses t are of the same shape, the distributions in α found experimentally in these thicknesses should become identical when expressed as functions of $u=\alpha t^{-\frac{1}{2}}$ if the scattering is purely multiple or purely of the Coulomb type (multiple or possibly single). Any departure from this rule shows that other forces are present besides the Coulomb force, and that scattering caused by these forces is single because single scattering is directly proportional to t, which with the one exception of single Coulomb scattering generally leads to distributions not transforming in the way described above. Since the actual paths taken by the rays are somewhat longer than t, and because of the approximations involved in Williams' theory, the values of the functions of u for $\alpha<30°$ may differ by an estimated 3 percent compared with actually observed departures of 40 percent or more. The object of the present discussion is to confirm and extend the conclusions drawn earlier making use of the new data.

The following illustrates how the number of mesotrons scattered anomalously, i.e., neither by any type of multiple process nor by a force varying with the square of the distance from the scattering center, can be determined from the experimental data. $A_1|_{u_1}^{u_2}$ and $A_2|_{u_1}^{u_2}$ shall designate the number of mesotrons scattered anomalously in the thicknesses t_1 and t_2, respectively, in the range $u_1 \leqq u \leqq u_2$. The letter E in place of A refers to the number of particles scattered electrically, and T is the total number deflected. According to the theory outlined above we then have

$$E_1|_{u_1}^{u_2}=E_2|_{u_1}^{u_2}, \tag{1}$$

and therefore

$$T_2|_{u_1}^{u_2}-T_1|_{u_1}^{u_2}=A_2|_{u_1}^{u_2}-A_1|_{u_1}^{u_2}. \tag{2}$$

T_1 and T_2 have been measured, A_1 and A_2 are unknown. Thus Eq. (2) is not sufficient, and further assumptions must be made. Transforming back to α we have from (2)

$$T_2|_{\alpha_{12}}^{\alpha_{22}}-T_1|_{\alpha_{11}}^{\alpha_{21}}=A_2|_{\alpha_{12}}^{\alpha_{22}}-A_1|_{\alpha_{11}}^{\alpha_{21}}, \tag{3}$$

where $\alpha_{11}=u_1t_1^{\frac{1}{2}}$, $\alpha_{21}=u_2t_1^{\frac{1}{2}}$, $\alpha_{12}=u_1t_2^{\frac{1}{2}}$, and $\alpha_{22}=u_2t_2^{\frac{1}{2}}$. Evidently one can write

$$A_1|_{\alpha_{11}}^{\alpha_{21}}=A_1|_{\alpha_{11}}^{\alpha_{12}}+A_1|_{\alpha_{12}}^{\alpha_{22}}-A_1|_{\alpha_{21}}^{\alpha_{22}}, \tag{4}$$

and thus from (3) and (4)

$$A_2|_{\alpha_{12}}^{\alpha_{22}}-A_1|_{\alpha_{12}}^{\alpha_{22}} =T_2|_{\alpha_{12}}^{\alpha_{22}}-T_1|_{\alpha_{11}}^{\alpha_{21}}+A_1|_{\alpha_{11}}^{\alpha_{12}}-A_1|_{\alpha_{21}}^{\alpha_{22}}. \tag{5}$$

The A_1 still present in Eq. (5) can easily be estimated. As pointed out before, any anomalous scattering observable by this method must be single, and therefore proportional to t. Thus generally

$$A_1|_{\alpha_a}^{\alpha_b}=(t_1/t_2)A_2|_{\alpha_a}^{\alpha_b}. \tag{6}$$

Furthermore we certainly have

$$0<A_2|_{\alpha_{11}}^{\alpha_{12}}<T_2|_{\alpha_{11}}^{\alpha_{12}} \tag{7}$$

[3] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).

TABLE I. Anomalous scattering between 4.5° and 27°.

	1	2	3	4	5	6	7	8	9	10	11
	$T_1\|_0^{90}$ 1 cm Pb, traversals	$T_2\|_0^{90}$ 5 cm Pb, traversals	$T_1\|_2^{12}$ 1 cm Pb %	$T_2\|_{4.5}^{27}$ 5 cm Pb %	$T_2\|_2^{4.5}$ 5 cm Pb %	$T_2\|_{12}^{27}$ 5 cm Pb %	$A_{2\,\min}\|_{4.5}^{27}$ 5 cm Pb %	$A_{2\,\max}\|_{4.5}^{27}$ 5 cm Pb %	$\frac{A_{2\,\min}}{T_2}\|_{4.5}^{27}$ %	$\frac{A_{2\,\max}}{T_2}\|_{4.5}^{27}$ %	$E_{\min}$ 10^8 ev
a Observed under 15 cm Pb and 60 cm of concrete	27200	13800	4.8	7.8	10.0	1.3	4.9 ± 0.5	(7.7 ± 0.5) 6.3 ± 0.5	48 ± 5	(76 ± 5) 63 ± 5	0.2
b Same as *a*, selected pictures	6900	3700	5.0	7.4	8.9	1.3	3.9 ± 0.8	(6.3 ± 0.8) 5.1 ± 0.8	41 ± 8	(66 ± 8) 53 ± 8	0.2
c Same as *a*, with triple coincidences	5300	2700	1.6	3.3	9.8	0.0	2.8 ± 0.7	(5.9 ± 0.7) 4.3 ± 0.7	65 ± 16	(138 ± 16) 100	4.5
d Observed under 88 cm Pb and 60 cm of concrete	5900	3100	2.0	5.9	8.3	0.8	6.3 ± 0.8	(8.7 ± 0.8) 7.7 ± 0.8	82 ± 10	(113 ± 10) 100	0.2

TABLE II. Anomalous scattering between 9° and 27°.

	1	2	3	4	5	6	7	8	9	10	11
	$T_1\|_0^{90}$ traversals	$T_2\|_0^{90}$ traversals	$T_1\|_4^{12}$ %	$T_2\|_9^{27}$ %	$T_2\|_4^{9}$ %	$T_2\|_{12}^{27}$ %	$A_{2\,\min}\|_9^{27}$ %	$A_{2\,\max}\|_9^{27}$ %	$\frac{A_{2\,\min}}{T_2}\|_9^{27}$ %	$\frac{A_{2\,\max}}{T_2}\|_9^{27}$ %	$E_{\min}$ 10^8 ev
a Observed under 15 cm Pb and 60 cm of concrete	27200	13800	2.0	2.4	6.4	1.3	0.6 ± 0.3	(2.3 ± 0.3) 1.5 ± 0.3	19 ± 10	(74 ± 10) 49 ± 10	0.2
d Observed under 88 cm Pb and 60 cm of concrete	5900	3100	0.8	1.7	4.9	0.8	1.5 ± 0.3	(2.8 ± 0.3) 2.2 ± 0.3	68 ± 13	(127 ± 13) 100	0.2

and

$$0 < A_2|_{\alpha_{21}}^{\alpha_{22}} < T_2|_{\alpha_{21}}^{\alpha_{22}} \tag{8}$$

Finally, it appears to be an experimental fact that

$$T_2|_{\alpha_{11}}^{\alpha_{12}} > T_2|_{\alpha_{21}}^{\alpha_{22}}. \tag{9}$$

Making use of Eq. (6) and substituting the inequalities (7) to (9) into Eq. (5) we obtain

$$A_{2\,\min}|_{\alpha_{12}}^{\alpha_{22}} = [T_2|_{\alpha_{12}}^{\alpha_{22}} - T_1|_{\alpha_{11}}^{\alpha_{21}}]t_2/(t_2-t_1) \tag{10}$$

and

$$A_{2\,\max}|_{\alpha_{12}}^{\alpha_{22}} = [T_2|_{\alpha_{12}}^{\alpha_{22}} - T_1|_{\alpha_{11}}^{\alpha_{21}} + (T_2|_{\alpha_{11}}^{\alpha_{12}} - T_2|_{\alpha_{21}}^{\alpha_{22}})t_1/t_2]t_2/(t_2-t_1) \tag{11}$$

as upper and lower limits for A_2, the number of mesotrons scattered anomalously through angles $\alpha_{12} \leqq \alpha \leqq \alpha_{22}$.

Previously[2] only the lower limit $A_{2\,\min}$ had been calculated which appeared to be sufficient on account of the large statistical errors involved then.

The data as they are needed for the calculations have been compiled in Tables I and II, columns 1–6. In columns 7–10 the results are given. Observations on the two 1-cm lead plates have been combined. In Table I $\alpha_{11} = 2°$ and $\alpha_{21} = 12°$ have been chosen, leading to values of $\alpha_{12} = 4.5°$ and $\alpha_{22} = 27°$, respectively, using $t_1 = 1$ cm and $t_2 = 5$ cm. The choice of the lower limit α_{11} is determined by the accuracy with which the angles can be measured, while the upper limit α_{21} is chosen such as to make $\alpha_{22}<30°$. In Table II $\alpha_{11}=4°$ has been selected, the upper limit being the same as in Table I.

An estimated correction of 30 percent has been added to all values of A_2 and the values of T_2 used for computation of columns 9 and 10 since only projections of the actual three-dimensional deflections onto the plane of the photographic camera have been measured.

The observations listed in row *a* of the tables were made under 15 cm of lead located immediately above the cloud chamber in addition to the 60 cm of concrete making up the structure of the building. For row *b* of Table I a number of pictures with particularly clear and straight tracks have been selected. Row *d* shows data obtained under 88 cm of lead in place of the 15 cm used before. Row *c* of Table I has been obtained in the following way. Again there were 15 cm of lead above the chamber, but in addition a large counter tray containing 56 counters was placed below the cloud chamber with 35 cm of lead interposed between chamber and tray. Double coincidences of the two upper counters still tripped the expansion mechanism regardless of the state of the lower counter tray. But, whenever a triple coincidence occurred between the top counters and the bottom tray, a small neon bulb mounted near the center of the front side of the chamber was lit up for a few seconds, thus indicating that the ray had penetrated 35 cm of lead after leaving the chamber. The light flash can be seen in Fig. 3.

The uncertainties indicated in columns 7–10 are standard errors calculated in the usual way.

Finally, the 11th column gives a lower limit for the kinetic energy of the particles as determined by the following criteria. In rows *a*, *b*, and *d* all tracks have been included except those which appeared to be heavily ionized. A mesotron ionizes appreciably more than normally when its energy falls below 0.2×10^8 ev. Thus the lower limit observed here is $E_{\min}=0.2\times10^8$ ev. However where a triple coincidence occurred the ray must have penetrated the 35 cm of lead below the cloud chamber. Here the theory of ionization leads to a value of $E_{\min}$ of 4.5×10^8 ev.

In columns 7 and 8, $A_{2\min}$ and $A_{2\max}$ have been tabulated showing the minimum and maximum percentages of mesotrons scattered anomalously in the 5-cm lead plate. These fractions refer to the total number of traversals through the plate. In columns 9 and 10 the fractions $A_{2\min}/T_2$ and $A_{2\max}/T_2$, respectively, are listed for comparison of the number of anomalously scattered particles with the total of rays scattered through the same range of angles.

Now, in column 10 there occurred two values for $A_{2\max}/T_2$ which were greater than 100 percent showing that the calculated $A_{2\max}$ is actually much too high. By putting the two values in question equal to 100 percent, all the other numbers involving $A_{2\max}$ have been reduced correspondingly by interpolation between $A_{2\min}$ and $A_{2\max}$. The original, too-high values have been enclosed in parentheses in the tables.

Comparing the results for A_2 obtained from the different sets of pictures, and noted in columns 7 and 8, one finds only slight disagreements outside the experimental uncertainties, the value in row *d* being somewhat too high, and the value in row *c* being too low. The latter value cannot be considered quite reliable because, although the large counter tray below the chamber was made as large as possible, making use of available counters, its size may yet have been somewhat too small to register all rays of interest. The significance of the discrepancies can be evaluated as follows. For the corresponding values of A_2/T_2 in columns 9 and 10 these discrepancies become quite considerable. First, comparing rows *a* and *c*, one sees that $A_{2\max}/T_2$, for instance, varies from a value of (63 ± 5) percent in row *a* to a value possibly as large as 100 percent in row *c*. The difference must be due to the fact that the lower energy limit $E_{\min}$ is considerably higher in row *c* than it is in row *a*. The mean electrical deflection for particles in the cut-off part of the energy spectrum ($0<E<4.5\times10^8$ ev) is $\geqq5°$, as follows from Williams' theory. Thus these particles of the lower energies contribute largely to electrical scattering through angles $>4.5°$, which is our lower limit here, and most of the scattering through $\alpha>4.5°$ observed for particles of energies higher than 4.5×10^8 ev is anomalous, in qualitative agreement with the results.

Next we compare the results for A_2/T_2 given in rows *a* and *d*. Here the energy limits for the particles observed in the cloud chamber are identical. Yet a very large discrepancy is found. The latter is even more significant here than it was before because the uncertainties in row d are smaller than in row c. The only possible reason for the disagreement appears to be that the energy distributions in the two cases are not identical, but that under 88 cm of lead the number of mesotrons of low energy is reduced considerably. The absorber of 88 cm of lead was piled as an inverted truncated pyramid covering the solid angle of the counter system and the cloud chamber. Its average width measured along the cloud-chamber plane was about equal to its height, but measured along the direction of the axis of the cloud chamber its average width was $\frac{1}{3}$ of its height only. The lead above the chamber also scatters mesotrons. Some of the particles are scattered out of the lead at the four almost vertical sides and thus lost from observation, and a few entering these boundaries from the outside may be scattered into the solid angle under observation. An estimate of this effect shows that in a cylindrical absorber of rectangular cross section the fraction of particles lost in this way at two opposite boundaries is of the order of $z \approx 10^7 t^{3/2}/wE_{\text{Av}}$, with w for the width and t for the thickness of the lead absorber. E_{Av} can be taken as the geometric mean of the energies of the mesotrons at the top and at the bottom of the lead pile. The expression for z represents an approximation as long as $z<1$ and cannot be used when $z \geqq 1$, of course. With our values of $t=88$ cm, $w=30$ cm (average width of the truncated pyramid), and for particles sensitive to electrical scattering of, say, 3×10^8 ev (energy at the top of the lead pile $\sim 1.5\times 10^9$ ev) one calculates that $z=40$ percent. For the truncated pyramid actually used the geometrical conditions are such that still more particles of these energies are prevented from entering the cloud chamber. Therefore, under a lead pile of $t>w$ we have to expect a very considerable reduction of particles sensitive to electrical scattering, and the high portion of anomalously scattered particles found in row d becomes understandable. It thus appears that above energies of $\sim 0.5\times 10^9$ ev the anomalous scattering becomes all-important.

Substituting the values of A_2 from columns 7 and 8 into expression (9) of reference 2 one can calculate limits for an average cross section for the anomalous scattering through $4.5° \leqq \alpha \leqq 27°$ One finds

$$14\times 10^{-28}\ \text{cm}^2 \pm 10\% < \sigma(4.5°, 27°) < 18 \times 10^{-28}\ \text{cm}^2 \pm 8\% \quad (12)$$

per neutron or proton in lead, averaged over almost the whole energy spectrum of the mesotrons, or

$$18\times 10^{-28}\ \text{cm}^2 \pm 12\% < \sigma(4.5°, 27°) < 22 \times 10^{-28}\ \text{cm}^2 \pm 10\% \quad (13)$$

per neutron or proton in lead, averaged over the part of the energy spectrum lying above 5×10^8 ev.

Proceeding in exactly the same way for the data listed in Table II one finds corresponding values of

$$2\times 10^{-28}\ \text{cm}^2 \pm 50\% < \sigma(9°, 27°) < 4 \times 10^{-28}\ \text{cm}^2 \pm 20\% \quad (14)$$

for mesotrons of practically all energies of the energy spectrum, and

$$4\times 10^{-28}\ \text{cm}^2 \pm 20\% < \sigma(9°, 27°) < 6 \times 10^{-28}\ \text{cm}^2 \pm 15\% \quad (15)$$

for mesotrons of energies $>5\times 10^8$ ev.

The observations of other investigators have been discussed in detail in reference 2.* Code's[4] results seem to be particularly well suited for a direct comparison with the present results. In 3.8 cm of tungsten (equivalent to ~ 6 cm of lead) Code found 10 particles with energies greater than 6×10^8 ev scattered through angles larger than 9° where only 1 or 2 were expected if the scattering were purely Coulombian. This leads to a value of $A/T=(80\pm 20)$ percent in qualitative agreement with our corresponding values listed in Table II, row d, columns 9 and 10, and also to a cross section of $\sigma(>9°)=5.7\times 10^{-28}$ $\text{cm}^2 \pm 35$ percent in agreement with our expression (15) referring to similar ranges of energy and deflections. But our expression (13) for the anomalous scattering through angles between 4.5° and 27° is 3 or 4 times larger than any calculated from the observations of others. Unless some systematic error not yet accounted

* *Note added in proof:* Comparison with results published quite recently by M. S. Sinha [Phys. Rev. **68**, 153 (1945)] has been made in a short article by the writer [Phys. Rev. **69**, 128 (1946)].

[4] F. L. Code, Phys. Rev. **59**, 229 (1941).

TABLE III. Mesotron showers.

Thickness of dense matter above cloud chamber		1	2	3	4	5	6	7	8	9
		Number of mesotron pairs forming angles between						Total No. traversing ≧6 cm of lead	Pairs (0°–4°) originating from a point in the lead above cloud chamber	Showers of more than 2 mesotrons, originating in lead above cloud chamber
		0° <2°	2° <4°	4° <6°	6° <8°	8° <10°	10° <20°			
60 cm of concrete +15 cm of lead	*a* Cases	15	8	2	3	2	22	13400	3	1 (6 mesotrons)
	b Cases per 1000 traversals	1.1 ±0.3	0.6 ±0.2	0.15	0.22	0.15	1.6	1000	0.2±0.1	0.07
	c Random cases expected per 1000	0.28	0.28	0.28	0.28	0.28	1.4		0.03	
60 cm of concrete +88 cm of lead	*d* Cases	7	3	5	2	1	2	3100	5	1 (3 mesotrons)
	e Cases per 1000 traversals	2.3 ±0.9	0.9 ±0.5	1.4 ±0.6	0.6	0.3	0.6	1000	1.6±0.7	0.3
	f Random cases expected per 1000	0.28	0.28	0.28	0.28	0.28	1.4		0.18	

for has entered our own observations the most plausible among several possible explanations for the disagreement may be that all the observations of others have been made with only a single scattering plate while measuring the energy of the individual particles. Usually mesotrons of all energies were present, and the apparently considerable overlapping of the effects of Coulombian and anomalous scattering would then make detection of the latter more difficult than if the energies at which particles are sensitive to Coulomb scattering are cut off. Since the anomalous scattering as dependent on the energy of the mesotrons is of considerable theoretical interest it seems to this author that an experiment pertaining to this matter could be performed most efficiently by measuring the energy of the individual particles in the usual way, but carrying out the experiment under a lead pile geometrically similar to that employed here, a method which apparently eliminated a large number of mesotrons of energies sensitive to Coulomb scattering from observation in the cloud chamber.

Previously our results agreed with those following from a theory of nuclear scattering of mesotrons of a spin of $\frac{1}{2}$ as developed by Marshak and Weisskopf. By means of a more rigorous calculation Heitler and Peng[5] have shown more recently that a spin of 1 for the mesotron would also be in qualitative agreement with the experimental results obtained so far. These authors calculate that the scattering cross section should be of the order of 10^{-27} cm^2 for mesotrons of an energy of 8×10^8 ev.

Summarizing we can say that the anomalous scattering becomes of particular importance at energies $>5\times10^8$ ev, when the behavior of mesotrons becomes essentially relativistic and therefore spin forces are important, and that the distribution of the deflections extends down to and probably below angles of 4.5°. Removing the mesotrons of energies below 5×10^8 ev by some means lets the effect appear much more clearly since this procedure eliminates the particles sensitive to Coulomb scattering from observation.

3. MESOTRON SHOWERS

The existence of showers of mesotrons first was indicated by experiments conducted by Schmeiser and Bothe.[6] When measuring the number of cosmic-ray showers as a function of the thickness of dense material under which the observations were made ("Rossi Curve") these investigators

[5] W. Heitler and H. W. Peng, Phys. Rev. **62**, 81 (1942).
[6] K. Schmeiser and W. Bothe, Naturwiss. **25**, 669 (1937).

found a small "second maximum" where only one maximum was expected from the electron cascade theory. The matter has been studied further by several observers employing counter methods, work having been done at sea level as well as at high elevations.[7–9] The most extensive counter studies performed at sea level are due to Janossy and Rochester.[10] Single cloud-chamber pictures of associated mesotrons have been obtained by many,[11–18] mostly at high elevations and with a frequency of one in 3000 or 4000 photographs of single tracks. A systematic study of the effect by means of the cloud-chamber method has been carried out more recently by Sinha.[19] Operated at sea level, Sinha's cloud chamber was controlled by an arrangement of counters such that only showers were recorded whose component rays formed small angles with respect to each other. The photographs include one case of 12 associated particles having a common point of origin in the lead block placed above the chamber and penetrating 2.2 cm of lead. The rays are not scattered appreciably and do not multiply in the lead, a fact which is commonly taken for sufficient evidence that actually mesotrons, and not electrons, are involved.

An analysis of the present data again confirms the existence of mesotron showers. The results are given in Table III. Only particles seen to penetrate at least 6 cm of lead inside the cloud chamber have been included in order to assure that no electrons are involved. All observations under 15 cm of lead have been combined in row *a* while those under 88 cm of lead are shown in row *d*. Rows *b* and *e* give the respective data reduced to a basis of 1000 traversals of single rays through the chamber. Standard errors are noted where they are of interest. Columns 1–8 concern showers of two mesotrons only. Two cases of showers of more than two mesotrons are listed in the ninth column. The projections of the angles between the pairs of tracks onto the cloud-chamber plane have been measured, and the results have been grouped into steps of 0° to, but not including 2° (expressed by $0^\circ<2^\circ$), 2° to, but not including 4° ($2^\circ<4^\circ$), etc., as indicated in columns 1–6. In these columns pairs diverging from a point above the cloud chamber have not been separated from those converging toward a point inside or below. It turns out that only small divergences are of interest, and two rays which originally may have appeared to diverge slightly may easily become convergent due to scattering. However, the pairs and multiple showers listed in columns 8 and 9, respectively, are only those which seem to diverge from a point in the lead above the chamber. Finally, column 7 gives the total number of mesotrons observed.

In these experiments a single mesotron was sufficient to trip the cloud-chamber mechanism. Thus any additional particle seen on a photograph either happens to be present at random or it is actually associated with the first one. To calculate the chance for random association of mesotrons in our arrangement we need the following quantities. Whether or not two mesotrons appear to be simultaneous in a cloud chamber depends on the relative width and luminous intensity of their tracks. From well-known theoretical and experimental investigations concerning the diffusion of ions in gases a "resolving time" of 1/20 sec. is found for this particular apparatus. The observations were made in a solid angle of 0.18. The counters covered an area of 40 sq. cm. With these values and a counting rate of 0.6 per minute per sq. cm per unit solid angle the expected number of chance coincidences of mesotrons has been calculated and tabulated in rows *c* and *f* of Table III.

Comparing within columns it is seen that the number of mesotron pairs is about as expected

[7] W. F. G. Swann, Rev. Mod. Phys. **11**, 250 (1939). W. F. G. Swann and W. E. Ramsey, Phys. Rev. **57**, 106 (1940). W. F. G. Swann, J. Frank. Inst. **230**, 323 (1940).

[8] M. Damy DeSouza Santos, P. A. Pompeia, and G. Wataghin, Phys. Rev. **59**, 902 (1941).

[9] J. F. Carlsson and M. Schein, Phys. Rev. **59**, 840 (1941). M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 930 (1941).

[10] L. Jánossy, Proc. Roy. Soc. **A179**, 361 (1942). L. Jánossy, Phys. Rev. **64**, 345 (1943). L. Jánossy and G. D. Rochester, Proc. Roy. Soc. **A183**, 181 (1944).

[11] J. C. Street, J. Frank. Inst. **227**, 765 (1939).

[12] H. J. J. Braddick and G. S. Hensby, Nature **144**, 1012 (1939).

[13] G. Herzog and W. H. Bostick, Phys. Rev. **58**, 278 (1940).

[14] W. M. Powell, Phys. Rev. **60**, 413 (1941).

[15] D. J. Hughes, Phys. Rev. **60**, 414 (1940).

[16] E. O. Wollan, Phys. Rev. **60**, 532 (1941).

[17] L. Jánossy, C. B. McCusker, and G. D. Rochester, Nature **148**, 660 (1941).

[18] W. H. Bostick, Phys. Rev. **61**, 557 (1942).

[19] M. S. Sinha, Trans. Bose Res. Inst., Calcutta **15**, 191 (1942/43).

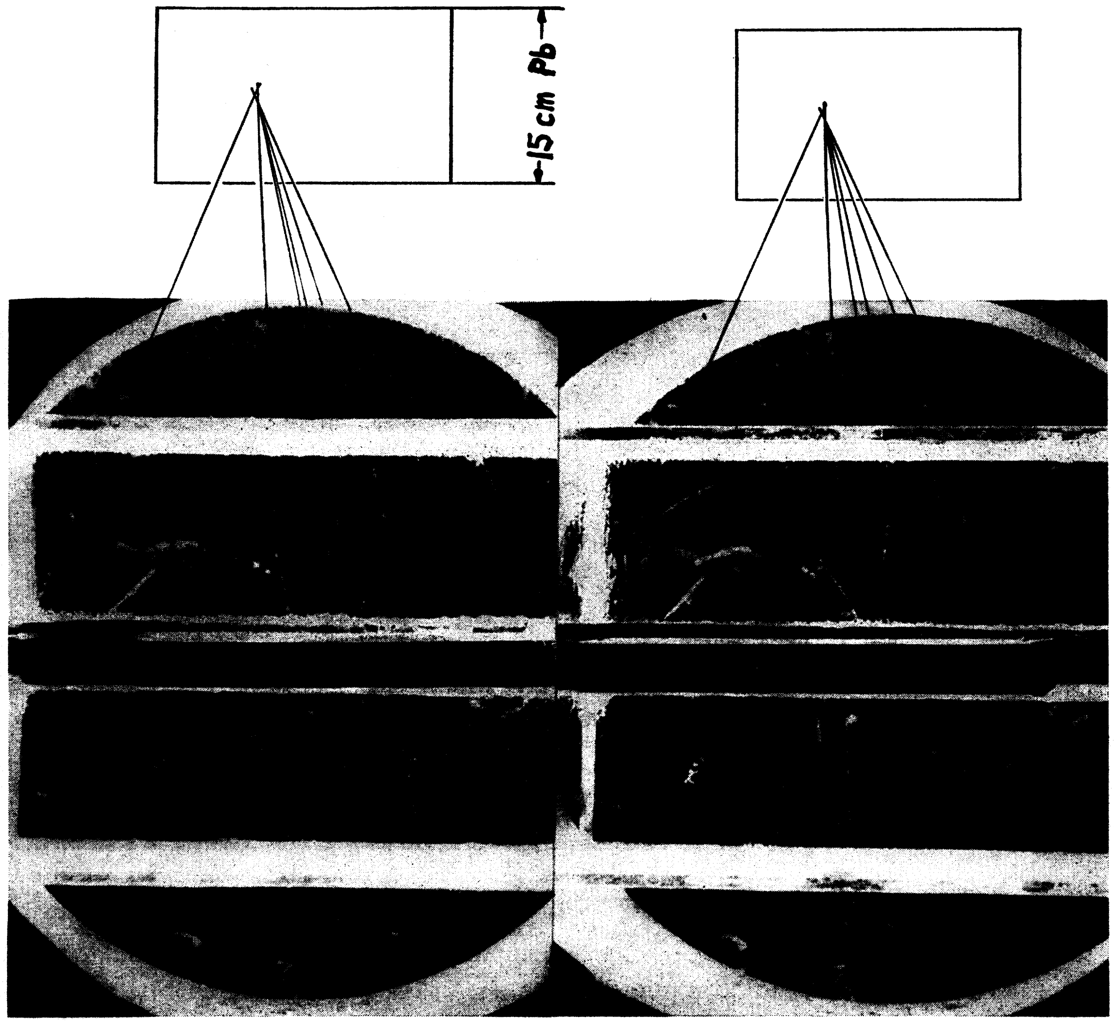


FIG. 1. A shower of 6 mesotrons produced near the center of a lead block 15 cm thick.

for random association for all angles larger than 6°. But for the smaller angles a discrepancy is present which is largest between 0° and 2°. This experiment thus confirms that there exist small angle showers of mesotrons whose angular spread ranges up to 6° or so.

Since most of the mesotrons occurring in the showers penetrate 6 cm of lead without any noticeable scattering effect, their energies must be of the order of 10^9 ev or more. This is in agreement with Jánossy's results.

For the rest of this section we shall be concerned only with the showers having their origin in the lead above the cloud chamber. From columns 7–9 of row *b* we have a rate of occurrence of about one mesotron shower for every 4000 single penetrating rays which is in agreement with previous rates observed in cloud chambers,[11–18] and also in qualitative agreement with a rate of one in 12,000 as reported by Jánossy.[10] In our arrangement 1000 traversals of single rays were observed in 5 hours. It follows that 5 mesotron showers were recorded in 100 hours which agrees with a value given by Sinha[19] for a similar experimental arrangement.

Sinha finds that the frequency of mesotron pairs is about equal to the frequency of showers containing more than two penetrating particles, while others, including ourselves (Table III, column 9), seem to have observed considerably

FIG. 2. A shower possibly containing as many as 11 mesotrons produced in 5 cm of lead.

less multiple showers than pairs. An explanation for this discrepancy may be found in the differences in geometry of the counters and cloud-chamber arrangements employed.

A serious discrepancy between these results and those of others appears in column 8, rows *b* and *e*. Both Jánossy and Sinha, observing under lead thicknesses ranging from 0 to ~20 cm, report saturation for the production of mesotron showers when the thickness of the lead absorber exceeds about 5 cm. Therefore we should expect to observe as many showers under 88 cm as were found under 15 cm. Instead we have 0.2 ± 0.1 cases for every 1000 traversals of mesotrons below 15 cm, and 1.6 ± 0.7 cases below 88 cm of lead. The ratio of these two values is 8 ± 5, while the ratio of the two lead thicknesses is 6. Thus indications are here that the number of mesotron showers is roughly proportional to the lead thickness traversed by the producing primary radiation, and that no saturation is reached up to thicknesses of 90 cm at least. However, it is felt that the large uncertainty resulting from the small number of cases observed here does not justify any further conclusions concerning this point at this time.

The most recent theory of the production of mesotrons by protons or neutrons is due to Hamilton, Heitler, and Peng,[20] and has been extended to cases of multiple showers by Jánossy.[10] In their treatment of the problem the existence of protons and neutrons of energies as high as 10^{12} ev is assumed, and reasonable agreement with Jánossy's and Sinha's experimental results is found, including the phenomenon of saturation which is not confirmed in the present article. If high energy protons or neutrons passing through or very close by nuclei of matter are responsible for the production of one or several mesotrons, a certain number of multiple mesotron showers might be expected to consist of particles which do not all have a common point of origin but

[20] J. Hamilton, W. Heitler, and H. W. Peng, Phys. Rev. 64, 78 (1943).

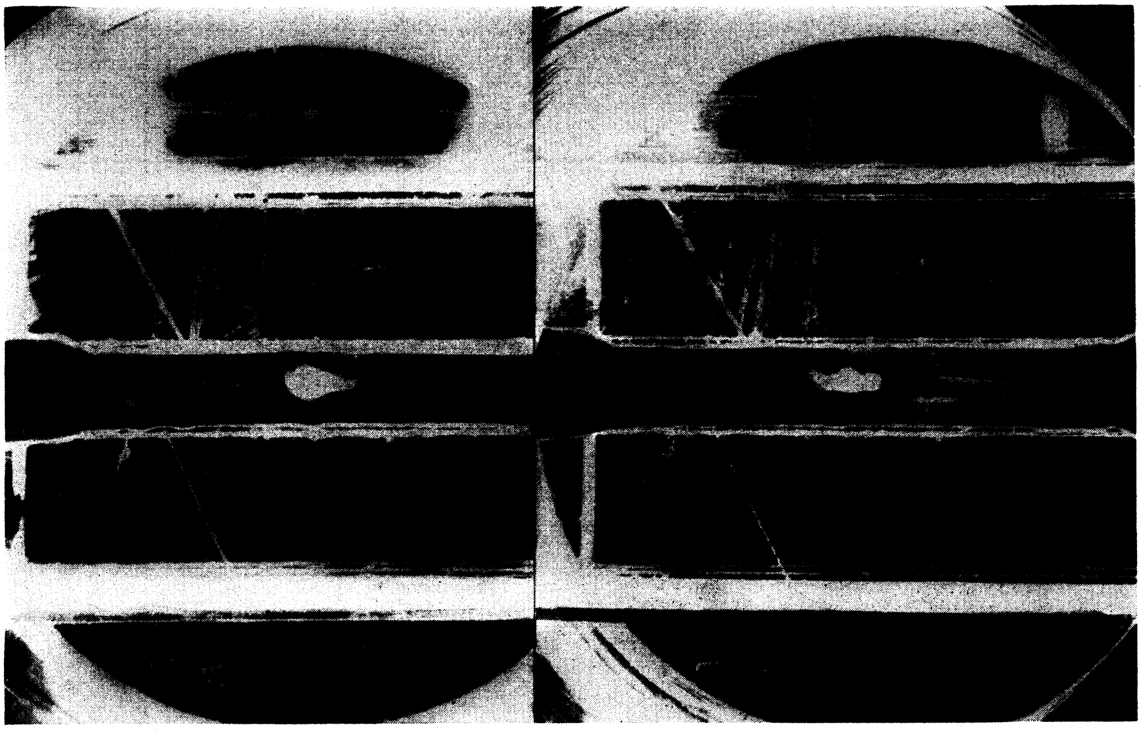


FIG. 3. A shower containing at least 4 mesotrons one of which ionizes heavily in the 3rd compartment. 3 heavily ionizing particles diverge backwards from a point near the top of the 5-cm lead plate.

were produced successively along the path of the primary. No definite case of this type has been observed so far. A process whereby protons of high energy may disintegrate spontaneously into several mesotrons in the presence of matter has been suggested by Swann.[21]

We shall now turn to a discussion of some photographs of special interest. In Fig. 1 a shower of at least 4, more probably 6, mesotrons is shown. The individual rays have been traced back to their origin, and it is seen that they intersect almost perfectly in one single point in both of the stereoscopic views. The particle at the extreme left has probably been scattered by the residual lead traversed after the production of the shower which explains the slight apparent deviation of this track from the common point of origin. Only 4 of the 6 rays definitely penetrate 6 cm of lead inside the cloud chamber while the remaining two rays are seen to traverse only one cm of lead which is not quite sufficient to ascertain that these particles are mesotrons, since it is not improbable that some electrons may penetrate one cm of lead without producing secondaries. However, the origin of the shower is found to lie near the center of the 15-cm lead block above the chamber. Thus all rays had had to traverse at least 7 cm of lead before entering the chamber. An electron of an energy sufficient to penetrate 7 cm of lead would produce a considerable number of secondaries, and in this process it would also very probably be deflected so that it could not be traced back to its origin. We therefore may identify all of the 6 particles as mesotrons produced in one single act. For the present experimental arrangement it is estimated that only one in 10^{20} photographs of this type may be expected to be due to random association of mesotrons.

During the course of these experiments one or two showers of mesotrons could have been expected to originate in the lead located inside the cloud chamber. One possible case of a mesotron shower produced in the 5-cm lead plate is shown in Fig. 2. The shower was produced by a proton or mesotron which had penetrated the 15 cm of

[21] W. F. G. Swann, Phys. Rev. **58**, 200 (1940); Phys. Rev. **60**, 470 (1941).

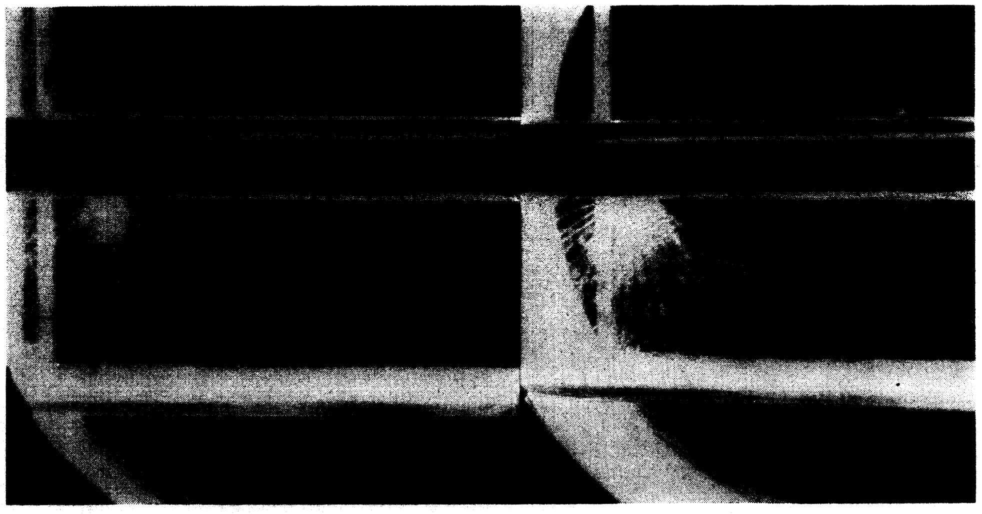


FIG. 4. A shower consisting of *ca.* 80 electrons of energies probably less than 15 Mev. No electrons of higher energies can be seen.

lead above the cloud chamber. The nature of the shower particles is doubtful because they are seen to penetrate only one cm of lead. Nevertheless indications are that some of the particles are mesotrons. One particle passing to the right ionizes 2 to 3 times as much as a fast particle and is found to stop in the one-cm lead plate. This particle is a mesotron because a proton ionizing that much could penetrate 3 or 4 cm of lead. Furthermore there are 3 rays passing through the plate without multiplication. These rays are not scattered appreciably which would usually be the case with an electron of an energy low enough to penetrate one cm of lead without multiplication. Finally the 7 particles forming the center "core" of the shower pass through the plate without being scattered. Some multiplication is present here, but most of these secondary electrons seem to be produced by one of the rays only. A calculation concerning the probability for the occurrence of a cascade shower of this structure is not possible because the energy of the individual particles is not known. But it is not impossible that this shower contains as many as 11 mesotrons produced in one single act.

TABLE IV. Particles stopping in lead.

Thickness of lead plate	Selected number of particles impinging on plate	Percent stopping
Upper, 1 cm	3100	0.3±0.1
Center, 5 cm	2700	1.8±0.2
Lower, 1 cm	2000	0.5±0.2
Upper and lower combined, 1 cm	5100	0.4±0.1

Mesotrons associated with large electron showers have been observed by Sinha.[19] In this experiment 18 large showers originating above the cloud chamber have been observed, at least 9 of which seem to contain one or more mesotrons. These showers were not further investigated since in most cases too many electrons were present to be sure of the number of mesotrons. One case containing only a moderate number of electrons is shown in Fig. 3. This shower originates at a point 14 cm inside the lead above the chamber. Associated with it are at least 4 mesotrons one of which ionizes heavily in the 3rd compartment and stops in the lower one-cm plate. If the shower reproduced in Fig. 2 were continued, it might have an appearance similar to that of the present one. The backward divergence of 3 heavily ionizing particles in the 2nd compartment is remarkable. Two of these particles are very probably protons of low energy. Showers with some slow rays passing backwards from a point in lead were observed previously by Street[11] and, of course, by several other investigators operating cloud chambers at high elevations. At the present time the most likely explanation is that a "nuclear evaporation" has been initiated by one of the shower particles.

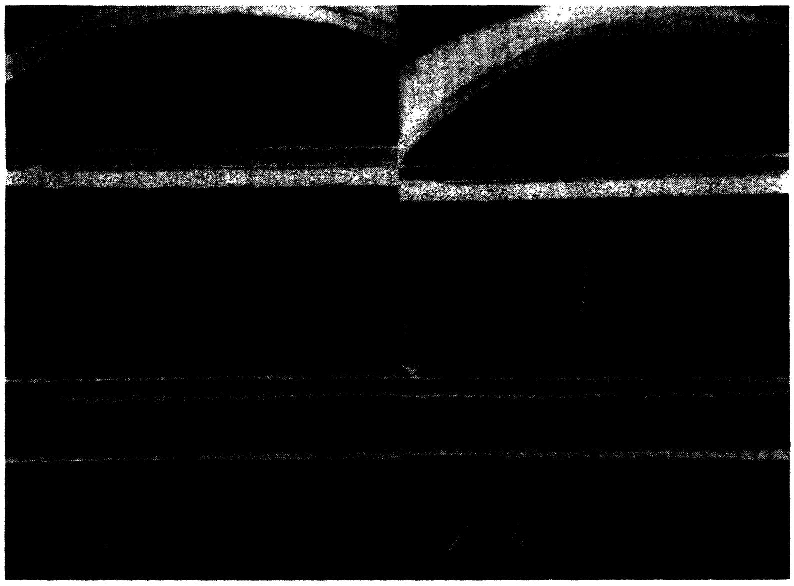


FIG. 5. A typical track of a slow proton ionizing heavily at both sides of a one-cm lead plate.

One of two observed cases of electron showers consisting of very many electrons of low energies is shown in Fig. 4. A similar picture was published by Street.[11] No ray is visible which could have been responsible for this shower. There are about 80 rays, 40 of which stop in the one-cm lead plate as can be ascertained when the picture is viewed stereoscopically, while the remaining rays pass out of view. The average direction of this shower is downward. It seems to the writer that a shower consisting of such a large number of electrons of relatively low energy ($\sim$15 Mev) with no high energy electrons at all visible would represent a very large fluctuation in terms of the cascade theory thus making the latter an improbable explanation of showers of this type. The possibility should not be excluded, therefore, that no cascade shower at all is involved.

4. Mesotrons of Low Energies

A study of slow mesotrons is of interest because of the possibility that such particles are removed from the energy spectrum by some hitherto unknown process such as capture by nuclei.

Investigating the relative stopping powers of lead and carbon for mesotrons Pomerantz and Johnson[22] found that, within the experimental uncertainties, no irregularity exists for mesotrons of energies as low as 40 Mev. The present data enable one to extend these studies to particles with energies below 20 Mev.

Table IV gives the percentages of particles stopped in the respective lead plates. The table has been compiled from a number of pictures selected with regard to clarity of the tracks and uniformity of background fog. From the photographs taken with the magnetic field of 1150 oersteds it is found that about 5 percent of the single particles stopped are electrons. This is negligible in view of the rather large probable errors.

Since the energy distribution of mesotrons at sea level has a maximum near 10^9 ev, which corresponds to a range of about 70 cm of lead, one would expect to find many more slow

TABLE V. Heavily ionizing particles.

Total number of tracks of penetrating particles in all compartments	Heavily ionized either above or below a 1-cm lead plate (Mesotron or proton)	Heavy above and below a 1-cm lead plate (Proton)
60,000	45	40

[22] M. A. Pomerantz and T. H. Johnson, Phys. Rev. 59, 143 (1941).

mesotrons under 88 cm of lead than are observed under 15 cm since mesotron decay can be neglected in dense materials. Actually the same number is present under both absorbers. It is believed that the missing particles have been deflected away from the cloud chamber by the lead absorber as was discussed in the first part of this article.

The ratio of the number of mesotrons stopped in the 5-cm plate to the number stopped in one cm should amount to approximately 5:1 if no abnormality is present. From the 3rd column of Table IV one actually obtains a ratio of $(1.8\pm0.2)/(0.4\pm0.1)=4.5\pm1.1$. The energy of a mesotron just stopped by 1 cm of lead is 30 Mev. Thus no irregularity is found for mesotrons below this energy. The value of ~ 0.4 percent found here for the fraction of the total mesotron component stopped by one cm of lead agrees with a value obtained from the data of Pomerantz and Johnson, making use of their correction factor for scattering.

Mesotrons with energies below about 20 Mev produce considerably more ions along their path than mesotrons of higher energies. The heavily ionized tracks are easily recognized by direct inspection. In the following, an analysis of these tracks is given. Here the picture is complicated by the presence of slow, and therefore heavily ionizing, protons whose ranges are 9 times as long as that of a mesotron of a rest energy of 10^8 ev producing the same density of ionization.

The number of heavily ionized tracks found in the 4 compartments of the cloud chamber is given in Table V. Only single particles which could have passed through the counters above the chamber have been included. Every particle passing through all 4 compartments of the chamber contributes 4 to the grand total of 60,000 tracks of penetrating particles observed. A particle which ionizes heavily either above or below one of the one-cm lead plates is included in the total of 45 counted. Such a particle could either be a mesotron or a proton. A particle seen to ionize heavily at both sides of a one-cm plate must be a proton,[23] thus contributing 2 to the total of 40 given in the table. A typical photograph of a proton track is shown in Fig. 5.

[23] T. H. Johnson, J. G. Barry, and R. P. Shutt, Phys. Rev. 57, 1047L (1940).

Arranging the data in the described manner facilitates the following calculation. N_m shall stand for the number of tracks which could be due either to mesotrons or to protons, N_p is the number of tracks definitely due to protons. n_m is the actual number of slow mesotrons present in a compartment with ranges below a certain limit, while the number of protons with ranges below the same limit has been called n_p. The ratio of proton-mass/mesotron-mass is $\mu=9$. The energy loss by ionization of a slow particle does not depend on its mass. Therefore the chance for detection of a proton is μ times as large as that for detection of a mesotron, and we can put

$$n_m+\mu n_p=N_m+N_p. \tag{16}$$

The maximum residual ranges of protons and mesotrons included in Table V are $R_p(q)$ and $R_m(q)$, respectively, where q stands for the minimum density of ionization still identified as abnormally heavy. Assuming that the range distributions of the protons and mesotrons are constant within the narrow limits considered here, we can write

$$R_p(q)=\mu R_m(q). \tag{17}$$

In order to be recognized, a slow proton has to penetrate $t(=1)$ centimeters of lead. Therefore we can observe only $R_p(q)-t$ of the total range $R_p(q)$ through which a proton is heavily ionizing, and we have

$$n_p\mu\frac{R_p(q)-t}{R_p(q)}=N_p. \tag{18}$$

From Eqs. (16) to (18) it follows that

$$n_m=N_m-N_p\frac{t}{\mu R_m(q)-t} \tag{19}$$

and

$$n_p=N_p\frac{R_m(q)}{\mu R_m(q)-t}. \tag{20}$$

Thus n_m and n_p can be calculated if some feasible assumption for $R_m(q)$ can be made. If mesotrons did not exist, then $n_m=0$, and from Eq. (19) we would find $R_m(q)=0.21\pm0.03$ cm of lead, by using $N_m=45$, $N_p=40$, and $t=1$ cm. From the theory of ionization follows $q=(2.8\pm0.03)\times q_{\min}$, where $q_{\min}$ is the density of ionization of a fast particle producing minimum ionization. Thus, if q had the given value, our data would be consistent even if all the heavily ionized tracks were due to protons. But there are indications that a lower value for q must be chosen. Figure 6 shows one out of several obtained photographs of a single, fast ray producing a collision electron in the 5-cm lead plate. It is seen that the track of the secondary coincides with that of the main ray in one of the stereoscopic photographs. The resulting double track shows that, under favorable conditions, a ray with a density of ionization of $q=2\times q_{\min}$ may still be recognized and thus be included among those listed in the table. In this case $R_m(q)$ becomes 0.5 cm of lead. But below $q\approx 3q_{\min}$ it is quite possible that some tracks may have been omitted and thus are not included in our results. Assuming that no tracks above $q=3q_{\min}$ have been omitted, and all below $q=2q_{\min}$, it has been estimated that the results for n_m and n_p calculated so far should be multiplied by a factor of 1.4. Furthermore n_m and n_p must be multiplied by estimated factors of 1.3 and 1.1, respectively, to correct for a certain number of particles scattered out of the field of view by the lead plates, an effect which is particularly serious at the low energies considered here. From (19) and (20), with $N_m=45\pm 7$, $N_p=40\pm 10$, $R_m(q)=0.5$ cm, $t=1$ cm, and the corrections given we obtain

$$n_m=62\pm 13 \tag{21}$$

and

$$n_p=9\pm 2, \tag{22}$$

or, if n_m is expressed as a fraction of the total number of penetrating rays observed,

$$n_m=(0.10\pm 0.02)\text{ percent.} \tag{23}$$

Now, the number of particles stopped by 1 cm of lead was (0.4 ± 0.1) percent as determined at the beginning of this section. Thus we should have expected a value of $n_m=(0.20\pm 0.05)$ percent which is in sufficient agreement with the value (23) found in view of the rather large estimated corrections, although there may be some slight evidence for a removal of mesotrons of low energies.

Next we shall compare the number of slow protons with that of the slow mesotrons of equal range. From (21) and (22) we find that $n_p/(n_m+n_p)=(12\pm 3)$ percent for a range of 0.5 cm of lead, and again making use of (20) one gets $n_p/(n_m+n_p)=(7\pm 2)$ percent for a range of 4.5 cm. Mesotrons of the latter range do not ionize heavily, of course, and the value of (0.4 ± 0.1) percent for the mesotrons stopped by one cm of lead again has been used. The two values of $n_p/(n_m+n_p)$ agree within the uncertainties. If we assume that slow protons are not removed by lead atoms, this agreement constitutes additional evidence that the number of slow mesotrons is about as large as expected, leaving only a slight indication that mesotrons

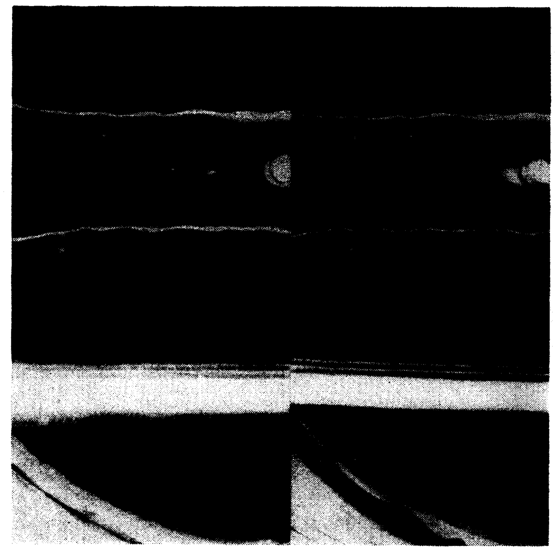


FIG. 6. The left picture shows a case of a track of a secondary electron superimposed upon the track of a fast primary particle, giving the impression of a doubly ionized track.

with energies below 20 Mev are removed by some effect.

The number of protons of low energy found here is in agreement with the results of Montgomery *et al.*[24]

The author wishes to express his appreciation to Dr. T. H. Johnson whose never-tiring interest and advice have contributed greatly to this work. Thanks are also due to Drs. S. DeBenedetti and W. F. G. Swann for advice and enlightening conversations on some of the subjects covered in this article, and to Messrs. M. H. Hornstine and W. C. Sheppard for their assistance in operating the cloud chamber.

Most of the present work has been supported financially by the Carnegie Institution of Washington.

[24] C. G. Montgomery, D. D. Montgomery, W. E. Ramsey, and W. F. G. Swann, Phys. Rev. **50**, 403 (1936).

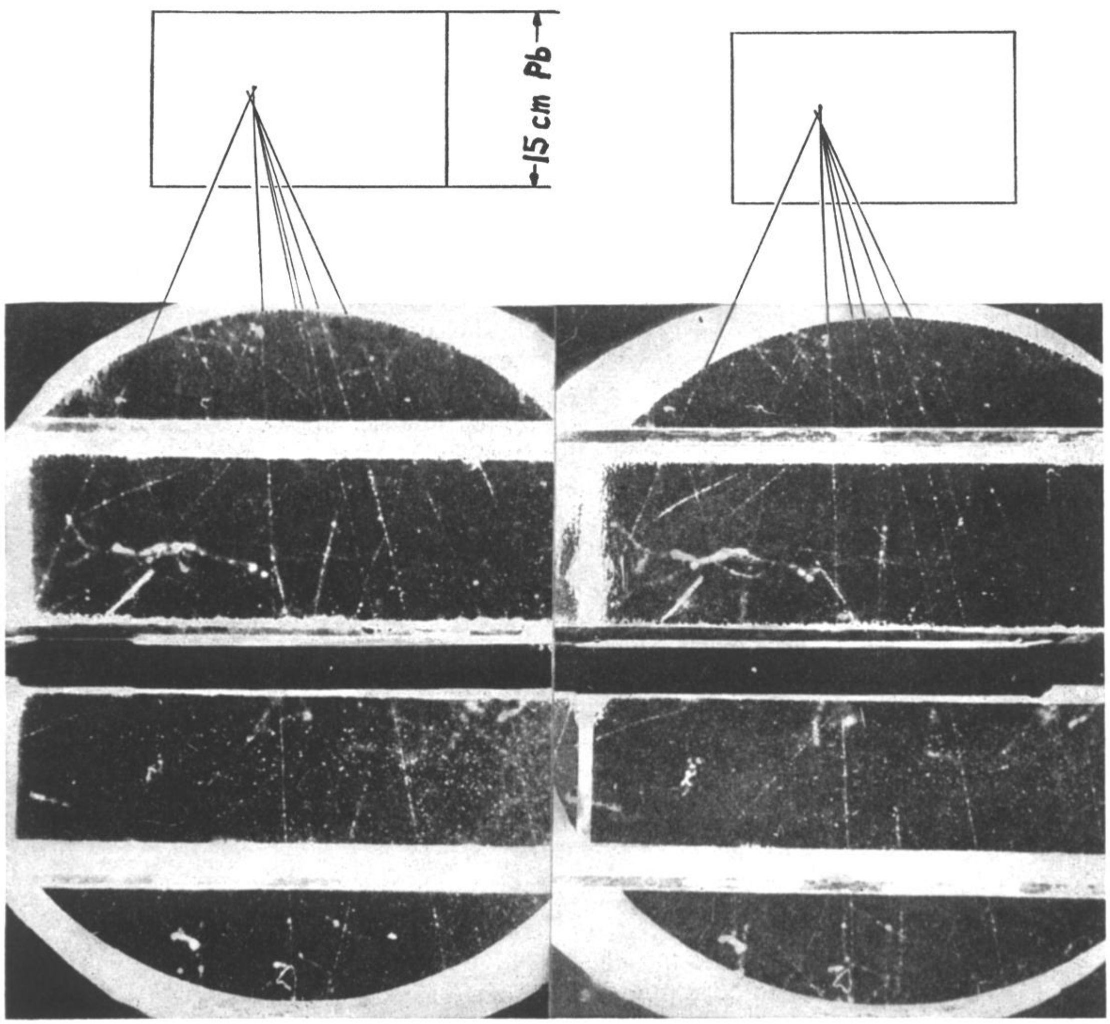


FIG. 1. A shower of 6 mesotrons produced near the center of a lead block 15 cm thick.

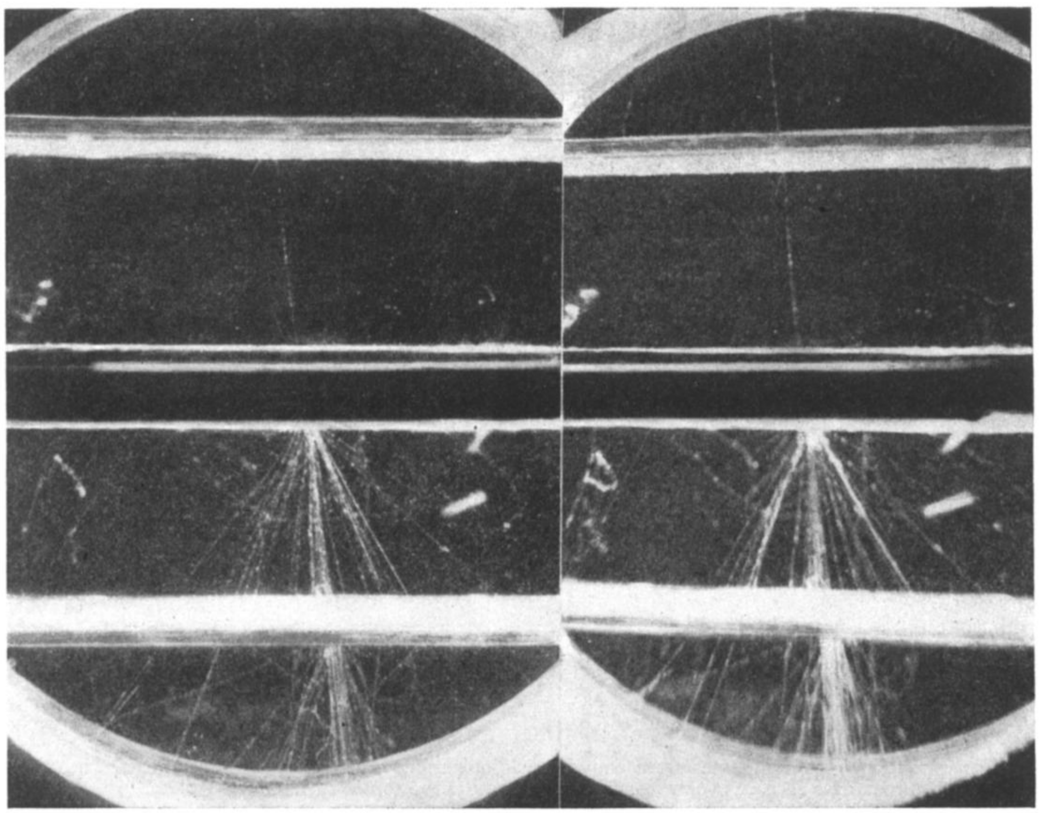


FIG. 2. A shower possibly containing as many as 11 mesotrons produced in 5 cm of lead.

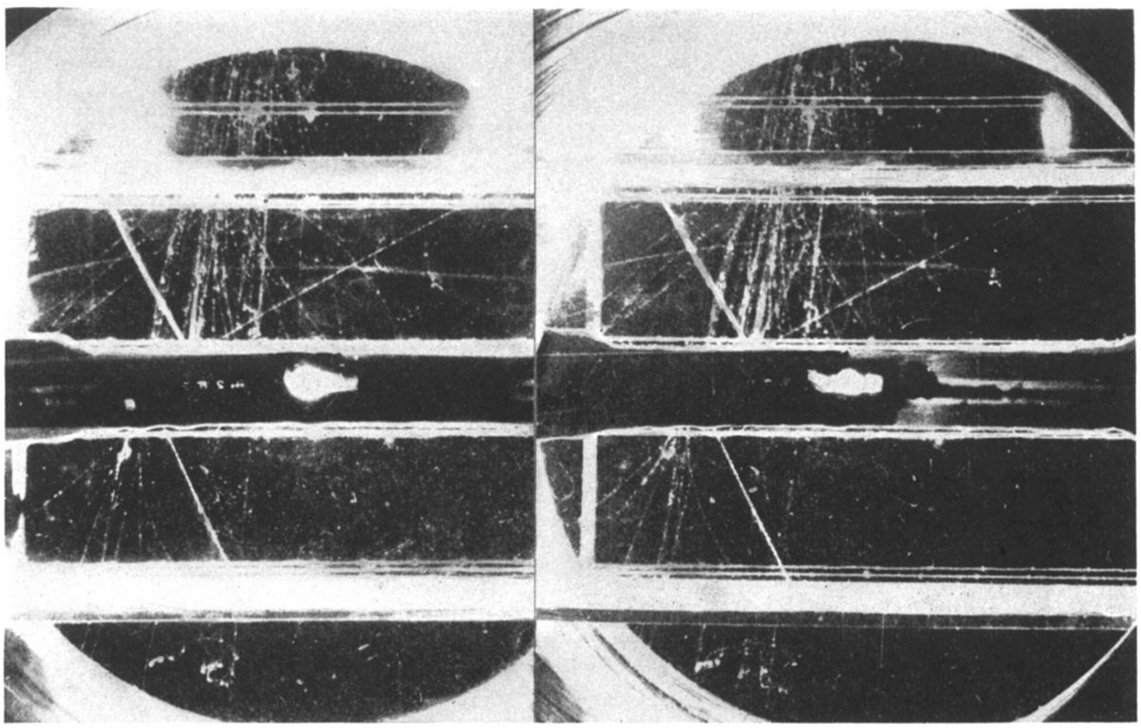


FIG. 3. A shower containing at least 4 mesotrons one of which ionizes heavily in the 3rd compartment. 3 heavily ionizing particles diverge backwards from a point near the top of the 5-cm lead plate.

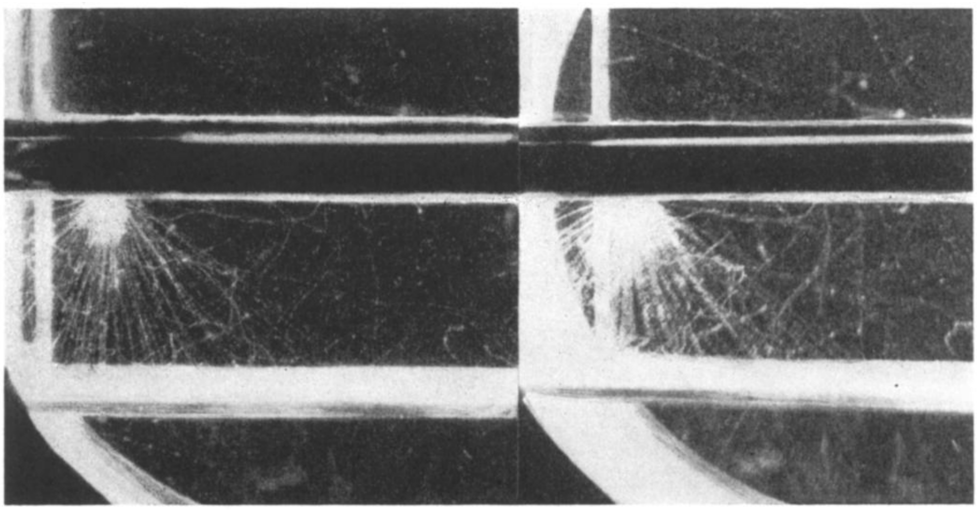


FIG. 4. A shower consisting of *ca.* 80 electrons of energies probably less than 15 Mev. No electrons of higher energies can be seen.

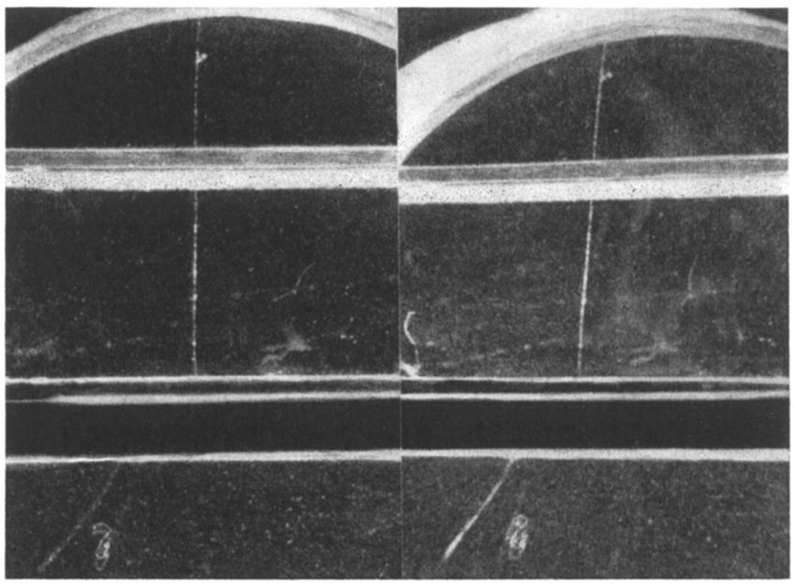
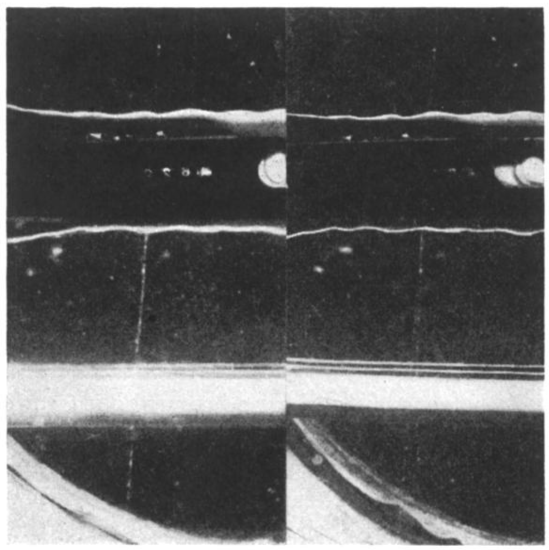


FIG. 5. A typical track of a slow proton ionizing heavily at both sides of a one-cm lead plate.



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