Mass Measurements of Slow Cosmic-Ray Mesons

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By observing the ionization and subsequent range of individual charged slow particles, using two cloud chambers set one upon another, we have determined the mass of 36 slow particles in the soft component whose ranges are less than 2.5 mm in aluminum and the mass of 12 particles in the hard component at 300 meters altitude.

With regard to the measured masses, we observed a significant difference between the results in the soft component and those in the hard component. In the latter, the 21 masses can be interpreted as representing 4 proton and 8 μ-meson masses. In the former, 11 masses are consistent with the proton mass, whereas the remaining 25, ranging over values from 54 to 649 electron masses, can hardly be interpreted as the observation of μ mesons only.

The results seem to indicate the possible existence of at least two new mesons, the masses of which would be about 100 and 600 electron masses, respectively.

INTRODUCTION

SEVERAL experimental studies[1] which have been recently made on the mass of cosmic-ray particles at sea level, have made it clear that they are composed of protons, μ mesons, and electrons. However, these studies have determined the masses of particles within a limited range region where the μ-meson intensity is near maximum, and the particles in extremely low and extremely high energy regions escaped these mass determinations. Merkle *et al.*[2] have measured the masses of particles in a comparatively short range region from 4 to 13 cm of lead; however, there are no data for the particles of shorter ranges, except for a few early ones, some of which[3] appeared to be inconsistent with the μ-meson mass.

Considering the complexity and variety of cosmic-ray phenomena in the atmosphere which have not yet been surveyed completely by experimental studies, we decided to test whether new hitherto unknown mesons exist among the slow particles in the soft component near sea level.

In our previous study,[4] we measured the β-decay probability of the slow mesons which stopped within a 2-mm carbon plate. It appeared that the result gives evidence for the existence of new mesons stable against β decay. On the basis of that result, this study has been carried out to determine their mass. To give a confirmation of the above view[5] that the new mesons exist only in the extremely low-energy region, we have also made mass determination for the particles in the hard component, filtering out the soft radiation with 30 cm of lead, using the same apparatus and the same method, and have made a comparison between the results.

[1] W. B. Fretter, Phys. Rev. **70**, 625 (1946); J. G. Retallack and R. B. Brode, Phys. Rev. **75**, 1716 (1949).
[2] Merkle, Goldwasser, and Brode, Phys. Rev. **79**, 926 (1950).
[3] A. J. Ruhling and H. R. Crane, Phys. Rev. **53**, 266 (1938).
[4] Inoki, Yasaki, and Matsukawa, Phys. Rev. **86**, 129 (1952).
[5] Yasaki, Inoki, and Matsukawa, Proc. of Faculty of Liberal Arts and Education (Yamanashi University Press, Kofu, 1952), No. 1.

EXPERIMENTAL APPARATUS

The arrangement of the apparatus is illustrated in Fig. 1. The upper cloud chamber CH_1, which is a rear illumination type, was expanded slowly in both side directions by using two bellows B of 150-mm diameter. This chamber was used for the ionization measurement by drop counting of diffused tracks. The effective size of the chamber was 300 mm in length, 80 mm in width, and 50 mm in depth, and it was set with the 300-mm $\times$80-mm effective faces vertical. A clearing field of 200 volts was supplied between two drilled plates E which produce a uniform electric field between them with the aid of two potential dividers R made of series resistance.

This field voltage was reduced from 200 to 60 volts as soon as possible after the passage of a slow particle through the proportional counters C_1 and C_2. A window of dimensions 400 mm$\times$30 mm was provided in each of the upper and lower walls of the chamber; the upper wall was packed against air with a 0.1-mm aluminum foil F_1 and the lower with a 0.2-mm aluminum foil F_2. The chamber was filled with air and saturated vapor of a 3:1 mixture of propyl and ethyl alcohol to a total pressure of 380 mm Hg at 15°C. Illumination was given with two argon flash lamps, each of which was excited by the discharge of a condenser of 20-μf capacity charged to 5000 volts. The tracks were photographed using a Serenar lens of 50-mm focal length at an aperture of $f/8$. During the cloud chamber expansion, the width of a counter-controlled track was diffused to

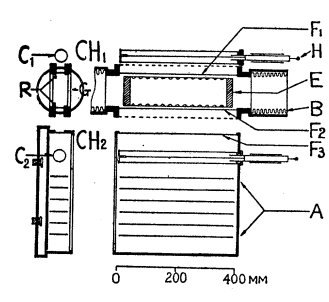


FIG. 1. Schematic arrangement of the apparatus showing the cloud chambers, CH_1, CH_2; the proportional counters, C_1, C_2; the plates, A; the aluminum foils, F_1, F_2, F_3; the bellows, B; the drilled plates, E; the resistance series, R; and the glass G.

about 6 mm and it was separated simultaneously into two parallel columns of positive and negative ions about 16 mm apart.

The lower multiplate cloud chamber CH_2 contained the proportional counter C_2 and 6 aluminum plates A each 0.3-mm thick, or 8 stylon plates (an organic compound of carbon and hydrogen); each of the 4 top stylon plates was 0.36-mm aluminum equivalent in thickness, and each of the remaining four was 0.73-mm aluminum equivalent. The chamber was 400 mm square by 80 mm deep. A window of dimensions 400 mm $\times$30 mm, which was packed against air with a 0.05-mm aluminum foil F_3, was provided in the upper wall of the chamber. The chamber was filled with air and saturated vapor of ethyl alcohol to a total pressure of 710 mm Hg at 15°C. Stereoscopic multiplate cloud chamber photographs were taken, using a front camera and a side camera 55 cm apart.

The proportional counters C_1 and C_2 were used not only to define the solid angle of incident particles but also to select them as to ionization. Each of the counter tubes, which are 40 mm in diameter, 340 mm in effective length, and 0.2 mm in wall thickness of aluminum, was filled with methane gas of 660-mm Hg pressure at 15°C. A stabilized voltage of 5000 volts was supplied to the terminal H of the central wire, 0.3 mm in diameter, through a high resistance of 50 megohms. All the apparatus was enclosed in a box inside which the temperature was kept at 15°±0.2°C during the winter and at 35°±0.4°C during the summer. The measured ionization at the latter temperature was corrected to the ionization at 15°C.

OBSERVATIONS

A set of preliminary observations was made for 50 fast cosmic-ray particles, penetrating 5 cm of lead. Their average ionization was 50.7 drops per cm in air of 700-mm Hg pressure at 15°C, when clusters larger than 40 drops were excluded. The probable error of the ionization for an individual track was 11 percent, provided that the 50 fast particles had the same ionization. By the relation of energy to ionization, their

TABLE I. Mass measurement for particles in the soft component, carried out in the first experiment. In the first column, track numbers followed by an asterisk refer to particles which emit a decay particle, and those enclosed with parentheses probably have systematic errors in either ionization or range. The plate number zero means that the particle stopped in the lower wall of the counter inside the lower chamber.

Track number	Plate number in which particle stopped	Deviation from the center line (mm) X_0	X_1	X_2	Range in aluminum R(mm)	Probable error in range ΔR(mm)	Total number of drops N	Length of track measured L(cm)	Ionization in minimum ionization units I	Probable error in ionization ΔI	Mass in electron mass units M	Probable error in the mass ΔM
1*	5	−4	−7	−10	2.49	0.08	644	6.7	4.8	0.2	234	21
2	6	4	1	−1	2.75	0.08	376	5.3	3.6	0.2	135	15
3	6	18	19	19								
4	6	−13	−13	−12	2.77	0.08	1045	7.4	7.2	0.2	649	45
5	2	8	12	15	1.48	0.08	888	6.4	7.0	0.2	318	29
(8)	2	−1	−1	−1	1.29	0.08	583	6.7	4.3	0.2	93	11
9	6	10	10	11	2.65	0.08	701	5.5	6.5	0.3	465	41
11	3	−12	−10	−9	1.66	0.08	608	5.8	5.2	0.2	189	18
13	1	−12	−14	−16	1.32	0.10	1250	6.9	9.2	0.3	583	60
14	3	2	2	1	1.59	0.08	858	5.0	8.6	0.3	600	55
15	2	−20	−18	−17								
16	3	−3	−10	−13	1.86	0.09	349	4.6	3.8	0.2	103	14
17	3	0	−3	−5	1.66	0.08	575	7.4	4.0	0.2	105	11
(19)	1	24	14	6	1.05	0.09	386	3.4	5.7	0.3	141	21
20	6	0	−2	−3	2.55	0.08	531	6.1	4.3	0.2	194	19
21	2	0	10	19	1.93	0.09	1012	7.7	6.6	0.2	364	31
(22)	2	16	9	2	1.30	0.08	754	5.8	6.5	0.3	236	25
23	1	−2	−2	−2	1.07	0.09	2767	8.0	18.2	0.4	2120	226
25	2	−11	−8	−5	1.44	0.10	1822	6.3	15.1	0.4	1870	173
26	2	12	13	14	1.42	0.08	1639	5.2	16.5	0.4	2260	188
27	4	2	3	7	1.97	0.08	1716	6.4	13.6	0.4	2020	140
28	5	−6	−7	−8	2.30	0.08	1175	5.0	11.8	0.4	1730	129
29	3	0	−6	−10	1.96	0.10	2165	8.8	12.6	0.3	1700	126
30	3	−4	−8	−13	1.59	0.08	814	7.4	5.5	0.2	200	18
31	2	−15	−15	−15	1.50	0.08	653	4.7	7.0	0.3	323	33
32	4	−5	−8	−11	1.99	0.08	1092	7.1	7.8	0.3	574	45
33	4	12	8	4	1.95	0.08	1772	7.2	12.5	0.3	1650	113
34	0	8	12	15	0.81	0.09	682	8.5	4.1	0.2	54	8
35	4	−4	1	6	2.04	0.08	904	7.2	6.3	0.2	337	28
36	4	4	8	12	2.01	0.08	890	5.6	8.0	0.3	628	52
(37)	4	−19	−11	−4	2.01	0.08	465	7.7	2.9	0.2	60	8
38	1	6	7	8	1.11	0.09	2319	7.2	16.6	0.4	1790	189
39	6	0	5	8	2.77	0.09	1585	7.7	10.5	0.3	1630	108
40	air	−8	−9	−10	1.20	0.00	637	7.4	4.2	0.2	82	10
41	2	1	−2	−6	1.41	0.08	1337	4.5	15.2	0.4	1850	165
42	2	10	2	−6	1.55	0.09	855	6.3	6.9	0.2	323	32
43	1	9	7	6	1.01	0.08	1207	5.7	10.8	0.3	645	72
44	2	2	−4	−8	1.63	0.09	2246	8.0	14.4	0.3	1880	157

TABLE II. Mass measurement for particles in the hard component, carried out in the second experiment. In the first column, track numbers followed by an asterisk refer to particles which emit a decay particle, and those enclosed with parentheses probably have systematic errors in either ionization or range.

Track number	Plate number in which particle stopped	Deviation from the center line (mm) X_0	X_1	X_2	Range in aluminum equivalent R(mm)	Probable error in range ΔR(mm)	Total number of drops N	Length of track measured L(cm)	Ionization in minimum ionization units I	Probable error in ionization ΔI	Mass in electron mass units M	Probable error in the mass ΔM
1*	2	−1	−2	−3	1.36	0.09	829	7.2	5.7	0.2	186	18
(2)	7	12	14	16	5.51	0.16	820	6.4	5.6	0.2	775	60
3*	2	12	12	12	1.95	0.16	779	7.1	5.1	0.2	191	23
4*	1	14	4	−4	1.19	0.18	961	7.2	6.2	0.2	192	37
(5)	4	−17	−9	−1	2.12	0.09	1651	5.8	13.1	0.3	1970	137
6	2	10	6	2	1.38	0.09	1708	5.6	13.6	0.3	1410	129
(7*)	4	3	−1	−5	2.19	0.09	571	6.9	3.7	0.2	112	12
8	7	−6	−7	−9	4.00	0.20	636	6.9	4.0	0.2	250	43
(9)	5	−19	−10	−2	2.70	0.16	511	6.9	3.2	0.1	100	11
10	1	0	−5	−10	1.05	0.09	2032	5.6	16.2	0.4	1600	177
11	5	−3	−5	−5	2.62	0.16	713	6.9	4.4	0.2	206	22
12	6	0	−6	−11	3.30	0.16	747	6.7	4.8	0.2	308	27

ionization is not the same and show a slight relativistic increase.

The ratio of positive to negative drops in all tracks was smaller than 3:1. When the ratio was decreased to about 1:1, no appreciable increase of the average ionization of positive ion tracks was observed. That means the condensation efficiency on positive ions is about 100 percent in the ratio of 3:1. However, to be on the safe side, the ratio was kept smaller than 2:1 throughout the whole period of the observations. Clusters larger than 40 drops were also excluded in the measurements.

As the criterion for exclusion of these clusters, discrimination of which in dense tracks was somewhat difficult by their appearance alone, the following procedure was applied. Each of the diffused tracks was printed in an enlargement to 3.2 times the full size. Then, dividing the positive ion track into small sections, each of 5-mm length, the drop number per section and their mean value n were obtained by drop counting. Any two successive sections whose total number of drops was larger than $2n+40$ were excluded from the measurement, as they were considered to show the fluctuation caused by the presence of clusters larger than 40 drops in about 1 cm square on the photograph, because the Gaussian fluctuation of $2n$ drops should be far smaller than 40. The total number of drops N of the individual track was obtained by subtracting background drops neighboring it from the total number of drops of all sections which passed the above excluding criterion. We used the minimum ionization, 20.7 ion pairs per cm in air and alcohol vapor mixture of 380-mm Hg pressure at 15°C, which is converted into 40 ion pairs at N.T.P. in dry air. The minimum ionization was determined from the measured ionization of 13 protons, described later. We neglected the overlapping correction for ionization measurement, since the computed value[6] of it was $0.0004I^2$. Following the method of Hazen,[7] the statistical error in the ionization was estimated by the assumption that it is caused essentially by the statistical fluctuation of the number of primary ions which was assumed to be 40 percent of the measured ionization. The probable error ΔI, therefore, was computed by a relation, $\Delta I/I=0.67/(0.4N)^{\frac{1}{2}}$, where I is the ionization in units of the minimum ionization. The value of N, I, and ΔI are shown in Tables I and II.

In Fig. 2, the ZZ' axis is a vertical line passing through the center of the two 30-mm×400-mm windows. The deviation of each individual track from the ZZ' axis, projected on the plane, at the counter wall X_2 and at the window of the lower chamber X_1, was determined from the stereoscopic photographs of the track. Its deviation at the window of the upper chamber X_0 was estimated by an extension of the path of the particle PN, assuming that all particles penetrated the aluminum foil F_3 without any scattering. In Table I and Table II, the values of X_0, X_1, and X_2 for the individual tracks are shown. A minus sign before a value of X indicates backward deviation.

The range of an individual particle was computed as the sum of the path lengths in the foils, the counter

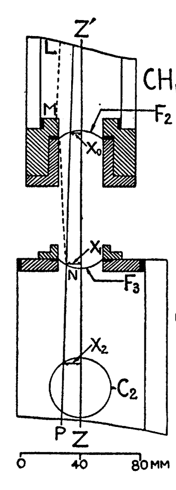


FIG. 2. A cross section of the windows of the upper and the lower chamber, illustrating the path of a particle between them. The dotted line LMN shows the path of a particle scattered at the window frame.

[6] R. H. Frost and C. E. Nielsen, Phys. Rev. 91, 864 (1953).
[7] W. E. Hazen, Phys. Rev. 65, 259 (1944).

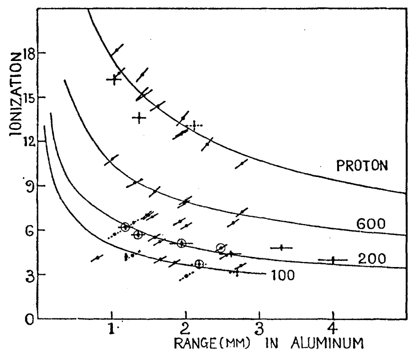


FIG. 3. Curves of ionization *versus* range, and the experimental observations. The projections of the line extending to both sides of each point show on the coordinate axes the probable errors, $\pm\Delta I$ and $\pm\Delta R$. The observations in the first experiment are represented by the points having extended diagonal lines and those in the second experiment are represented by the points having extended horizontal and vertical lines. In both cases, each observation with uncertain error is represented by points having extended dotted lines, and each point enclosed with a small circle represents the observation of a decaying meson.

wall, the plates, and the air traversed by the particle, assuming that it was stopped in the middle of the thickness of the stopping plate. As the probable error in range, we used one-fourth the thickness of the plate, divided by the cosine of the angle between the normal to the surface of the plate and the direction of the track.

On the assumption that the charge of the individual particle is identical with that of the electron, each mass was computed with the aid of the curves relating range to ionization;[8] the results are shown in Fig. 3. The probable error in the mass was computed by using the relation $M \propto RI^2$.

In the first experiment, the apparatus was operated without any absorber above it except a thin roof whose thickness was about 5-mm lead equivalent, and with 6 aluminum plates inside the lower chamber. During an effective working period of 400 hours, 262 slow particles of ionization larger than 3 times minimum were observed by both chambers, and 44 of these were stopped in the plates. 6 tracks, probably proton tracks, out of 44 were omitted since the drop counting of these was difficult due to a dimness of their drop figures caused by a blur in the glass of the chamber. Two tracks, No. 3 and No. 15 in Table I, passing outside the window of the lower chamber, were also omitted. Measurements were made on the remaining 36 tracks. 11 out of 36 masses are consistent, within the error, with the proton mass, whereas the remaining 25 spread over values from 54 to 649, as seen in Table I and in Fig. 4. Among the 25 tracks, No. 8 lacks a negative ion track and the other three tracks, No. 19, No. 22, and No. 37, may have entered into the lower chamber by scattering at the window frame of the upper chamber, as the passage along *LMNP* in Fig. 2 did, for instance.

[8] D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, 1949), Appendix E.

Therefore they probably have systematic errors in either ionization or range, causing uncertain masses smaller than the true one. However, by an estimation of their track densities in the lower chamber, they are probably mesons.

In the second experiment, the apparatus was operated by placing 30 cm of lead immediately above the proportional counter C_1 ,and using 8 stylon plates, or 6 stylon plates during first 20 hours, inside the lower chamber. During the effective working period of 370 hours, 59 slow particles of ionizations larger than 3 times minimum were observed and 13 of them were stopped in the plates. One track, probably that of a proton, was omitted due to a dimness of the drop figure. Measurement were made on the remaining 12. Among the 12 tracks, 6 masses were obtained whose average, 222 ± 14, is consistent, within the error, with the μ meson mass. Two tracks, No. 5 and No. 9, have the same kind of error as No. 19 in Table I. Two other tracks, No. 7 and No. 2, show diffused tracks, in which the number of negative ion drops is less than $\frac{1}{3}$ of the positive ones. Therefore these 4 also have uncertain masses. However, two of the above tracks, No. 7 and No. 9, should represent μ mesons, because one of these shows a decay particle and the other is not dense enough for protons in the lower chamber. The average mass of the 13 protons in Tables I and II is 1810 ± 39. The probable error in the mass of an individual proton, estimated from the mass distribution, is 142 which is consistent, within the error, with the mean value, 153, of $|\Delta M|$ of the 13 protons.

INTERPRETATION

Concerning not only the mass but also the intensity, there is a significant difference between the results of the first experiment and those of the second, the latter being consistent with the results of other investigators. By a statistical analysis, rejecting the uncertain masses, the two results do not represent two groups of measured values for the same set of events, with a level of signif-

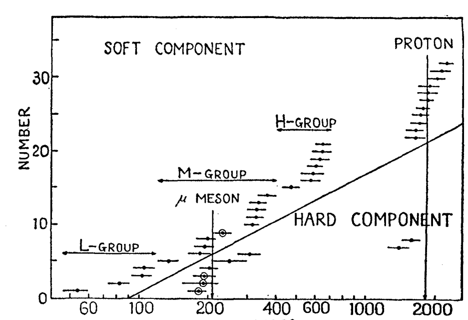


FIG. 4. Integral mass spectra showing the measured masses, arranged in order of increasing mass, obtained in the first and second experiments. Each point represents the measured mass on a logarithmic scale and the length of the lines extended on both sides of each point represents the probable error of the measured mass, $\pm\Delta M$. Each point enclosed with a small circle represents the measured mass of a decaying meson.

TABLE III. The observed intensities of the particles. The number of fast particles in the second column is a roughly estimated number of all fast particles penetrating the effective space of both chambers during the effective working period. The actual intensities of the slow particles in the ionization region, $3<I<6$, are about twice the observed ones, because the selection efficiency of these particles out of the fast ones, obtained by twofold coincidence of the proportional counters, was about 0.5.

	Effective working period (hours)	Number of fast particles penetrating the plates	Number of slow particles penetrating the plates $3<I$	Effective g/cm² of the plates used	Number of slow particles stopped in the plates		Observed number of decaying mesons	Expected number of according to the meson data of Merkle *et al.*
					Protons	Mesons		
1st exp.	400	96 000	220	0.49 (aluminum)	17	25	1	2
2nd exp.	370	62 000	46	1.18 (stylon)	5	8	4	

icance of one percent. In addition to this discrepancy, a great discrepancy exists in the first experiment between the observed meson intensity and the estimated μ-meson intensity, as is shown in Table III. Therefore, the observation of 25 "mesons" seems to imply the existence of new mesons as a necessary consequence. However, the foregoing view rests on the assumption that the errors of measurement are entirely statistical. There are a number of possible errors other than the statistical ones, as described below (see Figs. 5 and 6).

(1) If a proton or a μ meson is scattered at the window frame of the upper chamber and enters into the lower chamber, scattering again in the 0.05-mm aluminum foil at its top window, then the estimated range is too small by the amount of the path length inside the frame, and this results in too low a value of the mass. The deviations from the center line X_0 in Tables I and II, were obtained by assuming zero scattering angle of the incident particles in the 0.05-mm foil mentioned previously. The theoretical scattering angle in the foil for a proton or a μ meson which is to be stopped in the bottom plate, is 0.6° or 1.4°, respectively, by a relation of Annis *et al.*[9] However, these values are smaller than one-tenth of the angle which is needed in order to attribute the 25 subproton masses to the tracks of scattered protons and μ mesons.

(2) If a section of the multiplate chamber does not work properly and a proton or a μ meson which actually goes through a plate appears to be stopped, then it also simulates a lower mass. The increasing ratio of ionization in two successive sections immediately above the stopping plate can be used as an indirect identification for ending of the particles. On 16 tracks out of 25, the increases in ionization were seen on the photographs; however, the increases were not seen on the remaining 9. We think that the nonincrease of ionization of the tracks on the photographs was caused by the following reasons. (a) In our multiplate chamber, containing the 0.3-mm plates, the increasing ratio is small. The estimated ratio from the curve in Fig. 3, is between 1.3 and 1.7 for half of the stopped μ mesons. (b) The illumination intensity was not sufficient, and therefore we used a strong contrast developer which may have failed to reproduce the slight increases of ionization, mentioned above, on the film. (c) The illumination intensity and the condensation efficiency of vapor on ions were not perfectly uniform for each section. The illumination intensity was particularly weak at the top space. The majority of the 2700 multiplate chamber photographs, taken during the 400-hour period, recorded cosmic-ray showers or β rays produced by γ rays from earth. By examination of these, especially on the 9 photographs taken by the side camera, it was certain that all sections of the multiplate chamber were sensitive for fast particles during the operations.

If the 25 meson masses were simulated masses of slow protons caused by the errors previously described, then we find it hard to interpret the presence of the clearly isolated group of 11 protons in the first experiment and the disappearance of the unusual masses in the second experiment.

(3) If some particle experiences energy losses other than those due to ionization inside the counter wall or plates, then it appears to have a lower mass than it actually is. For example, if a meson is captured in flight by a nucleus in a plate, then the apparent range is smaller by the amount of the residual range at the place where it was captured. However, such energy losses by known particles are not frequent enough for the 25 mass distributions to be interpreted in this way.

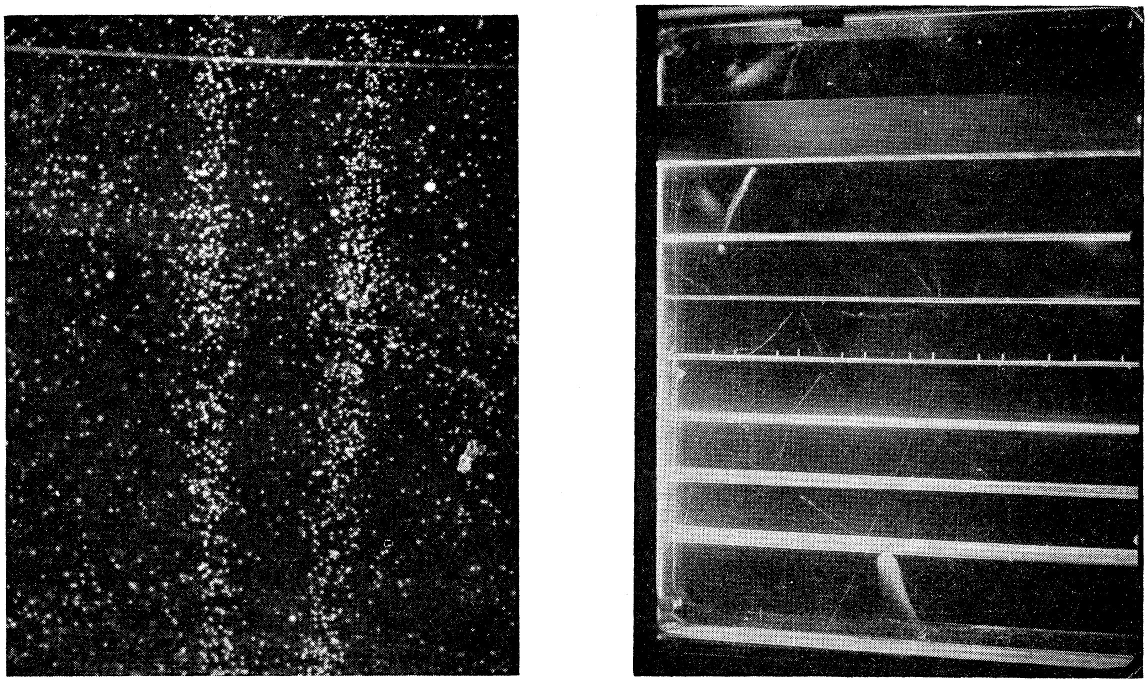
(4) If there exist τ and π mesons at sea level, the 25 masses, except for the six smaller than 105 electron masses, might be explained as representing τ, π, and μ mesons, so far as mass is concerned, assuming some systematic error in measurement. However, in that case about 6 decaying mesons should be observed, contrary to the result which shows only one, provided that half of them are positively charged and the geometrically computed detection efficiency of the decay particle emitted isotropically from the plate is 0.6. This value is consistent within the error with 0.5, which is obtained by the second experiment, showing 4 decaying mesons out of 8.

It seems to us that interpretation of the result in terms of the errors or of known mesons is hardly possible. To give a decisive conclusion for the existence of new mesons, accumulation of more exact data may perhaps be needed;[10] however, at the present stage, we propose the existence of new mesons of a new type as the most probable interpretation of our results.

We temporarily classified the 25 masses, rejecting 4

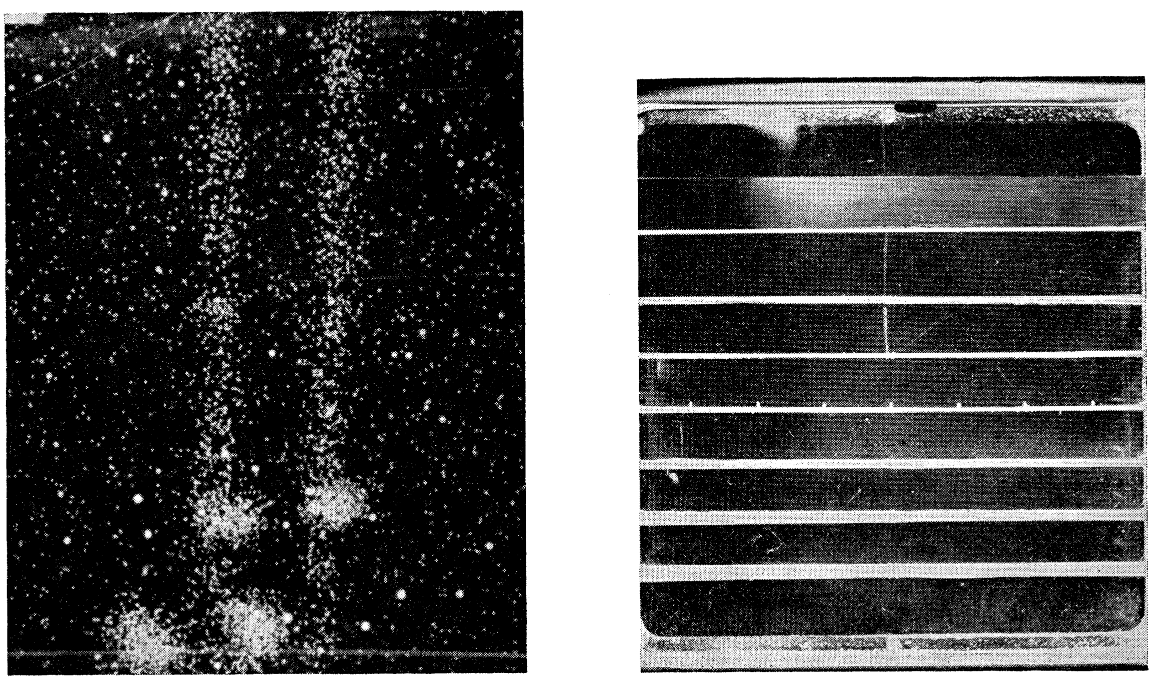
[9] Annis, Bridge, and Olbert, Phys. Rev. 89, 1216 (1953).

[10] For that purpose, a magnetic cloud chamber is under construction.



(a) (b)

FIG. 5. Typical cloud-chamber photograph of the meson, No. 40 in Table I, in the L group, showing the diffused tracks of positive and negative ions in the upper chamber, and the photograph of the track of the same meson stopped in air between the first and the second plate in the lower chamber, taken by the side camera.



(a) (b)

FIG. 6. Typical cloud-chamber photograph of the μ meson, No. 1 in Table II, showing the diffused tracks in the upper chamber, and the photograph of the track of the same meson emitting the decay electron at the second plate in the lower chamber, taken by the front camera.

uncertain ones, into 3 groups, namely *L*, *M*, and *H* groups, which represent 4 masses from 54 to $105m_e$, 10 masses from 135 to $364m_e$, and 7 masses from 465 to $649m_e$, respectively. The *M* group contains μ mesons, for which the number estimated by using the data of Merkle *et al.* is about 2, that estimated from the number of decay electron is about 3, and that expected from the measured mass is about 5. It is uncertain whether the remaining particles in the *M* group are π mesons or mesons of a new type. The *L* and *H* groups, in which the average masses are 86 and 592, respectively, are free from π and μ mesons, thus implying mesons of a new type. Concerning the decay of the new mesons, there is doubt whether they are a "non-decaying type" or a "long-lived type," or whether they produce a decay particle of such short range as to be undetectable, or whether they are negatively charged particles and are captured by nuclei before their spontaneous decay.

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Diurnal Variations of the Intensity of Cosmic Rays Far Underground*

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In the analysis of 249 762 coincidences due to cosmic rays at a depth of 1600 m.w.e. underground, no diurnal variation of the rate with respect to solar or sidereal time was found. With high confidence the amplitudes of such variations may be said to be less than one percent of the average intensity. The average energy of the primary cosmic rays responsible for the particles recorded was about 4×10^{13} ev.

In 1950 a series of measurements of the intensity of cosmic rays reaching a depth of 1600 meters water equivalent (m.w.e.) was begun in a salt mine near Ithaca, New York (geographical latitude $\lambda=42.5°$N). Analyses of the intensity-time variations, based on part of the results, have already been published.[1,2] Now these measurements have been completed, and the results we publish here supersede the previous ones.

Other experiments performed in the same mine[3] have shown that the observed particles are mu mesons created with an average energy of about 10^{12} ev by primary cosmic rays having an average energy of about 4×10^{13} ev.

The intensity was measured by several vertical telescopes, each containing two trays of G.M. counters (30 in.$\times$40 in.) separated by four inches of lead, and shielded above and below by two inches of lead. The number of coincidences in each telescope was recorded hourly. A total of 249 762 coincidences have been recorded during the period July, 1951 to August, 1953, with an average rate per telescope of 10.7 per hour. The accidental coincidences, which have not been subtracted, were about five percent of the total.

The data have been assembled according to the hour of solar time (Eastern Standard Time), or of local sidereal time in which the counts were recorded. Small corrections were applied for slight differences of running time in the different intervals. The results are plotted in Fig. 1, showing the apparent variation of intensity as a function of the solar time and as a function of the sidereal time. The errors indicated are standard errors.

On the solar time scale, the deviations from the mean have a quite normal distribution, with an rms value just equal to that which is expected from statistical fluctuations of the numbers of counts recorded. Fitting these data to a sinusoidal diurnal intensity variation can reduce the residual mean square deviation, the best fit occurring for an assumed amplitude equal to 0.5 percent of the mean counting rate, with 5.9 hours E.S.T. as the time of the maximum. However, the fit is

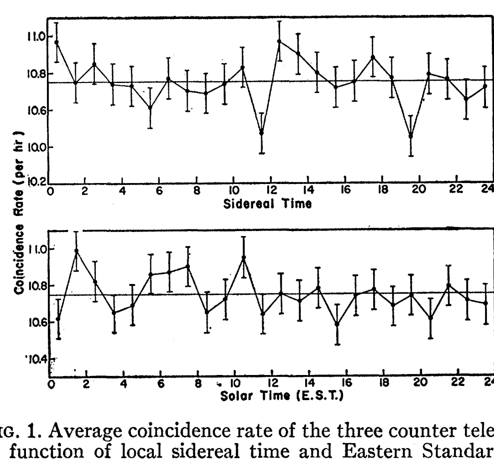

Fig. 1. Average coincidence rate of the three counter telescopes, as a function of local sidereal time and Eastern Standard solar time. The indicated errors are standard errors.

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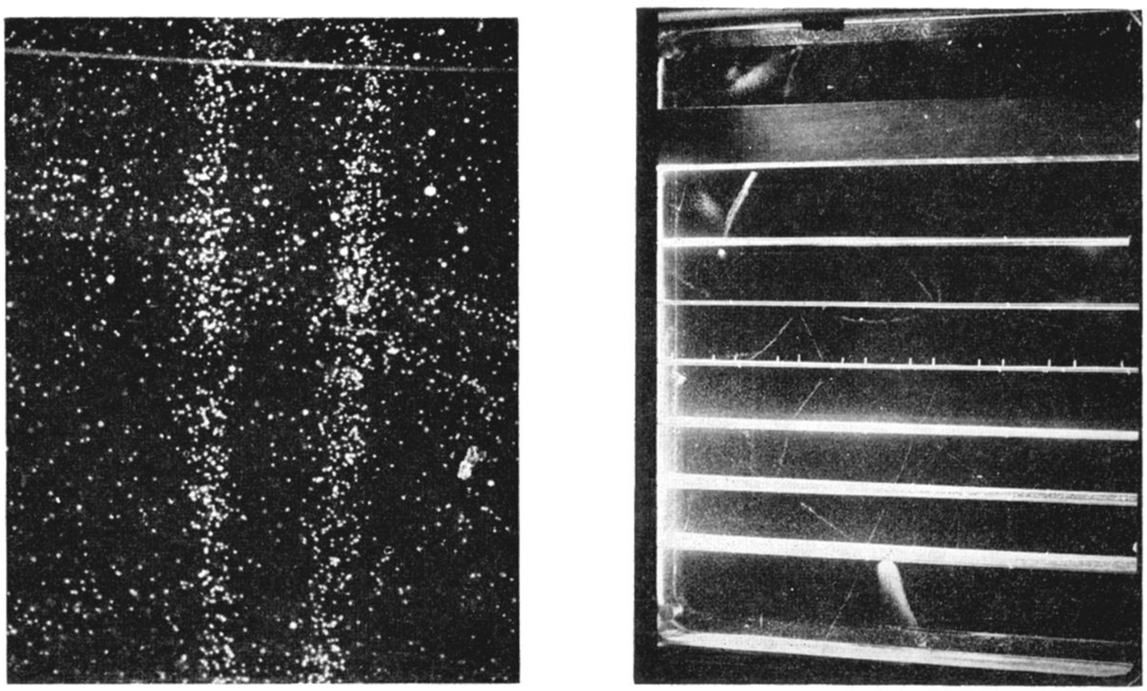
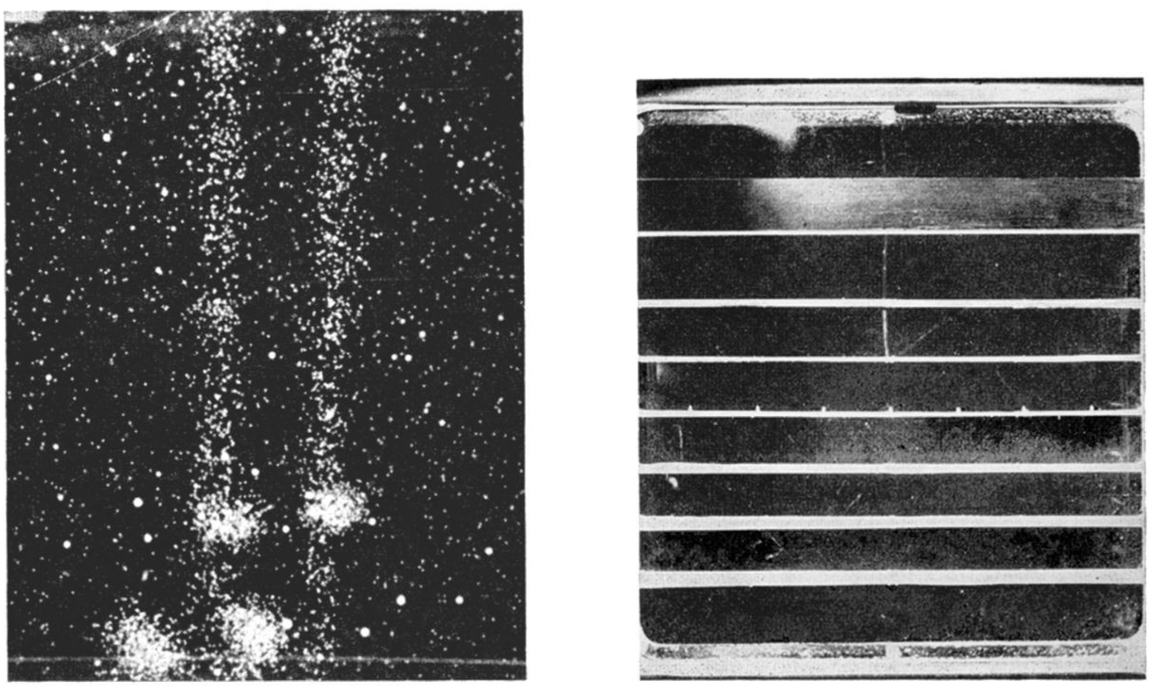


(a) (b)

FIG. 5. Typical cloud-chamber photograph of the meson, No. 40 in Table I, in the L group, showing the diffused tracks of positive and negative ions in the upper chamber, and the photograph of the track of the same meson stopped in air between the first and the second plate in the lower chamber, taken by the side camera.



(a) (b)

FIG. 6. Typical cloud-chamber photograph of the μ meson, No. 1 in Table II, showing the diffused tracks in the upper chamber, and the photograph of the track of the same meson emitting the decay electron at the second plate in the lower chamber, taken by the front camera.