Mass Measurements of Slow Cosmic-Ray Mesons

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The masses of slow charged cosmic-ray particles (except those of protonic mass) in the soft and hard components were separately determined by measuring momentum, momentum loss, and ionization with a magnetic cloud chamber at sea level. With respect to meson masses, however, we could not find any appreciable difference between the two components. Eighty out of 87 observed particles were interpreted as μ mesons, leaving 7 anomalous ones.

INTRODUCTION

THIS study was carried out to re-examine the results of our previous mass measurements[1] for slow charged cosmic-ray particles at sea level. In the study, a new magnetic cloud chamber was used to avoid the various possible errors[2] inherent in the apparatus used previously.

EXPERIMENTAL METHOD

The cloud chamber has a 300 mm×300 mm×30 mm effective volume which is divided into two parts, with a plate of aluminum or carbon horizontally set inside it. By using the cloud chamber, the momentum P_1 and ionization I_1 were measured for each slow particle and, in addition, P_2 and I_2 were determined for each particle penetrating the plate, where the indices 1 and 2 refer to the top and bottom parts of the cloud chamber, respectively. In the study, the observations were limited to particles for which approximately $2<I_1<6$ (except those of protonic mass).

The study was carried out with three runs. The experimental conditions and the number of observed particles in each run are listed in Table I and the arrangement of apparatus in each run is shown in Fig. 1. Bias against the observation of slow lighter mesons, of masses lying approximately between 200 and 20 in electron mass units, is almost eliminated in the second and third runs. Bias should be caused by the leakage magnetic flux and thick wall of the counters P_1, P_2, and G_2, and also of the top of the cloud chamber.

The cloud chamber was triggered by $G_1P_1P_2G_2$ coincidences in the first run, by $G_1'P_1P_2G_2'$, $G_1''P_1P_2G_2''$, and $G_1'''P_1P_2G_2'''$ coincidences in the second run, and by $G_1P_1P_2$ coincidences in the third. During these operations, a fast particle penetrating 15 cm of Pb was observed with no magnetic field once every hour by a G_1G_3 coincidence. By measuring these fast particle tracks, errors in P_1 and P_2 due to gas distortion and also errors in I_1 were estimated.

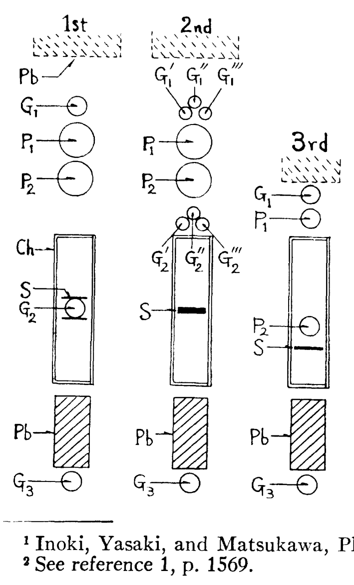

FIG. 1. Schematic arrangement of the apparatus in the first, second, and third runs, showing the magnetic cloud chamber, Ch, the G-M counters, G_1, G_2, and G_3, the proportional counters, P_1 and P_2, and the plate, S.

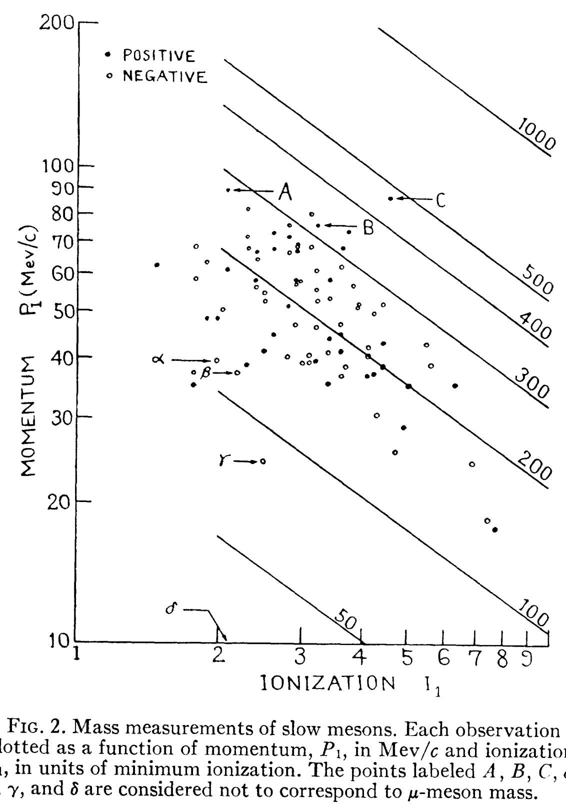

FIG. 2. Mass measurements of slow mesons. Each observation is plotted as a function of momentum, P_1, in Mev/c and ionization, I_1, in units of minimum ionization. The points labeled A, B, C, α, β, γ, and δ are considered not to correspond to μ-meson mass.

[1] Inoki, Yasaki, and Matsukawa, Phys. Rev. **95**, 1565 (1954).
[2] See reference 1, p. 1569.

TABLE I. Experimental conditions and number of observed particles in each run.

Run	No. of observed particles	No. of μ mesons	No. and label of unidentified particles	Momentum region in Mev/c	Average magnetic field in gauss	Thickness in g/cm² and material of the plate
First	34	32	2, A, C	$29<P_1<91$	3520	0.54, Al
Second	29	26	3, B, α, β	$18<P_1<77$	1950	0.92, C
Third	24	22	2, γ, δ	$10<P_1<62$	1510	0.14, Al

RESULTS

The slow particles in the soft and hard components were separately observed by setting and removing 25 cm of Pb above the apparatus alternately on every day. Concerning mass spectrum of the slow meson, however, we could not find any appreciable difference between both the components. Thus, in the study, the results of both components have been combined.

The observed values of P_1 and I_1 for each of 87 particles are plotted in Fig. 2. The mass was computed with the relation,[3]

$$M(P_1,I_1)=1.79I_1^{0.73}P_1, \quad \text{for} \quad 2<I_1<10.$$

The mass was also computed with the relation,[3]

$$M(P_1,P_2)^{2.27}=(0.63/\Delta R)[P_1^{3.27}-P_2^{3.27}],$$

where ΔR is the thickness of the aluminum plate in grams. The latter method is useful in practice only for particles with $P_2/P_1\ll 1$; for other particles, the error in the mass is too large as shown in the following relation:

$$\left(\frac{\Delta M}{M}\right)^2=\left(\frac{1.44}{1-a}\right)^2\left[\left(\frac{\Delta P_1}{P_1}\right)^2+a^2\left(\frac{\Delta P_2}{P_2}\right)^2\right],$$

$$a\doteq (P_2/P_1)^{3.27}.$$

Among 68 particles penetrating the plate, the masses were determined for only 9, selected by the condition, $P_2/P_1<0.7$.

For the purpose of searching for lighter mesons, the upper limit of the mass, $M(P_1,R)$, was computed for each particle penetrating the plate, using momentum-range relations.

Upon examining $M(P_1,I_1)$, $M(P_1,P_2)$, and $<M(P_1,R)$, 80 particles were interpreted as μ mesons; their average value of $M(P_1,I_1)$ was $(210.5\pm 3.8)m_e$.

For three particles labeled A, B, and C in Table II, the values of either $M(P_1,I_1)$ or $M(P_1,P_2)$ are too large to be the μ-meson mass, even taking the errors into consideration. If they are known mesons, they may be π mesons but not K mesons.

Four particles labeled α, β, γ, and δ in Table III are found to penetrate the plate in spite of the fact that the momentum of each of them is smaller than the threshold momentum for a μ meson to penetrate the plate. The deviation of each inverse momentum from the inverse threshold momentum ranges from 3.2 to 19.5 times the probable error of each as given in Table III. In addition to that, $P_2/P_1>0.9$ for each of them, whereas for μ mesons one expects $P_2/P_1\ll 1$, if one assumes that P_1 is underestimated by error. Thus these four particles, which are described as "lighter mesons," can hardly be considered as μ mesons. The distinction between the lighter mesons and electrons was examined by comparing the ionizations. Firstly measurements were made of the ionization of 109 electrons selecting from a total of 324 electrons those lying in the same momentum region as the lighter mesons. The average ionization was 11.9 ions/cm (including both positive and negative ions), and the probable error of a single observation was 1.9 ions/cm, in a mixed gas of 96% helium plus 4% butane at NTP. Relativistic corrections for the average ionization give the value 9.9 ions/cm as the minimum ionization. The smaller value of the minimum ionization compared with the value[4] 16.3 ions/cm should be caused by an average underexpansion of our cloud chamber. The ionization of each lighter meson is larger than the average ionization by as much as from 4.0 to 6.5 times the probable error of the average, as given in Table III. By statistical analysis based on the foregoing data, the identification of the lighter mesons is at a critical point of statistical significance; therefore, they can not be safely

TABLE II. Data for particles heavier than a μ meson.

Label in Fig. 1	Sign of charge	Momentum in Mev/c		Ionization in the minimum ionization unit		Thickness in g/cm² and material of the plate	Mass in the electron mass unit	
		$P_1\pm\Delta P_1$	$P_2\pm\Delta P_2$	$I_1\pm\Delta I_1$	$I_2\pm\Delta I_2$		$M(P_1I_1)\pm\Delta M$	$M(P_1P_2)\pm\Delta M$
A	+	91.0 ± 7.5	64.1 ± 3.8	2.1 ± 0.2	2.6 ± 0.3	0.55, Al	280 ± 30	535 ± 96
B	+	77.3 ± 6.3	40.5 ± 2.5	3.2 ± 0.4	4.0 ± 0.4	0.91, C	323 ± 40	430 ± 60
C	+	88.3 ± 5.7		4.5 ± 0.5			473 ± 49	

[3] These are based on the curves of D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, 1949), Appendix E.

[4] R. H. Frost and C. E. Nielsen, Phys. Rev. **91**, 864 (1953).

TABLE III. Data for particles lighter than a μ meson.

Label in Fig. 1	Sign of charge	Mean magnetic field in gauss Hm	Thickness in g/cm² and material of plate D	Inverse momentum in c/Mev $\Phi_1=1/P_1$ $(\Phi_1\pm\Delta\Phi_1)\times 100$	Threshold inverse momentum in c/Mev $\Phi_0\times 100$	Deviation of inverse momentum in units of $\Delta\Phi_1$ $(\Phi_1-\Phi_0)/\Delta\Phi_1$	Ionization in units of minimum ionization $I_1\pm\Delta I_1$	Deviation of ionization[a] in units of ΔI_0 $(I_1-I_0)/\Delta I_0$	Upper limit of mass in units of electron mass $<M(P_1R)$
α	−	2050	0.92, C	2.52±0.14	2.07	3.2	2.0±0.2	4.0	172+14
β	−	2100	0.93, C	2.59±0.14	2.04	4.6	2.2±0.3	5.0	166+13
γ	−	1510	0.35, Al	4.14±0.19	2.94	6.3	2.5±0.3	6.5	131+9
δ	+	1490	0.14, Al	10.31±0.33	3.86	19.5	2.1±0.3	4.5	51+2

[a] The average ionization of the electron is taken to be 1.2 times the minimum. The probable error of a single observation of the ionization is taken to be 0.2 in the same units.

identified as lighter mesons, unless they are more densely ionizing ones. Thus they may be electrons, but the possibility that some of them are lighter mesons is not excluded.

When one compares this result with that previously described, the relative intensity of unidentified particles to μ mesons is exceedingly reduced in this study.

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Isobaric Nucleon Model for Pion Production in Nucleon-Nucleon Collisions*

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A detailed quantitative model for pion production via excitation of one or both nucleons to an isobaric state with subsequent decay via pion emission is presented. The model is applied to the 0.8- to 3.0-Bev incident nucleon energy range and its predictions are compared to various experiments in this energy range performed at the Brookhaven Cosmotron. The isobaric state with isotopic spin and angular momentum $=\frac{3}{2}$ observed in the pion-nucleon scattering was assumed to be predominantly responsible for pion production in this energy range. The relative probability for isobar formation and subsequent decay with a variable total energy or mass in the isobar rest system were phenomenologically related to the π^+-p interaction cross section. The energy or momentum spectra of pions, and nucleons, the variation of the ratio of double to single production, the angular correlation, and the Q value distribution for pion-nucleon pairs have been calculated at various energies from 0.8- to 3.0-Bev and generally agree with the experimental results.

I. INTRODUCTION

THE early cosmic-ray studies[1] of pion production by incoming nucleons with energies ranging from 1 to ~100 Bev had been found generally consistent with the statistical theory which was proposed by Fermi[2] to explain them. The essential features of this theory were that a thermodynamic equilibrium was assumed to be established inside a collision volume of radius equal to to the pion Compton wavelength and then the relative probability of a final state—with n pions of momenta $(p_1,p_2\cdots p_n)$ and 2 nucleons (p_{n+1},p_{n+2}), was considered to be proportional to the phase space available for this state. Hence it was assumed that the matrix elements for all final states were essentially the same. The only final states which were applicable were, of course, those which conserved charge, energy, momentum, angular momentum, heavy particles, and isotopic spin.

The energy spectra and other characteristics of pion production in Be and hydrogen by 1.0- to 3.0-Bev protons were observed by Lindenbaum and Yuan[3] using the Brookhaven Cosmotron. These results did not agree with the predictions of the Fermi statistical theory which were calculated by Yang and Christian.[4] Over the incident proton energy range of 1.0–2.3 Bev, the observed experimental pion energy spectra in the

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[1] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), Chap. VIII.

[2] E. Fermi, Progr. Theoret. Phys. (Japan) **5**, 570 (1950); Phys. Rev. **92**, 452 (1953); **93**, 1435 (1954).

[3] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **93**, 917 and 1431 (1954); **103**, 404 (1956); *Proceedings of the Fourth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1954), p. 140; *Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1955), p. 531; *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1956), Chap. IV, p. 37.

[4] C. N. Yang and R. S. Christian, Brookhaven National Laboratory Internal Report (1953) (unpublished).