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The Variation of the Ratio of Positive to Negative Cosmic-Ray μ Mesons with Momentum and Altitude*†

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I. The mean lifetime of $\mu^\pm$ mesons in carbon and sulfur has been measured by the delayed coincidence technique. Data for decay times $>2\mu$sec were analyzed by the statistical method of Peierls and yield $\tau_s^+=2.09\pm0.05\mu$sec for the mean life of the μ^+ meson in sulfur and $\tau_s^-=1.92\pm0.04\mu$sec for the mean lifetime of the μ^- meson in carbon. τ_s^+ compares favorably with values found in material of low atomic number, but there appears to be a significant difference between these values and those obtained in high Z materials. Assuming a Z^4 dependent capture probability for μ^- mesons, τ_s^- is compatible with other lifetimes determined in materials of higher Z.

II. The integral time distributions of the delayed coincidences obtained above were extrapolated to zero delay time and allowance made for those μ^- mesons which are captured in carbon. These data were used to obtain the μ^+/μ^- ratio at a momentum of 325 ± 70 Mev/c at sea level: $\mu^+/\mu^-=1.06\pm0.03$. This ratio is compared with other experiments (which also provide good identification of the μ mesons) by plotting all ratios as a function of momentum at the top of the atmosphere (TOA). The best fit to the experimental points is given by the exponential expression

$$P=P_0\exp[\mu^+/\mu^-/K],$$

where

$$P<4 \text{ Bev}/c \text{ (TOA)},\quad P_0\simeq0.165 \text{ Bev}/c \text{ (TOA)},\quad \text{and}\quad K\simeq0.38.$$

The decrease of the μ^+/μ^- ratio with increasing altitude appears to be well established, although the exact values of P_0 and K are uncertain.

I. INTRODUCTION

FOR more than a decade it has been known that there is an excess of positive particles in the "hard component" at sea level. According to the best estimates[1-4] this excess amounts to ~20 percent of the total penetrating radiation. Early studies gave no information regarding the distribution of the excess in the differential sea-level spectrum, but recent experiments[5-7] have shown that in the region 1→2 Bev/c the positive/negative ratio increases, reaches a broad maximum at 2→5 Bev/c and then falls off more slowly at high momenta.

Still less detailed information is available concerning the positive excess of μ mesons at altitudes above sea level. Most cloud-chamber data[8-10] show that the positive/negative ratio of the "hard component" increases with altitude, especially at low momenta. However, this increase can be related directly to the large increase of the proton intensity with altitude rather than any increase in the relative number of μ^+ mesons. Similarly, a magnetic lens experiment[11] showed that the ratio increased from sea level to 3.5 km, but did not change substantially from this latter value in going up to 7.6 km. To further complicate matters, delayed coincidence experiments[12-14] (in which μ mesons were identified by their characteristic decay) showed that the μ^+/μ^- ratio of 1.20 was fairly evenly distributed in the sea-level spectrum but dropped to ~1 in going to 2.1 km and then increased with altitude.

Other experiments[15,16] in which the mesons were identified accurately by range-momenta criteria, showed no positive excess at 3.4 km.

Positive/negative ratios obtained from π mesons stopped in photographic emulsions[17-23] exposed at various altitudes and identified by their characteristic endings have generally exhibited ratios between 0.2 and 1.2.

It is the purpose of this paper to report an experimental determination of positive/negative ratio for low-energy μ mesons at sea level, and to compare this result with other experimental data in an attempt to resolve the major discrepancies which exist.

The delayed-coincidence technique was used in conjunction with absorbers of carbon and sulfur. A com-

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TABLE I(a). Differential data.

Channel	No. 1	No. 2	No. 3	No. 4
Width (Δt)	1.07μsec	1.80μsec	2.00μsec	1.41μsec
Edges (from $t=0$)	1.10–2.17μsec	2.17–3.97μsec	3.97–5.97μsec	5.97–7.38μsec
N_c (1408.9 hr)	12 816±113	10 281±101	4865±69	2022±45
N_s (1609.7 hr)	11 380±107	7862±88	4068±64	1805±42
N_b (822.2 hr)	2392±49	1676±41	1042±32	595±24

TABLE I(b). Differential data reduced to equal channel widths ($\Delta t=1.10$μsec).

Channel	No. 1	No. 2	No. 3	No. 4
Calculated "center"	1.58μsec	2.95μsec	4.83μsec	6.57μsec
$\frac{dN_{c-b}}{dt}$ (hr^{-1})	6.19±0.10	3.21±0.06	1.20±0.06	0.56±0.03
$\frac{dN_{s-b}}{dt}$ (hr^{-1})	4.16±0.09	1.74±0.03	0.69±0.03	0.31±0.03
$\frac{dN_{c-s}}{dt}$ (hr^{-1})		1.47±0.06	0.52±0.04	0.25±0.04

Due to these precautions, the shift in the channel widths over the period of observation was <0.02μsec. Average values for the time widths of the channels reported in Table I(a) were used in all calculations. This average was computed from weekly calibrations made with a delay line controlled double pulse generator developed in this laboratory[28-30] and used in previous delayed coincidence experiments.

All of the critical power supplies were either of the degenerative feedback type or were controlled by *VR* tubes.

III. EXPERIMENTAL PROCEDURE

The apparatus was operated for a total of 3840 hours. Of this time, 3018 hours were foreground and 822 hours were background (no absorber). The results are summarized in Table I.

Individual tray counting rates and the twofold and threefold prompt coincidence rates were monitored daily. In order to minimize any effects due to fluctuations in the incident intensity, runs with each of the two absorbers were alternately sandwiched in time with background runs. The measured background was subtracted so that all final results are based upon the true delayed coincidence rate for each absorber. Thus, delayed counts due to accidental coincidences and spontaneous counter lags are cancelled out. Mesons stopping in the support material or Geiger-Mueller counter walls are likewise eliminated from the results.

The differential time distributions plotted in Fig. 3 were obtained by reducing the data from each channel to correspond to equal widths ($\Delta t=1.1$μsec) and calculating the weighted "center" of each reduced channel. This procedure [see Table I(b)] was used only in plotting Fig. 3. *All other information was obtained from the raw data listed in* Table I(a).

IV. MEAN LIFETIMES OF μ MESONS

A. General

The mean lifetimes reported here were calculated from the data in Table I(a) by the statistical method of Peierls.[31] This procedure allows the mean lifetime and standard statistical error to be computed from an ob-

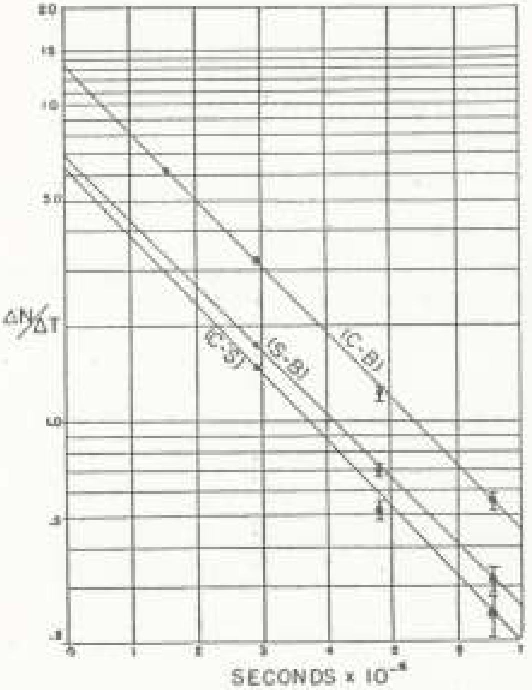

FIG. 3. Differential time distribution of delayed coincidence counts All channels reduced to equal widths ($\Delta t=1.1$μsec).

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[31] R. Peierls. Proc. Roy. Soc. (London) A149, 473 (1935).

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TABLE III. Mean lifetime of the μ^- meson at rest.

Author	Z	Z_{eff}	τ^- μsec	$\Lambda_{\text{cap}}{}^{a}\times10^{6}$ sec^{-1}
Hincks and Bell (1952)	3	3	2.15 ±0.09[b]	<0.035[b]
	4	3.93	2.05 ±0.06[b]	0.037 ±0.015[b]
	6	5.78	1.98 ±0.08[b]	0.055 ±0.021[b]
Present experiment (1952)	6	5.78	1.92 ±0.04	0.043 ±0.010
Ticho (1948)	8	7.36	1.89 ±0.15	0.051 ±0.043
Ticho (1948)	10	9.25	1.28 ±0.12	0.304 ±0.073
Ticho (1948)	12	10.83	0.96 ±0.06	0.562 ±0.065
Valley (1949)	12	10.83	1.1 ±0.2	0.431 ±0.166
Valley (1949)	13	11.58	0.81 ±0.06	0.76 ±0.09
Ticho (1948)	13	11.58	0.75 ±0.07	0.853 ±0.124
			0.82 ±0.05[c]	0.74 ±0.09
Cathey (1952)	14	12.33	0.60 ±0.09	1.19 ±0.25
Ticho (1948)	16	13.7	0.54 ±0.12	1.377 ±0.413
			0.66 ±0.05[c]	1.04 ±0.13
Conforto and Sard (1952)	20	16.1	0.81 ±0.24[d]	0.77 ±0.35
Keuffel *et al.* (1952)	26	19.5	0.163 ±0.027[e]	5.66 ±0.94[e]
	29	20.6	0.116 ±0.009[e]	8.15 ±0.63[e]

[a] Under the assumption that $\tau^+=2.09\pm0.02$ unless otherwise indicated.
[b] Calculated from the unseparated delayed-coincidence data under the assumption: $\mu^+/\mu^-=1.22$ and $\tau^+=2.22\pm0.02\mu$sec.
[c] Less the correction for 4 percent magnetic lens inefficiency included by Ticho (see footnote 32).
[d] Computed graphically from the data given by these authors. They attribute the large lifetime as compared to that obtained from a Z^4 law to magnetic lens inefficiency, although data taken with other absorbers in the same apparatus do not confirm this view.
[e] Obtained by detecting the capture neutrons and gammas.

been confirmed experimentally by Ticho,[24] and by Valley[33] and by Cathey[44] for $8<Z<16$, and by Keuffel *et al.*[45] for copper and iron. The latter group has recently shown that an anomaly, which is attributed to the influence of the shell structure of the nucleus,[47] occurs for large Z.

At the time of the present experiment no reliable evidence existed concerning the capture of μ^- mesons in materials of $Z<8$. Conversi *et al.*,[48] who were the first to observe the Z dependence of the μ^- meson capture process, found that all μ^- mesons decay in carbon. Similar results have been obtained by Kissinger and Cooper,[49] and Valley.[50] All of the references cited above have large statistical errors. Nereson,[51] however, found that in carbon only 76±17.6 percent of the μ^- mesons decay. In their experiments on the range of decay electrons in carbon, Shamos and Russek[29] observed that their results did not tend toward unit yield (i.e., one decay electron per stopped meson) at zero thickness of absorber. The general trend observed in both of these experiments is consistent with Wheeler's theory, which predicts that ~90 percent of the μ^- mesons decay in carbon.

Recently, Hincks and Bell[52] have reported a series of measurements somewhat similar in principle to the present one in absorbers of lithium, beryllium, and carbon. Their τ_c^- compares favorably with the value reported in the present paper. However, capture probabilities computed from their $\tau_{\text{Be}}{}^+$, $\tau_{\text{Be}}{}^-$, and $\tau_{\text{Li}}{}^-$ are not in agreement with other experiments[24,33] extrapolated to low Z by means of Wheeler's theory.[42]

The various experimental values of the lifetime of the μ^- meson as a function of Z are tabulated in Table III.

Under the hypothesis that the shortened μ^- meson lifetime is due solely to the competition between capture and decay processes,[44,56] the fraction of μ^- mesons which undergo spontaneous decay is given by[55]

$$f=\tau^-/\tau^+.$$

From the values of μ^+ and μ^- lifetimes determined in the present paper, it is seen that 92±3 percent of the μ^- mesons decay in carbon. This confirms previous estimates[29,51] as to the magnitude of this effect.

Using a similar hypothesis, the capture probability is given by

$$\Lambda_{\text{cap}}=1/\tau^- - 1/\tau^+,\quad \text{where}\quad \tau^+=2.09\pm0.02\mu\text{sec}.$$

The results of this calculation are plotted in Fig. 4 using the effective Z computed by Wheeler.[42] The slope of the resulting plot closely corresponds to the Z^4 effective law. However, one should expect to find local fluctuations in μ^- meson capture probabilities due to nuclear "shell structure" effects. This problem has been examined theoretically by Tiomno and Wheeler[56] for O^{16} and by Kennedy[47] for Ca^{40} and Pb^{208}. These authors find

$$\Lambda_{O^{16}}=2.29\times10^{103}g^2\ \text{sec}^{-1},$$
$$\Lambda_{Ca^{40}}=2.7\times10^{103}g^2\ \text{sec}^{-1},$$
$$\Lambda_{Pb^{208}}=1.56\times10^{104}g^2\ \text{sec}^{-1},$$
$$\Lambda_{Pb}=1.6\times10^{104}g^2\ \text{sec}^{-1}.$$

Kennedy has compared his calculated capture probability for Pb with the experimentally derived value obtained by Keuffel *et al.*[45] and finds $g\simeq3\times10^{-49}$ erg cm^3 with a probable error of 25 percent. Substituting this value in the expression for O^{16} and Ca^{40}, one obtains

$$\Lambda_{O^{16}}=2.06\times10^{6}\ \text{sec}^{-1},$$
$$\Lambda_{Ca^{40}}=2.43\times10^{6}\ \text{sec}^{-1}.$$

These agree, within the experimental error, with the

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[49] C. W. Kissinger and D. Cooper, Phys. Rev. 74, 349 (1948).
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[51] N. Nereson, Phys. Rev. 73, 569 (1948).
[52] E. P. Hincks and W. E. Bell, Phys. Rev. 88, 168 (1952); 88, 1424 (1952).
[53] In calculating their lifetimes, Hincks and Bell *assume* that the μ^+/μ^- ratio is 1.24 at 500 Mev/c at sea level in order to find the fraction of decays in each absorber which are due to μ^+ mesons. (As is shown by Fig. 6 of the present paper, $\mu^+/\mu^-\simeq1.1$ at 500 Mev/c at sea level.) Furthermore, they choose 2.22μsec as the μ^+ meson lifetime, and this may not be the correct lifetime of the μ^+ in materials of low Z (see Table II). Both effects combine to give τ^- lifetimes which are of the proper order of magnitude, but result in capture probabilities which are too large.
[54] A. M. Conforto and R. D. Sard, Phys. Rev. 86, 465 (1952).
[55] Several authors [see reference 24 and P. Budini, Nuovo cimento 9, 445 (1952); N. Dallaporta, Nuovo cimento 9, 450 (1952)] have suggested that the nucleus may emit an energetic charged particle directly after capture of a μ^- meson. In this case the fraction (f) of μ^- mesons which decay would not be equal to τ^-/τ^+.
[56] J. Tiomno and J. A. Wheeler, Revs. Modern Phys. 21, 144 (1949).

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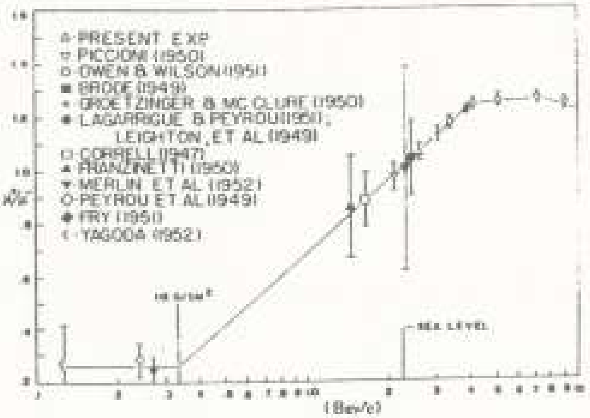

FIG. 6. μ^+/μ^- ratios *vs* momenta at the top of the atmosphere (TOA) for the selected experiments. Those points labeled (π) are obtained from π mesons stopped in photographic emulsions exposed above 60 000 ft.

stopped mesons are evenly distributed throughout each absorber[61] one finds that

$$E=1.01\pm0.10.$$

The estimated uncertainty in the computed ratio (E) is due in part to the uncertainty in the theoretical expressions for the average electron ranges, which are only good to about 5 percent. Such phenomena as backscattering, etc., were neglected. The geometrical correction for edge effects (which is included) is <2 percent.

An experimental value for the ratio of relative efficiencies of carbon and sulfur has been obtained by Piccioni[13] for the delayed coincidences from μ^+ mesons observed in hard showers. When his data are corrected for spurious showers actually produced by knock-on electrons accompanying incident μ mesons, the ratio of the efficiencies becomes

$$(E)=\frac{\mu^+\text{ delayed coincidences in carbon}}{\mu^+\text{ delayed coincidences in sulfur}}=1.08\pm0.10.$$

Another approach to this question can be obtained from the sulfur data alone in the present experiment. The data for decay times between 1.1 and 2.17μsec can be corrected for μ^+ mesons in this channel by extrapolating from the following channels. This procedure yields only one point on the decay curve for μ^- mesons in sulfur, but has the advantage that no questions of relative efficiencies are involved. If one assumes that $\tau_s^-=0.66\pm0.05\mu$sec (see reference 32), then one obtains

$$\mu^+/\mu^-=0.94\pm0.20.$$

When this is compared to Eq. (1) it implies

$$E=0.96\pm0.15.$$

These three estimates indicate that (E) is approximately unity, but do not permit an accurate evaluation of this quantity. It is for this reason that no corrections for this effect are included in the μ^+/μ^- ratio [Eq. (1)]. While a more accurate evaluation of the present data awaits a better determination of (E), it will be shown in the following section that the value obtained under the assumption that $E=1$ is in good agreement with the results obtained by other methods.

VII. COMPARISON WITH OTHER EXPERIMENTS

A. General

An attempt has been made to resolve the ambiguities concerning the variation of the μ^+/μ^- ratio as a function of meson momentum and as a function of the altitude at which the ratio is determined. It is possible to correlate both variations in a consistent way by studying the μ^+/μ^- ratio as a function only of meson momentum (P) referred to the top of the atmosphere (TOA).[62] Experiments *selected on the basis that they provide good identification of the μ mesons* have been compared in this manner; Fig. 6 shows the result of this compilation. The "selected" experiments can be fitted quite well by an expression of the form

$$P=P_0\exp\left[\frac{\mu^+/\mu^-}{K}\right], \tag{2}$$

where $P<4$ Bev/c (TOA), $P_0=0.165$ Bev/c (TOA), and $K=0.38$.

The fact that the experimental data seem to be only a function of momenta (TOA) implies that there is no appreciable meson production in the lower atmosphere as has been suggested by recent experiments.[10,63] However, it will be necessary to obtain data at different altitudes which overlap in momentum (TOA) before this can be confirmed. Furthermore, although *the decrease of the μ^+/μ^- ratio with increasing altitude appears to be well established*, the exact values of both P_0 and K in Eq. (2) are uncertain in the region below 2 Bev/c (TOA) because of the large statistical errors in the data obtained at altitudes above sea level.

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[61] Both the main experiment and the auxiliary experiment (Fig. 5) are performed in an approximately "flat" region of the sea-level momentum spectrum. This means that the stopped mesons are to a first approximation distributed evenly throughout the absorber. The indication of a dip at 26 g/cm² may be caused by a characteristic anomaly in the spectrum at 400 Mev/c [see A. Rogozinski and A. G. Voisin, Compt. rend. **230**, 2092 (1950); L. Eisen, Masters thesis, New York University, 1952 (unpublished); E. W. Kellerman and K. Westerman, Proc. Phys. Soc. (London) **A62**, 356 (1949)].

[62] In the discussion that follows, all momenta labeled (TOA) are given at the top of the atmosphere. We use the NACA standard atmosphere [see W. G. Brombacher, National Advisory Committee for Aeronautics Report NACA-538, 1935 (unpublished)] which approximates the yearly average of altitude as a function of pressure for latitude 40°N in the United States. All range (altitude in g/cm²) to momentum conversions are made by means of the Princeton tables [E. P. Gross, *Range-Energy-Ionisation Curves* (Princeton University, Princeton, 1947)]. These are based mainly upon the theoretical work of G. C. Wick [Nuovo cimento **1**, 310 (1943).], which includes polarization effects.

[63] W. L. Kraushaar, Phys. Rev. **76**, 1056 (1949).

μ^+/μ^- ratio at ~0.8 Bev/c at sea level and at 4 km. They determined the μ^+/μ^- ratio at two zenith angles in both the east and west azimuths. Using their raw data we have averaged[69] over both angles and azimuths and computed a single μ^+/μ^- ratio for each altitude. Their sea-level measurement contains no protons because the 40 cm of iron in the lens effectively attenuates those protons of ~0.8 Bev/c momenta which were present in the incident beam. Unfortunately this is not true at 4 km where protons constitute ~28 percent of the total incident beam at this momentum or ~18 percent of the positive particle beam capable of causing a coincidence. As a result this determination at 4 km indicates 20 percent more positive particles than do the selected experiments (see following section).

Leighton *et al.*[70] have observed 75 $\mu\rightarrow\beta$ decays in a cloud chamber with a magnetic field at sea level. Of these events, 12 occurred in an absorber (a mixture of paraffin and copper) whose atomic number (Z) could not be stated precisely, and one occurred in brass. (In the discussion that follows these 13 events are not considered.) The remaining decays occurred in carbon and Bakelite (54 events) or in glass and argon (8 events). Lagarrigue and Peyrou[71] have observed 150 $\mu\rightarrow\beta$ decays under 20 cm of lead at sea level by means of a cloud chamber and magnetic field. All of their decays occurred either in carbon or glass; but the majority took place in carbon.

The data of the two experiments were combined under the assumption that all of the decays occurred in carbon. Thus, allowing for those μ^- mesons which would be captured in "carbon," we compute the μ^+/μ^- ratio to be

$$\mu^+/\mu^-=1.04\pm0.14 \quad \text{at} \quad \sim 2.5\ \text{Bev}/c\ \text{(TOA)}.$$

This ratio is based on excellent identification, but only indicates the trend at low momenta at sea level because of the assumption involved and the poor statistical accuracy.

A cloud chamber in a magnetic field with an absorber placed below the chamber was used by Correll[13] to determine the μ^+/μ^- ratio for mesons of 125 to 250 Mev/c momenta at 3.5 km. Electrons were eliminated by shower production in three 1-cm lead plates (two were inside the chamber); protons were eliminated by range-momenta criteria. In this momentum region confusion with mesons is extremely unlikely. Although this measurement has a statistical precision of only 11 percent, the identification is good.

Franzinetti[15] exposed vertical photographic plates in a 30-kilogauss magnetic field at 11 000 ft and identified the particles which stopped in the plates both by their mass (momentum and residual range) and by their characteristic endings. Since he was primarily interested in a mass spectrum of the cosmic radiation at these altitudes, he included in his μ^+/μ^- ratio eight μ^+ mesons resulting from $\pi^+\rightarrow\mu^+$ decay in the plates. In using his results we have omitted these eight locally-produced μ^+ mesons. A histogram of the entrance angles of the stopped μ mesons shows that they were deflected by the magnetic field before entering the plates; the angles of incidence are consistent with the hypothesis that these mesons were not locally produced. Recently, Merlin *et al.*[72] have essentially repeated Franzinetti's experiment at sea level. The statistical errors of both experiments were large, but the identification was exceptionally good.

Piccioni[18] has performed a delayed coincidence experiment at 3.5 km under 19.5 in. of lead. Carbon and sulfur absorbers were used in a manner similar to that employed in the present experiment. Most locally produced μ^+ mesons were eliminated by not counting those events in which more than a single counter was discharged in the first tray of his telescope. (This precaution is necessary at mountain altitudes.) Since his experimental arrangement and the present one are similar, the same considerations employed in reducing the present data apply.

We have recomputed[73] from Piccioni's raw data the μ^+/μ^- ratio for those delayed coincidences unaccompanied by hard shower events and find that

$$\mu^+/\mu^-=0.97\pm0.05 \quad \text{at} \quad 2.09\ \text{Bev}/c\ \text{(TOA)}.$$

Because of the possibility that locally generated hard showers can contribute extra μ^+ mesons to the data, this ratio must be considered only as an upper limit.

There are two other experiments which tend to point up the various effects mentioned above, although they do not do this directly. In one of these experiments, Ticho[74] has measured the composite lifetime of the natural mixture of cosmic-ray mesons in aluminum both at sea level and at 3.5 km. Since the μ^- mesons decay with a considerably shortened lifetime in aluminum, a decrease in composite lifetime with altitude is consistent with a decrease in the μ^+/μ^- ratio with altitude, although the precision of this experiment does not permit definite conclusions to be drawn. In the second, Brode has reported a continuation of his sea-level magnetic lens experiments at 3.5 km altitude.[75] Although the reported ratios are diluted by an overcorrection (see the discussion above) they show that the ratio decreases with altitude, and that the altitude variation can be represented as a momentum variation, since the addi-

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[69] The ratios determined at the two zenith angles were not statistically different.

[70] Leighton, Anderson, and Seriff, Phys. Rev. 75, 1432 (1949).

[71] A. Lagarrigue and C. Peyrou, Compt. rend. 233, 478 (1951).

[72] Merlin, Vitale, and Goldschmidt-Clermont, Nuovo cimento 9, 422 (1952).

[73] Piccioni assumed that the mean lifetime of μ^+ mesons in sulfur as well as the composite lifetime of μ mesons in carbon was 2.2μsec. The carbon/sulfur ratio thus obtained corresponds to $\mu^+/\mu^-=1.2$. This is actually the ratio for delay times greater than 1.3μsec and only corresponds to the zero-time extrapolated value provided that the lifetimes are the same.

[74] H. K. Ticho, Phys. Rev. 71, 463 (1947).

[75] R. B. Brode, Phys. Rev. 78, 92 (1950).

Nonnemaker and Street[79] have used a cloud chamber at sea level to study the momenta of singly occurring particles which traversed 140 g/cm^2 and stopped in an additional 88 g/cm^2 below the chamber. This apparatus is somewhat similar to that of Correll's,[11] but no "shower plates" were provided in the chamber. The momentum cutoff is that of μ mesons; however single electrons could not be distinguished from μ^- mesons over most of the region of momentum considered.

VIII. COMPARISON WITH THEORY

Interpretation of the well-known 20 percent excess of positive mesons observed at sea level is generally based[80] on the model of a primary radiation consisting exclusively of protons which produce charged mesons upon colliding with air nuclei. Charge conservation then leads to the generation of more positive than negative mesons. That the simultaneous production in the primary collision of charged nucleons may upset the charge balance is not usually considered. Thus, it is not surprising that this simple picture is not entirely compatible with the results reported in the present paper. In fact, no theory of meson production is successful in accounting for the variation of the μ^+/μ^- ratio at momenta below 4 Bev/c (TOA).

One theory, based on plural production of mesons[81] has been proposed recently by Caldirola *et al.*[82] The theoretical variation of the μ^+/μ^- ratio at sea level does not fit the experimental points too well below 4 Bev/c (TOA). This theory also predicts that the μ^+/μ^- ratio should increase with altitude, which is distinctly at variance with the present results.

Other models, based upon multiple-production theories[83,84] give distributions of the ratio which vary with the inverse square root [85–87] of the meson energy. The poor agreement between the experimental results and these theories probably lies in the fact that they are applicable only at sufficiently high energies.

Puppi and Dallaporta[88] have attempted to construct a phenomenological theory to describe the momentum dependence of the ratio at sea level. They assume that the positive excess of mesons generated by the primaries is either uniformly distributed, or a slowly varying function of meson momentum. According to their picture, the initial excess is diluted by mesons produced throughout the atmosphere by secondary nucleons. These secondaries consist of approximately equal numbers of protons and neutrons, and, as a consequence the second generation of mesons shows no excess. By using Sands'[58] data for the production of slow mesons as a function of altitude and choosing 55 g/cm^2 as the mean free path for inelastic collisions of the nucleonic component, they obtain a rough fit to the experimental points at sea level. They conclude that better agreement would be obtained if they considered the small excess of neutrons in collisions after the first; this would diminish slightly the computed values at low energies and bring them more into agreement with the experimental ratios. Despite the good agreement at sea level, this theory must be treated with reserve since the dilution parameter would require the positive/negative ratio to increase with altitude or at least remain relatively constant.

The preponderance of negative mesons in the region below 2.25 Bev/c (TOA) can be attributed to the action of the incident neutrons contained in the heavy particle primaries.[89] (These neutrons constitute ~25 percent of the *incident nucleons* and are predominantly of low energy.) It is difficult to obtain more than a qualitative explanation of the observed momentum dependence of the μ^+/μ^- ratio since little is known about the relevant cross sections and modes of interaction, even at those values of momenta which are accessible to present day accelerators.[90]

IX. ACKNOWLEDGMENTS

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