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Experiments on Cosmic-Ray Mesons and Protons at Several Altitudes and Latitudes*

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Experiments to obtain further information about the meson component and the nucleonic component present in the atmosphere have been carried out near sea level, and in a B-29 aircraft flying at different altitudes and latitudes, using G-M counters simultaneously in delayed coincidence and in anticoincidence. A summary of the results obtained is given in Section V of this paper.

I. INTRODUCTION

EARLY investigations performed by means of counter telescopes showed, as is well known, that the ionizing particles of the cosmic radiation present near sea level may be empirically separated into two groups or components: a "soft" component, virtually absorbed by about 10 cm of lead, which has been recognized to be essentially of electronic nature, and a "hard" component made up of particles able to penetrate large thicknesses of material. As to the nature of the particles constituting the hard component, the investigations of the last decade have shown that near sea level these particles are mostly mesons. Since the discovery of the "heavy" or π-meson and of the $\pi-\mu$-decay process,[1] it has been generally believed that the mesons observed near sea level are the decay products of the π-mesons generated in the upper layers of the atmosphere by the interaction of the primary cosmic rays.

There is evidence, at present, that in addition to the generation of π-mesons the primary radiation is also responsible for the production of a large number of protons, of neutrons, and perhaps also of other elementary particles, which in their interaction with the nuclei of the atmosphere build up, possibly through a kind of "cascade process," the so-called nucleonic component. At high altitudes, therefore, the nucleonic component becomes presumably an essential part of the radiation observed, with a counter telescope, as the "hard" component.

Little information is available as yet about the structure of the hard component at high altitude, about the relative abundances and the energy distributions of the different particles of which it is composed. Investigations of this matter are mainly hindered by the difficulty of separating the different kind of particles.

Some information concerning the altitude dependence and the range distribution at high altitude of low energy mesons (less than 200 Mev) has been recently obtained by Rossi, Sands, and Sard,[2] and by Sands,[3] who, by means of delayed coincidences, separated ordinary mesons from other particles by taking advantage of the instability of the meson.

Information on the momentum distribution of the penetrating particles present at airplane altitudes, has also been obtained, with the cloud-chamber method, by Moore and Brode[4] and by Adams, Anderson, and Cowan.[5] Anderson and his co-workers have found evidence, moreover, of the presence of high energy protons at 30,000 feet.[6]

The research described in the present article was undertaken mainly with the aim of obtaining further information on the nature and the composition of the ionizing penetrating particles in the atmosphere, through an investigation of the altitude dependence and of the latitude dependence at airplane altitudes for mesons and for other ionizing particles ("X-particles") which are stopped after penetrating a certain thickness of lead. The method employed for distinguishing the meson component from the other ionizing particles consists essentially in the simultaneous observation of "delayed coincidences" and of "anticoincidences" associated with the stopping of the penetrating particles in a certain thickness of dense material (absorber). The exponential shape and the characteristic 2.2 μsec. decay constant of the curve representing the counting rate of the delayed coincidences *vs.* delay, yields, without ambiguity, the identification of ordinary mesons. By extrapolation, the number of stopped mesons is thus obtained. The anticoincidences, corrected for the contribution given by mesons, yield, on the other hand, the number of ionizing particles, different from mesons, stopping in the absorber. In comparing the two numbers it must be remembered, of course, that they may refer to particles of the same range but presumably not of the same energy.

The experimental method employed in the present research is suitable for measurements of absolute intensities. Indeed, using only delayed coincidences, in order

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[1] Lattes, Occhialini, and Powell, Nature **160**, 486 (1947).

[2] Rossi, Sands, and Sard, Phys. Rev. **72**, 120 (1947).

[3] M. Sands, Phys. Rev. **74**, 1237 (1948); M.I.T., Technical Report No. 28 (1949).

[4] D. C. Moore and R. B. Brode, Phys. Rev. **73**, 532 (1948).

[5] Adams, Anderson, and Cowan, Rev. Mod. Phys. **21**, 562 (1948).

[6] Adams, Anderson, Lloyd, Rau, and Saxena, Rev. Mod. Phys. **20**, 334 (1948).

to obtain from their observed counting rate the absolute number of mesons, it is necessary to know the average value of the probability, p, that a meson brought to rest in the absorber disintegrates into an electron which strikes the "delayed counters." This probability depends in particular on the range of the decay electrons in the stopping material. Owing to the distribution in energy of the decay products[7,8] and to the uncertainty of the range-energy relationship for electrons of such energies, a calculation of p appears to be rather unreliable. Instead, with the technique employed here, the average value of p can be deduced directly from the numbers of delayed coincidences and of anticoincidences obtained simultaneously under conditions in which practically all of the observed particles are ordinary mesons.

The same apparatus has also been used in order to obtain some information about the positive excess and the energy distribution of ordinary mesons.

Most of the measurements of the ratio between the numbers of positive and negative particles present in cosmic radiation have been performed so far using two different methods: (a) a cloud chamber in a magnetic field[6, 9–13] and (b) magnetized iron bars.[14–20] In general, the positive excess so observed may be due in part to protons and in part to an actual excess of positive mesons. Furthermore, the investigation of the positive excess by these techniques cannot be extended easily to the low energy region of the meson spectrum, partly because of the large percentage of electrons which are present in the radiation observed without using shielding material.

The distinction made between ordinary mesons and other particles by the method of the delayed coincidences takes advantage of one of the properties typical of ordinary mesons. Another property which can also be considered as typical of these particles is their low interaction with nuclear matter. Because of this, negative mesons are captured only in elements of comparatively high atomic number, whereas in light materials they undergo spontaneous decay.[21] One can take advantage of this property to obtain the excess of positive mesons from the comparison of the numbers of delayed coincidences produced by the decay of mesons stopped in two "absorbers," one of *low* and one of *high* atomic number.

This method for separating positive from negative ordinary mesons was first used by Shamos, Levy, and Lower.[22] The same method, in association with a de-

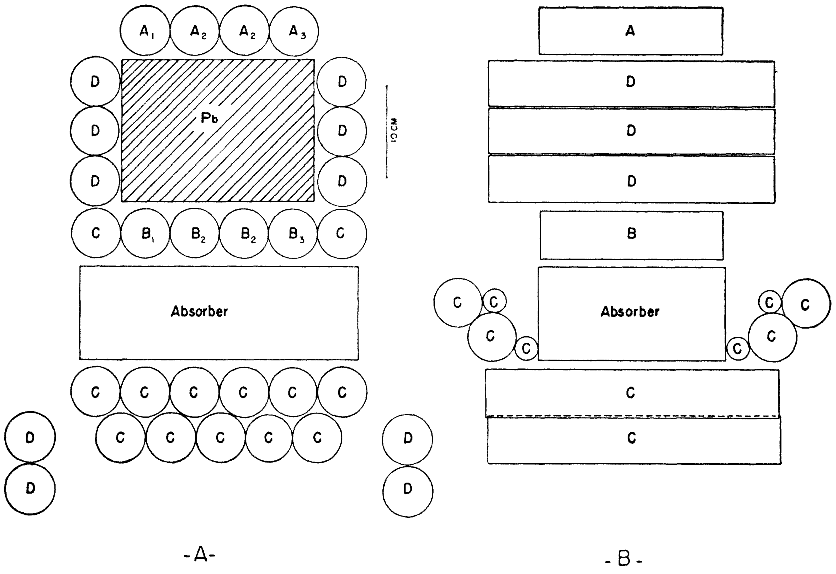

Fig. 1. Cross-sectional view of the counter tubes array.

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[7] J. Steinberger, Phys. Rev. **74**, 490 (1948).

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

[9] P. M. S. Blackett, Proc. Roy. Soc. **159**, 1 (1931).

[10] L. Leprince-Ringuet and J. Crussard, J. de phys. et rad. **8**, 207 (1937).

[11] H. Jones, Rev. Mod. Phys. **11**, 235 (1939).

[12] D. J. Hughes, Phys. Rev. **57**, 592 (1940).

[13] M. Correll, Phys. Rev. **72**, 1055 (1947).

[14] Bernardini, Conversi, Pancini, and Wick, Ricerca Scient. **12**, 1227 (1941).

[15] M. Conversi and E. Scrocco, Nuovo Cimento **1**, 372 (1943).

[16] Bernardini, Conversi, Pancini, Scrocco, and Wick, Phys. Rev. **68**, 109 (1945).

[17] N. Nereson, Phys. Rev. **73**, 565 (1948).

[18] Quercia, Rispoli, and Sciuti, Phys. Rev. **73**, 532 (1948); **74**, 1728 (1948).

[19] Ballario, Benini, and Calamai, Phys. Rev. **74**, 1729 (1948).

[20] R. B. Brode, Phys. Rev. **76**, 468 (1949).

[21] Conversi, Pancini, and Piccioni, Phys. Rev. **68**, 232 (1945); **71**, 209 (1947); T. Sigurgeirsson and K. A. Yumakawa, Phys. Rev. **71**, 319 (1947).

[22] Shamos, Levy, and Lower, Phys. Rev. **74**, 1237 (1948).

tector of penetrating showers, has been recently applied by Piccioni[23] to investigate the nature of the particle constituting penetrating showers locally produced in lead.

Some of the results of the experiment described in this paper have already been published in short reports.[24] Meanwhile a better determination of the constants of the instrument as well as a more refined evaluation of the corrections and of the experimental errors have been achieved. Some of the figures which appeared in the previous reports have undergone, accordingly, slight variations. Moreover, further measurements with graphite and sulfur absorbers have been taken near sea level, under different thicknesses of material, in order to obtain information as to the distribution of the positive excess in the low energy region of the meson spectrum.

II. APPARATUS AND EXPERIMENTAL METHOD

(A) Description of the Apparatus

Figure 1 represents, to scale, two cross-sectional views of the counters array. The effective length of counters A, B, of the two counters C (1 in. in diameter) adjacent to the absorber in Fig. 1B, and of the four lower[24a] counters D, was 20 cm. All other counters had an effective length of 32 cm. The thickness of the counter wall was 0.08 cm. The external diameter was 2 in. for all counters except for the four 1 in. diameter counters represented in Fig. 1B. All counters, filled with the usual alcohol-argon mixture, were of the all-metal type.

The two counters A_2 as well as the two counters B_2 were connected directly in parallel. Counters C as well as counters D were connected to a diode-mixer[25] so that their pulses were added at the output of the diode-mixer although each individual counter was uncoupled with respect to all of the others.

Counter A_1 was in coincidence with counters B_1 and B_2; counters A_2 were in coincidence with B_2; counter A_3 was in coincidence with counters B_2 and B_3. It can be seen from Fig. 1 that each one of the three solid angles defined by these double coincidences was completely covered by counters C and D.

The coincidence circuits (conventional diode-coincidence circuits[25] using crystal diodes) had a resolving time of about 2 μsec.

All of the indicated double coincidences, added by means of a diode-mixer, will be indicated in what follows as (AB).

The output pulse corresponding to any event (AB) started 0.7 μsec. after the time of occurrence of the *earliest* of the two counter pulses producing the coincidence, provided that both pulses occurred within 0.7 μsec. of each other. This was done, as suggested by Sands,[2,3] with the purpose of reducing the effect of the time lags of the G-M counters.

Most of the measurements have been performed with 6 in. of lead placed between counters A and counters B, as represented in Fig. 1. A 10-cm thick block of graphite (C) or sulfur (S), placed underneath counter B, was used as an "absorber" for the particles entering the solid angle defined by the coincidences (AB).[26] The pertinent dimensions of the absorber appear from Fig. 1. Mesons which were stopped in the C absorber after traversing in the vertical direction the 6 in. of lead interposed in the telescope, had energies in the range 224 to 255 Mev. With the S absorber the energy range was 224 to 257 Mev. The maximum permitted zenith angle for a meson entering the counter telescope and stopping in the absorber was about 35°.

Counters C were *at the same time* in delayed coincidences and in anticoincidence with respect to the coincidences (AB), while counters D were used only as additional "anticounters." An event was recorded as an anticoincidence $(AB-C)-$ or $(AB-(C+D))-$ if no counter $C-$ or $(C+D)-$ fired within 1.1 μsec. before or 7.8 μsec. after the time of occurrence of a double coincidence (AB).

The anticoincidences $(AB-C)$, registered in addition to the $(AB-(C+D))$, were used for introducing a correction in the number of the recorded delayed coincidences (see below).

The delayed coincidences were registered by four "channels," so that four points of the decay curve corresponding to the mesons stopped in the absorbers were obtained simultaneously.

The "time distance," θ, between each channel and the next one was 0.98 μsec. The "time width," $\Delta\theta$, of the channels was 2.8 μsec.

The "minimum delay," θ_m, for which a coincidence was recorded in the first channel was 1.15 μsec.

Some technical details concerning the electronic equipment are given in Appendix A.

(B) Corrections

A contribution to the delayed coincidences registered in each channel may be given by random events as well as by spurious delays associated with the discharge of the G-M counters. For an accurate determination of the decay curve of the stopped mesons a sufficiently exact knowledge of the spurious counting rate in each channel is required, especially if this counting rate is a considerable fraction (as it actually happens at high altitudes) of the total number of observed delayed coincidences.

For the interpretation of the experimental results, as

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[23] O. Piccioni, Phys. Rev. **77**, 1 (1950).

[24] M. Conversi, Phys. Rev. **76**, 311, 444, 849, and 851 (1949).

[24a] During one series of measurements (Section III B) also these counters D had an effective length of 32 cm.

[25] Howland, Schroeder, and Shipman, Rev. Sci. Inst. **18**, 551 (1947).

[26] The S absorber was contained in a can made of copper sheet 0.08 cm thick. The author wishes to take this opportunity of thanking the Research Department of the Texas Sulfur Company for providing the block of sulfur.

well as for a computation of the counting rate, N_r, of the delayed coincidences produced in each channel by *random* events, it must be mentioned that the pulse-forming circuit triggered by the pulses of counters C (B.O.3 in Fig. 9, Appendix A) had a "recovery time" of 12.5 μsec. This time was larger than the maximum delay (6.89 μsec.) for which delayed coincidences were registered by the last channel. Random delayed coincidences could be caused, therefore, only by events in which a particle producing a coincidence (AB), but failing to discharge counters C (let $n_{(AB-C)}$ be the counting rate of these events) was followed after a short time by a single discharge of counters C. If n_c represents the background counting rate of counters C, we have then:

$$N_r = n_{(AB-C)} n_c \Delta\theta. \tag{1}$$

N_r, which is practically negligible near sea level under 10 or more cm of lead, becomes quite appreciable at high altitudes. However, all the quantities appearing on the right side of Eq. (1) can be measured with great accuracy.

The spurious delayed coincidences due to the time lags of counters C were strongly reduced by using a double layer of counters, since thus most of the particles traversing the counter telescope discharged two counters C and the counter which was discharged first triggered the corresponding pulse-forming circuit (B.O.3 in Fig. 9). Under these conditions, the percentage of delayed coincidences due to spurious delays larger than 1.15 μsec. was found to be completely negligible in the measurements taken near sea level (Sec. III). In the measurements performed at high altitudes, however, an appreciable fraction of the delayed coincidences registered by the first channel was recognized to be due to the effect of these spurious delays. On the basis of measurements performed without an absorber it is found that at 30,000 feet the coincidences registered in the first channel using the C absorber, previously corrected for the random events given by Eq. (1), must be multiplied by the factor 0.885 in order to represent only the contribution of the decay electrons. In the measurements with S absorber this factor is found to be 0.81. (See Appendix B for a detailed discussion of this point.)

The loss of delayed coincidences and of anticoincidences is negligible, for our apparatus, wherever measurements have been taken. It is shown also, in Appendix C, that the difference between the rates of anticoincidences recorded with and without an absorber represents, within a good approximation, the number of "true anticoincidences"; that is, events associated with the stopping of ionizing particles in the absorber.

(C) Relations among Measured Quantities

For the four points corresponding to the coincidence rates produced in each channel by the decay of the stopped mesons, the *most probable* disintegration curve corresponding to a given lifetime, τ, can be drawn. Let N_c be the coincidence rate obtained, using the C absorber, by extrapolation to the zero time of such a curve. Since the time width of the channels is $\Delta\theta$, N_c represents the number of mesons which are stopped per unit time in the C absorber after penetrating the counter telescope and which disintegrate between O and $\Delta\theta$ into electrons that discharge counters C. Therefore, if p represents the average value of the probability that a meson stopped in the C absorber decays into an electron discharging counters C, the number of mesons stopped in the C absorber after traversing the counter telescope is given by

$$M = N_c/p[1-\exp(-\Delta\theta/\tau)]. \tag{2}$$

As is shown by the results of our measurements (Discussion, Sec. IV) the contribution given to the delayed coincidences by positive π-mesons locally produced appears to be quite small, for our apparatus, at all altitudes at which measurements have been taken. Hence Eq. (2) refers essentially to *ordinary* mesons coming from the atmosphere above the apparatus.

Let I_a be the intensity of the "true anticoincidences," and let us remember that events are registered as anticoincidences when no "anticounter" fires within 7.8 μsec. after the time of occurrence of a coincidence (AB). Since the percentage (2.8 percent) of mesons decaying after 7.8 μsec. can be neglected, the contribution given by mesons to the intensity I_a is $(1-p)M$.

If particles *other than mesons* are stopped in the absorber, they will give an additional contribution, X, to the intensity I_a; so that we shall write, in general:

$$I_a = (1-p)M + X. \tag{3}$$

For the sake of brevity we shall call the particles responsible for this possible contribution "X-particles," without thereby implying that they are all particles of the same kind. The instrumental characteristics of the method employed impose some restrictions on the possible types of events appearing as X-particles. More precisely we can state as follows:

(a) X-particles must be ionizing particles[27] coming from the atmosphere and either stopping in the absorber after traversing counters A and B, or producing (in the lead between counters A and B) other ionizing particles, of which at least one traverses counters B, stopping in the absorber, and none of which strikes the "anticounters"; (b) after they or their secondary particles have been stopped in the absorber, no emission of secondary ionizing rays striking the anticounters has to take place within 7.8 μsec.

The absolute numbers (per unit range) of mesons and of X-particles can be derived from Eqs. (2) and (3) if the value of p is known. Actually this value can be deduced from measurements performed under experimental conditions in which the contribution X in Eq. (3) is negligible in comparison with $(1-p)M$. In these

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[27] This is true for most of the measurements taken in the airplane, where a negligible amount of material was present above the apparatus.

TABLE I. Results of measurements of delayed coincidences performed in Chicago for the determination of p.

Series No.		1	2	3
Absorber (C)		on	on	off
Material above the absorber (g/cm^2)		228 Pb $+\sim 40$ concrete	398 Pb $+\sim 75$ concrete	
Duration (minutes)		7595	16,785	16,725
Delayed coincidences registered in channel	1	533	1123	201
	2	337	694	137
	3	211	470	75
	4	145	309	50
Random delayed coincidences, N_r		2.7	6.1	4.1
Extrapolated[a] delayed coincidences per hour, N		6.90 ± 0.27	6.73 ± 0.18	1.15 ± 0.075

[a] Correcting the number of counts registered in the four channels only for the random coincidences N_r (as given by Eq. (1)).

TABLE II. Results of measurements of anticoincidences performed in Chicago for the determination of p.

Series No.	1		2	
Absorber (C)	On	Off	On	Off
Material above the absorber (g/cm^2)	228 g/cm^2 of Pb $+\sim 40$ of concrete		398 g/cm^2 of Pb $+\sim 75$ of concrete	
Duration of observation (min.)	3780	4020	8440	5700
Anticoincidences per hour, N_a	60.8 ± 1.0	37.0 ± 0.74	75.7 ± 0.75	50.2 ± 0.73
True anticoincidences per hour (I_a)	23.8 ± 1.25		25.5 ± 1.05	
I_a/N_c	3.45 ± 0.22		3.79 ± 0.19	
p	0.286 ± 0.013		0.268 ± 0.010	

conditions, in fact, from Eqs. (2) and (3) it follows that:

$$1/p=1-[1-\exp(-\Delta\theta/\tau)](I_a/N_c). \qquad (4)$$

For the determination of the excess of positive mesons, delayed coincidences were measured using alternately absorbers of graphite (C) and of sulfur (S).

According to Ticho, 72 percent of the negative mesons stopped in sulfur are captured while the remaining 28 percent decay with a lifetime of about 0.5 μsec.[28] Since in the first channel events which occur with delays between 1.15 μsec. and 3.95 μsec. are recorded (θ_m to $\theta_m+\Delta\theta$), one sees that the first channel detects 43 percent of the positive, and 2.7 percent of the negative, mesons. This means that if the excess of positive mesons is ~ 20 percent, the counting rate of the coincidences registered in the first channel with S absorber must be multiplied by the factor 0.95 in order to represent the counting rate due *only* to positive mesons.[29] When this correction (which becomes completely negligible in the following channels) is applied in addition to the one due to the contribution of the spurious events, then by extrapolation of the decay curve so obtained one gets the number, N_s, of *positive* mesons which decay, between O and $\Delta\theta$, into electrons discharging counters C.

Let k be the ratio between the number of mesons stopped in the C absorber and the number of those stopped in the S absorber. Then let ρ represent the ratio between the probability for the decay electrons of mesons stopped in the C absorber to produce a delayed coincidence and the analogous probability relative to the S absorber. Setting $k\rho=1/a$ it is easily shown that the ratio of positive to negative mesons is given by

$$M_+/M_-=1/[a(N_c/N_s)-1] \qquad (5)$$

with the assumption that *all* mesons decay in C.[30]

III. RESULTS

(A) Experimental Conditions and Controls in the Measurements at High Altitudes

Measurements of delayed coincidences and of anticoincidences were performed in Chicago (about 600 feet above sea level), at China Lake, California (2100 feet), and in the rear pressurized cabin of a B-29 airplane at different altitudes and latitudes.

The measurements in the B-29 aircraft were carried out in two successive expeditions: the first from China Lake to Lima, Peru, and back; the second from China Lake to Fairbanks, Alaska, and back. The first expedition was undertaken entirely at a pressure altitude

TABLE III. Results of measurements of delayed coincidences at 30,000 feet, at different latitudes. Mesons observed belong to the energy range 224 to 255 Mev (momentum range 315 to 348 Mev/c). Absorber of graphite.

Expedition		1st	1st	1st	2nd	1st	2nd
Average geomagnetic latitude		9° N	28.5°	35.5°	40.0°	42.0°	59.0°
Duration (minutes)		350	298	220	290	142	220
Delayed coincidences registered in channel	1	203	208	204	271	[a]	249
	2	124	116	122	173	85	161
	3	83	86	[a]	120	56	106
	4	60	70	[a]	93	43	88
Anticoincidence ($AB-C$) per minute		35.1	46.7	51.6	53.8	56.2	64.3
Single counts (C) per 10^{-3} min.		38.5	43.1	45.7	50.6	48.4	59.3
Random delayed coincidence N_r		22.1	28.1	24.2	36.9	18.0	39.2
Corr.[b] extrapolated delayed coincidence N_c per hr.		46.5 ± 3.3	53.3 ± 3.9	72.0 ± 5.8	76.9 ± 4.8	73.2 ± 8.4	87.1 ± 5.4
Latitude ratio, $R(N_c)$		1.00 ± 0.07	1.14 ± 0.08	1.55 ± 0.12	1.65 ± 0.10	1.57 ± 0.18	1.87 ± 0.12

[a] Not recorded.
[b] Correcting all channels for the random coincidences N_r and the first channel also for the time lags of the counters (according to Eq. (9), Appendix B).

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[28] H. K. Ticho, Phys. Rev. 74, 1337 (1948).

[29] Neglecting the positive excess this factor would be 0.94.

[30] See footnote 40.

of 30,000 feet, while in the Northern flight observations were made at different altitudes. During both expeditions 6 in. of lead was placed between counters A and B. One flight was made over Lima with 4 in. of additional lead placed above counters A. The measurements were performed in both expeditions under the same experimental conditions with the following exceptions: (a) in the first expedition lateral blocks of lead (2 in. thick) were used in order to reduce the background counting rate of counters C; since their effect was not found to be considerable, they were removed at the end of the expedition; (b) only during the Northern expedition were the anticoincidences $(AB-C)$ recorded continuously; (c) only during the Northern flight was the background counting rate, n_c, of counters C measured directly by means of a 256-scaling unit. During the Southern expedition the value of n_c was obtained from the background counting rates of counters B as measured in flight (by means of a 64-scaler) assuming the same altitude dependence for the background counting rates of counters B and C; (d) during the Southern expedition measurements were taken alternately with and without a graphite absorber, while during the Northern one additional measurements with a sulfur absorber were performed alternately. It has to be mentioned, finally, that all counters were changed at the end of the first expedition. The consistency between the measurements performed in Chicago before and after the period of the expeditions shows, however, in a satisfactory manner, the stability of the performance of the apparatus.

During each flight the background counting rate of the different groups of counters was measured approximately every 20 minutes. Double coincidences (AB) were also measured in flight approximately every half-hour.

During the Northern expeditions, furthermore, the main points of the electronic apparatus were checked in flight by means of a syncroscope.

(B) Measurements for the Determination of p

The *hard* component of cosmic rays at sea level is known to be composed essentially of ordinary mesons. However, since no information is available on the energy distribution of the small percentage of protons which are believed to be present at sea level,[31,32] we cannot assume, without checking directly, that the contribution X in Eq. (3) is negligible at sea level under 20 or more cm of lead. For this reason, in order to obtain the value of the constant p defined in Sect. IIC two series of measurements, reported as No. 1 and No. 2 in Tables I and II.[33] have been carried out in Chicago under the amount of material specified in the third line of the tables. In both cases 6 in. of lead was placed between counters A and B, the remaining material being above the apparatus, in the solid angle of the counter telescope.

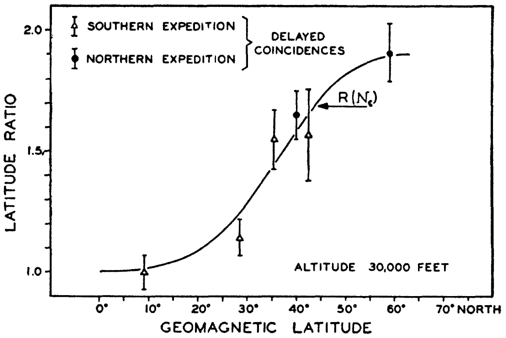

FIG. 2. Latitude dependence at 30,000 feet of mesons stopped in 10 cm of graphite after penetrating 6 in. of lead.

The "extrapolated delayed coincidences"[34] in the last line of Table I, have been obtained from the *corrected* delayed coincidences recorded in the four channels assuming a lifetime of 2.20 μsec. The percentage error in N has been assumed to be equal to the percentage error in the sum of corrected delayed coincidences registered in the first and last channels.[35]

The delayed coincidences recorded in each channel have been corrected only for the small contribution of random events, N_r, obtained through Eq. (1) and given in the sixth line of Table I. The correction for spurious delayed coincidences due to the time lags of the G-M counters is shown to be completely negligible by the results of measurements without an absorber reported in the same table as series No. 3. Indeed, within the experimental errors, the four points corresponding to the delayed coincidences recorded without absorber are on an exponential curve of 2.2 μsec. decay constant. Mesons slowed down in the counter walls and in the material (brass) of the frame are evidently responsible for the delayed coincidences so observed.

The anticoincidences reported in Table II have been measured simultaneously with the delayed coincidences reported in Table I. Table II contains, however, only those measurements which have been taken *alternately* with and without the graphite absorber. It will be observed that the ratio I_a/N_c between "true anticoincidences" and "extrapolated delayed coincidences" is the same, within statistical uncertainties, for both series of measurements. If particles other than mesons (X-particles) were present in appreciable amounts in the conditions of series No. 1, we should reasonably

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[31] L. Janossy, *Cosmic Rays* (Oxford University Press, London, 1948).

[32] B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).

[33] Errors indicated in these and in the following tables are statistical standard deviations.

[34] The quantities N_c, N_s, and N_0 (without absorber) will be indicated in general by the letter N.

[35] It can be proved easily that for a given value of the lifetime the percentage error of the most probable number of delayed coincidences extrapolated to the zero time from the numbers registered in two channels which are "independent" and "contiguous," is the same as for a single channel covering the same time interval as the two. Since in our case the first and fourth channels are "independent" but not exactly contiguous, the actual error of N is somewhat smaller than the one assumed.

TABLE IV. Results of measurements of anticoincidences with and without C absorber, taken at 30,000 feet, under 6 in. of lead, near the equator, at 32°, 40°, and above 55° N geomagnetic latitude. $R(N_a)$ and $R(I_a)$ represent the "latitude ratios" respectively of the anticoincidences with absorber and of the "true anticoincidences."

Geomagnetic latitude	5° N.		32°		40°		59°	
Absorber	on	off	on	off	on	off	on	off
Duration (minutes)	185	60	150	110	290	122	551	95
Anticoincidence per hour	1370±21	964±31	2117±29	1519±29	2579±23	1805±30	3276±19	2208±37
True anticoincidence per hour (I_a)	406±37.5		598±41		774±38		1068±42	
$R(N_a)$	1.02±0.016		1.58±0.022		1.92±0.017		2.44±0.015	
$R(I_a)$	1.02±0.094		1.50±0.102		1.94±0.095		2.68±0.105	

expect in passing from the first to the second series a decrease of the ratio I_a/N_c due to their absorption in the additional amount of material present in the conditions of series No. 2. Our results show, therefore, that X-particles are present in negligible amounts, if at all, in both cases. Then Eq. (4) holds and we obtain for p the values reported in the last line of Table II. By combining these two values we find

$$p=0.28\pm0.0085. \tag{6}$$

For $\Delta\theta=2.8$ μsec. we obtain, then, from Eq. (2):

$$M\approx 5N_c.$$

Although I_a is the same, within statistical errors, for both series of measurements, there is a considerable difference between the rates of anticoincidences N_a reported in the fifth line of Table II. This is explained by the fact that in the first series (performed before the B-29 expeditions) the four lower counters D had an effective length of 32 cm, while later they were exchanged for counters 20 cm long.

(C) Measurements at 30,000 Feet at Several Latitudes

Table III contains the results of measurements of delayed coincidences taken with a graphite absorber at 30,000 feet, at different latitudes. During these measurements 6 in. of lead were interposed between counters A and B so that the observed mesons had energies in the range 224 to 255 Mev (for a vertical direction of incidence).

The data reported in each column of the table include two or more flights undertaken at approximately the same average latitude, with the exception of one flight at 35.5° and one at 42°. During these latter two flights, unfortunately, part of the delayed coincidences were not recorded. The internal consistency of the measurements performed in different flights at the same latitude was always satisfactory.

In the last line of Table III is reported the "latitude ratio" $R(N_c)$, namely the ratio between the counting rates of the extrapolated delayed coincidences, N_c, observed at each latitude and near the equator (9° N.). *The intensity of the observed mesons is found to increase by a factor of 1.87±0.14 between the geomagnetic equator and 59° N.*

Owing to the small number of points obtained and to their large statistical errors, little information is available about the shape of the latitude curve, $R(N_c)$, which has been represented in Fig. 2 in a rather arbitrary way.

Measurements without an absorber were usually taken for a short period, so that each individual anticoincidence measurement was affected in general by a rather large statistical error. Thus no large number of accurate points could be obtained for the latitude curve of the "true anticoincidences" from measurements performed while the plane was flying at a variable latitude. Flights at a constant latitude, in the experimental conditions previously specified, have been undertaken only at 32° and at 40° north geomagnetic latitude. Nevertheless, measurements performed around the geomagnetic equator and around 60° N. may be considered to be taken at a practically constant latitude, for in these regions the intensities of the several components so far observed do not undergo any appreciable change. The results of these flights are reported in Table IV. The latitude ratio, at 5° N., of the true anticoincidences, I_a (and also of the anticoincidences with absorber, N_a) has been assumed to be 1.02, as suggested by a first analysis of the results. The increase in the number of true anticoincidences between the equator and 59° N. is so found to be 2.68±0.27. The four points of the latitude curve of the true anticoincidences corresponding to the data contained in the last line of Table IV are represented by double circles in Fig. 3.

In order to obtain further information as to the shape of this curve, we will assume that for latitudes lower than 55° N. the latitude ratio, $R(I_a)$, of the true anticoincidences, can be expressed in terms of the latitude ratio $R(N_a)$ according to the relation

$$R(I_a)=(1+\alpha|\lambda|)R(N_a), \tag{7}$$

where α is a constant and λ represents the geomagnetic latitude in degrees. Since (as is shown by the data contained in the two last lines of Table IV) there is not much difference between the values of $R(I_a)$ and of $R(N_a)$, this assumption appears to be quite reasonable provided that the intrinsic efficiency of the apparatus did not change during the entire period of the flights. By comparing the values of $R(I_a)$ and of $R(N_a)$ given[36]

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[36] In Table IV there have been included also values of N_a obtained with a sulfur absorber, during the Northern expedition. The ratio of anticoincidences with graphite and with sulfur

in Table IV at the four specified latitudes, we obtain for α four values which are consistent with one another within their statistical errors. By combining these four values we find $\alpha=8.3\cdot 10^{-4}$. From Eq. (7) and from the values of N_a given in Table V we obtain thus the values of $R(I_a)$ reported in the same table and represented graphically in Fig. 3. As is indicated in Fig. 3, *the rate of anticoincidences seems to reach a "saturation" in the neighborhood of 55°.*

Using Eqs. (2) and (3) it is easily shown that the latitude ratio, $R(X)$, of the X-component is given by

$$R(X)=[R(I_a)-bR(N_c)]/(1-b), \tag{8}$$

where $b=(1-p)(M/I_a)_{\lambda=0}$.

For the numerical values of $\Delta\theta$ and of p previously found, the ratio $(M/I_a)_{\lambda=0}$ between the numbers of stopped mesons and of true anticoincidences at the equator (which are given in Tables III and IV) is $\approx 5(0.115\pm 0.013)$. We find then $b=0.41\pm 0.05$. From Eq. (8) and from the latitude curves $R(N_c)$ and $R(I_a)$ represented in Figs. 2 and 3, respectively, we obtain the latitude curve[37] $R(X)$ drawn in Fig. 4.

As to the accuracy of *the latitude effect of the X-component*, it may be observed that using the values of $R(N_c)$ and $R(I_a)$ near the equator and at 59° as given in Tables III and IV and introducing the error on b *we obtain for* $R(X)$ *at 59° the value 3.21±0.49.*

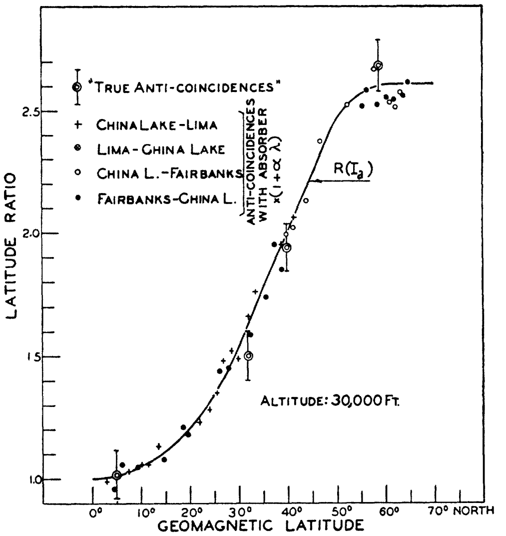

FIG. 3. Latitude dependence at 30,000 feet of the anticoincidences under 6 in. of lead. The "latitude ratio," $R(I_a)$, of the "true anticoincidences" is supposed to be $(1+\alpha|\lambda|)$ times the latitude ratio of the "anticoincidences with absorber," where λ is the geomagnetic latitudes and $\alpha=8.3\times 10^{-4}$ (degree)$^{-1}$.

TABLE V. Results of measurements at 30,000 feet of anticoincidences, N_a, with absorber, between 3° and 65° N. geomagnetic latitude. λ is the geomagnetic latitude in degrees; ϵ is the percentage error in the observed counting rate (N_a/hr.) of the anticoincidences N_a. The latitude ratio, $R(I_a)$, of the true anticoincidences is assumed to be $(1+8.5\cdot 10^{-4}|\lambda|)$ times the latitude ratio of the anticoincidences N_a.

λ	Flight	N_a/hr.	$R(I_a)$	ϵ	λ	Flight	N_a/hr.	$R(I_a)$	ϵ
3.0	1	1328	0.99	3.2	33.5	1	2298	1.76	3.0
4.5	2	1288	0.96	4.8	35.5	2	2262	1.74	3.0
6.0	2	1422	1.06	4.6	37.5	2	2557	1.95	3.5
7.5	1	1380	1.03	3.3	39.0	2	2406	1.85	3.5
9.0	2	1392	1.04	3.2	39.5	1	2518	1.94	1.9
10.0	1	1416	1.06	4.6	40.0	3	2579	1.99	0.9
11.5	1	1422	1.07	4.6	41.0	3	2606	2.02	2.3
13.5	1	1502	1.13	3.8	41.5	1	2663	2.06	2.1
14.5	2	1429	1.08	3.3	44.0	3	2754	2.13	2.3
18.5	2	1596	1.21	5.0	47.0	3	3069	2.37	2.1
19.5	2	1554	1.18	3.6	52.5	3	3241	2.52	2.1
22.5	1	1626	1.23	4.3	55.5	4	3223	2.51	1.8
24.0	1	1692	1.28	4.3	56.5	4	3308	2.58	1.9
25.5	1	1776	1.35	4.1	58.0	3	3408	2.65	2.4
26.0	2	1888	1.44	3.3	58.5	4	3238	2.53	1.8
27.0	1	1947	1.48	3.9	60.5	4	3275	2.55	1.8
27.5	2	1910	1.45	3.3	61.0	3	3240	2.53	2.5
28.5	1	2001	1.52	3.9	62.0	4	3257	2.54	1.8
30.0	1	1950	1.49	3.9	62.0	3	3219	2.51	1.75
32.0	1	2172	1.66	2.1	62.5	3	3302	2.57	1.7
32.0	2	2080	1.59	1.8	63.0	4	3284	2.56	2.5
					65.0	4	3358	2.61	2.4

Flight No. 1, China Lake to Lima.
Flight No. 2, Lima to China Lake.
Flight No. 3, China Lake to Fairbanks.
Flight No. 4, Fairbanks to China Lake.

(D) Measurements at 30,000 Feet Taken at the Geomagnetic Equator under Ten Inches of Lead

During the Southern expedition one flight was undertaken over Lima (geomagnetic equator), at 30,000 feet, adding 4″ of lead (in the solid angle of the double coincidences) to the 6″ of lead placed between counters A and B. The results of these measurements are summarized in Table VI.

(E) Measurements at Different Altitudes

Measurements with 6 in. of lead between counters A and B and with graphite absorber have been performed at 600 feet (Chicago), 2100 feet (China Lake), 22,500 feet, 30,000 feet, and 36,000 feet. The results are reported in Tables VII and VIII. The data at 30,000 feet include only the measurements of the Northern Expedition.

In comparing the results obtained at different altitudes it must be taken into account that they do not all refer to the same latitude. For lack of information we are forced to assume that for the observed mesons, as well as for the X-particles: (a) there is no appreciable correction between 41° N. and 53° N. at altitudes lower than 2100 feet; (b) the latitude correction at 36,000 feet is approximately the same as at 30,000 feet, between 40° and 50° N.

Then, from the latitude curves at 30,000 feet given in Fig. 2 for the meson component and in Fig. 4 for the

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absorbers at 30,000 feet was found to be 0.99±0.006, so that no correction needs to be applied in practice.

[37] In a previous report (reference 24) we used the value $p=0.29\pm 0.015$, as obtained from measurements which were not so accurate as those reported in the present paper, and we assumed that $\alpha\lambda \ll 1$ at all latitudes. This led to an underestimation of the latitude effect of the X-component.

X-component, we deduce the corresponding correction factors (reported also in the tables) to be used in order to refer all measurements to the same geomagnetic latitude of 50° N.

(F) Absolute Intensities

If Ω is the *effective* solid angle of the beam of particles which are stopped in the absorber after traversing the counter telescope, the absolute numbers of mesons and of X-particles per sec. steradian, and per gram of graphite, are obtained by multiplying respectively M and X by the factor $(3600\ \Omega s)^{-1}$, where s represents the *effective* thickness of the absorber in g/cm^2.

For the geometry of our counter arrangement (Fig. 1) some of the particles belonging to the solid angle defined by counters A, B, and C, do not traverse the absorber. More precisely, all those particles which traverse counters A, B, and one of the lateral counters C in Fig. 1B, do not traverse the *entire* thickness of the absorber. If we call $(ABC)_{\text{lat}}$ the counting rate of the threefold coincidences produced by these particles, then the difference $\Delta=(ABC)-(ABC)_{\text{lat}}$ represents the number of particles traversing the counter telescope and *the entire thickness of the absorber* per unit time.

Accurate measurements performed in the open air at Chicago with 6 in. of lead (271 g/cm^2) placed between counters A and B, yield $\Delta=0.883$ particles per sec. On the other hand, from measurements of Greisen[38] the corrected number of particles traversing at Ithaca (850 feet above sea level) 167 g/cm^2 of lead in the vertical direction is found to be[32] $I_v=0.85\times10^{-2}$ per cm^2 per sec., per sterad. Under the conditions of our measurements this figure must be decreased by about 1 percent, so that $I_v=0.84\times10^{-2}$. Thus we find $\Delta/I_v\approx\Omega=105$ cm^2 sterad. Since the vertical thickness of the absorber is about 16.5 g/cm^2, we have $s\approx16.5$ g/cm^2 and, therefore, $(3600\Omega s)^{-1}\approx1.6\times10^{-7}$.

TABLE VI. Results of measurements at 30,000 feet taken over Lima, Peru (geomagnetic equator) under 10 in. of lead, using absorber of graphite. The observed mesons had energy in the range of 350 to 381 Mev (momentum range 445 to 478 Mev/c).

(a) Delayed coincidences results			(b) Anticoincidence results	
Duration (minutes)		174	Duration (minutes)	174 with C absorber 68 without absorber
Delayed coincidences registered in channel	1	101		
	2	57	Anticoincidence per hour	1182 ±23 with absorber 748 ±26 without absorber
	3	43		
	4	31		
Anticoincidences $(AB-C)$ per minute		27.9	True anticoincidences per hour, I_a	434 ±35
Single counts (C) per 10^{-3} min.		33.9	X-particles per hour	263 ±39
Random delayed coincidences, N_r		7.6		
Corrected[a] extrapolated delayed coincidences, N_c, per hour		47.5 ±4.6		

[a] Correcting all channels for the random coincidences N_r and the first channel also for the time lags of the counters.

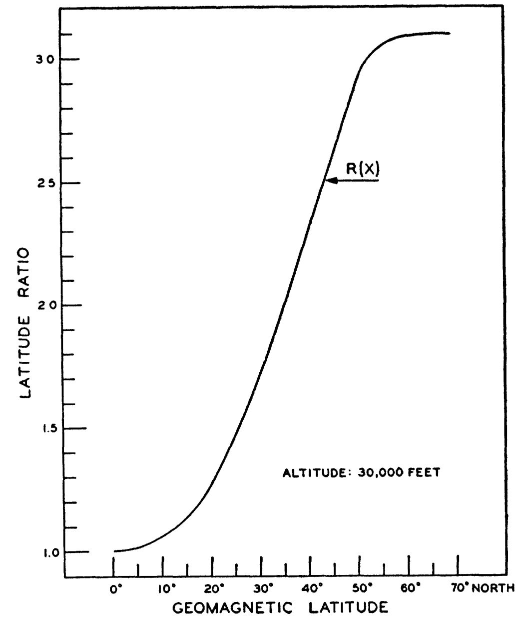

FIG. 4. Latitude dependence at 30,000 feet of the X-particles as deduced, through Eq. (8), from the curves $R(N_c)$ and $R(I_a)$ represented in Figs. 2 and 3.

By using this figure and introducing the corrections for the difference in latitude we obtain the absolute numbers of mesons (m) and of X-particles (x) reported in the last line of Tables VII and VIII and represented, as a function of the atmospheric depth, in Fig. 5.

Near sea level these absolute numbers refer to particles incident in the vertical direction if we assume the same zenith angle dependence for the particles stopped in the absorber and for those going through it. Although this assumption is certainly not true, the error related to it is very small on account of the comparatively narrow angular definition of our apparatus. It can also be observed that since Δ refers to particles traversing the *entire* thickness of the absorber, the previous absolute numbers have been somewhat overestimated by assuming $\Omega=\Delta/I_v$. On the other hand they have been somewhat underestimated by assuming the vertical thickness of the absorber to be nearly equal to its *effective* thickness. Both these errors are estimated to be only a few percent and the corresponding corrections have been therefore neglected.

(G) Positive Excess

Measurements of delayed coincidences with C and S absorbers have been performed in Chicago, under different thicknesses of material; at China Lake, without any lead in or above the counter telescope, and at 30,000 feet, during the Northern flight, with 6 in. of lead interposed in the counter telescope.

The results are reported in Table IX. This table also includes measurements with only C absorber, performed

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[38] K. I. Greisen, Phys. Rev. 61, 212 (1942).

TABLE VII. Results of measurements of delayed coincidences at different altitudes. Mesons observed belong to the energy range 224 to 255 Mev (momentum range 315 to 348 Mev/c). Absorber of graphite.

Altitude (ft.)	600	2100	22,500	30,000	36,000
Atmospheric depth (g/cm^2)	1010	957	427	306	231
Average geomagnetic lat.	51° N	42° N	50° N	49° N	40° N
Duration (minutes)	9470	6462	300	560	159
Delayed coincidences registered in channel 1	704	534	166	571	248
2	467	338	107	378	169
3	294	228	81	259	123
4	195	150	51	202	93
Anticoincidence ($AB-C$) per minute	1.98	2.33	29.4	59.6	79.1
Single counts (C) per per 10^{-3} min.	5.12	4.93	31.8	55.4	73.4
Random delayed coincidences, N_r	4.4	3.5	13.1	86.3	43.1
Corr.[a] extrapolated delayed coincidence, N_c, per hr.	7.50 ±0.25	8.3 ±0.32	53.0 ±3.8	79.5 ±3.5	120 ±8
Mesons stopped per hr. ($M \approx 5N_c$)	37.5 ±1.3	41.5 ±1.6	265 ±19	398 ±18	600 ±40
Correcting factor for 50° geomagnetic latitude	1	1	1.00	1.01	1.1
$10^6\times$no. of mesons per sec., g, steradian at 50° N	6.00 ±0.20	6.64 ±0.26	42.4 ±3.1	64.3 ±2.9	106 ±7.0

[a] Correcting all channels for the random coincidences N_r and the first channel, only in the measurements at 30,000 and 36,000 feet, also for the time lags of the counters.

in Chicago and at China Lake, under still different thicknesses of material, in order to obtain further points of the differential range spectrum of mesons (positive and negative) at the two stations.

The third column of Table IX contains the amount of material (in g/cm^2) that a particle had to penetrate before reaching the absorber. Series No. 1 was carried out on the roof of the Ryerson Building in the University of Chicago, under a military tent of negligible thickness. Series No. 6 was performed at China Lake in a cabin covered with a thin roof roughly equivalent to 5 g/cm^2 of air. The 2.7 g/cm^2 of brass reported in Table IX for both series corresponds to the thickness of the counter walls.

A rather accurate determination of the ratio between the numbers of positive and negative particles near sea level has been carried out by Conversi and Nappo[39] using magnetic lenses and G-M counters in anticoincidence. More precisely these authors have measured in Rome (~50 m above sea level) the numbers of anticoincidences produced by positive and by negative particles stopped in 7 cm of lead after traversing 28 cm of iron (thickness of the magnetic lens). As is indicated by the results of the measurements reported in Section III B, under similar conditions the number of protons should be negligible in comparison with the corresponding number of mesons. Hence, the ratio, 1.24 ±0.05, between the numbers of positive and negative particles as found in Rome,[39] may be assumed to represent the ratio M_+/M_- for mesons having energies in the neighborhood of 400 Mev. Since the mesons observed in Chicago under 228 g/cm^2 of lead plus 40 g/cm^2 of concrete (fourth series), belong approximately to the energy range of 350 to 380 Mev, the measurements of this series can be compared to those performed in Rome. From this comparison we obtain from Eq. (5), $a=1.03$.[40] The values of the ratio M_+/M_- for the different series of measurements reported in Table IX have been obtained from Eq. (5) using this value of a. The errors relative to the ratios M_+/M_- do not include the error of a.[41] Indeed, we are more interested in the

TABLE VIII. Results of measurements of anticoincidences at different altitudes.

Altitude (feet)	2100		22,500		30,000		36,000	
Average geomagnetic latitude	42° N		50° N		49° N		40° N	
Absorber	on	off	on	off	on	off	on	off
Duration (minutes)	6462	1484	300	73	560	237	159	30
Anticoincidence per hour	90.8±0.9	54.0±1.45	1350±19	787±19	2835±18	1910±23	3986±40	2850±79
True anticoincidence per hour (I_a)	36.8±1.7		563±27		925±30		1136±89	
X-particles per hour ($I_a-(1-p)M$)	6.2±2.1		372±30.5		638±33		704±93	
Correcting factor for 50° geomagnetic latitude	1		1.00		1.02		1.3	
$10^6\times$number of X-particles per sec., g, steradian at 50° N	0.99±0.34		59.5±4.9		104±5.4		146±19	

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[39] M. Conversi and F. Nappo, unpublished results (University of Rome, 1947).

[40] This result is found with the assumption that all mesons disintegrate in C. If the fraction of negative mesons which actually decay in C is assumed to be 0.95 [M. H. Shamos and M. G. Levy, Phys. Rev. **73**, 1396 (1948)] the value of a becomes 1.01 and, accordingly, $M_+/M_-=0.95/(1.01N_c/N_s-1)$. The values of M_+/M_- obtained from this formula do not differ appreciably from those deduced from Eq. (5), setting $a=1.03$.

[41] In the previous report (reference 24, p. 311) the error in a was included in the errors of the ratios M_+/M_-.

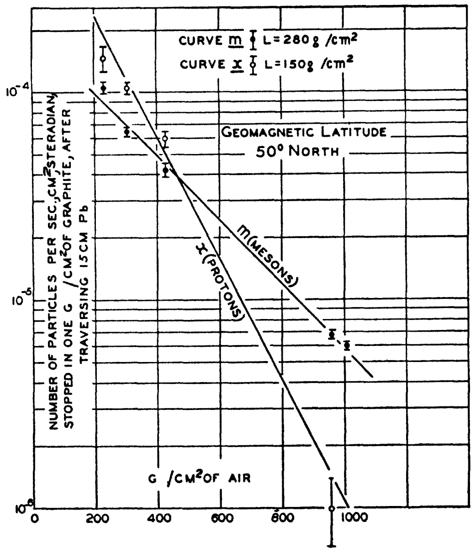

FIG. 5. Dependence upon altitude of the absolute numbers (sec.$^{-1}$, g^{-1}, sterad.$^{-1}$) of mesons (m) and of protons (x) stopped in 10 cm of graphite after traversing 6 in. of lead.

relative rather than the absolute values of the positive excess.

IV. DISCUSSION

Part 1: The Meson Component

(*A*) *Analysis of the Lifetime*

The results of the measurements of delayed coincidences at different altitudes, reported in Table VI, have been graphically represented in Fig. 6. It is seen from this figure that the decay curves obtained at all altitudes are consistent with a lifetime τ of approximately 2.2 μsec. The measurements of delayed coincidences corresponding to each flight have been also analyzed separately. When corrected for the random events given by Eq. (1) and for the spurious coincidences in the first channel due to the time lags of counters C (the second correction—see Appendix B—to be applied only in the measurements taken at 30,000 and at 36,000 feet), they have been found to be always in agreement, within experimental errors, with a 2.2 μsec. decay constant. Considering separately the results of the Southern and of the Northern flights the following values are obtained for the lifetime of the mesons observed at 30,000 feet under 6 in. of lead:

$$\tau = 2.01 \pm 0.18\ \mu\text{sec. from the Southern flight,}$$
$$\tau = 2.26 \pm 0.16\ \mu\text{sec. from the Northern flight.}$$

These two values of τ are equal within their errors. The difference between them, furthermore, is in the sense expected, because the correction for the time lags of the counters (which, as observed in Appendix B, is latitude dependent) has been applied, to the first channel, disregarding its latitude dependence. Of course, in computing the lifetime from the results of the Northern flight, where measurements have been taken using also S abosrber, allowance has been made for the small contribution given to the coincidences registered in the first channel by the decay of negative mesons in S (Section II).

By combining all of the measurements of the two expeditions (corresponding to the observation of approximately 1600 independent mesons) we find the value

$$\tau = 2.14 \pm 0.12\ \mu\text{sec. at 30,000 feet}$$

to be compared with the value

$$\tau = 2.18 \pm 0.05\ \mu\text{sec. near sea level}$$

obtained with the same apparatus through the observation, in Chicago and at China Lake, of about

TABLE IX. Results of measurements of delayed coincidences with absorbers of graphite (c) and sulfur (s).

1	2	3	4	5	6				7	8	9
Series	Place	g/cm² of material above the absorber	Absorber	Duration of observation (minutes)	Delayed coincidences registered in channel 1	2	3	4	Random delayed coincidences	Coincidence per hour from mesons decaying between 0 and $\Delta\theta$	M_+/M_-
1	Chicago	2.7 of brass	C	6015	433	270	184	133	24.4	6.8±0.28	$1.22^{+0.20}_{-0.15}$
			S	8997	420	267	175	114	37.5	3.85±0.18	
2	Chicago	∼75 of concrete	C	9490	751	475	319	237	32.4	7.6±0.25	$1.27^{+0.18}_{-0.12}$
			S	12,150	631	385	269	177	42.6	4.4±0.17	
3	Chicago	172 Pb	C	9470	704	467	294	195	4.4	7.5±0.25	
4	Chicago	228 Pb +∼40 concrete	C	7595	533	337	211	145	2.7	6.90±0.27	$1.24^{+0.18}_{-0.13}$
			S	10,988	427	276	179	120	4.2	3.93±0.17	
5	Chicago	398 Pb +∼75 concrete	C	16,785	1123	694	470	309	6.1	6.73±0.18	$1.37^{+0.14}_{-0.12}$
			S	20,453	871	501	347	233	7.5	4.01±0.12	
6	China Lake	2.7 brass +∼5 air[a]	C	7720	665	428	272	174	38.7	7.5±0.27	$0.99^{+0.16}_{-0.11}$
			S	5990	263	174	137	88	33.3	3.85±0.23	
7	China Lake	172 Pb	C	6462	534	338	228	150	3.5	8.5±0.33	
8	China Lake	398 Pb	C	7755	572	384	270	166	4.0	7.95±0.30	
9	30,000 feet	172 Pb	C	560	561	378	259	202	86.3	78.5±3.4	$1.54^{+0.28}_{-0.20}$
			S·	770	593	331	262	220	115	49.0±2.3	

[a] Roughly corresponding to the roof of the cabin in which the measurements were taken.

10,000 independent mesons. Both values are in good agreement with previous accurate determinations of the lifetime of the ordinary meson.[42] *

For purposes of comparison the two decay curves corresponding to all of the measurements taken at 30,000 feet and near sea level have been represented together in Fig. 7. In this figure the origin of the time scale has been made arbitrarily coincident with the delay of the first channel and the counting rate of the first channel has been assumed arbitrarily to be equal to 100 in the upper curve (30,000 feet) and equal to 50 in the lower one. Both curves are drawn for $\theta/\tau=0.45$.

The 5.5 percent accuracy in the value of the lifetime at 30,000 feet given above may appear somewhat optimistic because the error does not include the uncertainties related to the corrections introduced. One has to remember, however, that the main correction, which is represented by the random events, can be determined with a very high statistical accuracy, while the uncertainty in the other small corrections (applied only to the coincidences registered in the first channel) does not have a great influence in the determination of τ. Our results, therefore, seem to *rule out the possibility of the presence in the atmosphere of any considerable number of unstable particles having a lifetime different from, but comparable to that of the ordinary meson.*

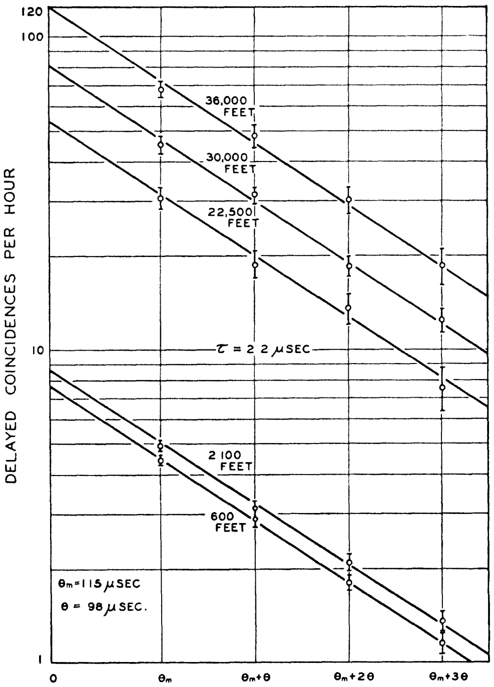

FIG. 6. Decay curves obtained at several altitudes for mesons stopped in 10 cm of graphite after penetrating 6 in. of lead. Each point of the decay curves is due to the contribution of mesons disintegrating between the instant t of the corresponding abscissa and $t+\Delta\theta$ ($\Delta\theta=2.8$ μsec.).

(B) *Altitude Dependence and Absolute Number of Mesons*

As shown by curve m of Fig. 5, the number of the observed mesons decreases with the atmospheric depth, h, approximately as $\exp(-h/L)$, with $L=280$ g/cm^2 of air. This value is not in agreement with the one (240 g/cm^2) obtained by Rossi, Sands, and Sard[2] and by Sands[3] for mesons of range smaller than 83 g/cm^2 of air equivalent. Since the mesons recorded with our apparatus had ranges between about 100 and 117 g/cm^2 of air equivalent, it does not seem possible to interpret the discrepancy between the results of the two experiments on the basis of the difference in the energies of the observed mesons.[43] It may be pointed out, instead, that due to the wide angle of the counter telescope employed by these authors, their data represent the altitude dependence of the *integrated intensity* rather than that of the *vertical intensity*,[32] whereas the opposite is true in the case of the present experiment. Although no information is available as yet concerning the dependence of the angular distribution of slow mesons on altitude, we shall expect a faster increase with altitude for the integrated intensity than for the vertical intensity. On the other hand, it should also be remembered

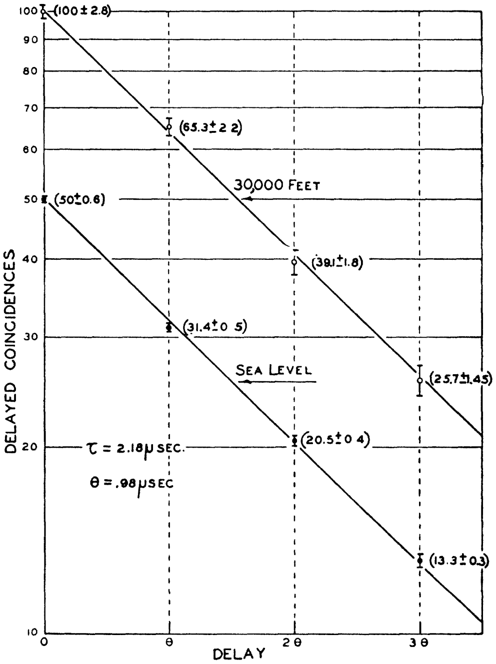

FIG. 7. Comparison between the decay curves obtained from measurements of delayed coincidences performed, with the same apparatus, at 30,000 feet (upper curve) and near sea level (lower curve). Ordinates are given in arbitrary units. The origin of the time scale is arbitrarily put in the first channel.

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* *Note added in proof.*—Measurements of θ recently performed with a greater accuracy give an average value $\theta=0.96$ μsec. Accordingly the value $\tau=2.13\pm0.05$ μsec. is obtained from the sea level data.

[42] N. Nereson and B. Rossi, Phys. Rev. **64**, 199 (1943). M. Conversi and O. Piccioni, Nuovo Cimento **2**, 40 (1944).

[43] Owing to the effect of the "time absorption" the rate of increase with altitude should become greater with decrease in the energy of the observed mesons.

that because of the rather large statistical errors, the measurements performed under different thicknesses of material by these authors give merely a rough indication that the rate of increase with altitude is the same for all mesons having range less than 83 g/cm^2.

The ordinates of Fig. 5 are given on an absolute scale based on the considerations reported in Section III F. By extrapolation of curve *m* in Fig. 5 *the absolute number of mesons at sea level traversing 6 in. of lead in the vertical direction* (approximately 100 g/cm^2 of air equivalent) and stopped by an additional g/cm^2 of graphite, is found to be about *5.2×10⁻⁶/sec.-g.-steradian*, in good agreement with the results obtained by other authors using different methods.[32, 44]

Actually, curve *m* of Fig. 5 can be interpreted as giving at each altitude the absolute number of vertical ordinary mesons provided that the two following assumptions are correct: (a) mesons locally produced do not give any appreciable contribution to the registered delayed coincidences; (b) the possible change with altitude in the angular distribution of the observed mesons can be neglected for our apparatus. Due to the rather narrow angular definition of our counter telescope the latter of the two previous assumptions may be considered to be true with good approximation, if the former is true.

As to the first assumption we can argue as follows: if production of positive π-mesons by ionizing particles takes place in the 6 in. of lead between counters *A* and *B*, then some of the produced mesons could be stopped in the absorber and decay, in a time of the order of 10^{-8} sec.,[45] into ordinary mesons of very short range,[1] thus contributing to the observed rate of delayed coincidences. However, due to the recovery time (12.5 μsec.) of the pulse-forming circuit connected to the counters *C*, positive π-mesons stopped in the absorber can cause a delayed coincidence to occur only if they are not accompanied by other particles discharging counters *C*. The probability of a similar event appears to be quite small on the basis of an estimate of the average energy of the nucleons after the nuclear collision with meson production takes place. This seems to be true even allowing for the few cases in which nuclear events occur in the bottom of the lead and the nucleons are emitted under angles so as to miss the anticounters. Furthermore, penetrating showers which seem to be the typical events in which π-mesons of considerable energy are produced,[23] increase with altitude much faster than ordinary slow mesons.[46] Consequently, if local production of energetic π-mesons were responsible for part of the delayed coincidences registered by our apparatus, we would find in our case a faster increase with altitude than the one obtained without any lead by Rossi, Sands, and Sard.[2]

A contribution to the delayed coincidences could also be given by π-mesons produced in low energy nuclear events (star-like) taking place in the absorber or in the lowest centimeters of lead between counters *A* and *B*. Observations of photographic plates, however, show that only in a small percentage of the stars is there emission of π-mesons.[1] The number of stars, furthermore, is known to increase with altitude again much faster[47, 48] than our delayed coincidences. It seems, therefore, that at least for altitudes of 30,000 feet or less[49] assumption (a) can be considered to be valid, with good approximation.

The determination of the altitude dependence of slow mesons may be used to obtain information about the production spectrum of mesons. This problem has been treated quantitatively by Sands,[3] with the assumption that mesons are created throughout the atmosphere by a primary component undergoing exponential absorption with an "absorption thickness" of 125 g/cm^2 of air. Qualitatively we can state here that our data indicate that the differential energy spectrum of mesons at production is even less abundant in low energy mesons than is indicated by the Sands results.

(C) *Positive Excess*

The rough indication of a disappearance of the positive excess at low energies previously reported[50] as given by the results of the sixth series in Table IX is not confirmed by the results of the first series, performed in Chicago after the end of the B-29 expeditions.

Although the percentage errors on the values of M_+/M_- are comparatively large in all series of measurements, the data of Table IX are consistent with the assumption that in the range of about 20 to 500 Mev, the excess of positive mesons is uniformly distributed in the differential spectrum near sea level.

For higher energies, instead, Brode[20] and Bassi, Clementel, Filosofo, and Puppi[51] have recently obtained an indication of an increase in the value of the positive excess. The experimental data mentioned above do not seem to agree with the theoretical prediction of Lewis, Oppenheimer, and Wouthuysen,[52] and of Heisenberg.[53] Indeed, according to these authors the positive excess should be inversely proportional to the square root of the meson energy at the point where mesons are created. If we assume that the mesons observed at sea level are the decay products of π-mesons produced essentially in the upper layers of the atmosphere, and if only

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[44] W. L. Kraushaar, Phys. Rev. **76**, 1045 (1949). References to earlier literature will be found in this article.

[45] J. R. Richardson, Phys. Rev. **74**, 1720 (1948).

[46] J. Tinlot, Phys. Rev. **74**, 1137 (1948).

[47] Bernardini, Cortini, and Manfredini, Phys. Rev. **74**, 845 (1948); **74**, 1878 (1948).

[48] J. J. Lord and M. Schein, Phys. Rev. **75**, 1956 (1949).

[49] Our results indicate that between 30,000 and 36,000 feet the number of observed mesons increases faster than it does between sea level and 30,000 feet.

[50] See reference 24, p. 311.

[51] Bassi, Clementel, Filosofo, and Puppi, Phys. Rev. **76**, 854 (1949).

[52] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[53] W. Heisenberg, Nature **164**, 65 (1949).

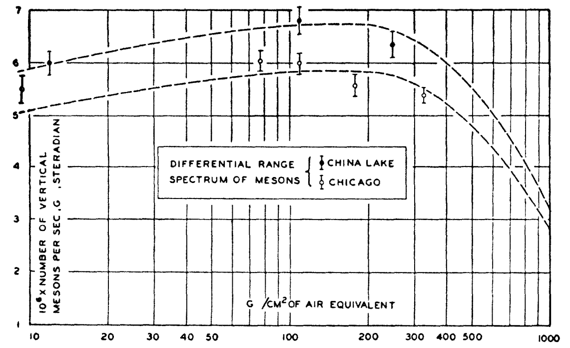

FIG. 8. Differential range spectrum of mesons in Chicago and at China Lake.

energy-loss for ionization is taken into account, then the mesons observed by Brode[20] have an *initial* energy of about 3.7 Bev, whereas those observed in the experiment of Conversi and Nappo[39] have initial energy in the neighborhood of 2.4 Bev. According to the theory, the ratio M_+/M_- should be 0.96 smaller in the former than in the latter experiment. The experimental results yield instead, $(1.37\pm0.04)/(1.24\pm0.05)=1.10\pm0.055$ for the ratio of the two values of M_+/M_-.

It should be pointed out, however, that the various experimental data now available do not always appear to be quite consistent with one another. For instance, the dependence of the positive excess of the hard component at sea level upon the zenith angle, as obtained by Ballario, Benini, and Calamai[19] seems to be consistent with the theoretical predictions mentioned above,[54] while accurate cloud-chamber observations recently reported by J. G. Wilson at the Como Conference[55] do not appear to fit well with these predictions. On the other hand, the investigation of the energy dependence of the positive excess does not appear to be a very sensitive test for deciding whether "multiple" or "plural production" takes place in the upper layers of the atmosphere.[52–54, 56–61]

The results of the ninth series in Table IX give an indication of an increase in the value of the positive excess at 30,000 feet as compared to the sea level value. This result agrees with the findings of Quercia, Rispoli, and Sciuti,[18] although in their experiment the mesons were not separated from the other particles.

If local production of π-mesons gave some contribution to the delayed coincidences observed at 30,000 feet, this would cause the ratio given by Eq. (5) to increase, because negative π-mesons are presumably captured in both elements. It can be seen, indeed, from Eq. (5) and from the data at 30,000 feet reported in Table IX, that the positive excess of ordinary mesons at 30,000 feet would still be 20 percent, as near sea level, if 13 percent of the delayed coincidences registered with C absorber were due to positive π-mesons. However, as has already been pointed out, the local production of π-mesons should not give any serious contribution to our delayed coincidences. The result of the ninth series in Table IX gives therefore an *indication of an increase of the positive excess of low energy ordinary mesons with increasing altitude.*

(*D*) *Differential Range Spectrum*

From the data reported in the eight column of Table IX corresponding to measurements performed using a graphite absorber, we obtain five points of the differential range spectrum of mesons (positive and negative) in Chicago and three points at China Lake. These points are reported in a semilogarithmic plot in Fig. 8. The abscissa of each point represents approximately the *average* range of the observed mesons expressed in g/cm² of air equivalent. Conversion into g/cm² of air has been made using the calculations of Wick.[62] The ordinates of Fig. 8 are given in an absolute scale so that each point of the curve represents the number of vertical mesons per sec., cm², steradian, which are stopped by one g/cm² of air (≈ 1 g/cm² of graphite) after traversing the thickness of air equivalent given by the abscissa.

The dotted curves in Fig. 8 reproduce (on an ordinate scale such as to obtain the best fit with our experimental points) the sea level differential range spectrum of mesons[63] as reported by Rossi[32] on the basis of most of the experimental data available. The results of Shamos and Levy[64] and those recently obtained by Kraushaar[44] are also in agreement with such a spectrum. At low energies, however, this spectrum gives a larger relative number of mesons than the Wilson spectrum.[65] The reason for the disagreement lies, perhaps, in the deversity of the two experimental methods; otherwise one should think that the range energy relationship for low energy mesons cannot be simply applied.

The absolute number of mesons at the end of their ranges, as given by the spectrum reported in Fig. 8, is about eight times as large as the number calculated by Rossi, Sands, and Sard on the basis of their measurements of delayed coincidences at sea level.[2] It is also partly than the number estimated on the basis of the observations of photographic plates made by Lattes, Occhialini, and Powell.[1] This latter discrepancy may

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[54] G. Bernardini, Bristol Conference (1949).

[55] The author wishes to thank Drs. G. Bernardini and M. Schein for information on this matter.

[56] W. Heisenberg, Zeits. f. Physik **113**, 61 (1939).

[57] J. F. Carlson and M. Schein, Phys. Rev. **59**, 840 (1941).

[58] W. Heitler, Proc. Camb. Phil. Soc. **37**, 291 (1941). W. Heitler and H. W. Peng, Proc. Camb. Phil. Soc. **38**, 296 (1942). Hamilton, Heitler, and Peng, Phys. Rev. **64**, 78 (1943).

[59] L. Janossy, Phys. Rev. **64**, 345 (1943).

[60] W. Heitler, Proc. Roy. Irish Acad. **50**, 155 (1945). W. Heitler and P. Walsh, Rev. Mod. Phys. **17**, 252 (1945).

[61] W. Heitler and L. Janossy, Proc. Phys. Soc. **67**, 374 (1949).

[62] G. C. Wick, Nuovo Cimento **1**, 302 (1943).

[63] The elevation of China Lake is sufficiently low to justify the assumption that the shape of the meson spectrum is the same there as at sea level.

[64] M. H. Shamos and M. G. Levy, Phys. Rev. **73**, 1396 (1948).

[65] J. G. Wilson, Nature **158**, 415 (1946).

partly be accounted for in terms of the fading of the plates. The former discrepancy is due, at least in part, to the fact that the authors have overestimated the probability of detection of the decay electrons for their apparatus. If our finding is correct, therefore, the disagreement recently pointed out by Morpurgo,[66] between the expected and observed number of slow mesons at sea level, disappears. But the conclusion reached by him, namely, that no appreciable production of mesons occurs between sea level and 4000 meters, loses its validity. As a matter of fact, as was pointed out by Bernardini,[67] the assumption of an appreciable production of mesons in the lower layers of the atmosphere would yield a simple explanation of the discrepancy between direct measurements of the lifetime and the mass μ of the meson, and the determination of the ratio τ/μ by measurements of anomalous absorption.

The comparison between the results of Table III and those of Table VI concerned with the meson component shows that the number of delayed coincidences at 30,000 feet at the geomagnetic equator does not change appreciably by adding 4 in. of lead (above counters A) to the 6 in. of lead already present between counters A and B. This result agrees[68] with the momentum spectrum of negative mesons at 30,000 feet as reported by Adams, Anderson, and Cowan[5] if an analogous momentum distribution is assumed for the positive mesons and if we assume that the maximum of the spectrum does not shift considerably with latitude.

Part 2: The Nucleonic Component[69]

(*E*) *Identification of the X-particles*

We have previously defined the X-particles as those particles which are responsible for the anticoincidence rate corrected for the contribution of mesons. A few restrictions on the possible types of events appearing as X-particles have also been listed in Section IIIC. On the basis of the experimental results reported in Section III, we shall make an attempt now to identify the nature of the X-particles.

It must be pointed out first that no appreciable percentage of the observed anticoincidences can be due to electrons. In fact, it appears very unlikely that a large electronic shower, able to penetrate the 6 in. of lead interposed between counters A and B, could end in the absorber without striking any of the anticoincidence counters.

In addition, we may recall the discussion given above about the results concerned with the meson component. It has already been pointed out there that no serious contribution is given by locally produced π-mesons to the recorded delayed coincidences. For similar reasons we are led to exclude the possibility of a large contribution given to the anticoincidences by negative π-mesons locally produced and captured in the absorber.

If we assume that the X-component does not contain any appreciable amount either of electrons or of mesons, then the simplest interpretation as to its nature is that X-particles (which must be ionizing particles) are mainly protons coming from outer space. In fact, as appears from Fig. 5, the number of X-particles stopped in one gram of graphite at 30,000 feet is even larger than the corresponding number of ordinary mesons, and we cannot easily explain such an abundance of X-particles in terms of ionizing particles different than protons (electrons and mesons being excluded). If, instead, one assumes that X-particles are single protons coming from outer space, then one sees that in order to penetrate the 6 in. of lead placed between counters A and B and in order to be stopped in the graphite absorber they must have momentum in the range of 0.984 to 1.043 Bev/c if they lose energy *only* for ionization. From the data of Table VIII one finds, on the other hand, that the absolute number of these protons per sec., per cm^2, per steradian, per Mev/c of momentum, would be about 3.10^{-5} at 30,000 feet. From the results of the Anderson group at 30,000 feet,[6] Rossi estimates[32] that the number of protons with momentum between 0.4 and 1 Bev/c is of the order of 10^{-2}. This figure corresponds to about 1.7×10^{-5} protons per sec., per cm^2, per steradian, per Mev/c. The results of the two experiments are different by a factor of 1.8. However, owing to the difference in the angular definitions of the apparatus employed in the two experiments and considering also the uncertainty in the deduction of absolute intensities from cloud-chamber measurements, the two figures may be considered to be essentially in agreement.

The energy of the protons contributing to our anticoincidences cannot be less than 421 Mev if this figure correctly represents the energy lost by ionization in traversing 6 in. of lead. It could be higher, however, if we think that part of the anticoincidences may be produced by protons which, traversing the lead, give rise to nuclear events. We may recall, nevertheless, the conclusion reached in the discussion of the meson component and state that no large number of anticoincidences should occur when energetic nuclear events take place (in which mesons of considerable energy are produced). The energy involved in star-like nuclear events, which in general does not exceed a few tenths of a Bev, presumably represents, therefore, the uncertainty of the energy of the protons contributing to the observed anticoincidences.

The interpretation of the nature of the X-component in terms of protons is strengthened by the following arguments. (a) As shown by Fig. 4, at 30,000 feet the

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[66] Morpurgo, Nuovo Cimento **5**, 285 (1948).

[67] G. Bernardini, Cracovie Conference (1947).

[68] Local production by neutral rays in the added 4 in. of lead should not affect appreciably the number of recorded delayed coincidences, for reasons similar to those discussed in Section IV B.

[69] The author wishes to thank Dr. G. Bernardini for valuable discussions on this topic.

intensity of the X-particles at 60° North geomagnetic latitude is about 3.2 times as large as the intensity at the equator. Such a large latitude effect as well as the shape of the latitude curve, are comparable to the results obtained, at the same altitude, on the neutron component[70] and on "bursts." [71] (b) As is shown by the curve x of Fig. 5, the dependence of the number of X-particles upon the atmospheric depth h may be approximately represented as $\exp(-h/L)$ with $L \approx 150$ g/cm^2. This result can be compared with those obtained for bursts[72–74] and for star-producing radiation.[47, 48] Both of these arguments show that the bulk of the X-component is of nucleonic nature.

Primary protons (which are believed to represent the largest part of the primary component[75]) cannot contribute to the X-component observed at high altitudes because the energy of a proton stopped in the absorber after penetrating the atmosphere above, and the 6 in. of lead, is less than the energy corresponding to the magnetic cut-off at 50° (which is more than 2.5 Mev for the vertical direction), even allowing for a few tenths of a Bev corresponding to low energy nuclear events which may possibly take place in traversing the lead. It appears, therefore, reasonable to conclude that at least *most of the X-particles are secondary protons arising from energetic nuclear events which take place in the upper atmosphere.*

Additional points would be necessary for a more exact determination of the shape of curve x, which has been represented in Fig. 5 as an exponential. The number of protons at sea level obtained by extrapolation of such an exponential is likely to be in excess. It will be observed, indeed, that the experimental points reported in Fig. 5 for the X-component seem to indicate a greater rate of decrease with increasing atmospheric depth. As a matter of fact, the increase between 2100 and 22,500 feet corresponds to an "absorption thickness" $L \approx 130$ g/cm^2 of air, while between 22,500 and 36,000 feet $L \approx 220$ g/cm^2, assuming an exponential dependence in both intervals.

The lower rate of increase with increasing altitude suggests that the equilibrium between primary and secondary protons is not yet reached at an altitude as low as 30,000 feet. If this is the case, then by adding 10 cm of lead above the counter telescope the number of X-particles at 30,000 feet should not decrease by more than about 20 percent, even if the possible contribution due to nuclear events produced by neutral rays in the added lead is entirely neglected. Although performed at the geomagnetic equator (whereas curve x in Fig. 5 refers to 50° North), the measurements reported in Table VI yield some support to the previous view. Indeed, the comparison between these measurements and those taken near the equator and given in the Tables III and IV shows that within statistical errors no change in the number of X-particles is observed after adding 4 in. of lead above counters A.

(*F*) *Remarks on the Mechanism of Production of Mesons*

The comparison between the latitude effect of the X-component and that of the meson component clearly shows that X-particles are originated by primary cosmic rays considerably more sensitive to the magnetic field of the earth than those responsible for the production of the observed mesons.

We shall discuss this result briefly in an attempt to obtain some information as to the mechanism of production of mesons.

In a recent work by the Rome group[76] it has been shown that the behavior of the nucleonic component (as observed experimentally) can be satisfactorily described by assuming that the nucleons can be separated into three categories: (a) nucleons of very high energy (kinetic energy $E \gg Mc^2 \approx 1$ Bev) which are absorbed essentially through radiative processes (high energy nuclear events involving meson production and correlated emission of secondary nucleons); (b) nucleons with E between 0.2 and 1 Bev, for which the absorption is assumed to be mainly due to nuclear evaporations (stars production) and roughly independent of E; (c) nucleons with $E<0.2$ Bev which lose their energy in one or two nuclear collisions and, if protons, by ionization. According to this scheme the total cross section of the nucleons is presumed first to decrease with decreasing energy E, afterwards to reach a broad minimum in the neighborhood of $\frac{1}{2}$ Bev, and then to increase. Thus, high energy nucleons quickly lose their energies and are brought into the energy region corresponding to category (b), where they are slowly absorbed because of the comparatively small value of the total cross section.

Since the protons observed with our apparatus as *X-particles* belong essentially to category (b), *a considerable part of them are presumably originated by primary nucleons of very high energy* ($E>10$ Bev) which have lost their energy in radiative collisions traversing the above atmosphere.

In the scheme of meson production as recently reported by Heitler and Janossy,[61] the total cross section for meson production at high energies E is independent of the energy E of the primary nucleon, while the average energy loss is proportional to E.[60, 61] Consequently at high energies the average number of mesons produced by a primary nucleon traversing a certain thickness of air is independent of E while the average energy of the produced mesons increases with increasing E.

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[70] J. A. Simpson, Jr., Phys. Rev. **73**, 1389 (1948).

[71] J. A. Simpson and R. B. Uretz, Phys. Rev. **76**, 569 (1949).

[72] H. Bridge and B. Rossi, Phys. Rev. **71**, 379 (1947).

[73] Bridge, Rossi, and Williams, Phys. Rev. **72**, 257 (1947).

[74] H. E. Tatel and J. A. Van Allen, Phys. Rev. **73**, 87 (1948).

[75] Schein, Jesse, and Wollan, Phys. Rev. **59**, 615 (1941). Schein, Iona, and Tabin, Phys. Rev. **64**, 253 (1943).

[76] B. Ferretti, Nuovo Cimento **6** (September, 1949); Bernardini, Cortini, Ferretti, and Manfredini (to be published).

Since the energy of a meson produced at the top of the atmosphere and stopped in our absorber[77] is about 0.8 Bev, *no considerable part of the observed delayed coincidences should be due to mesons produced by primary nucleons of very high energy* ($E > 10$ Bev).[78]

It follows that the latitude effect of the mesons observed with our apparatus should be larger than the latitude effect of the X-component, in contradiction to the experimental results. The discrepancy seems to disappear in the scheme of a "multiple meson production." In this case, indeed, the "multiplicity" of the created mesons is an increasing function of the energy of the primary nucleons, and this, at least qualitatively, could account for the smaller latitude effect of the meson component as compared to the one of the X-component.

Some further support to the view of a multiple production of mesons seems to be given by the comparison between the altitude dependence of the mesons observed in the present research and the altitude dependence of very slow mesons as obtained by Bernardini, Cortini, and Manfredini[47] and by Lord and Schein.[48] This comparison shows, in fact, that at high altitudes a large number of mesons are produced with very low energies. At the same time, the results obtained by these authors show that the ratio between the numbers of mesons and stars increases strongly with altitude. Hence it appears that no large contribution to the number of slow mesons thus observed is caused by nuclear evaporations. It seems, therefore, that with increasing altitude the meson spectrum undergoes a change due to the increasing contribution of very slow mesons which are largely produced by primary rays. As has been pointed out by Bernardini *et al.*,[47] such a change appears to be understandable in the scheme of the multiple production, but not easily understandable in the one of the plural production.

V. CONCLUSIONS

The results of the experiments reported in this paper can be summarized as follows:

(a) The differential range spectrum of mesons near sea level is nearly flat in the interval 10 to 200 g/cm^2 of air equivalent, in agreement with some recent findings of other authors.

(b) The assumption of a positive excess of sea level mesons *uniformly* distributed in the differential spectrum is consistent with our results for energies between about 20 and 500 Mev.

(c) The absolute number of vertical mesons at sea level having ranges in the neighborhood of 100 g/cm^2 of air is 5.2×10^{-6} per sec., per g, per sterad., in good agreement with other recent results.

(d) Within the statistical uncertainty of a few percent, the lifetime of the observed mesons is the same at 30,000 feet as at sea level, and is equal to about 2.15 μsec.

(e) Between 36,000 feet and sea level the number of ordinary mesons having ranges in the neighborhood of 100 g/cm^2 of air decreases with the atmospheric depth h, as $\exp(-h/L)$ with $L \approx 280$ g/cm^2.

(f) Between the geomagnetic equator and 60° N. the number of ordinary mesons present at 30,000 feet with ranges in the neighborhood of 100 g/cm^2 increases to about 1.9 ± 0.14.

(g) The positive excess of ordinary mesons having ranges in the neighborhood of 100 g/cm^2 seems to increase by a factor of 2 between sea level and 30,000 feet.

(h) At high altitudes a considerable number of ionizing particles (X) different from mesons are found to stop after traversing 6 in. of lead. While at sea level these particles are present in negligible amounts (if at all), at 30,000 feet their absolute number is found to be nearly 10^{-4} per sec., per g, per sterad., namely, 1.6 times the corresponding absolute number of ordinary mesons.

(i) The rate of increase in the number of X-particles seems to decrease with increasing altitude. If an exponential absorption is assumed for the X-particles between 2100 and 36,000 feet one obtains an "average absorption thickness" of about 150 g/cm^2 of air.

(j) Between the geomagnetic equator and 60° N. the number of X-particles present at 30,000 feet increases to 3.2 ± 0.5.

(k) A comparison between the results of this research and the results of other authors leads to the conclusion that the X-particles are mainly secondary protons of energy in the neighborhood of 0.5 Bev rising from energetic nuclear events which take place in the upper atmosphere. Their altitude dependence indicates then that the equilibrium between primary and secondary protons is not yet reached at an altitude as low as 30,000 feet.

(l) The comparison between the latitude effects of the mesons and of the X-particles at 30,000 feet, as well as the comparison between the altitude dependences of the mesons detected in our experiment and of the very slow mesons observed on photographic plates, seem to give support to the view that "multiple" rather than "plural" production of mesons takes place in the upper layers of the atmosphere.

VI. ACKNOWLEDGMENTS

The author is indebted to Dr. Samuel K. Allison for granting him a post-Ph.D. fellowship at the Institute for Nuclear Studies and for the many facilities that made this research possible. He wishes also to express

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[77] According to current ideas the meson produced is a π-meson which afterwards decays in flight into a μ-meson. For the following discussion we may as well neglect the distinction between the initial π-mesons and the secondary μ-mesons thus simplifying our language.

[78] According to the recent paper by Heitler and Janossy (reference 61) the average number of effective collisions after which a primary nucleon becomes ineffective for meson production is about two. Thus, the average energy of a primary proton producing at its second collision the meson observed by our apparatus should not be much larger than a few Bev.

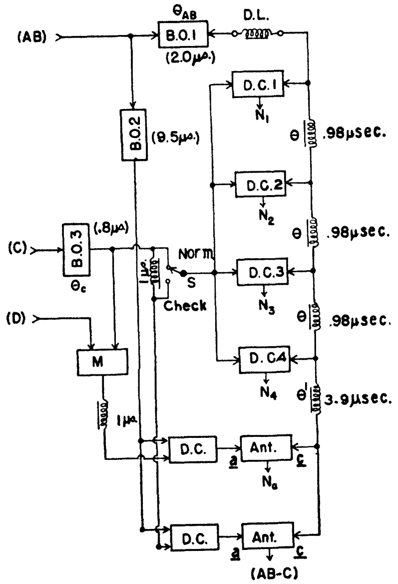

FIG. 9. Block diagram of the registering set. *Ant*: anticoincidence circuits; *BO*: pulse forming "blocking oscillator" circuits; *D.C.*: double coincidence circuits; *DL*, θ and θ': delay lines; *M*: crystal diode mixers; *S*: switch. Pulses are positive in all points except at the outputs of the anticoincidence circuits, where they are positive only when "anticoincidence events" take place. By setting short delay lines θ (0.1 or 0.2 μsec. instead of 0.98 μsec.) and for suitable values of *DL*, several points of the integral time distribution curve of the spurious delays of the counters can be quickly obtained. The flexion point of this curve yields the "zero" of the absolute time scale (reference 80). The points of the curve corresponding to the shortest delays are obtained with the switch *S* in "check position."

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APPENDIX A

The Registering Set

The simultaneous registration of delayed coincidences and anticoincidences was obtained by means of an electronic apparatus of which the main parts were connected as is schematically represented in Fig. 9.

As stated in Section II, the output pulse corresponding to a coincidence (*AB*) starts 0.7 μsec. after the time of occurrence of the earliest of the two counter pulses producing the coincidence, provided that both pulses occur within 0.7 μsec. of one another. Therefore a particle entering the counter telescope and producing a coincidence (*AB*) causes both circuits B.O.1 and B.O.2 to be triggered 0.7 μsec. later.[79] The square pulse, θ_{AB}, from the output of B.O.1, is fed into a series of continuous delay lines terminating, at the *c*-inputs of the two anticoincidence circuits, on their characteristic impedances. Thus, if the switch *S* is in the "normal position" (Fig. 9) and θ_0 is the value of the proper delay of the interchangeable delay-line, D.L., plus 0.7 μsec., the pulse θ_{AB} will start at the inputs (on the right side of Fig. 9) of D.C.1, D.C.2, $\cdots$D.C.4, respectively, θ_0, θ_0 plus θ, $\cdots\theta_0$ plus 3θ, after the arrival of a particle producing a coincidence (*AB*). The square pulse, θ_c, from the output of B.O.3 will give, therefore, a coincidence in D.C.1 (1st "channel") with the pulse θ_{AB} corresponding to a particle entering the telescope at the instant zero, only if counters *C* fire within the time interval $\theta_0-\theta_c$ to $\theta_0+\theta_{AB}$, or θ_m to $\theta_m+\Delta\theta$, where $\theta_m=\theta_0-\theta_c$ and $\Delta\theta=\theta_{AB}+\theta_c$. Similarly a coincidence will be registered by the second, . . . fourth channels, only if counters *C* fire within the time interval $(\theta_m+\theta)$ to $(\theta_m+\theta)+\Delta\theta$, $\cdots(\theta_m+3\theta)$ to $(\theta_m+3\theta)+\Delta\theta$, respectively. In this way four points of the decay curve corresponding to the mesons stopped in the absorber are obtained simultaneously.

Both pulse-forming circuits B.O.1 and B.O.2 are "blocking oscillators" controlled by delay lines. The time width $\Delta\theta=\theta_{AB}+\theta_C$ of the channels is therefore dependent only on the proper delay of these lines and no variation of its value can be expected to occur. Similarly no variation of the time distance, θ, between each channel and the next one can be expected.

The value θ_m of the minimum delay for which a coincidence is recorded in the first channel, has been determined by the method explained in a previous paper.[80]

APPENDIX B

Correction for the Spurious Delays Due to the Counter Discharge

The spurious delays associated with the counter discharge depend essentially on the position where the first ion pair is produced. More precisely, the rise time of the counter pulse (which is related to the propagation of the discharge along the wire after the first avalanche takes place) depends on the "axial coordinate" of the point where the first ion pair is produced;[81] the proper time lags, instead (which presumably represent the interval between the formation of the first ion pair and of the first avalanche) depend on the "radial coordinate." [82] Of these delays the former may be minimized by increasing the sensitivity of the input circuits; the latter by using counters of small radii;[83] both by operating the counter at the highest possible voltage.[84] In the present experiment, where events corresponding to delays shorter than 1.15 μsec. have not been recorded, the use of counters of 2 in. outer diameter, in a double layer, has still been possible. Nevertheless counters, previously selected, had to be operated at the upper limit of their plateau. Even in these conditions a contribution of spurious coincidences in the first channel is observed, but only in the measurements taken at high altitude. The appearance of this contribution at high altitude must be related to the increased background counting rate[85] of the counters *C* and can be qualitatively explained as follows.

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[79] In the following, delays due to the counter tubes and proper delays of the circuits are neglected. Furthermore, pulses θ_{AB} and θ_c (the same symbols are also used for the time-widths of these pulses) are supposed to be literally "square pulses."

[80] M. Conversi and O. Piccioni, Phys. Rev. **70**, 874 (1946).

[81] Alder, Baldinger, Hubber, and Metzger, Helv. Phys. Acta **20**, 73 (1947).

[82] C. W. Sherwin, Rev. Sci. Inst. **19**, 111 (1948).

[83] Den Hartog, Muller, and Vester, Physica **13**, 251 (1947).

[84] D. R. Corson and R. R. Wilson, Rev. Sci. Inst. **19**, 207 (1948). This article also gives references to other literature.

[85] As a matter of fact, measurements taken in Chicago irradiating counters *C* so as to reproduce artificially the background

If a particle discharges a certain counter C_0 of the C tray at the zero time, the probability that another particle traverses the counter telescope and C_0 in the time interval (of some hundred μsec.) between the dead-time and the recovery-time of C_0, becomes quite appreciable (several percent) when the background counting rate of C_0 is as large as at high altitude (of the order of 100/sec. at 36,000 feet). If such an event takes place, then the size of the second pulse given by C_0 will be smaller than usual and a spurious delay may occasionally occur because of the finite value of the sensitivity of the input circuit triggered by C_0. By using a double layer of counters C the probability of such an event is considerably reduced. But of course even if the probability of a spurious delay larger than 1.15 μsec. (θ_m) is only a fraction of one percent, the percentage of spurious delays in the first channel can still be quite considerable, since the number of mesons contributing to the coincidences in the first channel is not much more than one percent of the number of particles producing prompt coincidences (ABC).

The correction for the spurious delays of the counters can be evaluated using the results of measurements performed without absorber. In 465 minutes of measurements taken without absorber at 30,000 feet (including both expeditions) the numbers of coincidences registered in the four channels were respectively 134, 80, 66, 53. By using Eq. (1) and the average counting rates $n_{(AB-C)}$, $n_{(c)}$ as measured in flight, it is found that the corresponding number of random coincidences in each channel was about 43. Correcting for this it can be observed, first, that the point corresponding to the first channel falls off from the 2.2 μsec. decay curve passing for the three points corresponding to the remaining channels. Furthermore, the counting rate of the first channel is $(N_1)_0=(11.7\pm1.23)$ per hour, while the corresponding average counting rate, $(N_1)_C$, with graphite absorber (as deduced from the data reported in Table III) is $(N_1)_C=(42\pm1.35)$ per hour. The ratio $(N_1)_0/(N_1)_c$ is so found[86] to be 0.28 ± 0.028 whereas the value 0.17 ± 0.011 is obtained for the same ratio near sea level from the data reported in Table I.[87] Since only positive mesons (disintegrating in the brass of the counters and of the frame) contribute to the delayed coincidences registered without absorber, and since the ratio of negative to positive mesons seems to decrease from 0.81 to 0.65 between sea level and 30,000 feet (see Table IX), we would expect for this ratio at 30,000 feet the value $(1.81/1.65)(0.17\pm0.011)=0.185\pm0.012$, which is still considerably less than 0.28 ± 0.028.

It is reasonable to assume that the excess of coincidences registered in the first channel at 30,000 feet is caused, through the mechanism previously sketched, by the spurious delays associated with the counter discharge. Then, by assuming equal numbers of spurious delays with and without absorber, one finds that the corrected number of delayed coincidences with graphite absorber, registered in the first channel, is given by

$$(N_1)_{\mathrm{corr}}=\frac{1-0.28}{1-0.185}(N_1)_c=0.885(N_1)_c, \qquad (9)$$

where $(N_1)_c$ represents the number of coincidences, corrected only for the random events, registered in the first channel with the absorber on.

Since the number of spurious delays due to the discharge of the G-M counters is proportional to the "prompt" coincidences (ABC), the percentage of these spurious coincidence is larger with S absorber where the number of "true" delayed coincidences is smaller than in C. Taking into account the difference between the values of the positive excess of mesons near sea level and at 30,000 feet, as suggested by a first analysis of the data reported in Table IX, one finds that in the case of S absorber, 0.81 must be substituted to 0.885 in the previous equation.

These corrections have been applied disregarding their statistical uncertainties. The fact has also been neglected that because of the different latitude dependence of the stopped mesons and of the total hard component (which is proportional to the number of spurious delays) the corrections themselves are latitude dependent.[88] Furthermore, the same correction has been applied to the results of the one flight undertaken at 36,000 feet.

APPENDIX C

Spurious Anticoincidences

Due to the geometry of the apparatus and to the small amount of material represented by the absorber, it appears very improbable that a lateral shower which in the absence of the absorber would strike some of the "anticounters" does produce an anticoincidence when the absorber is on. For the same reasons it seems also rather unlikely that a low energy particle, which otherwise would be stopped in the absorber, is scattered near the bottom of the lead, in such a way as to traverse counters B but none of the "anticounters," thus giving rise to an anticoincidence independently of the presence of the absorber. All other causes of spurious anticoincidences (such as inefficiency of the counters, random events, etc.) are not appreciably affected by the presence of the absorber.

On the basis of these considerations we have assumed that the counting rate of the anticoincidences registered without absorber yields the number of spurious events which must be subtracted from the anticoincidences registered with absorber in order to obtain the number of "true anticoincidences."

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counting rate found at 30,000 feet have shown an appreciable increase in the spread of the time distribution curve of the spurious delays.

[86] Measurements with and without an absorber have been continuously alternated in flight. $(N_1)_0$ and $(N_1)_c$ refer, therefore, approximately to the same average geomagnetic latitude (about 35° N).

[87] Series No. 3 in Table I also includes measurements taken under amounts of material different from those of Series No. 1 and 2, but less than 300 g/cm^2 of air equivalent. Since the low range end of the differential meson spectrum at Chicago is nearly flat, the previous ratio may be assumed to be given by the ratio between the value of N_0 given by the last column of Table I and the average value $N_c=6.8\pm0.15$, deduced from the combined data of the two other series.

[88] If the ratio of the intensities between 60° N and the geomagnetic equator is 1.9 for the stopped mesons and 1.6 for the total hard component [see Biehl, Neher, and Roesch, Phys. Rev. **76**, 914 (1949), as well as D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, 1949)] the corrections increase from 1 to about 1.2 in going from 60° N to the equator.