THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 68, NOS. 7 AND 8 OCTOBER 1 AND 15, 1945

Meson Intensity in the Substratosphere

H. J. BHABHA, S. V. CHANDRASHEKHAR AIYA, H. E. HOTEKO, AND R. C. SAXENA
Cosmic Ray Research Unit, Indian Institute of Science, Bangalore, India
(Received July 29, 1945)

The vertical intensities of mesons penetrating 5.25 and 30 cm of lead have been measured to an altitude of 15,000 feet and of those penetrating 20 cm of lead to an altitude of 32,000 feet (275 millibars pressure) by coincidence counter telescopes sent up in an aeroplane from Bangalore, magnetic latitude 3.3°N. A comparison of our results with those of Schein, Jesse, and Wollan indicates that the latitude effect between 3.3°N and 52°N of the vertical intensity of mesons shows no marked increase even to altitudes corresponding to pressures of 275 millibars. This is in striking contrast with the total intensity, which shows a very pronounced increase of latitude effect to these heights.

INTRODUCTION

THE variation with altitude of the total vertical intensity of cosmic rays has been measured by several authors[1-7] at different latitudes using coincidence counter telescopes. The results of such experiments have definitely established the existence of a large latitude effect at high altitudes and are in satisfactory agreement with the deductions of the cascade theory. For brevity we shall call any curve giving the *vertical* intensity of some component or group of cosmic rays as a function of altitude the altitude-intensity curve of that component or group. Valuable information on the processes leading to the creation, annihilation, and scattering of mesons and their dependence on energy could also be obtained through measurements of the altitude-intensity curves of mesons of different energies. There are very few such measurements. Dymond[8] measured the altitude-intensity curve of mesons penetrating 10 cm of lead at Edinburgh, magnetic latitude 59°N, but the work was interrupted by the war and only a preliminary note has been published. Schein, Jesse, and Wollan,[9,10] and Schein, Wollan, and Grötzinger[11] have carried out similar measurements at Chicago, magnetic latitude 52.5°N, using lead absorbers of different thicknesses, and the results of these authors are the only ones available yet. Since cosmic-ray mesons are all produced in the atmosphere, a comparison of the altitude-intensity curves for mesons of different energies *at different latitudes* would give valuable information about the de-

[1] Pfotzer, Zeits. f. Physik **102**, 23 (1936).
[2] T. H. Johnson, Phys. Rev. **54**, 151 (1938).
[3] H. V. Neher and W. H. Pickering, Phys. Rev. **61**, 407 (1942).
[4] R. A. Millikan, H. V. Neher, and W. H. Pickering, Phys. Rev. **63**, 234 (1943).
[5] W. F. G. Swann, G. L. Locher, and W. E. Danforth, Phys. Rev. **51**, 389 (1937).
[6] Carmichael and Dymond, Proc. Roy. Soc. **A171**, 321 (1939).
[7] Regener and Pfotzer, Nature **136**, 718 (1935).
[8] Dymond, Nature **144**, 782 (1939).
[9] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **57**, 847 (1940).
[10] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **47**, 207 (1935).
[11] M. Schein, E. O. Wollan, and G. Grötzinger, Phys. Rev. **58**, 1027 (1940).

pendence of their creation on the energy of the primary rays. It is therefore important to know the altitude-intensity curves of mesons at different latitudes, and particularly near the geomagnetic equator. No such measurements have been made previously near the geomagnetic equator.

As is well known, India is particularly suited for such measurements. First, the geomagnetic equator passes through south India. Secondly, due to the fact that the magnetic field of the earth is not axially symmetric with regard to its geographic center, India lies in the region of the earth's surface where the cosmic-ray intensity is a minimum, according to the world survey by Millikan and Neher.[12] This means that only the most penetrating cosmic rays can reach the surface of the earth in south India. Even theoretically (cf. Johnson[13]) the critical energy required by a cosmic ray to reach the earth at the magnetic equator in India is over 15×10^9 ev whereas on the equator west of India this critical energy is lower, and reaches the minimum value of 13×10^9 ev in South America. Theoretically the critical energy should reach its maximum value in some region in the Pacific Ocean at about 140°E longitude, that is north of Australia. However, the earth's magnetic field is not that of a pure dipole and it is possible that owing to local variations in the field south India lies in the region where the critical energy is a maximum, as the sea-level survey of Millikan and Neher seems to indicate. In any case, south India lies sufficiently near, if not in, the region of maximum critical energy for a particular importance to attach to measurements made here of the altitude-intensity curves of mesons near the geomagnetic equator.

Vertical intensity measurements if properly carried out are capable of attaining an accuracy sufficient for a quantitative comparison with theory. It is desirable for a proper comparison with theory that in experiments designed to measure the vertical intensity the geometry of the apparatus should be such that the lengths of paths traversed in the atmosphere and the absorber by the different rays measured by it do not differ by more than about 10 percent. Although such a condition tends to reduce the counts per minute, this should be remedied by increasing the number of counters in a tray, and, where possible, by making measurements for a relatively longer period, rather than by reducing the distance between the extreme counters and thus spoiling the geometry, and consequently the accuracy of the measurements. Pfotzer's[1] arrangement for the measurement of the total vertical intensity satisfies this condition but the apparatus used by other workers does not always do so. For example, in the experiments of Neher and Pickering[3] for the measurement of the total vertical intensity, the maximum allowed angle was 47° from the vertical entailing a path length 47 percent greater than that of a vertical particle. Their geometry was further complicated by putting two counters in parallel at a horizontal distance roughly equal to half of the vertical separation of the counters.

It has been shown by Greisen and Nereson[14] that the effect of side showers on counter telescope measurements can be considerable. Since the vertical meson intensity increases much more slowly with altitude than that of the soft component, it is always necessary in measurements of meson intensity to reduce the effect of side showers to a minimum. According to Greisen and Nereson the effect of side showers for a triple coincidence counter telescope is about 14 percent at an altitude 4300 meters and it would be greater at higher altitudes. A quadruple coincidence counter telescope is therefore desirable in measurements of vertical meson intensity which at great heights is only a small fraction of the total intensity.

In order to obtain the maximum information possible from the various experiments it is necessary that the results of different authors should be easily comparable and reproducible. For example, quantitative information about the latitude effect of the different components can only be obtained if this is possible. To this end we suggest that in executing and communicating all future experiments for measuring the variation with altitude of the vertical intensity of cosmic rays of different penetrating power certain criteria be adopted which we indicate below.

[12] R. A. Millikan and H. V. Neher, Phys. Rev. **47**, 207 (1935).
[13] T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938).
[14] K. Greisen and N. Nereson, Phys. Rev. **62**, 316 (1942).

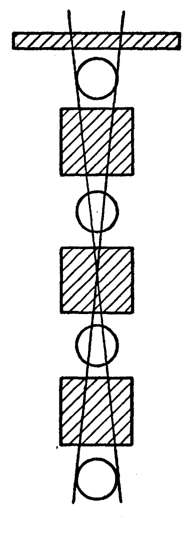

FIG. 1. Arrangement of counters.

The cosmic-ray intensity at any point in the atmosphere is mainly a function of the amount of matter traversed by the rays in reaching that point. Hence comes the importance of measuring the vertical rays only and keeping the variation of path length within about 10 percent by suitably designing the geometry of the apparatus, as we have already mentioned above. Now the pressure is a direct measure of the mass of air traversed by a vertical ray, and it is therefore appropriate that the intensity should be given as a function of pressure rather than in meters of water equivalent, as is often done. It is also what is always measured directly in the experiment. The conversion of pressure into meters of water equivalent involves certain physical assumptions about the relative absorbing powers of air and water and the small uncertainty it introduces is undesirable, especially in view of the fact that the accuracy of cosmic-ray measurements will continually increase in the future. A measurement of pressure in centimeters of mercury is however arbitrary and inconvenient for theoretical purposes. We therefore propose that in the future the intensity be given as a function of pressure measured in *millibars*. Since 1000 millibars, which is equal to the pressure of the standard atmosphere, corresponds to between 10 and 10.3 meters of water equivalent, the pressure in millibars divided by 100 gives immediately to within 3 percent the thickness of the intervening atmosphere in meters of water equivalent. This procedure would therefore have the advantage of communicating what is directly measured in any experiment in a form convenient both for a comparison with theory and with the past experimental results.

It is not the absolute intensities, but the relative values of the intensities which are of significance in comparing the work of different authors. It is therefore essential that the reading at sea level both with and without any absorber that may be used should always be measured with the apparatus concerned and communicated in the paper. Since the latitude effect at sea level and the absorption curve in lead at sea level at different latitudes is known, this would enable a fairly quantitative comparison of the curves of different authors to be made. We would also suggest that the final readings should always be given in a table, even if a graph is included, and the method of averaging the readings and the statistical accuracy be indicated.

We have planned a number of experiments on the basis of the foregoing discussion and carried out a preliminary measurement which is being reported here. In this preliminary experiment, we have measured the variation with height of the intensity of cosmic rays penetrating 20- and 30-cm thick blocks of lead absorbers at Bangalore, magnetic latitude 3.3°N, by sending up quadruple coincidence counter telescopes in an aeroplane. The intensity of mesons penetrating 5.25 cm of lead was also measured by Bhabha's method[15,16] with a triple coincidence counter telescope. Two flights were made, one on December 26, 1944 to an altitude of 15,000 feet and one on December 28, 1944 to an altitude of 32,000 feet. Although further experiments are still in progress, we think that the preliminary results which have already been obtained are of sufficient importance to merit being communicated now.

APPARATUS AND MEASUREMENTS

The counters used in the experiment were filled by a slightly modified form of the procedure

[15] Bhabha, Proc. Ind. Acad. Sci. **A19**, 23 (1944).
[16] Chandrashekhar Aiya, Proc. Ind. Acad. Sci. **A19**, 177 (1944).

given by Neher[17] and had a plateau of nearly 300 volts. They were 15 cm long and $1\frac{1}{4}''$–$1\frac{1}{2}''$ in diameter. The distance between the extreme counters was in every case 35 cm. Therefore no single particle making an angle of more than 22° to the vertical could traverse the telescope. Thus a particle recorded at this maximum angle of 22° would only travel a thickness of the atmosphere and absorber 8 percent greater than a particle arriving vertically.

Three distinct sets were used for the measurements. One was designed on the basis of Bhabha's method with a 5.25-cm thick lead absorber which allowed the measurement of the intensity of mesons with energies above 0.93×10^8 ev. It had three counters in a vertical plane working in coincidence with two additional counters in parallel on each side of the middle counter and put in anti-coincidence with the previous three. A lead absorber 1.25 cm thick was inserted below the top counter and a 4.0-cm lead block was put between the middle and bottom counters. A side view of the arrangement is shown to scale in Fig. 1. It has been shown[16] that this splitting of the lead absorber into two parts together with the anti-coincidence arrangement in fact allows the soft component to be cut out by only 5.25 cm of lead and that the two anti-counters to the sides of the middle counter are adequate for reducing the effect of side showers.

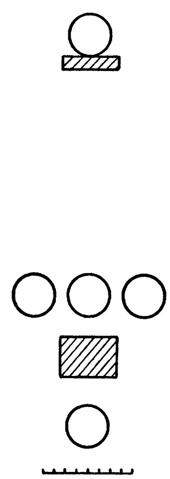

FIG. 2. Counter telescope.

[17] Strong and others, *Procedures in Experimental Physics* (Prentice-Hall, Inc., New York, 1938).

The second set had a quadruple coincidence counter telescope with 20 cm of lead as shown in Figs. 2 and 3. In the side view the horizontal lines indicate the active length of each counter. The third set was similar to the second one but had, in addition to the 20 cm of lead, another 10 cm of lead on the top. Each counter telescope, its amplifier, and its plate and bias batteries were all mounted in a box which was closed on all sides and waxed except for a small hole on the top made for the purpose of equalizing the pressure inside and outside the box. Inside each box was an electric heater operated from the aeroplane supply. The high voltage to the counters was supplied from a separate battery box which also had the necessary provision for heating.

The pressure was measured by a standard altimeter. The outside temperature was also measured throughout the flight and was required in order to calculate the real altitude from the indicated altitude. The measurements were made during ascent and descent in both flights. In addition, the airplane flew for half an hour at each "indicated" altitude of 5000, 10,000, 15,000, 20,000, 25,000, and 30,000 feet corresponding to pressures of 832, 671, 530, 430, 332, and 265 millibars, respectively.

The cosmic-ray counts of each of the three sets were recorded on three telephone call counters, and these together with a clock and the altimeter were photographed at the beginning

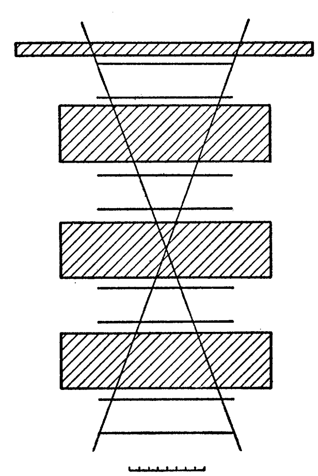

FIG. 3. Counter telescope.

TABLE I. Readings taken on airplane flights.

Indicated altitude in feet	Pressure in cm	Pressure in millibars	Readings with 5.25 cm of lead: counts	time in min.	counts per hr.	Readings with 20 cm of lead: counts	time in min.	counts per hr.	Readings with 30 cm of lead: counts	time in min.	counts/hr.
2900	68.8	906	42	60	42.0± 4.3	36	60	36.0±4.0	24	60	24.0±3.3
5000	63.2	832	22	30	44.0± 6.2	20	30	40.0±6.0	15	30	30.0±5.2
7500	56.4	742	40	38	63.1± 6.3	40	51	47.0±5.0	16	27	35.6±5.9
10000	51.0	671	32	30	64.0± 7.6	20	30	40.0±6.0	17	30	34.0±5.5
12500	45.5	599	60	40	90.0± 7.8	60	59	61.0±5.2	21	28	45.0±6.5
15000	40.3	530	58	31	112.3±10.2	36	31	70.0±6.7	22	31	42.6±6.1
20000	32.7	430				81	47	103.4±7.6			
25000	25.2	332				146	58	148.2±8.2			
30000	20.9	275				274	71	231.5±8.6			

and end of each of these intervals, as also at intermediate points on the way up and down. The results on the way up and down were consistent. No heating was required up to 15,000 feet and the heaters were not put in operation in the first flight. During the second flight two heaters failed to operate, and measurements up to 32,000 feet were obtained only of the intensity of mesons penetrating 20 cm of lead. The readings were consistent on the way up and down, and in good agreement with those made during the first flight. The combined readings of the two flights are given in Table I and plotted in Fig. 4.

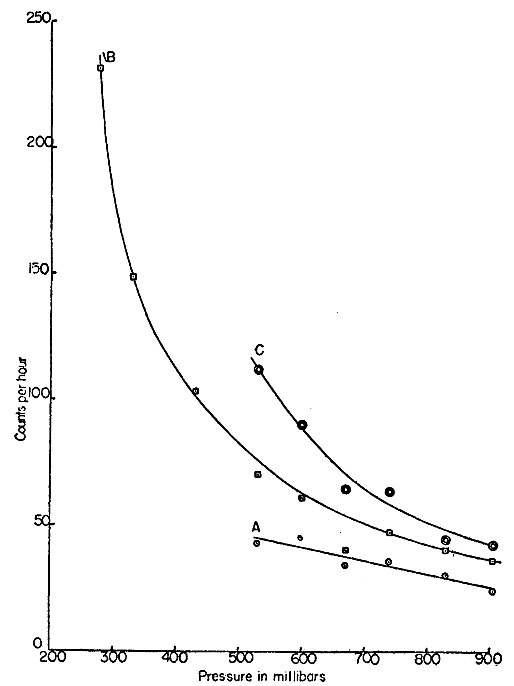

FIG. 4. Curve A—Vertical intensity of mesons penetrating 30 cm of lead. Curve B—Vertical intensity of mesons penetrating 20 cm of lead. Curve C—Vertical intensity of mesons penetrating 5.25 cm of lead. (Note: Since the counters were not of identical diameter in all the three cases, quantitative comparison of the three curves together is not to be made.)

INTENSITY OF MESONS OF DIFFERENT ENERGIES

Certain definite conclusions can be drawn from our results given in Table I and Fig. 4.

1. The intensity of cosmic rays capable of penetrating 30 cm of lead increases very slowly with altitude. The intensity at 15,000 feet (indicated) (530 millibars) is about twice the intensity at 2900 feet (905 millibars).

2. The intensity of mesons capable of penetrating 20 cm of lead also increases slowly with altitude, but at a more rapid rate than in case (1).

3. The intensity of *mesons* capable of penetrating 5.25 cm of lead, i.e., having an energy greater than 0.93×10^8 ev, increases perceptibly more rapidly with altitude. The intensity at 15,000 feet is nearly $2\frac{1}{2}$ times the intensity at 2900 feet.

Schein, Jesse, and Wollan[10] report that there is no difference in the intensity of rays penetrating any absorber thickness between 4 and 18 cm of lead and this appears to contradict the result of Schein, Wollan, and Grotzinger.[11] We are unable to understand the reason for their having found no absorption of rays between 4 and 18 cm of lead contrary to the theoretical expectation and our own experimental results and those of Bostick,[18] Rossi and Greisen,[19] and Hall[20] who find a great increase in the percentage of slow mesons with altitude.

[18] W. H. Bostick, Phys. Rev. **61**, 557 (1942).
[19] B. Rossi and K. Greisen, Phys. Rev. **61**, 121 (1942).
[20] D. B. Hall, Phys. Rev. **66**, 321 (1944).

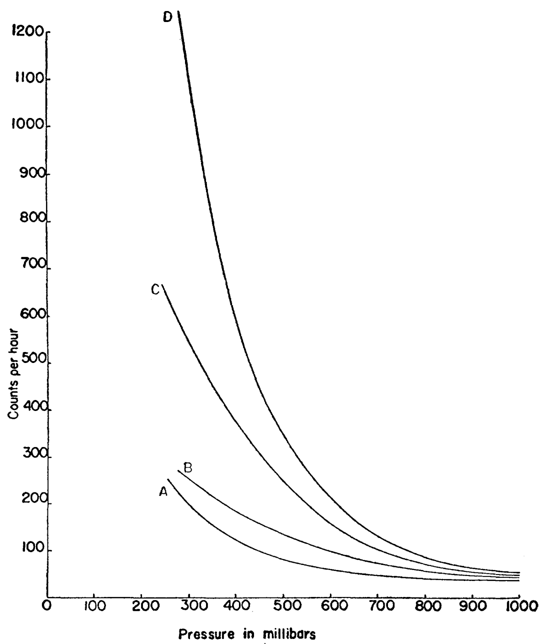

FIG. 5. Curve A: Vertical meson intensity at 3.3°N (Bhabha, Aiya, Hoteko and Saxena). Curve B: Vertical meson intensity at 52.5°N (Schein, Jesse and Wollan—1941). Curve C: Vertical total intensity at 3.3°N (Neher and Pickering). Curve D: Vertical total intensity at 49°N (Pfotzer).

It is worth mentioning that our readings at 10,000 feet for all the three apparatuses lie markedly below the three smooth curves drawn through the readings at the other altitudes, but there is not sufficient evidence to decide whether this result is purely a coincidence due to statistical fluctuations or is real.

LATITUDE EFFECT

In Fig. 5 we have plotted our results giving the intensity of mesons penetrating 20 cm of lead at 3.3°N as curve A and, for comparison, the latest results of Schein, Jesse, and Wollan[10] for the intensity of mesons at 52.5°N as curve B. The two curves have been fitted at sea level to allow for the known latitude and longitude effect[12] of 12 percent. In the same figure, we have plotted as curve C the variation of the total vertical intensity with altitude at 3.3°N as given by Neher and Pickering[3] for a triple coincidence counter telescope, this curve being fitted to our curve so as to show a ratio of vertical meson intensity to total vertical intensity of 80 percent as observed at ground level at Bangalore. Curve D gives the variation of the total vertical intensity with altitude as measured by Pfotzer[1] at a magnetic latitude of 49°N. The four curves together show at a glance the striking fact that *whereas the latitude effect between 3.3°N and 49°N of the total intensity shows a pronounced increase with altitude, the penetrating component shows practically no such increase of latitude effect even to heights corresponding to pressure of 275 millibars.* The theory of Hamilton, Heitler, and Peng[21] according to which the penetrating component should show only a slightly greater latitude effect than at sea level up to heights corresponding to a pressure of 100 millibars is therefore at least in qualitative agreement with our measurements. The difference in the geometry of the counter telescopes used by the different authors and the statistical accuracy of the results do not yet permit a quantitative comparison.

ACKNOWLEDGMENT

It is with pleasure that we express our great gratitude to Col. M. C. Robinson, Commanding Officer of the 84th Air Depot of the U. S. A. Air Force for giving the permission for the flight. We also wish to express our appreciation to the officers and men under his command who collaborated in the flight, and in particular to the engineering officer Major G. Denis, the pilot Capt. J. Claunch, Lt. Mack, and Sgt. Beaver for their whole-hearted and willing cooperation.

Our thanks are due the Trustees of the Sir D. J. Tata Trust who have financed this research. We are also grateful to Mr. D. R. D. Wadia for the loan of a Contax camera which was used in the experiment.

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