PHYSICAL REVIEW VOLUME 77, NUMBER 6 MARCH 15, 1950

The East-West Asymmetry of Positive and of Negative Mesons and the Excess of the Positives as a Function of Zenith Angle and Altitude*

GERHART GROETZINGER AND GORDON W. MCCLURE**
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received December 7, 1949)

The east-west asymmetry of positive and of negative mesons of energies around 800 Mev has been determined at altitudes of 260 and 4300 meters at a geomagnetic latitude of 50° north for zenith angles of 24 and 58 degrees. It is found that more positive mesons arrive from the west than from the east and more negative mesons arrive from the east than from the west, the asymmetries being equal but of opposite sign. From the magnitude of the asymmetries it can be concluded that the majority of the mesons observed under the above-mentioned conditions are produced in the top layer of the atmosphere. An increase of the positive excess for mesons of around 800 Mev is observed with an increase of the altitude from 260 to 4300 meters.

INTRODUCTION

THE east-west asymmetry of the hard component of the cosmic radiation which occurs at magnetic latitudes below 40 to 50 degrees (knee of the latitude effect) is interpreted as being mostly due to the deflection of the (at least preponderantly positive) primaries in the magnetic field of the earth. The secondaries (π-mesons) and the tertiaries (μ-mesons), which are eventually observed, preserve to a certain degree the direction of the primary producing them. This is due to the fact that the creation and the decay of the π-mesons take place at considerable energies so that little change of direction takes place in these events.

A much smaller asymmetry which is observed at higher latitudes, with which we will be concerned in this paper, is explained by Thomas H. Johnson[1] as being due to the magnetic deflection of the mesons after being produced by the symmetrically distributed primary radiation. This asymmetry is due to the energy loss of the mesons and would not exist were it not for an excess of the positives.

The following experimental results concerning the east-west asymmetry above the knee of the latitude effect and at higher altitudes were obtained on top of Mount Evans (49° geomagnetic latitude and 4300 meter height). J. C. Stearns and D. C. Froman[2] and T. H. Johnson[3] found, without any filter, asymmetries for zenith angles between 20° and 45° of somewhat below 0.02, and 0.005 for a zenith angle of 57°. On an airplane flight between 50° to 54° geomagnetic latitude at 9500 meter altitude, M. Schein, V. H. Yngve and H. L. Kraybill[4] found with a 22 cm lead filter an asymmetry of 0.13 for a zenith angle of 45°.

T. H. Johnson[1] calculated the high latitude asymmetries for sea level and an altitude of 4300 meters for a number of zenith angles under the assumption that the mesons are produced at the top of the atmosphere. First, the part of the deflection of either a positive or a negative meson in the magnetic field of the earth which leads to an asymmetry is calculated for various energies and zenith angles for both altitudes of the recorded mesons.[5] From these deflections the east-west asymmetry of the natural mixture of mesons of both signs is calculated for the case that mesons above a certain energy are recorded, that their energy-distribution at the two altitudes is of the form $N(E)dE = AE^{-3}dE$, and that the positive excess is 0.20 as determined by means of cloud chambers.[6] According to this theory the asymmetry on Mt. Evans should increase from 0.01 to 0.07 for an increase of the zenith angle from 20° to 57° if the E^{-3} distribution is cut off at 2.2×10^8 electron volts.

All previous experiments concerned with asymmetries were performed with instruments recording mesons without regard to their sign. A much greater amount of information can be obtained from the asymmetries if they are determined for particles of one sign only with a small spread in energy. The results of such experiments can be compared with consequences of Johnson's theory which are not based on a knowledge of the positive excess and depend to a lesser degree on a knowledge of the meson energy distribution. Actually the only necessary information is the dependence of the intensity of the hard component on the zenith angle, which follows from the energy spectrum at the altitude at which the asymmetry is observed. The expected asymmetries should furthermore exceed approximately by a factor of five, the asymmetries of the natural mixture of positive and negative mesons, which is, as

---

* This research was assisted in part by the Joint Program of the ONR and AEC.

** Now at Bartol Research Foundation, Swarthmore, Pennsylvania.

[1] Thomas H. Johnson, Phys. Rev. **59**, 11 (1941); see also I. S. Bowen, Phys. Rev. **45**, 349 (1943), and B. Rossi, Rendi Lincei **15**, 62 (1932).

[2] J. C. Stearns and D. C. Froman, Phys. Rev. **46**, 535 (1934).

[3] T. H. Johnson, Phys. Rev. **48**, 287 (1935).

[4] Schein, Yngve, and Kraybill, Phys. Rev. **73**, 928 (1948).

[5] If the isotropically produced mesons would not lose energy in the atmosphere, their angular distribution would remain unchanged in spite of the deflection by the magnetic field, so that no asymmetry would result. The observed asymmetry is caused by the additional deflection due to energy loss. Johnson's argumentation is little affected by the discovery of the heavy mesons being intermediaries between primaries and μ-mesons.

[6] L. J. Hughes, Phys. Rev. **57**, 592 (1940); P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937); L. Leprince-Ringuet and J. Crussard, J. de phys. et rad. **8**, 207 (1937).

explained before, due to the small difference in the number of positive and negative mesons.

We have performed an experiment using a magnetic lens type spectrometer focusing either positive or negative mesons with energies of approximately 800 Mev, but excluding protons, coming from the west and east respectively for two values of the zenith angle (24 and 58 degrees). The experiment was performed on Mt. Evans (altitude 4300 meters and geomagnetic latitude 49°) and in Chicago (altitude 260 meters and geomagnetic latitude 51°). Both locations are considered to be above the knee of the latitude effect.[7] If W_+, W_-, E_+, and E_- are the counting rates (corrected for background) where W_+, e.g., represents the rate for positive mesons arriving from the west, then the asymmetry for positive or for negative mesons is defined as

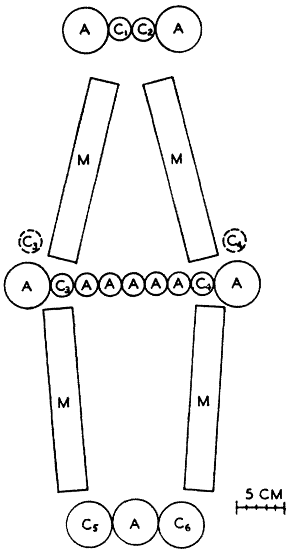

FIG. 1. Schematic diagram of the apparatus. (The two magnetic lens type telescopes consist of counters C_1, C_2 in parallel, with counters C_3 and C_5 in coincidence, and of counters C_1, C_2 in parallel, with counters C_4 and C_6 in coincidence.) During the experiment the apparatus is tilted either to the east or to the west.

A = Anticoincidence;
C = Coincidence;
M = Magnetic deflector.

$$\alpha_\pm=\frac{2(W_\pm-E_\pm)}{W_\pm+E_\pm}.$$

These counting rates allow one to obtain, furthermore, an expression for the positive excess for the two altitudes and for different zenith angles. In order to eliminate the influence of the asymmetries, the following expression was used as a measure of the excess:

$$\beta=\frac{2(W_++E_+-W_--E_-)}{W_++E_++W_-+E_-}.$$

G. Bernardini *et al.*[8] found an average positive excess both at sea level and at an altitude of 3500 meters of 0.20 for energies between 500 Mev and 4 Bev using a counter telescope containing magnetized iron deflecting plates. With a similar instrument, I. F. Quercia, B. Rispoli, and S. Sciuti[9] found that a quantity called the "experimental effect," which is somewhat smaller than the excess and which depends to a certain extent also on the energy spectrum, increases from 0.07 at an altitude of 88 meters to 0.14 at an altitude of 5100 meters, and decreases to 0.12 at 7300 meters for meson energies higher than 460 Mev. All these experiments refer to mesons having approximately vertical directions. C. Ballario, M. Benini and G. Calamai[10] report a decrease of the above-mentioned "experimental effect" at sea level from 0.101 for vertical incidence to 0.035 by inclining the instrument 60° from the vertical in an unspecified direction. The decrease of the excess with altitude and increasing zenith angle is interpreted by both groups as possibly indicating an increase in the multiplicity of the production of mesons with the energy of the primaries.

P. Bassi *et al.*[11] observed an increase of the positive excess from 0.16 to 0.25 at sea level by increasing the thickness of a lead filter in their telescope, in which the magnetic deflection takes place in air, from 290 to 1150 g/cm^2. The high asymmetry for the large absorber thickness is in agreement with a result of R. B. Brode[12] who reports a positive excess of 0.30 for mesons with energies between 1.4 and 2 Bev at sea level.

The results of Bassi and co-workers seem to contradict the results of the two groups mentioned before wherein essentially the positive excess decreases with increasing air absorber.

APPARATUS

A schematic diagram of the apparatus is shown in Fig. 1. The two top counters C_1 and C_2, in parallel, form in coincidence with the counters C_3 and C_5, one telescope, and in coincidence with counters C_4 and C_6 a second telescope. The selection of the particles with respect to charge and energy is provided by their deflection in the magnetized iron plates M_1, M_2, M_3 and M_4 (height 20 cm, thickness 3 cm, and length 60 cm). The plates M_1 and M_2 and the plates M_3 and M_4 represent parts of two closed magnetic circuits. The field strength in the plates was approximately 18,500 gauss. Counters marked A are anticoincidence counters. All of the counters have an effective length of 50 cm and their diameter is either one or two inches as can be seen in the figure.

Each of the counter telescopes constitutes a kind of magnetic spectrograph which selects mesons having certain energies and charges of a particular sign (depending on the direction of the magnetic field). The resolving power depends on the geometry of the apparatus and is influenced by the multiple scattering of

---

[7] Preliminary results are published. G. Groetzinger and G. W. McClure, Phys. Rev. **75**, 349 (1949), and G. W. McClure and G. Groetzinger, Phys. Rev. **75**, 340 (1949).

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

[9] Quercia, Rispoli, and Sciuti, Phys. Rev. **74**, 1728 (1948).

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

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

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

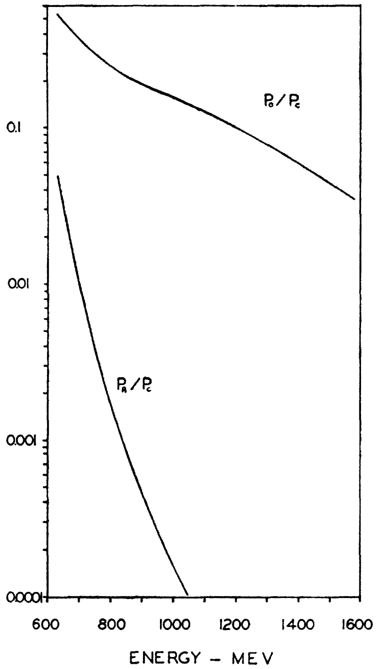

FIG. 2. Ratios of the probabilities of μ-mesons of the most favorable direction of incidence passing the telescope without being scattered out. P_c is the probability for the case of the magnetic field in a direction supporting the traversal, P for the case of the field rejecting the traversal, and P_0 for the case of no field.

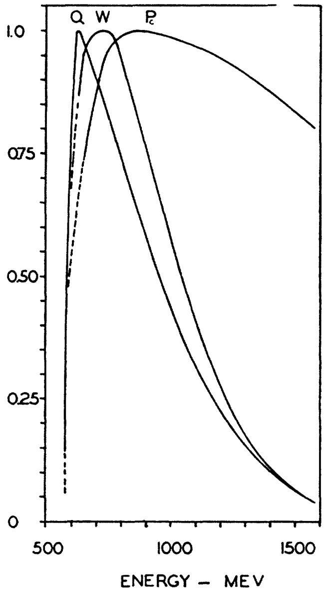

FIG. 3. Relative sensitivity, W, of the telescopes for particles of various energies. P_c is the relative probability for a μ-meson entering in the most favorable direction to traverse the telescope without being scattered out; Q is the relative probability for the traversal of unscattered μ-mesons of various energies. $W \approx P_c \times Q$.

the mesons in the deflecting plates. Due to the complicated geometry, a correct determination of the energy response is quite involved. For our purposes, however, the following rough estimate is sufficient.

We confine our attention to the projection of the trajectory of the particle onto a vertical plane perpendicular to the direction of the magnetic field in the deflecting plates. The condition that a particle traverse the telescope puts a lower limit on the magnitude of its momentum component in the direction of the magnetic field. Furthermore, the angular distribution of the incoming particles favors vertical incidence. Assuming an angular distribution of the recorded mesons proportional to $\cos^n\theta$, where θ is the zenith angle and n is a number between 2 and 3, it can be shown that, neglecting the scattering, the average energy, $\bar{E}$, of the particles passing through the telescope is only about 5 percent higher than the energy, E, corresponding to the momentum in the plane of projection considered here. The standard deviation about this mean is 8 percent which is small compared to the range of energies recorded by the telescope.

The curvature of a projected trajectory of a particle at a point in the deflecting plates can be considered as the sum of a "magnetic" and a "multiple scattering" curvature. Because of the appreciable energy loss in the iron parts of the telescope, the magnetic radius of curvature decreases along the trajectory. Using the well-known formula for energy loss by inelastic collisions, a "mean magnetic curvature," obtained as an average along the trajectory, was calculated for μ-mesons of various incident energies, assuming an effective magnetic field of 18,500 gauss. The multiple scattering of the mesons in the telescope was calculated according to the theory of Molière,[13] taking into account energy loss. The mean total curvature of the trajectory can be shown to be distributed approximately normally about the mean magnetic curvature with a standard deviation equal to the root mean square value of the multiple scattering curvature. By means of this distribution one can find the probability that the curvature of a meson incident with a certain energy will lie in that range—determined by the geometry of the telescope—which will allow passage. P_c is this probability for the magnetic field in the correct direction, P_r the probability for the field in reversed direction for the passage of the particle, and P_0 the probability in the absence of the field. The calculated ratios P_r/P_c and P_0/P_c are shown in Fig. 2 plotted against incident energy. It is seen that the probability that a particle of the wrong sign will pass the telescope is negligible. The relative number to pass in the absence of a magnetic field is considerable. It was found experimentally that the ratio of the counting rates (corrected for background, as will be described later) without a field and with the field collimating positive particles was about 20 percent, and the corresponding ratio for the case of the field collimating negative particles was about 15 percent. In order to compare these results with the curve for P_0/P_c it must be kept in mind that without a field the telescope is recording particles of both signs while P_0/P_c refers to the case where particles of only one sign are present.

The sensitivity of the telescope for mesons of a certain energy is approximately proportional to the probability P_c (correct field), which is a measure of the number of particles which traverse the telescope without

---

[13] G. Molière, Zeits. f. Naturforschung **3a**, 78 (1948).

being scattered out. P_c is shown in Fig. 3 (being normalized to unity at its maximum). The sensitivity depends, furthermore, upon the permissible angular spread of the projected direction of incidence which will lead to a traversal of the telescope. This spread is a function of the energy. The relative probabilities, Q, for particles of different energies, $\bar{E}$, which are assumed to suffer no deflections due to scattering, to traverse the telescope were determined by geometric construction assuming isotropic incidence and a path whose curvature increases due to energy-loss under the influence of the magnetic field. The probability, Q, as a function of the energy, $\bar{E}$, is shown in Fig. 3 (being normalized to unity at its maximum).

It is reasonable to assume that the (relative) sensitivity of the instrument for particles of various energies is given by the expression $W=P_c\times Q$ in spite of the fact that P_c and Q are not entirely independent. W, normalized to unity at its maximum, is shown in Fig. 3.

Due to the fact that the theory of multiple scattering is not applicable at very low energies, the curves P_c and W are dotted below $\bar{E}=600$ Mev. That the telescope is able to reject particles of improper charge even at the lowest energies which still allow a traversal of the iron deflecting plates is evident from the results of experiments in which a part of the mesons emerging from the telescopes were stopped in a lead plate. Twenty (delayed) neutron pulses were observed with the telescopes set for negative mesons, due to their capture in the lead while during an approximately equal time only one pulse was observed with the telescopes set for positive mesons.[14]

As can be seen from Fig. 3, the instrument records μ-mesons with an average energy of $\bar{E}_{\mathrm{av}}=800$ Mev. For this energy the average angle of incidence is inclined 17° with respect to the axis of the instrument, so that with both telescopes intensities of mesons coming from two directions 34° apart can be measured simultaneously. It follows from an analysis of the work done using photographic emulsions that the number of π-mesons which are produced in the atmosphere above the telescope or in the deflecting plates of the telescope by a charged primary entering through the top counters is small compared to the number of μ-mesons present at this altitude. In an experiment to be described in another paper we have determined an upper limit of 10 percent for the ratio of π- to μ-mesons recorded in our telescopes by investigating the ratio of positive and negative decay electrons emerging from a carbon plate which stops part of the mesons emerging from the two telescopes.

In order to determine the number of counts in the course of the experiment which are due to showers or chance coincidences the two counters C_3 and C_4 were brought to a position indicated by the dotted circles in Fig. 1 and the counting rates recorded. They were approximately the same whether the deflecting plates were magnetized or not. The counting rates were found to be 1.6±0.1 per hour on top of Mt. Evans and 0.28±0.03 per hour in Chicago for each telescope. (All the errors are probable errors.)

RESULTS

In the course of the experiment the polarity of the telescopes was changed every 24 hours and the telescopes were turned around approximately every six days, so that they were facing east or west approximately the same amount of time. The counting rates (per hour) (W_+, W_-, E_+, and E_-) for zenith angles of 24° and 58°, corrected for background, are shown in Table I. Since one of the telescopes was used for the smaller and the other one for the larger angle throughout the experiment, the counting rates have to be corrected for a difference of the sensitivities of the telescopes in order to obtain the true angular dependence of the cosmic ray intensities in the energy interval recorded by the instrument.

From these data follow the positive excesses β and the asymmetries α_+ and α_- in Table II. The last two columns of this table refer to Johnson's theory and will be discussed later.

DISCUSSION

(a) Positive Excess

The dependence of the excess on altitude which we find is smaller than that found by Quercia and coworkers.[9] Our experiments do not confirm a decrease of the positive excess with zenith angle of the magnitude reported by Ballaria and co-workers.[10] A possible explanation for this discrepancy might be that Ballaria's arrangement did not record mesons in a vertical north-south plane. In this case their results would be due

TABLE I. The counting rates (per hour) for zenith angles of 24° and 58°, corrected for background.

Location	Zenith angle	W_+	W_-	E_+	E_-
Mt. Evans	24°	11.7±0.2	9.1±0.15	10.9±0.2	9.6±0.15
Mt. Evans	58°	6.4±0.25	3.7±0.2	4.4±0.15	5.4±0.2
Chicago	24°	4.60±0.075	3.78±0.07	4.29±0.075	3.93±0.07
Chicago	58°	1.50±0.05	1.13±0.045	1.32±0.05	1.37±0.045

---

[14] G. Groetzinger and G. W. McClure, Phys. Rev. **74**, 341 (1948), and G. W. McClure and G. Groetzinger, Phys. Rev. **75**, 340 (1949)

TABLE II. Positive excesses β and the asymmetries α_+ and α_-.

Location	Zenith angle	β	α_+	α_-	$\alpha_{\pm\mathrm{th}}$	n
Mt. Evans	24°	0.180 ± 0.015*	0.07 ± 0.025	-0.055 ± 0.02	±0.057	3
Mt. Evans	58°	$0.17\ \pm0.035$	0.37 ± 0.055	-0.375 ± 0.06	±0.329	3
Chicago	24°	0.135 ± 0.011*	0.070 ± 0.024	-0.039 ± 0.024	±0.037	2
Chicago	58°	0.120 ± 0.036	0.128 ± 0.052	-0.192 ± 0.057	±0.197	2

* This result is partly based on data obtained for a zenith angle of 17°.

to the combined effect of an angular dependence of the excess and the difference in the asymmetry of positive and negative mesons, as described in this paper.

According to a recent theory of Heisenberg[15] the positive excess is approximately proportional to the square root of the energy of the mesons at their point of creation. Under the assumption that π-mesons are created at an altitude of 35 km (this value is not critical for the considerations) and that the μ-mesons into which they decay enter our telescope with an energy of 800 Mev, we have calculated the initial energies of the π-mesons for the cases of an angle of incidence of 24° on top of Mt. Evans and in Chicago. (These are the only two cases for which the excess is determined with a sufficient accuracy.) The ratio of the excesses according to Heisenberg is 0.826 while our experiments give a ratio of 0.75 ± 0.09.

(b) East-West Asymmetries

It can be seen from the results that more positive mesons arrive from the west than from the east, while more negative mesons arrive from the east than from the west, the asymmetries being approximately equal in magnitude but opposite in sign.

In order to compare the experimental results with the consequences of Johnson's theory[1] one has to keep in mind that his calculations refer to the case of particles in a vertical plane in the east-west direction only, while our telescope allows a small north-south component. As stated before, the average energy, $\bar{E}_{\mathrm{av}}$, of the mesons recorded by our instrument is approximately 800 Mev. In order to make our data suitable for a comparison with the theory, the energy, E_{av}, of approximately 750 Mev, corresponding to the projection of the particles in a vertical east-west plane, will be substituted in the formulas. If the zenith-angle distribution is given by

$$j=j_0\cos^n\theta,$$

where θ is the zenith-angle, then the east-west asymmetry $\alpha_{\pm\mathrm{th}}$ for purely positive or purely negative radiation is, according to Johnson,

$$\alpha_{\pm\mathrm{th}}=\pm2\bar{\delta}(\theta)n\tan\theta,$$

where $\bar{\delta}(\theta)$ is the average increase of the deflection resulting from atmospheric energy loss. Johnson obtains $\bar{\delta}(\theta)$ by averaging over the meson energy spectrum above a certain cut-off given by the apparatus. Because of the energy selectivity of our telescope we have chosen $\delta(\theta)$ corresponding to the mean energy, $E_{\mathrm{av}}=750$ Mev, recorded by our telescope. The value of the asymmetry is sensitive with respect to the choice of exponent n, which is taken by Johnson as being equal to two, for sea level and for the top of Mt. Evans. This value, to a good approximation, represents the zenith angle distribution of mesons of an inverse cube power law spectrum. Since our telescope selects mesons lying in a small energy range, one has to expect an exponent n somewhat smaller than three for such a spectrum. The values of n which gave good agreement with our experimental results were $n=3$ for Mt. Evans and $n=2$ for Chicago. The theoretical values for the asymmetries, and the exponents n on which they are based, are shown in the last two columns of Table II. A comparison of the sum of the counting rates W_+, W_-, E_+, and E_- at 24° and 58°, taking into account a slight difference in the sensitivity of the two telescopes leads to an exponent $n=2.2$ in the $\cos^n\theta$ distribution for the mesons recorded at Chicago, which is in good agreement with the exponent $n=2$ found from the asymmetries. No comparison of the sensitivities of the telescopes was made at Mt. Evans. The sensitivities are probably different from the ones at Chicago since the instrument was partly dismantled for transportation.

Since the exponent n on top of Mt. Evans can hardly exceed $n=3$, and the exponent $n=2$ is quite reasonable for Chicago, it follows from the observed asymmetries that the majority of mesons which are observed at altitudes up to 4 km at a geomagnetic latitude of 50° must be decay products of π-mesons (of both signs) produced in the top layer of the atmosphere by an isotropic primary radiation.

We are greatly indebted to Mr. Jack Aron for his help in constructing the equipment and performing the experiment, and to Dr. Byron E. Cohen and Dr. Mario Iona, Jr. of the Inter-University High Altitude Laboratory for their friendly support during our stay on Mt. Evans.

Note added in proof.—At the New York meeting of the American Physical Society (January 4, 1950) R. B. Brode presented (post-deadline paper) the results of an investigation of the east-west asymmetry in many respects similar to ours. With a magnetic lens type spectrometer collecting either positive or negative mesons of 2 Bev, he finds the asymmetries for the positive and for the negative mesons independent of the altitude up to approximately 4000 meters. The magnitude of the observed asymmetries are such that he is led to the conclusion that the recorded mesons are, in part, produced by negative primaries.

---

[15] Werner Heisenberg, Zeits. f. Physik **126**, 569 (1949).