Atmospheric Temperature Effect for μ Mesons Observed at a Depth of 846 m.w.e.*

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The experiment reported was a measurement of the effect of variations in atmospheric temperatures on the intensity of μ mesons observed underground at a depth of 846 m.w.e. The average energy of these particles is known to be $\sim 2\times 10^{11}$ ev. A total of $\sim 1.2\times 10^{6}$ coincidences, between two large trays of Geiger counters located in a salt mine, was collected over a two-year period. The correlation between variations in counting rate and simultaneous variations in effective atmospheric temperature was analyzed. The effective temperature was determined from radiosonde measurements of atmospheric temperatures at pressure levels up to 20 millibars performed by a U. S. Air Force weather observation unit near the salt mine. The resulting temperature coefficient is 0.22 ± 0.06 percent per degree and the correlation coefficient is 0.75. The results are compared with those obtained from similar measurements at 1574 m.w.e. and with the theoretical values of the temperature coefficient derived from various schemes describing the production of μ mesons with high energies.

1. INTRODUCTION

FROM consideration of the competitive processes of nuclear absorption and decay of unstable parent particles which give rise to the μ mesons observed in cosmic rays, it is expected that variations in atmospheric temperature should be accompanied by corresponding changes in the intensity of μ mesons. In the absence of a competitive process, the probability that an unstable parent, produced with a given energy, will decay into a μ meson is determined by its mean lifetime for this decay and does not depend on its surroundings. The probability of absorption, on the other hand, depends strongly on the density of the atmosphere that it traverses. An increase in local atmospheric temperature indicates a decrease in density which favors the probability of decay into a μ meson before the parent particle is absorbed. Therefore, an increase in μ-meson intensity would be expected to accompany the increase in temperature. Several experimenters[1–4] have investigated this phenomenon and their results have been summarized in the review article by the Cornell group.[4]

Since the magnitude of the temperature effect depends on the mean lifetime for the decay process, measurements of this effect on μ mesons of known energy can in principle provide information concerning the identity of their parents. It is well known that μ mesons with energies up to $\sim 10^{8}$ ev arise predominantly through the decay of π mesons. At much greater energies, however, the contribution made by other parents to the intensity of μ mesons is uncertain. The experiment reported in this paper is a measurement of the temperature effect on μ mesons observed at a depth of 8.46×10^{4} g cm^{-2} [846 meters water equivalent (m.w.e.)], where the average energy of these particles is known to be $\sim 2\times 10^{11}$ ev.[5] The experimental procedure will be described, and then the results will be discussed in terms of possible conclusions which can be drawn concerning the parentage and mode of production of high-energy μ mesons.

2. DESCRIPTION OF EXPERIMENT

The cumulative total of coincidences between two trays of Geiger counters located at a depth of 846 m.w.e. in a salt mine in Detroit, Michigan was recorded each hour. Each tray had ten counters, each of which was two inches in diameter and ninety inches long. The counters in each tray were separated by one-half inch from each other and the trays were separated by one inch of lead. The purpose of the Pb was to eliminate coincidences due to local radioactivity.

The low counting rate at the depth of the experiment ($\sim$107 hr^{-1}) indicated that considerable time would be required to obtain relatively small statistical errors in measuring the temperature effect. This required that precautions be taken to insure the elimination of systematic variations in counting rate which were not due to a temperature effect. The possible variations which required consideration were changes in local radioactivity which would be reflected in the rate of accidental coincidences, drift in the behavior of the apparatus, and temporal variation in cosmic-ray intensity. The latter possibility seems unlikely since the energies of the observed particles are so high that known causes of intensity variations such as changes in the earth's magnetic field, barometric pressure, and solar activity, would be negligible. Analysis of diurnal variations in the observed intensity of cosmic-rays underground has shown no appreciable effect.[6]

Weekly measurements were made of counter efficiencies, resolving time of the coincidence circuit, and

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background counting rates. The latter two measurements proved to be constant throughout the time of the experiment, assuring that the contribution from accidental coincidences ($\sim$1 percent of the total counting rate) showed no variation. However, several counters failed in the course of the experiment. These failures were immediately apparent at the times when tests were made and the counters were replaced. The data collected during the previous week were of course discarded. Since it is possible that the geometry of the counter array may have been slightly altered while replacing a counter, and crude estimation indicated that the resulting error in the temperature effect (owing to the change in the average counting rate after the alteration in geometry) could not be neglected in calculating the temperature effect, the data collected during the long intervals between counter changes were treated as if measured by different sets of apparatus. These data, collected between September 1, 1951 and June 27, 1953 are listed in Table I.

Atmospheric temperature information was supplied by an Air Force weather squadron from radiosonde observations made at Selfridge Field, Michigan (about 50 miles from the Detroit mine). The observations were made four times daily and temperatures at pressure levels up to 20 millibars were recorded. The treatment of the temperatures is described in the following section and the relevant data are listed in Table I.

In order to be confident that the temperatures measured at Selfridge Field were indeed representative of atmospheric conditions above the counter telescope, their correlation with simultaneous measurements made by the Weather Bureau at Toledo, Ohio, over a several month period, was analyzed. The correlation coefficient was 0.92. Since Detroit is approximately equidistant between Selfridge Field and Toledo, the temperature data were considered adequate in determining the temperature effect above the experiment.

TABLE I. Counting rate *vs* effective temperature of the atmosphere.

Period	T_{eff} (°C)	n (counts)	t (hours)
Interval 1 (1951)			
Sept. 1–Sept. 28	−48.8	62 812	581
Sept. 29–Nov. 2	−51.3	89 213	829
Nov. 3–Nov. 30	−52.8	70 310	653
Dec. 1–Dec. 14	−51.5	35 568	331
Interval 2 (1951–1952)			
Dec. 15–Jan. 4	−49.9	49 217	453
Jan. 5–Feb. 1	−54.3	71 511	666
Feb. 16–Mar. 14	−50.7	71 763	666
Interval 3 (1952)			
May 18–May 31	−48.2	35 603	330
June 1–July 3	−48.9	71 741	666
July 4–Aug. 7	−48.2	67 490	628
Interval 4 (1952–1953)			
Aug. 23–Sept. 2	−50.6	50 376	471
Sept. 18–Oct. 15	−49.8	69 258	642
Oct. 16–Nov. 5	−53.0	52 645	493
Nov. 6–Nov. 26	−53.7	53 458	500
Nov. 27–Dec. 19	−53.8	56 851	535
Dec. 31–Feb. 3	−54.0	86 072	807
Mar. 31–April 21	−50.7	54 914	507
April 22–May 19	−52.7	69 033	642
June 2–June 27	−49.6	60 735	563

3. DISCUSSION OF RESULTS

The temperature effect has been discussed in great detail in reference 4 which is a comprehensive review of cosmic-ray measurements performed at a depth of 1574 m.w.e. The same notation and definitions will be used here. The temperature effect for an isothermal atmosphere could be characterized by the temperature coefficient α defined by $\alpha=(1/I)(\partial I/\partial T)$, where I and T represent the intensity of μ mesons and atmospheric temperature, respectively. Since the atmosphere is not isothermal, a weighted average of temperatures measured at various altitudes is used instead of T and called the effective temperature T_{eff}. (The weighting factor weights higher atmospheric levels more heavily than lower ones, reflecting both the decreasing relative probability of decay of parent particles as they penetrate regions of increasing density and the reduced number of these particles which survive both absorption and decay at lower altitudes. See reference 4.) The effective temperatures are computed from the formula

$$T_{\mathrm{eff}}=(T_{20}+T_{40}+T_{80}+T_{125}+T_{250}+\tfrac{1}{2}T_{500})/5.5,$$

where the subscripts of the terms in the sum indicate the pressure levels (in millibars) at which the temperatures were measured. Since many of the radiosonde ascents do not reach the important upper levels and large (apparently random) fluctuations in temperature occur at these levels, the use of T_{eff} calculated from individual flights is not regarded as reliable in the correlation analysis. These difficulties are overcome[4] by taking the mean of the measurements made at each level during periods of about a month to represent the terms in the sum used to calculate T_{eff}. The experimental data were, therefore, conveniently divided into approximately such periods, the mean temperatures evaluated from individual ascents, and the T_{eff} for these periods calculated. The T_{eff} and corresponding numbers of counts collected during these periods are the data that appear in Table I.

For each of the four intervals between counter changes ($j=1$ to $j=4$) one can obtain an average effective temperature $\bar{T}_j=\sum_i t_{ij}T_{ij}/\sum_i t_{ij}$, where T_{ij} is the T_{eff} for the ith period in the jth interval and t_{ij} is the corresponding time. Similarly, an average counting rate can be obtained, $\bar{R}_j=\sum_i t_{ij}n_{ij}/\sum_i t_{ij}$, where n_{ij} is the number of counts recorded in the time t_{ij}. In the individual periods, t_{ij}, the number of counts, n_{ij}, differs from the expected number $\bar{R}_j t_{ij}$ by Δn_{ij}, and the temperatures differ from $\bar{T}_j$ by ΔT_{ij}. As in reference 4 we assume that the temperatures T_{ij} are accurate (any

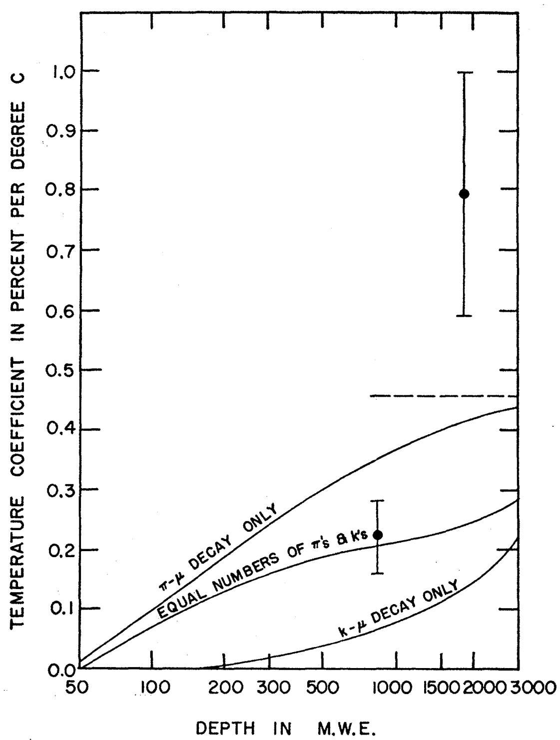

FIG. 1. Calculated temperature effect as a function of depth under various hypotheses as to the nature of the parents of the μ mesons and experimental values at 846 m.w.e. and 1574 m.w.e.

error in this assumption is only likely to reduce the calculated temperature effect) and that there are no causes of variation of the rate R_{ij} other than temperature changes and random statistical errors. The latter assumption can be checked after computation of the temperature effect by determining whether the residual fluctuations are as small as expected from statistical errors alone.

Under these assumptions, the most probable value of the temperature coefficient α and its standard error are given by

$$\alpha_0=\frac{\sum_j\sum_i\Delta n_{ij}\Delta T_{ij}}{\sum_j\sum_i\bar{R}_jt_{ij}(\Delta T_{ij})^2}\pm\frac{1}{[\sum_j\sum_i\bar{R}_jt_{ij}(\Delta T_{ij})^2]^{\frac{1}{2}}}.$$

The corresponding equation for the correlation coefficient r between counting rates and effective temperature is

$$r=\frac{\sum_j\sum_i\Delta n_{ij}\Delta T_{ij}}{[\sum_j\sum_i(\Delta n_{ij})^2/\bar{R}_jt_{ij}\cdot\sum_j\sum_i\bar{R}_jt_{ij}(\Delta T_{ij})^2]^{\frac{1}{2}}}.$$

The sum of the squares $S(\alpha_0)$ of the reduced deviations $\Delta n_{ij}^*=\Delta n_{ij}-\alpha_0\bar{R}_jt_{ij}$ relative to the statistical errors $(\bar{R}_jt_{ij})^{\frac{1}{2}}$ can be compared with the expected value of this sum, $\langle S(\alpha_0)\rangle$, in order to determine if the assumptions made above are correct. If the assumptions are correct, then $\langle S(\alpha_0)\rangle$ is given by

$$\langle S(\alpha_0)\rangle=m-m_j-1\pm[2(m-m_j-1)]^{\frac{1}{2}},$$

where m is the total number of terms in the double sum and m_j is the number of terms in the sum over j ($m_j=4$ and $m=19$). $S(\alpha_0)$ is related to the sum of squares using uncorrected deviations Δn_{ij} by

$$S(\alpha_0)=\sum_j\sum_i\frac{(\Delta n_{ij}^*)^2}{\bar{R}_jt_{ij}}=(1-r^2)\sum_j\sum_i\frac{(\Delta n_{ij})^2}{\bar{R}_jt_{ij}}.$$

Using the data in Table I in the preceding formulas, one obtains $\alpha_0=0.22\pm0.06$ percent per degree, $r=0.75$, $S(\alpha_0)=11.3$, and $\langle S(\alpha_0)\rangle=14\pm5.3$. The agreement (within expected statistical fluctuations) between the reduced deviations $S(\alpha_0)$ and the value expected from purely statistical errors $\langle S(\alpha_0)\rangle$ support the assumptions on which the equation for α_0 was based. Since the value of α_0 is more than three times its standard error, the results indicate a real positive temperature effect.

The Cornell group[4] has calculated α as a function of depth assuming various modes of production of μ mesons (including correction for $\mu-e$ decay which is negligible at 846 m.w.e.). The results were presented graphically for the three possibilities in which the parent particles are: π mesons exclusively, κ mesons exclusively, or equal numbers of π's and κ's; these curves are reproduced in Fig. 1 together with the values of α measured in the present experiment and at 1574 m.w.e. by the Cornell group.

If the calculations, which involve reasonable assumptions and approximations, are considered to be accurate, then the simplest interpretation of the present result indicates that 846 m.w.e. (i.e., for energies $>2\times10^{11}$ ev) μ mesons are decay products of π mesons and κ mesons in approximately equal numbers. However, other interpretations also seem reasonable. Since α differs by only two standard errors (which is not a highly improbable fluctuation) from the value derived on the assumption that π mesons are the only parents, the experimental value may be considered compatible with this mode of production. The latter interpretation is enhanced by the experimental results at 1574 m.w.e. which appear most easily reconcilable with the $\pi-\mu$ decay scheme. In any case, comparison with the accepted calculated values leads to the conclusion that the temperature effect reflects the influence of a decay process in the origin of the particles observed far underground and that the properties of the parent particles (ratio of mass to mean lifetime and absorption cross section) are similar to the known properties of π and κ mesons.

If, on the other hand, the experimental results at both depths are considered to be accurate, then either the theoretical calculations are in adequate or the mode of production of μ mesons changes rapidly in the energy range corresponding to the average energies at which mesons are produced that are observed at the two depths (4×10^{11} to 10^{12} ev).

Further information on unstable cosmic-ray particles could improve accuracy of the parameters used in the theoretical calculations, and measurement of the temperature effect at other depths might exclude some interpretations of the experimental data that now seem acceptable.

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Proton Intensities at Sea Level and 9000 Feet*

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The vertical intensities of protons which occur singly in the cosmic radiation have been measured at 9000 feet and at sea level. The particles observed were those whose momenta, recorded by cloud chambers above and below a magnetic field, were between 0.59 and 0.93 Bev/c after having traversed various thicknesses from 0 to 345 g/cm^2 of lead absorber placed over the apparatus. The identification of the particles was achieved by a mass determination based on the measured momentum and the range observed in a third cloud chamber containing copper plates. With no absorber over the apparatus, the differential momentum intensity at 9000 feet was found to be $8.9\pm0.9\times10^{-4}$ (Bev/c)$^{-1}$ sec^{-1} sterad^{-1} cm^{-2}. In conjunction with the data obtained at sea level with the same apparatus, an effective absorption length of 136_{-8}^{+13} g/cm^2 of air was found for protons of the mean momentum 0.76 Bev/c. From this absorption length and the evidence that production between the two levels of observation plays a predominant role, a value of 134 g/cm^2 for the absorption length of the primary particles was deduced.

INTRODUCTION

MORE or less direct measurements of single proton intensities in the momentum range of 0.3 to 8 Bev/c have been carried out in recent years by different observers at altitudes from sea level to approximately 30 000 feet. Particles have been variously identified by the utilization of determinations of curvature of path in a magnetic field plus ionization, scattering, or absorption in dense materials;[1–9] by some combination of ionization, scattering, or absorption determinations;[10–13] and by the simultaneous observation of delayed coincidences and anticoincidences from an absorber in a counter telescope.[14] Less direct information on intensities of protons in this as well as higher energy regions may be obtained from analyses of the rate of occurrence of nuclear interactions observed in photographic emulsions or in the plates of a cloud chamber.

The present experiment makes use of the momentum-absorption method to determine the proton intensity in the range from 0.59 to 0.93 Bev/c at sea level (Berkeley) and at 9000 feet (Camp Sabrina, California). The momentum range was extended to 1.3 Bev/c at the 9000-foot level by the use of absorber over the apparatus. The data with the absorber is of limited validity, however, because of the necessity for applying some necessarily approximate corrections for nuclear interactions and because of statistical uncertainties.

EXPERIMENTAL ARRANGEMENT AND METHOD

The schematic diagram of Fig. 1 shows the arrangement of the main parts of the apparatus. The original equipment designed by Brode[15] for operation in a B-29 as a mass measuring apparatus has been modified somewhat for the present work. It consists of three

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