Atmospheric Temperature Effect for Mesons Far Underground*

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A continuation of measurements previously reported has led to verification of the positive temperature effect for μ mesons detected at 1574 m.w.e. underground, which are created in the atmosphere with an average energy of about 8×10^{11} ev. The new result for the temperature coefficient at this depth is 0.33 ± 0.13 percent per deg C; and this value combined with the previous measurement yields an average of 0.46 ± 0.11 percent per degree, agreeing with the value expected if the $\pi-\mu$ decay process is responsible for all, or most, of these μ mesons.

THE effect of atmospheric temperature on the intensity of cosmic-ray mesons far underground has been discussed in previous publications,[1,2] in which experimental values of the temperature coefficient, $\alpha=(1/I)(\partial I/\partial T_{\rm eff})$ were reported for depths of 1574 and 846 meters water equivalent (m.w.e.) underground. The measurements in a salt mine at 1574 m.w.e. have been continued, with modified recording apparatus, in order to verify the existence of the effect and to reduce the rather large statistical error in the determination of α. It is the purpose of this article to report the results obtained.

The apparatus consisted of three independent telescopes, each containing two broad trays of counters (30 in.×40 in.) separated by four inches of lead, and shielded above and below by two inches of lead as in reference 1. Steps taken to ensure reliability of the record coincidence rates were the following:

1. Quenching circuits were used with the counters in order to prolong their lives and improve the constancy of their efficiency. The dead times imposed by the quenching circuits were measured periodically, and the indicated corrections for dead-time inefficiency (about one percent) were made. In the course of the experiment, the maximum variation of this correction was ±0.1 percent of the mean counting rate.

2. The coincidence resolving time was measured periodically, to prevent slow variations of the accidental coincidence rate from indicating a spurious seasonal variation of intensity. The indicated corrections, averaging six percent, were made; and the variations of these corrections affected the results appreciably, the standard deviation of the correction being one percent of the average counting rate, which is 0.7 times the statistical standard error of the monthly counting rates to which the corrections were applied.

3. The numbers of single pulses registered by the counter trays (mostly due to local radioactivity) were monitored continually. The statistical accuracy of this count was so high that failure of a counter would be indicated clearly without much delay. In addition, the plateaus of the counter trays were tested twice per week; and time intervals of doubtful reliability were discarded.

4. The two-fold coincidences in each telescope (about 10 per hour) were totalled on mechanical registers, and in addition were displayed (after passing through a scale of 4) on a clock-driven pen recording instrument. On the latter record, any spurious counts due to electrical disturbances were distinguishable.

The temperature information was obtained from the U. S. Weather Bureau, and consisted of radiosonde observations made at three Air Force stations: Rome, New York, about 75 miles northeast of the salt mine; Buffalo, New York, 120 miles WNW of the mine; and Hempstead, Long Island, about 240 miles southeast of the mine.

The radiosonde balloon flights are not uniformly successful, attaining a maximum elevation that varies greatly from one flight to another. It has been suggested[3] that correlations of intensity variations with changes of upper air temperature may be unreliable, because of the temperature measurements being nonrepresentative owing to a correlation between weather conditions and success of the flights. However, in the present case there seemed to exist other factors, entirely uncorrelated with air temperature, which exerted a much stronger influence on success of the flights (e.g., variations in the type of balloon used, and changes in personnel at the weather stations). These factors were so dominant that no relation between temperature and success of the flights was apparent.

The effective temperature of the atmosphere was defined as in the previous publications:

$$T_{\rm eff}=\int e^{-\lambda x}T(x)dx\bigg/\int e^{-\lambda x}dx,$$

where x represents the atmospheric pressure level in g/cm² and $\lambda=120$ g/cm². The integral was approximated by a weighted sum of the temperatures at all the pressure levels where temperatures were reported in the weather data. This is in contrast to the previous

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[1] Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. 24, 133 (1952).

[2] N. Sherman, Phys. Rev. 93, 208 (1954).

[3] H. O. Curtis, Proceedings of the Duke University Cosmic Ray Conference, 1953 (unpublished), Sec. IV, p. 14.

TABLE I. Average temperatures, running times, and numbers of counts recorded each month, corrected for accidental coincidences and dead-time inefficiency. (In calculating the results marked with an asterisk, the data in parentheses have been omitted.)

Month	$(T_{\text{eff}})_{\text{Av}}$	Telescope 1 t_i(hr)	Telescope 1 n_i	Telescope 2 t_i(hr)	Telescope 2 n_i	Telescope 3 t_i(hr)	Telescope 3 n_i
Nov. '52	−55.3°C	216	2060	99	1074	260	2509
Dec.	−55.9	623	6177	623	6795	419	4162
Jan. '53	−55.95	684	6834	734	8121	740	7345
Feb.	−55.05	364	3595	381	4209	197	1920
Mar.	−52.2	590	5849	609	6820	21	222
Apr.	−51.6	814	8310	810	8937	508	4965
May	−52.1	512	5094	580	6583	136	1332
June	−51.6	605	6064	441	4878	595	5826
July	−50.5	494	4914	494	5463	367	3678
Aug.	−50.5	(586)	(5560)	455	5262	526	5394
Totals		4902*	48 897*	5226	58 142	3769	37 353
Average rate (hr⁻¹):		9.975*		11.126		9.911	
Average of T_{eff}:		−53.2°C*		−53.0°C		−53.1°C	
Temperature coeff., α:		+0.29±0.22*		+0.42±0.20		+0.26 ±0.23%/deg C	
Correlation coeff., r:		+0.43*		+0.54		+0.34	

analyses,[1,2] where the temperatures at only six levels were used in approximating the integral. At altitudes above $x=20$ g/cm² the temperature was assumed to be the same as at 20 g/cm², for lack of other information.

Two independent methods of analysis of the data were used, the first depending only on the seasonal variations of temperature and counting rate (as in references 1 and 2), and the second depending only on short-period fluctuations of temperature and intensity.

For the first method, monthly averages were computed of the temperature at each of the pressure levels, and from the monthly averages, values of T_{eff} for the month were computed. Because of the different distances of the weather stations from Ithaca, the measurements at Rome, Buffalo, and Hempstead were combined with weighting factors in the ratio 3:2:1.

For each telescope, an over-all average temperature was computed from the relation $\langle T_j\rangle_{\text{Av}}=\Sigma_i t_{ij}T_{\text{eff}}/\Sigma_i t_{ij}$ and an average rate from the relation $\langle R_j\rangle_{\text{Av}}=\Sigma_i n_{ij}/\Sigma_i t_{ij}$; where t_{ij} represents the running time of telescope j in the ith month, and n_{ij} the number of counts recorded. ΔT_{ij} and Δn_{ij} represent the deviations of T_{eff} and n_{ij} from $\langle T_j\rangle_{\text{Av}}$ and from $\langle R_j\rangle_{\text{Av}}t_{ij}$, respectively. The pertinent data are given in Table I.

The temperature coefficient α is computed from the relation $\alpha=\Sigma(\Delta n\Delta T)/\Sigma(\langle R_j\rangle_{\text{Av}}t\Delta T^2)$, and the correlation coefficient is defined by

$$r=\Sigma(\Delta n\Delta T)\{\Sigma\Delta n^2/(\langle R_j\rangle_{\text{Av}}t)\cdot\Sigma(\langle R_j\rangle_{\text{Av}}t\Delta T^2)\}^{-\frac{1}{2}}.$$

In this form, the relations may be applied either to the data of a single telescope, by summing only over the index i for constant j, or to all of the data by summing over both i and j. These relations are based on the assumption that the only significant errors are the random statistical fluctuations of the (corrected) numbers of counts. Following that assumption, the standard errors are given by $\epsilon_\alpha=\{\sum(\langle R_j\rangle_{\text{Av}}t\Delta T^2)\}^{-\frac{1}{2}}$.

Of the thirty entries in Table I, one of them (in parentheses) exhibits a very improbable fluctuation: 3.5 standard errors even if there is no temperature effect, and 4.3 standard errors in view of the likely value of α. The probability of obtaining such a point among thirty samples is very small. It is not clear whether the entry represents an instrumental fault or a rare statistical fluctuation; but in either case, the point would exert abnormal influence on the calculated results if it were included. Including this point, the value of α obtained from all the data in Table I is $\alpha=0.22\pm0.12$ percent per deg C, and the correlation coefficient is $r=0.26$; excluding this point, which we consider gives a more probable result, $\alpha=0.33\pm0.12$ percent per deg C, and $r=0.44$.

In Fig. 1, the data obtained in months of nearly equal mean temperature have been combined, and summed over the three telescopes; the deviations of the counting rates from the 10-month average being plotted against the deviations of the temperature.

An estimate of the accuracy of the monthly averages of T_{eff} has been made on the basis of the differences between the values of T_{eff} obtained from measurements at the three stations, Rome, Buffalo, and Hempstead. On this basis, the rms error in the values of T_{eff} for single months, using the data of a single station, is is 0.58°C, and the expected rms error in the weighted average of the three stations is 0.35°C. The deviations included in this computation arise not only from errors of measurement during the balloon flights, but from sampling different days of the month at the different stations, and from real variations of temperature over the distance (about 350 miles) between the most distant stations. All of these factors enter also into the possible error in the assumed temperatures of

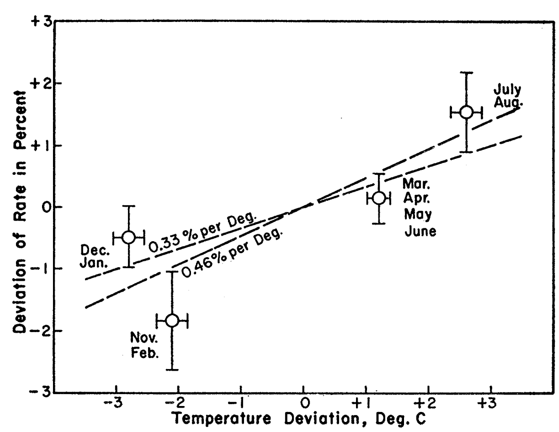

FIG. 1. Percent deviations of average counting rates from the over-all mean, as a function of the deviations of effective atmospheric temperature. The line drawn with a slope of 0.33 percent per degree is the least squares solution for these data; the line drawn at 0.46 percent per degree represents the result of combining the present data with a previous measurement.

the atmosphere over the salt mine. Because of the central location of the mine between the weather stations, the estimate of 0.35°C. for the rms error in $T_{\rm eff}$ is probably generous. Inclusion of this in the error calculation raises the standard error in α by only four percent.

The subtraction of accidental coincidences leads to another small increase of the statistical error in α, namely, by a factor 1.03. With these considerations, the result of the analysis based on the seasonal temperature variation is given as $\alpha=0.33\pm0.13$ percent per degree.

A test for the existence of deviations due to other causes than random statistical fluctuations and the temperature effect is given by the sum of the squares of the residual deviations relative to their statistical standard errors. Excluding the one entry discussed above, the 29 remaining entries in Table I yield 28 for the sum, in good agreement with the expected value 26 ± 7. This agreement suggests that the deviations not due to the simple statistical errors are comparatively small.

The above discussion relates entirely to the determination of α based on the seasonal temperature variation. In addition, the following method, based on short-term fluctuations, was applied. Each time there was a successful balloon flight reaching at least the 30 millibar level, the temperature measurement was assumed to be correct for a six-hour interval centered about the time of the balloon flight; and the numbers of counts recorded in that period were tabulated. The data for such periods were arranged in time sequence, and α was computed from the relation $\alpha=\sum(\Delta n\Delta T)/\sum(\langle n\rangle_{\rm Av}\Delta T^2)$, where Δn is the difference between the numbers of counts recorded in two successive periods, and ΔT the corresponding difference in temperature.

In this method of analysis, the seasonal variation of temperature has practically no effect; and a slow drift of the efficiency of the apparatus or the resolving time for chance coincidences is of no importance. However, the periods were such as to include only 45 percent of all the coincidences that were usable in the analysis of the seasonal temperature effect; and the rms temperature variation between successive intervals was smaller than the seasonal temperature variation; hence the statistical error obtained by the use of short-term fluctuations is comparatively large.

The result obtained by this method is $\alpha=0.42\pm0.46$ percent per deg C. This determination would not be significant in itself, but by agreeing well with the result of the first analysis it adds a little weight to the latter.

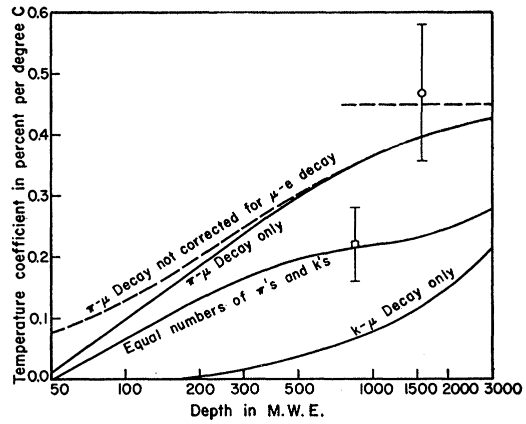

FIG. 2. Temperature coefficients measured at 1574 m.w.e. and 846 m.w.e. (Sherman, reference 2), compared with predicted variations of the coefficient with depth, calculated under different assumptions as to the mode of origin of the mesons (see reference 1).

There have thus been three independent measurements of the temperature coefficient at 1574 m.w.e.: the results being 0.79 ± 0.20,[1] 0.33 ± 0.13, and 0.42 ± 0.46 percent per deg C. The weighted average of these is: $\alpha=0.46\pm0.11$ percent per degree. This value is represented in Fig. 2 along with calculated curves of α *vs* depth underground, taken from reference 1. Also shown on the graph is the point obtained by Sherman[2] at 846 m.w.e.

It may be observed that the measurements at 846 and 1574 m.w.e. are in reasonable agreement with each other, considering the standard errors; and that both could be consistent with μ mesons of high energy ($3\times10^{11}-10^{12}$ ev) being generated only by decay of π mesons. They could also be consistent with generation by $\pi-\mu$ and $\kappa-\mu$ decay involving roughly equal numbers of π's and κ's; but not with an origin entirely by $\kappa-\mu$ decay unless the lifetime assumed for this process (2×10^{-9} sec) was too short. The uncertainty of the parameters of the $\kappa-\mu$ decay process at the present time must be emphasized, however; and the only definite conclusion that can yet be drawn from these experiments is that production of μ mesons of $\sim10^{12}$ ev still involves a decay process as it does at lower energy, the average ratio of lifetime to mass of the parent particles being not very different from that of the π meson.