number of observers who find values varying over a factor of two depending on the method of observation.

The work described here was carried out on the grounds of the Climax Molybdenum Company at Fremont Pass in Colorado. The generous cooperation of Mr. C. J. Abrams, General Manager, and other personnel of the company is recognized. Important contributions to the research have also been made by Mr. Don Eng, Electronic Technician, and Mr. Elmer Wright, Instrument Maker, of our staff.

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The Relative Intensity of Cosmic Rays at Sea Level at Geomagnetic Latitudes 56.8 and 83.0

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During the summer of 1950 two cosmic-ray counter telescopes were exchanged between Ottawa (geomagnetic latitude 56.8°N) and Resolute (geomagnetic latitude 83.0°N) in such a way that an accurate comparison of vertical intensities could be made. The telescopes were operated under almost identical conditions for about three weeks; then they were exchanged, the Ottawa telescope being flown to Resolute and the equipment there returned to Ottawa. Corrections were made for barometer and differences in altitude by reducing all counting rates to that at 1000 mb pressure using known barometer coefficients. Corrections were made for differences in the atmospheric temperature by integrating numerically through the mean atmosphere at each station to get the probability of meson decay between production levels and the 1000-mb layer. When all corrections were made there remained a difference in intensity of 1.76 ± 0.75 percent. No difference would be expected with the absorbers used ($14\frac{1}{2}$ inches of lead) at latitudes so high above the "knee." Arguments are presented to show that the difference is probably due to mesons produced by a group of field sensitive primaries and scattered into the telescope. This group of primaries could come from directions with large zenith angles, which would be allowed at Resolute but excluded at Ottawa.

I. INTRODUCTION

During the summer of 1950 an opportunity arose to exchange counter trays in two sets of cosmic-ray measuring apparatus, one located at Ottawa (geomagnetic latitude 56.8°N) and the other at Resolute in the Canadian Arctic (geomagnetic latitude 83.0°N). This opportunity made possible a precise measurement of the relative intensity of vertical cosmic rays at the two stations. Corrections for atmospheric changes in intensity could be made fairly accurately since the barometer coefficients had been measured with similar apparatus at both stations. Upper atmosphere data were also available from weather stations of the Canadian Meteorological Service.

Since the discovery of the geomagnetic latitude effect many measurements have been made on the variation in intensity with latitude. The survey of Compton and Turner[1] shows the sea level latitude effect,—the so-called "knee" occurring at about 40° geomagnetic latitude. Variations in intensity at sea level at latitudes above the "knee" have been observed[2,3] but these are mostly considered to be due to differences in the mean atmospheric conditions at different latitudes. At all latitudes where the low energy cutoff due to absorption in the atmosphere, plus the absorbers in the instrument, is well above the low energy cutoff due to the geomagnetic field, the intensity would be expected to be constant except for small differences caused by different atmospheric conditions. Any effect due to a solar magnetic field seems unlikely since recent measurements by Pomerantz[4] and Dolbert and Elliot[5] show evidence against any appreciable influence of a solar magnetic field on cosmic rays.

With present knowledge of the structure of cosmic rays a reasonable estimate of the differences to be expected due to differences in the atmosphere can be made, at least for altitudes up to the mean levels of production of the μ-mesons which are observed at sea level. Residual differences in intensity between the two stations after all corrections have been made may then be assumed to be due to geomagnetic effects on the primary rays, or due to some phenomenon in the process of production of mesons (τ to π to μ, or π to μ).

II. APPARATUS

The apparatus was designed to study meteorological variations in intensity and to watch for phenomenal changes in intensity such as those associated with solar flares.[6] It was identical at both stations and consisted essentially of three counter trays in a vertical line with 6 inches of lead between Nos. 1 and 2 (No. 1 on top) and $8\frac{1}{2}$ inches of lead between Nos. 2 and 3. Number 3 had 4 inches of lead on the sides and ends and one inch

[1] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).
[2] Caro, Law, and Rathgeber, Australian J. Sci. **A1**, 261 (1948).
[3] P. F. Gast and D. H. Laughridge, Phys. Rev. **59**, 127 (1941).
[4] M. A. Pomerantz, Phys. Rev. **77**, 830 (1950).
[5] D. W. N. Dolbert and H. Elliot, Nature **165**, 353 (1950).
[6] D. C. Rose, Can. J. Phys. **29**, 227 (1951); and Phys. Rev. **78**, 181 (1950).

underneath. It rested on the floor near the ground. Each tray contained two brass counters in parallel one inch in diameter and about 16 inches effective length. The trays were connected in two double coincidence circuits, (1–2) and (1–3). Trays 1 and 3 were exchanged. Therefore, the results described here concern only the results from a double coincidence telescope (1–3) with $14\frac{1}{2}$ inches of lead between counters and 4 inches surrounding the bottom counter. In addition there was the second counter tray made of 16-gauge aluminum between counters 1 and 3. As this was identical at both stations the effect of the center tray has been neglected.

The roof over the apparatus was roughly the same at both stations, consisting of two layers of plywood with rock wool insulation. The outer roof covering at Resolute was of sheet aluminum (about 18 gauge); at Ottawa tar paper. In addition to the roof, the counters at Resolute were housed in a wooden box with a top consisting of about one inch of wood and one inch of cork. The difference in covering of the telescope at the two stations was approximately 4 grams per sq cm of low atomic weight material. An examination of the integral range spectrum of mesons indicates that this difference (4 g/cm^2) would mean about 0.35 percent change in integral intensity. The effect of the differences in the geometry of the roofs is a little uncertain. The error in this correction, however, can hardly be greater than ± 0.1 percent. The thickness of covering over the telescope at Resolute was greater than at Ottawa and, therefore, in comparing the relative intensities the Resolute value has been increased by 0.3 ± 0.1 percent relative to the Ottawa value. The temperature around the counter trays was maintained very close to 70°F at both stations since the counters are argon-alcohol filled.

The electronic equipment for amplification, pulse shaping, coincidence mixing, and recording was designed for reliability and continuous service. Its reliability has been well proved in several experiments. Therefore it will not be described here.

III. MEASUREMENTS AND CORRECTIONS

The exchange of counter trays took place in the following way. Two counter trays had been in use at Resolute for some months; another two were in use in Ottawa for about one month before the exchange. Early in July 1950 the two trays including their preamplifiers which had been in use at Ottawa were flown to Resolute and exchanged for the two trays there. The Resolute trays were put in use in Ottawa. It was found that the counter voltage at Resolute was slightly higher than that at Ottawa, but after the exchange the voltage used in Resolute was applied in Ottawa and the former Ottawa voltage applied in Resolute. Therefore, the conditions of operation were as identical as possible.

The periods covered in the analysis of results, and the mean counting rates, after correction for barometer variations only, are shown in Table I.

TABLE I. Mean counting rates, after correction for barometer variations only.

	Before exchange	Counts/min
Ottawa	June 19 to 29	4.389 ± 0.025
Resolute	June 16 to 30	4.528 ± 0.018
	After exchange	Counts/min
Ottawa	Aug. 29 to Sept. 11	4.370 ± 0.020
Resolute	Aug. 7 to 31	4.541 ± 0.017

Though the operation was continuous over these periods, all the data were not used. Selections were made of periods in which the barometer did not vary by more than two or at most three millibars in twelve hours or more. The number of such periods during the four intervals shown in Table I are, respectively, 6 and 9 before the exchange, and 9 and 8 after the exchange. The errors in Table I are standard deviations based on the total number of counts in each case. The first measurement at Ottawa is the least accurate,—the standard deviation being 0.57 percent. The others are below 0.5 percent.

The barometer coefficients for each station were known[7] and the mean counting rate over each of the above selected periods was corrected to a pressure of 1000 millibars. The mean pressure over the periods used at Resolute was 1011.0 mb and at Ottawa 1005.7 mb. The same barometer coefficient was used at both stations, namely, -2.06 percent per cm of mercury or -0.155 percent per mb. Actually the measurements[7] indicate a slightly higher coefficient at Resolute than at Ottawa but not enough to make a significant difference. Reducing all values to a pressure of 1000 mb should also correct for differences in altitude above sea level at the two stations as accurately as such a correction can be made. The actual difference in sea level was about 100 feet, the Ottawa station being higher.

The correction for temperature is much more difficult. Corrections for sea level temperature are known to be of no value; therefore a correction was made for the differences in the mean atmosphere. Unfortunately there is no radiosonde at the weather station in Ottawa. Radiosonde data for four stations surrounding Ottawa (Sault Ste. Marie, Michigan; Moosonee, Ontario; Buffalo, New York; Albany, New York) had been examined in connection with previous measurements and it seemed that the atmosphere over Sault Ste. Marie was on the average much like that over Ottawa. Sault Ste. Marie is due west of Ottawa and is usually in the same air mass. The twice daily radiosonde data for the selected periods was plotted and a mean curve drawn. This was taken as the mean atmosphere over Ottawa.

An estimate was then made of the integral intensity of μ-mesons at production by a process of numerical integration similar to that used previously.[7] The method consisted of calculating the probability of decay of the mesons during their flight from a mean production level

[7] D. C. Rose, Can. J. Phys. 29, 97 (1951).

TABLE II. Intensity comparison between Resolute and Ottawa.

Ratio of intensity (reduced to 1000-mb pressure) at Resolute to that at Ottawa	1.031 ±0.005
Correction factors to reduce intensity at Resolute to that at Ottawa, due to differences in:	
Mean atmosphere	0.986 ±0.004
Geometry of counter supports	0.998 ±0.002
Roof covering	1.003 ±0.001
Side showers	1.000 ±0.003
Corrected ratio of intensities	1.0176±0.0075

to the 1000-mb level. This was calculated for the Ottawa atmosphere for a series of values of momenta at the lower level. By applying these results to the sea level spectrum a spectrum at production levels was obtained. The sea level spectrum chosen was that of Wilson, as described by Rossi,[8] with some modifications at higher energies suggested by analyses of barometer coefficients. These modifications are explained in reference 7. The exact spectrum chosen is of little importance as long as it represents the facts approximately, because the atmosphere corrections were compared relatively at the two stations and, as the differences were small, absolute values could be considerably in error with little effect on the comparison. The production spectrum was then integrated numerically from a point corresponding to an energy of about 500 Mev (actually a momentum of 600 Mev/c) at sea level up to a value beyond which the integral became negligible. This process was repeated for the mean atmosphere over Resolute during the periods selected for use there. Since Resolute has a radiosonde station the atmosphere there was more accuratley known. The sea level spectrum at Resolute was assumed to be the same as at Ottawa. Preliminary results from later measurements of the spectrum at both stations indicate that it is substantially the same. 500 Mev at sea level was used for the lower limit of integration because the lead absorbers and roof over the counters fix the lowest energy accepted by the telescope very close to this value. It might have been more precise to assume a production spectrum and calculate the sea level integral spectrum at each station and compare their values, but as a comparison factor between the two is all that is required, the inverse process which was followed would have negligible effect on the results.

These calculations show that if the production intensity were the same at both stations the intensity at Resolute would be expected to be 1.014 times higher than that at Ottawa, this difference being due to atmospheric differences only. To reduce the Resolute intensity to that at Ottawa, the correction factor is the reciprocal of the above figure, namely, 0.986. The accuracy of this figure is difficult to assess. Errors due to the constants used in the integration are likely to be small but the calculation is subject to the criticism that the mean atmosphere over Sault Ste. Marie is not necessarily identical with that at Ottawa. The differences would, however, be small compared to the differences between Sault Ste. Marie and Resolute. Therefore, an error of ±0.004 has been assumed.

Differences due to the different roofs over the equipment have already been considered but the results should also be corrected for slight differences in the geometry of the racks supporting the counters at the two stations and for any differences that there may be in side showers. The actual number of side showers for two counter telescopes is difficult to assess but two different arrangements of counter telescopes in triple coincidence with identical shielding around the bottom counter tray to that described here have been used at both stations. The results indicate that the side shower correction for these two counter telescopes would be approximately 1.6±0.3 percent and that the differences in the side shower correction at the two stations is not significant. Therefore, in the ratio between the intensities no correction was made for side showers but a statistical error due to this standard deviation was included. The final difference in intensity with all corrections is shown in Table II.

There remains, therefore, 1.76±0.75 percent difference between the intensity at Resolute and at Ottawa. The errors in Table II are liberally estimated. Where they are obtained from counting rates they are standard deviations. In the other cases they are considered to be the maximum possible error. However, the final error of the product is calculated as though the error in each factor were a standard deviation.

IV. DISCUSSION OF RESULTS

The final difference in intensity in Table II seemed too great to be discarded as insignificant and the consideration of possible contributing factors to this difference in intensity is interesting. The minimum energy with which primary rays can reach the earth in a vertical direction at different latitudes has been calculated by Vallarta.[9] These calculations and others have been summarized by Alpher[10] and Fig. 1 has been drawn from data obtained from Fig. 4 of reference 10. At the latitude of Ottawa the cutoff is about 0.7 Bev for protons and somewhat lower per nucleon for heavier primary particles. In the production of mesons or other secondary particles in the range of energies with which these measurements are concerned the energy per nucleon seems to be the critical factor, though the actual cut-off energy for a heavy nucleus might be much higher. The particles which were counted in the present measurements must have had sufficient energy to penetrate 418 grams per cm^2 of lead plus about 4 grams per cm of lighter material, a minimum energy of about 510 Mev. The energy loss for a meson going through the atmosphere from a mean production level to sea level is about 1900 Mev. The minimum energy which we are accepting is therefore 2410 Mev.

[8] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

[9] M. S. Vallarta, Phys. Rev. **74**, 1837 (1948).

[10] R. A. Alpher, J. Geophys. Research **55**, 437 (1950).

In order to reach the mean layer of production the primary particle, on the average, would have penetrated about 100 grams per cm^2 of air. Such a primary proton would have lost approximately 200 Mev of energy in reaching this level. Therefore, the primary particle must have had an energy of at least 2610 Mev when it reached the earth's atmosphere in order to produce the lowest energy particle observed. As this energy is much higher than the geomagnetic cutoff at the lower latitude (Ottawa) differences in intensity at the two stations due to geomagnetic effects would not be expected. The solid curve in Fig. 1 shows the cut-off energy based on the Stormer cone and the shadow cone. Vallarta[9] has also made some calculations on the cutoff due to the "penumbra" or the region between fully allowed and completely forbidden trajectories. His calculations indicate that the penumbra region at latitudes as high as Ottawa is mostly light. Therefore, it can be neglected. Actual calculations have not been made above about 40° latitude.

The two points marked in Fig. 1 represent the latitude of Ottawa and Resolute and are at the energy level of 2610 Mev. One sees that they are both well above the solid line for protons but if the broken line representing the limit of the penumbra were extrapolated to higher latitudes it might well be above the Ottawa point but not above that for Resolute. The difference in intensity between Resolute and Ottawa could therefore be explained simply if the penumbra at the Ottawa latitude were not entirely negligible. A calculation of its effect for this latitude is quite beyond the scope of this paper.

The effect of longitude can be ruled out. The two stations were at different geomagnetic longitudes but are not very different in geographic longitude (Ottawa 76°W and Resolute 95°W). Vallarta[9] has plotted corrections for the curves in Fig. 1 showing both the change in minimum energy and in the angle of the geomagnetic vertical due to longitude effects. His calculations extend only to 40° latitude but both corrections are much too small to affect the present results and no longitude effect would be expected where the minimum accepted energy fixed by absorbers is so much higher than that due to the geomagnetic field.

There are other contributing factors which should be discussed. The telescope was asymmetrical. The half-angle at right angles to the plane of the counters was about 5° and in that plane about 35°. The counter trays were aligned in the vertical direction with sufficient accuracy to be sure that any deviation from the vertical would make a negligible difference between the two stations. As the angular spread is large compared to the deflection of mesons in the earth's field during their path from production levels any asymmetry such as that calculated by Johnston[11] due to this deflection would be negligible.

[11] T. H. Johnston, Phys. Rev. **59**, 11 (1941).

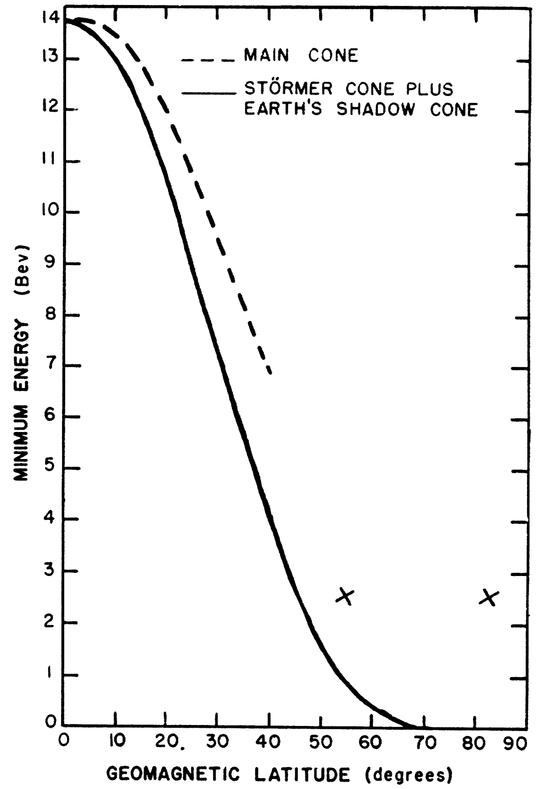

FIG. 1. Minimum allowed energy of arrival for vertical cosmic-ray protons.

An examination of the curves published by Alpher[10] shows that at high zenith angles the minimum energy allowed by the earth's field rises rapidly for particles coming into that field from an easterly direction. The minimum energy accepted after passage through the atmosphere and absorbers must vary roughly inversely as the cosine of the zenith angle. Alpher's curves show that at zenith angles above about 50° the minimum allowed energy of particles coming from easterly directions rises rapidly and at 60° it is of the order of 10 Bev, while remaining quite low from the west. At any angle included in the telescope the absorber (atmosphere plus lead) fixes a minimum energy which is well above that due to the geomagnetic cutoff but particles could enter the telescope from nuclear collisions in the upper atmosphere caused by primaries which have much larger zenith angles. For zenith angles in the neighborhood of 60° and higher there will be a group of primary rays with energies in regions from 5 to 25 Bev (depending on the angle) which if coming from the east (or north at the larger zenith angles) will be excluded at Ottawa and allowed at Resolute. Secondary mesons from these might have a zenith angle less than 35° and so be included in the telescope at Resolute and excluded at Ottawa. The direction of the widest aperture of the telescope at Ottawa happened to be NE–SW, a direction in which this exclusion would be expected to be appreciable. The direction at Resolute should not be of any importance. Actually it was slightly west of north.

An accurate calculation of the effect of these particles which move with large angles with respect to the primary which produces them is hardly possible but from the measurements of the angular distribution of energetic particles found in stars[12] in photographic plates and geometric considerations a rough estimate of the order of magnitude could be made. The estimate indicates that the effect at Ottawa is probably not negligible and might be as high as 1 percent.

If this effect is real the same telescope at Ottawa should show a variation in intensity when rotated from a NS to an EW direction. To check this the telescope was reassembled as nearly as possible under the same conditions as for the comparison measurements, but mounted on a turntable. It was rotated periodically from a NS to an EW direction and continuous records taken. Actually triple coincidences between the three counter trays were observed instead of doubles as previously. The NS–EW asymmetry was calculated from the four-hour averages before and after each time the telescope was rotated. Barometer corrections were made if the barometer changed appreciably during the eight-hour period. It was found that the asymmetry was 0.8 ± 1.4 percent. Double coincidence records were also taken between the top counter tray and the center tray with 6 inches of lead between trays and no other absorber surrounding either. The half angular widths of the telescope in this case would be about 60° in the direction in the plane of the counters and about 10° at right angles to this. This asymmetry was found to be -0.4 ± 0.4 percent. A positive asymmetry is inferred when the NS direction gives a greater intensity than the EW. For very large zenith angles the maximum asymmetry should be expected to be almost in a NE–SW direction. Therefore, for the largest zenith angles, the asymmetry between NS and EW might be expected to be small and these results, though not very satisfactory, are not necessarily inconsistent. Preliminary results from another investigation in this laboratory on NS and EW asymmetry using tilted telescopes indicate that the asymmetry seems to vary from time to time perhaps being influenced by disturbances in the geomagnetic field. A portion of the above asymmetry results was taken during a magnetic disturbance.

While these asymmetry results with a vertical telescope are not entirely satisfactory they do indicate that at least a portion of the difference in intensity between Ottawa and Resolute may be attributed to the angular distribution of mesons with respect to the direction of primary particles, and the fact that for large zenith angles the geomagnetic effect extends to high latitudes. Another factor that would contribute to the observed differences in intensity, if it were appreciable, is the possibility of a meson penetrating the telescope, having been produced by a primary of energy below cutoff due to absorption but reaching the telescope without appreciable loss of energy in the atmosphere. Such a particle would have to be tertiary, the intermediate particle being neutral. The probability of this happening seems very remote as the minimum energy accepted by the telescope is about 500 Mev. The geomagnetic cutoff at Ottawa is about 700 Mev for protons at vertical incidence. The number of occasions must be very small where a primary nucleon with around 700 Mev of energy will give nearly all of its energy to a neutral particle, the neutral particle would then penetrate the complete atmosphere without decay or another collision until reaching a position just above the telescope where another collision would produce some particle like a meson with enough energy to penetrate the telescope.

[12] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **40**, 862 (1949).

V. CONCLUSIONS AND SUMMARY

Measurements with a vertical counter telescope exchanged between Ottawa (geomagnetic latitude 56.8°) and Resolute in the Canadian Arctic (geomagnetic latitude 83.0°) indicate that after meteorological and local geometrical corrections have been made the intensity at Resolute is 1.76 ± 0.75 percent higher than at Ottawa. The absorbers in each telescope were $14\frac{1}{2}$ inches of lead plus about 4 grams per cc of light material. The meteorological corrections were made first by reducing the intensity during each period of observation to that at a pressure of 1000 mb by using known barometer coefficients. Then an integration was made over the mean atmosphere to correct for differences in the probability of meson decay in flight from a mean production level to the 1000-mb level. The residual difference in intensity is considered to be greater than can be accounted for by different atmospheric conditions. The conditions were such that no difference would be expected due to geomagnetic effects at any angles included by the telescope.

Other phenomena may contribute to the difference in intensity. These are (*i*) the penumbra in the theory of the geomagnetic effect, (*ii*) the effect of mesons produced by field sensitive primaries, the primary having directions not included in the telescope, the meson however coming from a direction from which it may enter the telescope, (*iii*) the possibility of particles being observed in the telescope being from a second collision, the intermediate particle being neutral.

Vallarta considers the penumbra at Ottawa latitudes to be mostly light though whether it is completely negligible is uncertain and calculations are very difficult. Calculations and a subsidiary experiment indicates that the second contributory effect mentioned above is probably dominant in accounting for the difference in intensity. The third is almost certainly negligible.