Primary Cosmic-Ray Alpha Particles and Protons at $\lambda = 55°N$

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The intensities of the primary cosmic-ray alpha particles and protons at geomagnetic latitude 55°N are determined from measurements of the ionization and range of the charged cosmic-ray particles observed at atmospheric depths of 8 g/cm² and deeper. The measurements were made with a balloon-borne Geiger-proportional counter telescope which contained absorbers of mercury or lead. Showers of particles in the telescope were detected by out of line counters and eliminated. The particles having residual ranges between 1.5 g/cm² and 43 g/cm² are shown to be secondary electrons and secondary protons. The penetrating particles having range greater than 43 g/cm² divide into singly and doubly charged particles. Extension of the penetrating particle intensity curves to zero depth yields values for the primary intensities of 0.19 (cm² sec sterad)$^{-1}$ for protons and 0.032 (cm² sec sterad)$^{-1}$ for alpha particles. The alpha particles are absorbed exponentially in the atmosphere and the slope of the absorption curve yields the value 35 ± 7 g/cm² for their mean free path in air. Data obtained by removing the absorbers in flight indicate that the net results are free of shower effects. Other systematic uncertainties in the values of the primary intensities are estimated to be $\pm10\%$, which is larger than the statistical uncertainties.

INTRODUCTION

THIS paper is a report of measurements of the intensities of primary cosmic-ray protons and alpha particles at geomagnetic latitude 55°N. The measurements were made with a balloon-borne counter arrangement similar to the one used by Perlow, Davis, Kissinger, and Shipman[1] in a rocket flown at 41°N. Proportional counters and absorbers were used to measure the specific ionization and range of particles selected by a Geiger counter telescope. Low-energy secondary particles could be identified by their limited range and eliminated, and the primary protons and alpha particles could be resolved by the difference in their specific ionization. Out of line counters were included to determine corrections for showers.

The results are based on two flights, made September 16, 1952 and October 20, 1952, using "Skyhook"-type plastic balloons that reached maximum altitudes corresponding to 20 g/cm² and 8 g/cm², respectively. The principal results are the primary intensities of alpha particles and protons which are obtained by extrapolating the measured intensities to zero depth. The data also allow a determination of the mean free path in air of the primary alpha particles and the intensities of secondary electrons and secondary protons down to depths of 500 g/cm² and 300 g/cm², respectively.

I. APPARATUS

The counter-absorber arrangement used in the experiment is shown in Fig. 1. A telescope formed by Geiger counter trays A, B, and C selected charged particles which passed through proportional counters P_1, P_2, and P_3. The proportional counters were used to measure the specific ionization of each selected particle. Counter trays D and E and absorbers 1 and 2, which covered the solid angle below the telescope, were used to separate the particles into three ranges. The six out of line counters S were paralleled to form a shower detection tray.

The block diagram of Fig. 2 shows the system used to analyze the counter data. Four Rossi-type coincidence circuits determined when the coincidences ABC, $ABCD$, $ABCE$, and $SABC$ occurred. Amplifiers P_1, P_2, and P_3 amplified the proportional counter pulses about 1000 times and shaped the pulses so that they peaked in 8 μsec. The amplified pulses were applied to the inputs of a threefold diode coincidence circuit[2] which selected the smallest pulse. Each ABC pulse intensified a cathode-ray tube for 20 μsec. During this time the selected proportional counter pulse was displayed as a vertical trace on the cathode-ray tube. Coincidence pulses $ABCD$ and $ABCE$ were shaped into pulses of different size and opposite polarity, mixed, delayed 15 μsec, and displayed as horizontal deflections of the

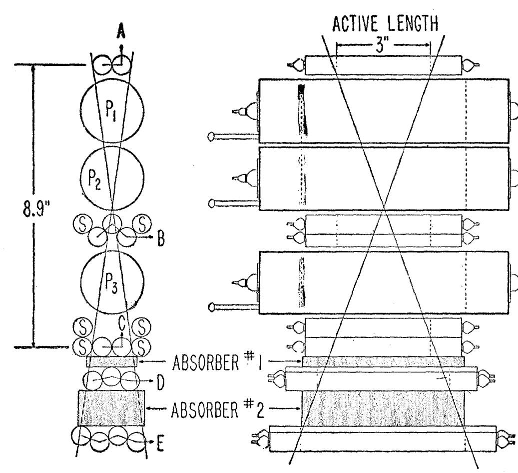

FIG. 1. The counter-absorber arrangement.

[1] Perlow, Davis, Kissinger, and Shipman, Phys. Rev. 88, 321 (1952).

[2] C. Y. Johnson, Naval Research Laboratory Report No. 4432, 1954 (unpublished).

return trace. In this way coincidence-anticoincidence combinations involving ABC, D, E, and the selected proportional counter pulse were formed with resolving times of about 7 μsec. Coincidence $SABC$ was indicated by flashing a neon bulb. The cathode-ray tube and the neon bulb were photographed continuously on 35-mm film. Coincidences between the traces and $SABC$ light could be formed on the film with a resolving time of about 0.2 sec.

The proportional counter tubes were 2 in. in diameter and had walls of 20-mil aluminum which were plated inside with a layer of copper. They were permanently joined by copper tubing to maintain a common gas mixture. The gas was an argon—2% CO_2 mixture at slightly more than atmospheric pressure. The center wires were 0.003 in. tungsten. At the operating potential of 1970 volts the gas multiplication was 2000. The Geiger counters were filled with 27 cm Hg of argon and 1.2 cm Hg of isobutane. Their plateaus extended from about 1000 volts to over 1400 volts and had a slope of less than 5% per hundred volts. The active lengths of the Geiger counters were determined by glass skirts placed inside the counters. In the A, B, C, and S counters these skirts were spaced 3.0 in. apart. The walls of these four counter sets were 4-mil stainless steel. All of the Geiger counters had 0.59 in. inside diameters.

The apparatus was housed in a pressurized cylindrical gondola made of $\frac{1}{32}$-in. sheet aluminum. The telescope was mounted vertically in the upper end of the gondola and no other equipment was placed above the level of the absorbers.

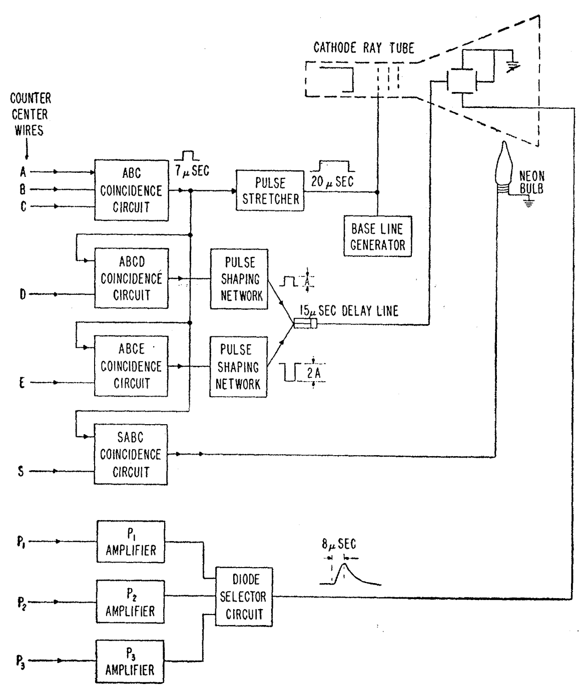

FIG. 2. Block diagram of the balloon-borne electronics.

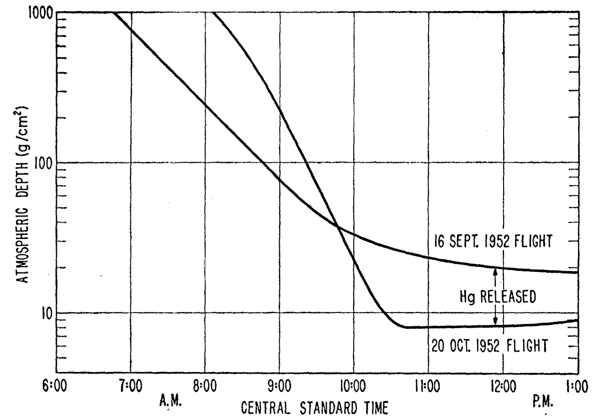

FIG. 3. Atmospheric depth-time curves for the two balloon flights.

The counter walls and the gondola skin set a lower range limit of 1.5 g/cm² for particles incident from above. This material was mostly aluminum (1.1 g/cm² Al and 0.4 g/cm² Fe). The next range limit was determined by the gondola skin, the counter walls, and the first absorber, which was 9.5 g/cm² of lead on the September 16 flight and of mercury on the flight of October 20. The second absorber was 32.0 g/cm² of mercury on both flights. Thus the coincidence-anticoincidence combinations ABC-(DES), $ABCD$-(ES), and $ABCDE$-(S) correspond to particles having residual ranges between 1.5 and 11 g/cm², 11 and 43 g/cm² and greater than 43 g/cm², respectively.

On both flights attempts were made to determine the effects of showers generated in the absorbers on the telescope counting rates. Tanks of mercury were used as absorbers and an alarm clock was arranged to unclamp a rubber hose at a preset time, allowing the mercury to drain into a bottle below the telescope. The clock released about one hour after the balloons had reached their peak altitudes and a little over one hour of data was obtained with the mercury removed. The shower effect was determined by comparing the telescope counting rates before and after the mercury was removed.

The previous paper[1] noted the advantage of making several ionization measurements on each particle and selecting the smallest. Briefly it is effective in reducing the fluctuations in ionization associated with knock-on electrons. In the previous experiment the pulse from each proportional counter was amplified and recorded, and the smallest pulse then selected. In the present experiment the pulses were separately amplified, the selection done electrically and only the selected pulse recorded. In order that the selected pulse correspond to the smallest ionization or energy loss in the counters, the amplifiers were adjusted to give, on the average, equal height pulses when the counters were exposed to the 10.5-kev x-rays from a Se^{75} source.[3] Calibrations,

[3] P. Rothwell and D. West, Proc. Phys. Soc. (London) **A63**, 541 (1950).

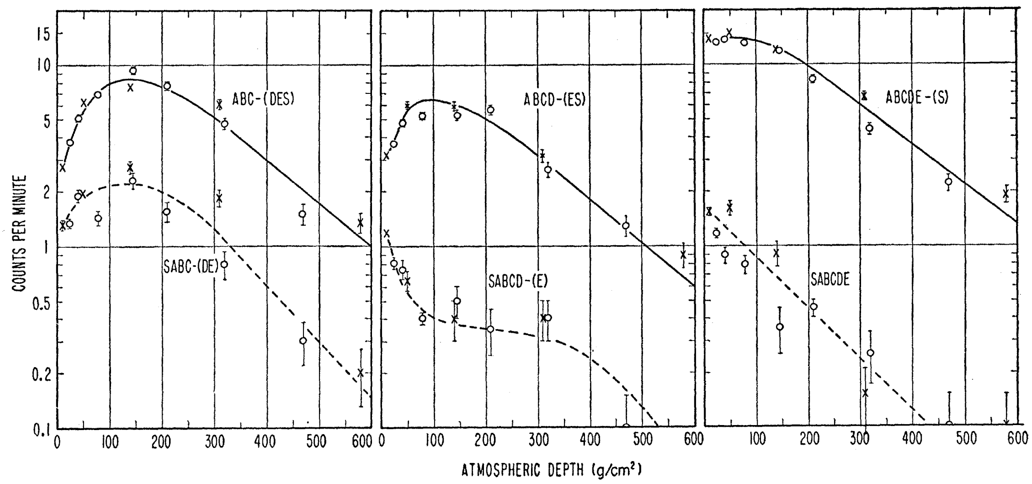

FIG. 4. Counting rates of the telescope events divided according to residual range; 1.5 g/cm^2 to 11 g/cm^2, 11 g/cm^2 to 43 g/cm^2, and greater than 43 g/cm^2. The solid curves are for the events detected as single particles. The dotted curves are for the events detected as showers.

made both before and after the flights, show that this adjustment was maintained to within $\pm 5\%$.

The ionization system was calibrated using the sea-level hard component. A pulse-height distribution of ground data is shown by the dashed line in the bottom of Fig. 5. We assume that the pulse height at which the distribution peaks corresponds to $I_{\min}$, the minimum most probable ionization of singly charged particles.

The area-solid angle product of the telescope (geometrical factor) was accurately determined by comparing the telescope counting rate on the ground with that of a large test telescope. The value so determined is 1.01 cm^2-sterad corrected to correspond to the case of an isotropic flux of particles incident from above. We estimate that the geometry of the test telescope is known to within $\pm 5\%$. Sufficient counts were obtained to reduce the statistical uncertainty in the counting rate ratio to $\pm 1\%$. It should be noted that the same telescope was used on both flights, only the absorbers were changed.

Atmospheric pressure, time, and gondola temperature were recorded by periodically illuminating a large bore mercury manometer, a watch, and a thermometer which were viewed by the 35-mm camera. The temperature changes that occurred on the flights were about 10°F. The manometer furnished data above 40 000 feet, for lower altitudes the readings of the meteorological type radio sonde were used. The errors in the pressures are estimated not to exceed $\pm 5\%$.

Figure 3 shows the atmospheric depth-time curves of the two flights. The slower decrease in depth (slower ascent) on the September 16 flight was a result of the balloon being ripped in launching. Because of this, somewhat more statistically significant data were obtained during the ascent of this flight than on the flight of October 20.

II. EXPERIMENTAL RESULTS

Counting rates for each type event are shown in Fig. 4 as a function of atmospheric depth. The *ABC-(DES)* and *ABCD-(ES)* curves show the intensity variation of particles in the soft component having residual ranges in the intervals 1.5 to 11 g/cm^2 and 11 to 43 g/cm^2, respectively. The *ABCDE-(S)* curve shows the intensity variation of the penetrating component, particles of range greater than 43 g/cm.^{2} The *SABC-(DE)*, *SABCD-(E)*, and *SABCDE* curves are the counting rates of the shower events. The data for the September 16 flight are shown as circles and the data for the October 20 flight are shown as crosses. The errors indicated by the vertical bars are the statistical probable deviations. From the figure it can be seen that there is good agreement between the results of the two flights.

Ionization distributions for each type event are shown in Fig. 5 for one hour of October 20 data at 8 g/cm^2 depth. The data is shown on a semilog plot so that distributions of monoenergetic particle groups of different most probable ionization will have about the same form and width.[4] The histogram of ground data is dashed in to show the form and width of a group known to ionize approximately as a monoenergetic group. The first interval in each histogram shows the number of events that recorded with ionization less than 0.25 $I_{\min}$, most of which are "zero" events. These events would occur when any one of the proportional counters was missed and are presumably due to showers even in the cases where there were no counts in the *S* tray. Calculated intervals in which the value of the most probable ionization must lie for particles in each range interval are shown for electrons (e), μ-mesons (μ), protons (P), and alpha particles (α). The *ABCDE-(S)*

[4] L. Landau, J. Phys. (U.S.S.R.) 8, 201 (1944).

histogram has a singly charged particle peak at I_{min} and a reasonably well-resolved alpha-particle peak at 4 I_{min}. The width of the singly charged particle peak is little if any wider than the ground data distribution showing that most of these particles ionized at the minimum rate. The *ABCD-(ES)* histogram has a peak that can be due to electrons or μ mesons and a proton peak. The *ABC-(DES)* histogram has an electron peak and a proton peak but no μ-meson peak.

Histograms similar to Fig. 5 for two samples of September 16 data are shown in Fig. 6, data at 20 to 26 g/cm², and Fig. 7, data at 80 to 270 g/cm². These figures show that the distributions changed significantly with increasing atmospheric depth, for example, in the *ABCDE-(S)* histogram of Fig. 7 there is no alpha-particle peak and the singly charged particle peak is wider than it was at 8 g/cm² (see Fig. 5). This widening of the singly charged particle peak shows that there is a fairly large intensity of secondary protons at this depth.

In using this data to compute particle intensities we have discarded the shower events. Experimental justification for this procedure is given in the section on shower events.

A. Penetrating Particles

Had the resolution of the ionization measurement been good enough the intensity of the penetrating

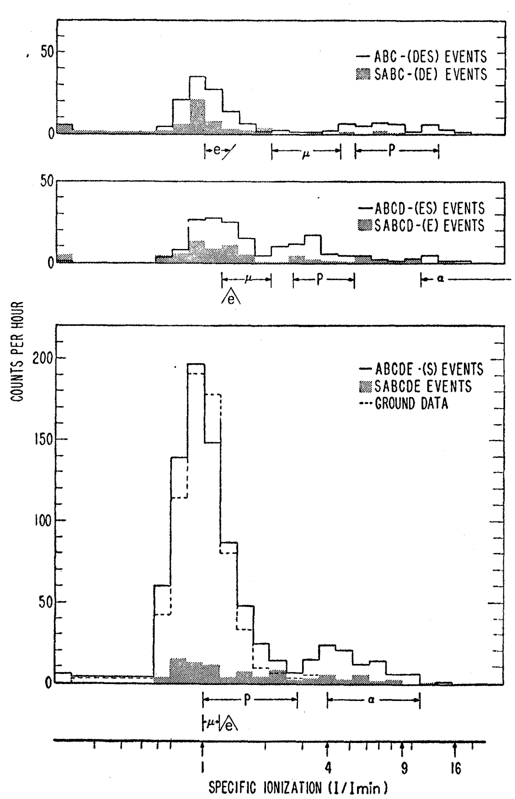

FIG. 5. Ionization distributions of data obtained at 8 g/cm² depth, 10:40 A.M. to 11:40 A.M. on October 20 flight.

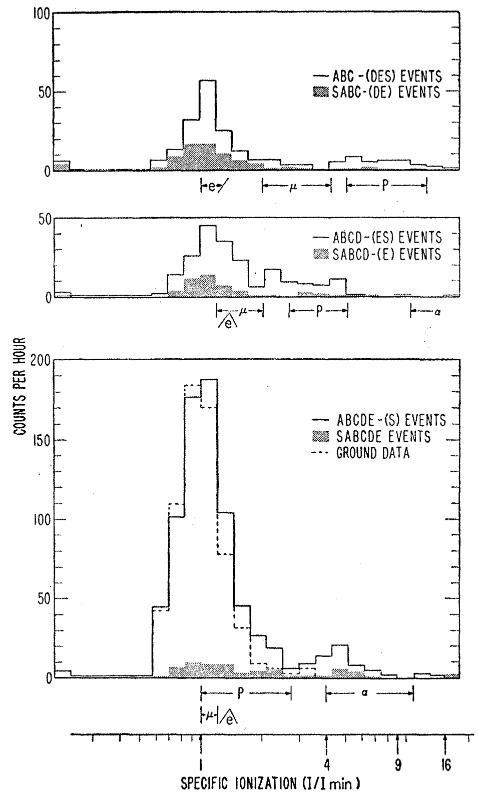

FIG. 6. Ionization distributions of data obtained at 20 g/cm² to 26 g/cm² depth, 10:40 A.M. to 11:40 A.M. on September 16 flight.

alpha particles and the penetrating singly charged particles could be obtained simply by counting the number in each peak. In our data the peaks are not completely resolved since, as the ground data distribution shows, the tail of the singly charged particle peak extends into the alpha particle peak. In the ground data 1.3% of the events recorded in the alpha particle region, i.e., with ionization greater than 2.5 I_{min}. We have estimated the number of singly and doubly charged particles by dividing the flight histograms at 2.5 I_{min} and then applying a correction for overlap equal to 1.3% of the events below 2.5 I_{min}. The resulting intensities are shown plotted as a function of atmospheric depth in Fig. 8 for alpha particles and Fig. 9 for singly charged particles. In the case of the alpha particles the corrections reduced the intensities by an amount approximately equal to the statistical uncertainties which are shown in the figure. The corrections increased the singly charged particle intensities and never amounted to more than half the corresponding statistical uncertainty.

It is known that the primary cosmic-ray particles are protons, alpha particles, and heavier nuclei and that at depths as small as those reached on our flights these penetrating particles reflect the properties of the primary radiation. The accuracy with which our measurements can be related to the primary intensities is

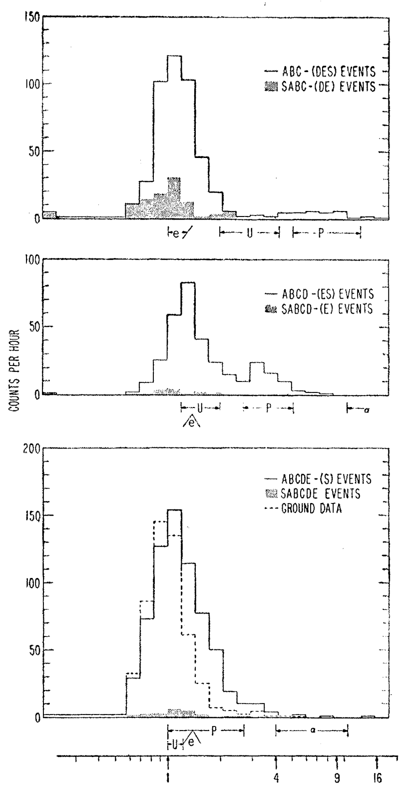

FIG. 7. Ionization distributions of data obtained at 80 g/cm² to 270 g/cm² depth, 8:00 A.M. to 9:00 A.M. on the flight of September 16.

governed by a number of factors of which the following are important: (1) While most of the primaries will penetrate to 8 g/cm² depth without colliding with air nuclei the fraction colliding is large enough to require a correction. The mean free path in air of the primary protons is known to be at least 70 g/cm² (geometrical) and Bradt and Peters[5] have given an empirical formula that predicts a value of 45 g/cm² for primary alpha particles. According to these values, 9% of the protons and 20% of the alpha particles would interact before reaching 8 g/cm² depth. As will be shown, the present data allow a direct determination of the alpha-particle mean free path.

(2) Studies of primary cosmic-ray interactions in emulsions[6] show that secondary singly charged particles having sufficient energy to penetrate 43 g/cm² Hg are produced with an average multiplicity of roughly two. Assuming this same average multiplicity for the interactions in air, the intensity of the penetrating singly charged particles should initially increase with increasing atmospheric depth and at 8 g/cm² be roughly 9% greater than the primary intensity of protons.

(3) In the case of penetrating alpha particles just the opposite would be true, since studies of primary proton interactions in emulsions[7] show that penetrating alpha particles are produced rarely if at all, and since Peters[8] has shown that the fast alpha particles produced in the breakup of heavy cosmic-ray particles would amount to only a few percent of the primary alpha-particle intensity. Thus the alpha-particle intensity should vary as $I(X)=I(0)\exp(-X/\lambda_{\text{air}})$, where X is atmospheric depth, $I(0)$ is the primary alpha-particle intensity, and λ_{air} is their mean free path in air.

(4) Of the primary particles entering the telescope, about 30% of the alpha particles and 24% of the protons would interact in the absorbers. For these to record as penetrating events, at least one energetic charged secondary must penetrate the remaining absorber and strike the E-tray. Rough calculations based on emulsion[6] show that over $\frac{3}{4}$ of the primary protons interacting in the absorber would record as penetrating events and therefore that more than 94% of the primary protons recorded as penetrating events. While there are no data on secondaries produced in alpha-particle interactions, it seems reasonable to assume that more would be produced than in proton interactions and therefore that a similar high percentage of the primary alpha particles would record as penetrating events. Since the calculated percentage is a lower limit we assume that all primaries entering the telescope recorded as penetrating events.

We assume that the primary intensity of protons can be obtained from the penetrating singly charged particle data by simply extending the curve in Fig. 9 to zero

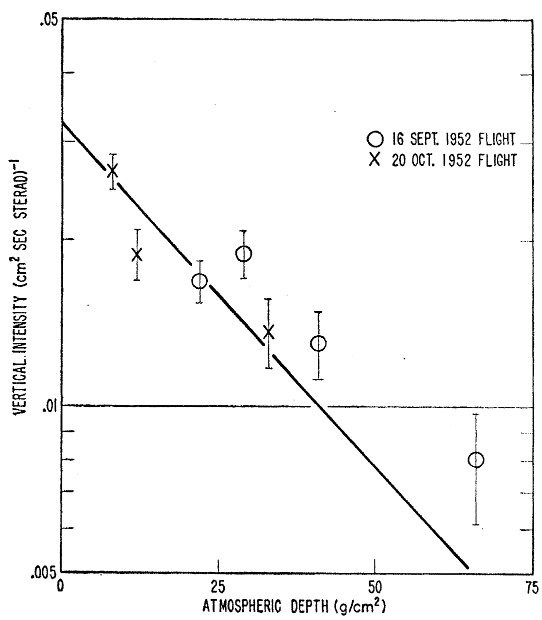

FIG. 8. Vertical intensity of alpha particles measured on the two flights.

[5] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1950).
[6] Camerini *et al.*, Phil. Mag. **42**, 1241 (1951).
[7] S. O. C. Sorenson, Phil. Mag. **42**, 188 (1951).
[8] B. Peters, *Progress in Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1952), Chap. 4.

depth. This yields the value 0.19 $(\text{cm}^2 \text{ sec sterad})^{-1}$ for primary intensity of protons with a statistical uncertainty of a few percent.

The measured intensities of the penetrating alpha particles shown in Fig. 8 are on a semilogarithmic plot. The straight line fitted to the experimental points can be represented by the equation $I(X) = 0.032e^{-X/35}$. Since agreement between this line and the experimental points is satisfactory, the data are in accord with (3). Therefore we adopt the value 0.032 $(\text{cm}^2 \text{ sec sterad})^{-1}$ for the primary intensity of alpha particles and the value 35 g/cm² for their mean free path in air. The statistical uncertainties for these values are $\pm 5\%$ and $\pm 20\%$, respectively.

The accuracies of these results are of course limited by a number of systematic uncertainties. The more important sources of these uncertainties appear to be the imperfect calibration of the telescope factor, the assumption that all primaries entering the telescope recorded as penetrating events, the incomplete resolution of the alpha particles, the extrapolation made in determining the primary intensity of protons, and the correction for shower effects. Excluding shower effects which are discussed below, the above discussions indicate that the resulting systematic uncertainties in the values of the primary intensities are about $\pm 10\%$ for both the protons and the alpha particles.

B. Soft Particles

The soft particles shown in the *ABC-(DES)* and *ABCD-(ES)* histograms can be divided into two groups, (1) electrons plus μ mesons and (2) secondary protons. Since μ mesons are not resolved in the *ABC-(DES)* histograms and since using Sands' μ-mesons momentum spectra[9] it can be shown that no more than a few percent

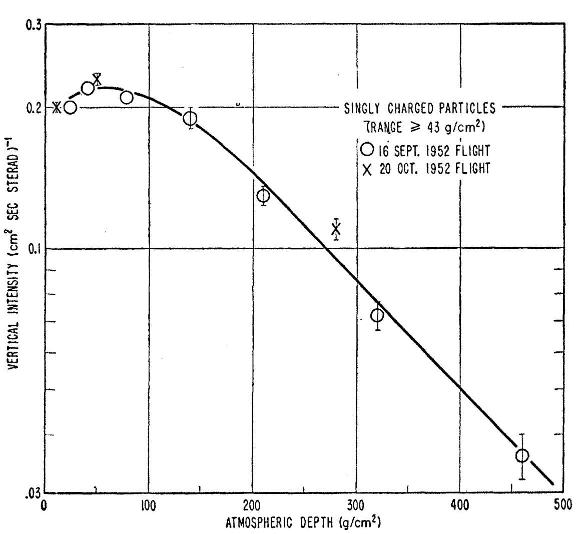

FIG. 9. Vertical intensity curve of singly charged particles having range greater than 43 g/cm².

[9] M. Sands, Phys. Rev. **77**, 180 (1950).

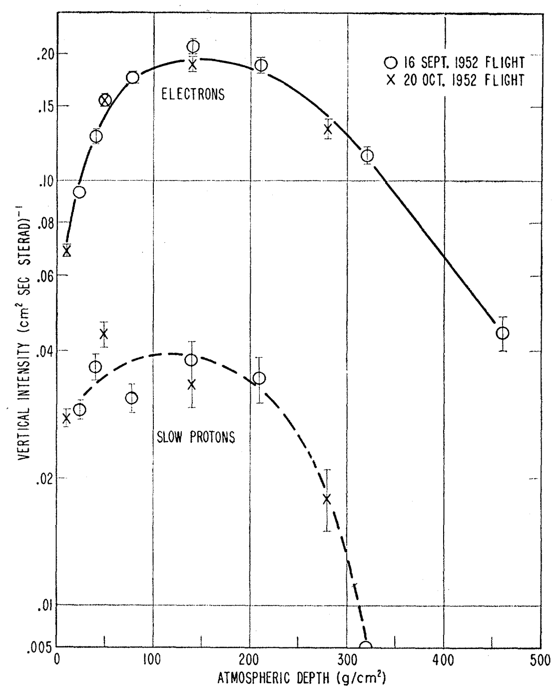

FIG. 10. Vertical intensity curves of secondary electrons and protons, range 1.5 g/cm² to 43 g/cm².

of either the *ABC-(DES)* or the *ABCD-(ES)* events are due to μ mesons, we assume that the events are all due to electrons and protons.

The computed intensities of the soft particles (range 1.5 to 43 g/cm²) are shown in Fig. 10, where the upper curve is for electrons and the lower curve is for protons. These intensities were computed without applying a correction for the overlap between the two peaks. However, the resulting errors should be small compared to the statistical uncertainties since (1) most of the electrons recorded as *ABC-(DES)* events and were completely resolved and (2) the number of *ABCD-(ES)* electrons does not greatly exceed the total number of soft protons.

C. Shower Events

The counting rates of the shower events are shown in Fig. 4 and ionization histograms of the shower events are shown in Figs. 5, 6, and 7. As may be seen in these figures, a fairly large fraction of the total counting rates is due to shower events, $\frac{1}{6}$ at 8 g/cm².

We have corrected for showers by simply discarding all the shower events. This reduced the intensities of primary protons and alpha particles by 9% and 20% respectively. It is possible that these corrections are too large since primary particles can pass through the telescope and produce secondaries that trigger the *S*-tray.

Auxiliary experiments were conducted on both flights near peak altitudes to determine the extent of shower production in the absorbers and to determine the effect

TABLE I. Counts recorded in the one-hour periods before and after the absorber was removed on the October 20 flight.

	Total number without shower counts			Total number with shower counts		
	$I<3\ I_{\min}$	$I>3\ I_{\min}$	Total	$I<3\ I_{\min}$	$I>3\ I_{\min}$	Total
Before	1011	189	1200	202	47	249
After	1017	182	1199	132	32	164

of the absorbers on the nonshower event counting rate. During the flight of October 20, all of the upper absorber and over 90% of the lower absorber was removed. The total nonshower events and total shower events recorded in one-hour periods before and after removal are tabulated in Table I. The table also lists the subtotals of events that recorded with ionization greater than and less than 3 $I_{\min}$. As may be seen, the number of shower events decreased by $\frac{1}{3}$ when the absorber was removed, showing that showers were generated in the absorbers. The most significant result to be noted is the absence of any significant change in the number of nonshower events, either in the totals or the subtotals. This result shows rather conclusively that the total particle intensity was unaffected by the presence of the absorbers. Since most of the nonshower events were either penetrating singly charged or doubly charged particles, this also strongly indicates that their intensities were unaffected, i.e., that few of the shower events were due to primary protons or alpha particles that passed through the telescope and produced showers in the absorbers.

On the September 16 flight, only the lower absorber was removed, and while the results cannot be simply interpreted they do not appear to contradict the conclusions drawn from the above data.

III. CONCLUSIONS

The primary intensities of protons and alpha particles at geomagnetic latitude 55°N have been determined by extrapolation from counter measurements of the intensities of penetrating singly and doubly charged particles down to 8 g/cm² depth. The primary intensities and the intensities measured at 8 g/cm² depth are summarized in Table II. The systematic uncertainties in the primary intensities are estimated to be ±10%. The statistical uncertainties are approximately the same as those shown for the measured intensities of penetrating singly and doubly charged particles, i.e., ±3% for protons and ±6% for alpha particles.

The mean free path in air of the primary alpha particles has been determined from the slope of the alpha-particle absorption curve. The resulting value, 35±7 g/cm², is somewhat lower than the value predicted by the empirical formula of Bradt and Peters,[3] i.e., 45 g/cm².

The present values of the alpha-particle intensity are to be compared with the value 0.028 $(\text{cm}^2\ \text{sec sterad})^{-1}$ measured at about 10 g/cm² by Ney and Thon[10] and the value 0.032±0.004 $(\text{cm}^2\ \text{sec sterad})^{-1}$ reported by Waddinton[11] who extrapolated his results to zero depth.

TABLE II. Summary of the vertical intensities of charged particles at geomagnetic latitude 55°N.

	Intensity[a]
Measured at 8 g/cm² atmospheric depth:	
Range ≥ 43 g/cm² Singly charged particles	0.206±0.005
Range ≥ 43 g/cm² Doubly charged particles	0.027±0.002
43 g/cm² > range ≥ 1.5 g/cm² Secondary protons	0.029±0.002
43 g/cm² > range ≥ 1.5 g/cm² Secondary electrons	0.060±0.003
Total intensity of particles having ranges ≥ 1.5 g/cm²	0.322±0.006
Extrapolated to zero depth:	
Primary protons	0.19
Primary alpha particles	0.032
Total primary intensity	0.22

[a] The intensities are in $(\text{cm}^2\ \text{sec sterad})^{-1}$, and the errors are the statistical standard deviations.

The primary proton intensity is the same as the value reported by Ney and Thon[10] and by Clark.[12]

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[10] E. P. Ney and D. M. Thon, Phys. Rev. **81**, 1069 (1951).
[11] C. J. Waddinton, Phil. Mag. **45**, 1312 (1954).
[12] M. A. Clark, Phys. Rev. **87**, 87 (1952).