Naval Unit, the Army Technical Section, and the General Electric Group, all of the White Sands Proving Ground. The Physical Science Laboratory of the New Mexico College of Agriculture and Mechanic Arts has carried a major share of the technical field work for the Aerobee in the conduct of preflight telemetering tests, flight telemetering, and in the reduction of tracking and telemetered data.

Within the Applied Physics Laboratory, we are particularly indebted to our director, Dr. R. E. Gibson, for continuing support; to Messrs. T. W. Sheppard, G. Melton, and R. O. Robinson of the Telemetering Group; to Mr. J. F. R. Floyd for assistance and advice with rocket problems; and to our immediate associates Messrs. L. W. Fraser, F. W. Loomis, R. O. Ostrander, R. J. McEvitt, and J. Vincent Smith.

This series of experiments was originally planned in conjunction with Dr. H. E. Tatel, now at the Department of Terrestrial Magnetism of the Carnegie Institution.

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The Properties of Cosmic Radiation at Very High Altitudes*

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The variation of the vertical cosmic-ray intensity as a function of altitude has been investigated in a series of free-balloon ascents with standardized quadruple-coincidence-counter trains containing various amounts of interposed absorber, to a maximum thickness of 7.5 cm Pb. The curves thus obtained converge at the "top of the atmosphere." A maximum occurs in the curve with 4 cm of Pb, but disappears with 6 cm of Pb. Cosmic-ray absorption curves at various altitudes above that corresponding to an atmospheric pressure of 250 mm of Hg are plotted from the data, as are integral and differential distributions-in-range. The relative stopping powers of carbon and lead are also available from the data.

Disturbing effects such as those arising from side showers and scattering appear to be negligible. An extrapolation procedure, which leads to results consistent with those of other experiments, provides a new picture of the composition of the cosmic rays in the atmosphere. With heavier particles ($P+M$) displaying a maximum intensity at a higher altitude than electrons (E), the conclusions drawn from the present investigation are compatible with a primary radiation consisting of protons (and possibly heavier nuclear particles) producing mesotrons which subsequently give rise to the electronic component.

Comparison of the results reported here with those of Schein and Allen indicate an absorption of primaries, by a process other than ionization, in thicknesses of Pb between 7.5 and 18 cm.

I. INTRODUCTION

ONE of the most widely used methods of investigating the nature and properties of cosmic-ray particles is based upon measurements of their absorption in matter. Although this technique has been pursued extensively near sea level, at great depths, and on mountain peaks, no experiments designed to obtain data of this type have been performed, even at altitudes accessible to aircraft. In the course of investigations of mesotron production, conducted by Schein, Wollan, and Groetzinger[1] in airplanes, and of the latitude effect of the penetrating component by Bhabha, Aiya, Hoteko, and Saxena,[2] and by Gill, Schein, and Yngve,[3] *intensity vs. altitude* curves have been determined with various counter arrangements embodying several different thicknesses of interposed lead. However, the authors do not regard the results as being

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* These investigations have been supported by the Office of Naval Research. Although the observations reported here were obtained at geomagnetic latitude 52°N, considerable experience in the techniques was obtained during The Joint National Geographic Society—Army Air Forces Eclipse Expedition to Bocaiuva, Brazil, during May, 1947.

[1] M. Schein, E. O. Wollan, and G. Groetzinger, Phys. Rev. **58**, 1027 (1940).

[2] Bhabha, Aiya, Hotenko, and Saxena, Phys. Rev. **68**, 147 (1945).

[3] P. S. Gill, M. Schein, and V. Yngve, Phys. Rev. **72**, 733 (1947).

amenable to the deduction of cosmic-ray absorption curves.

In free balloon ascents, Schein, Jesse, and Wollan[4] have obtained *intensity vs. altitude* curves for the cosmic rays capable of penetrating various large thicknesses of lead. Their published results appear to indicate equality of intensity from altitudes as low as that corresponding to 350 mm of Hg upward to 20 mm with 8 cm and 18 cm of Pb interposed in their counter trains. However, owing to statistical uncertainties at the lower altitudes and the variation of the geometrical arrangements with which the data were obtained, the authors attributed significance only to comparison at the very highest altitudes attained,[5] and regarded the close agreement there among the points for different lead thicknesses as constituting very strong evidence for the absence of primary electrons. Ehmert[6] has also measured the intensity of particles penetrating 9 cm of Pb, but the scatter of his points prevented him from drawing any conclusion other than one to the effect that there was a general constancy of intensity between 100 and 16 mm. Finally, using a shield of 10 cm of Pb, Dymond[7] conducted several flights, the results of which were not reported in detail. Only a general statement that a maximum of about nine times the sea-level intensity exists at 16 km was published.

A number of investigations of the variation with altitude of the total vertical cosmic-ray intensity have been reported previously.[8–10] The curves of Pfotzer,[11] obtained with a threefold coincidence counter arrangement, extended to altitudes of 10 mm.

In lieu of the desired data, quantitative comparisons frequently have been made of the results obtained by different investigators. This procedure could be subject to considerable error for several reasons. Principally, the geometrical differences introduce uncertainties in the method of reduction of the data to a common scale. In some instances, the curves have been fitted at high altitudes, in others at sea level. The change in the zenith angle distribution of intensity as a function of altitude, demonstrated by the experiments of Swann, Locher, and Danforth,[9] may vitiate comparisons based simply upon solid angle corrections, and the results obtained may depend upon the altitude at which the data are normalized. In some instances, where data are fitted near the top of the atmosphere, apparent agreement is attained merely as a consequence of the choice of scales, which are usually such as to mask the discrepancies at lower altitudes.

In principle, an idealized experiment whereby the desired ends might be realized is one in which a single apparatus with optimum geometrical arrangement is maintained at each of a number of high altitude stations for long periods of time. At each station various thicknesses of absorber would be interposed cyclically in the counter train, and the corresponding counting rates recorded. It is currently impossible to achieve this situation at altitudes exceeding those accessible to B-29 airplanes ($<40,000$ feet). However, the practical equivalent may be attained by sending aloft a number of identical instruments, each containing a different fixed thickness of absorber, and comparing the results. By utilizing standard sets, the counting rates of which are in agreement to within a rather small statistical uncertainty in both preflight and postflight runs, it is possible to compare counting rates directly without recourse to an arbitrary normalization.

II. EXPERIMENTAL PROCEDURE

A. Apparatus

Each individual apparatus contained a train of four G-M counters arranged to record vertical quadruple coincidences. The geometrical disposition of the counters was identical in all flights, which differed only in the amount of absorber interposed in the counter train.

The individual counters were 20 cm in length $\times 1$ cm in diameter. The problem of determining the average path length through a vertical coincidence counter train, of importance in selecting

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[4] M. Schein. W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941).

[5] This fact was not explicitly stated in reference 4, but was expressed in a private communication from M. Schein to the author.

[6] A. Ehmert, Zeits. f. Physik **115**, 320 (1940).

[7] E. G. Dymond, Nature **144**, 782 (1939).

[8] E. Regener and G. Pfotzer, Nature **136**, 718 (1935).

[9] W. F. G. Swann, G. L. Locher, and W. E. Danforth, Nat. Geog. Soc. Cont. Tech. Papers, Stratosphere Series No. 2, 13 (1936); J. Frank. Inst. **221**, 275 (1936); Phys. Rev. **51**, 389 (1937).

[10] T. H. Johnson, Phys. Rev. **54**, 151 (1938).

[11] G. Pfotzer, Zeits. f. Physik **102**, 23 (1936).

TABLE I. Summary of flight histories.

Flight no.	Date	Absorber thickness and composition	Rate of ascent**—feet per minute	Maximum altitude—feet	Length of time at maximum altitude—hours	Rate of descent**—feet per minute	Landing point	Air miles from launching site	Duration of radio contact—hours
	1947								
1A	July 17	2.5 cm Pb	865	95,000	*NL*	560	Riegelsville, Pa.	50	4¾
2A	July 22	0	660	95,000	6	—	Belmont, N. Y.	325	10½
3A	July 26	7.5 cm Pb	665	90,000	10¾	—	Lewisville, Ohio	350	13⅓
5A	Aug. 7	3.5 cm Pb	985	128,000	*NL****	770	Pleasant Gap, Pa.	145	6
8A	Sept. 3	7.5 cm C	370 to 68,000′ then 45 to 88,000′	88,000	68,000–88,000′ for 7 hours	1500	Peacedale, R. I.	230	10⅓
9A*	Sept. 9	4.0 cm Pb	550	85,000	*NL*	1200	West Grove, Pa.	23	4⅙
10A	Sept. 16	0	500	70,000	4	—	Bucksport, Maine	465	8
13A	Oct. 4	6.0 cm Pb	550	92,000	*NL*	450	Holmdel, N. J.	70	6
14A†	Oct. 25	7.5 cm C	530	85,000	*NL*	640	Not recovered	—	5
	1948								
15A	June 3	3.0 cm Pb	400	92,500	*NL*	1150	Shellsville, Pa.	100	4
17A	June 10	1.0 cm Pb	270	88,000	*NL*	1200	Not recovered	—	5
19A	June 24	4.0 cm Pb	530	95,000	*NL*	950	Pine Hill, N. J.	25	4¾

* Flight 9A contained an out-of-line counter for shower detection.
** Ascent and descent rates are approximate values at high altitudes.
*** *NL* indicates that, as a consequence of the particular inflation schedule selected, the flight did not level off.
† Flight 14A utilized the same instrument as Flight 8A.

an optimum geometry, has been treated by E. E. Witmer and the author.[12] The dimensions of the present apparatus are such that the average path length through the absorber is 7.3 percent greater than the thickness of the slabs for a $\cos^2\theta$ distribution of intensity with zenith angle, and 9.5 percent greater for an isotropic distribution. For present purposes, an intermediate value has been used in computing the absorber thicknesses when expressed in g/cm^2. Thicknesses stated in cm are measured values. The wall thickness of the Cu cylinders was 0.008″ and of the glass envelopes 0.063″. Thus, to produce a fourfold coincidence, a vertically-incident particle is required to penetrate a total of 4.2 g/cm^2 (1.3 g/cm^2 Cu and 2.9 g/cm^2 of glass). The filling consisting of a mixture of 86 percent argon and 14 percent butane at a total pressure of 12 cm of Hg provided stable self-quenching operation. Avoidance of the more commonly used organic vapors resulted in a counting rate plateau exceeding 200 volts (as measured in the balloon-borne instrument itself) which was independent of temperature over a range between $-60°$C and $+50°$C. The net efficiency of the counters, as determined in the customary manner, exceeded 99 percent.

Radio signals indicating the atmospheric pressure, temperature within the apparatus, and cosmic-ray events were continuously transmitted to the ground station where the information was recorded on paper tape by means of a high speed direct-inking recording oscillograph arrangement. Details regarding the complete balloon-borne apparatus, as well as a description of the ground station equipment will be given elsewhere.[13] It should be stated here, however, that the resolving and recovery times were sufficiently short to eliminate the necessity for applying corrections to the observed counting rates, such as were required, for example, in Pfotzer's experiments.

Furthermore, with no adjustment of the data, the absorption curve obtained on the basis of ground runs with different instruments, each containing a fixed amount of lead, agreed well with that measured with a single apparatus in which the lead thickness was varied.

B. Free Balloon Ascents

This series comprised a total of 18 flights. The weight of the instruments ranged between 4.3 kg and 5.9 kg, depending upon the amount of absorber. Flight plans varied considerably, and a summary of the vital statistics of representative ascents is embodied in Table I. Details regarding ballooning techniques and procedures

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[12] E. E. Witmer and M. A. Pomerantz, Phys. Rev. **73**, 651 (1948); J. Frank. Inst. **246**, 273 (1948).

[13] M. A. Pomerantz, to be published in Rev. Sci. Inst.

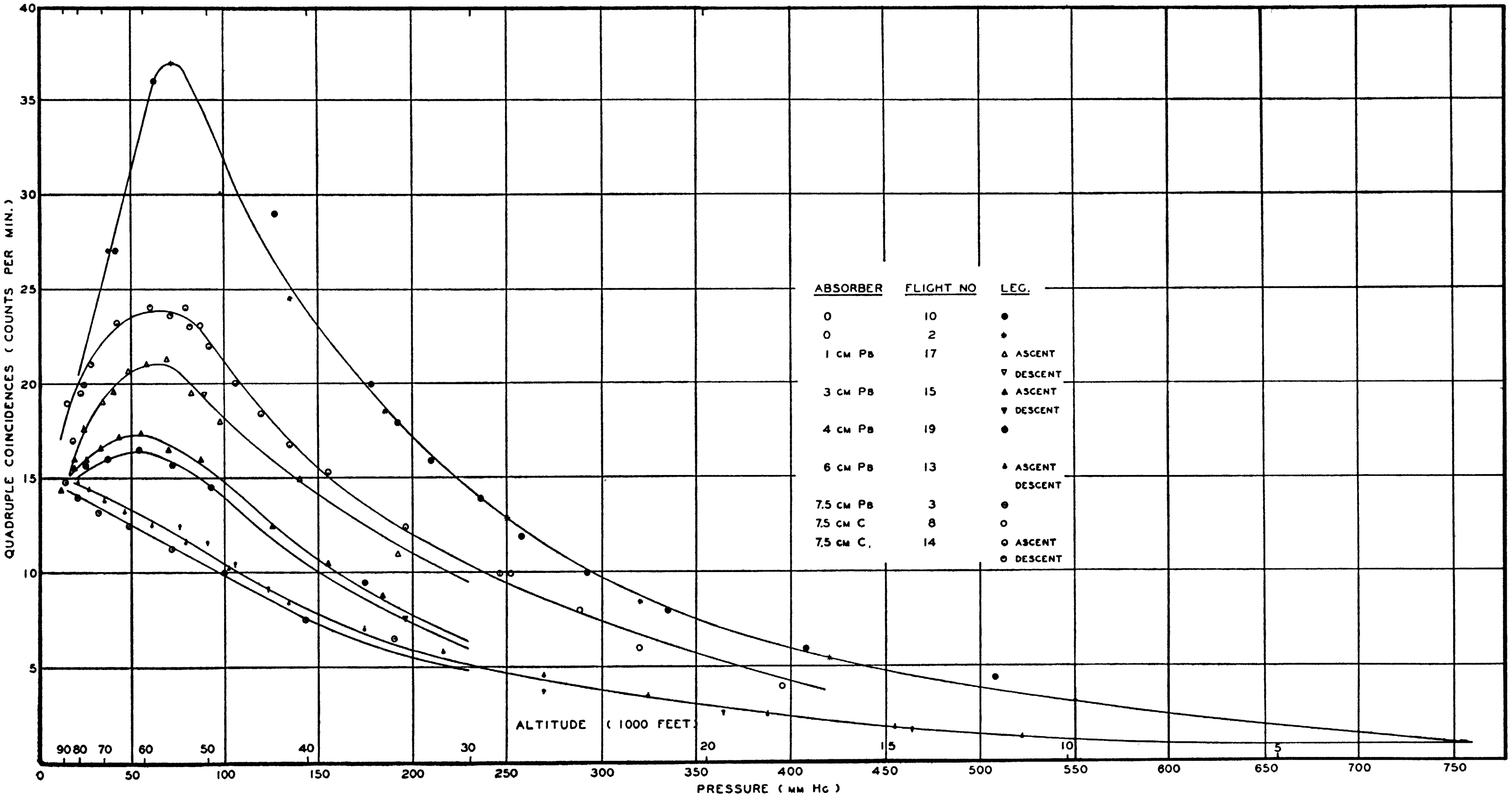

Fig. 1. *Intensity vs. altitude* curves for cosmic rays capable of penetrating various thicknesses of absorber. The actual quadruple-coincidence counting rates require no instrumental corrections, and are plotted directly as a function of atmospheric pressure.

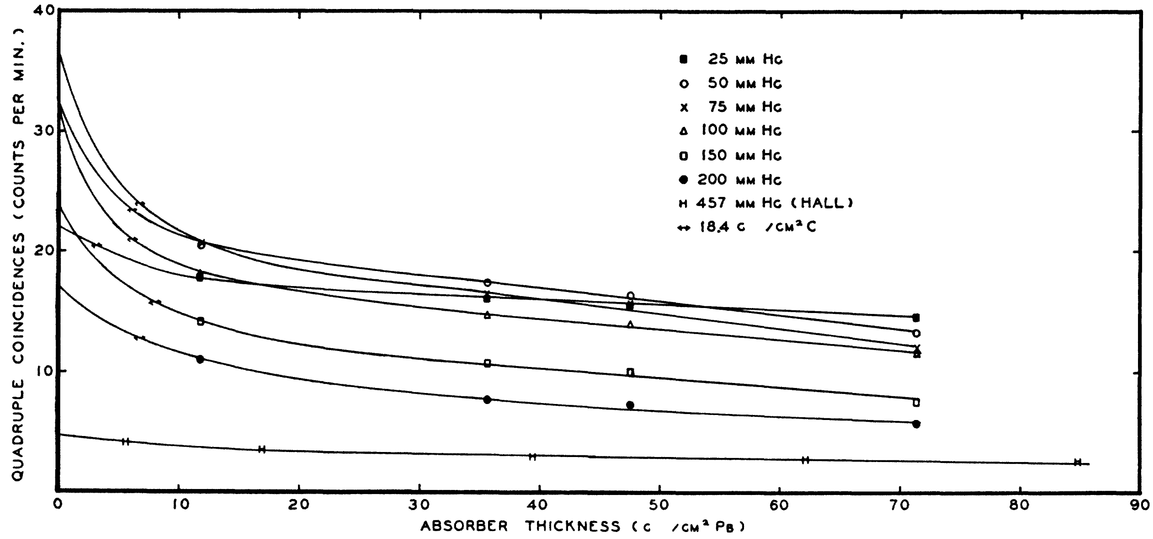

FIG. 2. Absorption in lead of cosmic-ray particles at various altitudes. A point representing the counting rate at the altitude indicated, with a constant thickness of interposed carbon, is plotted on each curve.

will also be omitted for the present. It is worth mentioning, however, that remarkable temperature constancy was maintained inside the apparatus by means of the well-known "greenhouse effect."

III. EXPERIMENTAL RESULTS

The experimental results will first be presented, and only the salient empirical features indicated. Detailed discussion of the implications thereof will be relegated to a later section.

A. Variation of Intensity With Altitude

The combined results are plotted in Fig. 1. The degree of reproducibility is best revealed by the agreement among the various flights having the same interposed absorber. Table I indicates, for each flight, whether the instrument was original or recovered, and it is seen that the agreement of data plotted in Fig. 1 is satisfactory in either case.

It is difficult to make general statements regarding the statistical uncertainties of the results. At altitudes lower than those corresponding to a pressure of 250 mm, the data are not significant.[14] This is a consequence of the combination of the briefness of the time interval spent by the apparatus in the regions of higher atmospheric pressure, and the low counting rates. An indication of the number of counts involved in any particular instance may be deduced on the basis of information contained in Table I. From the stated ascent and descent rates, and the counting rate at any point, a good approximation to the desired standard deviation may be obtained.

It is seen, as might be expected where true primaries are predominant, that the various curves obtained with thicknesses of lead up to 7.5 cm interposed in the counter train converge at the "top of the atmosphere."

A pronounced maximum exists in the *intensity vs. altitude* curves for interposed thicknesses up to 3 cm of Pb, becomes less definite with 4 cm,[15] and disappears with 6 cm.

Data of Pfotzer[11] and of Schein, Jesse, and Wollan[4] have been compared, but are not plotted on the graph here. In both instances, when the normalization is performed at the point of maximum intensity and no attempt is made to take

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[14] Measurements at airplane altitudes have been obtained recently with standard sets in B-29 flights sponsored jointly by the Air Forces and the National Geographic Society. Observations up to 14,250 feet were also made on Mt. Evans this summer. This program will make available cosmic-ray absorption curves obtained under standardized conditions at altitudes from sea level to the "top of the atmosphere." The results of the experiments conducted at the lower altitudes will be published shortly.

[15] This is in agreement with observations of the Chicago group. A maximum with 4 cm of Pb occurred at about 60 mm Hg pressure, according to a private communication from M. Schein.

Table II. Experimental values of S_C/S_{Pb} at various altitudes.

Atmospheric pressure—mm of Hg	Carbon thickness—g/cm²	Equivalent lead thickness—g/cm²	S_C/S_{Pb}
25	14.0	3.0	.21
50	14.0	6.0	.43
75	14.0	6.6	.47
100	14.0	6.0	.43
150	14.0	8.0	.57
200	14.0	6.4	.46

into account the differences among the instruments (see Section I), the shapes of the resulting curves are similar to their analogs in Fig. 1.

B. Variation of Intensity with Absorber Thickness

Utilizing the smooth curves of Fig. 1, a change in the parameter from *absorber thickness* to *altitude* affords a determination of the variation of counting rate with absorber thickness at any desired altitude. The results are shown in Fig. 2. Data obtained by D. B. Hall[16] on Mt. Evans are included for comparison. Approximate values of the relative stopping powers[17] of carbon and lead (S_C/S_{Pb}) are obtained by locating on each curve of Fig. 2 a point with ordinate corresponding to the counting rate with 7.5 cm of C at that altitude. The value of the corresponding abscissa then is the amount of lead which is equivalent in stopping power to 18.4 g/cm² of C. The numerical values of S_C/S_{Pb} are summarized in Table II.

C. Integral Distributions-in-Range

Figure 3 shows the integral distribution-in-range at various altitudes. The points (obtained directly from the corresponding points of Fig. 2 rather than from the smooth curves), thus represent the fraction of the total vertical intensity at the designated altitude capable of penetrating absorber thicknesses at least as great as the value of the corresponding abscissa. It is to be noted that the slopes in the region 200 mm − 50 mm are rather similar at larger absorber thicknesses. The absorption coefficients between 4 and 6 cm of Pb have values of approximately 0.008−0.006 cm²/g, as compared with 0.003 cm²/g from Hall's measurements over a similar absorber thickness interval much lower in the atmosphere.

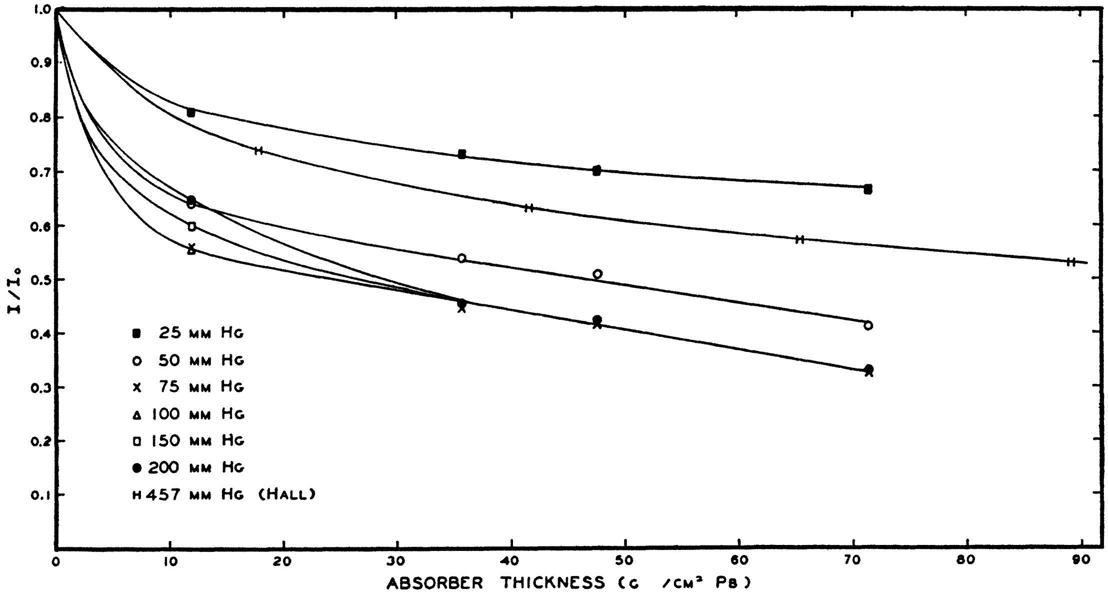

Fig. 3. Integral distributions-in-range at various altitudes.

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[16] D. B. Hall, Phys. Rev. 66, 321 (1944).

[17] For a definition of S_C/S_{Pb} see, e.g., M. A. Pomerantz, Phvs. Rev. 57, 3 (1940).

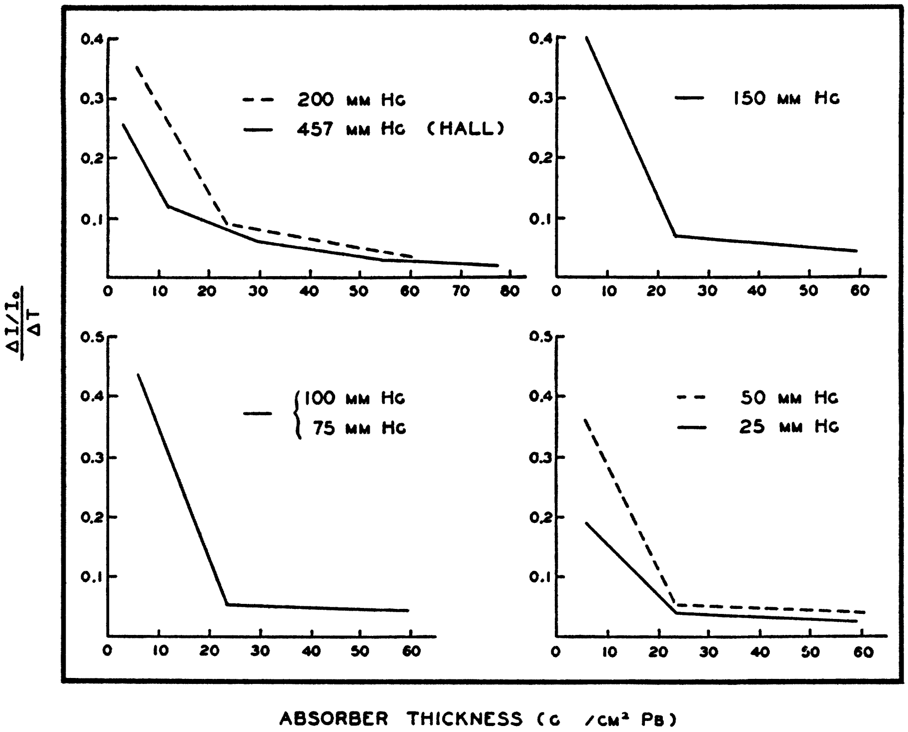

FIG. 4. Differential distributions-in-range at various altitudes.

D. Differential Distributions-in-Range

Differential distributions-in-range, computed directly from the points shown in the integral plots, are given in Fig. 4. Here, the units of the ordinates are *percent of total intensity per cm of Pb.* Values of the abscissa represent the corresponding average ranges, expressed in g/cm^2. The manner in which the composition of the cosmic radiation changes in the atmosphere is evident in this diagram.

It is striking that as the altitude increases upwards from sea level, the intensity of the soft component (defined in terms of range in Pb) also increases. At about 100 mm, a decrease sets in, until near the top of the atmosphere the particles actuating the apparatus are practically all primaries.

IV. EFFECTS OF SHOWERS AND SCATTERING

A. Showers

Either a determination of the effects of side showers or elimination of their effects is essential in any coincidence-counter measurements of cosmic rays. Various methods have been invoked for accomplishing this, and data bearing upon the present situation already exists.

In the present flights, specific precautions were taken to reduce shower effects to an absolute minimum. No heavy material was placed above or alongside the counters. In the interests of instrumental simplicity the inclusion of side-counter anticoincidence arrangements in the standard sets was avoided. It was considered preferable to ascertain the shower contribution (appreciable accidental coincidences having already been precluded) in a separate flight. This was accomplished with an apparatus which was standard except for the position of one of the counters, which was placed just out of line. Although the lead was interposed in a manner which was expected to be characterized by the maximum probability for the manifestation of shower phenomena, the highest out-of-line rate amounted to only about 5 percent of the lowest corresponding in-line rate. Hence the influence of showers upon these absorption measurements is negligible.

The first experiments embodying shielding banks of anticoincidence counters were performed by Swann, Locher, and Danforth.[9] Intensity measurements were obtained within the gondola of the National Geographic Society—U. S. Army stratosphere flights, and comparisons of results with shielded and unshielded telescopes revealed that the effect of showers was small. Johnson and Barry[18] arrived at a similar conclusion as a consequence of balloon flight experiments in which a counter was alternately shifted from an out-of-line to an in-line position in a coincidence counter train inclined at 60 degrees from the vertical. Neher and Pickering[19] likewise indicated the smallness of the shower effect in balloon experiments, as did Schein, Wollan, and Groetzinger[1] on the basis of results obtained in airplanes.

B. Scattering

Despite the fact that it is virtually impossible to arrive at an exact evaluation of the influence of scattering upon the present measurements, it is essential that cognizance be taken of the limitations this disturbing effect may impose upon the interpretation of some of the data. Although the scattering situation is not necessarily more severe here than in other coincidence counter experiments, it has often been entirely disregarded, occasionally under circumstances in which it is perhaps capable of accounting for observed effects.

The principal justification for regarding as small the contamination arising from scattering in the present absorption measurements is based upon the experimental fact that within statistical uncertainties the *counting rate vs. altitude* curves obtained with a particular absorbing layer are independent of the latter's position in the counter train. The magnitude of the effect of scattering is a function of the geometrical arrangement, and it was hence considered desirable to alter this factor as much as possible in different flights having the same total thickness of lead, and to look for discrepancies.

Several qualitative arguments relating to scattering may be mentioned. In the first place, the scattering effect of a block of material upon particles which would have been stopped by absorption anyway is of no consequence. Of those particles having ranges initially exceeding that defined by the lead block, the most susceptible to scattering are those which emerge from the block with just sufficient energy to penetrate the remaining G-M counter walls. Consequently, the rays which could be scattered out of the beam by the lead, thereby introducing a spurious additional absorption, have high energies in general and, consequently, small average scattering angles.[20] Moreover, it can be shown that for each of certain classes of ray which can be scattered out of the train exact compensation occurs. This is caused by the scattering, into the effective solid angle subtended by the train, of rays which would not have passed through all four counters in the absence of the scattering medium. A quantitative treatment of the problem is precluded by lack of precise information regarding the composition of the cosmic radiation and the energy distributions of the various components at high altitudes.

The presence of scattering effects may become somewhat more serious in measurements of the relative stopping powers of carbon and lead. Caution must be exercised in drawing conclusions from this type of data, owing to the fact that the scattering in carbon is negligible in comparison with that in lead.

V. ANALYSIS OF EXPERIMENTAL CURVES

A. Extrapolation of Counting Rate *vs.* Absorber Thickness Curves

It has been assumed previously that data obtained with coincidence-counter trains containing 8 cm of Pb represent the intensity of mesotrons.[21] This evidently involves the assumption, now completely untenable, that all particles incapable of penetrating this thickness are not mesotrons, but are electrons exclusively. The present experiments permit a somewhat more accurate evaluation of the relative intensities of the electron (E) and proton plus mesotron ($P+M$) components.[22]

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[18] T. H. Johnson and J. G. Barry, Phys. Rev. **57**, 245 (1940).

[19] H. V. Neher and W. H. Pickering, Phys. Rev. **61**, 407 (1942).

[20] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).

[21] This assumption has been made by many authors. See, e.g., M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **57**, 847 (1940).

[22] The $P+M$ component is here construed as including all nonelectronic charged particles having sufficient energy to penetrate the apparatus (see Section IIA). It embraces

This is accomplished by an extrapolation to zero absorber thickness of the straight lines through the three points in Fig. 2 representing the larger absorber thicknesses. This is the customary procedure used for separating the soft and hard components at low altitudes where, however, the absorber thicknesses are somewhat greater. The assumptions involved here are (1) that the intensity of electrons capable of penetrating more than 35 g/cm^2 of Pb[23] is relatively small, and (2) that the $P+M$ intensity varies linearly with the absorber thickness. For purposes of the present discussion, the results are not extremely sensitive to these admittedly arbitrary assumptions. It can easily be seen that a small admixture of high energy electrons would not significantly alter the values of extrapolated counting rates. Furthermore, factors which would compensate for the above are doubtless operative. Firstly, should scattering be important in removing slow mesotrons from the incident beam, it is clear that the M intensity might be higher than is indicated by the extrapolation. Secondly, the location of the maximum of the $P+M$ momentum distributions may correspond to a small range in lead at high altitudes, thereby vitiating the straight-line extrapolation. In the light of the present state of our knowledge, it seems probable that, if anything, the $P+M$ intensity has been underestimated.

Finally, the extrapolation leads to results which are entirely in accord with the existing experimental data gathered in airplane flights and on mountain peaks. The experiments of Hall[16] at an altitude corresponding to 458 mm of Hg revealed that the E intensity penetrating 3.5 cm of Pb amounts to approximately 8 percent of the corresponding $P+M$ intensity. Furthermore, at that station, an extrapolation analogous to that performed here yields results within 10 percent of those obtained by a more elegant method of distinguishing mesotrons from electrons based upon a shower-production criterion. Auger[24] concluded, from an analysis of aluminum and lead absorption curves, that electrons having a range exceeding 2.5 cm of Pb comprise 8 percent of the total, or 11 percent of the $P+M$ intensity at 490 mm, lending additional support to assumption (1). Rossi, Sands, and Sard[25] have measured the increase with altitude of the intensity of mesotrons stopped in 2″ of Al, utilizing an apparatus wherein these particles are identified by the occurrence of delayed disintegration electrons. Although comparison can only be rough because of statistical uncertainties, their ratios with respect to sea level of the intensity of slow mesotrons at different altitudes (range interval $=2.2$ g/cm$^2-13.8$ g/cm^2; momentum $=0.6\times10^8-1.2\times10^8$ ev/c; energy $=17\times10^6-56\times10^6$ ev) are in accord with those computed from the present data on the basis of extrapolation.

Herzog and Bostick[26] have reported that at 233 mm of Hg the slow mesotrons (range $=0.75$ cm Pb) amounted to 9 percent of the fast particles, a value in agreement with that computed from the extrapolated data at the same altitude. Indeed, the excellency of the agreement must be regarded as fortuitous.

These agreements have been cited primarily for the purpose of demonstrating that this admittedly arbitrary extrapolation procedure is actually not very radical. It leads to results which are consistent with those of other experiments which, by revealing the presence of many slow heavy particles, have already necessitated a revision of the prevalent concepts regarding the relative intensities of the so-called "soft" and "hard" components of cosmic radiation at very high altitudes.

B. Relative Intensities of E and $P+M$ Components as a Function of Altitude

The previous representation of cosmic-ray intensities in the atmosphere[27] was determined by subtracting from Pfotzer's[11] curve of the total vertical intensity as a function of pressure that obtained by Schein, Jesse, and Wollan[4] with 8 cm of Pb. The latter was regarded as characteristic of the mesotron intensity, and the difference was

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mesotrons of various types (π, μ, etc.), secondary protons, primary protons, and heavier nuclear primaries and secondaries.

[23] According to calculations by Bhabha, $E=3\times10^8$ ev for such electrons. H. J. Bhabha, Proc. Ind. Acad. Sci. **XIX**, 23 (1944).

[24] P. V. Auger, Phys. Rev. **61**, 684 (1942).

[25] B. Rossi, M. Sands, and R. F. Sard, Phys. Rev. **72**, 120 (1947).

[26] G. Herzog, Phys. Rev. **59**, 117 (1941) and G. Herzog and W. H. Bostick, Phys. Rev. **59**, 122 (1941).

[27] See reference 21.

attributed to electrons. Data on showers, obtained by Regener and Ehmert,[28] were shown as following closely the E curve. In this scheme, the intensity at the maximum and, in fact, at all high altitudes except near the top of the atmosphere was attributed almost entirely to electrons.

The new picture, based upon the results of the extrapolation described above, is shown in Fig. 5. It will be noticed that the E intensity now obtained by subtracting from the total intensity that of the more relevant $P+M$ component determined as described above is now less than that of the latter. The maximum of the $P+M$ curve occurs at an altitude of 60 mm of Hg, as compared with about 78 mm for the electrons. Furthermore, the agreement between the shower measurements and curve E is preserved.

It should be emphasized that the results plotted in Fig. 5 apply only to particles having energies exceeding the minimum for penetration of the apparatus (see Section IIA). Thus, mesotrons having energies less than 2×10^7 ev are excluded. Considering ionization losses alone, it follows that electrons with energies less than approximately 7×10^6 ev are not included. There may be a high intensity of such low energy electrons, and their numbers might easily be comparable with those of the other components. The relative intensities based upon the extrapolation procedure may be influenced near the top of the atmosphere by the fact that shower equilibrium has not been established.

VI. COMPARISON WITH RESULTS AT LARGE ABSORBER THICKNESSES

The uncertainties in the comparison of data obtained under different conditions have already been cited. Nevertheless, in view of the importance of exhausting the possibilities of existing data, it is appropriate to attempt a comparison of the present results with those of Schein and Allen[29] for larger thicknesses of absorber. For this purpose, the normalization evidently should be performed at sea level. The principal uncertainty then concerns possible differences between the results obtained with two different apparatuses arising from the change with altitude of the zenith angle distribution law. Calculations cited previously[12] afford a means for evaluating such effects. The average zenith angles of rays

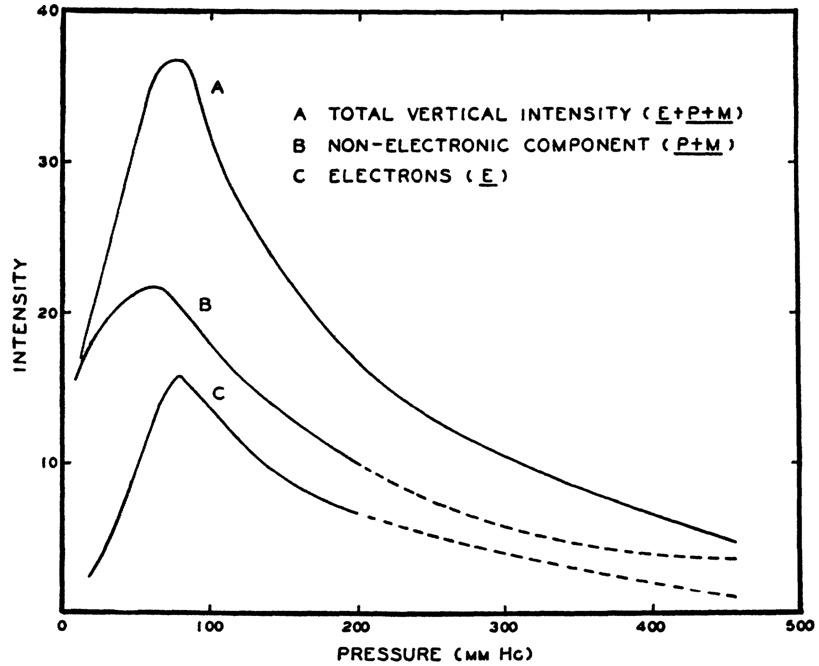

Fig. 5. Variation with altitude of total vertical intensity ($E+P+M$), heavy component intensity ($P+M$) as defined in reference 22, and electron intensity (E) on the basis of the present experiments. The shower intensity (not plotted) follows the E curve closely.

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[28] E. Regener and A. Ehmert, Zeits. f. Physik **111**, 501 (1939).

[29] Professor Schein has very kindly provided the author with this unpublished data obtained in collaboration with F. Allen.

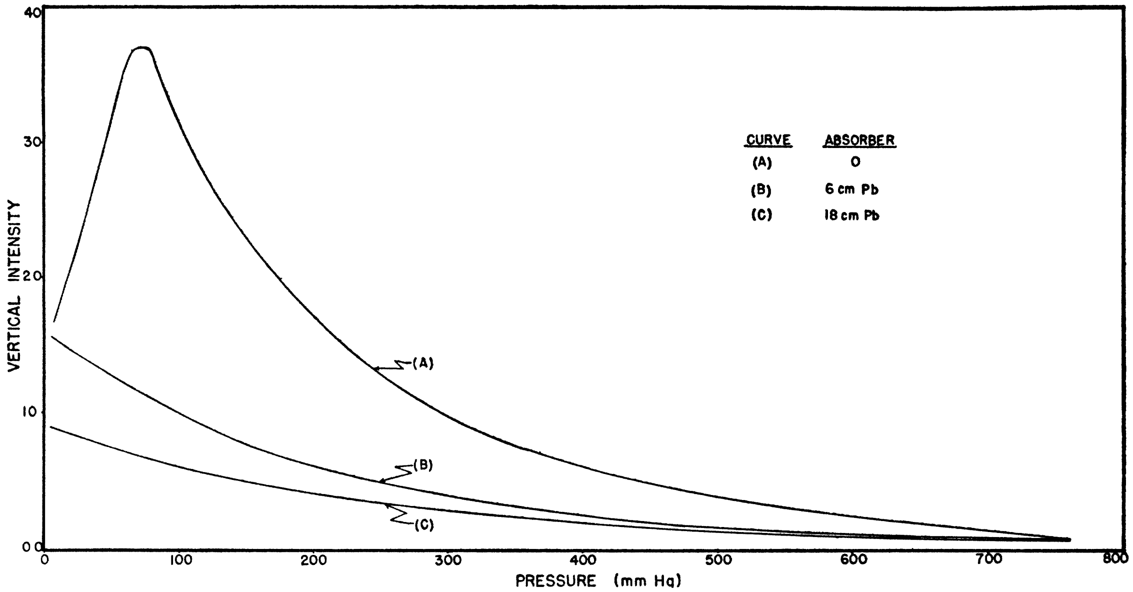

FIG. 6. *Intensity vs. altitude* curves with 0, 6, and 18 cm of Pb. The points of Schein and Allen, with 18 cm Pb, have been fitted to the others at 760 mm of Hg, in conjunction with absorption measurements at sea level.

capable of actuating the two counter trains are 20° and 10°, respectively, for a $\cos^2\theta$ distribution. In the case of the geometrical arrangements here being compared, these values are not very sensitive to the type of distribution law. In fact, for an isotropic distribution the average angles would be altered by less than 2°. Hence, a comparison appears warranted.

Figure 6 shows the resulting curves. Some absorption of the primary radiation appears to occur at thicknesses between 7.5 and 18 cm of Pb, even at the top of the atmosphere. It is possible that in these thicknesses, which are already comparable in superficial mass to one-tenth of an atmosphere, primaries having the minimum energy necessary to penetrate the earth's magnetic field (2.6 Bev for protons at 52° geomagnetic latitude) are completely stopped. Quantitatively, such a primary could conceivably lose all of its energy by the production of a number of mesotrons, none of which are sufficiently energetic to penetrate the remaining lead. For example the total energy of 2.6×10^9 ev could be transformed into 10 mesotrons of $\mu c^2=10^8$ ev each having a k.e. $=1.6\mu c^2$, corresponding to a range in lead of approximately 100 g/cm^2. Other modes of transformation might lead to a similar result. However, it is necessary to account for the absorption by some process other than ionization.

This is the first experimental evidence for the stopping of primary particles by an absorber interposed within a particle-detecting instrument. It is obviously of the utmost importance to perform similar experiments with absorbers having different atomic numbers, in order to obtain additional information regarding the nature of the primary interaction.

With smaller lead thicknesses, conditions are such that, as indicated by the convergence of the curves in Fig. 1, either the primary or its progeny created in the apparatus itself always has sufficient residual range to actuate the coincidence train.

The convergence also provides experimental evidence precluding the presence near the "top of the atmosphere" of an appreciable upward and outwardly directed component having sufficient energy to penetrate the counter train (see Sections IIA, and VB).

VII. CONCLUSIONS

The data presented above are in accord with a theory of cosmic radiation based upon the hypothesis that the primaries are heavy particles. The absorption characteristics at the top of the atmosphere, as pointed out by Schein, Jesse, and Wollan,[4] and the large intensity at high zenith angles, compared with azimuthal symmetry, as pointed out by Swann,[30] preclude the possibility of electron primaries. The heavy primaries, upon entering the atmosphere, produce mesotrons which subsequently give rise to electrons (by knock-on processes and by disintegration). Thus, the maximum intensity of the E component occurs deeper in the atmosphere than that of the $P+M$ group.

It has not been established whether the primaries consist exclusively of protons. Swann[31] has pointed out that the explanation of the magnitude of the horizontal intensity observed at high altitudes also requires helium primaries. Heretofore neither the resolution of the $P+M$ components near the top of the atmosphere, nor the identification of the primaries has been feasible experimentally. Devices now in operation, such as particle-discriminating G-M counter systems[32] and balloon-borne cloud chambers[33] should greatly facilitate the solution of this important problem.

VIII. ACKNOWLEDGMENTS

It is a pleasure to acknowledge herewith the valuable assistance rendered by F. Green and D. W. Watson throughout the course of this project. Thanks are also due M. V. Scherb for performing some of the tests of the large number of G-M counters required; F. L. Hereford, H. C. Taylor, G. Hay, P. Morris, D. Seymour, R. Kerr, J. Kane, and others for participating at various times in launching and flight operations; Commander G. Vaux for so efficiently arranging for the procurement of vital instrumental components; W. E. Ramsey, W. F. G. Swann, E. E. Witmer, and M. Schein for helpful discussions of these results. Finally, grateful appreciation is expressed to the National Geographic Society for cooperation in connection with certain phases of this program of cosmic-ray investigations through its Committee on Research, Dr. Lyman J. Briggs, Chairman.

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[30] W. F. G. Swann, Rev. Mod. Phys. **11**, 242 (1939); Phys. Rev. **59**, 770 (1941).

[31] W. F. G. Swann, J. Franklin Inst. **236**, 1 (1943).

[32] M. A. Pomerantz and F. L. Hereford—unpublished.

[33] R. B. Leighton and C. D. Anderson, Bull. Am. Phys. Soc. Houston Meeting, Nov. 1947; Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters; Phys. Rev. **74**, 213 (1948); a balloon-borne cloud chamber has also been developed by T. H. Johnson and R. P. Shutt.