range corresponding to the average energies at which mesons are produced that are observed at the two depths (4×10^{11} to 10^{12} ev).

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

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Proton Intensities at Sea Level and 9000 Feet*

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

INTRODUCTION

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

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

EXPERIMENTAL ARRANGEMENT AND METHOD

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

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1 Adams, Anderson, Lloyd, Rau, and Saxena, Revs. Modern Phys. **20**, 334 (1948).
2 Alikhanian, Alikhanov, and Weissenberg, J. Exp. Theoret. Phys. (U.S.S.R.) **18**, 673 (1948).
3 R. C. Jopson, Ph.D. thesis, California Institute of Technology, 1950 (unpublished).
4 Merkle, Goldwasser, and Brode, Phys. Rev. **79**, 926 (1950).
5 C. Peyrou and A. Lagarrique, J. phys. et radium **11**, 666 (1950).
6 E. L. Goldwasser and T. C. Merkle, Phys. Rev. **83**, 43 (1951).
7 Miller, Henderson, Potter, and Todd, Phys. Rev. **84**, 981 (1951).
8 M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) A64, 404 (1951).
9 W. L. Whittemore and R. P. Shutt, Phys. Rev. **86**, 940 (1952).
10 G. D. Rochester and M. Bound, Nature **146**, 745 (1940).
11 Hodson, Loria, and Ryder, Phil. Mag. **41**, 826 (1950).
12 B. P. Gregory and J. H. Tinlot, Phys. Rev. **81**, 667 (1951).
13 C. M. York, Phys. Rev. **85**, 998 (1952).
14 M. Conversi, Phys. Rev. **79**, 749 (1950).
15 R. B. Brode, Revs. Modern Phys. **21**, 37 (1949).

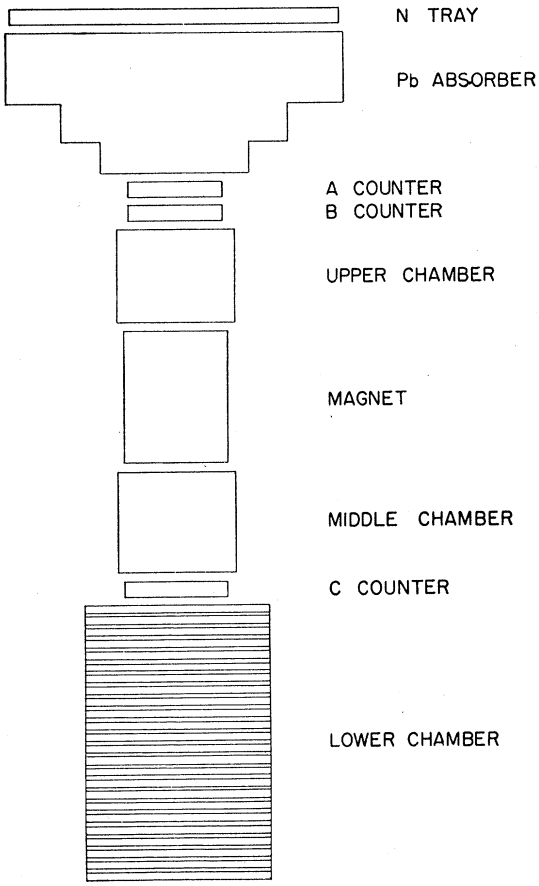

FIG. 1. Schematic diagram of the apparatus.

cloud chambers triggered by a threefold coincidence of counters A, B, and C. The upper and middle chambers record the angular deviation of particles passing through the region of the magnetic field which has for the vertical path line integral[16] a value of 1.94×10^5 gauss cm. The lower chamber records the particle's track through or terminating in one of 25 copper plates comprising 86.6 g/cm^2 of copper.

Additional paralleled counters labeled N, which, when fired in coincidence with the triggering telescope, produced a neon flash recorded on one of the cloud chamber photographs, were used to monitor uncharged particles which gave rise to secondary particles capable of producing a triggering coincidence.

TABLE I. Solid angle-area for particles stopping in plates 1, 13, and 25.

	Solid angle-area (sterad cm^2)		
Component	Plate 1	Plate 13	Plate 25
a. meson	0.108	0.169	0.164
b. proton	0.242	0.248	0.230
c. no field	0.257	0.253	0.236

From the angular deflection and the range of stopping particles the mass can be determined by making use of range-energy data, e.g., that calculated by Aron and co-workers.[17] The intensities of the identified particles in specific momentum regions may therefore be evaluated.

Absolute intensity determinations require knowledge of the total receptive time of the chambers and the solid angle-area which is momentum- and range-dependent in the present apparatus. The receptive time was calculated from the total time of operation and the time for resetting. The solid angle-area was evaluated graphically on the basis of the known curvature for particles of given mass and range and is shown, for mesons and protons stopping in the indicated plates, in Table I. For purposes of comparison, the third line indicates the solid angle-area of particles if not subject to angular deflection in a magnetic field. It is to be noted that stopping mesons have a considerably reduced solid angle-area because of their large angular deflection in the magnetic field whereas the proton solid angle-area is but slightly reduced from that corresponding to no deflection.

RESULTS AND DISCUSSION

The results of the operation pertaining to 0, 10, and 20 cm of lead absorber over the apparatus at 9000 feet and at sea level are summarized in Table II. The particles which stopped in the upper 13 plates of the range chamber and in the lower 12 plates are indicated by u and l, respectively. In addition, the columns labeled u' and l' indicate those heavy particles which were observed to stop, respectively, in the upper and lower sections but which, if protons, could not have done so be-

TABLE II. Summary of operation.

Altitude	Absorber (cm Pb)	Receptive time (hr)	Hard particles	Stopped mesons u	Stopped mesons l	Stopped protons u	Stopped protons u'	Stopped protons l	Stopped protons l'	N
9000 ft	0	181.7	1904	25	28	34	6	17	4	0
9000 ft	10	68.3	604	6	10	4	2	4	3	2
9000 ft	20	61.4	491	5	4	1	0	1	0	3
Sea level	0	689	...	37	46	12	2	10	1	...

[16] This is the pertinent field quantity in the evaluation of the momentum p from the angular deflection θ. Thus, $p(\text{Bev}/c) = 3.34/\theta^0$.

[17] Aron, Hoffman, and Williams, University of California Radiation Laboratory Report UCRL-121 (1949) (unpublished).

TABLE III. Intensities with no external absorber.

Altitude	Component	Range or momentum interval	Rate
Sea level	meson—differential	22.6–51.4 g/cm² of air equivalent	$3.75\pm0.41\times10^{-6}$ g^{-1} sec^{-1} sterad^{-1}
	range spectrum	51.4–89.7 g/cm² of air equivalent	$2.90\pm0.29\times10^{-6}$ g^{-1} sec^{-1} sterad^{-1}
Sea level	proton—differential	0.59–0.77 Bev/c	$9.1\pm1.9\times10^{-5}$ cm^{-2}(Bev/c)$^{-1}$ sec^{-1} sterad^{-1}
	momentum spectrum	0.77−0.93 Bev/c	$12.1\pm2.3\times10^{-5}$ cm^{-2}(Bev/c)$^{-1}$ sec^{-1} sterad^{-1}
9000 ft	hard—integral range spectrum	161 g/cm² Pb	$1.27\pm0.02\times10^{-2}$ cm^{-2} sec^{-1} sterad^{-1}
9000 ft	meson—differential	22.6–51.4 g/cm² of air equivalent	$9.6\pm1.3\times10^{-6}$ g^{-1} sec^{-1} sterad^{-1}
	range spectrum	51.4–89.7 g/cm² of air equivalent	$6.7\pm0.9\times10^{-6}$ g^{-1} sec^{-1} sterad^{-1}
9000 ft	proton—differential	0.59–0.77 Bev/c	$9.6\pm1.2\times10^{-4}$ cm^{-2}(Bev/c)$^{-1}$ sec^{-1} sterad^{-1}
	momentum spectrum	0.77–0.93 Bev/c	$7.9\pm1.2\times10^{-4}$ cm^{-2}(Bev/c)$^{-1}$ sec^{-1} sterad^{-1}

cause of ionization loss alone.[18] Consideration of these particles allows a direct correction for what are probably low-energy nuclear interactions in the range chamber. The column labeled N refers to additional stopping heavy particles for which there were no associated N counts. From this data one can calculate the intensities with no external absorber corrected for the interactions mentioned above. These are summarized in Table III.[19]

Correction for the effects of nuclear absorption of the incident proton beam in the external absorber were made on the basis of an absorption length estimated from several sources. Experiments on artificially accelerated neutrons in poor geometry,[20] as well as cosmic ray experiments,[21] give an interaction length of roughly 200 g/cm² for lead corresponding to 125 g/cm² for copper. In a calculation of the mean free path corresponding to the results shown in Table II, in which the u' protons of initial energy between 245 and 370 Mev and therefore of an ionization range corresponding to the l protons actually stop in the upper section, one obtains 120_{-30}^{+60} g/cm² of copper in agreement with the above result. Since reproduction below the momentum chamber can play no role in this result, and since the interactions are low-energy ones (approximately 50 Mev) in which no charged particles emerge from the copper plates, this agreement is not unreasonable. Reproduction in the external absorber may give rise to an absorption length perhaps as much as 50 percent higher than the above interaction length. This is in agreement with experiments[22] on the absorption in lead of star-producing radiation at 3500 m in which after a small transition region the absorption thickness is found to be 300 g/cm². With the use, then, of this value, the results for proton intensities with external absorber given in Table IV were calculated. These results as well as those of Table III show a variation in differential intensity with momentum of the protons at 9000 feet which is similar to that obtained by Mylroi and Wilson[8] at sea level and, by Whittemore and Shutt[9] at 3.4 km for momenta below 1.5 Bev/c. It is considerably flatter than for momenta above 1.5 Bev/c, for which the intensity as observed by the above workers was found to vary as $p^{-\alpha}$ with $\alpha=2.5$.

The ratio of the intensities of protons of momentum between 0.59 and 0.93 Bev/c at 9000 feet to those at sea level is calculated from Table III to be 8.5 ± 1.4. Assuming exponential absorption over the 290 g/cm² of air between the two altitudes, the absorption length is found to be 136_{-8}^{+13} g/cm² of air. Although this absorption length is a complex result of the effects of nuclear interaction and reproduction as well as ionization loss, it is reasonably independent of the apparatus used and thus can serve as a convenient quantity for comparison with other work. Thus Mylroi and Wilson, making use of the results of Anderson *et al.*[1] and Alikhanian *et al.*,[2] find for the absorption length between 30 000 feet and sea level a value of 140 ± 10 g/cm² for protons of momentum greater than 1 Bev/c. The data of Whittemore and Shutt at 3.4 km for protons of the momentum 0.8 Bev/c, together with those of Mylroi and Wilson at sea level at the same momentum, yield an absorption length corresponding to the intensity ratio of 15.8, of 130 g/cm². Conversi[14] found that the relative intensities at 1 Bev/c between 22 500 feet and 2100 feet also corresponded to an absorption length of 130 g/cm².

From this general agreement for the absorption length and from the form of the spectrum obtained at higher momenta, one can deduce an attenuation length which would characterize the effective attenuation if no ionization loss occurred. With the ionization loss being taken into account, the proton momentum interval at 9000 feet corresponding to an observed momentum interval of 0.59 to 0.93 Bev/c at sea level

TABLE IV. Proton intensities at 9000 feet under external absorber.

Thickness of Pb absorber (g/cm²)	Momentum interval (Bev/c)	Intensity [(Bev/c)$^{-1}$ sec^{-1} sterad^{-1} cm^{-2}]
113.5	0.94–1.16	$5.7\pm1.7\times10^{-4}$
227.0	1.16–1.34	$4.4\pm2.1\times10^{-4}$

[18] All u' particles but one would have stopped in the l section according to their measured momenta.

[19] The quoted probable errors are from statistics only. The meson intensities are given in terms of g/cm² of air equivalent to allow direct comparison with the results of other workers.

[20] J. DeJuren and B. J. Moyer, Phys. Rev. **81**, 919 (1951).

[21] B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952), pp. 500–13.

[22] Bernardini, Cortini, and Manfredini, Phys. Rev. **79**, 952 (1950).

is from 1.58 to 1.74 Bev/c. If one compares the intensity of the protons in this momentum interval at 9000 feet, deduced from the $p^{-2.5}$ variation fitted to the intensity values obtained in the present experiment, with the observed intensity in the momentum interval at sea level, one obtains an attenuation length of approximately 900 g/cm^2. This value is many times larger than the nuclear interaction length because of production of protons and because of the absence of ionization loss for the neutrons involved.

It is evident from the above calculation that the protons at the higher altitude have disappeared by nuclear interaction before reaching sea level and that therefore the source of the low-energy protons observed in this experiment are primaries which make protons near the level of observation. The detailed calculations on the proton component of the nuclear cascade including ionization loss by Messel[23] involve integral proton intensities so that the data of the present experiment are not directly comparable. However, a simplified calculation following Rossi[24] may be used to relate the observed altitude variation of the protons to the absorption mean free path for the primaries, λ. If one assumes that the production spectrum is of the form[25] $Ap^{-n}\exp(-x/\lambda)$, with $n=3$, at the depth x and the momentum p, and that the produced particles are absorbed as $\exp[-(L_1-x)/\lambda_a]$, where L_1 is the level of observation, then the observed intensity at the momentum p_1, $j(p_1, L_1)$, can be calculated. One finds that

$$j(p_1, L_1)=\frac{e^{-L_1/\lambda}}{\alpha(p_1)}\frac{A}{n-1}\left(\frac{1}{p_1^{n-1}}-\frac{1}{p_{m1}^{n-1}}\right),$$

where $\alpha(p_1)$ is the momentum loss due to ionization at the momentum p_1; that is, $\alpha(p_1)=-dp/dx$, and p_{m1} is the momentum at the top of the atmosphere of a proton of momentum p_1 at L_1. The ratio of the observed intensities at $L_1=740$ g/cm^2 and $L_2=1030$ g/cm^2 at the momentum $p_2=p_1=0.76$ Bev/c yields a value of 134_{-9}^{+12} g/cm^2 for the absorption length, λ, of the primary particles.

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[23] H. Messel, Phys. Rev. **83**, 26 (1951).
[24] Reference 21, pp. 486–488.
[25] See, for instance, reference 8, p. 417.