Electrons in Equilibrium with the Penetrating Component of Cosmic Rays in Lead at 10,000 Feet and at Sea Level

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The number of electrons (N) in equilibrium with the penetrating component of the cosmic rays in lead at 10,000 ft. and at sea level has been measured with Wilson cloud chambers containing lead plates. The value for N obtained at 10,000 ft. is 7.4 ± 0.2 percent, at sea level 6.8 ± 0.6 percent. Comparison is made with values for N calculated from the equations of Bhabha and Tamm and Belenky with a mesotron mass of 200 m and Blackett's cosmic-ray spectrum. If the loss of low energy electrons as a result of scattering in the lead is taken into account, the calculated values for N are only slightly larger than the experimental values. If the calculated values for N are assumed to be correct, the present results provide additional evidence that protons constitute only a small fraction of the cosmic-ray particles in the lower atmosphere.

THE study of the production of high energy collision electrons by the penetrating component of cosmic rays provides information concerning the origin of the soft component since these collision electrons and their cascade progeny constitute an appreciable fraction of the soft component. The actual production of the collision electrons in air cannot be conveniently studied, hence it is customary to introduce denser materials in order to produce collision electrons more copiously in the relatively small region under observation. In the present type of experiment the greater ambiguity of measurements with G-M counter arrangements more than offsets the greater time required in obtaining results with the Wilson cloud-chamber technique. There have been several cloud-chamber determinations of the number of electrons (N) in equilibrium with the penetrating component in dense materials at sea level.[1–5] Practically all of these electrons are high energy collision electrons or their cascade progeny. The present report is concerned with the results of a cloud-chamber study of N at Tioga Pass, Yosemite National Park, California (9950 ft.), in 1942, together with the results of a redetermination of N at sea level from photographs taken by M. A. Starr[6] at Berkeley in 1937.

[1] B. Trumpy, Zeits. f. Physik **111**, 338 (1938).
[2] J. G. Wilson, Nature **142**, 73 (1938).
[3] J. I. Hopkins, W. M. Nielsen, and L. W. Nordheim, Phys. Rev. **55**, 233 (1939).
[4] W. M. Powell, Phys. Rev. **57**, 1061 (1940).
[5] L. Seren, Phys. Rev. **62**, 204 (1942).
[6] M. A. Starr, Phys. Rev. **53**, 6 (1938).

APPARATUS

The front portion of the cloud chamber was a 30×30 cm cylinder containing eight evenly-spaced horizontal lead plates. Each plate had a thickness of 0.6 cm which, together with the steel reflecting sheets glued to each face, constituted the equivalent of a thickness of 0.7 cm of lead. Illumination was provided by discharging a 150-μf condenser bank through each of two cylindrical (2×15 cm) Edgerton-type argon flash tubes. The condenser units were charged to 1800 v with a 2000-v d.c. motor-generator set. The light beams were directed forward and across the chamber at an angle of 50° with the chamber axis. The photographs were taken on Agfa Ultraspeed 35-mm film in a stereoscopic camera equipped with Leitz Hektor 135-mm lenses. With the camera at a distance of 180 cm from the chamber and lens stops of $f:9$ most of the pictures were overexposed. Expansions were made at the rate of one per minute without counter control. The clearing field was reduced one-half second before the expansion in order to lengthen the sensitive time for diffuse tracks; the sensitive time for sharp tracks was of necessity very short even at the optimum expansion ratio,[7] since the lead plates effectively divided the large chamber into a group of small chambers.

The photographs were observed stereoscopically with 5-cm lenses as simple magnifiers; where necessary more accurate observations could be made by reprojection through the camera itself

[7] W. E. Hazen, Rev. Sci. Inst. **13**, 247 (1942).

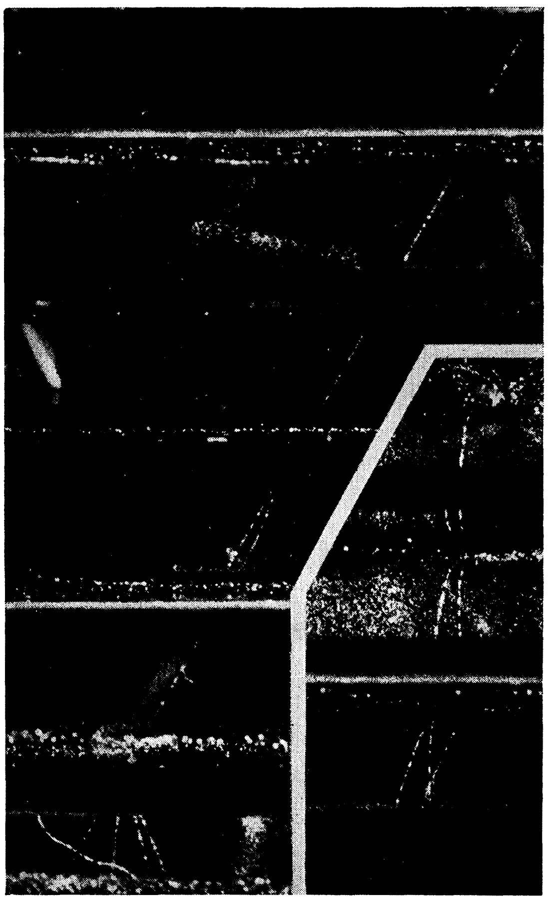


Fig. 1. Example of a penetrating ray accompanied by a single electron from one plate and a group of three electrons from another plate. The insert shows one of the few electrons that might possibly be confused with a mesotron. If the particle were a mesotron with sufficient energy to produce the accompanying electrons, it would continue through the lower plate.

onto an adjustable screen. Examples of the photographs are reproduced in Fig. 1.

RESULTS

Particles which passed through three or more of the lead plates without multiplying were listed as penetrating. From observations of the initial rate of multiplication of the high energy electrons observed in the same series of photographs, it is estimated that less than 0.1 percent of the particles listed as penetrating could have been electrons (see Fig. 1). About three-fourths of the traversals were classed as unsuitable for the observation of knock-on electrons and their progeny, either because they were not in the region of sharp focus or because of the presence of other tracks in the same region. Since only 2.7 percent of the collision electrons were sufficiently energetic to penetrate an additional lead plate, equilibrium was essentially established in the first plate (the correction would be negligible: an addition of one-eighth of 2.7 percent to the total number of accompanying electrons). In 13,260 traversals of a lead plate by a penetrating ray, 981 electrons were observed to emerge with the penetrating ray. Thus the probability (N) that an electron accompanies a penetrating ray in lead at 10,000 ft. is 7.4 ± 0.2 percent. There were five cases of three particles and three cases of four or more particles accompanying a penetrating ray; these were presumably mesotron-initiated electron showers. Two-particle cases were not considered separately from the general total since the probability of the chance occurrence of two unrelated accompanying electrons is of the same magnitude as the probability of occurrence of two shower electrons. Eight heavily ionizing particles were observed to accompany the penetrating rays in lead.

The probability of an electron accompanying a penetrating particle at sea level was redetermined by a study of the counter-controlled photographs taken by Starr.[6] A lead plate whose thickness varied from 0.65 to 1.65 cm in different sets of pictures was placed in the center of the cloud chamber, a 0.63-cm plate in the top of the cloud chamber, and a 0.37-cm plate above the top counter tube. Only those penetrating rays that passed through both of the plates in the cloud chamber were considered and electrons accompanying the selected penetrating rays from the lowest plate were counted. There were 148 electrons resulting from 2200 traversals, or a probability of 6.8 ± 0.6 percent that an electron accompanies a penetrating ray in lead at sea level.

DISCUSSION

The results of the present experiments are compared in Table I with those of previous investigations. In most cases the plate material was lead, in others it was gold or tungsten. The results can be compared directly, however, since the atomic numbers are nearly the same and the value of N varies less rapidly than the atomic number. One of the reproduced photographs with its accompanying description in Trumpy's article[1] indicates that electrons were included whose relation to the penetrating component is questionable; this would explain his high value for N. Since Wilson's chamber was in a strong magnetic field,[2] many low energy electrons would not be observed; hence we expect a low value for the total number of electrons from his data. Seren's value of N for tungsten is rather high; however, the statistical uncertainty is larger than in the other determinations. The other values are in reasonable agreement but it appears likely that subjective errors are not negligible. The values of N determined by the same observer at sea level and at 10,000 ft. are not significantly different.

Bhabha[8] has given a theoretical expression for the number (N) of collision electrons and their cascade progeny accompanying a penetrating ray of given energy and mass. If we make the calculations for a mesotron mass of 200 m (the average of the reliable mass determinations), the results for electrons of all energies as a function of mesotron energy are those indicated in Table II. The average value ($\bar{N}$) for all mesotrons, obtained by a numerical integration of N over the Blackett[9] energy spectrum, is 11 percent. This result is considerably higher than the experimental result of 6.8 percent, but it is not far outside the uncertainty of 30 percent which Bhabha suggests for his equations.

A calculation of $\bar{N}$ was also made for the energy spectrum to be expected at 10,000 ft. The number of mesotrons in an energy band E to $E+dE$ at 10,000 ft. is the number in a band $E-(5\times10^8)$ to $E+dE-(5\times10^8)$ at sea level, since the energy lost in traversing 10,000 ft. of air is 5×10^8 ev. We must also consider the effect of mesotron decay in reducing the number of particles reaching sea level from 10,000 ft. If $n(10M)$ and $n(0)$ are the numbers of mesotrons at 10,000 ft. and sea level, respectively,

$$n(10M)/n(0)=\exp\left[\mu_0 c\Delta h/\tau_0 E\right],$$

where μ_0 and τ_0 are the mesotron mass and lifetime, respectively, Δh is the difference in elevations, and E is the effective energy (approximately the mean energy).[10] The best experimental value for $\mu_0 c/\tau_0$ is probably 1.2×10^3 ev/cm.[11] A numerical integration of N over a 10,000-ft. spectrum obtained as indicated above gives a value of ten percent for $\bar{N}$ whereas the value of $\bar{N}$ calculated for the sea-level spectrum is eleven percent. The difference in the calculated values for $\bar{N}$ at the two altitudes depends on the fact that the cross section for production of high energy collision electrons increases with mesotron energy but it does not depend critically on the details of the subsequent behavior of the collision electrons. Hence the uncertainty in the relative values of $\bar{N}$ is small compared with the uncertainty of 30 percent in the absolute magnitudes since the latter arises almost entirely from uncertainties in the calculations of the cascade process. The observed values for $\bar{N}$ at the two altitudes are not significantly different; as previously mentioned, there are probably other experimental errors at least as large as the statistical uncertainty.

Tamm and Belenky,[12] in a more detailed analysis of the problem, have derived an expression for the number of electrons $N(E)$ with energy greater than a given energy E in equilibrium with mesotrons. If we follow their

TABLE I. The number of electrons (N) in equilibrium with the penetrating component determined experimentally.

		Material	Number of traversals	N in percent	Statistical error
Trumpy (ref. 1)		Lead	800	17	±2
Wilson (ref. 2)		Gold	900	4.8	0.7
Hopkins *et al.* (ref. 3)		Lead	1600	11	1
Powell (ref. 4)		Lead	2500	8.2	0.6
Seren (ref. 5)		Tungsten	500	15	2
		Lead	600	9.7	1
Hazen	Sea level	Lead	2200	6.8	0.6
	10,000 ft.	Lead	13000	7.4	0.2

TABLE II. The number of electrons (N) in equilibrium with a mesotron of mass 200 m and energy W calculated from Bhabha's equations.

W ev	4×10^8	10^9	10^{10}	10^{11}	10^{12}
N percent	0.6	5.4	18	26	32

[8] H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938).

[9] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).

[10] B. Rossi and D. B. Hall, Phys. Rev. **59**, 223 (1941).

[11] B. Rossi, K. Greisen, J. C. Stearns, D. K. Froman, and P. G. Koontz, Phys. Rev. **61**, 675 (1942).

[12] Ig. Tamm and S. Belenky, J. Phys. Acad. Sci. U.S.S.R. **1**, 177 (1939).

method for obtaining numerical results, but use 200 m in place of 160 m for the mesotron mass and Blackett's energy spectrum in place of the Heisenberg-Euler spectrum, we obtain a value for $N(E)$ of fifteen percent with $E=10^6$ ev (twice the experimental result).

Scattering has been neglected. The effective lower limit for the energy of observed electrons is determined by the scattering in lead, since scattering decreases the component of an electron's range parallel to the mesotron path by a factor which increases with decreasing electron energy. Sheppard and Fowler[13] have found that the mean scattering angle (θ) for electrons with energy (E) less than 10^7 ev in thin lead plates of thickness (t) is approximately

$$\theta=500t^{\frac{1}{2}}/E,$$

where E is in Mev and θ in degrees. If we consider the mean scattering angle for an electron which has travelled one-tenth of its range, we find that

$$\theta=30E^{-\frac{1}{2}}.$$

Thus the observed number of one-Mev electrons would be greatly reduced by scattering, whereas the observed number of ten-Mev electrons would not be appreciably altered. An effective lower limit would be in the neighborhood of two or three Mev and the resulting value for $N(E)$ would be 7.5 or 8.5 percent, in substantial agreement with the experimental values.

E. J. Williams[14] has calculated values for $N(E)$ using cascade theory only in estimating the number of electrons with energy less than E. His results for $E=3\times10^6$ ev indicate a value for N between eight and thirteen percent in lead.

The agreement between experimental and theoretical values for the number of electrons in equilibrium with mesotrons in lead indicates that the theoretical values for air are probably about right. For air we obtain from the equations of Tamm and Belenky $N=11$ percent for $E=2.5\times10^6$ ev and $N=5.5$ percent for $E=10^7$ ev; Williams gives $N=12$ to 16 percent in air for $E=3\times10^6$ ev, and Rossi and Klapman[15] give $N=6.7$ percent for $E=10^7$ ev.

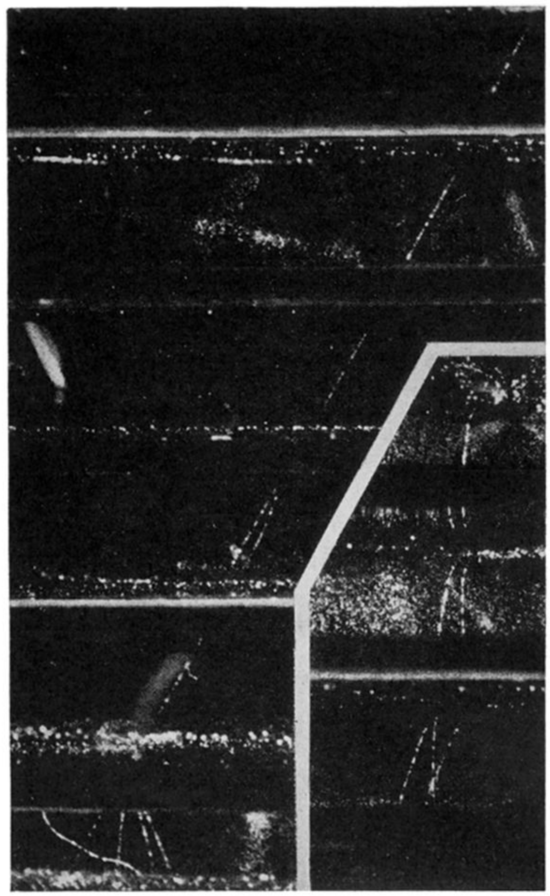
Considerable indirect evidence has already been accumulated indicating that high energy cosmic rays in the lower atmosphere are mostly mesotrons. The present results constitute another piece of evidence indicating that protons constitute only a minor fraction of the high energy cosmic rays if we assume that the theoretical values for N are correct. Since the number of electrons in equilibrium with protons of energy 10^{10} ev is only one-third as great as with mesotrons of the same energy and the number in equilibrium with protons of energy 3×10^9 ev is negligible, an admixture of ten or fifteen percent protons would lower N more than ten percent.

The author wishes to express his appreciation for the generous cooperation of Superintendent Frank A. Kittredge and other members of the staff of Yosemite National Park.

[13] C. W. Sheppard and W. A. Fowler, Phys. Rev. **57**, 273 (1940).

[14] E. J. Williams, Proc. Camb. Phil. Soc. **36**, 183 (1940).

[15] B. Rossi and S. J. Klapman, Phys. Rev. **61**, 414 (1942).



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