Precision Cosmic-Ray Measurements up to Within a Percent or Two of the Top of the Atmosphere

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(Received September 15, 1936)

Self-recording, constant pressure, argon-filled electroscopes sent into the stratosphere by sounding balloons at San Antonio, Texas, mag. lat. 39°N, yielded accurate readings of cosmic-ray intensities up to an altitude 98.3 percent of the way to the top of the atmosphere, where the pressure is but 12.9 mm of Hg. The ionization within these electroscopes passes through a definite maximum at 47.6 mm of Hg and falls 22 percent in rising to where the pressure is 12.9 mm of Hg. These results, combined with similar accurate measurements on the variation of cosmic-ray intensities as a function of latitude, both at sea level and at altitudes of 22,000 feet, indicate (1) that atmospheric cosmic-ray ionization is not produced in appreciable amount by incoming *protons*, and (2) that the Oppenheimer-Bethe-Heitler law of nuclear absorption is not valid for incoming electrons of a few billion *e*-volts of energy.

§1. THE PROBLEM

ALL cosmic-ray measurements at altitudes above those that can be reached by aeroplanes or by manned balloons have suffered from the limitation that though the rate of discharge of electroscopes at the highest altitudes attainable is in general of the order of 200 times that at sea level, yet we who have used this method (Bowen and Millikan[1] and Regener[2]) have been obliged to get our rates of discharge at all altitudes, low or high, from one single discharge of the electroscope spread over the whole time of ascent, or even ascent and descent. This means that if the electroscope has a sensitivity suitable to reasonable accuracy at high altitudes it is practically useless at low altitudes; and if adjusted to give good readings at low and intermediate altitudes it discharges almost instantly at high altitudes and hence yields no useful record at all.

The Neher electroscope, which charges up automatically from a battery, say every five minutes during a three or four-hour flight, eliminates this difficulty and multiplies the dependability of the measurements themselves that are involved in the determination of *the shape* of the whole cosmic-ray, altitude-ionization curve by the number of such rechargings taking place during the flight, i.e., by practically forty-fold in a three and a half-hour flight. Of course the fluctuations that are inherent in the rays themselves are quite beyond such control. The high altitude work done with the Neher electroscope in aeroplane and manned balloon flights is, then, very dependable up to the altitudes reached (62,000 ft. in the Fordney-Settle flight[3]), but for the higher reaches of the atmosphere we have up to the present had no way of repeatedly charging the detecting electroscopes for the reason that the weight involved precluded the carrying up of a three or four-hundred-volt battery. Two years ago, therefore, in the Norman Bridge Laboratory, Neher and Haynes went at the problem of trying to make condensers of sufficient lightness, electrical capacity and freedom from leakage to enable them to replace batteries as recharging sources. These condensers were tried out in August, 1935, in flights made by Millikan and Neher in collaboration with Colonel Prosser and the staff of the Signal Corps of the U. S. Army at Fort Sam Houston, San Antonio, Texas, but because of the imperfections both of the condensers and the balloons used no records higher than to 45,000 feet were then obtained.

By July, 1936, however, the foregoing weaknesses had been so completely eliminated that condensers of practically infinite capacity (10,000 cm) with respect to the capacity of the electroscope system could be used for three hours under the severe conditions existing in a strato-

* At the date of publishing at Williams College, Massachusetts.

[1] Bowen and Millikan, Phys. Rev. **43**, 695 (1933); **44**, 246 (1933); also Bowen, Millikan and Neher, *Nuclear Physics* (Cambridge University Press, 1934), p. 221.

[2] Regener and Pfolzer, Physik Zeits. **35**, 782 (1934).

[3] Bowen, Millikan and Neher, Phys. Rev. **46**, 650 (1934). The Stevens-Anderson 1935 flight reached 72,000 feet but unfortunately no electroscopes were taken up in the gondola.

sphere flight without a leakage of more than one-half percent per hour. Also, the new balloons made by the Dewey and Almy Chemical Company of Cambridge, Mass. proved to be peculiarly well adapted to obtaining very dependable cosmic-ray electroscope readings at the highest altitudes thus far attained in such work. It is the results of these flights that are reported herewith.

§2. The Flights

On July 6th, 7th and 8th, 1936, Millikan and Neher, in collaboration with Colonel Prosser, Lieutenant Mathews, and the staff of the Signal Corps Unit at Fort Sam Houston, sent up into the stratosphere five different Neher self-recording electroscopes which were automatically charged up every four minutes during the flight from Neher-Haynes condensers. The total weight of each instrument itself, with its clockwork, photographic film, recording barometer, thermometer and electroscope was 1200 grams, or about 2.5 pounds. With the parachute, the steel-wire basket for breaking the fall, the insulating covering for keeping the temperature nearly constant, and the supporting tape and cord, the total weight lifted, without counting the balloons themselves, was 1400 grams. A string of five balloons of one-meter diameter, when not at all stretched, arranged in tandem 20 feet apart were so inflated as to provide a lift which assured a rate of ascent of from 150 to 200 meters a minute. The whole string, with parachute and basket attached, was about 130 feet long. It is shown just ready to start with its load into the stratosphere in Fig. 1. (In this particular flight only four balloons were used, in all other flights, five were used.) This string makes a nicely visible object for eye or theodolite observation, but its chief advantage is the following. As it approaches the top of its flight the bursting of one balloon slows down the rate of rise considerably, the bursting of the second balloon enables the instrument to remain at nearly the same level for a long time or until a third balloon breaks, when it begins to descend. There is thus an automatic "leveling off" period such as a pilot can make in aeroplane ascents, and this occurs just where accurate readings are most needed.

The clock was provided with a special contact which at the end of three and a half hours detached the parachute, and the instrument hanging from it, from the string of balloons so that it could be brought relatively rapidly back to earth. The parachute was of red silk so as to attract the attention of farmers or passers by, and an envelope offering a reward for the return of the instrument was attached.

Three of the five instruments came back within two days of the flight, two having been found within twelve hours of their fall. All of these had good records, two of which are shown herewith. The third is now being measured, and the fourth has come back just at the time of writing, possibly with the record of the highest altitude reached. This instrument lay for two months underneath a tree in which the parachute caught, and flagged successfully, though belatedly, a passing horseman. It fell within thirty miles of San Antonio, while the other three fell some eighty miles distant from the starting point. The fifth instrument is still to be heard from.

§3. The Records

The amount of the change in temperature within the instruments during a flight was only some 20°C. All of the inclosed electroscopes, barometers and thermometers, were tested shortly before the flights in our laboratory vacuum chamber under essentially the conditions of the flight, so that the readings of all of them on the film were quickly obtained in terms of the laboratory's standard mercury manometers, thermometers, and electroscopes.

The sharpness of the lines on the film corresponding to barometer, thermometer and electroscope readings can be seen from the reproduction of the two films shown in Fig. 2. When measurements of these lines were made under the microscope of a comparator the barometer readings could everywhere be determined to within less than half of a millimeter of mercury. One of these two instruments rose to a point at which the pressure was 30.7 mm of Hg, the other to a point at which the barometer read but 12.9 mm of mercury. This latter reading corresponds to 98.3 percent of the way to the top of the atmosphere. It is the highest flight thus far made at which electroscope readings have been taken. What is the corresponding altitude *in feet* is not important since what we seek is cosmic-ray

FIG. 1. Launching electroscope for stratosphere flights.

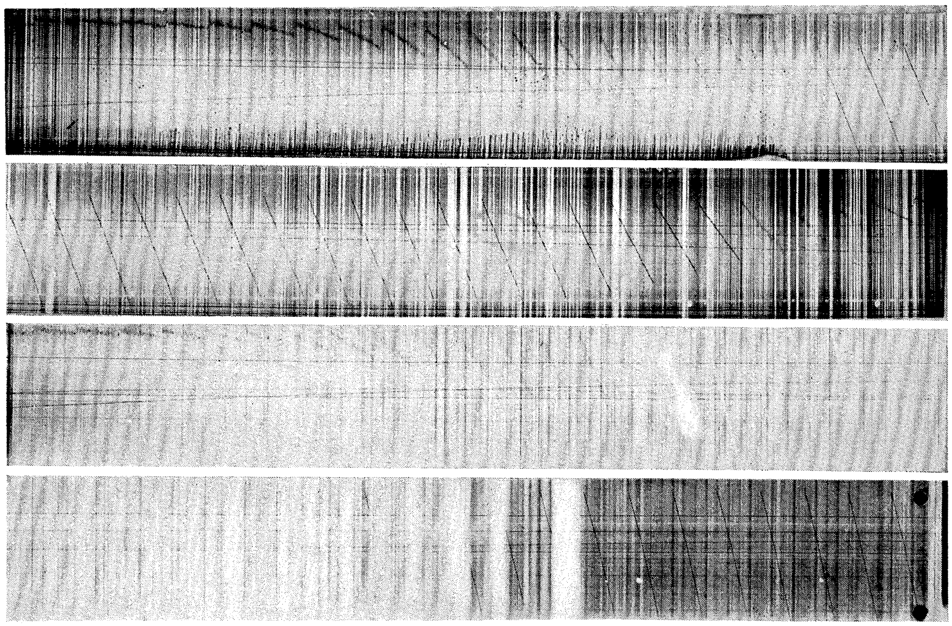


FIG. 2. The records of two separate flights. The two upper panels show the first half and the second half of the same film which has been cut in two in the middle. Similarly for the two lower panels. *B*, barometer line; *T*, thermometer line; *F*, fiducial line.

intensity as a function of the amount of air above the measuring instrument. This is given directly by the barometer reading. The reduction to altitudes measured in kilometers or feet can, of course, be made by the use of standard reduction tables if desired. The result will depend somewhat upon whose tables are used. Regener has heretofore made this reduction in terms of the "summer tables" given by Humphreys.[4] These tables give an altitude corresponding to 30.7 mm of Hg of 72,000 ft. and to 12.9 mm of Hg of 92,000 ft, or somewhat more than 28 kilometers.

As can be seen from Fig. 2, the film corresponding to instrument No. 0 is perfect from beginning to end. The rate of discharge of the electroscope is obtained from the slopes of the discharge lines which are so fine and clear that they can be measured with a very high precision. As can be seen from the film, the successive slopes cover the whole period of ascent and a portion of the descent before the release of the parachute and instrument occurred. This had been arranged to take place at the very end of the film.

The film corresponding to instrument No. 2 shows an excellent electroscope record up to the point at which the pressure was 12.5 cm of Hg. It then becomes illegible because too much sunlight blackened the film, but at the higher altitudes the record becomes a particularly sharp and perfect one of all three readings, barometer, thermometer and electroscope. The way in which the records of the two different flights agree is very convincing evidence of their dependability, as is also the agreement between the readings corresponding to ascent and descent in the case of No. 0.

§4. Results

The most striking result of these flights is shown in Fig. 3. It is, namely, this. At an altitude corresponding to a barometeric pressure of 47.6 mm of mercury or 64 cm of water in the argon-filled pressure electroscope, the ionization, which has been rising nearly exponentially up to 2 m of water, as shown in Fig. 4, suddenly reaches a maximum and then falls rapidly as the instrument continues to rise. By the time the pressure has fallen to 12.9 mm (92,000 ft.) it is 22 percent below the maximum value. Of course this means that the incoming rays, which are practically certainly a mixture of protons and electrons in

[4] Humphreys, *Physics of the Air* (1929), p. 74.

some as yet undetermined proportion, must penetrate down to a depth of 64 cm of water, or 47.6 mm of mercury, below the top of the atmosphere before, on the average in view of their direction as well as their composition, they get into equilibrium with their secondaries.

This is the first time this phenomenon has been observed when an electroscope, a single counter tube, or any instrument which responds to rays coming in from all directions has been used as the detector. A pair of counter-tubes arranged vertically so as to respond to rays coming in only

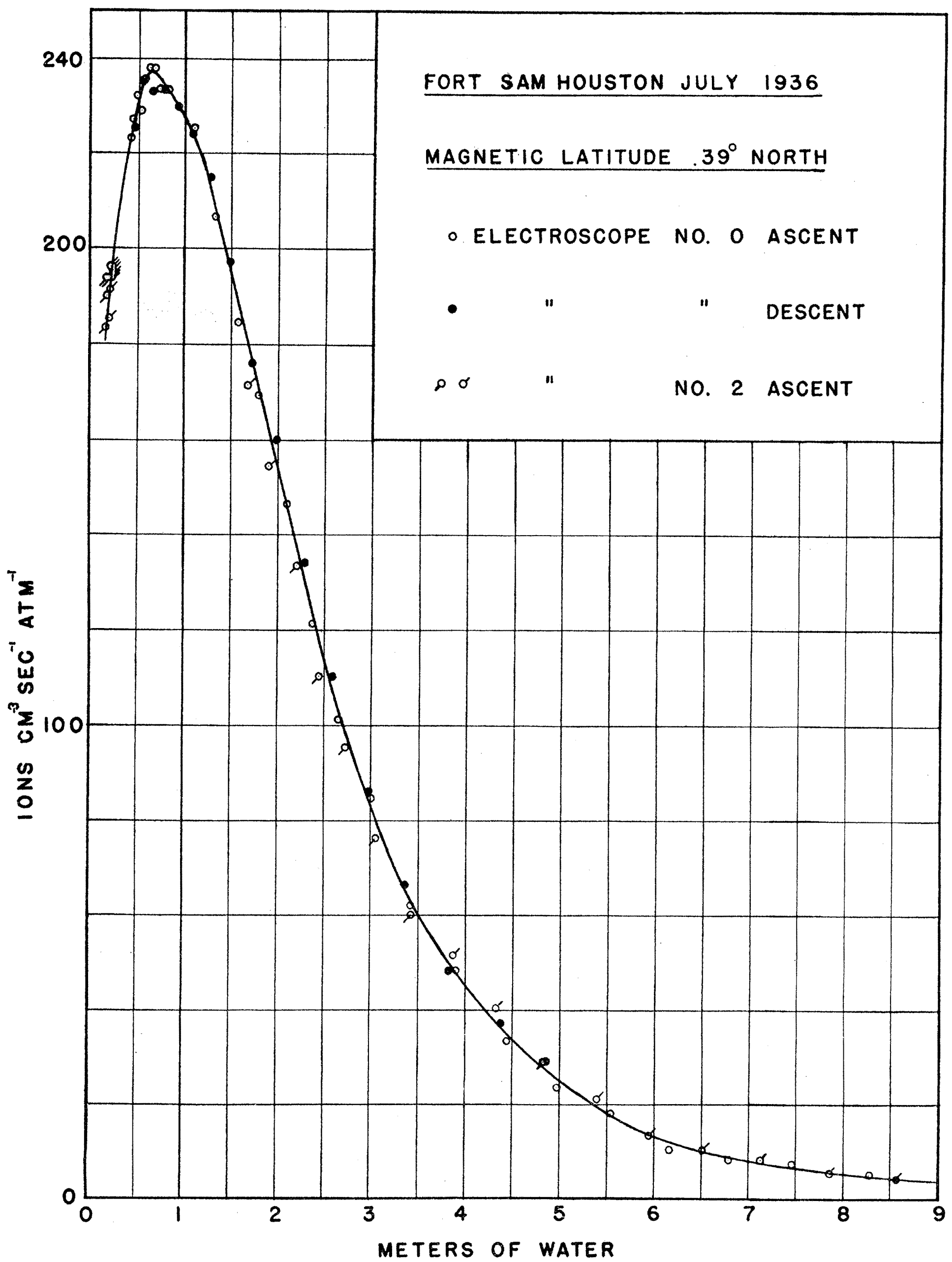


FIG. 3. Altitude-ionization curve for both flights, reduced to ions per cc at atmospheric pressure. The pressures are in meters of water below the top of the atmosphere (10 m = 1 atmos.).

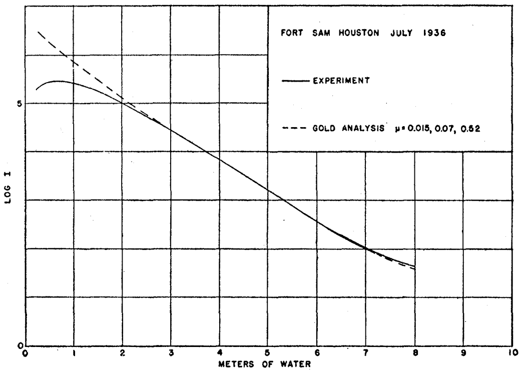


FIG. 4. Altitude-ionization curve plotted on logarithmic scale to show how well the three coefficients $\mu = 0.52$, $\mu = 0.07$, and $\mu = 0.015$ per m of water reproduce the observed curve.

from above shows a corresponding behavior at lower altitudes, as very recently reported by both Regener and Swann and as can be computed theoretically from Fig. 3 by the Gross[5] analysis without making any additional physical assumptions whatever.

Regener, using the single discharge method spoken of in §1, has made flights in Germany in magnetic latitudes about 50°N and reached an altitude very close to that here obtained, but his altitude-ionization curve showed only a flattening at the top[2] and not the marked drop in ionization shown in Fig. 3. The explanation of the difference between his curve taken in magnetic latitude 50°N and ours taken in magnetic latitude 39°N seems to require, as do some preceding experiments of ours, the breakdown in the field of cosmic rays of the Oppenheimer-Bethe-Heitler law of the nuclear absorption of electrons.

To see why this is so it is first necessary to discuss the new evidence for the conclusion that *incoming electrons (+ and −) not protons or other heavy charged particles produce practically all of the atmospheric ionization that is due to incoming particles at all.*

§5. Evidence that Protons Do Not Enter the Earth's Atmosphere in Appreciable Numbers

A Precision World Survey of sea-level cosmic-ray intensities[6] begun in 1932, was last year completed and published. Through it there has been established a world chart of equal cosmic-ray intensity lines. This chart first appeared in the Carnegie Institution Year Book No. 35, issued December 13, 1935.[6] It was the first such chart ever published. The new evidence for the foregoing conclusion is found in the fact that this precision survey shows that there is but one magnetic latitude, not two, at which in going southward from the north magnetic pole a sudden decrease occurs in the intensity of the sea-level cosmic-ray ionization, namely in mag. lat. 41°, just south of Pasadena. This, combined with the great constancy in the value of the sea-level ionization in going north from Pasadena to Victoria B.C. and then from Victoria to Churchill Manitoba, as shown by the tables found on p. 19 of the foregoing reference,[6] is inconsistent with the idea that the incoming cosmic rays contain an appreciable number of protons, or, indeed, of other heavy charged particles.

The single discontinuity at magnetic latitude 41° occurs because in that latitude it requires six billion volt electrons to get through in appreciable numbers the blocking effect of the earth's magnetic field, and it also requires six billion volt electrons to get through the resistance of the atmosphere. Electrons of smaller energy than this, such as get through the earth's magnetic field in large numbers farther north than 41°, cannot penetrate the atmosphere and make their effects felt at sea level. *This alone can account for the great constancy of the sea-level ionization north of magnetic latitude 41°.*

If protons came in from outside in appreciable numbers they must get through the atmosphere more easily than do electrons, since such heavy particles, unlike electrons, do not produce x-rays, i.e., do not make radiative collisions in plunging through matter, and yet at these speeds ionize the atoms through which they pass in essentially the same way as do electrons. Indeed, the resistance of the atmosphere for them is between 2 and 3 billion electron volts, instead of 6 billion electron volts as in the case of electrons, for we have shown[7] that radiative collisions account for about half of the resistance of the atmosphere to the passage of electrons.

On the other hand, high energy protons experi-

[5] Zeits. f. Physik **83**, 214 (1933).
[6] See also Phys. Rev. **50**, 15 (1936).
[7] *International Conference on Nuclear Physics* (Cambridge University Press, 1934), p. 206.

ence practically the same difficulty in getting through the blocking effect of the earth's magnetic field as do electrons. Hence, if they came into the earth in appreciable numbers they would be found at sea level in increasing numbers in going north from latitude 41° and in magnetic latitude about 54°, where the blocking effect of the earth's magnetic field is some 2.5 billion electron volts, they would produce a sea-level discontinuity such as incoming electrons produce at magnetic latitude 41°. The two facts, then, (1) that there is but one such discontinuity instead of two or more, and (2) that the sea-level ionization is constant between 41°N and 54°N instead of continuously rising, mean that *there is but one kind of incoming charged particle, namely + and − electrons.*

§6. Evidence for the Breakdown of the Oppenheimer-Bethe-Heitler Law in the Field of Cosmic Rays

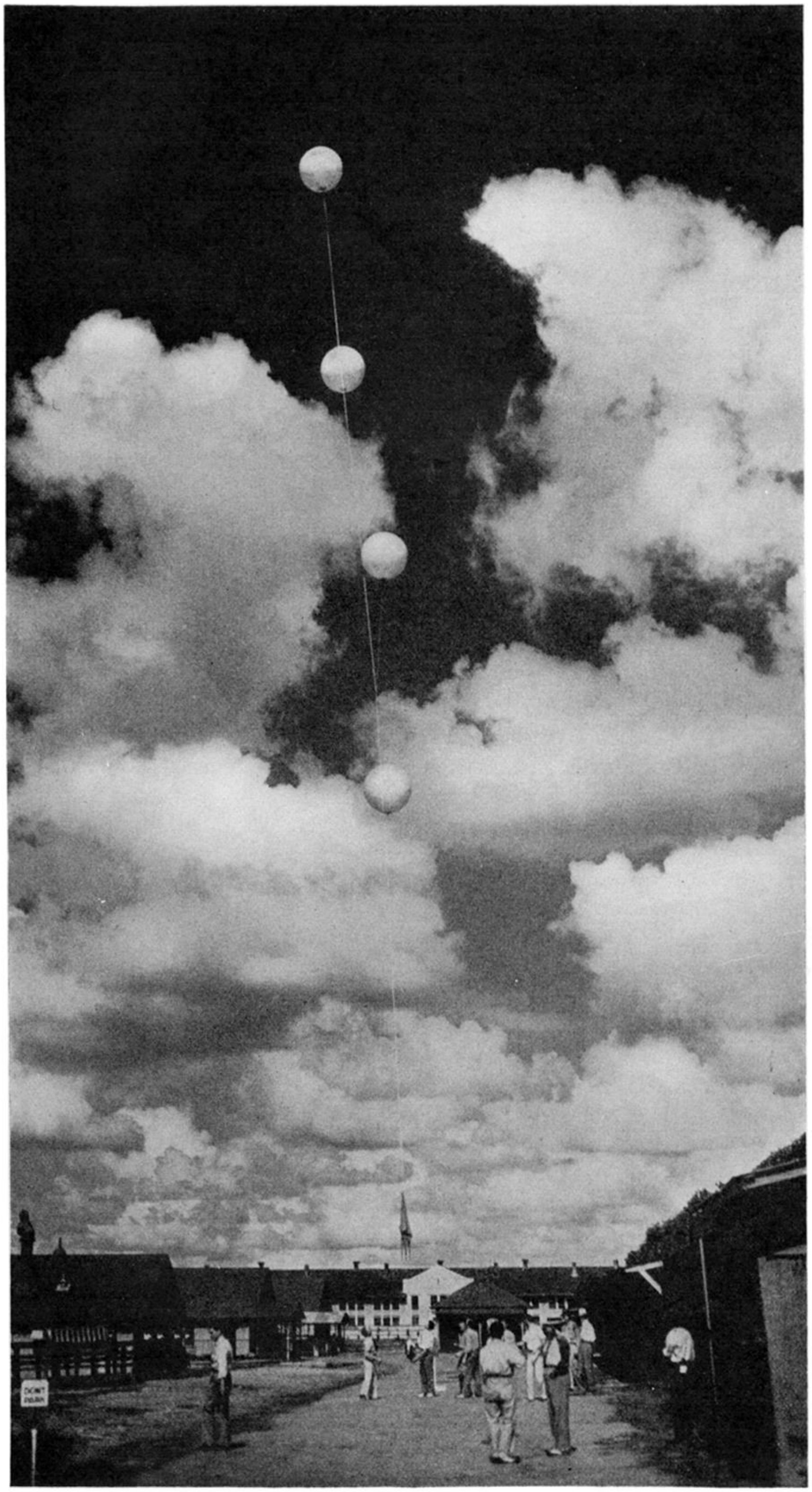
Bowen, Millikan and Neher have already shown[8] that the altitude-ionization curve taken at Spokane (magnetic latitude 54°N) up to 22,000 feet is identical with the altitude-ionization curve taken up to the same altitude at Cormorant Lake, magnetic latitude 63°N, while the same curve taken at Pasadena (mag. lat. 41°) is markedly lower than that at Spokane. This shows that the effects of the 2.5 billion volt electrons that can just get through the blocking effect of the earth's magnetic field in the latitude of Spokane cannot reach down to an altitude of 22,000 feet, though they are abundantly found above that altitude and though the effects of the electrons of energies between 2.5 and 6 billion electron volts make all the difference between the Spokane and Pasadena curves up to 22,000 feet. These definite proofs of a *range* in the incoming electrons of less than half an atmosphere for 2.5 billion volt electrons, and a range of a whole atmosphere for 6 billion volt electrons, show that the Oppenheimer-Bethe-Heitler absorption law heretofore proved to hold for low energy electrons cannot hold for energies of a few billion electron volts. For this law requires the absorption produced by a given thickness of matter to be proportional to the energy of the electrons incident upon it, and this means that 6 billion volt electrons would have nearly the same penetrating power as 2.5 billion volt electrons. That this is not the case is proved by the fact that at Pasadena the effect of incoming 6 billion volt electrons is felt at sea level, whereas the constancy of the ionization at an altitude of 22,000 feet between Spokane and Cormorant Lake means that the effect of 2.5 billion volt electrons cannot penetrate down to an altitude of 22,000 feet above the earth's surface. *In other words, 6 billion volt electrons actually are found to have more than twice the penetrating power, or range, of 2.5 billion volt electrons. This is in violation of the Oppenheimer-Bethe-Heitler law.*

The same relation is again shown qualitatively in the difference between Regener's curve at mag. lat. 50°N and Fig. 3 taken at mag. lat. 39°N. The whole difference between the two curves must be due to the difference in the energies of the electrons that can get through the blocking effect of the earth's magnetic field in mag. lat. 50°N and in mag. lat. 39°N for the proton component of the incoming rays must be the same in both latitudes. The electrons that get in at 50°N do not penetrate as far down into the atmosphere before they get into equilibrium with their secondaries, as do the electrons that get in at 39°. As in the preceding discussion, this shows, then, the breakdown at high energies of the Oppenheimer-Bethe-Heitler law of nuclear absorption of the electronic component of the cosmic rays.

This investigation has been carried out with the aid of funds provided by the Carnegie Corporation of New York, administered by the Carnegie Institution of Washington, to which organizations we wish to express our hearty thanks. The very skillful mechanical work involved in the construction of the electroscopes has been done by Mr. Julius Pearson. Many helpful suggestions have been contributed by Professor I. S. Bowen.[9]

[8] *International Conference on Nuclear Physics* (Cambridge University Press (1934), p. 210.

[9] As this proof was being read a detailed account by Georg P. Fotzer (Zeits. f. Physik **102**, 41 (1936)) of the experiments from Regener's laboratory in which vertical counters are sent in balloons to as high altitudes as those here reached, came to hand. By the "Gross transformation" our curve (Fig. 3) becomes transformed into one resembling his observed curve save for such differences as are to be expected from the difference in latitude and in instrumental precision.



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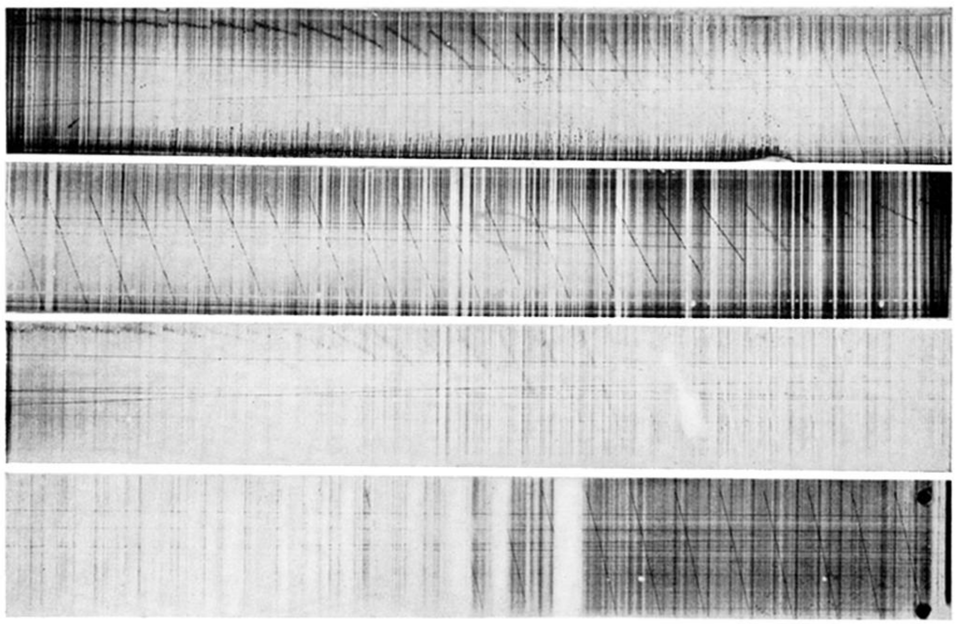

FIG. 2. The records of two separate flights. The two upper panels show the first half and the second half of the same film which has been cut in two in the middle. Similarly for the two lower panels. *B*, barometer line; *T*, thermometer line; *F*, fiducial line.