

layer is not altered by a five-hundred fold change in the surrounding pressure. Further evidence for believing that a condition characteristic of the metal itself has been reached is furnished by the fact that the photoelectric sensitivity of an outgassed specimen remains constant for twelve hours after heat treatment. The work of Davisson and Germer⁹ on electron reflection from nickel is also against such a point of view. They found that it takes several hours for the characteristic reflection to be obscured by the accumulation of gas on the surface.

The work is being continued and a more complete report will be published soon.

In conclusion, the author desires to acknowledge his appreciation to Dr. C. E. Mendenhall, under whose direction the work was carried on.

¹ DuBridge, *Phys. Rev.*, **29**, 451 (1927).

² Warner, *Proc. Nat. Acad. Sci.*, **13**, 56 (1927).

³ Kazda, *Phys. Rev.*, **26**, 643 (1925).

⁴ Dushman and Found, *Phys. Rev.*, **23**, 734 (1924).

⁵ Burgess and Kellberg, *Bull. Bur. Stds.*, **11**, 457 (1914-15).

⁶ Welch, Abstr. 19, N. Y. Meeting Amer. Phys. Soc. (1928).

⁷ Burgess and Scott, *Bull. Bur. Stds.*, **14**, 15 (1918).

⁸ Goetz, *Phys. Zeit.*, **24**, 379 (1924).

⁹ Davisson and Germer, *Phys. Rev.*, **30**, 705 (1927).

EVIDENCE FOR THE CONTINUOUS CREATION OF THE
COMMON ELEMENTS OUT OF POSITIVE AND
NEGATIVE ELECTRONS

BY R. A. MILLIKAN AND G. HARVEY CAMERON

NORMAN BRIDGE LABORATORY OF PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY

Read before the Academy April 23, 1928

The evidence obtained from the study of cosmic rays that the more stable and more abundant elements like helium (abundant in the heavens), oxygen, silicon and iron, are being formed *at the present time* out of the primordial positive and negative electrons, the former of which is the nucleus of the hydrogen atom, may be briefly summarized as follows:

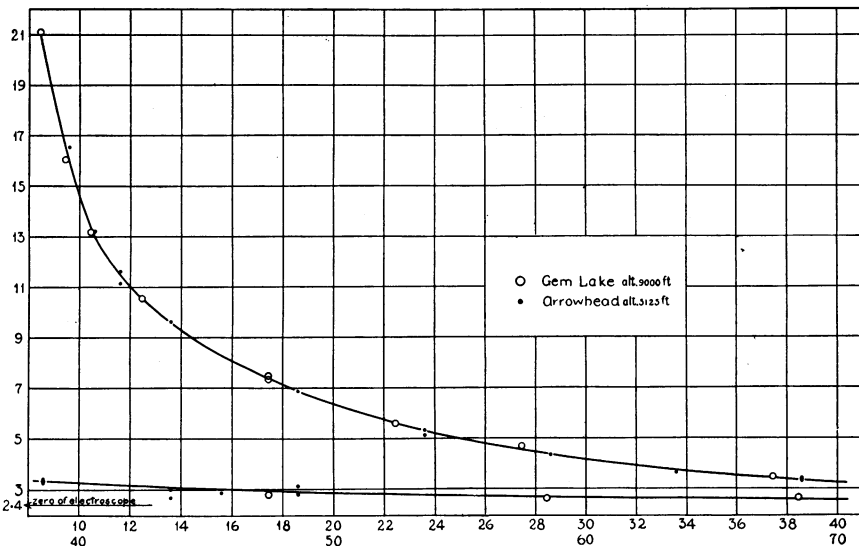
First.—The pilot-balloon experiments of Millikan and Bowen,¹ in which they sent up recording electroscopes 0.92 of the way to the top of the atmosphere and in which the absorption coefficient of the cosmic rays at, or near, the top of the atmosphere came out of the same order of magnitude as that found near sea-level,² show conclusively that these rays consist of a definite and distinct region of spectral frequencies, or oscillations, a hundred times more rapid than those produced by the most powerful sub-atomic changes heretofore known, namely, those accompanying radio-

active processes. Otherwise stated, these experiments show conclusively that there are no radiations of appreciable intensity entering the earth's atmosphere having frequencies intermediate between those of the gamma rays and those of the cosmic rays. For, since the hardest gamma rays are capable of penetrating a thickness of about 70 cm. of water, while, as indicated below, the cosmic rays are capable of penetrating 70 m. of water, and since penetrating power increases approximately as frequency, if rays of appreciable intensity came into the atmosphere having frequencies between those of gamma rays and those of the cosmic rays they would of necessity have caused the rapid discharge of an electroscope which rose to within the equivalent of 80 cm. of water of the top of the atmosphere, the whole of the earth's atmosphere being the equivalent of 10 m. of water. No such rapid discharge took place; hence there are no *strong* radiations entering the earth's atmosphere in that particular region of frequencies.

Second.—The experiments of Millikan and Cameron of the last Summer and Fall made in deep, high-altitude California lakes, with new electroscopes eight times more sensitive than those the authors had theretofore used, brought to light the definite proof that the cosmic-ray spectrum consists of definite bands, like those of neon or mercury lamps, containing spectral lines as much as three octaves apart, the highest frequency band having so enormous a penetrating power that it passes through as much as 200 feet of water (18 feet of lead) before becoming completely absorbed. This discovery of a banded structure in the cosmic rays shows that they are not produced as are x-rays by the impact upon the atoms of matter of electrons which have acquired large velocities by falling through powerful electrical fields as we earlier suggested³—the fields needed to produce frequencies of the order of the cosmic rays would be at least 150,000,000 volts—(3000 times as great as the field existing in x-ray tubes)—but that *they are rather produced by definite and continually recurring atomic transformations involving very much greater energy-changes than any occurring in radio-active processes.* The proof of the banded structure of the cosmic-ray spectrum is found in the fact that the new ionization-depth curve, (figure 1) which is seen to be of very much higher resolving power than any heretofore obtained, when taken in connection with the sounding balloon data, shows a nearly constant absorption coefficient from close to the top of the atmosphere down to about sea-level, 10 m. below the top, then bends quite suddenly and uncovers below 15 m. a new absorption coefficient, of only about one-sixth the former value, which continues down to 70 m. below the top with but little further change. The cosmic rays, therefore, consist of at least two, possibly more (see below), radiation bands of absorption coefficients (and therefore, roughly, also of frequencies) in the ratio 6 to 1. The sharpness of the bend in the ionization-depth curve is completely incompatible with any general dis-

tribution of the frequencies of cosmic rays, like that found in white light, or in the general x-radiation which is produced by the bombardment of the atoms of a target by high-speed electrons (cathode rays).

Third.—If the Einstein special theory of relativity may be taken as a sound basis of reasoning—and no results predicted by it have ever thus far been shown to be incorrect, while it has many striking successes to its credit—then it follows that radiant energy can never escape from an atomic system without the disappearance of an equivalent amount of mass from that system, these relations being contained in the now well-known and universally used equation of Einstein (1905) $Mc^2 = E$, where M is mass in grams, c is the velocity of light in centimeters per second and E is



Ionization in cc./sec. against depth in equivalent m. of water beneath top of atmosphere; upper curve 8 m. to 40 m., lower 38 m. to 70 m.

energy in ergs. Now through the recent, very exact work of Aston⁴ we know the mass of every one of the atoms with a great deal of certainty, and we can therefore compute the amount of ether-wave energy that can be generated by any sort of atomic transformation that can take place, and knowing this energy we can compute with the aid of the Einstein equation the frequency, and with the aid of the Dirac formula⁵ the penetrating powers of the rays resulting from all possible atomic transformations. *Such studies reveal the fact that there are no possible transformations capable of yielding rays of the enormous penetrating power observed by Millikan and Cameron except those corresponding to the building up or creation of the abundant elements like helium, oxygen, silicon and iron out of hydrogen, or in the case of the last two elements out of helium.* The entire annihilation

of hydrogen by the falling completely together of its positive and negative electrons might be an additional possibility, but it can be eliminated in this case for two excellent reasons. The first of these reasons is that there is practically no place whatever for such a radiation to occupy in the observed ionization-depth curve (see Fig. 1), for it would be between four and five times more penetrating than the radiation that has the smallest absorption coefficient mentioned above. The ionization due to it, if it exists, would then have to be included in the 2.4 ions which represents the "zero of the electroscope" as shown in the figure. But this 2.4 ions is only about one-tenth of the observed ionization at the top of the curve, viz., 21 ions, this topmost reading corresponding to a depth of 1 m. below the surface of Gem Lake. So that this hypothetical radiation can have nothing to do with the observed ionization-depth curve much above the reading 2.4, and below it there is of course room only for a radiation relatively negligible in intensity in comparison with the softer rays that are responsible for the observed curve. The second reason is that this hypothetical radiation, if it were present, would of necessity be homogeneous, and could not therefore exhibit the banded structure shown by the observed cosmic rays. Whether then this act of the entire annihilation of the hydrogen atom through the coming into complete coincidence of the positive and negative electrons takes place or not, it can certainly be eliminated as a cause of the *observed* cosmic rays. There remains, then, no other atomic transformation in which sufficient mass disappears to create the observed cosmic rays except the aforementioned *atom-building* processes. It is important to note that no step-by-step process of building up, or for that matter of disintegrating of atoms, in which one positive electron or one alpha particle is added or subtracted at a time will suffice for the generation of the cosmic rays, since the Einstein equation tells us that in no case can such a transformation produce rays of more than from one-fourth to one-twenty-fifth of the observed penetrating power. The observed extraordinarily penetrating cosmic rays present, then, when taken in connection with Einstein's equation and Aston's findings not only the first direct evidence that the more abundant elements *are now in process* of being created out of positive and negative electrons, but they also present the first indications as to the general character of the specific act or acts by which the atom-building process goes on. So far we have used only the general or qualitative evidence but it will be seen that from it alone the conclusion is scarcely escapable that the powerful cosmic rays here studied can be produced only by the creation *in a single act*, rather than by a step-by-step process, of some, at least, of the common elements out of the primordial positive and negative electrons.

Fourth.—The evidence herewith obtained is, however, not merely qualitative but fairly accurately *quantitative*. For we analyzed very

carefully our cosmic-ray curve empirically before we called on any theoretical considerations whatever to explain it, and we reported in scientific papers that our observed curve demanded three cosmic-ray bands of absorption coefficients 0.35, 0.08 and 0.04 per meter of water, respectively. It was after this work had been done, reported in seminars, written up and prepared for publication in essentially the form in which it will appear⁶ that we set about computing from the foregoing considerations what the theoretical absorption coefficients would be if our observed cosmic rays were produced (1) by the formation in one single act of helium out of hydrogen, (2) by the similar formation of oxygen out of hydrogen and (3) by the formation of silicon out of hydrogen. The results of this computation came out 0.30, 0.075 and 0.043, well within the limits of the resolving power of our curve of the observed values. Further, there are only a few elements so abundant that their formation needs to be considered as the possible source of the observed cosmic rays. For the spectroscopy of the heavens shows a very great abundance everywhere of the gases hydrogen, helium and nebium. But Bowen⁷ has just identified the last as nitrogen and oxygen so that these gaseous elements, hydrogen, helium, nitrogen and oxygen seem to be extraordinarily widely spread through space. As to the elements found in solids the meteorites have 96 per cent of their mass in the four elements, oxygen, magnesium, silicon and iron. Magnesium and silicon are close together in atomic weight, 24 and 28, respectively, so that their formation would constitute but one band, the mean energy of which lies approximately at $\mu = 0.04$. It was this joint band that we above called for convenience the silicon band. Similarly the atomic weights of nitrogen and oxygen are respectively 14 and 16, and the mean absorption coefficient 0.08 corresponds to this joint band. The helium band, most significant of all, corresponds to $\mu = 0.30$. There is no other abundant element except iron, and the formation of this out of hydrogen gives a cosmic ray for which $\mu = 0.021$. The existence of such a radiation helps rather than interferes with the fit of our theoretical and experimental curves, but on account of the lack of resolving power in the lower end of our curve it furnishes no trustworthy evidence that this particular act is the one by which iron is most commonly formed. This uncertainty does not exist however with respect to the bands corresponding to $\mu = 0.30$, $\mu = 0.08$ and $\mu = 0.04$. *This whole work constitutes, then, very powerful evidence that the sort of creative, or atom-building processes discussed above, are continually going on all about us, possibly also even on the earth, and that each such event is broadcast through the heavens in the form of the appropriate cosmic ray.*

¹ Millikan and Bowen, *Phys. Rev.*, **22**, 198 (1923); **27**, 353 (1926).

² Millikan and Cameron, *Ibid.*, **31**, 163 (1928).

³ Millikan and Cameron, *Nature*, **121**, 24 (1928).

⁴ Aston, *Proc. Roy. Soc.*, **115**, 487 (1927).⁵ Dirac, *Ibid.*, **109**, 206 (1925).⁶ Millikan and Cameron, *Phys. Rev.*, June, 1928.⁷ Bowen, *Astrophys. Jour.*, **57**, 1 (1928).

THE GENERAL X-RADIATION FROM MERCURY VAPOR

BY WILLIAM DUANE

DEPARTMENT OF PHYSICS, HARVARD UNIVERSITY

Communicated May 1, 1928

A recently published note¹ described experiments on the general or continuous spectrum radiation coming from the impacts of electrons against mercury vapor atoms. The electrons fell through a constant difference of potential produced by the high tension storage battery and, therefore, had substantially the same velocities when they struck the atoms. The radiation projected from the impacts at right angles to the stream of electrons did not appear to be homogeneous. After it had come through the thin glass window of the apparatus, 57.5% of it passed through a sheet of aluminum about $\frac{1}{10}$ of a millimeter thick. If the radiation had had the wave-length of the short wave-length limit of the spectrum corresponding to the voltage on the tube, 62% would have passed through the sheet of aluminum.

The object of the researches described in this note has been to investigate the radiation proceeding in the direction of motion of the electron stream, as well as at right angles to it, and, also, to compare the penetration of both rays with the penetration of the radiation that would come from the impacts of the electrons according to certain theories.

Figure 1 represents a horizontal cross-section of the apparatus employed. The electrons from a hot wire cathode, *C*, pass through an opening into the interior of an anode, consisting of two brass tubes, *A* and *B*, joined together by four curved wires, represented by dotted lines in the figures. The high tension storage battery produced a difference of potential of 11,780 volts, which was determined by measuring the current passing through a manganine wire resistance of 3,019,000 ohms in parallel with the tube. The stream of mercury vapor came up through the vertical tube, *D*, from an electrically heated furnace. It then passed across and down through the vertical tube, *E*. The apparatus was exhausted through the vertical tube, *F*, which communicated with a mercury diffusion pump, not shown in the figure. Although all parts of the apparatus contained at least a small amount of mercury vapor, most of the impacts of electrons against the mercury atoms occurred in the region,