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Data and Nature of Cosmic Rays

By KARL K. DARROW

"Cosmic rays" is the name of the ultimate cause which maintains that part of the ionization of the air which cannot be ascribed to the rays of radioactive substances on earth nor to any other known agency. The measurement of this residue, the discrimination between it and that part of the ionization which is due to familiar rays, is the first problem of cosmic-ray research. Second comes the problem of learning, from measurements made at as many places and under as many conditions as possible, the nature of the mysterious ionizing agent. One naturally begins by assuming it to be like in kind to one or another of the known types of ionizing rays, but different in quality; *e.g.* to consist of electrons faster than any known electrons, or photons of greater energy and lesser wave-length than any known photons. It is not yet certain whether one of these hypotheses will fit, or rays of some new type must be imagined. The direct measurements of ionization are supplemented by observations of material particles of evidently enormous energy which dart across the atmosphere in straight paths leaving trains of ions behind. On the whole it seems highly probable that these particles, or those (if such there be) from which they receive their energy, come to the earth from outer space; and the energy which they bear is so great, that its source must be some process not yet known.

THE subject of this article is unique in modern physics for the minuteness of the phenomena, the delicacy of the observations, the adventurous excursions of the observers, the subtlety of the analysis, and the grandeur of the inferences. The effect which is studied, which may be described as the liberation of electrons from the molecules of the air by agents otherwise unknown, amounts at sea-level to the liberation of only about 1500 of these per cubic decimetre of air per second. It is not the whole of the observed effect; these 1500 electrons are those which are left over out of a quantity often much greater, after allowance is made for the actions of all known ionizing agents. The methods employed are ranked among the most ingenious and sensitive of science; yet the apparatus is not invariably set up in the calm seclusion of the laboratory. Physicists with their frail machines have gone to high mountain ponds in the Sierras and the Andes, to the distant wildernesses about the earth's magnetic poles; they have scooped out cavities in Alpine glaciers, they have lifted hundredweights of lead to the tops of peaks above the snow-line, they have cruised the arctic and the tropical oceans, they have descended into tunnels and deep mines, they have ascended into the sky in aeroplanes and balloons. As for the analysis of the precious data obtained with so much labor, it will be evident from this article how intricate a process it now proves to be.

And the incentive for all these labors? At first, the problem seems little more exciting than the tracing of an insignificant leak in an apparatus supposedly insulated. There is, however, reason to suspect that *this* leak is due to causes really sensational. The comprehended part of the ionization of the air being due to known rays such as X-rays, light, and the radiations from radioactive substances, it is natural to ascribe the mysterious residue to rays as yet unknown. It turns out then that these hypothetical rays must lie beyond any yet discovered; if they are electrons, they must be swifter electrons—if protons, faster protons—if corpuscles of light, then corpuscles of higher frequency and higher energy, than any thus far known; or else they must be particles of a totally new variety. It is not easy to imagine where they could come from on earth, and there are various reasons for supposing that they wander in from outer space. Messengers from the depths of space and from the stars—corpuscles of visible light, meteorites, the electrons which are the presumptive causes of the aurora—are constantly being received and have been amply interpreted; it is probable that these cosmic rays have a message of value, perhaps of the first importance.

The dates of the beginnings of cosmic-ray research have been much disputed, in an unprofitable fashion. I like to set aside the controversies by choosing a time extravagantly remote, the year 1785! In that year, it is said, Coulomb made the first acceptable proof that the air of the atmosphere is conductive. It had long been known that an electrified body, mounted on the best available insulator and set up in the air, slowly loses its charge; it had, however, been thought that the "leak" is partly an escape through the insulator or over the surface thereof, partly a carrying-off of charge by particles of dust which drift up to the electrified body, touch it and depart—Coulomb found that in addition to these, there is an actual conduction through the air.

After this discovery, progress ceased for many years. Towards the end of the nineteenth century it was, however, learned that the air becomes much more conductive than normally it is, when rays of certain kinds pervade it—X-rays for instance, and the radiations from radioactive atoms. Further, it was found that some part, at least, of the normal conductivity of atmospheric air is due to rays from radioactive atoms blown about by the wind or embedded in the ground. Then came the time for asking: Is there a residual part of the normal conductivity of the air, which cannot be ascribed to rays of any kind hitherto known? With the asking of this question, the way was opened to the sequence of researches, which form the topic of this article. "Cosmic rays" are *by definition* the cause of that residue of the ionization of the atmosphere, which is left over after deduction of all of the ionization which can be traced to the action of the rays of radioactive substances, or any other known cause whatever.

I write "ionization" instead of "conductivity"; this is because it is well enough known that when a volume of gas is and remains conductive, it is constantly being ionized—which is to say, electrons are constantly being detached from its molecules. Molecule and electron become ions, the members of an "ion-pair"; if there is an electrified body nearby, those of the sign opposite to its charge are drawn to it (those of the other sign going to the earth) and step by step their charges neutralize its own. The question set above may therefore be rephrased: Are ion-pairs appearing in the atmosphere oftener than rays of known varieties are making them?

To answer this question, one must of course exclude all of the rays from radioactive substances (and, naturally, X-rays and other artificial kinds) from the volume of air which one is studying; or if they cannot be excluded altogether, one must estimate the ionizing-power of those which remain. They are important in cosmic-ray research as causes of error; they are important also in another way, as tentative models for theories of the cause of the residual ionization. In attempting to explain this mysterious residue, the procedure both natural and wise is to begin by supposing it similar to alpha-rays, or else to beta-rays, or else to gamma-rays. In the end it may be found needful to postulate some ionizing-agent entirely different from all of these; but in the beginning, they should be the guides.

Of the three named classes of rays, one (the alpha-particles or positive corpuscles) has a sharply-limited range in air so short, that such as come from the ground are stopped within a few inches; and a range in metal so extremely short, that even if one wished it would not be possible to build a durable air-chamber with solid walls so thin that the alpha-rays could get through.

The second (the beta-particles or fast electrons) have a range which varies from one radioactive element to another, and even from one particle to another among those emitted by a single element. This range is often much longer than that of an alpha-particle, and less precise. Air at a distance of many metres above the ground may be sensibly ionized by beta-corpuscles proceeding from the soil. All along their paths, beta-particles engender ion-pairs profusely—in air at normal (sea-level) density, never fewer than forty per cm. Nevertheless they do not enter an air-chamber walled by a very few centimeters of lead, and need not be a serious cause of confusion.

More formidable is the third kind, the gamma-rays or short electromagnetic waves. They also vary from one element to another, and different wave-lengths may proceed from a single element; some are innocuous, but some are much more penetrating than even beta-rays. One must be careful about the language here; one must not say that they have a great range. To speak of "range" implies that when a number of particles is started off side by side with equal speed along parallel paths into a stratum of matter, they continue to follow parallel paths—albeit with diminishing speed—until they are brought to a stop, this termination coming for each of them at the same distance from their source. Of alpha-particles this is nearly a true statement, of beta-particles it is a fair approximation. Of gamma-corpuscles or photons (for gamma-rays are high-frequency light, and may therefore be regarded alternatively as corpuscles and as waves) it is not true at all. If a number of these, all of identical wave-length, is started off side by side along parallel paths into a stratum of matter, one after another impinges on an atom, or (it is probably better to say) upon an electron belonging to some atom. Until such an impact, the photon does not ionize at all, but passes unperceived. The number which at a distance x from the source have not yet suffered an impact varies as an exponential function $e^{-\mu x}$ of that distance.

At such an impact the gamma-ray photon loses energy and suffers a deflection, which may or may not be considerable. It also liberates the electron, which is an act of ionization; but usually the electron itself, being started off with considerable speed, liberates a great number of additional electrons from other atoms of the gas, so that the direct ionization by the gamma-rays falls far behind the indirect; *most of the ionization by gamma-rays is done by the intermediacy of fast electrons.* One may say that the lower the value of μ, the more penetrating, or "harder," are the gamma-rays; one may compare values of μ for gamma-rays of different wave-lengths; but one may not compare a value of μ for these with a value of range for beta-particles or alpha-particles (unless one should arbitrarily define the range of a beam of gamma-rays as the distance over which its intensity is reduced by say 99 per cent, which would be very misleading).

These are very important matters, for the chance of deciding whether the cosmic rays are likest to gamma-rays or to material particles turns largely upon differences such as these. Another detail is important: the practice of stating values of μ for standard materials, such as water or lead. It is *approximately* true that slabs of various materials will absorb the same fraction of an incident beam of gamma-rays (of a single wave-length, be it understood) if their thicknesses are so adjusted that all of them have the same mass per unit of surface-area. The densities of air at sea-level, of water and of lead stand to each other in about the ratios .0013 : 1 : 11.4; a metre of water is therefore "equivalent" in this respect to about nine centimetres of lead or three-quarters of a kilometre of air at sea-level. After measuring μ in a material of density ρ, one may reduce it to a value approximately equal to that which would be found in a standard material (lead, for instance) of density ρ_0, by multiplying it with the factor (ρ_0/ρ). A better approximation yet, for the harder gamma-rays, is the statement that the slabs absorb the same fraction of the gamma-ray beam if the atoms under each unit of surface-area have the same number of bound electrons altogether. Denoting the number of bound electrons per unit volume of the material in question by E, the corresponding number for lead (say) by E_0, we find (E_0/E) for the value of the factor by which an observed value of μ is to be multiplied, in order to convert it into one approximately valid for lead.[1] To give a definite example, I will mention simply that ten centimetres of lead intercept all but a few per cent of the hardest gamma-ray corpuscles which come from radioactive bodies; and that a couple of kilometres above the earth, one need not worry about the influence of the radioactivity of the ground.[2]

So, to avoid ionization of air by the rays of the known radioactive elements at the surface of the earth, one surrounds the air which one is observing by matter more than thick enough to stop all of the alpha and all of the beta-particles, and thick enough to cut off all but a few per cent of the gamma-corpuscles. Often this is done by using plates of lead several cm. thick for the walls of the air-chamber. Sometimes it is done by sinking the chamber into a lake, or digging a hole into the ice of a glacier. A much greater thickness of water frozen or liquid is required to intercept the unwanted rays, than of lead; this thickness must surround the air-chamber on all sides, towards the bottom of the lake, towards its edges, even (if there be overhanging mountains, or radioactivity in the air) towards its surface; but water is inexpensive, and does not have to be carried about. Or by going up in a balloon, or sending up the air-chamber in a balloon without oneself attending it, one may put enough air beneath the apparatus to screen away the rays from the ground.

But are there not radioactive atoms in the very materials used to

[1] For an element of atomic weight A and atomic number Z and density ρ, the value of E is $Z\rho/Am_H$, the symbol m_H standing for the mass of the hydrogen atom. For lead $Z = 82$, $A = 206$, $\rho_0 = 11.4$. For a compound of known constitution the formula can easily be worked out; if the constitution is unknown but certainly involves atoms of high atomic number only, one may put $Z/A = \frac{1}{2}$ as a rough approximation.

[2] Millikan in a specific case says that 4.8 cm. of lead intercept 90 per cent of the gamma-rays from igneous rocks (*Phys. Rev.* (2), **28**, p. 862; 1926).

protect the ionization-chamber? the air, the ice, the water, the leaden walls themselves? Of the atmospheric air I have already admitted this; the quantity of radioactive gas commingled with it can, however, be measured, is generally very small, and does not seem to bother observers when they are not too close to the ground. As for the water: Millikan has always carefully chosen "snow-fed" lakes, high in the mountains where the water is derived not from springs which have seeped through soil, but from snow which has fallen onto bare rock from on high. Ice of glaciers, it is to be presumed, has an origin equally uncorrupted. The same cannot be said for the water of Lake Constance wherein Regener's data were taken, but he by special tests proved the effect of its radioactivity to be slight.

As for the lead (or whatever other metal or metals may be used in making the ionization-chamber) this too may be contaminated with radioactive atoms. Some people have mounted wire netting all around the interior of the chamber at some distance from the walls, so that such rays as come from the wall and are soft (in the sense opposite to that in which I spoke of gamma-rays as hard) may be largely absorbed between the wall and the net; voltages are so arranged that the ions produced in this space are not counted by the observer. This device is not always used, nor when used is it fully effective. A somewhat experienced man might expect to be able to allow for the radioactivity of the wall, through knowledge acquired by varying the density of the air and studying the ionization as function of density; this has been done, but we shall see that the results have added new mysteries to the problem.

The walls, then, must be expected to cause a permanent ionization in the air-chamber, constant and independent of the outside world. Moreover electrical leaks must occur, whereby the charged electrode gradually loses its charge by conduction through the not-quite-perfect insulators on which it is mounted. How can we hope to distinguish the joint effect of these from that of the cosmic rays? or, to put the same question more properly, how can we hope to find what part of the ionization, if any, is not due to either of these?

This is indeed a serious question, inasmuch as it is a problem not of distinguishing a known from an unknown, but two unknowns from one another. Of course, if one makes the gratuitous assumption that the "cosmic rays" cannot penetrate x feet of rock, then one may take the apparatus into a cave or hollow under more than x feet of rock, and measure the rate at which the charged electrode is discharged; and then, after deducting the allowance to be made for the rays from radioactive substances in the rock which penetrate into the chamber, one can say that the residue (*Restgang*, the Germans call it) is the joint effect of the causes aforesaid, and must thenceforth be subtracted from every reading made with the same apparatus. Kolhörster did this on a grand scale, going many hundreds of metres down into one of the potash-mines of Stassfurt, where there is a great hollow excavated in rocksalt; the thickness of the overlying rock was great, but as a drawback there was a powerful radioactivity of the potassium in the rock-salt, causing hard gamma-rays of which a perceptible fraction invaded the chamber. In Java the physicist Clay took his machinery into a tunnel, where he was covered by rock eighty-four metres thick and far less rich than rocksalt in radioactive atoms; in the Sierra Nevada Millikan descended 185 metres into granite.

More instructive is the customary procedure of Millikan and of Regener. We shall presently consider curves (Figs. 3, 4, 5) which show the rate of discharge of electroscopes in air-chambers sunk under water, plotted against the depth of submergence. The discharge-rate falls off as the air-chamber is lowered, but the decline grows slower and slower; the curve flattens out and seems to approach, seems even to attain, a certain horizontal line. It is the ordinate of this line which is taken as the *Restgang;* this is subtracted from all the other ordinates, the differences are ascribed to the cosmic rays. Now if one could be absolutely sure that this is the line to which the curve is making asymptotic approach, there would be no uncertainty. But since no measurement is perfectly precise, no one can say absolutely that the curve is not still gently sloping, towards an asymptote distinctly lower than the lowest value measured. Yet it is on some guess as to the answer of this unanswerable question that there rest, not (fortunately) the proof that there are such things as cosmic rays, but the estimates of their amount and of their greatest penetrating power. I revert to this question later; at present I merely mention it, in order to show how difficult these estimates may be.

A very important point now demands to be noticed. In taking these elaborate precautions to exclude the rays from radioactive substances beyond the walls of the air-chamber, is one not also keeping out some of the cosmic rays themselves? To deny this would be all but impossible; it would amount to assuming that *all* ionizing rays, apart from those which we recognize as proceeding from known radioactive atoms, are so much more penetrating than these that they pass absolutely undiminished through centimetres of lead and metres of water—an assumption which has only to be stated, to show itself improbable. True, *if* the unknown rays come altogether from above, and *if* the radioactivity of the air can be allowed for, one may omit to carry the screen of lead over the top of the air-chamber—or, one may float the apparatus on or just below the surface of the lake—or, one may rely exclusively on observations made in the upper air. But it is likely that part of the unknown radiation comes very obliquely downward through the atmosphere, and therefore is liable to be obstructed by lateral walls of lead which cannot be removed without admitting to the apparatus other rays which come very obliquely upward from the earth. So, every sort of screening by water or by metal probably keeps out some of the rays which are wanted, along with those which are unwanted. Only the observations in the uppermost air may give the full effect of the mysterious radiation, and perhaps not even they, for the walls of the chamber cannot be reduced to infinite thinness.

How great is the ionization left over to be ascribed to cosmic rays, after *Restgang* and radioactivity are allowed for? The absolute value is still a subject of controversy; fortunately it is a minor matter, knowledge of which is not required for solving the major problems; thus, to determine the penetrating power of the rays one needs only *relative* values at various depths of water. Concerning it I will merely state, that *in the atmosphere near sea-level, the number of ions of either sign appearing per cubic centimetre per second, and attributed to cosmic rays, averages about one and one-half.* Say we have an ionization-chamber of volume U (in cubic centimetres), at sea-level, filled with air at atmospheric pressure. Its charged electrodes will be discharged at a certain rate; part of this rate of discharge can be explained in the ways aforesaid; the rest, the inexplicable residue, will amount to about $1.5\,Ue$. This residue is the evidence for the cosmic rays. The electron-charge e is so small, that even when the volume of the chamber is thousands of cubic centimetres the product ($1.5\,Ue$) is no great quantity of electricity. High up, the effect is much greater; according to Piccard it is so great at sixteen kilometres over sea-level, that if the air up there were as dense as it is by the sea, there would be 200 ions of either sign appearing per cc. per second.

Stating the effect in ions per cc. per second has one disadvantage: it suggests that in each cubic centimetre of an ionization-chamber the ions are created at random,—one in the middle, perhaps, at a certain instant, the next somewhere else two-thirds of a second later, the next yet somewhere else two-thirds of a second later yet, and so on. What happens, however, is this: at practically a single instant hundreds, or even thousands, of ion-pairs are created along a single straight line traversing the chamber; this is followed by many seconds, or even minutes, during which nothing happens; then there is another such event, a train of ions suddenly appearing along a straight line, not however the same one; another interval, another train of ions, and so forth. The method of measurement which thus far I have been presupposing conceals these individual events, giving merely the sum of all the ions which come into being over a period of hours (or, at least, of many minutes). Towards the end of the article I shall speak of other, and very striking, methods which reveal them.

Passing now to the experiments, I will take up first the various groups of measurements made, each with a single instrument of the ionization-chamber or electroscope type, at various heights above the ground or various depths below the surfaces of lakes.

Imagine, to begin with, a metal-walled air-filled box, having inside it a pair of strips of gold-foil hanging side by side from a metal knob at the end of an insulating rod, and in one wall a window through which this "gold-leaf electroscope" can be seen. The metal wall is earthed, and the leaves of gold are charged, usually by a metal rod so mounted in a ground-joint in the wall that by turning the joint the rod can be touched to the knob which holds the leaves. The wall is disconnected from earth, the box is set up in whatever place is chosen for the measurement. The divergence of the gold-leaves is measured at the beginning and at the end of a chosen interval of time. By calibrating the device (I will not enter into the details of this process) one may determine how much charge of one sign has been lost from the leaves, how much charge of the opposite sign has been gained by the leaves, in the time allotted. This is the ultimate datum. The process is then repeated in other places.

All of the experiments which I shall now describe are in principle like this imagined one, but greatly improved in technical detail. Gold-leaves would be too frail for an apparatus meant to be moved about; for them are substituted sometimes a pair of quartz fibres brought together at both ends, not at one only (Fig. 1) or else a "string electrometer." Sometimes the observations are made fifteen kilometres up in the air, or two hundred metres down under water. It is not always convenient, sometimes not feasible, for the observer to go with his instrument; it is not always safe to make the initial reading before the apparatus is sent on its way, the final reading after it is brought back. The observations must then be delegated to a mechanism; the divergence of the fibres or the position of the string is recorded by photography, perhaps at intervals of time previously chosen and regulated by machine, perhaps continuously. The pieces of apparatus designed to do these things, and meanwhile to survive immersion or transportation to great heights and low temperatures, are often prodigies of compactness.

Though the work of Millikan and his school is unrivalled for extent, I will begin with Regener's, which is an unique example of a wide range of water-depths covered in a single experiment. The

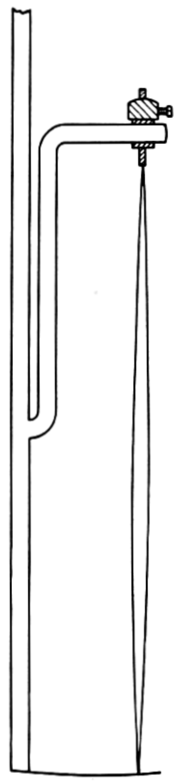

Fig. 1—Sketch of a two-fibre electroscope (after Millikan).

ionization-chamber (walls of steel a centimeter thick, 39 liters (!) in volume filled with carbon dioxide at a pressure of 30 atmospheres) was floated for days at a time at each of several levels in the great Lake of Constance (*Bodensee*) on the northern boundary of Switzerland. Every hour a light flashed for a few seconds, and the image of the fibre of the string-electrometer was impressed upon a film, wound about a slowly and equably revolving drum. One sees in Fig. 2 the successive images of the string, developed after the experiment was completed and the film removed from the drum; it is evident how they lie closer together as the chamber is lowered deeper and deeper beneath the surface, the ionization therefore becoming feebler and feebler. The water, as we shall see, is serving not merely as a screen for keeping out the rays of radioactive matter in the earth but as an instrument for studying the penetrative power of the unknown rays themselves. Records, as I just said, were made an hour apart, and ordinarily were continued over two days at each depth.

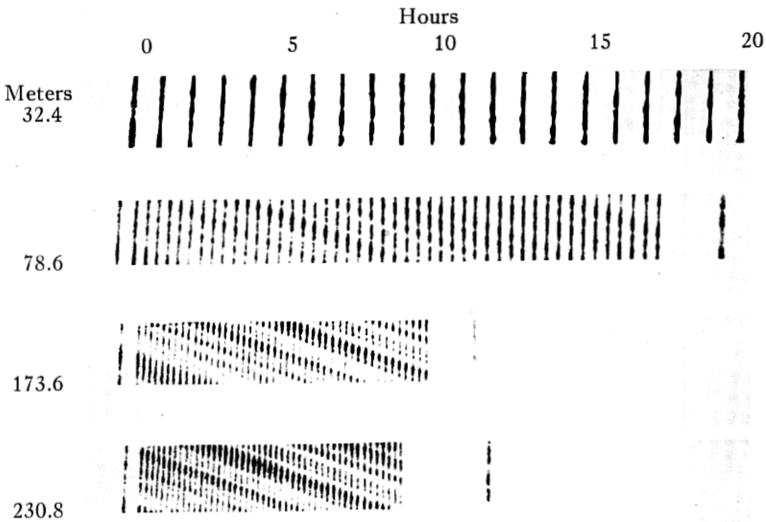

Fig. 2—Photographic registration of the position of the string of a string electrometer, showing gradual shift due to discharge by cosmic rays (Regener).

Measurements were made at seven depths: in metres, these amounted to 32.4, 78.6, 105.2, 153.5, 173.6, 186.3, and 230.8. They were plotted as function of depth; the resulting curve, *shifted downward by 0.78* (we need not consider the exact meaning of the units along the axis of ordinates) appears as J in Fig. 3. It is concave-upward, of a shape which suggests that there are both a *Restgang*, and ionizing-rays diminishing in strength as they descend through the water from above. But it is not sufficiently prolonged to permit the eye to decide with confidence the value of the *Restgang;* the exact effect of the ionizing rays is therefore not to be judged by inspection. How did Regener proceed? He postulated that the readings y at the three greatest depths (depth measured downward from the surface being denoted by x) are sums of a constant and an *exponential* term:

$$y = A + Be^{-\mu x}; \; x = 173.6, 186.3, 230.8,$$

and found what values must be given to A, B, and μ in order to get the best possible fit of such an expression to the data. He then noticed that the same expression would equally well fit the data for the next two of the depths, 153.5 and 105.2; and this convinced him that it is physically sound.

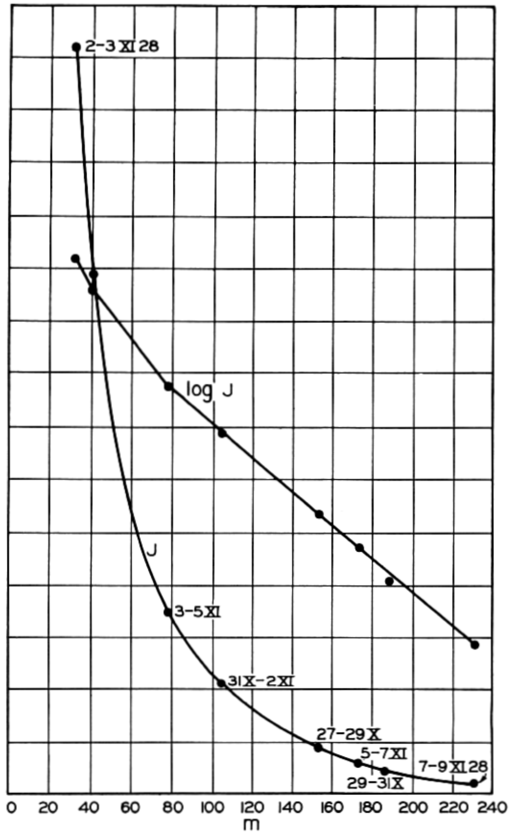

Fig. 3—Ionization ascribed to cosmic rays as function of depth beneath surface of Lake Constance (the straighter curve is a semi-logarithmic, the other a direct plot) (Regener).

The ionization has therefore been separated by assumption into a *Restgang A* and an effect of ionizing rays diminishing exponentially with increase of depth. The value of A is 0.78; it is the downward shift mentioned just above, so that the curve J in Fig. 3 shows the part of the ionization ascribed to cosmic rays. The other curve shows the logarithms of the ordinates of the curve J; the latter being exponential, the former is straight; it is the close fit of this line to the circles along its path (the logarithms of the data) that for the eye is the most striking evidence for Regener's procedure.

Now, of the three known kinds of rays from radioactive substances, one only is characterized by an exponential decline of its strength with increase of thickness of matter traversed: to wit, the gamma-rays. Regener was therefore assuming, as had many others before him, that *cosmic rays which have penetrated many metres of water behave like a beam of monochromatic gamma-radiation, corpuscles of light of a single frequency and energy, coming vertically from above.* The value of μ—.00018 in this case [3]—is many times smaller than that of any known variety of gamma-rays; this is expressed by saying that the cosmic rays are considerably more penetrating or "harder" than the hardest of gamma-rays.

While the expression $(A + Be^{-\mu x})$ fits tolerably the five experimental points at the five greatest depths, it misses the two others, giving for 32.4 and 78.6 metres lower values of ionization than those observed. One might add a second exponential term with a different, much larger value of μ; thus in effect assuming that the cosmic rays behave like a mixture of gamma-rays of two different wave-lengths, corpuscle-energies and hardnesses. This in fact is the custom, though Regener did not do it in the paper whence I am quoting, being interested mainly in the far end of the curve—in the range of depths at which, as is commonly said, *all but the hardest component of the cosmic rays have already been filtered out.* For, if a function of x is the sum of a number of terms of the form $B_i e^{-\mu_i x}$, with differing values of the constants μ_i: then as x is increased the various terms fall off, but in such a way that eventually the one with the lowest μ predominates more and more over all the rest, however small may be its coefficient B. This is "filtering," a process of great use in the science and practice of radioactivity; many of the radioactive elements, or of the mixtures thereof which are common, send out gamma-rays of various degrees of penetrating-power, among which the hardest may be almost isolated from the rest (at the price, of course, of a great cutting-down of its own intensity) by a thick screen of absorbing matter. Even if the screen is not thick enough to make the hardest component predominant, it may alter greatly the relative proportions of harder components and softer. The rays responsible for the 1.5 ions at sea-level, if of the nature of gamma-rays, must have undergone a good deal of this alteration and "hardening" in passing through the atmosphere; not nearly so much, however, as those deep down in Lake Constance, the whole of the atmosphere being no more powerful an absorber than a layer of ten metres of water.

We turn now to the great series of experiments made by Millikan

[3] Expressed in cm.$^{-1}$; in (metres)$^{-1}$, Millikan's customary unit, it would be .018.

and his school. Fig. 4 embodies the data of three, in each of which an air-chamber was lowered into a high-lying snow-fed [4] lake (Millikan's reasons for choosing such I have already stated). Crosses stand for

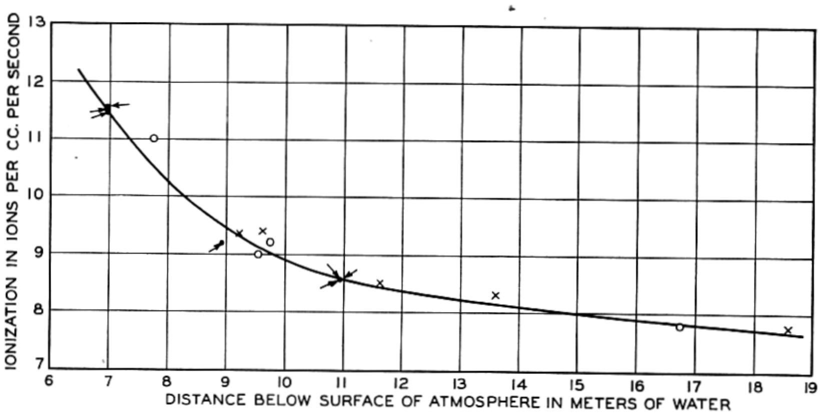

Fig. 4—Ionization ascribed to cosmic rays as function of depth beneath top of atmosphere (early curve of Millikan and Cameron).

data obtained in Arrowhead Lake, California (altitude 1550 metres); circles correspond to Muir Lake, California (3580 metres); the dots to which arrows point are the reward of a long hard journey, for they show data from a lake—Miguilla—no less than 4570 metres above the sea, in the Bolivian Andes. All of the measurements here plotted were taken at depths of a metre or more below the water surface, but none so great as Regener's—five metres was the maximum depth at Miguilla, fifteen at Arrowhead and twenty at Muir.[5]

The points of the three sets lie close to a single smooth curve. Each of the three, however, has been shifted horizontally, to make allowance for the different depths of air overlying the three lakes: it has been assumed that the air over Miguilla is the equivalent of 5.95 metres of water, over Muir to 6.75 and over Arrowhead to 8.6 metres. To figure out the equivalents it is necessary to know the distribution-in-height of the air (Millikan got it from the Smithsonian Institution

[4] Regener of course admits that Lake Constance is not of this character, but by later experiments (briefly mentioned in his note in the *Physikalische Zeitschrift*) he found that radioactivity of its water was not distorting his results.

[5] Data were obtained at lesser depths than a metre, but the values of ionization are higher than would be inferred by prolonging the curve which is valid for greater depths. This recalls a feature of Regener's data, but here the excess is ascribed by Millikan not to soft cosmic rays, but to the radio-activity of the overlying air and the nearby mountains. Of the points plotted in Fig. 4, the "two which fall farthest from the curve correspond to single readings, and hence should be given little weight in comparison with points which represent the means of three or four readings" (Millikan & Cameron).

tables) and the ratio of the absorbing-power of air of given density and the absorbing-power of water for the cosmic rays. This last not being known *a priori*, it is the custom to take the inverse ratio of the densities of the media (page 152)—another instance of assuming that cosmic rays are of the nature of gamma-rays. The assumption is strengthened by the success of the thus-made allowance in bringing all the points upon a single curve.

The data of Fig. 4 were obtained in 1925 and 1926; those of the following Fig. 5, in 1927. New readings were made in the waters of

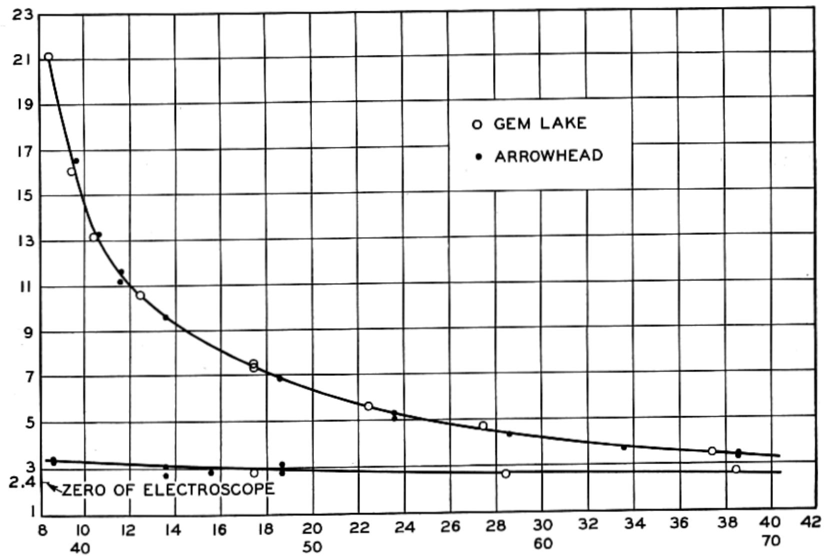

Fig. 5—Ionization ascribed to cosmic rays as function of depth beneath top of atmosphere (later curve of Millikan and Cameron).

Arrowhead Lake and in another not previously used, Gem Lake, 2,760 metres up in the high Sierras; into this last the ionization-chamber was lowered to a depth as great as sixty metres. The data for the two localities were altered to make allowance in the foregoing way for the different heights of air overlying the two lakes, and the values so obtained were plotted against "depth in metres-of-water beneath top of atmosphere." Evidently the data fit better to the curve than in the prior work: this Millikan and Cameron ascribe to improvements in the new ionization-chamber or "electroscope" (outwardly like that in Fig. 6) into which air was compressed to a pressure of *eight* atmospheres instead of *one*, as previously. Incidentally, in Fig. 5 the *Restgang* appears under the title "zero of the electroscope."

The observations had thus been extended over the range, of metres-of-water beneath the "top of the atmosphere," from 8.45 to 69. During the three following years Millikan and Cameron made yet another and more-closely-spaced aggregate of readings, over the same range with slight extensions at both ends, in the same two lakes, with

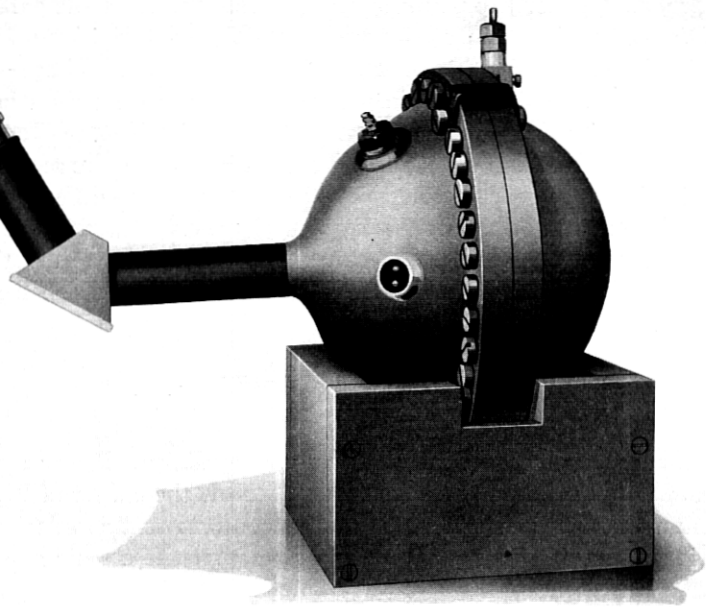

Fig. 6—Electroscope used in later under-water measurements of cosmic rays by Millikan and Cameron.

an electroscope (Fig. 6) into the 1622 cubic centimetres of whose volume air was forced to a pressure of 30 atmospheres. The reader can find the new curve in the issue of the *Physical Review* for February 1931; it is the one from which the next-cited deductions are drawn; but as it does not differ markedly from its two predecessors, and is much more trying to the eyes than these, I do not reproduce it here. (In studying it, or the curve here pictured as Fig. 5, one must remember that the ordinate is proportional to the number of ions appearing per second per cubic centimetre, not of the atmosphere at the level in question, but of air of a standard density.)

Is the whole of the curve, abstraction being made of the *Restgang*, an exponential curve such as would be found if the cosmic rays were a beam of gamma-rays of a single frequency descending vertically from above? The answer presumably is *no*. Millikan and Cameron, however, asked a slightly different question. Imagine that the cosmic rays, instead of coming altogether vertically from above, are gamma-rays traversing interstellar space uniformly in all directions, incident therefore upon the atmosphere at all angles between zero and 90°—much the most probable assumption if they do proceed from interstellar space, as it is hard to think of any possible action of the earth which might constrain them all to move straight toward its centre. The ionization at any depth x beneath the top of the atmosphere (continue to think of x as measured in metres of water) would then be due to beams coming from all directions above the horizon. These beams, having traversed different thicknesses of air, greater the more they are inclined to the vertical, would have been absorbed to different degrees; their intensities, originally (by hypothesis) the same, would be reduced in different proportions. It can readily be shown that the total intensity of all the beams should then vary, not as $e^{-\mu x}$, but as the following function of x:

$$y = C \int_1^{\infty} z^{-2} e^{-\mu x z} dz, \tag{2}$$

μ standing as before for the absorption-coefficient of any cosmic-ray beam coming from any one direction.[6] Now the curves of Figs. 4 and 5, and the new curve of 1931, do not conform to this relation either. It is consequently not possible to affirm that the cosmic rays behave like gamma-rays of a single wave-length.

Does the final extremity of the Millikan curve conform with formula (2), so that one may assume that after a certain and feasible amount of filtering, the radiation is almost altogether reduced to gamma-rays of a single wave-length? To this Millikan and Cameron respond, that of the curve of Fig. 5 the portion extending from abscissa 30 to abscissa 60 *does* conform, the value required for μ being .0005. Of the curve of 1931 they say, that from 40 to 80 metres-of-water it conforms, if for the value .00028 be chosen.

Recalling Regener's value of μ (.00018) for depths still greater, and joining it with these, one is led to wonder whether at 40 and even at 80 metres the filtering is sensibly incomplete, and whether even at 200 metres the value ascribed to μ may not be the ultimate "hardness" of the rays. Further, there now arises the great question: can the curve as a whole be regarded as the sum of a limited number of terms of the

[6] See R. Hellmann, *Phys. ZS.* **30**, 357–360 (1929); E. Gold, *Proc. Roy. Soc.* **A 82**, 43–70 (1909). Regener used formula (1) instead of formula (2) for interpreting his data.

type appearing in equation (2), with definite and distinctive values of μ? For if so, we may affirm that formally the cosmic rays behave like a mixture of gamma-rays having definite discrete frequencies, a sort of line-spectrum.

This is an extremely delicate question. What is needed is a method like that of Fourier analysis, whereby a given curve may be resolved into a sum, not of sines and cosines as result from the Fourier process, but of terms of the type of the right-hand member of (2); it seems that such a method is wanting. Millikan and Cameron, and independently their colleague Bowen, "built up . . . our observed curve out of four components—no smaller number would do—and in such a way that the synthetic and the observed curve [that of 1931] fitted exceedingly nicely from one to the other." These four components have the values .0080, .0020, .0010, .0003 of the coefficient μ; and their relative intensities, as inferred to exist at the confines of the atmosphere before the filtering commences, stand in the ratios 141000 : 130 : 80 : 33. It is evident that the portion of the radiation which survives at great depths of water, and for which the values of μ are extremely low, is a very small part of all that is to be found in the upper air. Yet even the highest of the values of μ here cited is much lower than the coefficient of absorption for the hardest known gamma-rays from radioactive substances.[7]

It would be deplorable to leave unmentioned some very romantic experiments in which the electroscope, with or without the observer, ascended by the aid of a balloon to heights of air hitherto unattained. Balloon-ascents were begun by German physicists (Gockel, Bergwitz, Hess, Kolhörster) in the five years before the war. Before, it had been maintained that the ionization of the air is due altogether to radioactive substances in the ground. The earliest balloon-flights impaired this argument, by proving that the amount of the ionization does not diminish rapidly as the observer flies upward; the later ones destroyed it, by proving that above a certain level (variously stated, and depending no doubt on the thickness of the walls of the chamber) the ionization rises with increase of height. I will however speak chiefly of more recent flights, those of Millikan's apparatus and that of Piccard.

The electroscope of Millikan and Bowen was borne aloft above the plains of Texas by a pair of balloons, one of which eventually burst and left the other to serve as a parachute in lowering its burden gently

[7] Though not higher than that of the gamma-rays excited by Bothe and Becker when bombarding beryllium with alpha-particles, as I learn from a letter of Professor Bothe.

back to earth. In two experiments the electroscope climbed to heights of 11.2 and 15.5 kilometres, heights to which it seemed (until last year) that no man could possibly ascend and live. The apparatus (there were four of them) had to make its own records and bring them back; it was a masterpiece of ruggedness and compactness jointly, as one sees in Fig. 7, on the left of which it appears assembled (with a

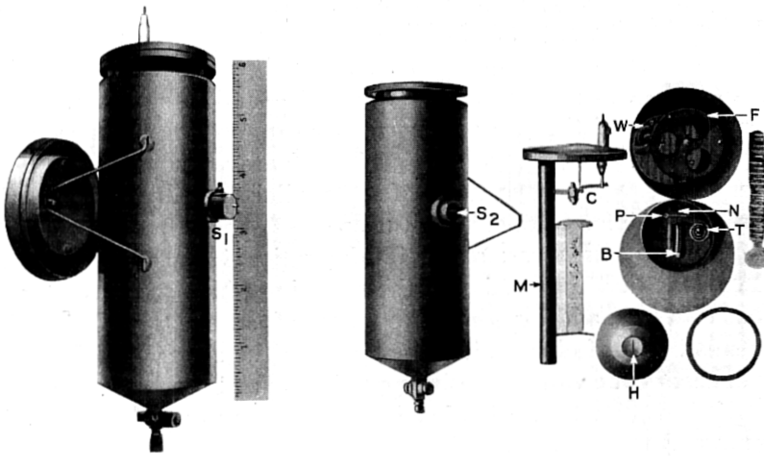

Fig. 7—Electroscope used in high-altitude measurements of cosmic rays by Millikan and Bowen (photographs somewhat retouched).

six-inch rule beside it to show its scale), on the right resolved into *disjecta membra*. The symbol B marks a manometer in the form of a U-tube with one arm closed, containing liquid; the symbol T, a thermometer in the form of a coil of metal with a pointer at its end. The light of the sky imprinted images of the meniscus of the barometer-liquid and the pointer of the thermometer-coil upon a moving film, kept in motion by the watch of which the mechanism is marked by W. Inside the cylinder M (so at least I read the text) were the two fibres of the electroscope already shown as Fig. 1, and they also were continually photographed by the light of the sky upon another film which the same watch kept in motion.

When one of these devices had ascended to 15.5 kilometres (nearly ten miles) and returned to earth eighty miles away from its starting-point, and had been picked up (by some casual wanderer, one infers) and returned to its authors, the films bearing the records of temperature and fibre-divergence looked as they do in Fig. 8. To determine the extent of the ionization at great heights without being deceived by the influence of temperature on the fibres, Millikan and Bowen compared the divergence of these when the balloon had reached a certain height (it was five kilometres) on the upward way, with their divergence as the apparatus passed the same level in descending. During the time while it was above this level, the fibres of

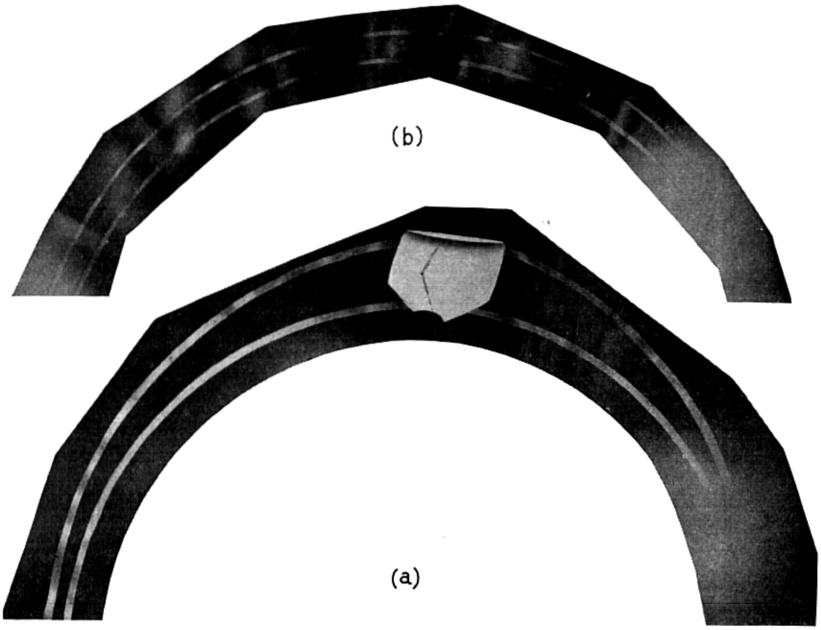

Fig. 8—Records obtained by automatic registration at high altitudes by Millikan and Bowen (somewhat retouched).

the electroscope lost three times the charge that would have leaked away, if the instrument had been left on the ground. This again is proof that the cosmic rays are stronger in the upper air than in the lower.

As I remarked above, until last year it had been deemed beyond the powers of living man to soar to heights so great as fifteen kilometres. This opinion was confuted by the superbly audacious flight of the Belgian physicist Piccard, which everyone will remember who reads the papers, though other things than cosmic rays were stressed in their accounts. Piccard seemingly has not yet published a full nor any extensive story of his measurements on cosmic rays, not at any rate in the physical journals; but in the bulletin of the French Physical Society I find an item in which he states as *provisional* result—awaiting further calibration of his instruments—that the ionization at a height of sixteen kilometres, in air at standard pressure, is of the order of 200 ions per cc. per second! This is considerably greater than the modest value of 1.5 prevailing at the level of the ground.

I must make at least a passing allusion to the *fluctuations* of the intensity of the cosmic rays—fluctuations which are smoothed over by some of the experiments and missed by others, for they are too small to be certainly detected by measurements of low precision, and many are too rapid to be noticed by measurements on the amount of discharge of an electroscope over a period so long as one or two hours.

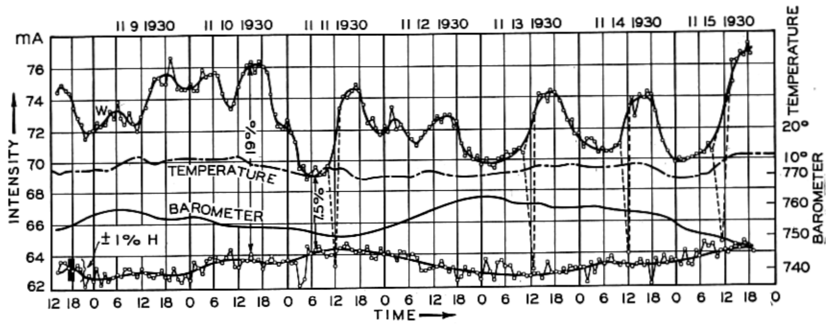

Fig. 9—Fluctuations of cosmic-ray intensity and attendant fluctuations of barometric pressure and temperature (Hoffmann).

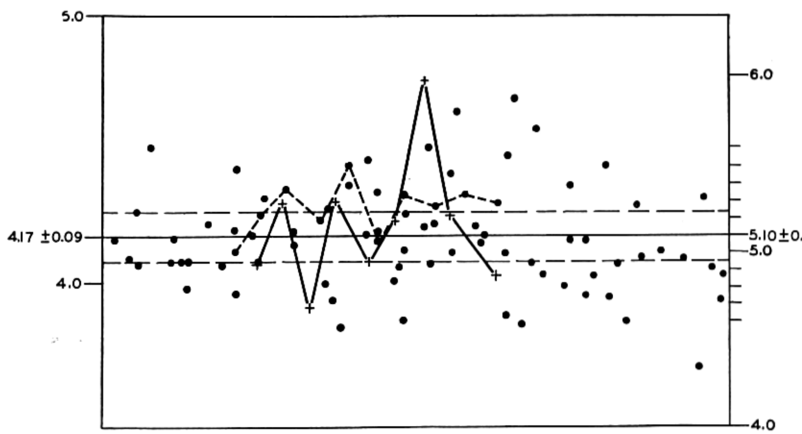

Fig. 10—Fluctuations of cosmic-ray intensity observed at high altitude in the Alps (von Salis).

Figs. 9 and 10 display examples of these: to appreciate the ratio of their average amount to the mean value of the ionization, one must take note of the scale of ordinates on the left. The former is especially instructive, for both the uppermost and the lowermost of the curves display the ionization of the air near the ground (in a basement at

Halle) measured at short intervals over the length of a week; the difference is, that the lowest shows the effect inside armor of lead ten cm. thick, while in getting the data for the topmost the plates of lead were removed from above the apparatus, though left in place at the sides and below. The lower curve thus represents the action of hard cosmic rays: one sees that it rises as the barometric pressure falls, falls as the latter rises—the heavier the blanket of air between Halle and the sky, the more these hard rays are reduced on their way to the ground. The upper shows the joint action of the hard cosmic rays, of others which are softer, and of soft rays from radioactive substances in the air: one sees how violently it fluctuates, supposedly (in Hoffmann's view) because the radioactive atoms wandering in the air change greatly in number as the weather changes. Figure 10 shows values of ionization obtained high up (3500 metres) in the Alps, on various August and September days of 1927, plotted against sidereal time; the zigzag lines connect observations made on two particular days. Corlin is said to have inferred, from a statistical study of data obtained in northern Sweden, that the ionization ascribed to cosmic rays decreases gradually and slowly before a magnetic storm, leaps suddenly to a high value at the onset of the storm, then decreases again.[8]

There is a related question which has been much debated: does the intensity of the cosmic rays vary as different celestial objects pass overhead, the sun for instance, or the Milky Way? As the years go on, the answer to this question becomes steadily more and more strongly in the negative. The opposite opinion has been held largely by German physicists; but a year ago one of them (Hess) reduced the proportion of the cosmic rays which he considers dependent on the sun, to half of one per cent of the total amount.

Certain perplexing data must be mentioned before we go on to the work which is done with other instruments than the ionization-chamber, for they impeach the reliability of this device. From many experiments of the pupils of Swann, it appears definitely established that if the quantity of air in an ionization-chamber is increased, the number of ions appearing in that chamber in unit time increases in a lesser ratio, and in fact approaches (and in some practical cases, even attains) a limiting value (Fig. 11). At first this seems natural enough: the limiting value should be attained when the air is so dense, that the ionizing rays are entirely absorbed before they have completely crossed the chamber. *But*, appreciable fractions of these ionizing rays are able to penetrate many metres of water, many centimetres of lead: it is pretty nearly a formal contradiction-in-terms, to assert that they

[8] See W. M. H. Schulze, *Nature* **128**, 837–838 (14 Nov., 1931).

can be fully absorbed in air of the density and thickness involved in these experiments. It seems necessary to suppose that as the pressure is increased, an ever-rising fraction of the total number of generated ions fails to make its way to the electrodes, positive ions and negative

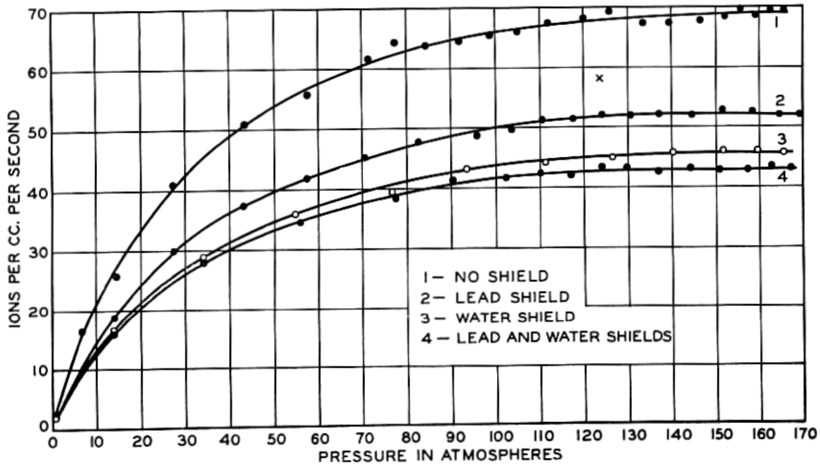

Fig. 11—Curves of ionization versus quantity of contained air in ionization-chamber (Broxon).

recombining with one another.[9] If so, there is reason to fear that the readings of a high-pressure ionization-chamber are affected by its temperature—a possible cause of spurious fluctuations.

I turn now to the other ways of experimentation: there are two of them, both furnishing data more striking and spectacular than those of electroscopes. They exhibit the immediate cause of the mysterious ionization, and open the question of its ultimate cause. We must now take up this question: is the *ultimate* cause to be compared with electromagnetic waves or gamma-rays descending from above, as in this article I have thus far let be assumed? or, is it a rain of fast-flying material particles such as electrons or protons? or a mixture of the two classes of radiation? or has it properties unlike those of any radiation so far known?

(This question is often put in the words: are the cosmic rays wavelike or corpuscular? I think that this phrasing is very much to be condemned, gamma-rays as well as material particles being at one and the same time *both* wavelike *and* corpuscular. However the reader should know that in current usage "corpuscular" signifies "composed of particles of electricity or matter, instead of photons.")

[9] This theory, almost simultaneously published from Millikan's school and from A. H. Compton's, is at present under test.

The question is much more difficult to answer than it seems: for *even if the cosmic rays are of the nature of gamma-rays, the effect which they produce in ionization-chambers (and in the kinds of apparatus yet to be described) is almost entirely due to fast electrons.*

Consider a beam of X-rays (of the same nature as gamma-rays but softer) projected into a gas. It is known by experiment that they free electrons from atoms in two distinct ways: some of the corpuscles or photons are entirely absorbed in atoms, and tightly-bound electrons are ejected (photoelectric effect); some on the other hand make elastic impacts against loosely-bound electrons, communicating a part of their energy to these and retaining a part (Compton effect). As the frequency of the X-rays is increased, the former effect becomes less usual; entering into the range of gamma-ray frequencies, we find it fading out; it is reasonable to suppose that if there are corpuscles of light of frequency even higher than that of the gamma-rays, they ionize only by Compton-effect or "Compton scattering." It remains of course conceivable that such corpuscles may ionize in ways unknown at lower frequencies, as for instance by shattering the nuclei of atoms into fragments some of which are fast-flying electrons or protons.

Now though these impacts are properly called "elastic," their laws are peculiar, owing to the differences between corpuscles of light and corpuscles of matter.[10] The electron acquires some, usually a considerable part, of the energy of the photon; this latter (or as some would prefer to say, a new photon) goes off more or less obliquely, with lessened energy and lessened frequency. Given the wave-length of the light, the laws of the impact determine the energy acquired by the electron, the energy retained by the photon, and the direction of departure of the photon, as functions of the direction in which the electron is projected. If we know the distribution-in-direction of the projected electrons, we can determine their average energy. For electrons ejected by X-rays this distribution is known. But if the cosmic rays are (or include) gamma-rays whereof the absorption-coefficient has such values as those given (*e.g.*) by Millikan and by Regener for μ, they are much harder than any otherwise-known gamma-rays or X-rays, hence presumably of much lesser wave-length. Then, for the distribution-in-direction of the electrons which they eject, we must resort to an untested theory. This theory indicates that a beam of short-wave gamma-rays proceeding through matter should provide for itself an escort of electrons, most of them moving in directions inclined at very small angles to the beam itself, and many

[10] See for instance my *Introduction to Contemporary Physics*, pp. 145–163, or the sixth article of this series.

of them starting out with values of kinetic energy which are considerable fractions of the energy of the original photon.[11]

It is this escort of fast electrons which should be the immediate cause of the ionization due to the short-wave gamma-rays. One easily sees how this result is destined to complicate the question of the nature of the cosmic rays. If it can be proved that the ionization attributed to these is caused by fast electrons, this may mean that the electrons are coming into the lower atmosphere from above, in which case most physicists would say "the cosmic rays are fast electrons." On the other hand it may mean that the electrons are produced in the lower atmosphere by photons coming from above, in which case most physicists would say "the cosmic rays are of the nature of gamma-rays." Yet in both cases the immediate agent would be the same; the term "cosmic ray" would be applied in the one case to it, and in the other to the ultimate cause of the immediate agent. This fine distinction, partly physical and partly verbal, is the source of a lot of confusion.

Consider now the evidence about the nature of this immediate agent. About three years ago the physicist Skobelzyn was engaged in studying the Compton scattering of gamma-rays from a certain radioactive substance, using the "expansion" or "cloud-chamber" method. By this method (it has often been described elsewhere,[12] I will therefore omit the details) the ions formed in a glass-walled container of gas are in effect rendered visible, each becoming the centre of a droplet of water, which appears on a photograph taken when the gas is illuminated. If during the experiment the chamber is traversed by a fast electron, its path is marked out by an unmistakable train of droplets. If a strong magnetic field is applied to the gas meanwhile, the trails of the fast electrons are visibly curved, and their speeds may be computed from the curvatures and the field strengths. Skobelzyn applied a field of 15000 gauss, in which the paths of the electrons liberated from atoms by the gamma-rays were curled up into beautiful spirals. But on examining the six hundred and thirteen photographs which he took, he found twenty-five trains of droplets resembling the curled ones due to the electrons of known cause, but not perceptibly curved at all! and two others of which the curvatures were perceptible, but so slight

[11] See for instance the article of H. Kulenkampff (*Phys. ZS.* **30**, 561–567; 1929) where he plots distribution-curves deduced by the quantum-mechanical theory of Klein and Nishina for electrons ejected by light of wave-lengths $2.4 \cdot 10^{-13}$ and $24 \cdot 10^{-13}$. He also considers the influence of the photons in continuing to eject new electrons after their first, second and later impacts; it appears that one photon is likely to start off several electrons at various points of the beam, instead of disappearing (so far as ionizing-power is concerned) after its first impact.

[12] As for instance in my *Introduction*, pp. 45–46, or the first article of this series.

that out of them he estimated the enormous values of 7 and 15 millions of equivalent volts for the energy of the two particles. As for those of which the tracks were not sensibly curved by the field, the energy of some at least (assuming them to be electrons!) must have exceeded 15.10^6 equivalent volts. (Of the rest, the paths were so unfavorably placed that absence of sensible curvature might have been compatible with energy-values as low as, but no lower than, 3.10^6.)

This method has also been adopted by Millikan's collaborator, C. D. Anderson, who has a magnetic field of great extent, pervading a large expansion-chamber so oriented that particles coming along or near the vertical (we shall see evidence that near sea-level, the particles do favor that direction) are subjected over a long distance to its deflecting power, and electrons with energy values amounting to scores of millions of equivalent volts are sensibly deflectible. On some of his plates there are trails curved in the right sense for electrons coming downward from above, with energy amounting to 70 millions. On some there are trails curved in the opposite sense; if they were made by electrons, these must have been travelling from the earth upwards; if they were made by descending particles, as seems more plausible, these must have been positively-charged. On one there appear three paths, two apparently springing from a common origin near the wall of the chamber; one is curved in the proper sense for an electron, one in the opposite sense—if it is the track of a proton, this must have had energy of 120 millions—the third is sensibly straight.[13] Skobelzyn too had got plates on which two or three tracks appeared, coming probably from a common point of departure.

It appears from these pictures that the immediate agents of the ionization ascribed to "cosmic rays" are able to produce long trains of ions closely crowded together (the number of ions per centimetre is probably of the order of one hundred) [14] which is so far as our experience runs, a distinctive feature of electrified material particles such as electrons and protons; that some are deflected in practicable magnetic fields; that from the deflections it probably follows that the charge is sometimes negative and sometimes positive (the uncertainty being due to the fact that from the curvature one cannot tell the sign of the charge unless one knows in which sense the particle is going along the path); that the ones which are known to be charged have enormous

[13] I am much indebted to Dr. Millikan for showing and interpreting these plates to me. They have been shown in scientific meetings and mentioned in the press; the publication of the pictures and the work in the scientific journals will be eagerly awaited.

[14] The values most highly esteemed are obtained not by counting droplets, but by using the third method to determine the number of ionizing particles, the first to determine the total ionization; Kolhörster and Tuwim give 135 ± 10%.

energies, the others (those of which the paths are uncurved) either have yet more enormous energies or else are neutral. These facts make it impossible to suppose that photons are the immediate agents. Before continuing with the deductions we will consider the third method.

The third method of studying cosmic rays involves the use of a "Geiger counter" or some modification thereof—a metal-walled gas-filled tube with a needle or (more commonly) a wire mounted inside it and insulated from the wall, which is connected to one pole of a battery, the needle or wire to the other. If the tube is properly designed and treated, the E.M.F. of the battery properly chosen (this seems to require a lot of experience) the passage of an ionizing particle across the gas between needle and wall is likely to evoke a sudden and violent and very short-lived current-flow. If a telephone-receiver is in the circuit, there is an audible click; if a galvanometer or electrometer is used with an optical device for recording its deflections upon a moving film, there will be a photographic trace of the discharge.

In experiments on cosmic rays with this device, it is the custom to employ a pair of counting-tubes (or even three) and to accept as valid data only the discharges which occur in either simultaneously with

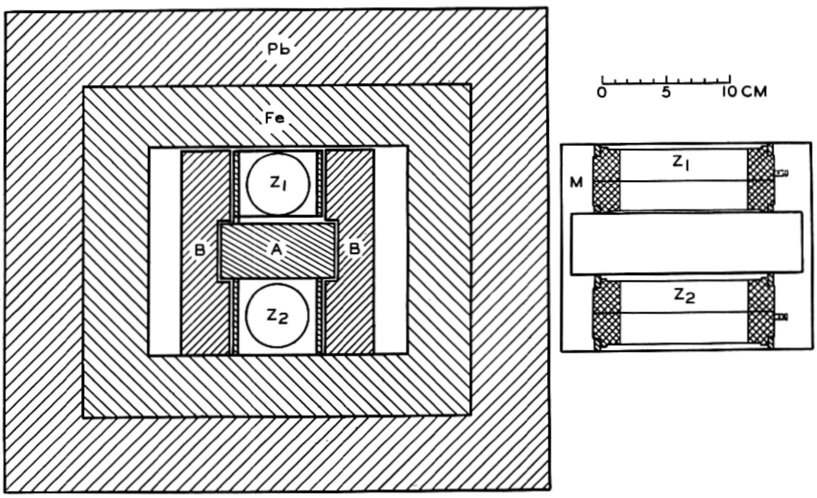

Fig. 12—Apparatus of Bothe and Kolhörster for counting ionizing particles and estimating the absorption thereof in metals.

discharges in the other. I illustrate the method by a sketch from the work of Bothe and Kolhörster (Fig. 12) in which on the right one sees the two counters in longitudinal section, on the left one sees them in cross-section as they lie within their heavy armoring of metal.

"Coincidences"—which is to say, pairs of discharges occurring so close in time to one another that they seem to be simultaneous, that is, within an interval which with good apparatus may be a hundredth or even a thousandth of a second—are much more frequent than they would be, if they were due only to chance. Some of course *are* due to chance: these are the "spurious" or "casual" or "accidental" coincidences, of which the number must be estimated and subtracted from the number observed.[15] After this is done, one is pretty safe in assuming that the remainder is a measure of the number of ionizing particles which have darted through *both* of the counters. By this drastic procedure, of course, the observer limits himself to the study of those corpuscles which happen to be moving along paths which intersect both of the chambers. There will also be corpuscles of which the paths traverse one of the counters, but not the two; it seems as though the observer were throwing away his opportunity of studying these, by rejecting the non-coincident discharges; but some of the discharges in either tube are probably due to radioactive substances in its walls, or to unknown causes inherent in the tube and not connected with cosmic rays; and by accepting only the coincidences, one guards to a great extent against being misled by these. Moreover, by varying the relative position of the counters—for instance, by putting one of them first above and then beside the other—one may study the distribution-in-direction of the ionizing particles. Such studies have not yet been plentiful; but it has been found that if the counters are placed one above the other, the coincidences are several times more numerous than if they are placed side by side.

We have just been considering the effect of magnetic field on the tracks of the corpuscles ascribed to cosmic rays, observed by the cloud-chamber method: it is suitable now to review what the counting-tubes

[15] Suppose that there are N_1 discharges per unit time in one of a pair of counters, N_2 per unit time in the other; and that if a discharge in either starts within a time T after the starting of a discharge in the other, the records of the two (whatever be the way of recording them) make them appear simultaneous. Then in unit time, the periods during which any discharge occurring in the first counter is not separately recorded add up altogether to an amount $2N_2T$. This is the fraction of time, discharges occurring during which are recorded as coincidences. If the events in the two counters are entirely uncorrelated, then out of N_1 discharges occurring per unit time in the first, $N_1(2N_2T)$ or $2N_1N_2T$ (on the average) will coincide with discharges in the second. If the discharges of each counter are recorded as peaks on tracings of separate films, one may determine N_1 and N_2 from the films, set for T the greatest time-difference which cannot surely be distinguished from zero and subtract $2N_1N_2T$ from the total number of coincidences. Or the number of accidental coincidences, together with N_1 and N_2, may be observed by placing the counters so far apart that no particle can traverse the two of them, and T thence computed. Or both sets of discharges may be recorded on the same tracing by connecting both counters to the same electrometer, in which case T will be the greatest interval for which two peaks merge apparently into one; or they may be so connected that no record whatever appears unless two discharges coincide.

have to say about that question. Of the three physicists who have announced experiments upon the problem, L. M. Mott-Smith has given the most impressive account. There are three tubes, of the type exhibited in Fig. 12, their cylindrical chambers being some four cm. wide. Two are in the same vertical line, 30 cm. apart; the third moves to and fro along a horizontal line which intersects that vertical, 35 cm. below the lower of the two which are stationary. Triple coincidences are counted; they are most frequent when all three of the tubes are in line, as one would expect; when the movable tube is shifted away from the line, the number declines, the curve of coincidences N versus displacement x having "about the shape which is expected from the geometry of the arrangement, assuming rectilinear passage of the ionizing particles."

There is another object in the vertical line beneath the lower of the stationary tubes, which I have not yet mentioned: it is a piece of iron 15 cm. thick, which in some of the experiments is unmagnetized, in some is magnetized in such a sense that charged particles which have descended vertically through the upper counters must be deflected, while remaining in that vertical plane which contains the horizontal line along which the movable tube is being shifted. If the particles are charged and of a single speed, the curve of N versus x should be shifted along the axis of x; if they are electrons of energy 10^9 (equivalent volts), it should be shifted by 2.2 cm., and should be easily distinguished from the curve obtained when the iron was demagnetized. Nevertheless, the two curves (or rather the three, for the iron was magnetized first in one and then in the opposite sense, in the hope of producing opposite deflections) are indistinguishable. Mott-Smith considers that if the ionizing particles be electrons, their energy must be not less than 2.10^9—a lower limit which may be halved, if they be protons. These values however are contingent upon an assumption, which I will mention in a moment.

The others who have entered upon this problem are Curtiss and Rossi. Rossi's first apparatus was remarkably like that which I have just described, independently and far apart though he and Mott-Smith were working—the one in Florence, the other in Texas. Later he modified the scheme, having two counters only, and a pair of slabs of iron so placed that when they are magnetized in one sense charged particles passing through the upper counter and thence into either slab should be deflected towards the lower counter, and when they are magnetized in the other sense the charged particles should be deviated away from the lower counter. Again the result was negative; and, says Rossi, "the corpuscular rays are not deflected . . . to such a great extent, as electrons or protons of 10 or 20 times 10^9 equivalent volts would be."

Unfortunately this, like Mott-Smith's, estimate is based upon a tentative answer to a question, one of the most perplexing in physics, though not so familiar as it should be to many who are interested in radiation, ionization of gases, and such phenomena: it is the ancient conundrum, *What is the strength of the magnetic field inside of a magnetized solid?* [16] Mott-Smith and Rossi both assume that the said field strength is equal to the induction B, admitting however that another assumption might be made. If instead one were to put it equal to the "magnetizing field" H, the lower limit inferred for the energy of the corpuscles would sink to a value so small, that the experiments would scarcely even be interesting. Considering this, it is especially important to recall the experiment of Curtiss which preceded the two others. He used two counters only, so foregoing the advantage of the narrow vertically-descending beam to which Mott-Smith confined his study; but between them he placed, not the iron of a magnet, but the space between the pole-pieces thereof; and he *did* get a positive result. The fieldstrength was 7000 gauss, the field extended over 24 cm. of the distance between the counters; vertically-descending electrons traversing the upper counter should have been deflected away from the lower, had their energy been 10^9 or less; actually "making allowance for accidental coincidences, a decrease of the order of 25 per cent has been observed."

We now take up a great but very thorny question: what do counters testify about the penetration and absorption of the cosmic rays in air, in water, and in metals?

Counting-tubes have been taken to great heights of air by Piccard, lowered to great depths of water by Regener. Neither has published (so far as I know) a full account of his data; but Regener implies that the curve of number-of-discharges-per-unit-time (it seems that one tube alone was used) versus depth-of-water agrees in shape with the curve of Fig. 3, especially in respect of its lowest end with the least value of μ. Bothe and Kolhörster took a pair of counters four hundred metres down into a mine, and found—if I read correctly—that there were no coincidences at all, apart from casual ones; a valuable result! The most striking work heretofore published was done in another way: by putting a thick piece of lead (or iron, or gold) either above or between a pair of counters set up in the same vertical line, and ascertaining in what proportion the coincidences are cut down.

The first who tried this out were Bothe and Kolhörster. In the

[16] I have discussed this question (without professing to solve it) in this journal, **6**, pp. 295–310 (1927). Or, see any textbook of magnetism.

particular experiment which I will quote, the apparatus of Fig. 12 was set up under a skylight on the top floor of a building not far above sea-level (the Reichsanstalt in Charlottenburg) *without* the upper part of the metal armor, so that rays coming vertically from above should reach the upper counter after passing through the atmosphere and a little glass. Between the upper and the lower counter, a block of gold 4.1 cm. thick was alternately inserted and removed. Over a period of twelve half-hours with the gold-block *absent* there were 19897 discharges in the upper counter, 12209 in the lower, 986 coincidences; over a period of twelve intercalated half-hours with the gold-block *present* there were 19814 discharges in the upper counter, 10562 in the lower, 743 coincidences. The presence of the gold had thus reduced the coincidences by 24.6 per cent; this the authors qualify by a considerable statistical uncertainty, stating it as (24.6 ± 4.2) per cent.

Rossi did the like experiment, with lead and roofing over the upper counter, equivalent in thickness to 77 cm. of water; in place of the gold he used a slab of lead 9.7 cm. thick; it reduced the number of coincidences by sixteen per cent, which he expresses as $(16 \pm 3)\%$. Only a week or so before I add these words, he reported yet another.[17] There were three counters in a vertical line, 7 cm. of lead and 6 cm. of roofing above them, 25 cm. of lead permanently between them; and an additional thickness of *no less than seventy-six cm.* of lead, which he could interpose between the counting-tubes (half of it between the upper two, half between the two lower). This enormous absorbing layer cut down the number of (triple) coincidences by only some forty per cent (Rossi writes 38.5 ± 5.1).

Now, the coincidences are ascribed to ionizing particles such as those of which the tracks are made visible by the cloud-chamber method: particles which make densely-crowded trains of ion-pairs along their paths. Let us forget for the moment about high-frequency photons, and think only of such particles, descending almost vertically from on high. The numbers 24 and 16 and 38, quoted above, are the percentages of these which are stopped by plates of gold and lead, of the stated thicknesses, in the situations stated. Now the remarkable and perplexing point about these numbers is, that they are about the same as the percentage declines of ionization which are found, by Millikan and Regener, on lowering an electroscope through the equivalent thicknesses of water![18]

[17] I have just received (February 1) a preprint of the report from Dr. Rossi; it is marked *Naturwissenschaften* **20**, 65 (1932).

[18] Bothe and Kolhörster, and Rossi, elect the following way of making the com-

At first glance this appears a simple and welcome result. Further study, however, dispels the pleasant impression: this is not an instance of the sort of observation which sometimes comes aptly to confirm a simple theory and smooth the path for further progress; it is instead a warning of dangerous complications. In introducing the curves of Figs. 3 and 4 and 5, I followed the policy of speaking of them as absorption-curves for rays analogous to gamma-rays descending from above; assuming in effect, that any ordinate of such a curve is a measure of the strength of the gamma-ray beam at the corresponding level of air and water. But if such rays there be, they ionize not directly, but by means of fast-flying electrons (or perchance, other particles) which they expel from atoms. A photon does not achieve the whole, nor even the most, of its ionization at the point where it dies; the effect is spread all along the path of the electron which is heir to a great part of its energy; and this path may be long. Thus, the ionization at a certain level of water or air may be due in part, it may even be chiefly due, to electrons which were unleashed at levels much higher. It may thus be chiefly due to photons which ended their careers far away from the place where it is being measured. It may then be no true measure of the number of photons which collide with electrons at the level in question, and no true measure of the strength of the gamma-ray beam at that level. Indeed it is not likely to be a true measure, unless the range R of the electrons be so short that the strength of the beam does not sensibly diminish as it descends through a distance equal to R. (There is an exception, as I mention on the next page; but in practice it may not help.) Now precisely this condition according to the testimony of Bothe and Kolhörster and Rossi, is *not* fulfilled.

Since the condition apparently is not fulfilled, all sorts of difficulties arise. If the ionizing particles have such ranges and such powers of penetration as the data suggest—not only the data just mentioned, but those of the cloud-chamber method and yet others—many of those which cause the ionization at any particular level of the air have come from points hundreds of metres, or even kilometres, farther up. Any ordinate of such a curve as that of Fig. 4 is a function of the whole of the (unknown) curve representing strength-of-gamma-ray-beam as

parison. Denote by I_0 the number of coincidences per unit time found with nothing between the counters, by I the number found with the block of gold (or lead) between, by d the number of grams per square cm. of gold (or lead). They equate I/I_0 to $exp\ (-\mu d)$, and compute the value of μ; in the first and the third of the experiments just mentioned, it comes out equal to $(3.5 \pm 0.5)\cdot 10^{-3}$ and $(1.6 \pm 0.3)\cdot 10^{-3}$; these are values of the same order of magnitude as those given by Millikan and by Regener for the quantity called μ in the analysis of their curves. In view of the objections to assuming exponential absorption-curves for rays which are or may be composed of fast-flying electrons, I doubt whether it is expedient to use this way of stating the results.

function of height, over an interval of this magnitude. This makes the problem of determining the trend of that curve (if such a curve there be) a formidable one.

Since the problem is so formidable and so important, let us linger over it. It is expedient to treat the very simplest conceivable case, a case which is certainly much simpler than reality, yet quite complicated enough for a first view. Suppose a beam of photons of a single wave-length descending vertically, first through vacuum, then (at $x = 0$) entering a horizontal sheet of some medium (water, say) of uniform density, in which they have an absorption-coefficient μ. Assume that every impact of a photon against an electron results in the total disappearance of the former, in the projection of the latter straight onward (vertically downward). Assume further that the projected electron engenders a constant number of ion-pairs per centimetre of its path, and that the length R of the path is the same for all the electrons.

Then, one readily sees that the ionization in the water, instead of being greatest at the top and diminishing steadily downward, actually increases from the top down to the depth R, and begins to decrease only beyond R. The formula is as follows, x standing for distance measured from the surface of the water downwards:

$$\begin{aligned} I &\propto 1 - e^{-\mu x} \qquad &\text{for} \qquad x < R, \\ I &\propto e^{-\mu x}(e^{\mu R} - 1) \qquad &\text{for} \qquad x > R. \end{aligned} \tag{3}$$

There is a "zone of transition" of thickness R, beyond which the ionization diminishes exponentially, with the same exponent as we have assumed for the absorption of the gamma-rays themselves. This is the exceptional case mentioned above, in which by diving to depths exceeding R one could arrive at a region where the trend of the ionization is the same as that of the strength of the beam of photons, and the value found for μ would apply to these last.

Unfortunately there is no actual case so simple. If there are cosmic gamma-rays coming from the sky, they evidently come from all directions, not merely vertically; and from the character of Millikan's curves it seems likely that they are of several or many wave-lengths, not one only. Conceivably at great depths of water the hardest of all may be filtered out, and these depths may be superior to the values of R for all the electrons; if so then the lowest values of μ, quoted by Millikan and by Regener, may pertain to actual photons. If there are cosmic gamma-rays of several frequencies descending vertically from above, then the actual ionization-curve should be a sum of terms such as (3), with numerical factors depending on the frequencies and the intensities, and values of μ depending on the frequencies; in principle, one might resolve the curve into these terms; but there is a great difference between "in principle" and "in practice." If instead of water we consider the atmosphere, there is reason to infer that the range R of the ionizing corpuscles discovered in cloud-chamber and counting-tube experiments may be greater than the thickness of the atmosphere itself! In this case, however, there should be a maximum of ionization lower down in the air, than the heights already attained by balloons; such a maximum has not been found. The possibilities are enormously complex; and after mentioning that Steinke has made a number of measurements with sheets of metal of thicknesses apparently inferior to the range of the electrons in the metal, with significant results (he speaks of *Uebergangseffekte* or "transitional effects"), I will pass to the description of an experiment by Rossi meant as a contribution to this problem.[19]

I have already quoted the value which Rossi obtained for the percentage drop in the number of coincidences occurring when a plate of lead is slipped between two counters—16 per 100. When he slipped the same lead plate above the upper counter, the drop was less—12 per 100. Let us imagine that photons coming from above were releasing fast forward-flying electrons from atoms in the plate of lead, these passing in the latter case through both of the counting-tubes, in the former through only one—causing coincidences therefore in the latter case, not in the former. The numerical values then oblige us to suppose that when 100 fast electrons dash from above into the upper counter, 16 of them can be stopped by ten centimetres of lead, but accompanying photons will generate four new ones in the slab, leaving a net decrease of 12 per 100. It is, then, this twelve per cent which is the decrease in the ionizing-power of the mixed beam, produced by interposing ten cm. of lead; Rossi thinks that the data prove that the photons are less penetrating than the electrons.

If so, how can it be that the charged particles responsible directly for the ionization have so great a penetrating-power? The electrons expelled from atoms by X-rays, and by the gamma-rays of known wave-length emerging from radioactive substances, are definitely less penetrating than the photons which set them on their ways. No theory gives the slightest indication that this relation should eventually be reversed as the frequency and penetrating power of the gamma-rays

[19] I take equation (3) from Rossi's paper in the *Zeitschrift für Physik*, where the reader can also find equations for cases somewhat more complicated but probably not more plausible. The region beyond R is often called the region where "the primary beam is in equilibrium with its secondaries." Notice also the argument of Kulenkampff, mentioned in footnote 11. I am indebted to Dr. P. M. Morse for a discussion of these questions.

increases. True, the theories are based on the assumption that the energy of the ionizing particles is derived from the photons: if some of them originate from disintegrated atom-nuclei, as the seeming presence of protons among them suggests, the energy of these may be greater than that of the primary photon itself.

Could we dispense altogether with the notion of a beam of electromagnetic waves coming from above, and imagine that there are no cosmic rays other than these fast-flying particles, which then must be supposed to come down into the lower atmosphere from above? This possibility cannot be dismissed; against it, however, speaks the strong testimony of several observers who have travelled far and wide in the search for indications that the intensity of the rays varies from point to point on the surface of the earth. For the earth is a magnet; and while the strength of its field is minute compared with that prevailing within a few inches of an electromagnet or even an ordinary horseshoe magnet, the extent thereof is so great that electrons or protons coming up to our planet from interstellar space are liable to be enormously deflected. Charged particles of energy-values such as I have been mentioning (millions or tens of millions of equivalent volts) should reach the earth prevailingly in the region of the magnetic poles, if they start uniformly from all directions. Now, Bothe and Kolhörster took their instruments—three electroscopes and a pair of counting-tubes—on a cruise through Arctic waters; the ship started from Hamburg and returned there, its course encircling Iceland and passing close to Spitzbergen; there was no sign of a systematic variation of the readings. Millikan, whose data in California had agreed with his data in Bolivia in the admirable way which Fig. 4 displays, made a still finer test: in the summer of 1930 he went "to the settlement which is much the nearest to the earth's north magnetic pole of any settlement on earth, namely, Churchill, 750 miles due south of the pole on the west side of Hudson's Bay—at present a construction camp. . . . The mean results, when compared with those similarly taken at Pasadena during the last week in July and the first in August, show that the cosmic rays have precisely the same intensity at Churchill, in latitude 59, as at Pasadena in latitude 34, the mean results in the two places being 28.31 ions per cc. per sec. and 28.30 ions per cc. per sec. respectively, as measured in my particular electroscope. I think the error in these measurements cannot possibly be as much as 1 per cent." A British expedition to the Antarctic made measurements of cosmic rays within 250 miles of the south magnetic pole, and found the same intensity there as in Australia.[20] It is difficult to doubt that anything

[20] K. Grant, *Nature*, **127**, 924 (1931).

so constant must come from without the terrestrial world, and on its way be exempt from the influence of the earth's magnetic field.[21]

Of the origin of the cosmic rays I have not spoken in this article, having so chosen its title as to exclude that mighty subject from its scope. In the data and in the nature of these rays there is enough of the mysterious and enough of the extraordinary, to suffice for an introduction. Modest as the data seem, what they reveal is sensational. It is found that the atmosphere of this earth is being traversed by ionizing particles, of which the qualities are amazing. If they are such familiar corpuscles as protons or electrons, their energy must be of the order of tens of millions of equivalent volts, values without precedent in our experience. If they are neutral particles they are in themselves unprecedented. If they are electrons or protons which derive their energy from photons or corpuscles of light, these last must have energy greater, frequency higher and wave-length smaller, than any form of light of which we have previous knowledge. Such quantities of energy, be it remembered, are enormously greater than the largest which atoms can emit in the course of their normal lives; they are several times larger even than those which are emitted by collapsing atom-nuclei, in those processes of transmutation of which we already have knowledge. If they come from individual atoms they must arise from processes heretofore unknown, of transmutation or synthesis or annihilation. The constancy of the effect of the ionizing rays, its independence (be it absolute or only approximate) of weather and time and direction and the earth's magnetic field, implies that these processes are spread, not over the earth nor even over the solar system by itself, but throughout the whole of the cosmos.

Literature

The literature of cosmic-ray research has already swollen to such proportions, that a complete bibliography would cover several pages of this journal. There seems to be no book devoted altogether to the subject, though in treatises on atmospheric electricity—I name especially *Die elektrische Leitfähigkeit der Atmosphäre*, by V. F. Hess, translated as *The Electrical Conductivity of the Atmosphere and its Causes* (Van Nostrand, 1926)—a chapter or a section is usually assigned to it.

The major publications of Millikan's school have appeared in the *Physical Review*, as follows:

R. A. Millikan & I. S. Bowen, *Phys. Rev.* (2), **27**, 353–361 (1926) (sounding-balloon observations).

Millikan & R. M. Otis, *ibid.*, **27**, 645–658 (1926) (mountain-peak and aeroplane observations).

Millikan & G. H. Cameron, *ibid.*, **28**, 851–868 (1926) (lakes in California).

Millikan & Cameron, *ibid.*, **31**, 163–173 (1928) and 921–930 (lakes in California and Bolivia).

[21] Nevertheless there have been opposing data; Clay, on a voyage to Java, from the Mediterranean, found the ionization increasing as he approached the equator, and Corlin is said to have observed an increase from south to north along the Scandinavian peninsula; recall also Corlin's assertion mentioned on page 169.

Millikan & Cameron, *ibid.*, **32**, 533–557 (1928) (interpretation).
Millikan, *ibid.*, **36**, 1595–1603 (1930) (approach to north magnetic pole).
Millikan & Cameron, *ibid.*, **37**, 235–252 (1931) (most recent and complete ionization-*vs.*-depth curve).
To this list should be added Millikan's address before the B. A. Symposium on the Evolution of the Universe (*Nature*, **128**, 709–715; 24 Oct. 1931), and the account of C. D. Anderson's work probably soon to be published.

Regener's observations at various depths of water are described in *Naturwissenschaften*, **17**, 183–185 (1929), with a later and regrettably brief note in *Phys. ZS.*, **31**, 1018–1019 (1930). Piccard's observation at the altitude of 16 km. is mentioned in the *Bulletin* of the French Physical Society for 4 Dec. 1931. Swann's observations at three altitudes appear in *Jour. Franklin Inst.*, **209**, 151–200 (1930), and an observation by A. H. Compton in *Phys. Rev.* (2) **39**, 55 (1932).

Skobelzyn's experiments by the expansion-chamber method are published in *ZS. f. Phys.*, **54**, 686–702 (1929); see also P. Auger & D. Skobelzyn, *C. R.*, **189**, 55–57 (1929). L. M. Mott-Smith and G. L. Locher made simultaneous observations by this and the Geiger-counter method (*Phys. Rev.* (2), **38**, 1399–1408; 1931).

The absorption-experiments with Geiger counters cited in this article are due to W. Bothe & W. Kolhörster, *ZS. f. Phys.*, **56**, 751–778 (1929), and B. Rossi, *ibid.*, **68**, 64–84 (1931); see also Rossi, *Lincei Rendiconti* (6), **13**, 600–606 (1931).

Experiments with Geiger counters to seek for deflection of ionizing particles by magnetic fields: Mott-Smith, *Phys. Rev.* (2), **37**, 1001–1003 (1931); Rossi, *Lincei Rendiconti* (6), **11**, 478–482 (1930), and *Nature*, **128**, 300–301 (22 Aug. 1931); L. F. Curtiss, *Phys. Rev.* (2), **35**, 1433; (1930).

Search for influence of earth's magnetism: Millikan, *ll. cc.;* K. Grant, *Nature*, **127**, 924 (20 June 1931) (approach to south magnetic pole); Bothe & Kolhörster, *Berl. Ber.* (1930) (cruise in Arctic waters); J. Clay, *Proc. Amsterdam Acad.*, **30**, 1115–1127 (1927), and **31**, 1091–1097 (1928) (cruise to tropics); Rossi, *Nuovo Cimento*, **8**, 3–15 (1931); W. M. H. Schulze, *Nature*, **128**, 837–838 (14 Nov. 1931) (magnetic storms).

On the dependence of cosmic-ray ionization on time there have been many researches, mostly by people desirous of finding (or of *not* finding) influences of barometric pressure, weather, variations of the earth's magnetic field, the position of the sun, the position of the Milky Way or other remote bodies. Most if not all of the attempts to determine the absolute value of the ionization to be ascribed to cosmic rays, on or above the ground, have involved by necessity studies of fluctuations. Fig. 9 of this article comes from G. Hoffmann, *ZS. f. Phys.*, **69**, 703–718 (1931); his paper contains references to earlier German work, some of it in a geophysical journal. Fig. 10 above comes from G. von Salis, *ZS. f. Phys.*, **50**, 793–807 (1928). Millikan discusses the fluctuations in his 1930 paper. The references to Hess' estimate of the influence of the sun are: *Nature*, **127**, 10–11 (3 Jan. 1931) and *ZS. f. Phys.*, **71**, 171–178 (1931); earlier work is mentioned there.

The estimate made by Kolhörster and Tuwim of the average number of ion-pairs produced (in air under standard conditions) per centimetre path of one of the high-speed ionizing particles detected by the Geiger counters, is stated in *ZS. f. Phys.*, **73**, 130–136 (1931); for the notation it seems to be necessary to study an earlier paper in *Berliner Berichte*, 1931.

For effects associated with the "transition-zone" mentioned above on page 180, see E. Steinke, *Phys. ZS.*, **31**, 1019–1022 (1930) and the earlier work there cited; A. Corlin, *ibid.*, 1065–1071.

For the variation of the ionization inside a high-pressure air-chamber with the pressure of the air, see J. W. Broxon, *Phys. Rev.* (2), **37**, 1320–1337 (1931) and the literature there cited; E. G. Steinke & H. Schindler, *Naturwiss.* **20**, 15–16 (1932) and literature there cited. For the theory mentioned on page 170 *supra*, see Millikan & Bowen, *Nature*, **128**, 582–583 (1931); A. H. Compton, R. D. Bennett & J. C. Stearns, *Phys. Rev.* (2) **38**, 1565–1566 (1931); Steinke & Schindler, *loc. cit.*