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WHAT TO BELIEVE ABOUT COSMIC RAYS[1]

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IT is almost inevitable that any new field in which there are many workers should appear to the public and even to many of the workers themselves to be in a state of hopeless confusion. This is because the individual workers, unrestrained in a new field by a body of established fact, tend to set up hypotheses that seem to fit their particular experiments or their particular theories and are themselves ignorant of, or at least incredulous about, the findings of others, so that the public soon loses itself in a maze of incompletely understood and apparently contradictory statements and opinions, and knows not whom or what to believe. This situation is not improved by the existence of the daily newspaper, which, as its very name implies, is under a greater pressure to find for its pages something that is new than something that is true. The truth is illusive, as Pilate long ago observed, and it can not possibly be determined in time for the three o'clock edition. If the present craze for the new regardless of the true, in art, science, society and government, goes much further the remedy may be found in the prospect that a nugget of sober uncolored truth may become the most exciting news there is just because of its rarity. I venture the prediction that our present age, because of its craze for the new regardless of the true, will be looked back upon by our children's children with more amazement and ridicule than we ourselves feel because of the credulity of the middle ages or the smugness and hypocrisy of the Victorian age.

In talking therefore, as I am asked to do to-day, to teachers who seek to know what to pass on to their pupils in order to instruct and develop rather than to excite and mislead them, I propose to stick closely

[1] Address on the occasion of a special conference of the Committee on the Place of Science in Education, American Association for the Advancement of Science, Pittsburgh, December 29, 1934.

to the results upon which there is to-day large agreement among the most informed and competent workers and definitely to raise a red flag whenever I come down from the bench and begin to act as an advocate or even as a propounder of unestablished opinions.

But when does an opinion become established? In physics when nine tenths of the competent and informed workers in the field are in agreement upon it. I say nine tenths because I have lived long enough to discover that no matter how simple the problem or how inevitable the conclusion there will always be a small percentage of people who will vote no, and that for no reason whatever except that they are built that way. Here one has left the field of physics and entered the domain of psychology or perhaps pathology. But as I propose to deal with physics to-day rather than with either psychology or pathology I am going to define a practical, working knowledge in physics as that which gets the votes of nine tenths of a competent jury. Parenthetically, you will have noticed that I am quite safe in that definition since I have not specified who is to determine "the competence," and have, therefore, left room for the advocates of "authority and omniscience" still to stay in the party. With that "working formula" to start with, let us get down to articles 1, 2, 3, etc., of the platform.

ARTICLE 1. What are we to believe about the penetrating power of the cosmic rays?

Here we can talk fact, which, up to a certain limit, nobody, so far as I know, will deny. Indeed it was penetrating power alone that led to the discovery of the cosmic rays. Up to 1910 the most general penetrating radiations known, of any sort whatever, were the gamma rays resulting from the radioactive disintegration of uranium and thorium, elements found scattered everywhere in small amounts throughout the earth's crust. The most penetrating of these gamma rays—those from thorium C double prime—were known to be able to pass through a meter and a half of water or 16 cm (about 6 inches) of lead before being reduced to a half per cent., or one two-hundredth part, of their initial strength. These rays were known, too, to have an energy of 2.6 million electron volts. No one prior to 1910 had known of or even seriously suggested the existence of any more penetrating radiations. Such rays given off in the earth's crust were known to be able to make their effect weakly detectable about a kilometer above the earth's surface. The simplest way of detecting them was through measuring their well-known power of discharging electroscopes. When therefore the Swiss physicist Gockel in 1910 took up an electroscope in a balloon to a height of 4 kilometers and found it discharging there even faster than at the surface he had not indeed yet discovered a radiation more penetrating than the gamma rays of thorium, but he had proved definitely that there were other radiations coming in from above in addition to those coming from radioactive substance in the earth's crust. Otherwise stated, he had discovered that the discharging effects observed in his electroscope at a height of 4 kilometers did not arise from these radioactive materials in the earth but from some other cause. But the only other possible causes even of the penetrating rays found at the earth's surface had been discussed at length in preceding years and discarded in favor of radioactive materials in the earth's crust. They were (1) radioactive materials distributed in the upper atmosphere which would presumably have a low penetrating power, like gamma rays, or (2) radiations coming in from outside the atmosphere, which would of necessity contain rays of a high penetrating power, since they would have to get through the earth's atmosphere in order to be felt at the surface. These two causes were both advanced again by Hess the next year, after he had repeated Gockel's experiments, risen to higher altitudes and found the discharging effects continuing to increase with increasing altitude. He favored the second cause, but with correct scientific judgment presented both possibilities, since no measurements on penetrating power had yet been made.

Kolhörster in the next years (1912–14) did commendably precise work of the same kind, rising to 9 kilometers and finding the electroscope discharging effects continuously rising and reaching a value some 6 or 8 times that found at sea level. Nothing further of importance happened until 1922, when Millikan and Bowen first sent electroscopes into the stratosphere (altitude 15.5 kilometers) and obtained electroscope-discharge rates that did not keep rising exponentially in the regions above those reached by Kolhörster as they expected them to do if the rays came in from outside. Up to this time no one had made any direct measurements of penetrating power such as could alone differentiate between these two hypothetical causes and determine unambiguously whether or not rays of a higher order of penetrating power than gamma rays existed.

In the years 1922–25 that question was definitely and finally settled by experiments made in Europe by Kolhörster and in America by Millikan, Otis and Cameron. Kolhörster took electroscope-discharge rates above and beneath shallow bodies of water and also above and in cracks below alpine glaciers and computed from these observations penetrating powers of the order of ten times those of gamma rays, though the effects of local rays from the soil were hard to eliminate and left uncertainties in the minds of some critics. Millikan and Cameron in America analyzed the waters of snow-fed lakes and thus completely elim-

inated the possibility of local effects, and brought to light unambiguously the existence of rays of at least 18 times the penetrating power of gamma rays. In succeeding summers by the same method and with greater accuracy they brought to light rays coming in from above the lake and penetrating with certainty down to a depth of 300 feet or about 100 meters without being reduced to as small a fraction of their surface value as the Thorium C″ rays were found to be at a depth of 1.5 meters; in other words, they found without question rays more than 50 times as penetrating as the gamma rays.

Regener has followed the same kind of measurements in Lake Constance in Switzerland down some two and a half times as far as did Millikan and Cameron in Gem Lake, Calif., with results in substantial agreement with theirs as far as they went down.

The existence, then, of a radiation coming in from above and having a penetrating power varying from six to a hundred times that of gamma rays you may definitely believe in. No one, so far as I know, any longer doubts that much nor has doubted substantially that since 1925.

The existence of rays of any kind of such enormous penetrating power is naturally exciting to the imagination.

But here goes up the red flag! You need not as yet believe claims to much higher penetrating powers. For when one is trying to measure the minute high penetrating tail of the cosmic ray depth-ionization curve caution is the word. Whenever the cosmic ray ionization which it is sought to measure sinks below the zero of the instrument, *i.e.*, below the discharge rate due to internal wall effects and the external radioactive contamination of the surroundings, do not let the sale be consummated until you have got concurring reports from different, independent and dependable appraisers. My own rule for under-water work has been to doubt the dependability of discharge rates less than a thirtieth the discharge rate at the surface. Under especially good conditions this might be stretched to a hundredth, but beyond that do not report to your pupils any conclusions as even probably until two or three independent observers get into agreement upon them. It is just too bad to drag an interested public through all our mistakes as we cosmic ray experimenters have done in numerous instances during the past four years.

So much about what you may believe about the existence of a new and an enormously penetrating radiation.

ARTICLE 2. What may we believe about the place of origin of the cosmic rays?

Here, too, I think I can get my jury into agreement if the word "place" is not too narrowly understood, though it has been a hard job to convince it. From statements widely circulated in the papers, I could not have expected agreement two years ago. Now, however, I think I may say that you may believe that the cosmic rays come from beyond the Milky Way. Some meticulous person may think that a bit roomy to be properly described by the word "place."

Cameron and I convinced ourselves of the correctness of this view in 1925 when we proved by our observations in Muir Lake (altitude 11,800 feet) and Arrowhead Lake (altitude 5,100 feet) that the atmosphere between these two levels acted merely as a blanket and had no effect as a new source of radiation, for we thought that this, combined with the enormous penetrating power of the rays, made it practically certain that they did not originate anywhere in our atmosphere. As I indicated above, both Hess and Kolhörster had favored that view before us, but neither their suggestions nor our arguments seemed to convince the jury, for at the Volta centenary, held at Como, Italy, in 1927, one of the most distinguished and competent of living physicists took the platform after my address and said that although our work had proved indubitably the enormous penetrating power of the cosmic rays and had also shown that these rays did not originate in the lower atmosphere he still preferred to think that they originated in the remoter upper atmosphere. I then advanced the further evidence that we had tested very carefully the independence of the intensity of the rays upon the presence of the sun and felt that it was scarcely thinkable that any events could be taking place in the outer regions of our atmosphere of such a nature as to produce rays of the observed penetrating power that would not also be taking place in the remoter regions of the sun's atmosphere, and if this were true we should detect a very large change in cosmic ray intensity as the earth turned her face toward the sun. To this argument there was no answer and I was later informed by the same authority that he regarded it as quite convincing. But still further evidence has appeared. It consists in the findings made by Clay of Amsterdam as early as 1928 and by a whole group of us since the beginning of 1932 of the influence of the earth's magnetic field on the particle component at sea level of the incoming rays. This shows that these particles must have come in from a distance of at least four or five thousand miles, since the earth's magnetic field, extending as it does out to a distance of ten thousand miles and more, could have no such effect as is observed upon these particles if they originated even in the upper regions of our atmosphere, which extends in appreciable density only for a distance of a few hundred miles at most.

All this evidence taken together has, I think, by this

time convinced the jury that the rays at least do not originate in our upper atmosphere. Even within two years, however, the confusion of thinking that has existed in this field is brought into evidence by newspaper comments and even technical paper comments, to the effect that somebody thinks these rays originate in the stratosphere, said stratosphere having apparently recently become to the public a solvent of all riddles—a kind of cosmic Houdini in the performance of the miraculous.

If, then, the upper atmosphere is excluded as a place of origin, then lack of any significant direct influence of the sun and the Milky Way clearly places the place of origin "beyond the Milky Way." This argument is quite independent of whether the sun may or may not be ultimately shown to exert some minute direct influence. Theoretically it might do this through the effect of secondaries stimulated in its atmosphere by primary cosmic rays that could be assumed to traverse space uniformly in all directions. The only significant consideration for our purpose is that if the sun, or other stars like it, were the original source of the cosmic rays, then on account of its closeness to us it should cause an enormous difference to appear between the daytime and the night-time intensities, which it in fact does not do. The indirect influence of the sun arising from the heating effects in the earth's atmosphere is well known and universally accepted. These, combined with the fluctuations in the rays themselves, have apparently masked any direct influences if they exist. This is a matter on which there is as yet no complete agreement, but it is not important for the action of the jury on the question, Do the cosmic rays come to us from beyond the Milky Way? I think that the jury will answer, "You may believe that they do."

ARTICLE 3. What may we believe about the energies of the cosmic ray particles?

Here again the answer is now very definite so far as it goes. Up to 1931 it was not at all definite. Indeed most of the errors that cosmic ray workers like Millikan, Regener, Jeans and others have themselves made in the years preceding 1931 and passed on in double measure to the public were due to the assumption that one might compute the energies of the cosmic rays from their penetrating powers with the aid of the earlier formulas relating to energy and penetration.

As soon as in the fall of 1931 the workers at the California Institute got into actual use our apparatus for directly measuring these energies the uselessness of these earlier formulae, like that of Klein-Nishina, became at once apparent. For the first thing that we clearly demonstrated was that the most significant factor in the absorption of cosmic rays is the nucleus, while all absorption formulas that had appeared up to that time had ignored it entirely. This result followed from the fact that both positive and negative particles appeared, and in approximately equal numbers, in the Wilson cloud chamber photographs taken by Dr. Anderson, and it had been known for 20 years that positive particles could come only from nuclear encounters.

Do not then believe anything now as to cosmic rays that depends for its credentials upon any theoretical absorption formulae whatever. Some of the newer formulae that try to handle nuclear absorption may be correct, but not one of them has yet established its credentials in the range of cosmic-ray energies.

These Anderson measurements have, however, extended the range of directly measured particle-energies from 15 million electron volts, the highest attained up to 1931, up to 6,000 million electron volts, and you may therefore now believe with entire assurance that charged particles of such energies as these—energies undreamed of five years ago—actually exist. Not only that, but the existence of both a latitude and a longitude effect proves to the satisfaction of the jury that some of these particle-energies reach up to an even higher figure, namely, up to 10 billion electron volts and more. The existence then of charged particle energies of at least 6 billion electron volts and probably of more than 10 billion electron volts is one of the most amazing facts of modern physics.

ARTICLE 4. What are we to believe about the kind of processes that give rise to charged particle bullets of such stupendous energy?

Here goes up the red flag! You may not believe anything as yet about that! The atom-building processes which I earlier thought were adequate to account for the then estimated energies, and which might still be adequate from a purely energetic standpoint to be responsible for the less energetic and more numerous of the cosmic rays, are certainly completely inadequate to account for the highest of these observed energies. There are no processes whatever, that we can have any sort of assurance are taking place, that can be called upon to produce such energies as the highest of those observed. The atom-building processes can not reach higher than to about 2 billion electron volts. Of course there are processes that might be taking place, but remember that everything that anybody says about that subject is purely speculative, legitimately speculative if you will, but do not confuse it with anything that you can now believe!

ARTICLE 5. What may we believe about the nature of the energy-bullets with which the super-bandits of the universe are shooting up our earth and everything

upon it? Are they photon bullets or are they charged-particle bullets?

This last question can be partially answered with definiteness, but only partially. Since photons can only ionize the matter through which they pass by knocking charged particles out of atoms and since the cosmic rays must have come through some matter before entering the earth's atmosphere, the entering cosmic rays must in any case have some of these charged particles as constituents. There has never been any doubt about that in anybody's mind so far as I know.

Further, the existence of an effect of the earth's magnetic field upon the intensity of the cosmic ray—and this is agreed upon by everybody—proves directly that there are these incoming particles. This much, then, you may surely believe. The only question that there has ever been for experiment to determine is whether the incoming rays are all particles or whether they are a mixture of photons and charged particles. Upon this question the jury is still working. It has not yet got into agreement. I expect it to hand in its verdict within a twelvemonth. But for the present believe nothing.

ARTICLE 6. What are we to believe about the effect upon the nucleus of an atom of being hit by cosmic ray shots of the foregoing energy?

Here the results are definite. You may believe that both positive and negative electrons result from that encounter. It was through actually observing in a Wilson cloud chamber such encounters that Anderson made the discovery of the existence of the free positive electron—a discovery that seems to me the most fundamental one that has been made since the discovery of the quantum by Planck in 1900—fundamental because it has forced us to relinquish the beautifully simple concept we had heretofore been content with of a universe built up of but two primordial elements, positive and negative unit charges, the former called the proton because the positive unit charge was thought by its very nature to be about 2,000 times heavier than the negative unit and therefore to carry all save 1/2,000 of the mass of matter. The discovery of the existence of the free positive electron with a mass the same as that of the free negative electron destroys that picture. We need now at least 3 fundamental elements, namely, either (1) positive and negative electrons and neutrons or (2) positive and negative electrons and protons. The discovery, during the preceding year, of the neutron forced no such change in our thinking, for according to its discoverers the neutron was then merely a proton and a negative electron in close association. As many as 15 positive electrons and 7 negative electrons have been actually seen to emerge from a photon encounter with a nucleus of lead. Whether those electrons are all knocked out of the nucleus or are created as positron-negatron pairs by the encounter we do not yet know. But that both free positive and free negative electrons result from the encounter of a cosmic-ray photon with a nucleus there can be no doubt.

ARTICLE 7. What are we to believe about the final fate of these newly found positrons?

They are certainly created, or released, in great numbers by photon encounters of sufficient energy with the nuclei of atoms, probably also, though very much less frequently, by electron encounters with nuclei, and they certainly quickly disappear somehow—since we do not find them in our ordinary studies of either metallic or gaseous conduction. They are thrown out into a world that swarms with extra-nuclear negative electrons, and I think the jury will agree that as soon as their energy is spent they rush together under the influence of the mutual attraction of positive for negative, and the pair thus passes out of existence as electrons, their joint mass, however, being transformed, in accordance with Einstein's equation, into radiant energy in the form of two oppositely directed photons each of an energy value of half a million volts.

These are called annihilation rays and have been many times directly observed. They were first brought to light by Chao at the Norman Bridge Laboratory in 1930 and described by him as isotropically distributed, half million volt rays resulting from the impact of the 2.6 million-volt gamma rays from Thorium C″ upon the nuclei of both lead and aluminum. Chao, however, did not know that these were annihilation rays. This was first proved very beautifully by Jean Thibaud of Paris in 1933.

ARTICLE 8. In addition to the foregoing you may of course believe any direct experimental findings from which the personal equation and the judgment of the observer have been entirely eliminated. Many observers could show you such, and I wish to close this very brief statement of some of the articles that you may believe because of the vote of a jury by showing you a group of photographs that tell their own story quite independently of any interpretation which either I or the jury have brought in.

Through most of these photographs[2] you will be the direct witness of the terrible bombardment to which you and everything on this earth of ours is being continuously subjected by some unseen, universally distributed but largely unknown cosmic agency.

[2] These photographs are all found in a book issued in January, 1935, by the University of Chicago Press entitled, "Electrons + and −, Protons, Photons, Neutrons and Cosmic Rays."