THE SIGNIFICANCE OF RECENT COSMIC-RAY EXPERIMENTS

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The particular recent cosmic-ray experiments, the significance of which we wish to discuss, are (1) as yet unpublished results of work by Millikan and Cameron on absorption coefficients of cosmic rays on high mountains and at great depths in mountain lakes, (2) recent experiments by Millikan and Bowen on the absorption of gamma rays in mountain lakes, (3) new experiments in the Norman Bridge Laboratory by Chao on gamma-ray absorption, and (4) experiments by Bothe and Kolhörster and by Curtis on coincidences obtained with the use of cosmic rays in Geiger-Müller ionization counters.

The significance of these four groups of experiments in their relation to the atom-building interpretations of cosmic rays first presented by Millikan and Cameron in 1928[1] can best be seen by a brief review of the reasons for, and the nature of, this hypothesis.

In their review of the field presented at Leeds in September, 1927, Millikan and Cameron stated that in their trip to, and work in, the High Bolivian Andes in the summer of 1926, they had established, at least to their own satisfaction, the independence of cosmic-ray effects upon both latitude and direction *within the limits of their observational uncertainty*, which they estimated at about three per cent—a figure, however, which they then doubled so as to have an ample margin of safety. At the time of these experiments they were alone in these findings, but very recent European work by Hoffman and Lindholm,[3] Steinke[4] and Hess and Mathias[5] has apparently removed all doubt as to the correctness of these important conclusions within the aforementioned limits of uncertainty. This lack of dependence of cosmic-ray intensities upon the direction of the sun, of the Milky Way or of the nearest of the spiral nebula, Andromeda, is certainly one of the most strange and most significant properties of these rays. Minute variations with both latitude and direction may still be found without necessarily modifying the following conclusion, which is to be drawn from this practical uniformity of the flow of cosmic-ray energy into the earth from all directions, namely: that the cosmic rays do not come more abundantly from those directions in the universe in which matter is most abundant, means, when combined with the fact that they can penetrate but a few hundred meters of water at most, that they must originate in those portions of the universe where matter is very rare, or, as stated in the *Nature* article, "in the depths of space."

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In this *Nature* article the authors inclined toward the view that these rays are due to very high-speed electrons that have acquired their energies through falling through cosmic electrical fields reaching values of hundreds of millions of volts. However, within six months of that time they were forced to abandon that hypothesis by their discovery of a *definite banded structure in their cosmic-ray curve.* This banded structure, combined with independence of latitude and direction, required continually recurrent processes, which release a definite sequence of energies, to be going on practically uniformly all about us "in the depths of space."

Aston's very precise measurements of atomic weights then appeared in the fall of 1927, and Millikan and Cameron by combining these measurements with Einstein's equation $MC^2 = E$ found that their sequence of observed cosmic-ray penetrating power was about what was to be expected from the sequence of energies computed to be released by the building out of hydrogen of the celestially abundant elements helium, oxygen and silicon. Not only did the *sequence of penetrating powers* and relative intensities seem to fit pretty well the *sequence of energies and intensities* to be expected on the basis of the abundance of the elements, but the only formula then available for translating energy into penetrating power, that of Dirac, reproduced roughly the observed penetrating powers.

As was then stated, this last point needed further testing, especially at high altitudes and at great depths beneath water, for the hypothesis of atom-building required a very weak radiation of greater penetrating power than any we had observed and corresponding to the formation of the heavy but rare elements out of hydrogen. Also the Dirac formula required that the ionization-depth curve be somewhat *less steep* at high altitudes than our first observations had seemed to indicate was the case.

Meanwhile the Dirac formula had been called in question by the theorists and replaced by one they thought theoretically sounder, though still resting upon uncertain assumptions. This was the so-called Klein-Nishina formula. This formula required that the observed ionization-depth curve become considerably *more steep* at high altitudes than the Dirac formula permitted, or even than the preliminary earlier observations had indicated.

The first as yet unpublished results, the significance of which we are discussing herewith, are those of Millikan and Cameron reported briefly at the meeting of the National Academy in November, 1929. These revealed, first, also in accord with Regener's findings, a very weak, very penetrating radiation at great depths beneath the surface of Gem Lake, 300 feet and more, due, according to the atom-building hypothesis, to the formation of the heavy and rarer elements out of hydrogen. Second, *they also revealed at great altitudes on mountain peaks the steeper ionization-depth curve predicted by the Klein-Nishina formula from the hypothetical*

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formation of helium out of hydrogen. In other words, *the development of the Klein-Nishina formula has strengthened rather than weakened the evidence for the atom-building interpretation of the cosmic rays.*

The second group of experiments upon which we are herewith making a preliminary report represent observations taken by Millikan and Bowen last summer (1929) in the waters of Arrowhead Lake for the sake of comparing directly the absorption coefficient of the monochromatic radiations from ThC″, first with the demands of the Klein-Nishina formula, and, second, with the absorption coefficient of the softest of the cosmic radiations.

The Klein-Nishina formula was found to predict fairly well the observed results on these rays. Further, the penetrating power of the softest of the cosmic rays into the waters of the lake was found to be roughly five times that of these gamma rays of ThC″ into the waters of the same lake. This relative penetrating power corresponds, according to the Klein-Nishina formula, to an energy of the softest cosmic rays about ten times that of these hardest gamma rays, and *this is also the relative energy of the gamma rays from ThC″ and the energy of the softest cosmic ray as computed from the Einstein equation, the Aston curve and the assumption that the softest cosmic ray is produced by the formation of helium out of hydrogen.* These facts then support strongly the atom-building theory.

The only other hypotheses that have been put forward as to the origin of the cosmic rays are first, the falling of electrons through many million of volts of cosmic P. Ds.—an hypothesis that seems to be barred out by the banded structure of the cosmic rays—and second, the annihilation of positive and negative electrons through their complete union. This act should release an energy *350 times* that of the hardest gamma rays, instead of 10 times, as required by the union of four hydrogen atoms into helium, *and as given by observation,* if the Klein-Nishina formula is taken as a guide.

The weakness in the foregoing argument is that there is some little uncertainty about the legitimacy of extrapolating by means of the Klein-Nishina formula from ThC″ rays to rays five times as penetrating. This Klein-Nishina formula is certainly only an approximation, for it assumes that absorption is proportional to the number of external electrons and Mr. Chao's new results[6] obtained in the Norman Bridge Laboratory show that this is not true even for the ThC″ rays, the heavy elements like lead showing an absorption that is greater than that given by the atomic number (or external-electron) law, or even by the mass-absorption law. *Millikan and Cameron's new results show that this same sort of a breakdown is even more pronounced with cosmic rays,* thus suggesting a similarity in nature between gamma rays and cosmic rays. Bothe and Kolhörster have recently argued for the corpuscular character of cosmic rays because

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beta rays also show this same sort of behavior with respect to light and heavy elements, but Chao's results remove the validity from that argument.

All of the recent results obtained by the Pasadena group of observers are then favorable to the atom-building hypothesis, the main evidence for which is found, first, in the banded structure of the rays, second, in the energy relations found in Aston's curve and in Einstein's equation, and checked by observed penetrating powers translated into energies with the aid of the Klein-Nishina formula, and third in the practical lack of dependence of the rays upon latitude and direction. All these relations, except the last, are *energy* relations, and as such are quite independent of whether the rays are themselves photons or electrons. The last, however, speaks rather strongly in favor of photons, and indeed the photon hypothesis is much the simpler one, for when helium is formed out of hydrogen, for example, or indeed when hydrogen is annihilated, there is no electron available to carry away the released energy, while an ether wave is in general the universal way in which, as we well know, Nature provides for throwing out surplus energy. The principle of minimum hypothesis, then, rather requires us to assume a photon until evidence to the contrary appears. *So far as we can see none has appeared thus far.* As soon as one of these photons strikes matter it will of course share its energy by a Compton encounter with an electron, about half the energy on the average remaining in the photon and half going into the electron, and there will be thus produced a beta ray. It is these beta rays, as the authors point out, that must yield the coincidences in the Bothe-Kolhörster experiments that have been repeated by Curtis.

These experiments are of great importance because they show that *beta rays of the enormous energies involved in the cosmic rays have a penetrating power of the same order of magnitude as the cosmic rays themselves.* This is a new and an important discovery, and *it is the whole significance of these experiments.* Also that beta rays have absorption coefficients of the same order of magnitude as the cosmic rays means, of course, that there may be beta rays in the cosmic-ray beam that have come from as far as the beam itself. The practical lack of dependence on latitude of cosmic-ray intensities would indicate, however, that most of this beam reaches the earth in the form of ether waves or photons that cannot be influenced by the earth's magnetic field and that therefore the beta rays are in the main produced in the earth's atmosphere by Compton encounters with photons. Bothe and Kolhörster suggest this possibility, though they argue against it.

The Bothe-Kolhörster coincidence experiments *say nothing as yet about the energies* of the beta rays producing the coincidences. If the foregoing views are correct they gain their energies from the atom-building processes

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discussed above, and these energies would therefore lie between 15 million and 500 million volt-electrons. If measurements upon these energies should reveal much higher values than these, then the theory of atom-building in interstellar space as the source of the cosmic rays would have to be abandoned. This theory postulates the drawing together of hydrogen atoms into clusters under the low-temperature conditions existing in interstellar space and the occasional sudden clamping of these clusters into helium, oxygen, silicon, etc., when suitable probability conditions chance to be fulfilled. The formation of some of the heavier atoms from helium, after it has once been formed from hydrogen, is not, however, necessarily precluded. Temperature is supposed to be inimical to the foregoing clustering, which is antecedent to atom-building—a reason why such atom-building does not seem to be occurring in the stars, where, according to the astronomers, only atom-annihilation is occurring.

The complete annihilation in one act, not of individual positive and negative electrons, but of the whole atom of hydrogen, helium, oxygen, silicon, etc., would indeed yield, if it could be reasonably assumed, something like the right *sequence* of penetrating powers observed in the cosmic rays, but the energies released would in that case be of the order 1, 4, 15, etc., billion volt-electrons, instead of, as now seems most probable, one-thirty-fifth these amounts. If beta rays of any such energies as these higher values should ever be actually found to exist in cosmic rays it might be possible to reconcile the observed properties of these rays with the view favored by certain English physicists that they are the signals of *atom-annihilating* rather than *atom-building* processes taking place independently of temperature all throughout space. Space would, however, then have to be assumed to have many times more matter distributed throughout it than is found in the stars, so that a line drawn out in any direction from the earth would always pass through an amount of matter thick enough to absorb all these "annihilation rays" generated within it. This would make all directions alike, so far as radiations coming into the earth are concerned.

[1] Millikan and Cameron, *Phys. Rev.*, **32**, 533 (1928).
[2] Millikan and Cameron, *Nature*, **121**, 19 (1928).
[3] Lindholm, *Gerlands Beitrage zur Geophysik*, **22**, 141 (1929).
[4] E. Steinke, *Zeit. Phys.*, **42**, 570 (1927), and **48**, 647 (1928).
[5] Hess and Mathias, *Wien Ber.*, **137**, 327 (1928).
[6] Chao, *Proc. Nat. Acad. Sci.*, **16**, 426 (1930).

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