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COSMIC-RAY LIGHT ON NUCLEAR PHYSICS[1]

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(1) ENERGY RELATIONS COMPATIBLE WITH ASTON'S CURVE

IT was Aston's success in 1927 in measuring with his isotope method the exact masses of most of the elements and then in plotting a smooth curve connecting the mass of the hydrogen atom as it appeared in each element against the atomic weight that first gave us a quantitative, thermodynamic way of getting definite information about nuclear transformations. For if the mass-energy equation of Einstein, $E = mc^2$ (1905), was a valid generalization—and every week is now adding new proof of its validity—it and Aston's curve together told at once what kind of nuclear transformations were possible and what impossible among the 92 elements which make up the entire physical world as we now know it. Cameron and I then first tested whether this method would predict correctly the observed release of energy in known radioactive transformations, and its success in so doing[2] at once emboldened us to try to use it for the interpretation of the banded structure of the cosmic rays brought sharply to light by our 1925 and 1927 and 1928 studies of the absorptive characteristics of these rays as a function of depth beneath the surface of the atmosphere. These measurements, carried out in deep mountain lakes, extended from about 8 equivalent meters of water beneath the top of the atmosphere to 80 meters, and could only be interpreted as due to three or more cosmic-ray bands, to the absorption coefficients of which per meter of water we had given at that time the values .35, .08, .04 and .02, respectively,[3] though we pointed out with great care

[1] Address delivered at the "Century of Progress" meeting of the American Association for the Advancement of Science held in Chicago on the evening of June 21, 1933. It immediately followed Dr. F. W. Aston's address on "The Story of the Isotopes," SCIENCE, 78: 5, 1933.

[2] Millikan and Cameron, *Phys. Rev.*, 32: 537, 1928.

[3] Millikan and Cameron, *Phys. Rev.*, 31: 929, 1928, and 32: 548, 1928.

that our data only made it possible to explain the general type of solution, and that the numbers themselves must not be taken too seriously. The only thing we insisted upon was at least three bands of absorption coefficients, one in the general neighborhood of 0.35, one in something like one fourth of that or around 0.1, and still another something like a fourth of that or around 0.02. And with the theoretical formulae that we then had connecting absorption coefficients and energy we computed from Aston's data that the only way bands of such penetrating power could be formed, through the release of energy brought about by any possible atomic transformation was by the synthesis of helium out of hydrogen, for the .35 band, of oxygen out of hydrogen for the second band, and of heavier elements for the higher bands. But I felt it very necessary to find more direct ways of getting the energies of these bands, since all theoretical formulae are suspect when they have to be extended into regions so remote from those in which experimental checks have been obtained. Hence, a good deal of my own time and that of my associates has been directed since 1929 to more direct and dependable measurements of these energies. It is the main results thus far obtained of these direct energy measurements that I wish to present herewith.

But first as to what can be predicted from Aston's curve. The idea of using atomic synthesis to produce energy which manifests itself in electro-magnetic radiation is no new idea. Harkins and a great many others used it as early as 1915 or 1916 to explain the enormous radiation from the stars. But to apply it to the explanation of the banded structure of the cosmic rays and yet account for their most extraordinary property, namely, the uniformity of their distribution over the celestial dome, *i.e.*, their complete independence of the sun or the Milky Way, required a clustering of hydrogen atoms under the extremely low temperatures and pressures existing in interstellar space into cosmic dust or condensed vapor not unlike the clustering of water molecules that take place at higher temperatures in our atmosphere when clouds are formed, and then an occasional sudden formation of a helium atom, an oxygen atom, an iron atom, or, if you will, a uranium atom. According to Aston's measurements, the energy released in that synthetic process would be about 27,000,000 volt electrons for the formation of helium, 116,000,000 volt electrons for oxygen, 500,000,000 for iron, and about 1,650,000,000 (1.7×10^9) for uranium. But if this type of process actually occurs there is no reason for stopping with uranium, for even heavier elements might be formed by the same process, which would, however, be unstable and begin to slide down the Aston curve, just as uranium is doing, until they thus become transformed into the more stable atoms. In other words, they might reach this end result by two routes: (1) direct formation out of hydrogen atoms or ions; and (2) direct formation of heavier elements and the subsequent slipping of those elements by the throwing off of alpha particles down to the end nuclear results. This hypothesis would make it possible for energies to appear considerably above the 2×10^9 volt value.

(2) A Free Positive and Negative Electron-Pair often Result from the Collision of a Sufficiently Energetic Photon with an Atomic Nucleus

Now, the first new result I wish to show to-night has to do with the degree of success which such a synthesis hypothesis has had to date in fitting the observed *directly measured* energies of the cosmic rays.

On the road to it, however, I must point out that everybody now knows that these energy measurements have resulted, as reported by Dr. Anderson in September, 1932,[4] in the discovery, first, that the cosmic rays, in being absorbed by the nucleus of the atom, yield free positive as well as free negative electrons. I had the pleasure of showing Dr. Aston one of the positrons, as we now call them, when he came as a visitor from the Cavendish Laboratory at Cambridge to the Norman Bridge Laboratory at Pasadena early in September, 1932. I told him we should not publish the discovery until we had several more, but we got them within a few weeks, and released the preliminary publication,[5] and within the next few months had made the evidence quite as convincing as that I am showing you to-night. In February or early March Dr. Anderson was delighted to hear, through the daily press, that the Cavendish Laboratory group had repeated and confirmed his findings on their own account. The most surprising aspect of this discovery is that these positrons are obtained not alone from cosmic-ray nuclear encounters, but just as well, as Dr. Anderson announced in April,[6] and as I shall show you in detail to-night, when gamma rays from thorium C″ collide with a nucleus of the atom. Indeed, the photographs I am showing you to-night indicate that *both in the case of thorium C″ rays and in that of cosmic rays a common procedure when a photon is absorbed by the nucleus of an atom is for a positive and negative pair to appear together,* both generally having the same mass, namely, the mass conventionally associated with the free negative electron. Indeed, the pictures I am this evening presenting show the first quantitative measurements of the

4 Carl D. Anderson, SCIENCE, 76: 238, 1932; see also *Phys. Rev.*, 43: 491, 1933.

5 Millikan and Cameron, *Phys. Rev.*, 32: 537, 1928.

6 Carl D. Anderson, SCIENCE, 77: 432, 1933.

mass of the positron. Dr. Anderson's former results fix that mass as not different from the mass of the electron by more than a factor of 20, but these results herewith shown actually *measure* the mass of the positron and reveal it the same as the mass of the free negative electron, with an error of not more than 30 per cent.

(3) THE DISTRIBUTION OF ENERGIES AMONG COSMIC-RAY PARTICLES AT SEA-LEVEL

But now as to our findings at the Norman Bridge Laboratory from the measurement of the energies of the cosmic rays. The most striking result of Anderson and Neddermeyer's energy determinations is that in the group of measurements on particles of energies between 60,000,000 and 3,000,000,000 volt electrons, *the positive and negative energies are alike both as to their numbers and the distribution of their values.* It is true that when the energy measurements are confined to values below 60,000,000 volts and when, further, associated tracks alone are considered, the negatives are 5 or 10 times more numerous than the positives. This last result is presumably due to the fact that close collisions of either positives or negatives with the *extranuclear* negatives of course produce in general only *low energy* negatives, so that this particular source of negatives quite naturally vanishes for energy ranges of the order of 60 million volts or more. The first result, however, namely, that the positives and negatives show an approximate equality both in number and in energy distribution in these high energy ranges, is a very important and at first sight a very surprising one, since the positives can only come from nuclear encounters, while Compton encounters of photons with extranuclear electrons would be expected to make the yield of negatives much greater than of positives. To understand why this is not so one must consider the results of Anderson and Neddermeyer's recent measurements[7] of the energies of the pairs produced by the absorption within their cloud chamber of the gamma rays of ThC″. The sum of the measured energies of such a pair, not at all, however, equally divided between two, comes out in practically all the cases tested within about a million volts of the total incident energy, which is in this case 26 million volts, and since, according to the Dirac theory, it requires an energy of $2mc^2$, which for the electronic mass is equivalent to a million volts, to produce a pair, the foregoing figures mean that in this case, from the point of view of this theory, *the absorption of the photon by the nucleus has been of the photoelectric sort, the total energy of the incident photon appearing in the ejected pair of electrons.* The general validity of this conclusion, however, does not depend upon the correctness of the Dirac theory, for it follows approximately, at least, from the energy measurement alone in the case of ThC″. That it holds also in the cosmic-ray field is suggested by the fact that here, too, the typical result of a nuclear collision is the appearance of a positive and negative electron pair, the positive seeming generally to have the greater energy. In our very first paper on the direct measurement of cosmic-ray energies,[8] Dr. Anderson and I, though not guided particularly by the Dirac theory, drew the conclusions, from our observed fact of the large percentage of *associated* tracks in which positives and negatives appeared together, that "the incident cosmic rays are absorbed *primarily* by the nucleus, rather than by extranuclear electrons as heretofore generally assumed," and that "practically the whole of the energy of the incident photon, or any fraction thereof, should be able to appear in a single ejected proton or electron, or in a number of such." These conclusions are strongly supported by Dr. Anderson's new measurements, for these show that, though the negatives appear in notably greater number than do the positives when the incident rays are the gamma rays from ThC″ (for here Compton encounters with extranuclear electrons add single negatives to the positive and negative pairs coming from nuclear encounters), yet when the energies rise to values of the order of 100 million volts or more the Compton encounters with extranuclear electrons have become negligibly small in comparison with the nuclear encounters so that practically the whole absorption is nuclear. Whether the whole energy of the incident primary goes into the electron pair, as Dirac's theory requires, or whether more general conditions of nuclear collision will need to be set up, it is too early to say with certainty, though for reasons stated below the Dirac theory should be treated with great caution. Oppenheimer and Plesset, of this laboratory, have just published a paper[9] dealing in detail with the application of that theory to Dr. Anderson's results. The theory thus far (1) fails to account for "showers," (2) it seems to require an absorption proportional to Z^2 (Z = atomic number) which cosmic-ray experiments definitely do not confirm at all (see below), and (3) one of Dr. Anderson's photographs gives the sum of the energies of the particles coming from one nuclear encounter somewhat over 2,000,000 volts instead of a million volts less than the incident energy of 26 million. But in any case, whether this Dirac theory fails or not, the experimental evidence so far obtained at least favors the view that very frequently (1) the positives and negatives appear in pairs, and (2) the whole energy of the

[7] Anderson and Neddermeyer, *Phys. Rev.*, 43: 1034, 1933.

[8] Robert A. Millikan and Carl D. Anderson, *Phys. Rev.*, 40: 325, 1932.

[9] Oppenheimer and Plesset, *Phys. Rev.*, 44: 53, 1933.

incident primary ray appears in the group of charged particles (two or more) which result from a nuclear encounter.

This in itself, if correct, is of great significance for the interpretation of cosmic-ray ionization, for it means that *the observed energy distribution of the cosmic-ray particles is not far from the energy distribution of the primary rays producing these secondary ionizing particles.*[10] This lends new interest to Dr. Anderson's new and very careful measurements on this distribution, the results of which may be roughly stated thus. One third of a group of seventy carefully selected and measured tracks, obtained in our apparatus here at sea-level, all of which actually fall within the energy range 60 million volts to 3,000 million volts, have an energy under 350 million volts. One half have an energy under 550 million volts, 75 per cent. have an energy under 1,000 million volts. The ten highest energy tracks all lie between 2×10^9 and 3×10^9 volts. This distribution, in substantial agreement with that obtained by Kunze,[11] whose figures, however, require some correction in view of the fact that the positives are positrons, seems to settle the fact that *the large number of coincidences observed by Rossi*[12] *with counters separated by a meter of lead can not possibly be due to the passage of one and the same charged particle through both counters for* (see below) *it requires a three billion volt* (3×10^9) *particle to traverse a meter of lead and there is actually a negligible number of such particles.*

The foregoing observed distribution of energies also means that if in the equatorial belt at sea-level there are asymmetries in particle-directions due to the earth's magnetic field, as seems to be indicated by reports from Johnson's counter experiments at Panama,[13] these asymmetries must find their explanation in the effect of the earth's field *upon the secondary charged particles released within the atmosphere* by the absorption therein of the magnetically undeviated primary cosmic rays, since no appreciable number of particle rays of the energies actually observed by Anderson and Kunze could have come through the earth's magnetic field into the equatorial belt anyway. According to our latest observations the retardation of the earth's atmosphere can scarcely be more than 3,500,000,000 volts, while to get to the earth at the equator through the earth's magnetic field requires, according to Epstein and LeMaitre and Vallerta's computations, at least 7,000,000,000 volts. If incoming rays of that or of higher energies were responsible for an appreciable part of the equatorial ionization at sea-level they would of course appear prominently in Anderson's measurements, as they do not. There can be no question that these same *low energy* rays observed by Anderson, all of which at the magnetic equator and more than nine tenths of which in temperate latitudes are secondaries, are the very rays which produce the great bulk of Johnson's counter responses. If there are more of these that correspond to positives than to negatives in the equatorial belt it may be because, though the same number of positives and negatives are formed within the atmosphere, the negatives disappear by atomic captures, while the positives do not, or, on the other hand, because more positives are produced by photon collision with the nucleus, but outside the equatorial belt this excess is balanced by the entrance of some excess of negatives entering with the photons in sufficient numbers to account for Anderson's observed equality of positives and negatives at Pasadena. Some high energy negatives due to Compton encounters with extranuclear electrons contributed to bring about this equality. The evidence here reported for this equality is of course statistical and might therefore conceivably involve an error of as much as 10 per cent. Indeed, Anderson and I[14] have heretofore published the estimate, based upon less careful counts, that the positives are somewhat in excess and Kunze[15] agrees with this conclusion. If this former estimate of ours should turn out to be correct this situation would constitute a fourth and probably fatal blow for the Dirac theory, but would support our own earlier view[16] that these positrons are in some way definite elements of nuclear structure. It is a very significant fact that we have never found a pair the sum of whose energies was as high as the highest energies exhibited by single tracks of both positive and negative sign, thus suggesting the possibility of nuclear photo-electric absorption of the non-paired type.

The fact that for cosmic rays practically the whole absorption is nuclear of course means that *all the computations made thus far, both by myself and by others, in the endeavor to obtain cosmic-ray energies from absorption coefficients through the aid of the Klein-Nishina formula are now invalid.* How this nuclear absorption actually varies (1) with the atomic number of the absorber, and (2) with the incident energy, we have already some indications which we hope will soon lead to a quantitative law, but for the present we can present only the following statements.

10 This will be particularly true with an arrangement like Anderson's, in which most of the observed secondary particle rays are near the beginning of their ranges when they enter the observing chamber, since most of them originate in the iron and other dense materials of roughly estimated thickness of say 12 cm immediately around that chamber.

11 Paul Kunze, *Zeit. für Physik*, 80: 559, 1933.

12 Bruno Rossi, *Zeit. für Physik*, 82: 151, 1933.

13 See also Johnson and Alvarez's reported observations in *Phys. Rev.*, 43: 834–35, 1933.

14 *Op. cit.*

15 *Op. cit.*

16 Millikan and Anderson, *op. cit.*

Both according to Schindler's[17] indications and our own, this nuclear absorption seems to increase very slowly with the atomic number of the nucleus—apparently somewhat less rapidly than with the first power of Z. As to its variation with incident energy, we have the following definite facts. The absorption coefficient of the hard monochromatic component of ThC″ of energy 2.6 million volts is but some seven times that of the softest component of the cosmic radiation. For Neher and I have recently measured very accurately this softest component up to an altitude of 8.9 km. (29,200 ft.) in lat. 34 N. and up to 6.7 km. in the equatorial belt, and in the latter region, where the earth's magnetic field has removed all incoming charged particles, we find the absorption coefficient of this quite homogeneous band to be 0.55 per meter of water, and this checks nicely with Kölhorster's original measurements at this 9 km. height. This is from 4 to 5 times our measured value of the absorption coefficient of the rays existing at sea-level, where Anderson's direct measurements place the energy of the average cosmic-ray particle at about 500 million volts. Since, further, Anderson finds the absorption even at 2.6 million volts to be at least 30 per cent. nuclear, it becomes possible to make some sort of a reasonable interpolation between 2.6 million volts and 500 million volts, and thus arrive without the aid of any theory at limits for the mean energy of this least penetrating cosmic-ray band. We shall soon be able to narrow the spread between these estimated limits, but for the present in order to be very conservative I will merely say that this mean energy of the softest cosmic-ray band—which actually carries 90 per cent. of the energy arriving at the earth in the form of cosmic rays, must from this mode of approach lie somewhere between 25 million and 250 million volts.

But there is a second way in which we are able to gain some definite knowledge as to the energies of the cosmic-ray particles. Dr. Anderson has measured directly by means of the changes in curvature, in a 17,000 Gauss magnetic field, the loss in energy of electrons in going through thick lead bars inserted within the cloud chamber, and has found that 300 million volt electrons lose on an average about 35 million volts of energy per cm. of lead traversed, and this checks reasonably well with Heisenberg's theoretical calculations. But I find the number of cosmic-ray ions produced in my unshielded electroscope at Pasadena to be 36.2, while inside of a lead shield 10 cm. thick it is but 25.3, which means that at least 30 per cent. of the cosmic-ray particles existing in this locality have insufficient energy to pass through 10 cm. of lead, that is, have energies below 350 million volts. This 30 per cent. is of course a lower limit, since in this reasoning I am neglecting the new particles produced within the lead by the absorption of the primary cosmic rays. But I may be altogether certain in this way that *at least* 30 per cent. of the rays at sea-level have energies under 350 million volts, and this conclusion is in entire agreement with Dr. Anderson's direct measurement of 33 per cent., as given above. As a further check on this method I made precisely similar measurements at Pasadena with and without lead screens 7.4 cm. thick, and found thus that the cosmic-ray ionization inside the lead was 76 per cent. of the cosmic-ray ionization obtained without the lead shield, which means that at least 24 per cent. of the particle rays at sea-level have energies under $(7.4 \times 35 \times 10^6) = 260$ million volts. This also checks well with Dr. Anderson's measured tracks, for he finds that 17 out of 70, or 24 per cent. of these, have energies under 260 million volts. It is of course to be strongly emphasized that this method gives only *a minimum value* for the number of particles having energies under the computed voltage, since it ignores all the new secondary particle rays which are created within the lead and find their way into the ionization chamber. The error thus introduced becomes larger as the thickness of the lead is decreased until when this thickness reaches, for example, 15 mm., the ionization at 29,000 feet, according to our experiments, is actually a trifle larger than when the lead is removed. But the point that is important here is that the percentage of particle rays that have energies under 35 million times the thickness of the lead in centimeters is necessarily greater than that found by this method. About this there can be no question.

To obtain information, then, as to how cosmic-ray particle energies vary with altitude we took our new vibration-free Neher electroscopes to an altitude of 22,000 feet, obtained the ionization accurately as the plane flew for an hour at that altitude, then repeated precisely the same experiment when the electroscope was surrounded by the 10 cm. lead shield. We thus found that the ionization within the lead was now but 32.5 per cent. of that when the lead shield was removed. In other words, certainly more than 67.5 per cent., and I think it altogether safe to estimate that more than 75 per cent. of the particle rays existing at 22,000 feet have an energy under 350 million volts. *The rays at this altitude are, then, on the average very much less penetrating than the rays at sea-level,* where this same method gave 30 per cent. as a minimum with energies under 350 million volts. By then taking up lead screens 7.6 cm. thick we proved definitely that at 14,000 feet more than 50 per cent. of the cosmic-ray particles there found have energies under 260 million volts. And, finally, by similarly taking up to an altitude of 29,000 feet these vibration-free

[17] Heinz Schindler, *Zeit. für Physik,* 72: 650, 1931.

electroscopes, first without lead shields and then with lead shields 3.1 cm. thick, we have been able to show that certainly 20 per cent. of the cosmic-ray particles existing at 22,000 feet have energies under 115 million volts, as heretofore shown, and since the rays found at that altitude are quite homogeneous a very large percentage is presumably under that energy.

All these new but very direct approaches to the energy problem seem, then, to leave no escape from the conclusion that though the mode of approach to energy through absorption coefficients can no longer be relied upon, yet *the major part of the ionization of the atmosphere by cosmic rays is due to incoming rays of an energy corresponding in order of magnitude to the synthesis of one of the lighter elements out of hydrogen.* Whether this chief band corresponds better to the energy of formation of helium out of hydrogen or of oxygen out of hydrogen these direct methods are not yet sufficiently precise to determine, though it is hoped that they may soon be made so.

It seems to be becoming popular now for the astronomers to use this synthesis-hypothesis instead of the annihilation hypothesis to explain the evolution of the heat energy by the stars. Indeed, the annihilation hypothesis seems at present to be in a state of eclipse, and the question may then be raised whether synthesis can explain both the cosmic-ray and stellar energy. There is no reason why it may not be called upon for both purposes, but with a different mechanism. The most essential element in the foregoing hypothesis as applied to the cosmic rays is the formation of clusters of hydrogen atoms which I have called hydrogen dust, and of course such clusters could not possibly either be formed or hold together save a exceedingly low temperatures, where there are ver few impacts to destroy them. This kind of atom synthesis would then be one in which a heavy nucleu might be formed out of hydrogen by one single clamp ing act. If this kind of an act were possible in th atmospheres of the stars we should of course obtai cosmic rays from stellar sources, which we do not d In Professor Lawrence's experiments, however, w find synthesis taking place when hydrogen atoms a thrown with enormous energy into the nuclei of oth atoms, and of course this kind of process may tal place inside the stars because of the enormous ten peratures existing there, so that it is at least concei able that within the stars atomic synthesis results this step by step atom building while out in inte stellar space the other catastrophic type of ato building occurs.

There is one final result of all our recent measur ments, both with airplanes and with balloons ascen ing close to the top of the atmosphere, with which might conclude. It is that according to our estimat the total cosmic-ray energies falling into the earth approximately one half of the total energy coming from the stars, while, inasmuch as the stellar energ is much more intense in our galactic system than intergalactic space, the cosmic energy out there is ve much more intense. From the astronomical estimat of the distribution of the nebulae we conclude that t total radiant energy in the universe existing in t form of cosmic rays is from 30 to 300 times great than that existing in all other forms of radiant energ combined.

A HISTORY OF THE NATIONAL RESEARCH COUNCIL 1919--1933

VIII. DIVISION OF ANTHROPOLOGY AND PSYCHOLOGY[1]

By Professor A. T. POFFENBERGER

CHAIRMAN

The Division of Anthropology and Psychology is an offspring of two committees of the Division of Medical Sciences of the National Research Council, namely, the Committee on Anthropology and the Committee on Psychology. In the course of a reorganization of the Council following the Armistice, these two committees were invited to consider plans for the formation of "sections" of the Council. A happy decision of the far-sighted representatives of these two fields, at a meeting on October 20, 1919, consolidated anthropology and psychology into the single divisi as it now exists.

This newly constituted division, at the first meeti after its authorization, adopted the following obje tives: (1) To coordinate research activities now progress or in prospect; (2) to encourage the dev opment of research personnel, by a systematic sear for promising material, by furnishing to possil research students information about facilities a opportunities, and by fostering the establishment fellowships and facilities for training; (3) to fost a small number of selected research projects; and (to act *in an advisory capacity* on research proje

[1] This is the eighth of a series of ten articles prepared to describe briefly the nature of the activities with which the National Research Council has been engaged during the past fourteen years.