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THE ORIGIN OF THE COSMIC RAYS

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Abstract

Maximum energy released by atomic-disintegration (radioactivity.)—From Einstein's equation $Mc^2 = E$ and Aston's curve the maximum possible energy that can be released in radioactive changes can be computed. The theoretical and experimental values are in satisfactory agreement.

Energy released in step-by-step atom-building.—No step-by-step atom-building process can produce rays as penetrating as the observed cosmic rays. The absence of the radiations corresponding to such step-by-step processes probably means that atom-building does not in general occur in this way.

The creation of helium out of hydrogen.—About 80 percent of the observed cosmic rays appear to be due to the act corresponding to the sudden union of four positive and two negative electrons into the nucleus of the atom of helium. This produces a cosmic ray of absorption coefficient $\mu = 0.30$ per meter of water.

The creation of oxygen and silicon out of hydrogen.—The observed cosmic rays of absorption coefficients $\mu = 0.08$ and $\mu = 0.04$ appear to be produced by the sudden building of positive and negative electrons into atoms of oxygen and silicon, the former act giving rise to a ray of absorption coefficient $\mu = 0.08$, the latter to $\mu = 0.04$. This last is a definitely observed ray having an energy corresponding to the fall of an electron through 216,000,000 volts.

Possible rays due to the creation of iron and to the annihilation of hydrogen.—The cosmic-ray indications are reconcilable with the view that iron is produced by the union in a single act of positive and negative electrons into the atom of iron, but the cosmic rays show no direct indications of the transformation of the whole mass of the hydrogen atom into radiation.

Synthetic cosmic-ray curves.—The observed cosmic-ray curve can be built up fairly satisfactorily by the assumption that the relative intensities of the cosmic rays reaching the earth's atmosphere are proportional to the abundance of the common elements in meteorites and the earth's crust, 96 percent of these bodies being made of the four elements, oxygen, magnesium, silicon and iron.

The kinetics of atom-building.—While the kinetics of atom-building are more bothersome than the thermodynamics, with suitable assumptions, presented herewith, they may not offer wholly insuperable difficulties.

The place of origin of the cosmic rays.—Evidence is presented to show that cosmic rays do not originate in the stars, but only in the depths of space where temperature and densities are practically zero.

Cosmic rays and the Second Law of Thermodynamics.—The observed properties of cosmic rays, indicating that the creation of the common elements occurs only in interstellar or intergalactic space, suggest the possibility of avoiding the "wärmetod," and of regarding the universe as already in "the steady state."

1. Introduction

IN PRECEDING papers[1] we have presented an ionization-depth curve of high "resolving power" and have shown that this curve indicates a cosmic-ray spectrum consisting of two main sets of bands nearly three octaves apart, the long wave-length band which is responsible for most of the ionization in the atmosphere having an absorption coefficient of about $\mu = 0.35$ while the short wave-length band is resolvable into two wave-lengths of the values $\mu = 0.08$ and $\mu = 0.04$, the first having an intensity about half that of the second.

These results were obtained from an empirical analysis of the ionization-depth curve and entirely without the guidance of any theory. They represented solely the general type of solution demanded by the nature of the curve itself. This solution had at once one consequence of great significance. For it required us to discard the suggestion which we had made earlier that these rays might be due to the impact of very high speed (up to 216,000,000 volt) electrons against the nuclei of atoms. For any such cause would produce a *general* cosmic-ray radiation instead of a spectrum consisting of bands. *The existence of cosmic-ray bands, definitely shown by our curve, demands that the cosmic rays originate in some nuclear act or acts having sharply defined energy-values translatable, like quantum jumps, into spectral-line frequencies.*

2. General Significance of a Banded Cosmic-Ray Spectrum

After we had made the foregoing empirical analysis, prepared the foregoing paper in essentially the form in which it appears in the Physical Review for June 1928, and presented the results (Feb. 16, 1928) in detail to the physics seminar at the Norman Bridge Laboratory, our minds being up to this time completely unbiased by any knowledge as to whether bands might be expected, or if so where they might occur, we set at the task of seeing whether we could find any theoretical justification for their existence, or for their energy-values.

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

[1] Millikan and Cameron, Nature Jan. 7, 1928, Science Apr. 13, 1928, 401, Phys. Rev. **31,** 921 (1928). The analysis of the curve into three definite spectral bands was presented at the Physics seminar of the California Institute Feb. 16, 1928. The proof that these bands constitute the signals of atom-building processes was presented publicly to the California Institute Associates on March 16th and carried in Associated Press reports the next day March 17, 1928.

Now, through the recent, very exact work of Aston[2] supplemented by preceding atomic weight determinations, we know the mass of every one of the atoms with a great deal of certainty, and we can therefore compute the amount of ether-wave energy that can be generated by any sort of atomic transformation that can take place, and knowing this energy we can compute, with the aid of the Einstein equation, the frequency, and with the aid of the Dirac formula,[3] the penetrating power of any rays resulting from all possible atomic transformations. *Such studies reveal the fact that there are no possible transformations capable of yielding rays of the enormous penetrating power observed by us except those corresponding to the building up or creation of the abundant elements like helium, oxygen, silicon and iron out of hydrogen, or in the case of the last two elements out of helium.*

The entire annihilation of hydrogen by the falling completely together of its positive and negative electrons might be an additional possibility, but it can be eliminated in this case for two excellent reasons. The first of these reasons is that there is practically no place whatever for such a radiation in the *observed* ionization-depth curve, for it would be between four and five times more penetrating than the radiation that has the smallest absorption coefficient mentioned above. The ionization due to it, if it exists, would then have to be included in the 2.4 ions which represents the "zero of the electroscope."[1] But this 2.4 ions is only about one-tenth of the observed ionization at the top of the curve, viz. 21 ions, this topmost reading corresponding to a depth of 1 m below the surface of Gem Lake (Alt. 9000 ft.). So that this hypothetical radiation can have nothing to do with the observed ionization-depth curve much above the reading 2.4; and below it there is of course room only for a radiation relatively negligible in intensity in comparison with the softer rays that are responsible for the observed curve.

The second reason is that this hypothetical radiation, if it were present, would of necessity be homogeneous and could not therefore exhibit the banded structure shown by the observed cosmic rays. Whether then this act of the entire annihilation of the hydrogen atom through the coming into complete coincidence of the positive and negative electrons takes place or not, it can certainly be eliminated as a cause of the *observed* cosmic rays. There remains, then, as shown more in detail below, no other atomic transformation in which sufficient mass disappears to create the observed cosmic rays except the aforementioned *atom-building* processes.

3. Energy Released in Atomic Disintegrating Processes—Radioactivity

It is easy to show that no *radioactive* change will suffice for the generation of the cosmic rays, since the Einstein equation tells us that in no case can a radioactive transformation produce rays of more than from one-fourth to one-twenty-fifth of the observed penetrating power. This can be

[2] Aston, Proc. Roy. Soc. **A115,** 487 (1927).

[3] Dirac, Proc. Roy. Soc. **A111,** 423 (1926).

seen from a glance at Aston's curve which for convenience is reproduced herewith (Fig. 1). The radioactive, or *disintegrating* process is always one in which the products of the disintegration are either an alpha particle and an atom of atomic weight four units lower than the parent atom, or else a beta particle and an atom of practically the same atomic weight as the parent atom. In the latter case there has been no *measurable* change in mass, and this is of course also true when the radioactive process emits both beta and gamma rays, so that the only *measurable* source of radioactive energy of any sort is the change in mass associated with the expulsion of an alpha ray. The case of the radioactivity of potassium and rubidium, which emit only beta rays, is no exception to this rule since with methods thus far available there is no measurable change in mass involved in these activities—a fact altogether in keeping with the minute evolution of energy that accompanies them.

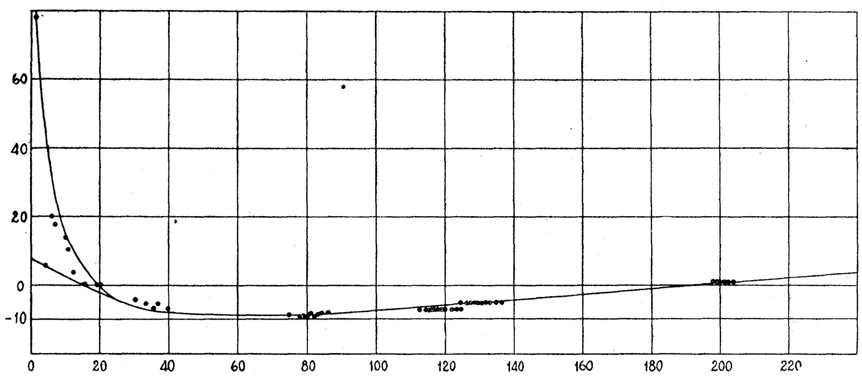

Fig. 1. Aston's mass spectrograph curve. Abscissas: mass numbers of the elements; Ordinates: $(m-1)\times 10^4$ where m is the mass of the hydrogen nucleus in the atom considered.

There can now be but little doubt that the mass of the hydrogen nucleus in all the atoms lies very close to Aston's smooth curve shown in Fig. 1; and if this is so it follows at once that no atom of atomic weight less than 80 can possibly be radioactive in the sense of emitting alpha rays. For the curve up to its lowest point, or minimum, which is reached at about atomic weight 80, requires that the total mass after such hypothetical alpha-ray emission from an atom lighter than one of atomic weight 80, be *greater than* the total mass before the act. This of course means that no act calling for the emission of energy can take place. In other words, the disintegration, by the emission of alpha rays or of hydrogen nuclei, of all atoms of atomic weight less than 80 must be an *endothermic*, not an *exothermic* process, i. e. *it is one that cannot take place at all of itself.*

This disposes quite effectively of the suggestion made many times within the past thirty years that there is the possibility of obtaining energy out of the *disintegration* of the common elements. If Aston's curve is even approximately correct it is only very heavy elements that can possibly *evolve* energy through disintegrating, and *there are no abundant elements at all above atomic weight 80*. The whole of such elements taken together constitute not one percent of all matter.[4]

The condition which must be satisfied in order that even a heavy atom may liberate energy through the emission of an alpha particle may be seen at once from Aston's curve. *Such liberation can only happen in that part of the curve that is rising so rapidly with increasing atomic weight that*

$$n\Delta y > 4 \times (0.00054 - y_n)$$

in which n is the atomic weight of the atom ejecting the alpha ray, Δy is the difference in ordinate between $(n-4)$ and n, y_n is the ordinate corresponding to the atomic weight n, and 0.00054 is the value of y for helium (See Fig. 1), i.e. it is the mass of the hydrogen nucleus as it appears within the alpha particle.

This equation not only shows that it is the very heavy atoms alone that can disintegrate with the ejection of alpha rays and the evolution of energy, but it enables us to compute the maximum hardness, or penetrating power, of any radiations that can be produced by the process of radioactive disintegration.

Thus when thorium, for example, throws off an alpha particle, since the curve shows that at $n = 232$, $y_n = 0.00031$, the *increase* in the mass of the alpha particle per gram-atom by virtue of the fact that it has escaped from the nucleus is

$$4(0.00054 - 0.00031) = 0.00092$$

The *loss* in mass of the residue of the disintegrating thorium atom

$$n\Delta y = 0.000034 \times 228 = 0.007752.$$

Therefore the total loss in mass through the emission of the alpha ray is

$$0.00775 - 0.00092 = 0.00683 \text{ grams per gram-atom.}$$

By Einstein's equation the total energy available for emission in any form because of this loss of mass is $0.00683c^2$ ergs per gram-atom. The total energy that can be given off in each act of ejection of an alpha particle is this divided by the Avogadro number 6.062×10^{23} or 1.004×10^{-5} ergs. Now the highest speed alpha ray known to be given off from radium, according to Kovarik and McKeehan's recent tables, has an energy of 7,700,000 volts which is equivalent to 1.2×10^{-5} ergs.[5] ThC′ ejects in one instance an alpha ray with 14 percent more energy than this. Similarly according to the same tables the "upper limit" for the speed of a beta ray ejected by any of the disintegration products of thorium or radium is 7,540,000 volts or

[4] F. W. Clark, Chem. News, **123,** 341 (1921) shows that the nine elements—O, Si, Al, Fe, Ca, Na, K, H and Te—all light elements—constitute 98% of the earth's crust.

[5] Kovarik and McKeehan, Nat. Res. Council Report on Radioactivity, p. 68.

again 1.2×10^{-5} ergs[6] so that *Einstein's equation predicts very beautifully quite within the limits of reliability of Aston's measurements of mass, the maximum energy available in the radioactive process.*

In general it is the loss of mass when the alpha particle is ejected that must furnish the energy not only for the alpha ray, but also for the beta and gamma rays, since these last two ejections by themselves involve no appreciable loss of mass. Hence most of the alpha, beta and gamma rays given off by the radioactive process will contain very much less energy than the foregoing maximum value, as the radioactive tables show is in fact the case. There are actually no gamma rays from radium or thorium that correspond to an energy of more than about 2,000,000 volts,[7] and these (from RaC and ThC'') have an absorption coefficient of 4.0 per meter of water,[8] which means that they are completely absorbed, i.e. reduced to less than say 2 percent of their initial value, in going through one meter of water. It is not strange that the hardest gamma ray has only about one-fourth the energy of the swiftest alpha and beta rays, since Meitner[9] Ellis[10] and Rutherford[11] have shown that the emission of a charged particle is the primary act in the radioactive process, the emission of a gamma ray being a secondary phenomenon.

The Einstein equation then, taken in connection with Aston's determinations of the precise mass relations of the atoms, not only shows that the property of radioactivity involving the emission of alpha rays must be limited to a very few, very heavy and relatively very rare atoms, for all of the very heavy atoms are non-abundant, but it predicts altogether satisfactorily the observed energy-characteristics of the radiations emitted. The important point for the present argument is that these considerations show that almost all conceivable atomic disintegrating processes involve the *input*, i.e. the *absorption*, rather than the emission of energy, and that none of the few possible exothermic disintegrating processes can in any case give rise to an ethereal radiation of greater energy than would correspond to the fall of an electron through about 8,000,000 volts. A radiation of this theoretical upper limit of penetrating power for a ray arising from a radioactive transformation would be four times as penetrating as the hardest observed rays from RaC or ThC'', i.e. it would pass through approximately four meters of water before becoming completely absorbed (reduced to less than 2 percent of its initial value). *The cosmic rays found by us to pass through eighteen times this amount of matter or 70 meters of water must therefore have an entirely different origin. They correspond to the fall of an electron through 216,000,000 volts and cannot be produced by any atomic disintegrating process whatever since there is no such process that can liberate enough mass to supply the needed energy.*

[6] Kovarik and McKeehan, Nat. Res. Council Report on Radioactivity, p. 92.

[7] Kovarik and McKeehan, l.c. p. 122 also Meyer and v. Schweidler, Radioaktivität, p. 641.

[8] Kovarik and McKeehan, l.c. p. 114.

[9] Meitner, Zeits. f. Physik **26**, 169 (1924).

[10] Ellis and Wooster, Proc. Camb. Phil. Soc. **22**, 844 (1925).

[11] Rutherford and Wooster, Proc. Camb. Phil. Soc. **22**, 834 (1925).

4. Inadequacy of Any Step-by-Step Building-up Process

On the other hand Aston's curve and Einstein's equation show that the process of *building-up* of the more abundant elements out of positive and negative electrons is not only a process capable of producing rays of the observed penetrating power, but that it is the only atomic process capable of producing such rays. This will be discussed quantitatively in §§5 and 6. The foregoing qualitative situation alone, however, is probably sufficient to warrant the conclusion that the observed cosmic rays are the signals sent out through the ether announcing the continuous creation of the heavier elements out of the lighter.

But the Aston curve and the Einstein equation also bring with them entirely new knowledge as to the precise nature of the atom-building processes, namely they show that the atom-building process that results in the observed cosmic rays cannot be one in which positive electrons are added *in successive unit steps* to form the heavier elements out of the lighter. For the Aston curve shows that the maximum mass that could disappear if an element like iron were thus formed by the addition of one hydrogen nucleus to the nucleus of the atom just below iron in the atomic-weight series would be

$$0.00778+0.0008=0.00858 \text{ grams per gram–atom}.$$

This is an energy of the same general magnitude as that found above to be released in the disintegration of thorium (viz. 0.00683). Hence the ether wave sent out when such an act occurred would have but little more penetrating power than that computed above, even if the whole energy of a radioactive change could be concentrated in a gamma ray. As above shown such a ray would be completely absorbed in about four meters of water.

The foregoing argument holds with approximately the same cogency for the formation of any atom whatever by the addition to the atom next below it in the atomic-weight series of one hydrogen nucleus; although in the single case of the formation of carbon out of boron by the addition of one positive electron the energy released would be (See Aston's points)

$$11\times 0.0007+0.0076=0.0153$$

or a little under twice that just computed for the similar formation of iron. But even this radiation would be completely absorbed in about eight meters of water so that *even it could not get into the general region of our cosmic-ray measurements.*

The argument is obviously still more cogent against the generation of the cosmic rays by the process of the building-up of the heavier atoms through the step-by-step addition of an alpha particle to the nuclei of the lighter atoms, since the largest energy that could be released by this process would correspond to a disappearance of mass equal to

$$4(0.00054+0.0008)=0.0054 \text{ grams per gram–atom}$$

and this would produce a radiation that would be completely absorbed in about $4\times 0.0054/0.0068$ or three meters of water. *The observed cosmic rays cannot then be produced by any atom-building process involving so small a disappearance of mass as that corresponding to the addition of either a single hydrogen nucleus or a single helium nucleus to any atom to produce the atom one or four units heavier respectively.*

The results obtained by Millikan and Bowen in the flight of their sounding balloon carrying recording electroscopes 0.92 of the way to the top of the atmosphere enable us to go even farther, and to assert that no radiation *of strong intensity* comes into the earth's atmosphere of a penetrating power between that of the hardest gamma rays and that of the observed cosmic rays, since any strong rays which could penetrate more than 80 cm of water (the amount of matter above the highest point reached in the highest balloon flight) would have discharged the electroscope toward the top of its flight. All of the foregoing radiations, computed on the basis of the assumption of a step-by-step atom-building where either the positive electron, or the alpha particle, is the unit considered to be consecutively added, would correspond to radiations of hardness intermediate between gamma rays and our observed cosmic rays. We may therefore conclude *not only that such atom-building acts do not produce the observed cosmic rays, but also that none of these atom-building acts which could send rays into the earth's atmosphere in this region of frequencies have anything like the probability of occurrence in the heavens that is possessed by the more energetic acts about to be considered.*

5. Quantitative Evidence for the Creation in a Single Act of Helium out of Hydrogen

The foregoing evidence has consisted chiefly in the elimination of other possibilities than those herewith urged; but the direct computation from Einstein's equation of the penetrating powers of the observed cosmic rays furnishes quantitative evidence of a still higher order of certainty.

If all the atoms are built up out of positive and negative electrons, as isotope-evidence indicates is the case, and if step-by-step atom-building, with either hydrogen nuclei or alpha particles as units, must be eliminated, for the reasons detailed in §4, as the source of the cosmic rays, then obviously the first and most fundamental atom-building process that is to be looked for is the instantaneous binding of four positive electrons by two negatives, so as to create *in a single act* the nucleus of helium. The subsequent union of a number of such helium nuclei into heavier elements, if it occurs, would in any event have to be of much less frequent occurrence than the primary one of helium-building out of hydrogen, since it is obliged to use the results of a number of these primary acts for its own existence. Or again, if the heavier elements are built up directly out of hydrogen without going through the intermediary process of the formation of helium, the increased complexity of the process with increasing atomic weight would lead to the expectation that the most frequent occurrence would be the helium-building one. The whole case then for atom-building must rest quite largely upon whether the radiation corresponding to this particular liberation of energy is found in great abundance in the cosmic rays. The way in which the observed rays respond to this test is most illuminating, as the following shows.

According to Einstein's equation and Aston's findings the loss in mass due to this sort of a helium-building act is

$$4\times 1.00778-4\times 1.00054=0.029 \text{ grams per gram-atom}$$

and the radiant energy released each time this act happens is

$$(0.029\times 9\times 10^{20})/(6.062\times 10^{23})=4.3\times 10^{-5} \text{ ergs}$$

The frequency of the ether wave produced is obtained from $E_1-E_2=h\nu$ i.e. $\nu=(4.3\times 10^{-5})/(6.547\times 10^{-27})=6.57\times 10^{-21}$ which corresponds to $\lambda=$ 0.00046A. To find the absorption coefficient of an ether wave of this energy (or wave-length) we may use with a great deal of confidence Dirac's relativity-quantum-mechanics formula[12] viz:

$$\frac{\mu}{\rho}=\frac{ZN}{A}\frac{2\pi e^4}{n^2c^4}\frac{1+\alpha}{\alpha^2}\left\{\frac{2(1+\alpha)}{1+2\alpha}-\frac{1}{\alpha}\log(1+2\alpha)\right\}$$

in which Z is the atomic number (for water, 10), A the atomic weight (18), e the charge on the electron (4.774×10^{-10}), m the electronic mass (9.05×10^{-28}), $c=3\times 10^{10}$, and

$$\alpha=h/mc^2=0.0242/\lambda=53$$

These figures yield $\mu/\rho=0.0030$, *or* 0.30 *per meter of water, in place of the value* 0.35 *which we arrived at purely empirically.*

The two figures agree well within the limits of experimental uncertainty at the upper end of the curve, for it will be remembered that in this region the observed slope of the curve gave $\mu=0.22$ and that the figure 0.35 was arrived at by first subtracting from the observed ionization that due to the more penetrating components as determined by the lower end of the curve, and then finding what coefficient would best reproduce *the residuals.* Errors in the correct assignment of the wave-lengths and intensities of these more penetrating components would influence somewhat, though not largely, the residuals and the coefficient computed from them; so that the above agreement may be taken as at present quite satisfactory. We hope, however, soon to have data which will enable us to make the argument somewhat more precise.

There is one further source of some little uncertainty which should be mentioned before stressing the quantitative agreements. It is found in the fact that Dirac's formula gives the value of μ for a homogeneous, monochromatic radiation, while our measurements are made upon rays some of which have degenerated into secondaries (of one-half the value of $h\nu$)[13]

[12] Dirac, Proc. Roy. Soc. **A111**, 423 (1926).

[13] Millikan and Cameron, Phys. Rev. **28,** 866 (1926).

tertiaries ($h\nu/4$), etc. This should not vitiate the foregoing comparison provided the following condition, probably satisfied in this case, has been met. We have earlier pointed out[13] that after a given primary radiation has gone far enough through matter to get *into equilibrium* with its secondaries, the composition of the beam, or the ratio of the energy of any secondary to that of the primary, thenceforth remains unchanged. As soon as this state is attained the coefficient of absorption of the mixed beam must obviously be the same as that of the primary. It is only when the originally monochromatic beam is *starting* on its path through matter that its absorption coefficient will be diffierent from, and somewhat less than, that of the mixed beam. We assume then in the foregoing that near the earth's surface, where the measurements here considered are made, this condition of equilibrium between secondaries and primary has been attained. Even if this were not so the error thus introduced, were it as high as thirty or forty per cent, would not entirely vitiate the argument here in review for the building, through one single energy-transformation of helium out of hydrogen—an act which releases the cosmic ray for which μ is about 0.30. For the great strength of that argument is found not merely in one quantitative fit, but rather in the agreement between quite a group of experimental facts, as set forth in (1) below, and the set of theoretical facts set forth in (2) below.

1. Our experimental curve combined with the Millikan-Bowen high-flight data shows that the great bulk of the cosmic-ray ionization of the atmosphere from one meter below the top down to 10 or 12 meters below it is in fact carried *by one single monochromatic radiation of about* $\mu = 0.3$ per meter of water. Only at great depths, i.e. from 25 to 70 meters below the top, after the foregoing radiation has been all absorbed, (see Fig. 2), does another ray come into the picture, and this has at least four times the penetrating power of the foregoing radiation so that this radiation for which μ is approximately 0.3 per meter of water stands out quite alone on the wave-length scale, and of great intensity.

2. From a theoretical point of view the atom-building process that creates helium out of hydrogen ought to be the most common one taking place in the universe, both because it is the first and most elementary atom-building process that can occur, and also because there is abundant evidence that the alpha particle (helium nucleus) formed by this process appears in the constitution of many atoms. Further the theoretical value of the absorption coefficient in water of the radiation produced by this particular atom-building act is in fact exactly $\mu = 0.3$ per meter. Still further *there are no abundant elements* between helium, atomic weight 4, and oxygen (or nitrogen) of atomic weight about four times as much, so that the helium-building cosmic ray ought to stand out quite alone, *as it actually does*, with nothing nearer it on either side, i.e. of higher frequency or lower frequency, than a ray four times more penetrating. All of the foregoing theoretical facts in (2) are then precisely in accord with the experimental facts in (1). The abundance of this radiation, its isolated position in the spectrum, and

the numerical value of its absorption coefficient all unite to form a powerful argument for the interpretation here given, even though the uncertainties in the exact numerical relationships have not yet been completely removed.

6. Quantitative Evidence for the Building of Oxygen out of Hydrogen

Only second in cogency to the atom-building argument drawn from the upper end of our curve is that which comes from a comparison of the penetrating powers represented by the lower end of the curve with the energies released by the building of all of the small number of *abundant* elements out of hydrogen.

Bowen's discovery[14] that nebulium consists of oxygen and nitrogen, when combined with the enormous extent of these nebulosities, some of them being visible at least 20°—many many light-years—away from the exciting star, means that these two gases are enormously abundant in the heavens. No other lines are found in the nebulae except hydrogen and helium, both very strong, and carbon, very weak. So far then as evidence from the nebulae goes, the only possible cosmic radiations to look for would be those corresponding to the creation of oxygen, nitrogen and carbon out of hydrogen, or else out of helium. Now the energy released by the formation of oxygen out of hydrogen is

$$16 \times 0.00778 = 0.1245 \text{ grams per gram-atom.}$$

This should give rise to a radiation having, by Dirac's formula, an absorption coefficient $\mu = 0.074$ per meter of water, while the radiation produced by the similar formation of nitrogen, releasing 0.108 g per gram-atom should correspond to $\mu = 0.086$. *The mean of these two is* 0.08 *in exact coincidence with one of the two coefficients, in addition to* $\mu = 0.35$, *that we found we had to introduce to fit our experimental curve.*

The creation of carbon, relatively non-abundant, out of hydrogen, an act releasing 0.0933 g per gram-atom would produce merely a slight broadening of this band on the long wave-length side, unobservable with our limited resolution. It is our judgment, then, that the foregoing quantitative agreement, taken in connection with the fact that theoretically this band for which μ is about 0.08, (henceforth, merely for convenience, called "the oxygen band,") should stand out quite alone between the helium band and the silicon band (see below) is sufficient to warrant the conclusion that the direct formation by a single act of oxygen, (and nitrogen), out of hydrogen actually takes place.

The other way by which oxygen might be formed, namely by the union of four helium atoms, would release an energy per gram-atom equal to $0.00054 \times 16 = 0.00858$ g. This is almost exactly that computed on p. 539 for the maximum possible energy released in a radioactive change, the resulting radiation having a sufficient hardness to be completely absorbed in 4 meters of

[14] Bowen, Astroph. Jour. **67**, 1 (1928).

water. In other words this radiation, if it is produced, would not get into our region of observation at all. If it were abundant, however, it would have made its presence known in the Millikan and Bowen high balloon-flight. And indeed, it may be that the reason our observed helium band had a coefficient 0.35, when the computed came out 0.30, is that there is some weak radiation of the sort here considered in the upper regions of our atmosphere; for so far as the data obtained in mountain lakes are concerned the value $\mu=0.30$ reproduces the observed points altogether satisfactorily as may be seen from the synthetic curve shown in Fig. 2 (see below). But this coefficient $\mu=0.30$ yields, as we have indicated heretofore, an *integrated* ionization some thirty percent lower than that observed in the Millikan and Bowen high balloon-flight[15] and this was the sole reason that we pushed the value above $\mu=0.30$ in originally fixing upon the empirical values of the coefficients that best fitted our data.[16]

So far then as the gaseous elements are concerned *there are only two possible frequency bands which could be formed by any conceivable atom-building process suitable to produce the cosmic rays observable at the earth's surface,* for there are no abundant gases save hydrogen, oxygen and nitrogen, and helium, all extraordinarily abundant in comparison with other elements, and these two bands are actually found in the cosmic rays just where they belong, viz. at about $\mu=0.30$ and $\mu=0.08$. The oxygen band then, though less certainly established than the helium band, adds no little strength to the interpretation of the cosmic rays herewith being presented.

7. Quantitative Evidence for the Building of Silicon out of Hydrogen

Turning next to the solid elements there are just three ways of estimating their abundance, viz. (1) the composition of meteorites, (2) the constitution of the earth, (3) the spectroscopy of the stars, and these all tell roughly the same story. Thus 95% of the weight of all meteorites [17] consists of the four elements, oxygen (54%) magnesium (13%), silicon (15%), and iron (13%), while 76% of the earth's crust[18] is composed of the three elements oxygen (55%), silicon (16%), aluminum (5%), no other element rising to over 2%. Iron constitutes only 1.5% of the crust but it is supposed to be very largely represented in the interior. The evidence from the spectroscopy of the stars is less definite, but it too assigns a very great abundance to the foregoing elements, and gives no others a prominent place unless they be calcium and sodium. Calcium constitutes 1.5% of the earth's crust and 1% of meteorites, while sodium is 2% of the earth's crust and negligible in meteorites. Silicon then appears to be the next most abundant element to oxygen, the only others that need to be considered at all being aluminum

[15] Millikan and Cameron, Phys. Rev. **31**, 921 (1928).

[16] This is why our original tables, Phys. Rev. **31**, 929 (1928), show that our so-called experimental values at the top of the curve are higher than our computed values.

[17] Harkins, Phil. Mag. **42**, 313 (1921).

[18] Cecilia H. Payne, Stellar Atmospheres, Harvard Univ. Press, 1925, p. 5.

and magnesium. But for the purposes of the cosmic rays, aluminum and silicon are altogether identical, their atomic weights being 27 and 28 respectively, while magnesium, atomic weight 24 is so close to them that it releases practically the same mass when it is formed out of hydrogen. In other words *there are no elements between oxygen and iron the formation of which out of hydrogen could give rise to cosmic rays of appreciable intensity except silicon and its immediate neighbors*, and these should give rise to a cosmic-ray band which for covenience we shall call the *silicon band*, because of the fact that silicon is by far the most influential element in it.

The energy released by the formation of silicon out of hydrogen should, according to Aston's curve and Einstein's formula be

$$28(0.00778+0.00050)=0.232 \text{ g per gram-atom}$$

According to Dirac's formula this should have an absorption coefficient of $\mu=0.041$ per meter of water. This is exceedingly close to the empirical coefficient 0.04 which actually carries our curve from 30 meters down to 70 meters below the top of the atmosphere Its energy corresponds to the fall of an electron through 216,000,000 volts. There is no uncertainty at all about the presence in the cosmic rays of a radiation of about this penetrating power, but here again the exactness of the quantitative agreement is less significant than the fact that the elements are so distributed in abundance that this silicon band is the first which can appear, in appreciable intensity, harder than the oxygen band, or better that silicon (and its neighbors) is the only element which can produce a cosmic-ray band between that of oxygen and that of iron where a cosmic-ray band certainly appears.

There is, however, just one other way in which silicon might be formed and produce a radiation of cosmic-ray hardness, namely by the instantaneous union of seven alpha particles, or helium atoms, into an atom of silicon. This act would release an energy per gram-atom of

$$28(0.00054+0.00050)=0.029$$

which is exactly the same as that released (0.029) when four hydrogen atoms unite to form helium. This radiation would then be indistinguishable from the helium band, but at the very most it could only be one-seventh as common an occurrence, since at least seven helium atoms must form out of hydrogen before it can take place. The possibility of its occurrence could not then affect in any significant way the interpretations made above.

8. The Formation of Iron

Thus far we have found all three of the cosmic-ray bands the theoretical existence of which we have predicted from the abundance of the elements, the Aston curve, and the Einstein and Dirac formulas.

There is but one more possible cosmic-ray frequency, of appreciable intensity, higher than that due to the formation of silicon out of hydrogen, namely that due to the formation of iron out of hydrogen, for there are no abundant elements between silicon and iron and none of larger atomic weight than iron. Calcium and potassium, astrophysically somewhat common, may be thought of as providing merely a weak satellite on the high frequency side of the silicon band, while nickel and titanium are identifiable, from the cosmic-ray standpoint, with iron. The hypothetical band due to the formation of iron out of hydrogen corresponds to a release of energy equal to

$$56(0.00778+0.00080)=0.48 \text{ g per gram-atom}$$

and would have an absorption coefficient $\mu=0.019$. Such a radiation could be brought to light with certainty only by making very careful measurements on the shape of the curve at its lower end. The resolving power of our present curve is insufficient to make it possible to assert that it shows the existence of such a radiation. However, we may assert that our curve is not inconsistent with it and even that its introduction improves somewhat the fit of our experimental and theoretical points as will be seen from the discussion of the next section.

As in the case of silicon there is just one other way in which iron might be produced with a sufficient disappearance of mass to produce a radiation of cosmic-ray hardness, namely through the union of fourteen helium atoms in a single act into one atom of iron. This would release an energy equal to

$$56(0.00054+0.00080)=0.075 \text{ g per gram-atom}$$

which gives a radiation practically identical with that produced by the formation of carbon out of hydrogen. In other words it would be a part of the oxygen band already found. We have nothing to show that this process may not take place. Incidentally iron might also be formed by the union of two atoms of silicon, but this act would release

$$56(0.00080-0.00050)=0.0168 \text{ g per gram-atom}$$

and would give rise to a radiation capable of penetrating 8 meters of water (See p. 539). The Millikan and Bowen experiments show that there is no abundant radiation of this sort though there may be a weak one. Also the formation of iron by the union of four atoms of nitrogen, an act releasing

$$56(0.0008+0.0002)=0.056 \text{ g per gram-atom}$$

would give rise to a radiation about twice as penetrating as that produced by the formation of helium out of hydrogen. Our curve does not bring to light evidence of any abundant radiation of this type.

9. The Prediction of the Cosmic-Ray Curve

It will be clear from the foregoing analysis that if we make the assumption that elements are now being created at a rate roughly proportional to the abundance of their occurrence in nature, the problem of predicting the origin of the cosmic rays is enormously simplified by the fact that, broadly speaking, there are only four abundant elements besides the primordial hydrogen, which appears in great abundance everywhere in the heavens, namely helium, oxygen, silicon and iron.

The first two of these, helium and oxygen, can only be formed in one particular way, namely by the coming together in one act of the requisite number of hydrogen atoms, if the mass released is to be such as to give rise to radiations of cosmic-ray hardness. That this mode of coming together actually occurs is further attested by the quantitative agreements between the observed and the computed penetrating powers.

In the case of silicon there are just two different possible modes of formation, viz., first the foregoing one, twenty-eight atoms of hydrogen uniting in one act to form silicon, and second, the union in one act of seven alpha particles to form one atom of silicon. There is *direct, positive* evidence that the first mode of formation occurs, the ray of just the predicted penetrating power actually appearing in our curve. There is no direct evidence that the second mode does not occur, since it would produce a radiation of the same hardness as does the formation of helium out of hydrogen—the most abundant cosmic ray,—but there is a little indirect evidence that it is less likely to occur than the first mode. This is found in the fact that *oxygen* is not formed abundantly, if at all, by the union of four alpha particles as the Millikan and Bowen balloon flight showed (See above p. 544), and if four alpha particles do not unite frequently to form oxygen, there is even less reason to suppose that seven will unite frequently to form silicon.

In the case of the last of the abundant elements, iron, there are a considerable number of possible modes of its formation; but the one which, by analogy with oxygen and silicon, we shall take as most likely of occurrence is its direct formation in one act out of hydrogen.

In endeavoring then to predict from a theoretical standpoint our cosmic-ray curve we have taken the mean proportions in which oxygen, silicon (i.e., silicon+aluminum+magnesium), and iron are found in meteorites and in the earth's crust, viz., 55%, 26% and 7% respectively. Assuming that these three atoms are being formed out of hydrogen in these proportions, we have computed with the aid of the Gold tables the relative intensities of these three frequency bands *after the three radiations corresponding to them, viz. those for which* $\mu=0.08$, $\mu=0.04$ *and* $\mu=0.02$ *have traversed 30 meters of water.* The foregoing sequence of numbers is thus reduced to the sequence O 1.4, Si 2.9, Fe1 .8, i.e., oxygen and iron have about the same influence and silicon has approximately twice that of either of them. We have then divided up our observed cosmic-ray intensity at 30 meters in about these proportions, the ionization at a depth of 30 m being taken as a starting point merely because the ionization due to the helium band ($\mu=0.30$) would have entirely disappeared at this depth. As a matter of fact the observed ionization at 30 m was 1.79 ions of which we gave 0.45 each to oxygen and to iron and the remainder, twice as much, to silicon, these being roughly the proportions given by the abundance of these elements in meteorites and the earth after the radiations have been filtered through 30 meters of water.

TABLE I. *Comparison of observed and computed ionization*

Depth	Iron $\mu = .02$	Silicon .04	Oxygen .08	Helium .30	Total Sum	Exp'l Curve
70	0.13	0.10	0.015		0.245	0.16
60	0.18	0.17	0.03		0.38	0.24
50	0.24	0.28	0.07		0.59	0.44
40	0.32	0.47	0.19		0.98	0.85
30	0.45	0.84	0.50		1.79	1.79
20	0.64	1.52	1.42	0.12	3.70	3.95
15	0.83	2.09	2.46	0.65	6.03	6.24
12	0.89	2.56	3.50	1.90	8.85	8.60
10	0.96	2.94	4.46	3.84	12.20	12.20
9	1.01	3.17	5.06	5.62	14.86	16.05
7	1.10	3.69	6.55	12.18	23.52	
5	1.23	4.34	8.64	27.6	41.81	
3	1.37	5.24	11.75	64.4	82.76	
2	1.46	5.75	13.9	105.1	126.21	192.0*

* This point is obtained from the Millikan and Bowen sounding-balloon data. The experimental error may possibly be as high as 30%. Also, as indicated above, there may be some weak softer rays coming into the top of the atmosphere.

Having thus fixed a starting point, i.e., a value of the ionization I at some point for each of these three radiations, we have computed, with the aid of

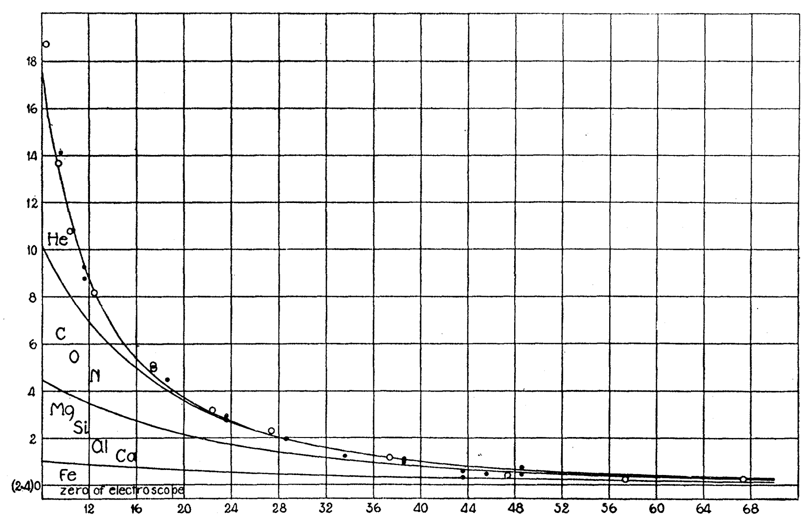

Fig. 2. Comparison of experimental data with a built-up curve compounded from four absorption coefficients. Abscissas: depth in equivalent meters of water beneath surface of atmosphere; Ordinates: ionization in ions per cc per second. Dots are readings in Lake Arrowhead; circles, Gem Lake.

the Gold table and the known absorption coefficient for each radiation, viz., $\mu = 0.08$, $\mu = 0.04$, $\mu = 0.02$, the complete ionization curve for each radiation at all depths. The results are shown in Table I and graphically in Fig. 2. In Fig. 2 the area between the zero horizontal line and the first curve above it represents the ionization due to the formation of iron; the area between the iron line and the curve above it represents the ionization due to silicon, and that between the silicon line and the one above it the ionization due to oxygen. We then took the difference between the reading on this upper line, at 10 m, and the observed ionization at 10 m to fix a starting point, or an I, for helium, and with this starting point, the coefficient $\mu=0.30$ and the Gold table we computed the ionization at all depths due to the formation of helium. The area between the upper two curves represents this ionization. It will be seen that the upper curve, built up in this theoretical way, fits the observed points about as satisfactorily as any curve which could be drawn through them. There is no very great importance to be attached to this synthetic curve, since the mean proportions in which elements occur in meteorites and the earth is not definitely known to be a measure of the abundance of their formation. The curve and table are of some significance, however, first in emphasizing the fact that the four elements, helium, oxygen, silicon and iron are all that are needed to build up the observed cosmic-ray curve; second, in showing pictorially and tabularly how the ionization due to the formation of these four elements varies with depth, for example the total ionization at all depths due to iron is so small that it does not make a great deal of difference whether it is considered or not, while the curves and table show at once that at the top of the atmosphere more than 80% of all the ionization is due to the helium band; third, in showing that there is perhaps a little direct evidence for the formation of iron out of hydrogen since the significant experimental points at 12 m, quite accurately determined, are fitted better when we add the iron coefficient 0.02, than they were when we were locating all our coefficients purely empirically.[19]

10. Thermodynamic and Kinetic View-points as to the Origin of Cosmic Rays

The argument for the sort of interpretation of the cosmic rays herewith suggested has been thus far wholly a thermodynamic one. We have not troubled ourselves at all with the mechanism of atom-building, but have confined our attention to seeing what sort of atomic transformations and combinations were demanded in order to satisfy what we consider to be the fundamental and necessary energy relations. This mode of attack has been the most infallible that physics has thus far devised, but the kinetics of the situation ought not to be wholly ignored.

At first sight these seem to present great difficulties. For first, it has been assumed that positive electrons are able to rush together against their mutual repulsions and, under the inducement of a number of negatives not more than half the number of positives for the lighter atoms, to become

[19] In table IV Phys. Rev. **31**, 929 (1928) at the one point at 12m the agreement between computed and observed readings scarcely fell within the limits of observational uncertainty. This is rectified above without throwing any points on the curve outside that limit.

locked in a new nucleus which always has a net positive charge of from 2 to 92. The evidence is strong that the inverse square law holds for the mutual repulsions of such systems, at least up to distances of the order of 10^{-12} cm. The introduction of the idea of the spinning electron, which makes of it a magnetic doublet, each side of which is capable of attracting an opposite pole with a force that varies with the inverse cube of the distance, may help in the picturing of a mechanism by which one negative can bind two positives, as it does in helium for example, and also in explaining the fact that energy is evolved rather than absorbed in the formation of helium out of hydrogen; but it does not provide any escape from the conclusion that, up to distances of the order of nuclear dimensions, work should be required to bring a new positive up to the distances at which the nucleus-building polar forces can act. Further, this work should in general be so enormous that no known temperatures could be of any avail in providing the requisite kinetic energies to bring a new positive up to within nuclear distances of another positively charged nucleus which might bind it. This will be obvious from the fact that at the highest estimated temperatures in the interior of stars, viz., 40,000,000°C, the wave-length of maximum energy in the black-body radiation curve is at only about 1A, not enough even to strip the k electrons from the heavier atoms, for it takes an energy corresponding to from 0.2A to 0.7A to do even that, to say nothing of pushing nuclei up to distances of 10^{-13} cm at which they might conceivably unite. *These considerations seem to us to show that high temperatures cannot be expected to help at all in the solution of the problem of nucleus-formation. They are probably inimical to such formation.*

The second difficulty which the kinetics of atom-building encounters is that of explaining how four positive and two negative electrons can possibly *chance* to come together at a given instant, at the same spot, and under suitable conditions for uniting into an atom of helium; and this difficulty is, of course, progressively increased in going to the consideration of oxygen, silicon and iron.

Our own way out of the first difficulty is to assume, as elaborated below, that nucleus-building is a phenomenon which, in some as yet unknown way, is favored by the extreme and thus far unexplored conditions of *low temperature and density* existing in interstellar space.

A possible way of escape from the second difficulty is the following; without at this moment hazarding a judgment as to where positive and negative electrons come from—through the condensation of radiation or otherwise—we may at least affirm that they exist in great numbers throughout space. Under the influence of their mutual attractions a positive and a negative begin to fall together in quantum-jumps, and in so doing they give rise to the spectrum of atomic hydrogen so conspicuous in the heavens. When the negative has reached the inmost quantum orbit, it has still not approached close enough to the positive to have occasioned any appreciable loss in mass. This normal atomic hydrogen may next be supposed to gather in another positive electron thus producing ionized molecular hydrogen, a system which the positive-ray spectrograph shows to be a stable one. Up to this point there has not been sufficient closeness of approach between any positives and negatives to cause appreciable loss in mass. Two of these ionized hydrogen systems may then be assumed to come together. Under nearly all conditions of such impact they may if desired be considered to rebound in accordance with the usual assumptions of the kinetic theory of gases. But let it be now imagined that once in a long, long time the conditions of approach governed by the unknown probability law above suggested are just right for the four positives and the two negatives to clamp themselves together into a helium nucleus. Practically the whole change in mass will then occur at this instant of clamping so that the radiation given out will have the full value 4 $(0.00778-0.00054)$, and the necessity of having six electrons (four positives and 2 negatives) *happen to find* themselves at the same spot at the same time has been avoided. They have been *gathered in* by a step-by-step process, but the clamping, or nucleus-building, has all taken place at one instant. These considerations may be extended to oxygen silicon and iron, and *it may well be that the loose clustering which precedes clamping may be facilitated by the exceedingly low temperatures that exist in interstellar space.* In other words energy of impact may well be inimical to the *clustering* which, according to the suggestion herewith put forth, would have to precede nucleus-building. It might be interesting to see whether even in the laboratory hydrogen at liquid helium temperatures will show any tendency to be transformed into helium.

After all, the problem of the kinetics of atom-building need not be so different from the kinetics of complex-molecule-building or crystal-building. If in the latter case the atoms take their assigned places one at a time, then the two problems would, indeed, be essentially different, but if a large group of them fall into position at the same instant the two problems would not be altogether dissimilar. Again crystal-building is facilitated by low temperature not by high, and as will appear more fully in the next section, this seems to be also a definite characteristic of the process of atom-building.

11. The Place of Origin of the Cosmic Rays

All observers are now agreed that if there be any directional effect at all in the cosmic rays it is but a slight one. We, ourselves, have not yet detected any favored direction whatever, though Kolhörster[20] and Büttner[21] report doing so. In any case the rays certainly come into the earth *nearly* equally from all directions. This means that they are either formed (1) out in the interplanetary and interstellar spaces, including of course the nebulous regions above the earth, or else (2) in stars that are more or less uniformly distributed throughout the heavens. These are the only two possible alternatives. In both of these localities matter exists under extreme and as yet unexplored conditions, and in view of the history of the last thirty years of physics, it would no longer be surprising if matter were again found to

[20] Kolhörster, Sitz. Ber. d. Preuss. Akad. **34,** 366 (1923).
[21] Büttner, Zeits. f. Geophys. **21,** 87 (1926); **21,** 291 (1926).

behave in some hitherto unknown and unexpected way as a new field of observation is entered.

Of the two foregoing alternatives we think it possible to eliminate the first and to establish the second with considerable definiteness, and that for the two following reasons.

First. If the mere presence of matter in large quantities and at high temperatures favored in any way the atom-building processes which give rise to the cosmic rays, then it is obviously to be expected that the sun, in view of its closeness, would send to the earth enormously more of them than could any other star. But the fact is that all observers are agreed that the change from midday to midnight does not influence at all the intensity ofthe cosmic rays.[22] This can only mean that *the conditions existing in and about the sun, and presumably also in and about other stars as well, are unfavorable to the atom-building processes which give rise to these rays.*

Since, however, the rays do come to us at all times, day and night, and, according to all observers, at least very nearly equally from all directions—according to some as accurately so as they have as yet been able to make the measurements—there is scarcely any escape from the conclusion that *the atom-building processes giving rise to the cosmic rays are favored by the conditions existing in interstellar space.* If then, in going from a point in interstellar space toward the center of a star the favorable conditions for atom-building existing in outer space have disappeared as the surface of the star is reached, it is well-nigh inconceivable that they will again reappear in penetrating from the surface to the center—a path along which the changes in physical conditions all continue unchanged in direction. So that from the foregoing we may not only conclude quite definitely that the stars are not the sources of the cosmic rays, but also that the main *atom-building processes probably do not take place inside of stars at all.*

Second. The foregoing conclusions may also be arrived at from an entirely different mode of approach, namely from our measurements upon the absorption coefficients and the total energy content of the cosmic rays.

The hardest rays which we have observed are completely absorbed (reduced to say 2% of their initial intensity) in going through 70 meters of water. This means that, even if the atom-building processes went on inside a star, the resulting cosmic radiations could not possibly get out, but would all be frittered away in heat[23] before emergence, save in the case of those rays that originated in the star's very outermost skin—a skin equivalent in absorbing power to a hundred or so meters of water.

But we have also found that the total energy coming into the earth's atmosphere in the form of cosmic rays is about one-tenth the total heat and light energy coming to the earth from the stars exclusive of the sun.[24] This

[22] R. A. Millikan and G. H. Cameron, Phys. Rev. **31,** 169 (1928).

[23] It is important to remember that, as we have already shown, Phys. Rev. **28,** 866 (1926), rays of this kind become frittered away into heat in this passage through matter *without any change in the quality* (i.e. frequency or absorption coefficient) *of the residual beam.*

[24] R. A. Millikan, and G. H. Cameron, Phys. Rev. **31,** 929 (1928).

last fact means that *if the cosmic rays have their origins within the stars they cannot, even at the points of their origin, have an intensity more than ten times that which they have when they reach the earth's atmosphere, for if they had the cosmic-ray energy transformed into heat by absorption on the way out would yield a total heat outflow from the stars larger than the observed ten to one ratio.* In other words, if the stars are the sources of the observed cosmic rays, it follows from our measurements on absorption coefficients and on total energy content that the total heat output of the stars must be furnished by the atom-building processes going on in their merest outer skins of a thickness equivalent in absorbing power to about a hundred meters of water, and that therefore no atom-building processes, nor any other activities capable of furnishing heat, can then be going on in their interiors.

It is, however, so altogether absurd to suppose that atom-building processes are going on actively at the surface of a star and down to a depth of a hundred meters, and then suddenly stop there that we are forced back by this present mode of approach to the same conclusion arrived at from the direct determination of the lack of cosmic-ray activity of a particular star, the sun, namely to the conclusion that *the observed cosmic rays do not originate in the stars at all, but that they must originate under the extreme influences of exactly the opposite sort existing in interstellar space.*

These considerations bring us then from two entirely new points of view to the conclusion that the heat output of the stars must be derived from an entirely different source from the atom-building processes which produce the cosmic rays. Jeans[25] and Eddington,[26] from other considerations, based wholly upon the lifetimes of the stars, have repeatedly emphasized the necessity of finding a source for this output other and greater than the process of atom-building, but we can now go further and say that the process of energy emission by atom-building does not take place in the stars at all, or at least in such amount as to make the stars an appreciable factor in the output of cosmic rays, for if it did the stars would have to be radiating heat much faster than is the case.

As is well known, Eddington and Jeans have found this new source of stellar heat *not in an atom-building process, but rather in an atom-annihilating process* which they assume to be going on in the interior of stars, positive electrons being thought to be continually transforming their entire mass into ether waves in accordance with the demands of Einstein's equation. As indicated above, we have sought in vain among our cosmic rays for a ray of penetrating power corresponding to this act. It will be recalled that the mass which disappears in the creation out of hydrogen of one gram-atom of silicon—this produced the hardest cosmic ray that we can say with certainty that we have yet observed, for the iron rays are still to some degree hypothetical—was 0.23 g. The complete annihilation of the mass of hydrogen would obviously then produce, in accordance with Einstein's equation, a ray having approximately 4 times (accurately 1.0778/0.23 times) the energy and

[25] J. H. Jeans, Problems of Cosmogony and Stellar Dynamics, Cambridge, 1919, p. 286.

[26] A. S. Eddington, The Internal Constitution of the Stars, Cambridge, 1926, Chap. XI.

penetrating power of our hardest definitely observed ray. *Our failure to find this ray, however, is no argument at all against the existence of the process in the interior of stars* where the pressures are colossal and the densities may be enormous. Indeed our failure to find this ray means rather that, if the act occurs at all, as Eddington and Jeans think it must, it is obliged to occur precisely in the interior of stars where the resulting radiation is hidden away behind an impenetrable screen of matter—a screen that transforms all its energy into heat before the ray can get out. If the cosmic rays originate within the stars they would of course be similarly screened.

On the other hand, that the atom-building processes responsible for the cosmic rays, as distinct from the atom-destroying process just considered, actually occur, as our experiments definitely show, *outside the stars*, or at least where the rays produced by them can get to us, and in an energy that is of the same order of magnitude as that of the heat poured out by the star, is an extraordinarily illuminating fact. For it suggests at once, when combined with Eddington's argument, the following incomplete cycle each element in which now has the *experimental* credentials indicated in the brackets:

(1) Positive and negative electrons exist in great abundance in interstellar space (see the evidence of the spectroscope).

(2) These electrons condense into atoms under the influence of the conditions existing in outer space, viz., absence of temperature and high dispersion (see the evidence of the cosmic rays).

(3) These atoms then aggregate under their gravitational forces into stars (see the evidence of the telescope).

(4) In the interior of stars, under the influence of the enormous pressures, densities and temperatures existing there, an occasional positive electron, presumably in the nucleus of a heavy atom, transforms its entire mass into an ether pulse the energy of which, when frittered away in heat, maintains the temperature of the star and furnishes most of the supply of light and heat which it pours out (see the evidence of the lifetimes of the stars—Eddington-Jeans).

The foregoing is as far as the experimental evidence enables us to go, but the recent discovery of the second element of the above unfinished cycle, namely that the supply of positive and negative electrons is being used up continually in the creation of atoms the signals of whose birth constitute the cosmic rays, at once raises imperiously the question as to why the process is still going on at all after the eons during which it has apparently been in process—or better *why the building stones of the atoms have not all been used up long ago*. And the only possible answer seems to be to complete the cycle, and to assume that these building stones are continually being replenished throughout the heavens by the condensation with the aid of some as yet wholly unknown mechanism of radiant heat into positive and negative electrons.

This is a new mode of approach to a conclusion, a portion of which at least is old. For the Einstein assumption itself that mass is convertible into radiant energy, requires the existence also of the inverse process, unless the validity of the Second Law of Thermodynamics in its most widely accepted form is to be denied. In other words, in the strict thermodynamic sense there can be no such thing as *equilibrium* within a closed system containing radiation and matter unless the convertibility of mass into radiant energy is a reversible process. The effort to work out the thermodynamics of a cycle containing this process has recently been made by Stern[27] Tolman[28] Zwicky.[29]

But we have in the foregoing gone farther than they. For the mere assumption of the reversibility of the foregoing process is not sufficient of itself to avoid the "wärme-tod," i.e., the ultimate disappearance of all available energy. The essence of the Second Law lies in the assumption that an isolated system tends towards a state of uniform temperature characterized by the black-body law of distribution of radiant energies and of gas-molecular velocities. The mere assumption that radiant energy is transformable into atoms in no way modifies the consequences of the Second Law, provided the atoms, when created out of radiation, are endowed with the kinetic energies appropriate to the temperature of the radiation out of which they have been formed, and they must on the average be so endowed if Second Law reasoning is to be used, since otherwise temperature differences would establish themselves in an enclosure once brought to a uniform temperature. Indeed, from the Einstein point of view radiation is essentially corpuscular in its very nature.

On the other hand, if the universe is to be treated as a closed system the only way to avoid the "wärme-tod" is to assume that after potential energy has been once transformed into heat, it can somehow, somewhere in the universe go back again completely into the potential form—in particular that the *kinetic energy of light-quants* is actually re-transformable in toto into the *potential energy of statically attracting systems*. This is the essence of the assumption that we have made above in supposing that only under the conditions of temperature and pressure existing in inter-stellar space, radiant energy is transformed into *positive and negative electrons* which can then fall together under the influence of their mutual attractions, aggregate in turn into the heavier atoms, and then develop new "hot spots" in space, (stars) as these atoms rush together, and in so doing re-transform their potential energies again into heat. This is a violation of the Second Law of Thermodynamics as applied to the universe, and, it is this violation that we have been led to suggest by the observed properties of the cosmic rays; but we leave the Second Law intact for all the purposes of the small scale, terrestrial phenomena for which it has been used so successfully in the past. *The essentially new element that we have introduced is the experimental observation that the creative, or atom-building, processes do not appear to take place at all in the stars*, or in those parts of the universe where matter is found in appreciable densities and temperatures, but only in the interstellar or

[27] O. Stern, Zeits. f. Elektrochemie, **31**, 448 (1925).

[28] Richard C. Tolman, Proc. Nat. Acad. **14**, 268, 348, 353 (1928).

[29] F. Zwicky, Proc. Nat. Acad. July, 1928.

intergalactic spaces where densities and temperatures are essentially zero. Our *experimental evidence* does not, indeed, extend to the creation of the lightest element, hydrogen, out of radiation, but the inclusion of this also among the creative processes going on only in interstellar space is a natural extension of our observational data on the other abundant elements, for hydrogen is well-nigh inevitably being created in those portions of space in which the elements that use it for their building material are also being created. But in making this extension we are denying the reversibility at ordinary temperatures and pressures of the process of the transformation of matter into radiation. This is why our conclusion differs from that of Stern and Tolman and why we are able to regard the universe as in a steady state now, though a state not satisfying the condition of microscopic reversibility.

In a certain formal sense our assumption may be considered as *not* a violation of the Second Law since, in accordance with the Carnot's statement of that law, viz.: efficiency $=(T_1-T_2)/T_1$, heat is indeed transformed completely into work *when* T_2 *is at absolute zero*. Nevertheless we have in our assumption denied the applicability of the usual thermodynamical reasoning to *cosmical* processes. This is, however, not the first time that doubts as to the legitimacy of applying such reasoning to the cosmos as a whole have been expressed. Our assumption is scarcely more radical than was Einstein's assumption of 1905, and it is certainly one the validity of which cannot be denied until we have more information than we now have about the behavior of matter in interstellar space. Indeed it seems to us the least radical of the three possible hypotheses between which a choice must in any case be made by all who admit the validity of Einstein's equation, $Mc^2=E$. These three hypotheses are as follows:

1. The first is that of Jeans and others that electrons, and hence atoms and molecules, are convertible into radiant energy, but that the process is nowhere reversible. A very recent statement of Jeans reads[30] "Thus observation and theory agree in indicating that the universe is melting away into radiation. Our position is that of polar bears on an iceberg that has broken loose from the ice pack surrounding the pole and is inexoraby melting away as the iceberg drifts to warmer latitudes and ultimate extinction."

This is the old hypothesis of the "wärme-tod." It conflicts with no observed facts, and before the advent of Einstein it was a necessary consequence of the Second Law *provided the universe were treated as a closed system.* Scientists, however, have always objected that such treatment represents an extravagant and illegitimate extrapolation from our very limited mundane experience, and modern philosophers and theologians have also objected on the ground that it overthrows the doctrine of Immanence and requires a return to the middle-age assumption of a Deus ex machina. Since the advent of Einstein it meets the further difficulty that it injects into modern thermodynamics one single process which violates the principle of "microscopic reversibility" required by the modern statement of the Second Law.

[30] J. H. Jeans, Nature **121**, 467 (1928).

2. The second possible hypothesis is that of Stern, Tolman and Zwicky that the foregoing processes are all everywhere reversible. This hypothesis keeps the Second Law intact, including microscopic reversibility, denied by Jeans' assumption, but so far as can now be seen, it does not avoid the "wärme-tod," and it is not favored by the evidence herewith presented that the atom-building processes which give rise to the cosmic rays do not seem to be taking place everywhere, e.g., in the stars, but do seem to be taking place solely in the depths of space.

3. The third hypothesis,—that herewith presented,—is just as radical as (1), but no more so, in denying microscopic reversibility, but it provides an escape sought in vain by both (1) and (2) from the "wärme-tod." Also it is just as radical as (2) but no more so in assuming that radiant energy can condense into atoms somewhere, but it is in better accord with the cosmic-ray evidence that the atom-creating processes seem to take place only in interstellar space.

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