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ATOMIC THEORIES OF RADIATION[1]

Twenty years ago the system of theoretical physics seemed so complete as to justify the opinion, not infrequently expressed, that it was probable that the great discoveries in physics had all been made, and that future advances were to be looked for in the sixth place of decimals. And yet, in the very midst of these predictions, came the announcement, made just eighteen years ago this week, of Roentgen's discovery which showed that there were great mines of physical gold as yet unworked. Since that time discoveries of fundamental importance have followed one another with such amazing frequency that one who is at all familiar with the history of physics will scarcely challenge the statement that the past fifteen years is quite unparalleled in the number and the significance of its advances. At the present time, too, the air is full of suggestion of still more fundamental developments.

Most of these recent advances find a place under the general title, "The Triumphs of an Atomistic Physics." Within the past decade, the atomistic conception of matter has silenced the last of its enemies, and today we are counting the number of atoms and molecules in a given mass of matter with as much certainty and precision as we can attain in counting the inhabitants in a city. No census is correct to more than one or two parts in a thousand, and there

[1] Address of the vice-president and chairman of Section B—Physics—American Association for the Advancement of Science, Cleveland, December, 1912.

is little probability that the number of molecules in a cubic centimeter of a gas under standard conditions differs by more than that amount from 27.09 billion billion.

We have learned, too, a great deal about the insides of the atom. We have proved that it has electrical constituents, and that these also have an atomic structure. In other words, we have superposed upon an atomic theory of matter a much more fundamental and at the same time a much more simple theory of electricity. And we have found most convincing demonstrations of the correctness of the view that every electrical charge is built up out of an exact number of electrical atoms, and that every electrical current consists in some kind of a transport of these electrical atoms through the conducting body. In fact, we can now count the number of free electrons upon a small charged body as directly and as infallibly as we can count our fingers and toes.[2] We have measured, too, the exact value of this elementary electrical atom, and found it to be 4.774×10^{-10} absolute electrostatic units.[3]

Furthermore, we have added much to our knowledge about how atoms and molecules behave as aggregates. We have found the most convincing demonstrations, both quantitative and qualitative,[4] of the correctness of the fundamental assumptions of the kinetic hypothesis, and have proved experimentally that every molecule in a gas, whether of the size of the hydrogen unit or ten billion times as big, is endowed at a given temperature with exactly the same average kinetic energy of agitation. And we have measured with a fraction of a per cent. of accuracy the value of this universal constant.

Finally, we have tremendously extended our kinetic conceptions of matter through the study of radioactive processes, and have recently actually seen on photographic plates[5] the tracks of alpha and beta corpuscles as they shoot out spontaneously from radioactive atoms with speeds undreamed of in connection with projectiles of any kind twenty years ago—speeds which are of the same order of magnitude as the velocity of light.

In a word the last fifteen years have shown the atomic and kinetic conceptions to be certainly the most fruitful, may we not also say the most fundamental conceptions, not excepting even the principle of the conservation of energy, which have ever been introduced into physical science. Only in one domain have atomistic points of view failed completely to possess the field, and that, oddly enough, the only domain in which they were securely entrenched two hundred years ago, but from which they were driven, apparently forever, at the beginning of the last century, by the epoch-making work of Fresnel and Young. Upon this lost domain of *radiant energy* they are now making renewed attack. It is my purpose to-day to survey this field of conflict and to endeavor to appraise the successes and failures of each of the opposing forces from the point of view of *experimental* physics alone.

My first observation is that in this attack upon the domain of radiant energy, atomistic conceptions do not at present show a united front. In other words, there is not one sharply defined atomistic theory, but there are five distinct brands of "quantum" theory of various degrees of concentration. These are alike in that they all have to do with certain assumptions as to the nature of radiant energy, or as to the conditions under which such energy is ab-

[2] *Physical Review*, XXXII., p. 349, 1911.

[3] *Physical Review*, 1913.

[4] *Popular Science Monthly*, LXXX., p. 417, 1912.

[5] C. T. R. Wilson, *Proc. Roy. Soc.*, Vol. 87, p. 277, 1912.

sorbed or emitted by atomic or sub-atomic oscillators. Let us glance in succession at these various atomistic theories and inquire, first, what are the experimental facts which have called these five different types of assumption into being.

1. The first and least concentrated form, namely, that of Planck,[6] grew out of the fact that we had two radiation formulas, (1) that of Rayleigh,[7] and (2) that of Wien,[8] the first of which fitted the experimental facts for long wave-lengths (for which, indeed, it was alone suggested), while the second fitted the experimental curve at the other end of the spectrum only, although it was originally hoped that it would give the correct distribution of energy throughout the spectrum. Wien's general formula had been deduced from his displacement equation—an equation which rests only on thermodynamic reasoning and the proved facts of radiation pressure—with the aid of two additional assumptions, namely, (1) that the velocities of gas molecules follow the Maxwell distribution law; and (2) that the frequency of the vibrations sent out from a given molecule depends only on the temperature. Since this equation failed at long wave-lengths, and yet contained no more *particular* assumptions than those just mentioned, and since the first of these assumptions is one which we have the best of grounds for making, there was nothing to do but to modify the last one. Planck modified it in such a way as to obtain an equation that would go over into Rayleigh's equation at long wave-lengths, and into Wien's at short wave-lengths. I do not mean to imply that this sort of crass empiricism is all that there is behind Planck's equation. It is fair to point out, however, that this was the experimental situation which guided him in his search for a new radiation formula. His own argument is, in brief, somewhat as follows:

Boltzmann's identification of the concept of entropy in thermodynamics with the concept of probability in statistical mechanics, a step which Planck calls the "emancipation of the entropy concept from the limitations of man's experimental skill, and the elevation of the second law to a real principle," carries with it as a necessity not only the atomistic conception of matter, but also some sort of an atomistic conception of radiant energy. For the assigning of an exact numerical value to the probability of a given physical condition can be accomplished only by considering that condition as dependent on a finite member of equally likely possibilities or complexions. The greater the number of these complexions, the greater the value of the probability. For example, in the throwing of two dice, there are three equally likely complexions with which a throw of four dots can be realized, namely, a 3 with the first die and a 1 with the second, a 1 with the first and a 3 with the second, and a 2 with each. On the other hand, a throw of 2 dots can be realized through but one complexion, namely, a one with each. The probability, then, of a four-dot throw is just 3 times that of a two-dot throw. Now when the entropy of a physical condition is made to depend in this way on the probability of its occurrence, we see at once that entropy tends toward a maximum simply because a change to a new state will not take place unless that new state has a greater probability than the old one. But, says Planck, there is no way of making the appearance of a given physical condition in a system depend in this way upon a definite, countable number of

[6] "Vorlesungen über die Theorie des Wärmestrahlung," 1906, and "Acht Vorlesungen," etc., 1910.

[7] Rayleigh, *Phil. Mag.*, 49, p. 539.

[8] Wien, *Wied. Ann.*, 58, p. 662, 1896.

possibilities, except by conceiving the system to be made up of a definite number of concrete and definite elements—for a continuum can not have countable elements. Hence, an atomistic structure of the system is a fundamental condition for the representation of its entropy by a probability. All systems, then, which possess an entropy must possess an atomic structure. Now experiment justifies the carrying over of the entropy concept to an enclosure filled with radiant energy, for it is only in this way that the Stefan-Boltzmann law and the Wien displacement law, both of which are found experimentally to be correct, are deduced. Hence we are forced to conclude that an atomistic structure of some sort must be applied to radiant energy. Planck then proceeds to apply it as follows: He imagines an enclosure having perfectly reflecting walls to be filled with black-body radiation. In this enclosure, and in equilibrium with the black-body radiation, are linear electromagnetic oscillators of a given frequency ν. The relation between the energy U_ν in each oscillator of frequency ν, and the energy per unit volume u_ν of black-body radiation of frequency ν, is given by the ordinary electrodynamic laws as,

$$U_\nu = \frac{c^3}{8\pi\nu^2} u_\nu.$$

in which c represents the velocity of light. Now let us call in the idea of *atoms of energy* and assume that each oscillator contains at each instant an exact multiple of an element of energy ϵ. From a consideration then of the total number of oscillators, and the total number of energy elements in all the oscillators, we can obtain an expression, as in the case of the dice, for the total number of complexions of the system, that is, the total number of possible distributions of the energy elements among the oscillators. This leads to an expression for the entropy of the system of the form

$$S = F\left(\frac{U}{\epsilon}\right).$$

But the second law of thermodynamics, as applied by Wien,[9] had shown that

$$S = F\left(\frac{U}{\nu}\right).$$

Hence we must place $\epsilon = h\nu$, that is, the energy element ϵ is proportional to the natural frequency ν of the oscillator, and the proportionality factor h is a universal constant, which Planck calls the *Wirkungs quantum*. He thus arrives at his celebrated formula for the relation between the density of black-body radiation and frequency, namely,

$$u_\nu = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/ckT} - 1}$$

or the intensity E_λ of black-body radiation of wave-length λ, and temperature T, is

$$E_\lambda = \frac{2c^2h}{\lambda^5(e^{ch/k\lambda T} - 1)}.$$

This formula meets the requirements of passing over, at small values of λT, into Wien's equation, namely,

$$E_\lambda = \frac{2c^2h}{\lambda^5} e^{-\frac{ch}{k\lambda T}},$$

and for large values of λT, into Rayleigh's equation, namely,

$$E_\lambda = \frac{2ckT}{\lambda^4}.$$

To this brief sketch of the origin of Planck's equation should be added the statement that Planck[10] finds a further proof of the necessity of taking some such step as that which he has taken in the faultlessness of Jeans's logic[11] in showing that the Hamiltonian equations, combined with the theory of probability, lead inevitably to Rayleigh's radiation equation, which is contradicted by experiment. There is,

[9] Wien, *Wied. Ann.*, 52, p. 132, 1894.

[10] Planck, *Ann. der Phys.*, 31, p. 758, 1910.

[11] Jeans, *Phil. Mag.*, 18, p. 209, 1909.

then, nothing whatever to do, in his judgment, except to deny the general validity of the Hamiltonian differential equations, and this is precisely what he has done. Furthermore, the fact that his own equation goes over into Rayleigh's equation when h is made infinitely small, seems to him to show decisively that certain elementary radiation processes, which in Jeans's theory are assumed to be continuous, are in fact discontinuous.

Now it would be presumptuous in me to attempt to pass upon the cogency of these arguments, especially as they have been made the subject of review by the foremost of the world theorists, among them the late Poincaré.[12] Nevertheless I shall pause just long enough to express the inevitable point of view of every man who has worked long enough in a laboratory to know from painful experience how large is the entropy, *i. e.*, the probability of the event, that *experimental* results will come out differently from the way in which, according to the inevitable logic of things, they must come out, and that for the reason that in five cases out of ten, the inevitable logic of the experimentalist, at least, involves some undiscovered or unconsidered element. He is prone to wonder, therefore, whether even the theorist's inevitable logic is absolutely inevitable.

However, it should be said that Poincaré,[12] while stating that the assumption that physical phenomena do not obey laws expressible by differential equations would constitute the most profound revolution which physics has undergone since Newton's day, yet sees no way of escape from Planck's conclusion, unless it be found in the fact that to obtain the relation between his linear oscillator and the density of black-body radiation, Planck assumes the very electrodynamic laws the validity of which he in the end denies. While this is indeed a weakness in his theory, it doesn't in any way affect his argument for the necessity of some such step as that which he has taken. To my own mind, the uncertainty in this last argument lies in the fact that the general validity of the law of equipartition of energy is assumed to be a necessary consequence of the Hamiltonian equations. If this be so, then the Hamiltonian equations certainly must go, for we have known for over thirty years that the law of equi-partition can not have any general validity.

Planck has appreciated fully from the beginning the above-mentioned weakness in the method of development of his equation, and within a year[13] he has modified his statement of his theory in the endeavor to meet Poincaré's objection. The theory as outlined above implies that, since energy is always contained in the oscillator in exact multiples of an energy unit, both the absorption and emission of energy by the oscillator must take place in units—that is discontinuously. Planck now assumes that emission alone takes place discontinuously, while the absorption process is continuous. At the instant at which a quantity of energy $h\nu$ has been absorbed, an oscillator has a chance of emitting the whole of its unit, a chance which, however, it does not necessarily take. If it in this way misses fire, it has no other chance until the absorbed energy has arisen to $2h\nu$, when it has again the chance of throwing out its 2 whole units, but nothing less. If again it misses fire, its energy rises to $3h\nu$, $4h\nu$, etc. The ratio between the chance of not emitting when crossing a multiple of $h\nu$, and the chance of emitting, is assumed to be proportional to the intensity of the radiation which is falling upon the oscillator. This, then, is at present the most fundamental and the least revolutionary form of quan-

[12] *Journal de Physique*, Se. 5, Vol. 2, p. 5, 1912.

[13] Planck, *Ann. der Phys.*, 37, p. 642, 1912

tum theory, since it modifies classical theory only in the assumption of discontinuities in *time*, but not in *space*, in the emission (not in the absorption) of radiant energy.

When we lay aside all consideration of the origin of this theory, and ask for its experimental credentials, we find two great successes commonly attributed to it, (1) it gives a correct energy-distribution curve; (2) it enabled Planck to deduce from radiation constants a value of the elementary electrical charge which agrees within its own limits of uncertainty—about 4 per cent.—with the values obtained by other and more accurate methods. The first of these claims is apparently justified, though too much stress must not be laid upon it in view of, first, the origin of the equation, and, second, the fact that from the shortest observable wave-lengths, clear down to the longest visible red, Wien's equation also fits the facts perfectly for all temperatures up to those of the arc. In other words, from the experimentalist's standpoint Planck's equation may be considered as Wien's equation with but a small correction term applied to it at one end. Such correction terms can often be obtained from a great variety of assumptions.

The second claim can not be considered at all, since the deduction of the value of e from the radiation constants has nothing whatsoever to do with quantum theory. The result comes just as well from Rayleigh's equation[14] as from Planck's and the significance of the fact that the correct value of e is obtained is that for certain ranges of temperature the kinetic energy of an oscillator in equilibrium with a gas is indeed the same as the translational kinetic energy of a gas molecule. Further successes of Planck's theory will be considered after the discussion of the other atomistic theories of radiation.

[14] Einstein, *Ann. der Phys.*, 17, p. 132, 1905.

2. The second of these theories is somewhat more radical than the first, and is, in fact, merely that originally proposed by Planck. It assumes that both emissions and absorption of energy are discontinuous in time. Despite the fact that Planck has renounced this point of view, the theory refuses to die. Nernst and most of the investigators who are working in specific heat relations still adhere to it. What is the experimental situation which seems to demand it? It is a situation brought about by the recent development of methods of studying specific heats at high and low temperatures. I refer especially to the liquefaction of hydrogen and helium. Let us consider first the simplest case, namely, that of the specific heats of gases.

One of the most brilliant triumphs of the kinetic theory was the prediction that the molecular heat of a monatomic gas should be 2.98 calories, or approximately 1 calorie per degree of freedom of the molecule, a prediction accurately verified by experiment. Next, the theory said that the molecular heat of a more complex gas should be as many calories as its molecule has degrees of freedom. If then the molecule of a diatomic gas acts like a rigid frictionless dumbbell, no energy whatever going into vibrations along the line of connection of its two atoms, or into rotations about this line as an axis, then its degrees of freedom should be three translational, and two rotational, and hence its molecular heat should be 5 calories, which is, as a matter of fact, the value found for all of the so-called permanent diatomic gases at ordinary temperatures.

Now, however, come the facts which call for some modification of the simple dynamical theory. We have long known that even at ordinary temperatures the molecular heats of gases like chlorine and bromine, which have more loosely connected atoms than have the so-called permanent gases, are nearly a calorie too high; that, further, they grow higher as the temperature rises. Recent work,[15] too, shows that as the temperature is slowly raised from 300° to 1,200° C. the molecular heats of all the permanent gases rise from 5 to 6 calories, while at the temperature of 2,000° C. they have gone up to nearly 7, just as though two new degrees of freedom had gradually been added. This we should expect if at high enough temperatures energy begins to go into vibrations of the atoms along their line of connection in the diatom. Very recent work,[16] too, which seems to be reliable, shows that when the temperature of the diatomic gas H_2 falls from 200° absolute to 60° absolute, its molecular heat falls from 5 calories to 3 calories. In other words, at 60 degrees absolute, and presumably at lower temperatures, H_2 acts like a monatomic gas.

Now, say the quantum theorists, all these facts are beautifully explained by our hypothesis. For, according to it, no atomic vibrator can absorb any energy at all except in whole units of size $h\nu$, or multiples of $h\nu$. The diatomic vibrator then, consisting of the 2 atoms of a diatomic gas, can absorb no energy at all from the molecular impacts experienced by the molecule as a whole, until the energy of these impacts exceeds $h\nu$. Then it begins to absorb, and as the temperature rises still farther the number of atomic vibrators which begin to take on an energy load increases as rapidly as it can in view of the limitations imposed by the law of distribution of energy among the molecules, and the necessity of absorbing only in whole multiples of $h\nu$. In the end, as the temperature rises, each atomic vibrator takes on the share of the energy which properly belongs to it in accordance with the law of equi-partition. The atomic vibrators of the chlorine and bromine molecules begin to do this at lower temperatures than those of the other diatoms, because the bonds holding the chlorine and bromine atoms together are relatively weak, and consequently their *frequencies* are small. Hence the energy units $h\nu$, characteristic of these absorbers, are correspondingly small, and therefore the temperature at which the kinetic energy of the molecular impacts reaches this value is low.

The explanation of the fact that H_2 acts like a monatomic gas at low temperatures is this. The two rotational degrees of freedom of the H_2 molecule drop out at low enough temperatures, for the reason that these rotations correspond at a given temperature to a definite *mean* rotational frequency ν, and when the energy of impact falls below this value of $h\nu$ no energy can go into these rotations.

Coming now to the atomic heat relations of solid bodies, these have been much studied of late and are interpreted by Nernst and others in terms of this same form of quantum theory. Dulong and Petit's law of the equality of the atomic heats of the elements, and Kopp's law of the additive properties of atomic heats in compounds, were, until very recently, the most suggestive of the unexplained laws of experimental physics. Boltzmann[17] gave a fascinating interpretation of these relations by assuming that the atoms of solids have natural periods of vibration, and, if so, that they must be in thermal equilibrium with a gas when their mean vibratory kinetic energy is the same as the mean translational energy of the gas molecules. If this

[15] Nernst, *Zeit. f. Elek. Chem.*, 17, p. 272, 1911.

[16] Euken, *Ber. der Preuss. Akad.*, February, 1912, p. 141.

[17] Boltzmann, *Wien. Sitz. Ber.*, 63, 2 abt., p. 731.

be so the total energy content of an atom of a solid, in view of its three potential and three kinetic degrees of freedom, must be twice that of a molecule of a monatomic gas. In other words, the atomic heats of solids should be twice the molecular heats of monatomic gases, *i. e.*, they should be 6 calories, as in fact they are in most cases found to be. But brilliant and successful as was this stroke, it only made the abnormally small values of the atomic heats of the elements of low atomic weight (C, Bo, Si) the more inexplicable, especially after it was found that these substances all behave normally at high enough temperatures. Now the recent work of a number of experimenters, notably of Nernst[18] and his pupils, shows that at sufficiently low temperatures *all* substances show abnormally low atomic heats, and that, in general, the lower the atomic weight, the higher the temperature at which the abnormality begins to appear. This means that if a degree of rise in temperature means a given increase in the energy of vibration of the atoms of any substance, then at low enough temperatures only a fraction of the atoms take on their normal energy load. But this is precisely what the quantum theory demands. No atom can take on any energy at all until the impacts of the molecules of the surrounding gas possess an energy as high as $h\nu$, and hence the higher the ν the higher the temperature at which energy can begin to be absorbed. Further, *ceteris paribus,* the smaller the atomic weight, the higher the ν and hence the sooner, with decreasing temperature, should atomic heats lower than 6 calories begin to appear.

One can not withhold his admiration from the beauty of the qualitative agreement between this theory and experiment. But can the theory stand a quantitative test? Such a test has been made as follows. Lindemann,[19] by assuming simply that a fixed relation holds at the melting point, T_s, of any substance between the amplitude of its atomic vibrations and the distance between its atoms, that is, its atomic volume, v, obtained without the aid of a quantum theory, a formula of the form

$$\nu \propto \sqrt{\frac{T_s}{mv^{\frac{2}{3}}}},$$

by which the frequency ν in the solid state of an atomic vibrator of atomic weight m can be computed. This formula yields results which agree fairly well with direct measurements of ν by means of "reststrahlen" wherever the latter have thus far been made. With the aid of this formula, then, we may first check our rough guess that the order of diminishing frequencies is the exact order in which atomic heats begin with decreasing temperature to fall below 6 calories, and, second, we may compare the frequencies computed by Lindemann's formula with those given by Planck's equation and the observed departure from Dulong and Petit's law at low temperatures. The method of doing this was pointed out by Einstein.[20] The agreement is sufficiently good to warrant the conclusion that the departures from Dulong and Petit's law are in fact fundamentally conditioned by atomic frequency. But it can not be said that Planck's equation, as applied by Einstein to the computation of the relation between atomic heats and temperatures, succeeds in predicting very accurately the observed curves.[20] Furthermore, the departures are in the same direction with all substances. They may be explained by introducing additional hypotheses into the quantum theory, as Nernst and Lindemann have

[18] Nernst and Lindemann, *Sitz. Ber. d. Preuss. Akad.*, XIII., p. 306, 1910.

[19] F. A. Lindemann, *Phys. Zeit.*, 11, p. 509, 1910.

[20] Einstein, *Ann. der Phys.*, 22, p. 180, 1907.

sought to do,[21] or by seeking for causes of these specific heat relations which have nothing to do with quantum theory. The one conclusion which this experimental work in atomic heats drives home is that the principle of equi-partition of energy, while valid when applied to atomic vibrators for certain ranges of temperature, has no general validity. This is, however, nothing new. If we can not get rid of it without a quantum theory, as Planck and Poincaré and Jeans all imply, then some form of quantum theory has been demonstrated to be a necessity. If these atomic heat experiments stood alone, however, I fancy that other and more easily visualizable explanations would be sought. For example, so far, they seem to be qualitatively consistent with an assumption like this, namely, that as the absolute zero is approached, the atoms begin to freeze together, and thus the number of effective carriers of energy is diminished. The higher the atomic frequency the higher the temperature at which this freezing-up process begins. The atoms of solids would then be imagined to freeze into rigid systems of continually increasing size, each system being endowed, however, with the kinetic energy of agitation appropriate to its temperature. It might then become possible, before absolute zero was reached, for the total kinetic energy content of the whole mass to become that of a single molecule of the surrounding gas. Such an hypothesis would seem to account well for the exceedingly high thermal conductivity of non-metals at low temperatures,[22] since the transfer of energy from point to point would be effected by a diminishing number of intermediaries as the temperature fell. If, however, a quantum theory must be called in to account for phenomena in other fields, it is of course in the interest of simplicity to make it do service in the field of atomic heats as well. All that can now be said is that the attempts thus far made to apply it quantitatively in this field have not been particularly successful, though they have been sufficiently suggestive to stimulate to further experimenting. New data are sure to pour in rapidly in the near future.

3. We now come to the forms of atomistic theory which make radical assumptions regarding the distribution of radiant energy in *space*, rather than in *time*. The least radical of these, because the least general, is that of which Professor Bragg[23] is the most active exponent. It is frankly corpuscular. It was developed, however, with a view of explaining the properties of one type of radiation only, namely, X- and γ-rays, and at a time when there was some justification for regarding these as isolated phenomena. Recent developments have strongly emphasized the similarities, rather than the differences, between these and other types of so-called ethereal radiations. But this in no way weakens the positive arguments for a corpuscular form of X-ray. The most compelling of these arguments is as follows:

X-rays unquestionably pass over, or pass all but an exceedingly minute fraction of the atoms contained in the space traversed, without spending any energy upon them or influencing them in any observable way. But here and there they find an atom from which they hurl an electron with enormous speed. This is the most interesting and most significant characteristic of the X-ray, and one which distinguishes it from α- and β-rays just as sharply as does the property

[21] Nernst and Lindemann, *Zeit. für Elektrochemie*, 17, p. 867, 1911.

[22] Euken, *Ann. der Phys.*, 34, p. 185.

[23] Bragg, "Studies in Radioactivity," 1912.

of non-deviability in a magnetic field. For neither α- nor β-rays ever eject electrons from the matter through which they pass with ionizing speeds. The energy which the X-ray or the γ-ray imparts to its chosen electron has been conclusively shown by many observers to be altogether independent of the intensity of the X-rays, and also independent of the nature of the atom from which the electron is hurled.[24] It depends solely upon the penetrating power, or hardness, of the X-ray. In fact, there is strong evidence now for the statement that although only a thousandth part of the energy of the cathode-ray beam in an X-ray tube is transformed into X-rays at the anticathode, yet when these same X-rays, weak in energy as a whole, fall upon matter outside the tube, they eject electrons from it with energies as great or nearly as great as those of the individual electrons of the original cathode rays.[25] It is as though the same energy were passed on in new form whenever an X-ray produces a β-ray, or a cathode-ray, an X-ray. These facts seem to be completely inexplicable on any sort of a spreading wave theory. The assumption of a continuous absorption by an atom of X-ray energy until the atom accumulates a sufficient store to eject an electron with the observed speed is completely untenable, for the time required for it to do this, according to the spreading pulse theory, would be longer than the life of any X-ray bulb, yet as a matter of fact this ejection begins the instant the X-ray bulb is started. Precisely the same argument holds for γ-rays. For these are found to eject electrons from matter through which they pass with .9 the velocity of light. This corresponds to an energy of 7×10^{-7} ergs. According to Rutherford, the total energy of the γ-rays per gram of radium is 4.7×10^{-4} ergs, and if we assume that the number of γ-ray pulses is the same as the number of β-rays emitted, namely, 7×10^{10}, then the whole energy in a γ-ray is very nearly 7×10^{-10} ergs, *i. e.*, it is precisely the same as the energy communicated by the γ-rays to the ejected electron even though this ejection may happen at a distance of 50 or 100 meters from the source. There is then no escape from the assumption in the case of X-rays, nor in the case of γ-rays, unless it be found in the uncertainty of the assumption of the identity of the number of γ-ray pulses and the number of β-rays, that the emitted energy keeps together as an entity, or quantum, which may be transformed back and forth between a β-ray and an X- or γ-ray. This energy is slowly dissipated into heat in its passage through matter while it is in the form of a β-ray, but apparently not at all while in the form of an X- or γ-ray. This argument is so close to the undeniable experimental facts, at least as they now stand, that if X- and γ-rays stood by themselves it is probable that there would be few opponents to Bragg's theory as to the corpuscular nature of these rays. His actual assumption is that X- and γ-rays consist of neutral doublets whose velocity determines the hardness of the ray. This is an assumption the truth or falsity of which could be tested if we could find the speed of X-rays. Opinion is still divided, however, as to the validity of conclusions drawn from the attempts that have been thus far made to identify the velocity of X-rays with the velocity of light.[26] Even

[24] Innes, *Proc. Roy. Soc.*, LXXIX., p. 442; Sadler, *Phil. Mag.*, March, 1910; Bestelmeyer, *Ann. d. Phys.*, 22, 429.

[25] Bragg and Madsen, *Phil. Mag.*, May and December, 1908; Whiddington, *Proc. Roy. Soc.*, 1911 and 1912.

[26] Marx, *Ann. d. Phys.*, 33, p. 1305, 1910, and Franck and Pohl, *Ann. d. Phys.*, 34, p. 936, 1911.

though these two velocities should be definitely proved to be the same, Bragg's argument for some sort of a corpuscular theory of X-rays would still stand.

But, aside from the minor difficulty of accounting for the so-called polarization of X-rays, that is, the dissymmetry of their emission about the point at which they originate, Bragg's theory encounters the supreme difficulty of accounting for the rapidly growing evidence of a complete parallelism between optical and X-ray effects. Thus:

(1) Ultra-violet light, like X-rays, ejects electrons with speeds which have been repeatedly shown to be completely independent of the intensity of the source. I have myself raised a doubt about this conclusion, but have recently shown that the doubt is unjustified,[27] and that the conclusion holds even when the intensity varies in the ratio 1,000 to 1.

(2) In the normal photo-electric effect, which has none of the earmarks of a resonance phenomenon, all observers now agree that the speeds of the ejected electrons increase regularly with the frequency of the light,[28] just as the speeds of electrons ejected by non-homogeneous X-rays increase with the hardness of the rays. Apparently, too, the law of increase is the same in each case.

(3) There is a selective photo-electric effect characterized by the emission at a particular frequency of the exciting rays of an abnormal number of electrons. This emission can not be excited until the frequency of the incident light reaches a definite value which is characteristic of the illuminated substance. This selective effect bears all the earmarks of an absorption band.[29] Precisely similarly there is a selective X-ray effect characterized by the emission at a given hardness of an abnormal number of electrons, and also by the excitation of a new type of X-ray radiation, which differs from the ordinary or scattered X-ray in being homogeneous, symmetrical about the origin, and having a penetrating power which is characteristic of the emitting substance instead of the quality of the exciting X-ray. This so-called homogeneous or characteristic X-radiation can not in general be excited until the hardness of the exciting ray exceeds a definite value. This critical value is nearly proportional to the atomic weight of the excited substance. The exciting rays experience absorption at the hardness at which the new increase in β-ray emission occurs. In other words, this selective X-ray effect, like the selective photo-electric effect, bears all the earmarks of an absorption band.[30]

(4) Light rays, X-rays and γ-rays all behave exactly alike in throwing more electrons forward in the direction in which the rays are moving than backward in the direction from which they came.[31]

(5) Finally, Laue, Friedrich and Knipping,[32] by using as a diffraction grating the regular arrangement of the molecules themselves in a crystalline substance, have recently obtained beautifully sharp photographic patterns which resemble very closely diffraction patterns in light. The wave-lengths of the X-rays computed from assumed intermolecular distances is about

[27] *Physical Review*, January or February, 1913.

[28] E. Ladenburg and K. Markan, *Phys. Zeit.*, 9, p. 821; Hughes, *Phil. Trans.*, CCXII., p. 205, 1912.

[29] Pohl and Pringsheim, *Verh. d. D. Phys. Ges.*, 1911 and 1912.

[30] Barkla and Sadler, *Phil. Mag.*, May, 1909; Sadler, *Phil. Mag.*, March, 1910; Whiddington, *Proc. Roy. Soc.*, 1911 and 1912.

[31] Bragg, "Studies on Radioactivity"; Kleeman, *Proc. Roy. Soc.*, 84, p. 93, 1910; Stuhlmann, *Phil. Mag.*, 20, p. 331, 1910; and Robinson, *Phys. Zeit.*, 13, p. 276, 1912.

[32] *Münch. Ber.*, pp. 303–322, 1912.

10^{-9} centimeters, or .0001 that of the shortest known ultra-violet waves. These experiments present strong evidence that some types of X-rays at least possess a periodic character. In a word, then, all these similarities suggest inevitably the hypothesis that ordinary scattered X-rays are white light, of short wave-length, and that characteristic X-rays are monochromatic light of short wave-length. If Bragg's neutral pair theory is to have any future, it must in all probability, then, be extended to all electro-magnetic radiations.

But how, when a charged pitch ball, for example, swings back and forth on its silk-thread suspension in our laboratories, are the periodic electromagnetic disturbances which it sets up in the neighborhood to be interpreted in terms of the emission of neutral pairs? No one is bold enough at present to attempt to thus resurrect a straight corpuscular theory of all ethereal radiation, with all that it implies regarding the dependence of the velocity of light, on the velocity of the source, the interpretation of interference phenomena in light and of Hertz's wave phenomena in the realm of wireless telegraphy. We need, then, a more general hypothesis than that of Bragg.

4. Such a general hypothesis was made by J. J. Thomson in his Silliman lectures in 1903.[33] It was, historically, the first form of the modern atomistic theories of radiation as regards space relations, although it is here treated in the fourth place, because it stands fourth in the violence of the assumptions involved. Like Bragg's theory, it postulates radiant energy which is emitted by the source in bundles or quanta, though no necessary multiple relationship was at first assumed between the different elements emitted by the same source. It goes farther than Bragg's theory in endeavoring to reconcile this quantum notion with the wave theory by assuming a fibrous structure in the ether, and picturing all electromagnetic energy as traveling along Faraday lines of force conceived as actual strings extending through all space. This is nothing more than a new picture of the structure of the ether and one which is perhaps no more impossible than all its rivals. To the support of such a hypothesis are brought all the arguments urged for Bragg's theory, while the arguments which I have urged against Bragg's theory are removed. It may be difficult, not to say repugnant, to some of us to attempt to visualize the universe as an infinite cobweb spun by a spider-like creator out of threads that never become tangled or broken, however swiftly electrical charges may be flying about or however violently we enmeshed human flies may buzz, but such is the hypothesis, and the objections to it will be treated along with those of the next and most concentrated form of quantum hypothesis.

5. This was proposed by Einstein[34] in 1905, and is simply the J. J. Thomson theory of the discontinuous distribution of radiant energy in space, assumed still to be electromagnetic and hence to have a velocity independent of that of the source, with the addition of Planck's original assumption that a given source emits and absorbs energy in units which are multiples of $h\nu$. This amendment has apparently been accepted by Thomson and seconded by Larmor. For the energy units, $h\nu$, have had some experimental successes, the consideration of which it was thought best to defer to this point.

In the normal photo-electrical effect the kinetic energy of the escaping electron increases with the frequency of the incident

[33] "Electricity and Matter," pp. 63 et seq.

[34] *Ann. der Phys.*, 17, p. 132, 1905.

light, and the experimental evidence is now fairly strong, especially in view of the recent work of Hughes,[35] that it is directly proportional to ν. This is what we should expect from the fact that the energy of an electron ejected by an X-ray is proportional to the energy of the cathode particle which produces the X-ray. For the ether disturbance set up by stopping a cathode particle corresponds exactly to the ether disturbance set up by a half swing of a vibrating electron. We may then compare roughly the wave-length of one of the prismatically resolved components of white light with the wave-length of a Röntgen ray impulse by comparing the half-period of the light with the time of stopping the electron. This time can be shown to be inversely proportional to the energy of the electron, *i. e.*, the frequency of the X-ray produced by stopping an electron may be taken as directly proportional to the energy of the cathode-ray particle producing it. If, then, an X-ray ejects an electron with an energy proportional to the energy of the original cathode ray, ultra-violet light should eject an electron with an energy proportional to its frequency. Notice that this result is obtained without the aid of Planck's equation, but rather immediately from the fairly well demonstrated inter-convertibility of X-rays and β-rays and the assumption that light rays are nothing but soft X-rays. But not only is the absorption of energy by an electron from a light wave proportional to ν, its numerical magnitude is approximated at least by multiplying the frequency of the light by Planck's value of h. It is true there is here no accurate agreement as yet; for part of the energy absorbed by the electron is lost in getting out of the metal, and the exact amount of this loss has not been measured with as much accuracy as we hope soon to be able to attain. Nevertheless the agreement is now sufficiently good (within some 70 per cent.)[36] to lend some support to the notion that the amount of energy actually absorbed from the light by the escaping electron is $h\nu$.

A still further test of the hypothesis can be made by computing the frequency of X-rays from the observed velocity of emission of corpuscles ejected by them; *i. e.*, from the potential difference between the terminals of the X-ray bulb which produces them. Thus we have

$$h\nu = \frac{hc}{\lambda} = eV,$$

or if $V = 40{,}000$ volts (this would correspond to fairly hard X-rays such as Laue used),

$$\lambda = \frac{hc}{eV} = \frac{6.55 \times 10^{-27} \times 3 \times 10^{10}}{4.774 \times 10^{-10} \times \frac{40{,}000}{300}} = 3 \times 10^{-9}.$$

Laue[37] gets from his diffraction patterns wave-lengths ranging from 1.27 to 4.83 $\times 10^{-9}$. Walter and Pohl's previous diffraction measurements[38] also gave a value of the order 10^{-9}. This is certainly striking agreement, and lends some support at least to the attempts to extend Bragg's assumption of the inter-convertibility of X- and β-rays to the inter-convertibility of light rays and β-rays, or more generally, to the assumption that whenever an electron is emitted a quantity of radiant energy $h\nu$ is absorbed.

Furthermore, according to the most recent experimental results it doesn't seem to make any difference in what form this energy approaches the atom which is to take it on and reemit it. Thus Whiddington[39] and Beatty[40] show that characteristic X-rays are excited either by other characteristic X-rays which are harder than

[35] *L. c.*

[36] Hughes, *l. c.*

[37] *Münch. Ber.*, 363, 1912.

[38] Sommerfeld, *Ann. der Phys.*, 38, p. 473, 1912.

[39] *L. c.*

[40] *Proc. Roy. Soc.*, 87, p. 516, 1912.

those to be emitted, or by the direct impact of β-rays of a corresponding energy; and again, there is now good evidence to show that whenever an electron ionizes a gas its energy of impact must exceed $h\nu$ where ν is now the natural period of vibration of the resonator within the atom which is responsible for the selective photo-electric effect.[41] All of these results are certainly successes of Planck's "Wirkungs quantum" h, though in directions scarcely contemplated originally by the theory; for in Planck's theory it is the natural period of the oscillator which determines the emission of energy in units of size $h\nu$, but in the normal photo-electric effect the emitted electron has an energy which has nothing to do with its natural period, if it has one. It is rather the period of the incident waves which determine the energy with which the electron is ejected.

I think I have now stated most of the important experimental facts which we proposed at the outset to review in the light of atomistic theories of radiation. When we look back over these experimental data there are two main results which stand out conspicuously through it all. *The first is that neither atoms nor electrons appear to be able to absorb any energy until it comes to them in a certain degree of intensity, and this degree varies with different substances.* We see this in the realm of low intensity heat waves where, in the measurement of atomic heats, different kinds of atoms seem to take on their normal energy load at different stages, as temperature rises, the lighter atoms taking it on in this case last; we see it in the realm of high intensity heat waves, such as are dealt with in finding black-body radiation curves; we see it in the realm of photochemical or photo-electric radiations, where different substances begin to emit electrons at different frequencies of the incident light; and finally we see it in the realm of X-rays, where different substances are excited to emit characteristic X-radiations at different hardnesses, the heavy atoms in this case responding last, instead of first. We see further that *one intensity factor h proves itself, to say the least, exceedingly useful in every one of these domains.*

The second important fact that stands out is this, that *in all types of experiments in which the absorption of energy results in the emission of electrons there is apparently a complete, or nearly complete, inter-convertibility of energy between an electron and a so-called ether ray, whether it be an X-ray or a light ray.* Now the first of these two facts is the one upon which one group of quantum theorists is focusing its attention and demanding a unitary theory which emphasizes primarily an emission of energy which is discontinuous in time. The second fact, and it is the one which is the more striking and the better established, is that upon which the other group of theorists is focusing its attention and demanding an atomistic theory of radiation as regards space relations. Now the fifth and last of the quantum theories which I have presented is that which, in view of both of these groups of facts, demands a quantum theory which combines both of these characteristics. The facts *which have been here presented* are obviously most completely interpreted in terms of such a theory, however radical it may be. Why not adopt it? *Simply because no one has thus far seen any way of reconciling such a theory with the facts of diffraction and interference so completely in harmony in every particular with the old theory of ether waves.* Lorenz will have nothing to do with any ether-string theory, or spotted wave-front theory, or electro-magnetic corpuscle theory.

[41] Franck u. Hertz, *Ber. d. D. Phys. Ges.*, 13, p. 967, 1911, and 14, p. 167, 1912.

Planck has unqualifiedly declared against it, and Einstein gave it up, I believe, some two years ago; and yet a quantum theory which fails completely to interpret or take any account of the most striking and the best established experimental fact which demands a modification of old theories, viz., the independence of the energy of emission of electron upon the intensity of the source, or, more generally, the inter-convertibility of β-rays and ether rays is, at best, a very impotent affair. If we are going to leave either of these two main groups of facts out of account I think almost any experimentalist would say that the first group (that having to do with the universal constant h) can most easily be spared; for if we could have radiant energy localized in space we might possibly account for all the experimental facts without having it emitted by a given source in exact multiples of something, but spreading ether pulses which contain energy in multiples of something are certainly wholly inadequate. They go but a short way toward accounting for the present experimental situation. In conclusion then we have at present no quantum theory which has thus far been shown to be self-consistent or consistent with even the most important of the facts at hand, and yet it looks as though one had to come, and when it comes I can scarcely believe that it will be one of the milder forms. That we shall ever return to a corpuscular theory of radiation I hold to be quite unthinkable. The facts of the static field alone seem to preclude such a possibility. But I see no a priori reason for denying the possibility of assigning such a structure to the ether as will permit of a localization of radiant energy in space, or of its emission in exact multiples of something, if necessary, without violating the laws of interference. That no one has as yet been able to do this can scarcely be taken as a demonstration that it can not be done. Fifty years ago we knew that such a thing as an atom existed, but we knew absolutely nothing about its structure, and it was customary to assume that it had none. To-day we know a great deal about the structure of the atom, but the position formerly occupied by it has been assumed by that thing which we call the ether. We know that there is a vehicle for the transmission of electromagnetic energy, but we know nothing whatever about its structure and it has been customary to assume that it has none. To deny the existence of this vehicle, which we have been in the habit of calling the ether, and to use the word "vacuum" to denote *all* the properties heretofore assigned to it by the experimentalist, viz., those of transmitting electromagnetic disturbances, is a bit of sophistry in which he is little interested. We seem to be on the eve of learning something more about the properties of this vehicle, call it by what name you will, than we have known heretofore. Certainly there has never been a time when physics offered such tasks to its followers as now, nor ever a time when it needed more and better brains applied to these tasks. It may be that "THOU art come to the Kingdom for such a time as this."

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EDUCATIONAL DIAGNOSIS[1]

UP till a score of years ago theories of intellectual and moral diagnosis suffered from two defects. They had not fully abandoned the notion that mysterious inner forces or agents existed—memory, attention, courage, imitativeness, constructive-

[1] Address of the vice-president and chairman of Section H—Education—American Association for the Advancement of Science, Cleveland, December, 1912.