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A. Einstein (Zurich), On the development of our understanding of the nature and composition of radiation.

Since one [(we)] had seen that light exhibits the phenomena of interference and diffraction, it appear[ed] that there [could] hardly be [any] doubt that light [was] to be understood as wave motion. Since light can propagate in a vacuum, one had to imagine that here there must exist a special kind of material that mediates the propagation of light waves. For the concept of the laws of propagation of light in ponderable bodies it was necessary to assume that that material, which is called the ether, exists and that it is also in the interior of ponderable bodies that the ether is a fundamental constituent which mediates the propagation of light. The existence of this ether seemed without doubt. In the first volume of the excellent textbook on physics of Chwolson appearing in 1902, one can find in the introduction of the ether the sentence concerning the ether: "The probability of [the truth of] the hypothesis of the existence of this agent comes extraordinarily close to certainty."

Arguably today, however, we must view the ether hypothesis as fundamentally flawed. It is undeniable that there is an extended body of facts pertaining to radiation which indicate that light has certain inherent qualities that put its comprehension far from either the Newtonian emission theory of light or the view of wave theory. Hence it is my opinion that the next phase of the growth of theoretical physics will bring us a theory of light which will reveal itself as a kind of mixture of wave- and emission theory. It is the purpose of the following exercise to elucidate and substantiate this position: that a fundamental change of our understanding of the nature and constitution of light is essential.

The greatest stride which theoretical optics has made since the introduction of the wave theory consists arguably of Maxwell's ingenious discovery of the possibility that light could be understood as an electromagnetic process. This theory introduces into consideration in place of the mechanical quantities, namely deformation and velocity of the particles of the ether, the electromagnetic state of the ether and matter, and thereby reduces optical problems to electromagnetic ones. The more the electromagnetic theory advanced, the more relevant became the question as to whether electromagnetic processes lead back to mechanical ones in the background. One has got [We have gotten] used to treating the concepts of electric and magnetic field strengths, electric space charge density, and so forth as elementary concepts that do not need a mechanical interpretation.

The basic concepts of theoretical optics were simplified by the introduction of the electromagnetic theory; the number of arbitrary hypotheses was lessened. The old question of the direction of vibration of polarized light became irrelevant. The difficulties concerning the boundary conditions at the interface between two media yielded themselves up [were resolved] on the basis of the theory. There is no more need to associate oneself with the arbitrary hypothesis of longitudinal light waves. Light pressure, measured recently, which plays so important a role in the theory of radiation arose as a consequence of the [electromagnetic] theory. I will in no wise undertake the exhaustive enumeration of the well-known attainments here, but will keep one train of thought in mind, in reference to which the electromagnetic theory coincides with the kinetic, or, better, appears to coincide.

For both theories light waves appear fundamentally as an embodiment of states of a hypothetical medium, the ether, that exists everywhere even in the absence of radiation. Thus it was to be assumed that movements of this medium must have influence on optical and electromagnetic phenomena. The search for the laws that govern the phenomena prompts a metamorphosis in the basic understanding [of] the nature of radiation, which [metamorphosis] I suggest we consider briefly.

The basic question which consequently presented itself forcefully was the following: Does the ether move with matter, or in the interior of moving matter does it move differently than [the matter] or, finally, [does it] have no stake at all in the movement of matter but always remain at rest? In order to decide these questions, Fizeau conducted important research on interference which [research] rests on the following consideration. Light travels in a body with speed V when [the body] is at rest. In the event that this body carries its ether with it when it moves, light would propagate relative to the body the same as if [the body] were at rest. The velocity of propagation of a light wave relative to the body would then in this case also be V. In the absolute sense, that is relative to an observer not moving with the body, the velocity of propagation will be equal to the geometrical sum of V and the velocity v of the body. In the case where V and v have the same magnitude and direction, V_{abs}, [the magnitude of the sum] is simply the sum of the two magnitudes, that is,

$$V_{abs} = V + v.$$

In order to verify whether this consequence of the hypothesis that the ether is entirely [dragged along] obtains, Fizeau had prepared for him two monochromatic light rays each passing axially through a tube filled with water and afterwards interfering. When at the same time he allowed the water to flow axially in the tubes, in one in the direction of the light ray and in the other in the opposite direction, there would arise a displacement of the interference fringes from which he inferred a relationship [between] the body's velocity [and] the absolute velocity.

As is generally known, the result was that an influence of the body's velocity exists in the sense that it was expected. It is, however, always smaller than [is indicated by] the hypothesis that the body carries the ether along with it. This [dependence] is:

$$V_{abs} = V + \square v,$$

where $\square << 1$. Under [this approximation] the dispersion is

$$\square = 1 - \frac{1}{n^2}.$$

From this experiment it followed that a body does not drag the ether entirely along with it, that therefore a relative motion of the ether against the body generally exists. Now the earth is a body whose velocity over the course of a year has changing direction with respect to the solar system. And it was to be expected that the ether in our laboratories would *en masse* participate just as little in the motion of the earth as Fizeau's experiment appeared to show for its participation *en masse* in the motion of water. It would therefore follow that there would exist a relative velocity of the ether with respect to our instruments, changing by day and year, and one would expect that this relative velocity would evidence itself by optical experiments as an anisotropy of space. That is, that the optical effects would be dependent on the orientation of the apparatus. The most widely varying experiments into the details of such an anisotropy have been done without being able [to demonstrate] the expected dependence of the phenomena on the orientation of the apparatus.

This inconsistency was removed in the largest part by the ground-breaking work of H. A. Lorentz in the year 1895. Lorentz [showed that] we have arrived at the underpinnings of an ether at rest, passive, and independent of the movement of matter without assuming any other hypotheses to the theory, which theory will account for essentially all phenomena. In particular, it clarified the results of the above mentioned investigations of Fizeau as well as the negative results of the experiments to determine the motion of the earth with respect to the ether. The Lorentz theory did not seem to be compatible with one particular experiment however; namely with the interference experiment of Michelson and Morley.

Lorentz had shown that according to his theory, barring terms of second and higher order in the ratio of speed of the body to the speed of light, a translational motion of the apparatus in the direction of the optical path would not be detected. Yet at that time the interference experiment of Michelson and Morley was already well-known. [This experiment] showed that in a special case, terms of second order in v / c also were not noticeable in spite of [the fact] that they were expected from the standpoint of the theory of a non-moving ether. So that this experiment would be consistent with the theory, the assumption was made by Lorentz and Fitzgerald that all bodies, therefore also those which together made up the constituents of the experimental apparatus of Michelson and Morley, alter their form in the same way when they move relative to the ether.

This circumstance was a supremely unsatisfying [one]. The only theory that was practical and clear in its basic assumptions was the Lorentz theory. This [theory] is based on the assumption of an absolute unmoving ether. The earth must be regarded as moving relative to this ether. All experiments, however, to discover this relative motion came up fruitless so that one is forced to the [construction] of a very peculiar hypothesis in order to be able to conceive that that relative motion does not reveal itself.

The Michelson-Morley experiment suggested the premise that all phenomena relative to [in] a coordinate system moving with the earth, or more generally [in] a moving, non-accelerating system obey exactly the same laws. In the following we will call this the "Relativity Principle" for short. Before we address the question [as to] whether it is possible to adhere rigidly to the relativity principle, we want briefly to reflect on what becomes of the ether hypothesis from this adherence.

On the basis of the ether hypothesis, the experiment leads to the assumption that the ether is not moving. The Principle of Relativity means, then, that all natural laws are the same in a coordinate system *K'* moving uniformly with respect to the ether as the corresponding laws are in a coordinate system, *K,* at rest with respect to the ether. If that is true, however, then we have just as much basis for suggesting that the ether is at rest relative to *K'* as with respect to *K*. It is then altogether unnatural to single out one of the two coordinate systems, *K, K',* as being at rest relative to the ether. It follows from this that one can then only arrive at a satisfactory theory if one rejects the ether hypothesis. The electromagnetic fields that constitute light appear, then, no longer as states of an hypothetical medium but as independent things which are emitted as light waves exactly according to the Newtonian theory of light emission. Just as according to that theory, it appears that a space free of ponderable bodies and not permeated with radiation is really empty.

[At first glance] it seems impossible to bring the canonical Lorentz theory into harmony with the Principle of Relativity. In particular, if a light ray propagates *in vacuo*, it does so, according to the Lorentz theory, always with the fixed velocity *c* independent of the state of motion of the emitting body. We will call this assumption the Principle of the Constancy of the Speed of Light. According to the addition theorem for velocities the same light ray will not travel with velocity *c* in relation to a coordinate system *K'* moving uniformly relative to the ether. The laws for the propagation of light seem, then, to be different in [the] two coordinate systems and from that it seems to follow that the Principle of Relativity is not compatible with [these] laws.

The addition theorem for velocities rests meanwhile on the arbitrary assumption that the nature of time, like the nature of moving bodies, has a meaning independent of the conditions of movement of a particular coordinate system. One convinces oneself in the definition of time and the form of moving bodies, however, that one has to introduce clocks that are at rest relative to the particular coordinate system [i.e. the one at rest with the bodies]. For this reason one must stick to that [convention] for this coordinate system and it is not obvious that this definition holds at the same time for two coordinate systems *K* and *K'* moving with respect to one another.

From this it emerges that the transformation equations, common up to now, for going over from one coordinate system to a coordinate system moving uniformly with respect to it rest on haphazard [questionable] assumptions. If one ignores these arbitrary assumptions it appears that one can bring the basis of the Lorentz theory, that is the general principle of the constancy of the speed of light, into agreement with the Relativity Principle. Through these two principles, one [concludes], because of certain new equations for coordinate transformation which are characterized by a suitable choice of the origin of the coordinates and time, that the equation

$$x^2 + y^2 + z^2 - c^2 t^2 = x'^2 + y'^2 + z'^2 - c^2 t'^2$$

becomes an identity. Here c means the speed of light *in vacuo*, x, y, z, t are space-time coordinates with respect to K; x', y', z', t' with respect to K'.

This track leads to the so-called Relativity Theory of whose consequences I would like to [mention] a single one here only because it brings a certain modification of [the] basic views in the area of Physics. It appears, to wit, that the inertial mass of a body decreases by L/c^2 if it emits radiant energy L. To that end, one can pursue the following course.

We consider a stationary free-swinging body which emits the same amounts of energy in two opposite directions. In this way the body remains at rest. If we denote by E_o the energy of the body before the emission, by E_1 its energy after the emission, and by L the quantity of emitted radiation, one has the following energy principle:

$$E_o = E_1 + L.$$

We consider now the body as well as the radiation emitted from it from a coordinate system relative to which the body moves with velocity v. It is by means of relativity theory that we calculate the energy of the emitted radiation relative to the new coordinate system. One obtains thereby the value

$$L' = L \cdot \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Because the principle of the conservation of energy must hold in relation to the new coordinate system, one obtains in analogous notation,

$$E_o' = E_1' + L \cdot \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

By subtraction one obtains, after discarding terms of 4th and higher order in v/c,

$$(E_o' - E_o) = (E_1' - E_1) + \frac{1}{2}\frac{L}{c^2}v^2.$$

Now, however, $(E_o^{'} - E_o)$ is nothing other than the kinetic energy of the body before the emission of light. If one denotes by m_o the mass of the body before the emission, m_1 its mass after the emission, then, ignoring terms of higher than second power, one writes,

$$\frac{1}{2} m_o v^2 = \frac{1}{2} m_1 v^2 + \frac{1}{2} \frac{L}{c^2} v^2$$

or

$$m_o = m_1 + \frac{L}{c^2}$$

Therefore the inertial mass of a body decreases as a result of the emission of light. The energy given up figures as part of the mass of the body. Further, one can conclude from this that every energy increase or decrease brings with it a increase or decrease of the mass in question. It appears that energy and mass are quantities every bit as equivalent as heat and mechanical energy.

Relativity Theory has therefore changed our views of the nature of light inasmuch as [that understanding] holds light not as a manifestation of conditions in an hypothetical medium but as something that matter itself consists of. Further, this theory has a characteristic in common with the corpuscular theory of light: the transferring of inertial mass from emitting to absorbing bodies. The Relativity Theory changes nothing of our concept of the structure of radiation, particularly of the propagation of energy in the irradiated space. It is, however, my opinion that with respect to this part of the question we stand at the threshold of an evolution that is undoubtedly of highest importance and which cannot be ignored. What I will put forward in the following is largely my personal opinion or conclusion from considerations which have not had sufficient review by others. Even so, if I offer these here, it is not in order to attribute undue trust to these views but in the hope they are able to induce one or the other of you to consider them with these questions.

Also, without going deeper into any theoretical consideration, one sees that our *theory* of light is unable to explain certain fundamental properties of the *phenomenon* [Italics added by translator.] of light. Why does whether a particular photochemical reaction proceeds or not only depend on the color of the light and not on its intensity? Why are the short wave rays universally more effective chemically than long wave ones? Why is the speed of photoelectrically emitted cathode rays independent of the intensity of the light? Why does it require a higher temperature and therefore higher molecular energy for the radiation emitted from a body to exhibit short wave properties?

In its current form the wave theory gives no answer to any of these questions. In particular it is absolutely incomprehensible why the photoelectric rays, as the cathode rays emitted due to Röntgen rays are called, achieve a speed that is independent of the intensity of the radiation. The impingement of such large quantities of energy on a molecular structure under the influence of a wave in which the energy is so finely divided that we must describe it by means of the wave theory in terms of light and Röntgen rays, makes excellent physicists take refuge in quite a far-fetched hypothesis. They assume that light in its propagation merely plays a dissipating role, while the molecular energies that arise are, on the other hand, of a radioactive nature. Because this hypothesis has already been largely abandoned, I will not present any grounds against it.

The basic property of the wave theory that brings these difficulties with it seems to me to lie in the following. While in the kinetic molecular theory there exists an inverse process for every process, e.g. for every molecular collision, this is not the case under the wave theory for elementary radiation processes. An oscillating ion radiates, according the theory we accept, a spherical wave that propagates outward. The reverse process, as an elementary process, does not exist. A spherical wave propagating inward is indeed mathematically possible but it needs a colossal number of emitting elementary structures for its precise realization. Therefore the process of the emission of light, as such, does not have the character of reversibility. It is here, I think, that our wave theory does not give the correct result. It seems that, in relation to this point, the emission theory of Newton holds more truth than the wave theory, i.e. according to the former, the energy which a light particle carries upon its emission will not be distributed over infinite space but remains available for an elementary process of absorption. One is reminded of the case of the emission of secondary cathode rays by Röntgen rays.

If primary cathode rays fall on a metal plate, P_1, then Röntgen rays are emitted. If these fall on plate P_2, then again cathode rays are emitted whose speed is of the same order of magnitude as [that of] the primary cathode rays. The speed of the secondary rays depends, so far as we know today, neither on the spacing between plates P_1 and P_2 nor on the intensity of the primary cathode rays. Let us assume for a moment that this is strictly true. What will happen if we let the intensity of the primary cathode rays or the size of the plate, P_1, on which they fall reduce so that we can consider the incidence of one of the electrons in the primary cathode ray as an isolated process? If the foregoing is actually correct, because of the independence of the speed of the secondary rays on the intensity of the primary cathode rays that we have assumed, at P_2, as a result of the incidence of an electron on P_1, either nothing is emitted or at P_2 a secondary emission of an electron follows with its speed being of the same order of magnitude as that of the electron that fell on P_1. In other words the elementary radiation process seems to take place in a way that it does not, as the wave theory predicts, divide and distribute the energy of the primary electron in a spherical wave expanding on all sides. But it seems that at least a large part of this energy is able to be deposited at some place on P_2 or elsewhere. The elementary process of the emission of radiation seems to be directional. It further appears that the process of emission of Röntgen rays from P_1 and the emission of secondary cathode rays from P_2 are essentially inverse processes.

The constitution of the radiation therefore appears to be other than our wave theory would infer. The theory of temperature [thermal] radiation has yielded certain salient points on this issue and indeed first and in first priority the theory on which Herr Planck has based his radiation formula. Since I must not assume [for sure] that this theory is generally known, I will give a short account of [its] highlights.

Inside a cavity at temperature T, one finds radiation of a certain composition, independent of the nature of the body. In the cavity each volume element contains an amount of radiation $\rho d\nu$ whose frequency is between ν and $\nu + d\nu$. The problem is to find ρ as a function of ν and T. If there is an electric resonator of natural frequency ν_0 and small damping then the electromagnetic theory of radiation allows [us] to calculate the average energy $(\overline{E})$ as a function of $\rho(\nu_0)$. The problem is thus reduced to ascertaining the energy, $\overline{E}$, of the resonator as a function of T. This last problem, however, can be further reduced to the following. Let there be a large number, *(N)*, of resonators of frequency ν_0 in the cavity. How does the entropy of this resonator system depend on that energy?

In order to solve this question, Herr Planck employed the general relationship between entropy and state probability as it was derived by Boltzmann from his gas theoretical investigations. It is in general

$$Entropy = k \cdot \log W$$

where *k* is a universal constant and *W* is the probability of the observable state. This probability is measured by the “Number of microstates [Komplexionen],” a number which indicates how many different ways the state at hand can be realized. In the case of the above formulation of the question, the state of the resonator system is defined by its total energy so that the question to be answered is as follows: In how many different ways can the total energy be distributed among the N resonators? In order to find this [number] Herr Planck divided the total energy into equal parts [each] with fixed energy ε. A microstate [Komplexion] is determined in this way as how many parts, ε, are allocated to each resonator. The number of such microstates that have the given energy is determined and set equal to *W*.

Herr Planck deduces further from the Wien displacement law, derivable from thermodynamic considerations, that $\varepsilon = h\nu$ must be assigned, where h is a number independent of ν. Thus he finds his radiation formula that agrees with all experiments up to now:

$$\rho = \frac{8\pi h \nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{kT}} - 1}.$$

It could appear at first that the Planck radiation formula might be seen as a consequence of the current electromagnetic theory. This, however, is not the case for the following reason. One could regard the number of microstates which were just spoken of only as an expression of the manifold nature of the possibilities for distributing the total energy among the *N* resonators if every possible distribution of the energy came about, at least to a certain approximation, under the microstates required for the calculation of *W*.

For this it is necessary that for all ν that correspond to a particular λ, the energy quantum, $h\nu$, is small compared to the average resonator energy, $\overline{E}$. Now, however, after a simple calculation, one finds that $h\nu/\overline{E}$ for the wavelength 0.5μ and an absolute temperature, $T = 1700$, is not only not small with respect to unity but is actually very large with respect to unity. It has the value of about $6.5 \cdot 10^{7}$. It will behave, for the given example number [of the count] of microstates, as if the energy of the resonators can have only the value zero, the $6.5 \cdot 10^{7}$-fold product of its mean energy, or a multiple thereof. It is clear that one must consider, by the method of the foregoing, only a truly vanishingly small part of that kind of distribution of the energy as possible for the calculation of the entropy. The count of these microstates is therefore, according to the basics of the theory, not an expression of the probability of a state in the Boltzmann sense. To assume the Planck theory [above] means, in my view, to discard the underpinnings of our theory of radiation.

I have at this point sought to indicate [suggest] [by the above] that we must discard our present foundation of the radiation theory. In any case, one cannot consider refusing [rejecting] the Planck theory [just] because it does not harmonize with every basic tenet. This theory has led to the definition of the elementary quantum which [quantum] has been brilliantly verified by the newest measurements of these quantities on the basis of the counts of alpha-particles. Rutherford and Geiger established for the quantum of electricity an average value of $4.65 \cdot 10^{-10}$ [statcoulombs], Regener $4.75 \cdot 10^{-10}$, while Herr Planck, with the help of his radiation theory ascertained from the constants of the radiation formula the intermediate value $4.69 \cdot 10^{-10}$.

The Planck theory leads to the following conjecture. If it is really true that a radiation resonator can only attain those energy values which are multiples of $h\nu$, then it goes not much farther to suppose that the emission and absorption of radiation only occurs in quanta of this energy value. On the basis of this hypothesis, the light quantum hypothesis, one can answer the above raised question on the absorption and emission of radiation. So far as our current knowledge reaches, the consequences of the quantitative content of the light quantum hypothesis are verified. Now the following question arises. Would it not be conceivable that if indeed the radiation formula given by Planck were correct that, however, a formulation could be given that did not depend on such an atrocious seeming assumption as the Planck theory? Would it not be possible to replace the light quantum hypothesis by another postulate by means of which one could equally [well] explain the known phenomena? If it is necessary to modify the elements of the theory, couldn't one at least retain the equations for the propagation of radiation and only conceive the elementary processes of emission and absorption differently?

In order for us to be clear about this we wish to investigate going in the direction opposite of Herr Planck in his radiation theory. We assume that the Planck formula is correct and ask ourselves whether from it anything follows relative to the constitution of the radiation. I will only sketch for you here two observations which I have developed along this line which seem to me to be somewhat convincing because of their clarity.

In a cavity, let there be an ideal gas as well as a plate, made of a solid substance, which is free to move perpendicular to its plane. Because of the randomness of the collisions between the gas molecules and the plate, the latter will be set in motion and indeed its mean kinetic energy [will be] one third of the mean kinetic energy of a mono-atomic gas molecule. This follows from statistical mechanics. We now assume that besides the gas, which we can think of as being composed of tiny molecules, there is radiation present in the cavity and indeed that this radiation is the so-called thermal radiation of the same temperature as the gas. This will be the case, if the walls of the cavity are at the same fixed temperature as the gas, opaque to radiation, and not everywhere perfectly reflective. We further assume provisionally that our plate is perfectly reflective on both sides. In this case not only the gas but also the radiation interacts with the plate. Namely the radiation will exert a pressure on both sides of the plate. The pressures are the same on both sides if the plate is at rest. However if it is moving, more radiation will be reflected from the surface in the direction of motion (the front side) than from the back surface. The backwards-acting force due to the pressure on the front surface is therefore greater than the force due to the pressure on the back surface. There remains as a result of the two a net force which retardsthe motion of the plate and is dependent on the speed of the plate. We want to call this resultant "radiation friction" for short.

Assuming for the moment that we have, [with this], taken into consideration the entire mechanical effect of the radiation on the plate, we come to the following understanding. Because of collisions by the gas molecules, the plate will receive impulses in random directions at random intervals. The speed of the plate between two such collisions still suffers the effect of [the] radiation friction whereby the kinetic energy of the plate is converted into energy of radiation. The consequence would be that unrevealed[1] energy of the gas molecules [would] be converted, by means of the plate, into [the] energy of radiation until all available energy is converted to radiation energy. Therefore no thermal equilibrium between gas and radiation would obtain.

This observation is, for this reason, flawed because the resulting forces due to the pressure of radiation on the plate can't be considered to be any more constant in time or free from iregularities than the pressures on the plate produced by the gas. Those variations of radiation pressure, in order that thermal equilibrium be possible, must now be so constituted that, on average, they compensate for the plate's loss of velocity due to radiation fiction in connection with which the mean kinetic energy is equal to 1/3 the mean kinetic energy of a monatomic gas molecule. If the radiation law is known then one can calculate the radiation friction and from that the mean value of the impulse which the plate must get as a result of the variations in radiation pressure in order that statistical equilibrium can be maintained.

This observation becomes even more interesting when one selects a plate that only totally reflects radiation in the frequency range $d\nu$, radiation of other frequenc[ies] pass[ing] through without absorption; one obtains then variations of the pressure of the

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[1] Heat energy. The process alluded to here would result in a decrease of entropy of the system hence Einstein's concern.

radiation in the frequency range $d\nu$. In this case I will only give the result of the calculation. If one denotes by Δ the impulse that is imputed to the plate during the time τ as a result of the random variations of the radiation pressure, one obtains for the average of the square of Δ the expression[2]

$$\overline{\Delta^2} = \frac{1}{c}\left[h\nu\rho + \frac{c^3}{8\pi}\frac{\rho^2}{\nu^2}\right]d\nu f\tau$$

To begin with, the simplicity of this result strikes [one]. There could be no simpler radiation formula given agreeing with what is known, within the bounds of observation error, which is as simple an expression for the statistical characteristics of radiation pressure as that given by Planck.

By way of interpretation it is to be noted first that the expression for the mean of the squared variation is the sum of two terms. It is therefore as if two different [and] independent causes of the variation of radiation pressure were present. From [the fact that] $\overline{\Delta^2}$ is proportional to *f* one concludes that the pressure variations for neighboring parts of the plate whose linear dimensions are large compared to a wavelength of the reflection frequency are unrelated.

The wave theory only provides a clarification for the second term of $\overline{\Delta^2}$. According to the wave theory, similar wave packets of slightly differing direction, slightly differing frequency, and slightly differing polarization states interfere with one another, and the totality of these resulting interferences arising in an uncorrelated way correspond to variations in the radiation pressure. That this variation must be according to the expression in the form of the second term of our formula can be seen by a simple dimensional analysis. One sees that the oscillatory structure of the radiation in reality provides a cause for the expected variation of the radiation pressure.

How, on the other hand, is the first term of the formula to be explained? This [term] is by no means to be neglected, but is uniquely calculated in the purview of the so-called Wien radiation law. Thus this term, for $\lambda = 0.5\mu$ and $T = 1700$, is about $6.5 \cdot 10^7$ times greater than the second. If the radiation consists of very slightly spread out microstates of energy $h\nu$, which move in the cavity independently of one another and are reflected independently of one another – a notion which embodies the crudest form of the light quantum hypothesis – then the resulting variations of the radiation pressure will give rise to a certain impulse on our plate, as it was described by the first term of our formula alone.

In my opinion the following must therefore be concluded from the above formula, which for its part is a consequence of the Planck radiation formula. Besides the spatial nonuniformity in the distribution of the impulse of the radiation which results from the

[2] The derivation of this expression was alluded to in the discussion on pg. 190 of this same volume of Phyzikalische Zeitschrift. The factor *f* denotes surface area.

wave theory, yet other nonuniformities in the spatial distribution of impulse are present, whose influence far exceeds [tower above] these when the energy density of the radiation is small. I add to this that another view relative to the spatial distribution of the energy yields results which are entirely consistent with those indicated previously relative to the spatial distribution of the impulse.

As far as is known to me, the formulation of a mathematical theory of radiation which does justice to the vibrational structure and the structure derived from the first term in the above formula (Quantum Structure) is not satisfactorily completed yet. The difficulty lies primarily in [the fact that] the characteristic qualities of the variations of the radiation as they are expressed through the above formula present little formal leverage for the advancement of a theory. One supposes it would be refraction and interference phenomena as yet not understood but one knows that the mean value of the random variations of the radiation pressure is determined by the second term in the above formula where // is a parameter of unknown meaning determined by the color. Who would have enough imagination to construct a theory of vibration from [on] this foundation?

In spite of everything it appears to me for the present [that] the most natural interpretation [is] that the introduction of the electromagnetic field of light is just as bound to singular points as the [role] of the electrostatic field [is] to the theory of electrons. It is not inconceivable that in such a theory the entire energy of the electromagnetic field would be able to be seen as localized in these singularities, just as in the old action-at-a-distance theory. I imagine perhaps every such singular point surrounded by a force-field which has in essence the character of a smooth wave, and whose amplitude decreases with distance from the singular point[3]. If there are many such singularities in a region which is small compared to the size of the force-field of a singular point, the force-fields [of the singularities] will overlap [each other] and yield in their composite an oscillating field in a sense perhaps only a little different from an oscillating field in the sense of the electromagnetic theory of light. That such a picture isn't to be accorded value [if] it doesn't lead to an exact theory really doesn't need to be pointed out. By this [above] I was only trying to demonstrate briefly that the two structural properties (Wave- and Quantum structure) which, according to the Planck formula, should both be associated with radiation, should not be considered to be non-unifyable.

Discussion.

Planck: If I may be permitted a brief remark to the discussion, first of all I can only express the thanks of the whole assembly which has listened with great interest to what Herr Einstein has brought forward and which, where perhaps a contradiction arises, will be prompted to further thoughtful considerations. I will naturally confine myself to that [part of the presentation] where I have another opinion than that put forward. Most of what the speaker has brought forward will meet with no contradiction. Also, I stress the

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[3] This observation provides motivation for experiments trying to detect the presence of a wave in regions of an interferometer where the particle is known not to be (cf. Wave-particle duality, edited by Franco Selleri. New York : Plenum Press, c1992.)

indispensability of the investigation of various quanta. We can proceed no farther with the complete radiation theory without distributing the energy, in a certain sense, in quanta that are to be thought of [effectively] as atoms. The question now is where one should look for them. According to the latest [above] development of Herr Einstein it would be necessary that free radiation in a vacuum, and therefore light waves themselves, be considered as atomically constructed and therefore to abandon Maxwell's equations. That seems to me a step that in my view is not yet necessary. I do not want to go into it in detail but only note the following. In Herr Einstein's last treatment he draws conclusions based on the movement of matter due to the variations of free radiation in a pure vacuum. This conclusion seems to me only free of objection if one completely understands the interaction between the radiation *in vacuo* and the movement of the material. If that is not the case, the bridge that is necessary to is missing. Now it seems to me that this interaction between free electrical energy *in vacuo* and the movement of the atoms of the material is very little understood. It rests in essence on the emission and absorption of light. Also, the radiation pressure consists in this, at least according to the generally accepted dispersion theory which also relates reflection to absorption and emission. Now emission and absorption are the obscure point [phenomena] about which we know very little. About absorption we perhaps know rather a little but how is it with emission? One advances this [phenomenon], as has been presented above, as [due to] the acceleration of electrons. But this point is the weakest of the entire electron theory. One postulates that an electron takes up a particular volume and a particular finite charge density[4], be it space or surface charge. Without this, one cannot proceed. It contradicts again, in a certain sense, the atomic understanding of electricity. Those are not impossibilities but difficulties and I am surprised that they have not given rise to more disagreement.

At this point I can, I think, introduce the quantum theory to advantage. We can state the laws only for long time [intervals]. But for short time [intervals] and for large accelerations one, for the time being, [is faced with] a hole who's filling requires new hypotheses. Perhaps one can assume that an oscillating resonator does not possess a continuously changeable energy, but that its energy is a simple multiple of an elementary quantum. I think if one employs this proposition, one can arrive at a satisfactory radiation theory. Now the question always is, how does one imagine such a theory? That is, one requires a mechanical or electrodynamic model of such a resonator. But in mechanics and the current electrodynamics, we have no discretely operating elements and therefore we cannot construct a mechanical or electrodynamic model. Mechanically, it seems impossible, therefore, and one must get used to that. Also our endeavors to portray the ether mechanically have completely failed. Also one wanted to picture electric current mechanically and thought of a comparison with a stream of water. But one also had to give that up, and just as one has gotten used to [this], one will also have to get used to such a resonator. Obviously, this theory would have to be worked out much further in detail than as has been shown here. Perhaps there is another one here luckier than I. In any case, I think one would first have to try to shift the entire difficulty of the quantum theory to the realm of the interplay between matter and radiation energy. Provisionally,

[4] Dirac had not yet introduced the idea of the delta-function.

one could yet interpret the phenomenon in a pure vacuum by [means of] Maxwell's equations.

H. Ziegler: If one [re]presents the primitive atoms of a material as invisible little spheres which have unchangeable light-speed, then all interactions between corporeal conditions and electromagnetic phenomena allow themselves to be portrayed and thereby the bridge between the material and the non-material that Herr Planck misses would be constructed[5].

Stark: Herr Planck has pointed out that provisionally, we don't need to go to the Einsteinian Consequence of considering the radiation as concentrated in space where it appears as separate from matter. At first I was of the view that for the present one could, in that regard, limit oneself to going back to the elementary law of a particular behavior of the resonators. But I still think that there is a phenomenon that indicates that electromagnetic radiation freed from matter must evidence itself as concentrated in space. That is, namely, the phenomenon that radiation that propagates from a Röentgen tube into the surrounding space can remain concentrated enough over large distances (up to 10 m) to affect a single electron. I think that the phenomenon is surely a reason to focus on the question as to whether or not the energy of electromagnetic radiation is to be considered as concentrated even where it appears separated from matter.

Rubens: A practical consequence that allows for experimental proof would arise out of the view presented by Herr Einstein. As is generally known not only //-rays but also □-rays induce scintillating light emission from a fluorescent screen. According to the view developed, the same must also result0 for □- and Röentgen rays.

Planck: It is a special case with the Röentgen rays. I would not like to claim too much about [them]. Stark has brought up something in favor of the Quantum Theory; I want to bring something up against it. That is the interferences between the colossal [number of] different motions of hundreds of thousands of wavelengths. If a quantum interfered with itself it would have to have an extension of hundreds of thousands of wavelengths. That is also a certain difficulty.

Stark: The interference phenomena can easily be set against the Quantum hypothesis. If one treats the Quantum hypothesis with greater respect, one will also gain a clarification. I would like to put that forward as a hope. Regarding the experimental side, it must be stressed that the experiments Herr Planck alluded to were conducted with very concentrated radiation so that very many quanta of the same frequency were concentrated in the light beam. That must be carefully born in mind in the treatment of [any] interference experiment. The interference phenomena would be very different for very weak radiation.

Einstein: The interference phenomena would really not be so difficult to arrange as one imagines and indeed on the following ground[s]: one must not assume that the radiation consists of quanta that are not in interaction. That would be impossible for the

[5] This may be a little logical-positivist sarcasm.

clarification of the interference phenomena. I think of a quantum as a singularity surrounded by a large vector field[6]. A large number of quanta compose a vector field that differs little from what we currently accept as radiation. I can imagine that a compartmentalization of the quanta takes place at the impingement of the radiation on the boundary surface through [its] effect on the boundary surface, [wall], perhaps every [one] according to the phase of the resultant field with which the quanta reach the separating surface[7]. The equations for the resulting field would differ very little from those of the existing theory. It is not to say [I'm not saying] that we would have to change many of the views that we currently hold with respect to interference phenomena. I would like to compare that with the process of the molecularization of the medium of the electromagnetic field. The field, as presented as small, atomized electric particles, is not essentially different from the earlier view and it is not impossible that something related will happen in radiation theory. I don't see a fundamental difficulty with the interference phenomena.

(Translated by Charles A. Crummer. Footnotes by the translator. Many thanks to Dr. Walter Campbell for his clarification of the original German and to Professor Clemens Heusch for advice on appropriate wording.)

[6] De Broglie's pilot wave approach may have come out of this thought.

[7] De Broglie and Bohm's requirement for the motion of a particle is that it remain in phase with its "pilot wave."