On the development of our view into the essence and nature of radiation

When it was recognized that light exhibits the phenomena of interference and refraction, it became indubitable that light was to be conceived as an undulatory movement. Since light is able to propagate through void space, it was necessary to imagine the existence within the vacuum of some special matter mediating the propagation of light waves. With respect to the laws of propagation of light within ponderable matter, it was necessary to assume that this material entity, being called "ether of light", filled up also the interior of ponderable matter, thus mediating the propagation of light therein. The existence of such an "ether of light" seemed out of doubt. The excellent textbook of physics by Chwolson, having appeared in 1902, stated in its first volume, when the concept of ether was introduced: "The probability of the hypothesis concerning the existence of this agent is almost close to certitude".
Today, however, we must consider the hypothesis of ether as an obsolete standpoint. It cannot even be denied that there is a large class of facts concerning radiation which show that light is endowed with certain properties which can far easier be understood from the standpoint of Newton's emission theory than from the standpoint of the undulation theory. Therefore, it is my opinion that the next step in the development of theoretical physics will bring us a theory of light which must be conceived as some sort of fusion between emission and undulation theory. The following statements are intended to give reason to this opinion and to show that a deep change of our intuitions into the essence and nature of light is unavoidable.
The greatest progress of theoretical physics since the introduction of the undulation theory was Maxwell's ingenious discovering that light could be conceived as an electromagnetic process. This theory introduced an electromagnetic condition of ether and matter instead of mechanical magnitudes (such as the deformation and velocity of parts of the ether), thus reducing optical problems to electromagnetic ones. With each further development of the electromagnetic theory, the question of reducing electromagnetic processes to mechanical ones became less significant; One got accustomed to treat concepts like the electric and magnetic field strength, the electric spatial density etc. as elementary concepts which need not be interpreted in a mechanical way.
When the electromagnetic theory was first introduced, the foundations of theoretical optics became simplified and the number of arbitrary hypotheses diminished. The old question about the oscillation direction of polarized light became meaningless. The difficulties concerning the boundary conditions at the border of two media followed from the foundation of the theory. No arbitrary hypotheses were needed to exclude longitudinal light waves. The only recently detected light pressure, which plays such an important role in the theory of radiation, followed as a consequence of the theory. I wouldn't try here to exhaustively enumerate the well known achievements but rather focus on one main point in whose respect the electro-magnetic theory agrees, or better: appears to agree with the kinetic theory.
According to both theories, light waves appear essentially as the totality of states of a hypothetical primordial medium, the ether, being present everywhere also in the absence of radiation. It was supposed, therefore, that movements of this medium should take influence on optical and electromagnetic phenomena. The search for the laws underlying these influences gave rise to a transformation of our basic intuitions concerning the nature of radiation which we will go through briefly.
The basic question intruding here was the following: Does the light ether take part in the movements of matter, or is it agitated differently inmidst of matter than matter itself, or does it finally perhaps not take part at all in the movements of matter, but rather remain always at rest? In order to answer this question, Fizeau set up an important interference assay with the following underlying reason: Light is propagating within a body with the velocity V if it is at rest. If the ether is carried fully by the body, then light will propagate within a moving body in the same way as if it was at rest. The propagation velocity relative to the body will in this case

be V as well. Taken absolutely, however, i.e. relative to an observer not moving along with the body, the propagation velocity of a light ray will equal the geometric sum of V plus the velocity v of the moving body. If the propagation velocity and the forward velocity have the same direction and the same sense, V_{abs} simply will equal the sum of both velocities, i.e.

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

To test whether this conclusion from the hypothesis of the fully convected light ether is correct, Fizeau made two coherent monochromatic light bundles pass axially each of two tubes filled with water and then bring them to interference. Having allowed at the same time the water to be axially moved across the tubes, namely across the one tube in sense of the light and across the other tube in the opposite sense, Fizeau found a shift of the interference stripes, from which he was able to infer the impact of the bodily movement on the absolute velocity.

As it is well known, it turned out that the influence of the bodily velocity showed up indeed in the expected sense, but this influence was always smaller than what corresponded to the hypothesis of complete convection. It holds

$$V_{abs} = V + \alpha v$$

Where α is always <1. Neglecting dispersion it holds

$$\alpha = 1 - 1/n^2.$$

From this experiment it followed that a complete convection of the ether by the matter doesn't take place, in other words that a relative movement of the ether with respect to the matter is in general existent. Now, our earth is a materiel body exhibiting velocities of different direction with respect to the solar system during the course of the year and it may well be that the ether in our laboratories isn't convected completely by the movement of the earth either, as it was seemingly the case in Fizeau's experiment with respect to the movement of the water. From this it followed that the ether exhibited a relative movement with respect to the earth which is alternating during day time and seasons of the year. And it was to be expected that this relative velocity induced an apparent anisotropy of space in optical experiments, i.e., that the optical phenomena were dependent on the orientation of the optical devices. Most different experiments have been conducted to demonstrate such an anisotropy, but the expected dependence of the phenomena on the orientation of the apparatus could not be confirmed.

This conflict was almost eliminated by the pioneering work of H.A. Lorentz in 1895. Lorentz showed that, with the assumption of a resting and non convecting ether, almost every phenomenon was accounted for without advancing any other hypotheses. In particular, the results of the above indicated experiment of Fizeau and the negative result of the mentioned experiments trying to demonstrate the movement of the earth with respect to the ether, were explained. Only one single experiment appeared to be at variance with Lorentz's theory, namely the interference experiment of Michelson and Morley.

Lorentz has shown that, according to his theory, even neglecting terms containing the quotient v/c in second or higher order as a factor, no influence of a common translatory movement of the apparatus onto the path of the ray could be detected. By this time Michelson and Morleys interference experiment was already known having shown that in a particular case terms of second order with reference to the quotient v/c were not detectable, although this was to be expected from the standpoint of the theory maintaining an ether at rest. In order to comprise this experiment by the theory, Lorentz and Fitzgerald, as is well known, introduced the assumption that every body, therefore also those from which Michelson and Morley's device is composed, changed their shape in a specific way if they were moving relatively to the ether.

This situation was highly unsatisfactory. The sole theory being useful and transparent in its foundations was Lorentz's theory. This theory rested on an absolutely immovable ether. The earth had to be considered as moving with respect to this ether. Anyone experiment intended to demonstrate such a relative movement ended up with negative results, such that one was

forced to advance most weird hypotheses to account for the fact that a relative movement was not observed.
Michelson's experiment suggested to presume that every appearance occurring within a coordinate frame convected by the earth or, more generally spoken, occurring relative to a non-accelerated moving system, obeyed exactly the same laws. This presumption we will call in the following shortly the "relativity principle". Before treating the question whether it is possible to maintain the Relativity Principle, let us briefly consider what will happen to the ether hypothesis if we maintained this principle.
Taking the ether hypothesis as a basis, the experiment led us suppose the ether as motionless. The Relativity Principle, then, told us that every natural law which is valid for a coordinate system K' being uniformly moved with respect to the ether will be valid in the same way also for a coordinate system K being at rest with respect to the ether. If this is the case, we have all the same reason to imagine the ether at rest with respect to K' as with respect to K. It is therefore altogether totally unnatural to distinguish one of the two coordinate systems K, K' by introducing an ether at rest relative to one of them. Therefore it follows that one may arrive at a satisfactory theory only if one forgoes the ether hypothesis. The light constituting electromagnetic fields appear then no longer as states of a hypothetical medium but as separate entities emitted from light sources just as Newton's emission theory states. Similarly, with respect to the last mentioned theory, space devoid of ponderable matter and of permeating radiation will really appear as void.
If viewed superficially, it appears impossible to reconcile the essential point of Lorentz's theory with the Relativity Principle. Because a light ray propagating in vacuo will exhibit, according to Lorentz's theory, the strict velocity c with respect to a coordinate system K at rest in the Ether, independently from the state of motion of the emitting body. We shall call this proposition the principle of constancy of light velocity. Following the addition theorem of velocities, the same light ray could not exhibit the same velocity c with respect to a coordinate system K' being in uniform translational movement with respect to the Ether. Hence, the laws of the propagation of light appear to be different with respect to different coordinate systems and it seems to follow thereof, that the Relativity Principle is inconsistent with the laws of the propagation of light.
The addition theorem, however, rests on arbitrary presuppositions implying that statements concerning time and shape of moving bodies will be independent from the state of movement of the coordinate system used. The definition of time and shape of moving bodies evidently requires the introduction of clocks which are supposed at rest relative to the coordinate system used. Therefore, one has to define those concepts separately for every coordinate system and it is not obvious that these definitions will yield the same time parameters t and t' for particular events happening in coordinate systems K and K' being moved relative to each other. Similarly, it could not be said that every proposition concerning the shape of bodies within the coordinate system K will hold also for the coordinate system K' being moved relatively to K.
Thereof it follows that the so far used transformation equations describing the transition from one coordinate system to another, being in uniform relative motion to the first, rest on arbitrary assumptions. If these assumptions are dropped, it turns out that the fundamentals of Lorentz's theory, i.e. the principle of the constancy of the velocity of light, can be reconciled with the Relativity Principle. One is lead to introduce new transformation equations for coordinate systems which unequivocally satisfy both principles. Adopting appropriate origins of coordinates and times these transformation equations are characterized by the fact that the equation
$$x^2 + y^2 + z^2 - c^2t^2 = x'^2 + y'^2 + z'^2 - c^2t'^2$$
yields identity. Here c is the velocity of light in vacuo, and x, y, z, t and x', y' z', t' are the respective space-time coordinates in the systems K and K'

Proceeding in this way leads to the so-called Relativity Theory of whose consequences I wish to mention here but one, because she entails a certain modification of our basic intuitions in the field of physics. It turns out, namely, that the inertial mass of a body decreases with L/c^2, if the latter emits the radiation energy L. One may arrive at this conclusion in the following way.

Consider a motionless freely floating body emitting into opposite directions the same amount of radiation energy. Thereby the body remains at rest. If we indicate the bodys energy before the emission by E_0, its energy after emission by E_1 and the amount of emitted radiation by L, we have, following the principle of energy conservation:

$$E_0 = E_1 + L.$$

Let us consider now the body with its emitted radiation from the standpoint of a coordinate system relative to which the body is moved with the velocity v. For this case the Relativity Theory furnishes the means to calculate the energy of the emitted radiation with respect to the new coordinate system. Thus, we get:

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

Given the fact that the principle of energy conservation must hold also for the new coordinate system, we get analogously

$$E'_0 = E'_1 + L\ \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

By subtraction and neglecting terms in v/c of forth and higher order we get:

$$(E'_0 - E_0) = (E'_1 - E_1) + \tfrac{1}{2} L\ (v^2/c^2)$$

Now, the term $E'_0 - E_0$ represents nothing but the kinetic energy of the body before the emission of light, the term $E'_1 - E_1$, on the other hand, its kinetic energy after the emission of light. Indicating the mass of the body before and after emission by M_0 and M_1 respectively, we may set, again neglecting terms of higher than second order:

$$\tfrac{1}{2} M_0 v^2 = \tfrac{1}{2} M_1 v^2 + \tfrac{1}{2} L\ (v^2/c^2)$$

i.e.: $M_0 = M_1 + L/c^2$.

Thus, the inertial mass of a body is diminished by the emission of light. The transferred energy figures as part of the body mass. One may conclude from this further that every uptake or output of energy entails an increase or a decrease of the mass of the body in case. Energy and mass appear equivalent in the same way as heat and mechanical energy are.

Relativity Theory has changed our intuitions concerning the nature of light in as much as it doesn't conceive light anymore as a consequence of states of a hypothetical medium but instead considers light, similar to mass, as a self-supporting entity. Light, according to this theory, fits with a corpuscular theory of light in as much as it transmits inertial mass from an emitting to an absorbing body. Our conception concerning the structure of radiation, and in particular the distribution of energy within the irradiated space remains unchanged by the Relativity Theory. Nevertheless, I do believe that, with respect to this side of the question, we stand at the eve of a still unconceivable but doubtless extraordinary important development.

What I wish to put forward in the following represents by and large my personal opinion as a result of reflections which still haven't been verified sufficiently by others. If I wished to put them forward here in spite, this is not because I am too confident with my opinions but because I hope that one or another of you may be led to take these questions under his scrutiny.

Without going into detailed theoretical considerations of any type, one may notice that our theory of light is unable to explain certain fundamental properties of light phenomena. Why does it depend on the color only but not on the intensity of light whether a specific photochemical reaction takes place or not? Why are radiations with shorter waves chemically more effective in general than those with longer waves? Why is the velocity of light-electrically generated cathode rays independent from the intensity of light? Why are high temperatures, i.e. high molecular energies, required to allow radiations emitted by bodies to contain short-waved components?

None of these questions are given an answer by contemporary undulation theory. In particular, it is quite impossible to conceive why cathode rays generated light-electrically or by X-rays attain such an important speed independently from the radiation intensity. The occurrence of such large amounts of energy in a molecular piece of matter under the influence of a source in which the density distribution of energy is as low as presumed by undulation theory, has brought capable physicists to have recourse to a quite remote hypothesis. They assumed that light played only a role as a trigger of the process, whereas the resulting molecular energy was of radioactive nature. I wouldn't argue against this hypothesis because it has already for the most been abandoned.

The essential feature of undulation theory causing these types of difficulties seems to me to reside in the following: The molecular kinetic theory allows any process in which only few elementary constituents are involved – as is the case, e.g. in individual molecular collisions - to be reversed. This is not the case, according to the undulation theory, for elementary radiation processes. An oscillating ion will give rise, according to current theory, to a spherical wave propagating outwards. The inverse process doesn't happen, however, as an *elementary* process. An inward propagating spherical wave could be conceived mathematically; but for its approximate realization a huge amount of emitting elementary entities would be necessary. The elementary process of light emission as such lacks the trait of reversibility. It appears that, up to this point, Newton's emission theory of light is holding more of the truth than undulation theory, because according to the first, the energy conveyed to the light particle during emission will not be scattered over an infinite space but remain disposable for the elementary process of absorption, thus keeping with the laws for the generation of secondary cathode rays by X-rays.

Primary cathode rays hitting a metal plate P_1 will give rise to X-rays. If the latter are hitting a second metal plate P_2, cathode rays are produced again whose speed will be of the same range as the speed of the primary cathode rays. The speed of the secondary cathode rays depends, as far as we know, neither from the distance of the plates P_1 and P_2 nor from the intensity of the primary cathode rays, but depends exclusively from the velocity of the primary cathode rays. Let us take this for granted. What would happen then, if the intensity of the primary cathode rays or the size of the plate P_1 is diminished up to the point that the incidence of a single electron of the primary cathode rays can be viewed as an isolated process? If the previous description is correct indeed, we would have to assume, due to the independence of the speed of the secondary rays from the intensity of the primary cathode rays, that P_2 would either give rise to nothing (since the electron has hit P_1) or give rise to the secondary emission of an electron with a velocity of the same range as the one of the electron having hit P_1. In other words, the elementary radiation process seems to proceed, not as the undulation theory predicts, namely such that the energy of the primary electron is spread and scattered by a spherical wave propagating in every direction. Instead, it appears that at least most part of this energy remains disposable at some point of P_2 or elsewhere. Thus, the elementary process of radiation emission appears to exhibit a direction. Furthermore, we get the impression that the generation of the X-ray in P_1 and the generation of the secondary cathode ray in P_2 are essentially inverse processes.

The constitution of radiation seems to be different from what can be followed from the undulation theory. Important clues in this respect were furnished by the theory of temperature radiation, namely first and in first line by the theory which gave Mr. Planck reason to

elaborate his radiation formula. May be this theory is not generally known. Therefore, I wished to sketch shortly the most important parts.
In the interior of a hollow space with temperature *T* there is a radiation whose composition does not depend on the nature of the body forming the hollow space. The hollow space is filled with a quantity of radiation $\rho d\nu$ whose frequency varies between ν and $\nu+d\nu$.
The task consists in finding ρ given as a function of ν and *T*. Provided the hollow space is containing an electrical resonator with the eigen-frequency ν_0 and negligible damping, electromagnetic theory of radiation enables us to calculate the temporal mean of the energy ($\overline{E}$) of the resonator as a function of $\rho(\nu_0)$. The problem thus reduces to find the mean energy $\overline{E}$ as a function of *T*. The latter problem, however, may be reduced to the following: The hollow space be filled with a large number (*N*) of resonators of frequency ν_0. How does the entropy of this resonating system depend from the energy?
To solve this question, Mr. Planck uses the general relation between the entropy and the probability of states as deduced by Boltzmann in his gas-theoretical investigations. Hence, the following general relation holds:

$$\text{Entropy} = k.\log W,$$

where *k* is a universal constant and *W* gives the probability of the considered state. This probability is given by the "number of complexions", i.e. a number indicating in how many ways the considered case can possibly be realized. In the above mentioned case the state of the resonator system is defined by its total energy, so that the question to be solved reads as follows: In how many ways can the given total energy be distributed amongst the *N* resonators? To find this number, Mr. Planck divides the total energy in equal parts of defined size ε. One complexion is defined by the number of parts ε falling to share each resonator. The number of complexions giving the total energy is found and set equal *W*.
Mr. Planck further concludes by applying the thermodynamically based dislocation law (Wien) that $\varepsilon = h\nu$, where *h* indicates a number which is independent from ν. In this way he finds his radiation formula being consistent with every experience hitherto:

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

It may appear that, according to this derivation, Planck's radiation law could be seen as a consequence of the actually held electromagnetic theory of radiation. This, however, is not the case for the following reason. The number of the just mentioned complexions could be seen as an expression of the distributional heterogeneity of the total energy amongst the *N* resonators only, if each thinkable distribution of energy was at least approximately reflecting the number of complexions used to calculate *W*. For this to be the case, it is necessary that for every ν contributing appreciably to the energy density ρ, the energy quantum ε be small compared to the mean resonator energy $\overline{E}$. Now it is found easily by calculation that $\varepsilon.\overline{E}$ for the wave length 0.5μ and the absolute temperature $T = 1700$ is not at all small compared to unity but indeed very big. It has the value 6.5×10^7. With respect to the given numerical example, the counting of the complexions is dealt with as if the energy of the resonator could assume only the value zero, or the 6.5×10^7 fold of the median energy or any multiple of this value. It is evident that this kind of procedure considers only a vanishingly small part of the – according to the basics of the theory - available energy distribution to compute the entropy. The number of complexions, therefore, is no expression of the probability states according to Boltzmann's original theory. To adopt Planck's theory implies, in my opinion, indeed rejecting the basis of our radiation theory.
The foundations of our actual radiation theory have to be revised, as I have shown earlier. Indeed, we cannot think of refusing Planck's theory, because of its being at variance with those foundations. This theory has led to the determination of the elementary quantum, whose

value has been verified in most recent measurements counting the alpha-particles. As concerns the elementary quantum of electricity, Rutherford & Geiger obtained as an average the value of 4.65×10^{-10}, Regener 4.79×10^{-10}, whereas Mr. Planck ascertained, using his radiation theory and applying the constants of the radiation formula, the intermediate value 4.69×10^{-10}.

Planck's theory leads to the following conjecture: If it is true indeed that a radiation resonator can adopt only those energy values which are multiples of $h\nu$, then it will be natural to assume that any emission and absorption of radiation can proceed only in energetic quantities of this size. On the basis of this hypothesis, the light quanta hypothesis, one is able to answer the questions which have been raised above concerning the emission and absorption of radiation. As far as we know, also the quantitative implications of the light-quanta hypothesis are confirmed. Now, the following questions may be raised: Wouldn't it be possible that Planck's promoted radiation formula was correct, but not its derivation? Could one derive the same formula without recurring to such an apparently monstrous assumption as Planck's theory? Wouldn't it be possible to replace the light-quanta hypothesis by another assumption which would account for the known phenomena as well? If it is necessary to modify the elements of the theory, could one at least maintain the equations for the propagation of radiation and just perceive the elementary processes of emission and absorption differently from so far?

In order to clarify these questions, we will try to proceed in inverse direction as Planck did with his radiation theory. We adopt Planck's radiation formula as correct and ask, if something could be followed thereof with reference to the constitution of radiation. Having carried out two considerations in this respect, I wish to sketch for you but one of them, which seems to me particularly convincing because of its perspicuity.

Imagine a hollow space filled with an ideal gas and equipped with a plate from solid material which can be moved freely in a perpendicular plane only. Because of the irregularity of the collisions between the molecules of the gas and the plate, the latter will be set in motion, such that its mean kinetic energy equals the third part of the mean kinetic energy of a one-atomic gaseous molecule. This follows from statistical mechanics. Let us admit now that within the hollow space there exists, apart from the gas which we assume as consisting from only a few molecules, some kind of radiation, namely a so-called temperature-radiation exhibiting the same temperature as the gas. This will be the case, if the walls of the hollow space are of the defined temperature T, are impermeable for radiation and not totally reflecting everywhere. We further admit for the moment that our plate is completely reflecting on either side. Given this state of affairs, both the gas and the radiation will act upon the plate. Hence, the radiation will exert pressure on both sides of the plate. The pressure forces acting on both sides equal each other, if the plate is at rest. If however the plate is moved, more radiation will be reflected from the anterior side than from the back side. The pressure force acting upon the anterior side backwards will be greater than the pressure force acting upon the back side forwards. Therefore, a resulting force shows up which counteracts the movement of the plate and which increases with the speed of the plate. We will call this resulting force shortly "friction of radiation".

Let us assume for the moment that with this we have taken into account the whole mechanical action of the radiation upon the plate. In this case it follows: The gaseous molecules hitting the plate in irregular intervals confer momentum to the plate in irregular directions. The velocity of the plate will decrease between any two such collisions because of the friction of radiation, thereby transforming kinetic energy of the plate into radiation energy. Consequently, the kinetic energy of the gaseous molecules will steadily be transformed by means of the plate into radiation energy. Hence, there would be no equilibrium of temperature between gas and radiation.

This consideration is faulty indeed, because the pressure forces exerted by the radiation onto the plate are neither temporally constant nor free from statistical fluctuations. This is also the case for the pressure forces exerted onto the plate by the gas. In order to render thermal equilibrium, the fluctuations of the pressure forces exerted by radiation have in the mean to be such as to compensate for the damping of the plates speed due to radiant friction. The mean kinetic energy of the plate equals one third of the mean kinetic energy of a one-atomic gaseous molecule. If the radiation law is known, it will be possible to compute the friction caused by radiation and from this the mean quantity of the moments which have to act upon the plate because of the fluctuations of the radiation pressure, in order to assure statistical equilibrium.

This consideration will be of even more interest, if one chooses a plate which is able to reflect completely the radiation of frequencies in the range $d\nu$ but allows other frequencies to pass without absorption. One obtains, then, the fluctuations of the radiation pressure in the frequency range $d\nu$.

For this case I will give the result of the computation. Let us indicate by Δ the quantity of movement transferred to the plate within time τ because of the irregular fluctuations of the radiation pressure. The mean value of the square of Δ will then be given by the expression

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

First, the simplicity of the expression attracts attention. There is probably no radiation formula of such a simple type as Planck's one fitting our experience within the limits of observational error and reproducing the statistical properties of the radiation pressure.

Next, interpreting the formula I wished to draw your attention to the fact that the expression for the mean square of fluctuation results as the sum of two terms. It looks as if two different and independently working causes were responsible for the fluctuations of the radiation pressure. The fact that $\overline{\Delta^2}$ is proportional to f allows the conclusion that the pressure fluctuations for neighboring parts of the plate, whose linear size is large against the wave length of the reflection frequency, are indeed events which are independent from each other.

The undulation theory yields an explanation for only the second term of the expression found for $\overline{\Delta^2}$. Because, according to undulation theory, radiation bundles of slightly different direction, slightly different frequency and slightly different state of polarization must interfere with each other and, in addition, the whole collection of these fully disordered interferences must correspond to a fluctuation of the radiation pressure. By a simple dimensional analysis it may be realized that this fluctuation, i.e. its expression, is of the form of the second term of our formula. Hence, the undulatory structure of radiation gives indeed reason for the expected fluctuations of the radiation pressure.

Now what about the first term of the formula? This term must not be neglected at all, since it controls almost by itself alone, within the realm of its validity, the so-called Wien's radiation law. Hence, for $\lambda = 0.5\mu$ and $T = 1700$, this term is about 6.5 x 10^7 times larger than the second one. If the radiation consisted of rather distinct energy packets $h\nu$, which were traversing the space independently and were being reflected independently from each other – a vision bringing the hypothesis of light quanta to the extreme – then this kind of fluctuations of the radiation pressure would transfer moments onto our plate, which were to be described solely by the first term of our formula.

In my opinion, the above formula which, for its part, is a consequence of Planck's radiation formula, leads necessarily to the following conclusion: Apart from the spatial asymmetries in the motional distribution of radiation resulting from the undulation theory, there must exist other asymmetries in the spatial distribution of moments which exceed at low radiant energy densities the first mentioned asymmetries by far. I wish to add that another consideration concerning the spatial distribution of the energy will yield to almost the same results as the foregoing one concerning the spatial distribution of moments.

As far as I know, a mathematical theory of radiation taking into account both the undulation theory and the structure inferred by the first term of the above formula (quantum structure) has so far not been successfully established. The difficulty resides essentially in the fact that the fluctuating character of the radiation, as expressed in the above formula, has given little formal clues to establish such a theory. Imagine the phenomena of refraction and interference were still ignored but it was known that the mean quantity of the irregular fluctuations of radiation pressure was determined by the second term of the above equation, with ν as a parameter of unknown significance determining the color, - who would have enough inventiveness to construct on this basis the undulation theory?

At least it seems to me in the meantime most natural to conceive the occurrence of electromagnetic fields of light as being bound to singular points akin to the occurrence of electrostatic fields in the electron theory. It is not excluded that in such a theory the whole energy of the electromagnetic field can be seen as being localized in these singularities, quite as in the old theory of the action at distance. I imagine each such singular point being eventually surrounded by a force field with the character of a plane wave whose amplitude diminishes with increasing distance from the singular point. If there are many such singularities at a distance from each other which is small compared to the size of the force field of one singular point, an overlap of the force fields will ensue yielding as a whole an undulatory force field which, may be, differs but barely from the undulatory field of present day electromagnetic light theory. There is no need to point out that a picture of that kind is of no value as long as this picture is not founded in an exact theory. I just wished to illustrate by means of such a picture that both structural properties (undulation structure and quantum structure), which according to Planck's formula are both attributed to the radiation, need not be seen as mutually exclusive.

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D i s c u s s i o n

P l a n c k: If I am permitted to add a few remarks to this presentation, I wish first to thank in the name of the whole assembly, who has listened with the utmost interest to what Mr. Einstein has brought forward. If in some respect a disagreement has arisen, this will elicit more profound considerations. I will, of course, restrict myself to where I disagree with the speaker. Yet, most of the speakers performance will provoke no controversy. I myself emphasize the need to introduce certain quanta. We can't come along with the whole radiation theory without dividing the energy into certain quanta which can be thought of as "atoms of action". The question now is where to look for these quanta. According to Mr. Einstein's last statement, it would be necessary to presume that the free radiation in vacuo, thus the light waves themselves, have an atomistic constitution. This would imply to give up Maxwell's equations. This step appears in my view not necessarily mandatory. Without going into details, I just wished to remark the following- In his last consideration, Mr. Einstein inferred from the movement of matter to the fluctuations of free radiation in net vacuo. This inference seems to me incontestable only, if we were knowing exactly about the interaction between the radiation in vacuo and the movement of matter. As long as this relationship is ignored, the necessary bridge is missing, in order to establish the connection between the movement of the mirror and the intensity of the incident radiation. Very little appears to be known indeed about the interaction between free electric energy in vacuo and the movement of atoms in matter. It refers essentially to the emission and absorption of light. Also the pressure of light resides in this process, at least according to the currently held Dispersion Theory, which attributes reflection to absorption and emission. But emission and absorption are still like a black box where we haven't got to look into. The process of absorption may rather be known perhaps to some extent, but what about the process of emission? One believes it is generated by an acceleration of electrons. But this point is the weakest of the whole electron theory. One imagines the electron as being endowed with a certain volume and a certain finite charge density, either in a spatial or a plain sense – we can't do without these prerequisites. This, however, contradicts in a certain sense the atomistic concept of electricity. There are no impossibilities, but yes difficulties, and I am almost astonished that no more opposition has arisen against.

At this point, I believe, the quantum theory can be helpful. We may express the respective laws only for large time intervals. But for small time intervals and large accelerations, we are confronted still with a gap, whose completion requires new hypotheses. We can, may be, argue that an oscillating resonator does not possess a steadily changing energy but that his energy is a simple multiple of an elementary quantum. I believe, if one utilizes this concept, we will end up with a satisfactory radiation theory. Now the question is always: how can we conceive such a thing? This means, one has to look for a mechanical or an electro-dynamical model of such a resonator. But in mechanics and in present day electrodynamics we don't have discrete elements of action and this is why we can't establish a mechanical or electro-dynamical model. In a mechanical sense this appears impossible and we will have to familiarize with this fact. Too, our attempts to represent the light ether in a mechanical way have failed completely. Even it has been tried to represent the electric current mechanically, e.g. by comparing it with a water flow, but also this image had to be abandoned. We have got accustomed to this situation and we will have to accustom also to such a kind of resonator. Of course, this theory would have to be elaborated in much more detail as has been done so far; perhaps somebody else is more fortunate in this respect than I.