BOOK REVIEW

THE CREATIVE PATH OF M. PLANCK

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On the centennary of the birth of Max Planck, April 23, 1958, the Union of German Physics Societies and the Max Planck Society for the Advancement of Science (Max Planck Gesellschaft zur Förderung der Wissenschaften e.v.) issued a collection of Planck's original papers, published by the well known Vieweg Publishing House in Braunschweig. The editorial committee, which prepared this edition, consisted of Dietrich Hahn, Max Laue, and Wilhelm Westfahl. The foreword to the first volume was signed by M. Laue, a student and friend of Planck, who obviously was also the editor of the publication. As already mentioned, the publication was undertaken by several societies, including the Max Planck Society. It may be appropriate to explain what this society represents. As is known, at the beginning of the 20th century there was organized in Germany the so-called "The Kaiser Wilhelm Society for the Advancement of Sciences" ("Kaiser Willhelm Gesellschaft zur Förderung der Wissenschaften"). Organized with the support of the major industries, this society was something like an unofficial academy. It founded and financed many research institutes. The first president of this society was the historian A. Harnack. The second, from 1930 to 1937, was Max Planck. After the second world war, Planck was again president of this society until 1946, when the society itself was renamed the Max Planck Society.

Returning to a description of the collection of Planck's papers, we note that this collection includes only the published original papers and some of his lectures and reports of general physical and philosophical nature. The textbooks (Thermodynamics, Radiation Theory, the five volumes of the Textbook of Theoretical Physics), and the monographs (Principle of Conservation of Energy, Eight Lectures on Theoretical Physics) are not included in this collection. We can note with satisfaction that all these books by Planck, without exception, are available in Russian, and that his text on thermodynamics was published in Russian at least twice.

To conclude the description of the external aspect of the reviewed collection of Planck's papers, we note that the first two volumes contain, approximately in chronological order, his original research in the field of theoretical physics. The third volume contains articles of general physical, historical, and philosophical nature. In spite of the fact that most articles have been reproduced by offset, the appearance of the publication is very good. Only in those cases when some article was published in large-scale journals (for example, Physikalische Zeitschrift or Naturwissenchaften) did the reduction in the format cause the type size of the articles to become too small.

Using this collection of Planck's papers, we can follow his creative path. In one of his autobiographical articles, Planck writes that from early youth he was interested mostly in the more general laws of physics, which are of importance to all natural phenomena (III, 255*). Since the years of his youth coincided with the time when the fundamental principles of thermodynamics were established, it is no wonder that indeed this branch of physics, characterized exactly by its unusual generality, was the center of his first scientific interests. Even in his school years, a lasting impression was made on him by the law of conservation of energy. In the university, he was no less impressed by the second law of thermodynamics, which he studied independently by reading Clausius. It is therefore quite understandable that Planck's first two papers in the first volume are devoted indeed to the principles of thermodynamics. These two papers — his doctoral dissertation (On the Second Law of the Mechanical Theory of Heat, 1879) and the so-called "habilitation paper ("Habilitations

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*We shall henceforth refer to the reviewed collection of Planck's works: the Roman number denotes the volume, the arabic the page.

Schrift" — The Status of Equilibrium of Isotropic Bodies at Different Temperatures, 1880) presented, in the German custom to the Munich University to gain the right to teach there. These papers can be briefly classified as the foundation and the application of the most important thermodynamic function, entropy. No one before Planck, not even Clausius himself, who introduced the entropy concept in 1866, used this concept to solve specific problems in thermodynamics. The usual method, developed principally by Clapeyron and Clausius, was to construct a reversible cyclic process for each case.

As to thermodynamic quantities, only one, the temperature, was essentially used in the first papers. Considerably later, in an article devoted to Boltzmann (Boltzmann Festschrift, Leipzig 1904; Planck Collection, Vol. II, pp 79-88), Planck formulated very clearly the shortcomings of the temperature concept and the advantages of the entropy: while one can speak of temperature only in the equilibrium state, the concept of entropy in statistical thermodynamics can be defined for all possible processes. In this interesting article Planck analyzes in detail Boltzmann's statistical definition of entropy and Gibbs' three statistical definitions. In his first papers, however, Planck did not use statistics and introduced entropy and other thermodynamic functions purely phenomenologically. As to the application of thermodynamic functions instead of cycles, this method, as is known, was introduced into thermodynamics gradually and by now completely replaced the cycle method. Gibbs' papers, "discovered" by Ostwald at the beginning of the 20th century, were not known to Planck at that time. In his scientific autobiography, Planck expresses his regret of this fact and acknowledges Gibbs' priority (III, 379).

Planck's early scientific work brought him some disappointment, for his papers on the principles of thermodynamics went simply unnoticed. Planck commented that his dissertation was not even understood by the members of the faculty, who granted him a degree, not on the basis of his dissertation, but thanks to the reputation he acquired by participating in special seminars etc. Not being deterred by this, Planck continued working along these lines and applied successfully the thermodynamic method in his well known papers on the theory of weak electrolytes, on electrochemistry, and other physical and chemical problems. These papers occupy more than one half of the first volume of the reviewed collection, and in spite of the fact that all these have been included in his textbook of thermodynamics, familiarity with the original papers is of great interest to students of physical chemistry and thermodynamics.

During that period, the preoccupation with thermodynamics influenced also the general physical viewpoint of Planck. Being a zealous adherent of the phenomenological method of thermodynamics, Planck was skeptical about atomistics during the first half of his scientific activity. His atitude towards these problems, which interested physicists during the end of the last century and the first years of the present century, was characterized by Planck himself in his scientific autobiography. Recalling the struggle between the most ardent exponent of atomistics, L. Boltzmann, and its opponent, W. Ostwald, Planck wrote:

"Understandably, this struggle between Boltzmann and Ostwald was a rather lively one and led to numerous bright sayings, since both opponents were equally strong in their striking ability and in their sharp native wit. I myself... could act here only as a second for Boltzmann, who not only failed to acknowledge my services, but even considered them undesirable. This is because Boltzmann knew very well that my point of view differed substantially from his. He particularly disliked the fact that I was not merely indifferent to atomistics, which served as the basis for his research but opposed it to a certain extent (sogar etwas ablehnend gegenüberstand). The reason for that was that I then considered the principle of entropy increase as inviolate as the principle of conservation of energy, while Boltzmann considered the principle of entropy increase only a probabilistic law, which admits of exceptions as such. The value of H can also sometimes increase.* Boltzmann did not treat this point at all in his derivation of the so-called H theorem, and my talented student E. Zermelo pointed this out and emphasized that his theorem has no rigorous basis. In fact, Boltzmann's calculations contain no mention of the "molecular chaos" premise needed to substantiate his theorem." These objections of Zermelo and Planck are equivalent to stating that, in view of the strict reversibility of purely mechanical processes, it is impossible by means of Newtonian dynamics alone to explain logically, without contradiction, the irreversibility of real processes, called for the second law of thermodynamics. The resultant discussion indeed led to the missing link in the logical chain, in the form of the molecular-chaos postulate.

After the application of thermodynamics to the

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* As is well known, Boltzmann succeeded in defining a certain quantity H, which diminished constantly with time, so that its negative value could be identified with entropy (Remarks by É. Sh).

study of physico-chemical processes proved to be so fruitful in the hands of Planck, he turned to a study of a new problem by thermodynamic means, that of the radiation from a black body. As is well known, this study has led to the discovery that has immortalized his name — the discovery of the elementary quantum of action. The discovery of the quantum laws has played a tremendous role in Planck's personal life since, as we shall see, it was associated on one hand with a crisis in his entire scientific outlook, and on the other hand, it was experienced by him as a real tragedy. The path followed by Planck when solving this problem was as follows. Since, by Kirchhoff's law, thermal radiation is independent of the nature of the radiating body, Planck chose to represent matter in the simplest form, that of a linear harmonic oscillator or resonator which, owing to its electric charge, can exchange energy with the surrounding electromagnetic field. Planck wrote in the above-mentioned article on the history of the establishment of the radiation law bearing his name (III, pp 258 ff): "I had hoped that for any initial state of this system (i.e., linear oscillator — É. Sh.) Maxwell's theory will lead to irreversible radiation processes, which terminate in a stationary state of thermodynamic equilibrium, in which the radiation from the cavity has the sought black-body energy distribution.

"I therefore began to investigate first resonant absorption and emission of electromagnetic waves. Here I adhered to the theory that the interaction between an oscillator, excited by an electrodynamic wave that emits and absorbs energy, and the exciting wave is an irreversible process. However, this opinion, expressed in so general a form, is erroneous as was convincingly pointed out by L. Boltzmann.* The entire process could proceed just as well in the opposite direction. It is merely necessary, at a certain instant of time, to reverse the signs of the magnetic field intensities while retaining the previous directions of the electric intensities. Now the oscillator will again absorb the energy, radiated in the form of spherical waves by similar spherical waves, and again emit energy absorbed from the exciting radiation. Consequently, there can be no talk of irreversibility in such a process.

"To be able to progress further in the theory of radiation, it was necessary to introduce a limiting condition that would immediately exclude processes never occurring in nature, such as concentric inwardly-directed sperical waves, and would at the same time exclude the possibility of simultaneous reversal of the signs of all magnetic intensities. I made this step by introducing the hypothesis of "natural radiation," which is tantamount to assuming that the individual partial harmonic waves, which constitute the thermal radiation are fully incoherent."*

Using the "hypothesis of natural radiation" as a base, thereby insuring the irreversibility of the interaction between the oscillators and the radiation, Planck then derived a simple formula, connecting, in the stationary state, the oscillator energy U with the radiation intensity K_ν. This formula is

$$K_\nu = \frac{\nu^2}{c^2} U,$$

where K_ν is the radiation intensity (more accurately, the surface density of radiation), and U is the oscillator energy. The procedure then followed a purely thermodynamic path. In fact, Planck found (obviously by trial and error) an expression for the entropy of a system made up of oscillators and radiation, expressing S as a function of U and ν, which, in addition, contains two universal constants. Using next the thermodynamic relation

$$\frac{dS}{dU} = \frac{1}{T}$$

and eliminating the oscillator energy U from the result of the application of this formula to the foregoing expressions, Planck obtained the Wien formula, i.e., an expression of the form $A\nu^3 \exp(-\beta\nu/T)$, containing the temperature in the exponent. At first this result appeared satisfactory, since the Wien formula, which gave good results for the visible portion of the spectrum and for short waves in general, was considered valid in those days. In an extensive article, summarizing the accomplishments of this stage of the work (I, 614-667) and published in 1900 in Annalen der Physik, Planck wrote the following concerning his formula (p. 661): "This, however, is none other than the law, estab-

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*We omit the literature references cited in the original. An analysis of the absorption and radiation of electromagnetic radiation by an oscillator was reported by Planck in five communications to the Berlin Academy of Sciences, which bear the common title "On Irreversible Processes of Radiation." In the reviewed collection of Planck's papers, these are printed in the first volume, pp 493–601. It is interesting, from the historical point of view, that Boltzmann's objection, raised immediately after the first communication, Planck attempted to attribute in the second communication to a misunderstanding, and that only later on did he understand this objection. (–É. Sh.)

*It is obvious that the "hypothesis of natural radiation" in the statistics of radiation plays exactly the same role as the "hypothesis of molecular chaos" in the statistic of material systems. Thus, in this respect Boltzmann in his criticism avenged the Zermelo-Planck criticism of the proof of his H-theorem. (–É. Sh.)

lished by W. Wien for of the energy distribution, which was found to be correct, at least approximately, by the thorough research of F. Paschen, F. Paschen and G. Wanner, O. Lummer, and E. Pringsheim.

"Wien derived his law by making a specific assumption concerning the number of radiation centers contained per unit volume and concerning their velocity. In the theory developed here, these quantities do play no role whatever, but the law follows as the necessary consequence of the definition, established in Section 17, of the electromagnetic entropy of radiation. The question of the validity of this law thus coincides with that of the validity of this definition."

Actually, this result could not be considered satisfactory. By the time this paper was published, the was also published the Rayleigh-Jeans formula was made public. The latter, derived by a logically indisputable, exceedingly clever, and perfectly direct application of classical statistics to radiation, it differed substantially from the Wien formula, particularly in that the temperature dependence in this law was not exponential but in the form of a direct proportionality. Although this formula led to the well-known "discrepancies" ("ultraviolet catastrophe"), measurements made in the same year, 1900, by F. Kurlbaum and G. Rubens showed that for very long waves the absolute black-body radiation comes closer and closer, with increasing temperature, to being proportional to the temperature, in sharp contradiction to the Wien law and in agreement with the Rayleigh-Jeans law. The subsequent events developed with dramatic speed.

Planck himself reported on these clearly and with great frankness in the historical article already cited, written shortly before his death.

The work of Kurlbaum and Rubens was reported at a session of the German Physical Society on October 19, 1900. Planck wrote in the cited article: "Since this result (i.e., the proportionality of the radiation intensity to the temperature at long waves and high temperatures — É. Sh.) became known to me from a conversation with the authors a few days prior to the session, I had time, even before the session, to draw conclusions from this result by my own method and to use it to calculate the entropy of resonating oscillators" (III, 262-263). As a result, Planck derived a formula for the energy spectrum which he reported, after transforming the frequency distribution into a wavelength distribution, to the same session during the discussions following the paper of Kurlbaum and Rubens, and which he proposed to check further.

"During the next morning," continues Planck, "my colleague Rubens looked me up and mentioned that after the session (which took place in the evening — É. Sh.) he compared, that very night, my formula with the results of his measurements and obtained satisfactory agreement everywhere. Lummer and Pringsheim, too, who first thought that they found deviations, soon withdrew their objections in view of the fact, as reported to me personally by Pringsheim, it became clear that the deviations they found were due to errors in the calculations. Subsequent measurements again and again confirmed the equation, with an accuracy that increased with the accuracy of the experiments."

Soon afterwards Planck published a brief note, in which he reported his equation (I, 687-689), which became the well-known "Planck formula."

However, history did not stop there. There is no doubt that the Planck formula was obtained by interpolation between those of Wien, valid for short waves and low temperatures, and of Rayleigh-Jeans, which hold for long waves and high temperatures. Were this all, Planck's services would be limited to solving a certain very special problem although of practical importance. However, Planck did not stop with a successful empirical formula. He undertook to explain it theoretically, and at the December 14, 1900 meeting of the Physical Society he reported a proof of his formula, based on the concept of the discrete nature of the resonator energy. This date, December 14, 1900, should indeed be considered the birthday of the quantum theory. In his Nobel-prize address (III, 120-124) Planck remarked that the work performed by him during the few weeks between the sessions of October 19 and December 14 was the most difficult he ever did in his life. The intermediate stages, are not mentioned by Planck anywhere. According to M. Laue [Naturwiss. **45**, 221 (1958)], he never spoke of the intermediate stages of his work. But it can be stated with full assurance that the change from the empirically-derived radiation formula to its theoretical justification was connected with a sharp reversal in his entire scientific viewpoint, from the phenomenologically-thermodynamic method, which Planck used exclusively prior to introducing the quantum hypothesis, to statistics. In particular, this manifested itself in the use of the Boltzmann's premise of the connection between the entropy and probability, i.e., the admission of atomistics. However, an even sharper turn was connected with the introduction of the hypothesis of the discrete nature of the energy, i.e., with a break with one of the principal premises of classical physics in general. Judging from later papers and from evidence of persons who knew him intimately (for example, the same M. Laue), this break tormented Planck for several decades after this paper appeared.

By now the initial derivation of the radiation formula, given by Planck, is dated, in view of Einstein's much simpler and logically more rigorous derivation. However, from the historical point of view, particularly for a correct historical perspective, it is interesting to recall the principal features of Planck's derivation and to cite verbatim that portion of his paper, in which the discreteness of energy is first mentioned.

The derivation leading to the correct radiation formula, is analogous in its general features to that indicated above, except that the expression used for the entropy is somewhat different from the one that led Planck previously to Wien's formula. However, when Planck attempted to justify this expression for the entropy, he was forced to use statistics. Planck himself wrote (III, 264-265): "I myself have not resorted so far to the relation between the entropy and probability; this relation did not attract me, since any probability law admits exceptions, while I believed the second law as admitting of no exceptions. It is only in the course of time that it became clear to me that I could prove the irreversibility of the radiation processes only by admitting the "hypothesis of natural radiation," and that consequently, this restricting hypothesis in the theory of radiation was just as necessary and played exactly the same role as the hypothesis of "molecular chaos" in gas theory. "But since I could find no other way out, I attempted to use the Boltzmann method and wrote a general expression for any state of any physical system

$$S = k \ln W, \tag{9}$$

where W is a suitably calculated probability of the state.

Now to apply (9) to the given case, I postulated a system consisting of a very large number N of identical oscillators and attempted to calculate the probability that such a system would have a specified energy U_N. But since the probability could be obtained only by calculation, it was necessary first to consider the energy U_N as the sum of discrete elements ϵ, all equal, the number of which should be represented by a very large number P. Consequently

$$U_N = NU = P\epsilon\text{."} \tag{1}$$

In the paper read on December 14, 1900, Planck formulated his basic assumption in the following manner (I, page 698): "It is merely necessary to find, in addition, the energy distribution over the individual resonators within each class of resonators and, above all, the distribution of the energy E over N resonators with frequency ν. Were E to be considered as a quantity that can be subdivided without limit, the distribution would have an infinite number of possibilities. But we consider — and this is the essential point of the entire calculation — E as being composed of a definite number of finite equal parts and use for this purpose a universal constant (Naturkonstante) $h = 6.55 \times 10^{-27}$ erg-sec. This constant, multiplied by the number of oscillations ν of the resonators, gives the energy element ϵ in ergs, by dividing ϵ into E we obtain the number P of the energy elements, which must be distributed over the N resonators." As can be seen, the premise is quite clearly formulated. However, it is not emphasized anywhere that this is a hypothesis that contradicts radically all of classical physics.

Furthermore, much later, in 1909 (i.e., after the publication of Einstein's paper on light quanta and on specific heat), Planck emphasized an opposite idea in lectures delivered at Columbia University. We cite this interesting excerpt from a lecture devoted to the atomistic theory of matter: "If . . . we wish to reduce the entropy of radiant heat to probability, then, as previously, we see that atomistics should play a significant role in radiant heat. Since, however, radiant heat is not connected with matter, atomistics should pertain not to matter but to energy, from which it follows that certain energy elements should play a substantial role in radiant heat. No matter how strange such a conclusion may sound — and the lively protest which is raised against it in many circles even now is quite understandable — physical science cannot fail to accept it, more so since it is quite satisfactorily confirmed experimentally. We shall return to this problem in lectures on radiant heat; here I should like to add also that the introduction of atomistics to the study of radiant heat represents nothing new, nothing that should revolutionize our concepts, as may appear at first glance,* since there is no need, at least in my opinion, of imagining, from the atomistic point of view, radiation phenomena in absolute vacuum, but is is enough to apply the atomistics to the source of the radiation, i.e., to those phenomena that take place in the centers where rays are emitted and absorbed.†

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*Emphasis mine (É. Sh.)

†I cite from the Russian translation: M. Planck, Theoretical Physics, Eight Lectures Delivered at Columbia University in New York. Translated by I. M. Zapchevskiĭ, St. Petersburg, 1911, p. 59.

This tendency to retain somehow the concepts of classical physics, in spite of the fundamental facts that he himself discovered and that call for a break with these concepts, indicates the conflict which Planck felt painfully during the rest of his life.

Let us return again, however, to the historical paper delivered on December 14, 1900. Using the above formula to relate the radiation energy density with the resonator energy and with Wien's law, Planck derives the following formula for the radiation from an absolutely black body.

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

Changing from frequencies to wavelengths, we obtain the Planck formula in the form used for practical radiation calculations:

$$u_\lambda \, d\lambda = \frac{8\pi ch}{\lambda^5} \cdot \frac{d\lambda}{e^{\frac{ch}{k\lambda T}} - 1}.$$

Either form of Planck's formula contains the two universal constants h and k. The constant k is usually called the Boltzmann constant, since it is also the proportionality coefficient in the Boltzmann formula that relates entropy and probability. Planck, however, pays attention to the fact that Boltzmann himself never used this constant (he used the quantity R), and that its numerical value was first calculated by Planck. The constant h is the elementary quantum of action, the discovery of which has immortalized Planck's name Using empirical data for the intensity of radiation from an absolutely black body, Planck, as mentioned above, calculated the numerical values for these constants and obtained (I, 727)

$$k = 1.346 \cdot 10^{-16} \text{ erg-deg}^{-1},$$
$$h = 6.55 \cdot 10^{-27} \text{ erg-sec.}$$

For comparison, we cite the modern exact values:

$$k = 1.3804 \cdot 10^{-16} \text{ erg-deg}^{-1}, \qquad h = 6.625 \cdot 10^{-27} \text{ erg-sec.}$$

With the aid of the value of k obtained by him and of the well known value of the universal gas constant R, Planck calculated Avogadro's number; from this, using the Faraday number, he found the charge of the electron

$$e = 4.69 \cdot 10^{-10} \text{ CGS electrostatic units.}$$

This number was greatly different from the result obtained that time by direct experiment. In fact, J. J. Thomson's measurements (1898), which were deemed the most reliable, yielded $e = 6.5 \times 10^{-10}$, and the old measurements of F. Richarz (1894) yielded $e = 1.29 \times 10^{-10}$. The discrepancy between the value of e calculated by Planck and that determined experimentally was used as an argument by the critics of the quantum hypothesis of whom, as always in the case of radically new ideas, there was no shortage. However, we know now that it was Planck who was considerably closer to reality, since the modern most precise value of e is 4.805×10^{-10}.

Further progress in theoretical physics was marked by a literal victory march of quantum theory. Let us recall the principal stages of this development: in 1905 Einstein transferred the quantum concepts from the mechanism of radiation to the nature of radiant energy itself, thereby radically resolving many accumulating substantial contradictions. Somewhat later (1908) he introduced quantum concepts into solid-state physics, to explain the puzzling drop in specific heat near absolute zero. In 1913 N. Bohr generalized the quantum postulates and applied them with brilliant success to the theory of atomic structure; finally, in 1925-1927 W. Heisenberg, M. Born, and P. Jordan on one hand, and L. de Broglie and E. Schrödinger on the other, created and completed the formulation of non-relativistic quantum mechanics, while P. Dirac established the relativistic wave equation of the electron. Planck no longer participated directly in this rapid progress. And although the break with classical physics was painful to him, he understood with the intuition of a great scientist its inevitability and depth. In 1912, in the foreword to his second edition of "Lectures on the Theory of Heat Radiation" he wrote: ". . . anyone who wants to base his relationship to the quantum hypothesis on whether it is possible to explain fully the significance of the quantum of action to elementary physical processes or at least to illustrate it by some simple dynamic model, does not understand, in my opinion, the character and meaning of the quantum hypothesis. A substantial new principle cannot be reproduced by models that obey the laws of the old theory" (emphasis mine — É. Sh.). These clever words should serve as a lesson to those few "lovers of antiquity" who sometimes, without realizing, make attempts to reduce the unique quantum laws to some models that perform in accordance with the laws of classical physics.

It is not our purpose here to present a complete survey of Planck's papers, and we shall dwell here on some of his important works not directly related to the discovery of the quantum of action. Such is his interpretation of the third law of thermodynamics, discovered by W. Nernst, requiring that the entropy vanish at the absolute zero of the temperature (III, 54-64). Such, too, are his investigations on relativity (see particularly II, 176-209), with which he enthusiastically sided from its inception.

The third volume differs greatly in character from the first two. It contains a collection of articles, papers, and lectures of philosophic and popular character, and also articles devoted to outstanding physicists (H. Hertz, H. A. Lorentz, P. Drude and others) in connection with various anniversaries. This volume includes also articles of autobiographic character: "Personal Recollections" (358-363), "On the History of the Discovery of the Physical Quantum of Action" (255-267), and "Scientific Autobiography" (pages 374-401). The last article is known to the readers of our journal (see Usp. Fiz. Nauk **64**, 625, 1958).

All the articles in this volume remain highly interesting to this day. A detailed analysis of Planck's scientific-philosophical views cannot be given in this article, which is a general survey of the collection of Planck's works. Let us note only two points. In the speech "Unity of the Physical Picture of the World" (III, 6-29), which contains the scientific-philosophical "credo" of Planck, he spoke up with vigorous objections to the positivism of E. Mach which, at that time, (1908) was quite popular among the natural-science writers. In his thermodynamic papers he showed the inconsistency of Ostwald's energetics. Nor did Planck stay outside the latest scientific-philosophical discussions, arising in connection with the problem of causality and, like Einstein, he decisively supported classical determinism in many articles and papers (see, for example, "The Concept of Causality in Physics," III, 219-239).

Planck deserves honor for the most important discovery, the existence of an elementary quantum of action of finite (not infinitesimal) value. He gave the first formulation of one of the great ideas that are the basis of modern physics and separate so radically modern from classical physics — the idea of the quantum and of universal discreteness in natural phenomena. This idea was formulated in its time, and as we know, became exceedingly fruitful.

Surveying the development of the quantum theory from its inception in 1900 to the present day, we cannot help but wonder at the tremendous distance covered by physics in approximately 60 years. We have left far behind the first steps of quantum theory, which more than 30 years ago has been converted from a "quantum hypothesis" into an ordered system of quantum mechanics, not inferior to classical mechanics in its completeness and logical consistency. The universal role of discreteness in the laws of nature, exhibited by Planck's discovery, has not merely been incorporated in the "flesh and blood" of modern physics as a fact, but has raised the problem of explaining the origin of this discreteness itself. We are not dealing now with the admission of the existence of elementary particles and their mutual transformations, but with an explanation of why these exist and have precisely these properties. It is therefore understandable that, against the background of the deepest and most difficult problems of modern theory of elementary particles, the discussions that excited the physicists at the beginning of our century in connection with the appearance of quantum theory appear now so simple and almost naive! Yet an acquaintanceship with the many articles contained in the three volumes of Planck's papers is highly interesting from the historical point of view and deeply instructive, particularly for those studying theoretical physics. Therefore the commemoration of Planck's 100th birthday by publishing a collection of his original papers is not only due homage to the activity of this outstanding scientist, but a valuable contribution to the education of a new generation of physicists.