The Solvay Meetings and the Development of Quantum Mechanics

Niels Bohr at the occasion of the 12th Solvay Conference in Physics, 9-14 October 1961

"Quantum Theory of Fields"

The series of conferences originally convened, just fifty years ago, at the far-sighted initiative of Ernest Solvay and continued under the auspices of the International Institute of Physics founded by him, have been unique occasions for physicists to discuss the fundamental problems which were at the center of interest at the different periods, and have thereby in many ways stimulated modern development of physical science.

The careful recording of the reports and of the subsequent discussions at each of these meetings will in the future be a most valuable source of information for students of the history of science wishing to gain an impression of the grappling with the new problems raised in the beginning of our century. Indeed, the gradual clarification of these problems through the combined effort of a whole generation of physicists was in the following decades not only so largely to augment our insight in the atomic constitution of matter, but even to lead to a new outlook as regards the comprehension of physical experience.

As one of those who in the course of time have attended several of the Solvay conferences and have had personal contact with many of the participants in the earliest of these meetings, I have welcomed the invitation on this occasion to recall some of my reminiscences of the part played by the discussions for the elucidation of the problems confronting us. In approaching this task I shall endeavor to present these discussions against the background of the many-sided development which atomic physics has undergone in the last fifty years.

I

The very theme of the first Solvay conference in 1911, Radiation Theory and Quanta, indicates the background for the discussions in those days. The most important advances in physics in the former century were perhaps the development of Maxwell's electromagnetic theory, which offered so far-reaching an explanation of radiative phenomena, and the statistical interpretation of the thermodynamical principles culminating in Boltzmann's recognition of the relation between the entropy and probability of the state of a complex mechanical system. Still, the account of the spectral distribution of cavity radiation in thermal equilibrium with the enclosing walls presented unsuspected difficulties, especially brought out by Rayleigh's masterly analysis.

A turning point in the development was reached by Planck's discovery, in the first year of our century, of the universal quantum of action revealing a feature of wholeness in atomic processes completely foreign to classical physical ideas and even transcending the ancient doctrine of the limited divisibility of matter. On this new background the apparent paradoxes involved in any attempt at a detailed description of the interaction between radiation and matter were early stressed by Einstein, who did not only call attention to the support for Planck's ideas offered by investigations of the specific heat of solids at low temperature but, in connection with his original treatment of the photoelectric effect, also introduced the idea of light quanta or photons as carriers of energy and momentum in elementary radiative processes.

Indeed the introduction of the photon concept meant a revival of the old dilemma from Newton's and Huygens' days of the corpuscular or undulatory constitution of light, which had seemed resolved in favour of the latter by the establishment of the electromagnetic theory of radiation. The situation was most peculiar since the very definition of the energy or momentum of the photon, given by the product of Planck's constant and the frequency or wave number of the radiation, directly refers to the characteristics of a wave picture. We were thus confronted with a novel kind of complementary relationship between the applications of different fundamental concepts of classical physics, the study of which in the course of time was to make the limited scope of deterministic description evident and to call for an essentially statistical account of even the most elementary atomic processes.

The discussions at the meeting were initiated by a brilliant exposition by Lorentz of the argumentation based on classical ideas leading to the principle of equipartition of energy between the various degrees of freedom of a physical system, including not only the motion of its constituent material particles but also the normal modes of vibration of the electromagnetic field associated with the electric charge of the particles. This argumentation, following the lines of Rayleigh's analysis of thermal radiative equilibrium led, however, to the well known paradoxical result that no temperature equilibrium was possible, since the whole energy of the system would be gradually transferred to electromagnetic vibrations of steadily increasing frequencies.

Apparently the only way to reconcile radiation theory with the principles of ordinary statistical mechanics was the suggestion by Jeans that under the experimental conditions one did not have to do with a true equilibrium but with a quasi-stationary state, in which the production of high frequency radiation escaped notice. A testimony to the acuteness with which the difficulties in radiation theory were felt was a letter from Lord Rayleigh, read at the conference, in which he admonishes to take Jeans' suggestion into careful consideration. Still, by closer examination it was soon to become evident that Jeans' argument could not be upheld.

In many respects the reports and discussions at the conference were most illuminating. Thus, after reports by Warburg and Rubens of the experimental evidence supporting Planck's law of temperature radiation, Planck himself gave an exposition of the arguments which had led him to the discovery of the quantum of action. In commenting on the difficulties of harmonizing this new feature with the conceptual framework of classical physics, he stressed that the essential point was not the introduction of a new hypothesis of energy quanta, but rather a remoulding of the very concept of action, and expressed the conviction that the principle of least action, which was also upheld in relativity theory, would prove a guidance for the further development of quantum theory.

In the last report at the conference, Einstein summarized many applications of the quantum concept and dealt in particular with the fundamental arguments used in his explanation of the anomalies of specific heats at low temperatures. The discussions of these phenomena had been introduced at the meeting in a report by Nernst on the application of quantum theory to different problems of physics and chemistry, in which he especially considered the properties of matter at very low temperatures. It is of great interest to read how Nernst in his report remarked that the well known theorem regarding the entropy at absolute zero, of which since 1906 he had made important applications, now appeared as a special case of a more general law derived from the theory of quanta. Still, the phenomenon of the superconductivity of certain metals at extremely low temperatures, on the discovery of which Kamerlingh Onnes reported, presented a great puzzle, which should first many years later find its explanation.

A new feature, commented upon from various sides, was Nernst's idea of quantized rotations of gas molecules, which was eventually to receive such beautiful confirmation in the measurements of the fine structure of infra-red absorption lines. Similar use of quantum theory was suggested in the report by Langevin on his successful theory of the variation of the magnetic properties of matter with temperature, in which he made special reference to the idea of the magneton, introduced by Weiss to explain the remarkable numerical relations between the strength of the elementary magnetic moments of atoms deduced from the analysis of his measurements. Indeed, as Langevin showed, the value of the magneton could at any rate be approximately derived on the assumption that the electrons in atoms were rotating with angular momenta corresponding to a Planck quantum.

Other spirited and heuristic attempts at exploring quantum features in many properties of matter were described by Sommerfeld, who especially discussed the production of x-rays by high speed electrons as well as problems involving the ionization of atoms in the photoeffect and by electronic impact. In commenting upon the latter problem, Sommerfeld called attention to the resemblance of some of his considerations with those exposed in a recent paper by Haas, who in an attempt at applying quantum ideas to the electron binding in an atomic model like that suggested by J.J. Thomson, involving a sphere of uniform positive electrification, had obtained rotational frequencies of the same order of magnitude as the frequencies in optical spectra. As regards his own attitude, Sommerfeld added that instead of trying from such considerations to deduce Planck's constant, he would rather take the existence of the quantum of action as the fundament for any approach to questions of the constitution of atoms and molecules. On the background of the most recent trend of the development this utterance has indeed an almost prophetic character.

Although at the time of the meeting there could, of course, be no question of a comprehensive treatment of the problems raised by Planck's discovery, there was a general understanding that great new prospects had arisen for physical science. Still, notwithstanding the radical revision of the foundation for the unambiguous application of elementary physical concepts, which was here needed, it was an encouragement to all that the firmness of the building ground was just in those years so strikingly illustrated by new triumphs for the classical approach in dealing with the properties of rarefied gases and the use of statistical fluctuations for the counting of atoms. Most appropriately, detailed reports on these advances were in the course of the conference given by Martin Knudsen and Jean Perrin.

A vivid account of the discussions at the first Solvay meeting I got from Rutherford, when I met him in Manchester in 1911, shortly after his return from Brussels. On that occasion, however, Rutherford did not tell me, what I only realized some months ago by looking through the report of the meeting, that no mention was made during the discussions at the conference of a recent event which was to influence the following development so deeply, namely his own discovery of the atomic nucleus. Indeed, by completing in such unsuspected manner the evidence about the structure of the atom, interpretable by simple mechanical concepts, and at the same time revealing the inadequacy of such concepts for any problem related to the stability of atomic systems, Rutherford's discovery should not only serve as a guidance, but also remain a challenge at many later stages of the development of quantum physics.

II

By the time of the next Solvay conference in 1913, the subject of which was the Structure of Matter, most important new information had been obtained by Laue's discovery in 1912 of the diffraction of Roentgen rays in crystals. The discovery removed indeed all doubts about the necessity of ascribing wave-properties to this penetrating radiation, the corpuscular features of which in its interaction with matter, as especially stressed by William Bragg, had been so strikingly illustrated by Wilson's cloud chamber pictures showing the tracks of high speed electrons liberated by the absorption of the radiation in gases. As is well known, Laue's discovery was the direct incentive to the brilliant explorations of crystalline structures by William and Lawrence Bragg, who by analyzing the reflection of monochromatic radiation from the various sequences of parallel plane configurations of atoms in crystal lattices were able both to determine the wave length of the radiation and deduce the type of symmetry of the lattice.

The discussion of these developments, which formed the main topic of the conference, was preceded by a report by J.J. Thomson about the ingenious conceptions regarding the electronic constitution of atoms, by which without departing from classical physical principles he had been able, at least in a qualitative way, to explore many general properties of matter. It is illuminating for the understanding of the general attitude of physicists at that time that the uniqueness of the fundament for such exploration given by Rutherford's discovery of the atomic nucleus was not yet generally appreciated. The only reference to this discovery was made by Rutherford himself, who in the discussion following Thomson's report insisted on the abundance and accuracy of the experimental evidence underlying the nuclear model of the atom.

Actually, a few months before the conference my first paper on the quantum theory of atomic constitution had been published, in which initial steps had been taken to use the Rutherford atomic model for the explanation of specific properties of the elements, depending on the binding of the electrons surrounding the nucleus. As already indicated, this question presented insurmountable difficulties when treated on ordinary ideas of mechanics and electrodynamics, according to which no system of point charges admits of stable static equilibrium, and any motion of the electrons around the nucleus would give rise to a dissipation of energy through electromagnetic radiation accompanied by a rapid contraction of the electron orbits into a neutral system far smaller than the size of atoms derived from general physical and chemical experience. This situation therefore suggested that the treatment of the stability problems be based directly on the individual character of the atomic processes demonstrated by the discovery of the quantum of action.

A starting point was offered by the empirical regularities exhibited by the optical spectra of the elements, which, as first recognized by Rydberg, could be expressed by the combination principle, according to which the frequency of any spectral line was represented with extreme accuracy as the difference between two members of a set of terms characteristic for the element. Leaning directly on Einstein's treatment of the plioto-effect, it was in fact possible to interpret the combination law as evidence of elementary processes in which the atom under emission or absorption of monochromatic radiation was transferred from one to another of the so-called stationary states of the atom. This view, which permitted the product of Planck's constant and any of the spectral terms to be identified with the binding energy of the electrons in the corresponding stationary state, also offered a simple explanation of the apparently capricious relationship between emission and absorption lines in series spectra, since in the former we are confronted with transitions from an excited state of the atom to some state of lower energy, while in the latter we generally have to do with a transition process from the ground state with the lowest energy to one of the excited states.

Provisionally picturing such states of the electron system as planetary motions obeying Keplerian laws, it was found possible to deduce the Rydberg constant by suitable comparison with Planck's original expression for the energy states of a harmonic oscillator. The intimate relation with Rutherford's atomic model appeared not least in the simple relationship between the spectrum of the hydrogen atom and that of the helium ion, in which one has to do with systems consisting of an electron bound to a nucleus of minute extension and carrying one and two elementary electric charges, respectively. In this connection it is of interest to recall that at the very time of the conference, Moseley was studying the high frequency spectra of the elements by the Laue-Bragg method, and had already discovered the remarkably simple laws which not only allowed the identification of the nuclear charge of any element, but even were to give the first direct indication of the shell-structure of the electronic configuration in the atom responsible for the peculiar periodicity exhibited in Mendeleev's famous table.

III

Owing to the upsetting of international scientific collaboration by the first world war, the Solvay meetings were not resumed until the spring of 1921. The conference, entitled Atoms and Electrons, was opened by Lorentz with a lucid survey of the principles of classical electron theory, which in particular had offered the explanation of essential features of the Zeeman effect, pointing so directly to electron motions in the atom as the origin of spectra.

As the next speaker, Rutherford gave a detailed account of the numerous phenomena which in the meantime had received such convincing interpretation by his atomic model. Apart from the immediate understanding of essential features of radioactive transformations and of the existence of isotopes which the model provided, the application of quantum theory to the electron binding in the atom had then made considerable progress. Especially the more complete classification of stationary quantum states by the use of invariant action integrals had, in the hands of Sommerfeld and his school, led to an explanation of many details in the structure of spectra and especially of the Stark effect, the discovery of which had so definitely excluded the possibility of tracing the appearance of line spectra to harmonic vibrations of the electrons in the atom.

In the next following years it should indeed be possible through the continued study of high frequency and optical spectra by Siegbahn, Catalan and others, to arrive at a detailed picture of the shelf-structure of the electron distribution in the ground state of the atom, which clearly reflected the periodicity features of Mendeleev's table. Such advances implied the clarification of several significant points, like the Pauli principle of mutual exclusion of equivalent quantum states, and the discovery of the intrinsic electron spin involving a departure from central symmetry in the states of electron binding necessary to account for the anomalous Zeeman effect on the basis of the Rutherford atomic model.

While such developments of theoretical conceptions were still to come, reports were given at the conference of recent experimental progress regarding characteristic features of the interaction between radiation and matter. Thus Maurice de Broglie discussed some most interesting effects encountered in his experiments with x-rays, which in particular revealed a relationship between absorption and emission processes reminding of that exhibited by spectra in the optical region. Moreover, Millikan reported about the continuation of his systematic investigations on the photo-electric effect which, as is well known, led to such improvement in the accuracy of the empirical determination of Planck's constant.

A contribution of fundamental importance to the foundation of quantum theory was already during the war given by Einstein, who showed how the Planck formula of radiation could be simply derived by the same assumptions that had proved fruitful for the explanation of spectral regularities, and had found such striking support in the famous investigations by Franck and Hertz on the excitation of atoms by electron bombardment. Indeed, Einstein's ingenious formulation of general probability laws for the occurrence of the spontaneous radiative transitions between stationary states as well as of radiation induced transitions, and not least his analysis of the conservation of energy and momentum in the emission and absorption processes, was to prove basic for future developments.

At the time of the conference, preliminary progress had been made by the utilization of general arguments to ensure the upholding of thermodynamical principles and the asymptotic approach of the description of the classical physical theories in the limit where the action involved is sufficiently large to permit the neglect of the individual quantum. In the first respect, Ehrenfest had introduced the principle of adiabatic invariance of stationary states. The latter demand had come to expression through the formulation of the socalled correspondence principle, which from the beginning had offered guidance for a qualitative exploration of many different atomic phenomena, and the aim of which was to let a statistical account of the individual quantum processes appear as a rational generalization of the deterministic description of classical physics.

For the occasion I was invited to give a general survey of these recent developments of quantum theory, but as I was prevented by illness from taking part in the conference, Ehrenfest kindly undertook the task of presenting my paper, to which he added a very clear summary of the essential points of the correspondence argument. Through the acute awareness of deficiencies and warm enthusiasm for any even modest advance, characteristic of Ehrenfest's whole attitude, his exposition faithfully reflects the state of flux of our ideas at that time, as well as the feeling of expectation of approaching decisive progress.

IV

How much remained to be done before appropriate methods could be developed for a more comprehensive description of the properties of matter was illustrated by the discussions at the next Solvay conference in 1924, devoted to the problem of metallic conduction. A survey of the procedures by which this problem could be treated on the principles of classical physics was given by Lorentz, who in a series of famous papers had traced the consequences of the assumption that the electrons in metals behaved like a gas obeying the Maxwell velocity distribution law. In spite of the initial success of such considerations, serious doubts about the adequacy of the underlying assumptions had, however, gradually arisen. These difficulties were further stressed during the discussions at the conference, at which reports on the experimental progress were given by experts as Bridgman, Kamerlingh Onnes, Rosenhain and Hall, and the theoretical aspects of the situation were commented upon especially by Richardson, who also tentatively applied quantum theory on the lines utilized in atomic problems. Still, at the time of the conference it had become more and more evident that even such limited use of mechanical pictures as was so far retained in the correspondence approach could not be upheld when dealing with more complicated problems. Looking back on those days., it is indeed interesting to recall that various

progress, which should be of great importance for the subsequent development, was already initiated. Thus Arthur Compton had in 1923 discovered the change in frequency of x-rays by scattering from free electrons and had himself, as well as Debye, stressed the support which this discovery gave for Einstein's conception of the photon, notwithstanding the increased difficulties of picturing the correlation between the processes of absorption and emission of photons by the electron in the simple manner used for the interpretation of atomic spectra.
Within a year such problems were, however, brought in a new light by Louis de Broglie's pertinent comparison of particle motion and wave propagation, which soon was to find striking confirmation in the experiments by Davisson and Germer and George Thomson on the diffraction of electrons in crystals. I need not at this place remind in detail how de Broglie's original idea in the hands of Schroedinger should prove basic for the establishment of a general wave equation, which by a novel application of the highly developed methods of mathematical physics was to afford such a powerful tool for the elucidation of multifarious atomic problems.
As everyone knows another approach to the fundamental problem of quantum physics had been initiated in 1924 by Kramers, who a month before the conference had succeeded in developing a general theory of dispersion of radiation by atomic systems. The treatment of dispersion had from the beginning been an essential part of the classical approach to radiation problems, and it is interesting to recall that Lorentz had himself repeatedly called attention to the lack of such guidance in quantum theory. Leaning on correspondence arguments Kramers showed, however, how the dispersion effects could be brought in direct connection with the laws formulated by Einstein for the probabilities of spontaneous and induced individual radiative processes.
It was in fact in the dispersion theory, further developed by Kramers and Heisenberg to include new effects originating in the perturbation of the states of atomic systems produced by electromagnetic fields, that Heisenberg should find a stepping stone for the development of a formalism of quantum mechanics, from which all reference to classical pictures beyond the asymptotic correspondence was completely eliminated. Through the work of Born, Heisenberg and Jordan as well as Dirac this bold and ingenious conception was soon given a general formulation in which the classical kinematic and dynamical variables are replaced by symbolic operators obeying a non-commutative algebra involving Planck's constant.
The relationship between Heisenberg's and Schrbdinger's approaches to the problems of quantum theory and the full scope of the interpretation of the formalisms were shortly after most instructively elucidated by Dirac and Jordan with the help of canonical transformations of variables on the lines of Hamilton's original treatment of classical mechanical problems. In particular, such considerations served to clarify the apparent contrast between the superposition principle in wave mechanics and the postulate of the individuality of the elementary quantum processes. Dirac even succeeded in applying such considerations to the problems of electromagnetic fields and, by using as conjugate variables the amplitudes and phases of the constituent harmonic components, developed a quantum theory of radiation, in which Einstein's original photon concept was consistently incorporated. This whole revolutionary development should form the background for the next conference, which was the first of the Solvay meetings I was able to attend.

V

The conference of 1927, the theme of which was Electrons and Photons, was opened by reports by Lawrence Bragg and Arthur Compton about the rich new experimental evidence regarding scattering of high frequency radiation by electrons exhibiting widely different features when firmly bound in crystalline structures of heavy substances and when practically free in atoms of light gases. These reports were followed by most instructive expositions by Louis de Broglie, Born and Heisenberg as well as by Schroedinger about the great advances as regards the consistent formulation of quantum theory, to which I have already alluded.
A main theme for the discussion was the renunciation of pictorial deterministic description implied in the new methods. A particular point was the question, to what extent the wave mechanics indicated possibilities of a less radical departure from ordinary physical description than hitherto envisaged in all attempts at solving the paradoxes to which the discovery of the quantum of action had from the beginning given rise. Still, the essentially statistical character of the interpretation of physical experience by wave pictures was not only evident from Born's successful treatment of collision problems, but the symbolic character of the whole conception appeared perhaps most strikingly in the necessity of replacing ordinary three-dimensional space coordination by a representation of the state of a system containing several particles as a wave function in a configuration space with as many coordinates as the total number of degrees of freedom of the system.
In the course of the discussions the last point was in particular stressed in connection with the great progress already achieved as regards the treatment of systems involving particles of the same mass, charge and spin, revealing in the case of such " identical " particles a limitation of the individuality implied in classical corpuscular concepts. Indications of such novel features as regards electrons were already contained in Pauli's formulation of the exclusion principle, and in connection with the particle concept of radiation quanta Bose had at an even earlier stage called attention to a simple possibility of deriving Planck's formula for temperature

radiation by the application of a statistics involving a departure from the way followed by Bolzmann in the counting of complexions of a many-particle system, which had proved so adequate for numerous applications of classical statistical mechanics.

Already in 1926 a decisive contribution to the treatment of atoms with more than one electron had been made by Heisenberg's explanation of the peculiar duplexity of the helium spectrum, which through many years had remained one of the main obstacles for the quantum theory of atomic constitution. By exploring the symmetry properties of the wave function in configuration space, considerations independently taken up by Dirac and subsequently pursued by Fermi, Heisenberg succeeded in showing that the stationary states of the helium atom fall into two classes, corresponding to two non-combining sets of spectral terms and represented by symmetrical and antisymmetrical spatial wave functions associated with opposite and parallel electron spins, respectively.

I need hardly recall how this remarkable achievement initiated a true avalanche of further progress, and how within a year Heitler and London's analogous treatment of the electronic constitution of the hydrogen molecule gave the first clue to the understanding of nonpolar chemical bonds. Moreover, similar considerations of the proton wave function of the rotating hydrogen molecule led to the assignment of a spin to the proton and thereby to an understanding of the separation between ortho and para states, which, as shown by Dennison, supplied an explanation of the hitherto mysterious anomalies in the specific heat of hydrogen gas at low temperature.

This whole development culminated in the recognition of the existence of two families of particles, now referred to as fermions and bosons. Thus, any state of a system composed of particles with halfintegral spin like electrons or protons is to be represented by a wave function which is antisymmetrical in the sense that it changes its sign, when the coordinates of two particles of the same kind are interchanged. Conversely, only symmetrical wave functions come into consideration for photons, to which according to Dirac's theory of radiation the spin one has to be ascribed, and for entities like alpha-particles without spin.

This situation was soon beautifully illustrated by Mott's explanation of the marked deviations from Rutherford's famous scattering formula, in the case of collisions between identical particles like alpha-particles and helium nuclei, or protons and hydrogen nuclei. With such applications of the formalism we are indeed not only faced with the inadequacy of orbital pictures, but even with a renunciation of the distinction between the particles involved. Indeed, whenever customary ideas of the individuality of the particles can be upheld by ascertaining their location in separate spatial domains, all application of Fermi-Dirac and Bose-Einstein statistics is irrelevant in the sense that they lead to the same expression for the probability density of the particles.

Only a few months before the conference Heisenberg had made a most significant contribution to the elucidation of the physical content of quantum mechanics by the formulation of the so-called indeterminacy principle, expressing the reciprocal limitation of the fixation of canonically conjugate variables. This limitation appears not only as an immediate consequence of the commutation relations between such variables, but also directly reflects the interaction between the system under observation and the tools of measurement. The full recognition of the last crucial point involves, however, the question of the scope of unambiguous application of classical physical concepts in accounting for atomic phenomena.

To introduce the discussion on such points, I was asked at the conference to give a report on the epistemological problems confronting us in quantum physics, and took the opportunity to enter upon the question of an appropriate terminology and to stress the viewpoint of complementarity. The main argument was that unambiguous communication of physical evidence demands that the experimental arrangement as well as the recording of the observations be expressed in common language, suitably refined by the vocabulary of classical physics. In all actual experimentation this demand is fulfilled by using as measuring instruments bodies like diaphragms, lenses and photographic plates so large and heavy that, notwithstanding the decisive role of the quantum of action for the stability and properties of such bodies, all quantum effects can be disregarded in the account of their position and motion.

While within the scope of classical physics we are dealing with an idealization, according to which all phenomena can be arbitrarily subdivided, and the interaction between the measuring instruments and the object tinder observation neglected, or at any rate compensated for it was stressed that such interaction represents in quantum physics an integral part of the phenomena, for which no separate account can be given if the instruments shall serve the purpose of defining the conditions under which the observations are obtained. In this connection it must also be remembered that recording of observations ultimately rests on the production of permanent marks on the measuring instruments, like the spot produced on a photographic plate by impact of a photon or an electron. That such recording involves essentially irreversible physical and chemical processes does not introduce any special intricacy, but rather stresses the element of irreversibility implied in the very concept of observation. The characteristic new feature in quantum physics is merely the restricted divisibility of the phenomena, which for unambiguous description demands a specification of all significant parts of the experimental arrangement.

Since in one and the same arrangement several different individual effects will in general be observed, the recourse to statistics in quantum physics is therefore in principle unavoidable. Moreover, evidence obtained under different conditions and rejecting comprehension in a single picture must, notwithstanding any apparent contrast, be regarded as complementary in the sense that together they exhaust all well defined information about the atomic object. From this point of view, the whole purpose of the formalism of quantum theory is to derive expectations for observations obtained under given experimental conditions. In this connection it was emphasized that the elimination of all contradictions is secured by the mathematical consistency of the formalism, and the exhaustive character of the description within its scope indicated by its adaptability to any ii-naginable experimental arrangement.

In the very lively discussions on such points, which Lorentz with his openness of mind and balanced attitude managed to conduct in fruitful directions, ambiguities of terminology presented great difficulties for agreement regarding the epistemological problems. This situation was humorously expressed by Ehrenfest who wrote on the blackboard the sentence from the Bible, describing the confusion of languages that disturbed the building of the Babel tower.

The exchanges of views started at the sessions were eagerly continued within smaller groups during the evenings, and to me the opportunity of longer talks with Einstein and Ehrenfest was a most welcome experience. Reluctance to renounce deterministic description in principle was especially expressed by Einstein, who challenged us with arguments suggesting the possibility of taking the interaction between the atomic objects and the measuring instruments more explicitly into account. Although our answers regarding the futility of this prospect did not convince Einstein, who returned to the problems at the next conference, the discussions were an inspiration further to explore the situation as regards analysis and synthesis in quantum physics and its analogies in other fields of human knowledge, where customary terminology implies attention to the conditions under which experience is gained.

VI

At the meeting of 1930, Langevin presided for the first time, after the demise of Lorentz, and spoke of the loss sustained by the Solvay Institute through the death of Ernest Solvay, by whose initiative and generosity the Institute was created. The President also dwelled on the unique way in which Lorentz had assumed the leading of all previous Solvay meetings and on the vigour with which he had continued his brilliant scientific researches until his last days. The subject of the meeting was the Magnetic Properties of Matter, to the understanding of which Langevin himself had given such important contributions, and the experimental knowledge of which had been so much augmented in those years, especially through the studies of Weiss and his school.

The conference was opened by a report by Sommerfeld on magnetism and spectroscopy, in which he in particular discussed the knowledge of the angular momenta and magnetic moments, which had been derived from the investigations of the electron constitution of atoms, resulting in the explanation of the periodic table. As to the interesting point of the peculiar variation of the magnetic moments within the family of rare earths, van Vleck reported about the latest results and their theoretical interpretation. A report was also given by Fcrmi on the magnetic moments of atomic nuclei, in which, as first pointed out by Pauli, the origin of the so-called hyperfine structure of spectral lines was to be found.

General surveys of the rapidly increasing experimental evidence about the magnetic properties of matter were given in reports by Cabrera and Weiss, who discussed the equation of state of ferromagnetic materials, comprising the abrupt changes of the properties of such substances at definite temperatures like the Curie point. In spite of earlier attempts at correlating such effects, especially by Weiss' introduction of an interior magnetic field associated with the ferromagnetic state, a clue to the understanding of the phenomena had first recently been found by Heisenberg's original comparison of the alignment of the electron spins in ferromagnetic substances with the quantum statistics governing the symmetry properties of the wave functions responsible for the chemical bonds in Heitler and London's theory of molecular formation.

At the conference a comprehensive exposition of the theoretical treatment of magnetic phenomena was given in a report by Pauli. With characteristic clearness and emphasis on essentials he also discussed the problems raised by Dirac's ingenious quantum theory of the electron, in which the relativistic wave equation proposed by Klein and Gordon was replaced by a set of first order equations allowing the harmonious incorporation of the intrinsic spin and magnetic moment of the electron. A special point discussed in this connection was the question, how far one can regard such quantities as measurable in the same sense as the electron mass and charge whose definition rests on the analysis of phenomena which can be entirely accounted for in classical terms. Any consistent use of the concept of spin, just as that of the quantum of action itself, refers, however, to phenomena resisting such analysis, and in particular the spin concept is an abstraction permitting a generalized formulation of the conservation of angular momentum. This situation is borne out by the impossibility, discussed in detail in Pauli's report, of measuring the magnetic moment of a free electron.

The prospects which recent development of experimental technique opened for further investigations of magnetic phenomena were at the meeting reported upon by Cotton and Kapitza. While by Kapitza's bold constructions it had become possible to produce magnetic fields of unsurpassed strength within limited spatial extensions and time intervals, the ingenious design by Cotton of huge permanent magnets permitted to obtain

fields of a constancy and extension greater than hitherto available. In a complement to Cotton's report, Madame Curie drew special attention to the use of such magnets for the investigations of radioactive processes, which especially through Rosenblum's work should give important new results as regards the fine structure of alpha-ray spectra.
While the principal theme of the meeting was the phenomena of magnetism, it is interesting to recall that at that time great advances had also been made in the treatment of other aspects of the properties of matter. Thus many of the difficulties hampering the understanding of electric conduction in metals, so acutely felt in the discussions at the conference in 1924, had in the meantime been overcome. Already in 1928 Sommerfeld had, by replacing the Maxwell velocity distribution of the electrons by a Fermi distribution, obtained most promising results in the elucidation of this problem. As is well known, Bloch succeeded on this basis by appropriate use of wave mechanics in developing a detailed theory of metallic conduction explaining many features, especially regarding the temperature dependence of the phenomena. Still, the theory failed in accounting for the superconductivity, to the understanding of which a clue has been found only in the last years by the development of refined methods for treating interactions in many-body systems. Such methods also seem suitable to account for the remarkable evidence recently obtained about the quantized character of the supercurrents.
A special reminiscence, however, from the meeting in 1930 is connected with the opportunity it gave to resume the discussion of tile epistemological problems debated at the conference in 1927. At the occasion Einstein brought up new arguments, by which he tried to circumvent the indeterminacy principle by utilizing the equivalence of energy and mass derived from relativity theory. Thus he suggested that it should be possible to determine the energy of a timed pulse of radiation with unlimited accuracy by the weighing of an apparatus containing a clock connected with a shutter releasing the pulse. However, by closer consideration the apparent paradox found its solution in the influence of a gravitational field on the timing of a clock, by which Einstein himself had early predicted the red-shift in the spectral distribution of light emitted by heavy celestial systems. Still the problem, which most instructively emphasized the necessity in quantum physics of the sharp distinction between objects and measuring instruments, remained for several years a matter of lively controversy, especially in philosophical circles.
It was the last meeting which Einstein attended, before the political developments in Germany forced him to emigrate to the United States. Shortly before the following meeting in 1933 we were all shocked by the news of the untimely death of Ehrenfest, of whose inspiring personality Langevin spoke in moving terms -when we were again assembled.

VII

The conference of 1933, especially devoted to the Structure and Properties of Atomic Nuclei, took place at a time when this subject was in a stage of most rapid and eventful development. The meeting was opened by a report by Cockcroft, in which, after briefly referring to the rich evidence about nuclear disintegrations by impact of alpha-particles obtained in the preceding years by Rutherford and his co-workers, he described in detail the important new results obtained by bombardment of nuclei with protons accelerated to great velocities with appropriate high voltage equipment.
As is well known, Cockcroft and Walton's initial experiments on the production of high speed alpha-particles by the impact of protons on lithium nuclei gave the first direct verification of Einstein's formula for the general relation between energy and mass which in the following years afforded constant guidance in nuclear research. Moreover, Cockcroft described how closely the measurements of the variations of the cross section for the process with proton velocity confirmed the predictions of wave mechanics, to which Gamow was led in connection with the theory of spontaneous alpha-decay developed by himself and others. In the report comprising the whole evidence available at that time as regards so-called artificial nuclear disintegrations, Cockcroft also compared the results of the experiments in Cambridge with proton bombardment with those just obtained in Berkeley with deuterons accelerated in the cyclotron newly constructed by Lawrence.
The following discussion was opened by Rutherford who, after giving expression for the great pleasure that the recent development of what he used to call modern alchemy had given him, told about some most interesting new results, which he and Oliphant had just obtained by the bombardment of lithium with protons and deuterons. Indeed, these experiments yielded evidence about the existence of hitherto unknown isotopes of hydrogen and helium with atomic mass 3, the properties of which have in recent years attracted so much attention. Also Lawrence, .who in more detail described his cyclotron construction, gave an account of the latest investigations of the Berkeley group.
Another progress of the utmost consequence was Chadwick's discovery of the neutron, which represented so dramatic a development, resulting in the confirmation of Rutherford's anticipation of a heavy neutral constituent of atomic nuclei. Chadwick's report, beginning with a description of the purposeful search in Cambridge for anomalies in alpha-ray scattering, ended up by some most pertinent considerations of the part played by the neutron in nuclear structure, as well as of its important role in inducing nuclear transmutations. Before the

theoretical aspects of this development were discussed at the conference, the participants had been told about another decisive progress, namely the discovery of so-called artificial radioactivity, produced by controlled nuclear disintegrations.
An account of this discovery, which was made only a few months before the conference, was included in a report by Frederic Joliot and Irene Curie, containing a survey of many aspects of their fruitful researches, in which processes of beta-ray decay with emission of positive as well as negative electrons were ascertained. In the discussion following this report, Blackett told the story of the discovery of the positron by Anderson and himself in cosmic ray researches and its interpretation in terms of Dirac's relativistic electron theory. One was indeed here confronted with the beginning of a new stage in the development of quantum physics, concerned with the creation and annihilation of material particles analogous to the processes of emission and absorption of radiation in which photons are formed and disappear.
As is well known, the starting point for Dirac was his recognition that his relativistically invariant formulation of quantum mechanics applied to electrons included, besides the probabilities of transition processes between ordinary physical states, also expectations of transitions from such states to states of negative energy., To avoid such undesired consequences he introduced the ingenious idea of the so-called Dirac sea, in which all states of negative energy are filled up to the full extent reconcilable with the exclusion principle of equivalent stationary states. In this picture the creation of electrons takes place in pairs, of which the one with usual charge is simply lifted out of the sea, while the other with opposite charge is represented by a hole in the sea. This conception was, as is well known, to prepare the idea of antiparticles with opposite charge and reversed magnetic moment relative to the spin axis, proving to be a fundamental property of matter.
At the conference, many features of radioactive processes were discussed, and a most instructive report was given by Gamow on the interpretation of gamma-ray spectra, based on his theory of spontaneous and induced a-ray and proton emission and their relation to the fine structure in alpha-ray spectra. A special point, which was eagerly discussed, was the problem of continuous beta-ray spectra. Especially Ellis' investigations of the thermal effects produced by absorption of the emitted electrons seemed irreconcilable with detailed energy and momentum balance in the beta-decay process. Moreover, evidence on the spins of the nuclei involved in the process seemed contradictory to the conservation of angular momentum. It was, in fact, to evade such difficulties that Pauli introduced the bold idea, which should be most fruitful for the later development, that a very penetrating radiation, consisting of particles with vanishing rest mass and spin one-half, the so-called neutrinos, were emitted in beta-decay together with the electrons.
The whole question of the structure and stability of atomic nuclei was dealt with in a most weighty report by Heisenberg. From the point of view of the uncertainty principle he had acutely felt the difficulties of assuming the presence of particles as light as electrons within the small spatial extensions of atomic nuclei. He therefore grasped the discovery of the neutron as foundation for the view of considering only neutrons and protons as proper nuclear constituents, and on this basis developed explanations of many properties of nuclei. In particular Heisenberg's conception implied that the phenomenon of beta-ray decay be considered as evidence of the creation of positive or negative electrons and neutrinos under release of energy in the accompanying change of a neutron to a proton, or vice versa. In fact, great progress in this direction was soon after the conference achieved by Fermi who on this basis developed a consistent theory of beta-decay, which in subsequent developments should prove a most important guidance.
Rutherford, who with usual vigour took part in many of the discussions, was of course a central figure at the Solvay meeting in 1933, which should be the last he had the opportunity to attend before his death in 1937 ended a life-work of a richness with few counterparts in the history of physical science.

VIII

The political events leading to the second world war interrupted for many years the regular succession of the Solvay meetings, which were only resumed in 1948. In those troubled years, the progress of nuclear physics had not relented and had even resulted in the realization of the possibilities of liberation of the immense energy stored in atomic nuclei. Though the serious implications of this development were in everybody's mind, no mention of them was made at the conference, which dealt with the problem of Elementary Particles, a domain in which new prospects had been opened by the discovery of particles with rest mass between that of the electron and the nucleons. As is well known, the existence of such mesons was already before their detection in cosmic radiation by Anderson in 1937 anticipated by Yukawa as quanta for the short range force fields between the nucleons, differing so essentially from the electromagnetic fields studied in the first approach to quantum physics.
The richness of these new aspects of the particle problem had just before the conference been revealed by the systematic investigations by Powell and his collaborators in Bristol of the tracks in photographic plates exposed to cosmic radiation, and by the study of the effects of high energy nucleon collisions first produced in the giant cyclotron in Berkeley. In fact, it had become clear that such collisions lead directly to the creation of so-called -

pi-mesons which subsequently decay under neutrino emission into mu-mesons. In contrast to the pi-mesons, the mu-mesons were found to exhibit no strong coupling to the nucleons and to decay, themselves, into electrons under emission of two neutrinos. At the conference, detailed reports on the new experimental evidence were followed by most interesting comments from many sides on its theoretical interpretation. In spite of promising advances in various directions there was, however, a general understanding that one stood before the beginning of a development where new theoretical viewpoints were needed.

A special point discussed was how to overcome the difficulties connected with the appearance of divergences in quantum electrodynamics, not least conspicuous in the question of the self-energy of charged particles. Attempts at solving the problem by a reformulation of classical electron theory, fundamental for the correspondence treatment, were clearly frustrated by the dependence of the strength of the singularities on the kind of quantum statistics obeyed by the particle in question. In fact, as first pointed out by Weisskopf, the singularities in quantum electrodynamics were largely reduced in the case of fermions, whereas in the case of bosons the self-energy diverges even more strongly than in classical electrodynamics, within the frame of which, as was already stressed in the discussions at the conference in 1927, all distinction between different quantum statistics is excluded.

Notwithstanding the radical departure from deterministic pictorial description, with which we are here concerned, basic features of customary ideas of causality are upheld in the correspondence approach by referring the competing individual processes to a simple superposition of wave functions defined within a common spacetime-extension. The possibility of such treatment rests, however, as was stressed during the discussions, on the comparatively weak coupling between the particles and the fields expressed by the smallness of the non-dimensional constant a = ee/hc, which permits a distinction with high degree of approximation between the state of a system of electrons and its radiative reaction with an electromagnetic field. As regards quantum electrodynamics, great progress was just at that time initiated by the work of Schwinger and Tomonaga, leading to the so-called renormalization procedure involving corrections of the same order as a, especially conspicuous in the discovery of the Lamb-effect.

The strong coupling between the nucleons and the pion fields prevented, however, adequate application of simple correspondence arguments, and especially the study of collision processes, in which a large number of pions are created, indicated the necessity of a departure from linearity in the fundamental equations and even, as suggested by Heisenberg, the introduction of an elementary length representing the ultimate limit of space-time-coordination itself. From the observational point of view such limitations might be closely related to the restrictions imposed on space-time measurements by the atomic constitution of all apparatus. Of course, far from conflicting with the argument of the impossibility in any well-defined description of physical experience of taking the interaction between the atomic objects under investigation and the tools of observation explicitly into account, such a situation would only give this argumentation sufficient scope for the logical comprehension of further regularities.

The realization of prospects involving, as condition of the consistency of the whole approach, the possibility of the fixation of the constant a, as well as the derivation of other non-dimensional relations between the masses of elementary particles and coupling constants, was at the time of the conference hardly yet attempted. Meanwhile, however, a way to progress was sought in the study of symmetry relations, and has since been brought to the fore by the rapid succession of discoveries of a manifold of particles exhibiting a behavior so unexpected that it was even characterized by various degrees of " strangeness ". Thinking of the very latest developments, a great advance has, as is well known, been initiated by the bold suggestion by Lee and Yang in 1957 of the limited scope of the conservation of parity, verified by the beautiful experiments by Mrs Wu and her collaborators. The demonstration of the helicity of the neutrino was indeed anew to raise the old question of a distinction between right and left in the description of natural phenomena. Still, the avoidance of an epistemological paradox in such respect was achieved by the recognition of the relationship between reflection symmetry in space and time and the symmetries between particles and antiparticles.

Of course it is not my intention with such cursory remarks in any way to anticipate problems which will form the main theme for the discussions at the present conference, taking place at a time of new momentous empirical and theoretical advances, about which we are all eager to learn from the participants of the younger generation. Yet we shall often miss the assistance of our deceased colleagues and friends, like Kramers, Pauli and Schroedinger, who all took part in the conference of 1948, which was the last one I, so far, attended. Likewise we deplore the illness that has prevented the presence of Max Born among us.

In concluding, I want to express the hope that this review of some features of the historical development may have given an indication of the debt which the community of physicists owe to the Solvay Institute, and of the expectations which we all share for its future activity.