Niels Bohr

Atomic Physics and Human Knowledge

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increasing mastery of the forces of nature has so completely changed the material conditions of life, but also because the study of these sciences has contributed so much to clarify the background of our own existence. What has it not meant in this respect that we no more consider ourselves to be privileged in living at the centre of the universe, surrounded by less fortunate societies inhabiting the edges of the abyss, but, through the development of astronomy and geography, have realized that we all share a small spherical planet of the solar system which again is only a small part of still larger systems. How forceful an admonition about the relativity of all human judgments have we not also in our days received through the renewed revision of the presuppositions underlying the unambiguous use of even our most elementary concepts such as space and time, which, in disclosing the essential dependence of every physical phenomenon on the standpoint of the observer, has contributed so largely to the unity and beauty of our whole world-picture.

While the importance of these great achievements for our general outlook is commonly realized, it is hardly yet so as regards the unsuspected epistemological lesson which the opening of quite new realms of physical research has given us in the latest years. Our penetration into the world of atoms, hitherto closed to the eyes of man, is indeed an adventure which may be compared with the great journeys of discovery of the circumnavigators and the bold explorations of astronomers into the depths of celestial space. As is well known, the marvellous development of the art of physical experimentation not only has removed the last traces of the old belief that the coarseness of our senses would forever prevent us from obtaining direct information about individual atoms, but has even shown us that the atoms themselves consist of still smaller corpuscles which can be isolated and the properties of which can be investigated separately. At the same time we have, however, in this fascinating field of experience been taught that the laws of nature hitherto known, which constitute the grand edifice of classical physics, are valid only when we deal with bodies consisting of practically infinite numbers of atoms. The new knowledge concerning the behaviour of single atoms and atomic corpuscles has, in fact, revealed an unexpected limit for the subdivision of all physical actions extending far beyond the old doctrine of the limited divisibility of matter and giving every atomic process a peculiar individual character. This discovery has, in fact, yielded a quite new basis for the understanding of the intrinsic stability of atomic structures, which, in the last resort, conditions the regularities of all ordinary experience.

How radical a change in our attitude towards the description of nature this development of atomic physics has brought about is perhaps most clearly illustrated by the fact that even the principle of causality, so far regarded as the unquestioned foundation for all interpretation of natural phenomena, has proved too narrow a frame to embrace the peculiar regularities governing individual atomic processes. Certainly everyone will understand that physicists have needed very cogent reasons to renounce the ideal of causality itself; but in the study of atomic phenomena we have repeatedly been taught that questions which were believed to have received long ago their final answers had most unexpected surprises in store for us. You will surely all have heard about the riddles regarding the most elementary properties of light and matter which have puzzled physicists so much in recent years. The apparent contradictions which we have met in this respect are, in fact, as acute as those which gave rise to the development of the theory of relativity in the beginning of this century and have, just as the latter, only found their explanation by a closer examination of the limitation imposed by the new experiences themselves on the unambiguous use of the concepts entering into the description of the phenomena. While in relativity theory the decisive point was the recognition of the essentially different ways in which observers moving relatively to each other will describe the behaviour of given objects, the elucidation of the paradoxes of atomic physics has disclosed the fact that the unavoidable interaction between the objects and the measuring instruments sets an absolute limit to the possibility of speaking of a behaviour of atomic objects which is independent of the means of observation.

We are here faced with an epistemological problem quite new in natural philosophy, where all description of experiences has so far been based upon the assumption, already inherent in ordinary conventions of language, that it is possible to distinguish sharply between the behaviour of objects and the means of observation. This assumption is not only fully justified by all everyday experience but even constitutes the whole basis of classical physics, which, just through the theory of relativity, has received such a wonderful completion. As soon as we are dealing, however, with phenomena like individual atomic processes which, due to their very nature, are essentially determined by the interaction between the objects in question and the measuring instruments necessary for the definition of the experimental arrangements, we are, therefore, forced to examine more closely the question of what kind of knowledge can be obtained concerning the objects. In this respect we must, on the one hand, realize that the aim of every physical experiment—to gain knowledge under reproducible and communicable conditions—leaves us no choice but to use everyday concepts, perhaps refined by the terminology of classical physics, not only in all accounts of the construction and manipulation of the measuring instruments but also in the description of the actual experimental results. On the other hand, it is equally important to understand that just this circumstance implies that no result of an experiment concerning a phenomenon which, in principle, lies outside the range of classical physics can be interpreted as giving information about independent properties of the objects, but is inherently connected with a definite situation in the description of which the measuring instruments interacting with the objects also enter essentially. This last fact gives the straightforward explanation of the apparent contradictions which appear when results about atomic objects obtained by different experimental arrangements are tentatively combined into a self-contained picture of the object.

Information regarding the behaviour of an atomic object obtained under definite experimental conditions may, however, according to a terminology often used in atomic physics, be adequately characterized as *complementary* to any information about the same object obtained by some other experimental arrangement excluding the fulfilment of the first conditions. Although such kinds of information cannot be combined into a single picture by means of ordinary concepts, they represent indeed equally essential aspects of any knowledge of the object in question which can be obtained in this domain. The recognition of such a complementary character of the mechanical analogies by which one has attempted to visualize the individual radiative effects has, in fact, led to an entirely satisfactory solution of the riddles of the properties of light alluded to above. In the same way it is only by taking into consideration the complementary relationship between the different experiences concerning the behaviour of atomic corpuscles that it has been possible to obtain a clue to the understanding of the striking contrast between the properties of ordinary mechanical models and the peculiar laws of stability governing atomic structures which form the basis for every closer explanation of the specific physical and chemical properties of matter.

Of course I have no intention, on this occasion, of entering more closely into such details, but I hope that I have been able to give you a sufficiently clear impression of the fact that we are here in no way concerned with an arbitrary renunciation as regards the detailed analysis of the almost overwhelming richness of our rapidly increasing experience in the realm of atoms. On the contrary, we have to do

with a rational development of our means of classifying and comprehending new experience which, due to its very character, finds no place within the frame of causal description that is only suited to account for the behaviour of objects as long as this behaviour is independent of the means of observation. Far from containing any mysticism contrary to the spirit of science, the viewpoint of complementarity forms indeed a consistent generalization of the ideal of causality.

However unexpected this development may appear in the domain of physics, I am sure that many of you will have recognized the close analogy between the situation as regards the analysis of atomic phenomena, which I have described, and characteristic features of the problem of observation in human psychology. Indeed, we may say that the trend of modern psychology can be characterized as a reaction against the attempt at analyzing psychical experience into elements which can be associated in the same way as are the results of measurements in classical physics. In introspection it is clearly impossible to distinguish sharply between the phenomena themselves and their conscious perception, and although we may often speak of lending our attention to some particular aspect of a psychical experience, it will appear on closer examination that we really have to do, in such cases, with mutually exclusive situations. We all know the old saying that, if we try to analyze our own emotions, we hardly possess them any longer, and in that sense we recognize between psychical experiences, for the description of which words such as "thoughts" and "feelings" are adequately used, a complementary relationship similar to that between the experiences regarding the behaviour of atoms obtained under different experimental arrangements and described by means of different analogies taken from our usual ideas. By such a comparison it is, of course, in no way intended to suggest any closer relation between atomic physics and psychology, but merely to stress an epistemological argument common to both fields, and thus to encourage us to see how far the solution of the relatively simple physical problems may be helpful in clarifying the more intricate psychological questions with which human life confronts us, and which anthropologists and ethnologists so often meet in their investigations.

Coming now closer to our subject of the bearing of such viewpoints on the comparison of different human cultures, we shall first stress the typical complementary relationship between the modes of behaviour of living beings characterized by the words "instinct" and "reason." It is true that any such words are used in very different senses; thus, instinct may mean motive power or inherited behaviour, and reason may denote deeper sense as well as conscious argumentation. What we are concerned with is, however, only the practical way in which these words are used to discriminate between the different situations in which animals and men find themselves. Of course, nobody will deny our belonging to the animal world, and it would even be very difficult to find an exhaustive definition characterizing man among the other animals. Indeed, the latent possibilities in any living organism are not easily estimated, and I think that there is none of us who has not sometimes been deeply impressed by the extent to which circus animals can be drilled. Not even with respect to the conveyance of information from one individual to another would it be possible to draw a sharp separation between animals and man; but of course our power of speech places us in this respect in an essentially different situation, not only in the exchange of practical experience, but first of all in the possibility of transmitting to children, through education, the traditions concerning behaviour and reasoning which form the basis of any human culture.

As regards reason compared with instinct, it is, above all, essential to realize that no proper human thinking is imaginable without the use of concepts framed in some language which every generation has to learn anew. This use of concepts, in fact, not only is to a large extent suppressing instinctive life, but stands even largely in an exclusive relationship of complementarity to the display of inherited instincts. The astonishing superiority of lower animals compared with man in utilizing the possibilities of nature for the maintenance and propagation of life has certainly often its true explanation in the fact that on the part of such animals we can detect no conscious thinking, in our sense of the word. Similarly, the amazing capacity of so-called primitive people to orientate themselves in forests or deserts, which, though apparently lost in more civilized societies, may on occasion be revived in any of us, might justify the conclusion that such feats are only possible when no recourse is taken to conceptual thinking, which on its side is adapted to far more varied purposes of primary importance for the development of civilization. Just because it is not yet awake to the use of concepts, a newborn child can hardly be reckoned as a human being; but belonging to the species of man, it has, of course, though more helpless a creature than most young animals, the organic possibilities of receiving through education a culture which enables it to take its place in some human society.

Such considerations confront us at once with the question whether the widespread belief that every child is born with a predisposition for the adoption of a specific human culture is really well founded, or whether one has not rather to assume that any culture can be implanted and thrive on quite different physical backgrounds. Here we are of course touching a subject of still unsettled controversies between geneticists, who pursue most interesting studies on the inheritance of physical characters. In connection with such discussions, however, we must above all bear in mind that the distinction between the concepts genotype and phenotype, so fruitful for the clarification of heredity in plants and animals, essentially presupposes the subordinate influence of the external conditions of life on the characteristic properties of the species. In the case of the specific cultural characters of human societies the problem is, however, reversed in the sense that the basis for the classification is here the traditional habits shaped by the histories of the societies and their natural environments. These habits, as well as their inherent presuppositions, must therefore be analyzed in detail before any possible influence of inherited biological differences on the development and maintenance of the cultures concerned can be estimated. Indeed, in characterizing different nations and even different families within a nation, we may to a large extent consider biological traits and spiritual traditions as independent of each other, and it would even be tempting to reserve by definition the adjective "human" for those characters which are not directly bound to bodily inheritance.

At first sight, it might perhaps appear that such an attitude would mean unduly stressing merely dialectic points. But the lesson which we have received from the whole growth of the physical sciences is that the germ of fruitful development often lies just in the proper choice of definitions. When we think, for instance, of the clarification brought about in various branches of science by the argumentation of relativity theory, we see indeed what advance may lie in such formal refinements. As I have already hinted at earlier in this address, relativistic viewpoints are certainly also helpful in promoting a more objective attitude as to relationships between human cultures, the traditional differences of which in many ways resemble the different equivalent manners in which physical experience can be described. Still, this analogy between physical and humanistic problems is of limited scope and its exaggeration has even led to misunderstanding the essence of the theory of relativity itself. In fact, the unity of the relativistic world picture implies precisely the possibility for any one observer to predict within his own conceptual lutely exclusive relationships as those between complementary experiences about the behaviour of well-defined atomic objects, since hardly any culture exists which could be said to be fully self-contained. On the contrary, we all know from numerous examples how a more or less intimate contact between different human societies can lead to a gradual fusion of traditions, giving birth to a quite new culture. The importance in this respect of the mixing of populations through emigration or conquest for the advancement of human civilization need hardly be recalled. It is, indeed, perhaps the greatest prospect of humanistic studies to contribute through an increasing knowledge of the history of cultural development to that gradual removal of prejudices which is the common aim of all science.

As I stressed in the beginning of this address, it is, of course, far beyond my capacities to contribute in any direct way to the solution of the problems discussed among the experts at this congress. My only purpose has been to give an impression of a general epistemological attitude which we have been forced to adopt in a field as far from human passions as the analysis of simple physical experiments. I do not know, however, whether I have found the right words to convey to you this impression, and before I conclude I may perhaps be allowed to relate an experience which once most vividly reminded me of my deficiencies in this respect. In order to explain to an audience that I did not use the word prejudice to imply any condemnation of other cultures, but merely to characterize our necessarily prejudiced conceptual frame, I referred jokingly to the traditional prejudices which the Danes cherish with regard to their Swedish brothers on the other side of the beautiful Sound outside these windows, with whom we have fought through centuries even within the walls of this castle, and from contact with whom we have, through the ages, received so much fruitful inspiration. Now you will realize what a shock I got when, after my address, a member of the audience came up to me and said that he could not understand why I hated the Swedes. Obviously I must have expressed myself most confusingly on that occasion, and I am afraid that also to-day I have talked in a very obscure way. Still, I hope that I have not spoken so unclearly as to give rise to any such misunderstandings of the trend of my argument.

natural philosophy characteristic of the novel development of physics which was initiated in the first year of this century by Planck's discovery of the universal quantum of action. This discovery, which revealed a feature of atomicity in the laws of nature going far beyond the old doctrine of the limited divisibility of matter, has indeed taught us that the classical theories of physics are idealizations which can be unambiguously applied only in the limit where all actions involved are large compared with the quantum. The question at issue has been whether the renunciation of a causal mode of description of atomic processes involved in the endeavours to cope with the situation should be regarded as a temporary departure from ideals to be ultimately revived or whether we are faced with an irrevocable step towards obtaining the proper harmony between analysis and synthesis of physical phenomena. To describe the background of our discussions and to bring out as clearly as possible the arguments for the contrasting viewpoints, I have felt it necessary to go to a certain length in recalling some main features of the development to which Einstein himself has contributed so decisively.

As is well known, it was the intimate relation, elucidated primarily by Boltzmann, between the laws of thermodynamics and the statistical regularities exhibited by mechanical systems with many degrees of freedom, which guided Planck in his ingenious treatment of the problem of thermal radiation, leading him to his fundamental discovery. While, in his work, Planck was principally concerned with considerations of essentially statistical character and with great caution refrained from definite conclusions as to the extent to which the existence of the quantum implied a departure from the foundations of mechanics and electrodynamics, Einstein's great original contribution to quantum theory (1905) was just the recognition of how physical phenomena like the photo-effect may depend directly on individual quantum effects.[1] In these very same years when, in the development of his theory of relativity, Einstein laid down a new foundation for physical science, he explored with a most daring spirit the novel features of atomicity which pointed beyond the framework of classical physics.

With unfailing intuition Einstein thus was led step by step to the conclusion that any radiation process involves the emission or absorption of individual light quanta or "photons" with energy and momentum

$$E = h\nu \quad \text{and} \quad P = h\sigma, \tag{1}$$

respectively, where h is Planck's constant, while ν and σ are the

[1] A. Einstein, *Ann. Phys.*, *17*, 132 (1905).

number of vibrations per unit time and the number of waves per unit length, respectively. Notwithstanding its fertility, the idea of the photon implied a quite unforeseen dilemma, since any simple corpuscular picture of radiation would obviously be irreconcilable with interference effects, which present so essential an aspect of radiative phenomena, and which can be described only in terms of a wave picture. The acuteness of the dilemma is stressed by the fact that the interference effects offer our only means of defining the concepts of frequency and wave-length entering into the very expressions for the energy and momentum of the photon.

In this situation, there could be no question of attempting a causal analysis of radiative phenomena, but only, by a combined use of the contrasting pictures, to estimate probabilities for the occurrence of the individual radiation processes. However, it is most important to realize that the recourse to probability laws under such circumstances is essentially different in aim from the familiar application of statistical considerations as practical means of accounting for the properties of mechanical systems of great structural complexity. In fact, in quantum physics we are presented not with intricacies of this kind, but with the inability of the classical frame of concepts to comprise the peculiar feature of indivisibility, or "individuality," characterizing the elementary processes.

The failure of the theories of classical physics in accounting for atomic phenomena was further accentuated by the progress of our knowledge of the structure of atoms. Above all, Rutherford's discovery of the atomic nucleus (1911) revealed at once the inadequacy of classical mechanical and electromagnetic concepts to explain the inherent stability of the atom. Here again the quantum theory offered a clue for the elucidation of the situation and especially it was found possible to account for the atomic stability, as well as for the empirical laws governing the spectra of the elements, by assuming that any reaction of the atom resulting in a change of its energy involved a complete transition between two so-called stationary quantum states and that, in particular, the spectra were emitted by a step-like process in which each transition is accompanied by the emission of a monochromatic light quantum of an energy just equal to that of an Einstein photon.

These ideas, which were soon confirmed by the experiments of Franck and Hertz (1914) on the excitation of spectra by impact of electrons on atoms, involved a further renunciation of the causal mode of description, since evidently the interpretation of the spectral laws implies that an atom in an excited state in general will have the

In connection with a thorough examination of the exigencies of thermodynamics as regards radiation problems, Einstein stressed the dilemma still further by pointing out that the argumentation implied that any radiation process was "unidirected" in the sense that not only is a momentum corresponding to a photon with the direction of propagation transferred to an atom in the absorption process, but that also the emitting atom will receive an equivalent impulse in the opposite direction, although there can on the wave picture be no question of a preference for a single direction in an emission process. Einstein's own attitude to such startling conclusions is expressed in a passage at the end of the article (*loc. cit.*, p. 127f.), which may be translated as follows:

These features of the elementary processes would seem to make the development of a proper quantum treatment of radiation almost unavoidable. The weakness of the theory lies in the fact that, on the one hand, no closer connection with the wave concepts is obtainable and that, on the other hand, it leaves to chance (*Zufall*) the time and the direction of the elementary processes; nevertheless, I have full confidence in the reliability of the way entered upon.

When I had the great experience of meeting Einstein for the first time during a visit to Berlin in 1920, these fundamental questions formed the theme of our conversations. The discussions, to which I have often reverted in my thoughts, added to all my admiration for Einstein a deep impression of his detached attitude. Certainly, his favoured use of such picturesque phrases as "ghost waves (*Gespensterfelder*) guiding the photons" implied no tendency to mysticism, but illuminated rather a profound humour behind his piercing remarks. Yet, a certain difference in attitude and outlook remained, since, with his mastery for co-ordinating apparently contrasting experience without abandoning continuity and causality, Einstein was perhaps more reluctant to renounce such ideals than someone for whom renunciation in this respect appeared to be the only way open to proceed with the immediate task of co-ordinating the multifarious evidence regarding atomic phenomena, which accumulated from day to day in the exploration of this new field of knowledge.

In the following years, during which the atomic problems attracted the attention of rapidly increasing circles of physicists, the apparent contradictions inherent in quantum theory were felt ever more acutely. Illustrative of this situation is the discussion raised by the discovery of the Stern-Gerlach effect in 1922. On the one hand, this tion laws, on the other hand. While the combination of these concepts into a single picture of a causal chain of events is the essence of classical mechanics, room for regularities beyond the grasp of such a description is just afforded by the circumstance that the study of the complementary phenomena demands mutually exclusive experimental arrangements.

The necessity, in atomic physics, of a renewed examination of the foundation for the unambiguous use of elementary physical ideas recalls in some way the situation that led Einstein to his original revision of the basis for all application of space-time concepts which, by its emphasis on the primordial importance of the observational problem, has lent such unity to our world picture. Notwithstanding all novelty of approach, causal description is upheld in relativity theory within any given frame of reference, but in quantum theory the uncontrollable interaction between the objects and the measuring instruments forces us to a renunciation even in such respect. This recognition, however, in no way points to any limitation of the scope of the quantum-mechanical description, and the trend of the whole argumentation presented in the Como lecture was to show that the viewpoint of complementarity may be regarded as a rational generalization of the very ideal of causality.

At the general discussion in Como, we all missed the presence of Einstein, but soon after, in October 1927, I had the opportunity to meet him in Brussels at the Fifth Physical Conference of the Solvay Institute, which was devoted to the theme "Electrons and Photons." At the Solvay meetings, Einstein had from their beginning been a most prominent figure, and several of us came to the conference with great anticipations to learn his reaction to the latest stage of the development which, to our view, went far in clarifying the problems which he had himself from the outset elicited so ingeniously. During the discussions, where the whole subject was reviewed by contributions from many sides and where also the arguments mentioned in the preceding pages were again presented, Einstein expressed, however, a deep concern over the extent to which causal account in space and time was abandoned in quantum mechanics.

To illustrate his attitude, Einstein referred at one of the sessions [9]

[9] Institut International de Physique Solvay, *Rapport et discussions* du 5[e] Conseil, Paris 1928, 253ff.

tary phenomena appear under mutually exclusive experimental arrangements (cf. p. 40) and are just faced with the impossibility, in the analysis of quantum effects, of drawing any sharp separation between an independent behaviour of atomic objects and their interaction with the measuring instruments which serve to define the conditions under which the phenomena occur.

Our talks about the attitude to be taken in face of a novel situation as regards analysis and synthesis of experience touched naturally on many aspects of philosophical thinking, but, in spite of all divergencies of approach and opinion, a most humorous spirit animated the discussions. On his side, Einstein mockingly asked us whether we could really believe that the providential authorities took recourse to dice-playing ("... *ob der liebe Gott würfelt*"), to which I replied by pointing at the great caution, already called for by ancient thinkers, in ascribing attributes to Providence in everyday language. I remember also how at the peak of the discussion Ehrenfest, in his affectionate manner of teasing his friends, jokingly hinted at the apparent similarity between Einstein's attitude and that of the opponents of relativity theory; but instantly Ehrenfest added that he would not be able to find relief in his own mind before concord with Einstein was reached.

Einstein's concern and criticism provided a most valuable incentive for us all to reeaxamine the various aspects of the situation as regards the description of atomic phenomena. To me it was a welcome stimulus to clarify still further the rôle played by the measuring instruments and, in order to bring into strong relief the mutually exclusive character of the experimental conditions under which the complementary phenomena appear, I tried in those days to sketch various apparatus in a pseudo-realistic style of which the following figures are examples. Thus, for the study of an interference phenomenon of the type indicated in Figure 3, it suggests itself to use an experimental arrangement like that shown in Figure 4, where the solid parts of the apparatus, serving as diaphragms and plate-holder, are firmly bolted to a common support. In such an arrangement, where the knowledge of the relative positions of the diaphragms and the photographic plate is secured by a rigid connection, it is obviously impossible to control the momentum exchanged between the particle and the separate parts of the apparatus. The only way in which, in such an arrangement, we could insure that the particle passed through one of the slits in the second diaphragm is to cover the other slit by

The epistemological problems touched upon here were more explicitly dealt with in my contribution to the issue of *Naturwissenschaften* in celebration of Planck's 70th birthday in 1929. In this article, a comparison was also made between the lesson derived from the discovery of the universal quantum of action and the development which has followed the discovery of the finite velocity of light and which, through Einstein's pioneer work, has so greatly clarified basic principles of natural philosophy. In relativity theory, the emphasis on the dependence of all phenomena on the reference frame opened quite new ways of tracing general physical laws of unparalleled scope. In quantum theory, it was argued, the logical comprehension of hitherto unsuspected fundamental regularities governing atomic phenomena has demanded the recognition that no sharp separation can be made between an independent behaviour of the objects and their interaction with the measuring instruments which define the reference frame.

In this respect, quantum theory presents us with a novel situation in physical science, but attention was called to the very close analogy with the situation as regards analysis and synthesis of experience, which we meet in many other fields of human knowledge and interest. As is well known, many of the difficulties in psychology originate in the different placing of the separation lines between object and subject in the analysis of various aspects of psychical experience. Actually, words like "thoughts" and "sentiments," equally indispensable to illustrate the variety and scope of conscious life, are used in a similar complementary way as are space-time coordination and dynamical conservation laws in atomic physics. A precise formulation of such analogies involves, of course, intricacies of terminology, and the writer's position is perhaps best indicated in a passage in the article, hinting at the mutually exclusive relationship which will always exist between the practical use of any word and attempts at its strict definition. The principal aim, however, of these considerations, which were not least inspired by the hope of influencing Einstein's attitude, was to point to perspectives of bringing general epistemological problems into relief by means of a lesson derived from the study of new, but fundamentally simple, physical experience.

At the next meeting with Einstein at the Solvay Conference in 1930, our discussions took quite a dramatic turn. As an objection to the view that a control of the interchange of momentum and energy between the objects and the measuring instruments was excluded if instruments, if these are to serve their purpose—the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality. In fact, as we shall see, a criterion of reality like that proposed by the named authors contains—however cautious its formulation may appear—an essential ambiguity when it is applied to the actual problems with which we are here concerned.

As regards the special problem treated by Einstein, Podolsky and Rosen, it was next shown that the consequences of the formalism as regards the representation of the state of a system consisting of two interacting atomic objects correspond to the simple arguments mentioned in the preceding in connection with the discussion of the experimental arrangements suited for the study of complementary phenomena. In fact, although any pair q and p of conjugate space and momentum variables obeys the rule of non-commutative multiplication expressed by (2), and can thus only be fixed with reciprocal latitudes given by (3), the difference $q_1 - q_2$ between two space-coordinates referring to the constituents of the system will commute with the sum $p_1 + p_2$ of the corresponding momentum components, as follows directly from the commutability of q_1 with p_2 and q_2 with p_1. Both $q_1 - q_2$ and $p_1 + p_2$ can, therefore, be accurately fixed in a state of the complex system and, consequently, we can predict the values of either q_1 or p_1 if either q_2 or p_2, respectively, is determined by direct measurements. If, for the two parts of the system, we take a particle and a diaphragm, like that sketched in Figure 5, we see that the possibilities of specifying the state of the particle by measurements on the diaphragm just correspond to the situation described on p. 48 and further discussed on p. 57, where it was mentioned that, after the particle has passed through the diaphragm, we have in principle the choice of measuring either the position of the diaphragm or its momentum and, in each case, making predictions as to subsequent observations pertaining to the particle. As repeatedly stressed, the principal point here is that such measurements demand mutually exclusive experimental arrangements.

The argumentation of the article was summarized in the following passage:

> From our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by Einstein, Podolsky and Rosen contains an ambiguity as regards the meaning of the expression "without in any way disturbing a system." Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure. But even at this stage there is essentially the question of

Even if such an attitude might seem well balanced in itself, it nevertheless implies a rejection of the whole argumentation exposed in the preceding, aiming to show that, in quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded. The peculiar individuality of the quantum effects presents us, as regards the comprehension of well-defined evidence, with a novel situation unforeseen in classical physics and irreconcilable with conventional ideas suited for our orientation and adjustment to ordinary experience. It is in this respect that quantum theory has called for a renewed revision of the foundation for the unambiguous use of elementary concepts as a further step in the development which, since the advent of relativity theory, has been so characteristic of modern science.

In the following years, the more philosophical aspects of the situation in atomic physics aroused the interest of ever larger circles and were, in particular, discussed at the Second International Congress for the Unity of Science in Copenhagen in July 1936. In a lecture on this occasion,[14] I tried especially to stress the analogy in epistemological respects between the limitation imposed on the causal description in atomic physics and situations met with in other fields of knowledge. A principal purpose of such parallels was to call attention to the necessity in many domains of general human interest of facing problems of a similar kind as those which had arisen in quantum theory and thereby to give a more familiar background for the apparently extravagant way of expression which physicists have developed to cope with their acute difficulties.

Besides the complementary features conspicuous in psychology and already touched upon (cf. p. 52), examples of such relationships can also be traced in biology, especially as regards the comparison between mechanistic and vitalistic viewpoints. Just with respect to the observational problem, this last question had previously been the subject of an address to the International Congress on Light Therapy held in Copenhagen in 1932,[15] where it was incidentally pointed out that even the psycho-physical parallelism as envisaged by Leibniz and Spinoza has obtained a wider scope through the development of atomic physics, which forces us to an attitude towards the problem

[14] N. Bohr, *Philosophy of Science*, *4*, 289 (1937).

[15] IIe Congrès international de la Lumière, Copenhague 1932 (reprinted in this collection, p. 3).

turbing of phenomena by observation" or "creating physical attributes to atomic objects by measurements." Such phrases, which may serve to remind of the apparent paradoxes in quantum theory, are at the same time apt to cause confusion, since words like "phenomena" and "observations," just as "attributes" and "measurements," are used in a way hardly compatible with common language and practical definition.

As a more appropriate way of expression I advocated the application of the word *phenomenon* exclusively to refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement. In such terminology, the observational problem is free of any special intricacy since, in actual experiments, all observations are expressed by unambiguous statements referring, for instance, to the registration of the point at which an electron arrives at a photographic plate. Moreover, speaking in such a way is just suited to emphasize that the appropriate physical interpretation of the symbolic quantum-mechanical formalism amounts only to predictions, of determinate or statistical character, pertaining to individual phenomena appearing under conditions defined by classical physical concepts.

Notwithstanding all differences between the physical problems which have given rise to the development of relativity theory and quantum theory, respectively, a comparison of purely logical aspects of relativistic and complementary argumentation reveals striking similarities as regards the renunciation of the absolute significance of conventional physical attributes of objects. Also, the neglect of the atomic constitution of the measuring instruments themselves, in the account of actual experience, is equally characteristic of the applications of relativity and quantum theory. Thus, the smallness of the quantum of action compared with the actions involved in usual experience, including the arranging and handling of physical apparatus, is as essential in atomic physics as is the enormous number of atoms composing the world in the general theory of relativity which, as is often pointed out, demands that dimensions of apparatus for measuring angles can be made small compared with the radius of curvature of space.

In the Warsaw lecture, I commented upon the use of not directly visualizable symbolism in relativity and quantum theory in the following way:

Even the formalisms, which in both theories within their scope offer adequate means of comprehending all conceivable experience, exhibit deep-going analogies. In fact, the astounding simplicity of the generalization of classical physical theories, which are obtained by the use of multidimensional geometry and non-commutative algebra, respectively, rests in both cases essentially on the introduction of the conventional symbol $\sqrt{-1}$. The abstract character of the formalisms concerned is indeed, on closer examination, as typical of relativity theory as it is of quantum mechanics, and it is in this respect purely a matter of tradition if the former theory is considered as a completion of classical physics rather than as a first fundamental step in the thoroughgoing revision of our conceptual means of comparing observations, which the modern development of physics has forced upon us.

It is, of course, true that in atomic physics we are confronted with a number of unsolved fundamental problems, especially as regards the intimate relationship between the elementary unit of electric charge and the universal quantum of action; but these problems are no more connected with the epistemological points here discussed than is the adequacy of relativistic argumentation with the issue of thus far unsolved problems of cosmology. Both in relativity and in quantum theory we are concerned with new aspects of scientific analysis and synthesis and, in this connection, it is interesting to note that, even in the great epoch of critical philosophy in the former century, there was only question to what extent *a priori* arguments could be given for the adequacy of space-time coordination and causal connection of experience, but never question of rational generalizations or inherent limitations of such categories of human thinking.

Although in more recent years I have had several occasions of meeting Einstein, the continued discussions, from which I always have received new impulses, have so far not led to a common view about the epistemological problems in atomic physics, and our opposing views are perhaps most clearly stated in a recent issue of *Dialectica*,[17] bringing a general discussion of these problems. Realizing, however, the many obstacles for mutual understanding as regards a matter where approach and background must influence everyone's attitude, I have welcomed this opportunity of a broader exposition of the development by which, to my mind, a veritable crisis in physical science has been overcome. The lesson we have hereby received would seem to have brought us a decisive step further in the never-ending struggle for harmony between content and form, and taught us once again that no content can be grasped without a formal frame and that any form, however useful it has hitherto proved, may be found to be too narrow to comprehend new experience.

Surely, in a situation like this, where it has been difficult to reach mutual understanding not only between philosophers and physicists

[17] N. Bohr, *Dialectica*, *1*, 312 (1948).

Unity of Knowledge

1954

Before trying to answer the question to what extent we may speak of unity of knowledge, we may ask for the meaning of the word knowledge itself. It is not my intention to enter into an academic philosophical discourse for which I would hardly possess the required scholarship. Every scientist, however, is constantly confronted with the problem of objective description of experience, by which we mean unambiguous communication. Our basic tool is, of course, plain language which serves the needs of practical life and social intercourse. We shall not be concerned here with the origins of such language, but with its scope in scientific communication, and especially with the problem of how objectivity may be retained during the growth of experience beyond the events of daily life.

The main point to realize is that all knowledge presents itself within a conceptual framework adapted to account for previous experience and that any such frame may prove too narrow to comprehend new experiences. Scientific research in many domains of knowledge has indeed time and again proved the necessity of abandoning or remoulding points of view which, because of their fruitfulness and apparently unrestricted applicability, were regarded as indispensable for rational explanation. Although such developments have been initiated by special studies, they entail a general lesson of importance for the problem of unity of knowledge. In fact, the widening of the conceptual framework not only has served to restore order within the respective branches of knowledge, but has also disclosed analogies in our position with respect to analysis and synthesis of experience in apparently separated domains of knowledge, suggesting the possibility of an ever more embracing objective description.

When speaking of a conceptual framework, we refer merely to the unambiguous logical representation of relations between experiences. This attitude is also apparent in the historical development in which formal logic is no longer sharply distinguished from studies of semantics or even philological syntax. A special role is played by mathematics which has contributed so decisively to the development of logical thinking, and which by its well-defined abstractions offers invaluable help in expressing harmonious relationships. Still, in our discussion, we shall not consider pure mathematics as a separate branch of knowledge, but rather as a refinement of general language, supplementing it with appropriate tools to represent relations for which ordinary verbal expression is imprecise or cumbersome. In this connection, it may be stressed that, just by avoiding the reference to the conscious subject which infiltrates daily language, the use of mathematical symbols secures the unambiguity of definition required for objective description.

The development of the so-called exact sciences, characterized by the establishing of numerical relationships between measurements, has indeed been decisively furthered by abstract mathematical methods originating from detached pursuit of generalizing logical constructions. This situation is especially illustrated in physics which was originally understood as all knowledge concerning that nature of which we ourselves are part, but gradually came to mean the study of the elementary laws governing the properties of inanimate matter. The necessity, even within this comparatively simple theme, of paying constant attention to the problem of objective description has deeply influenced the attitude of philosophical schools through the ages. In our day, the exploration of new fields of experience has disclosed unsuspected presuppositions for the unambiguous application of some of our most elementary concepts and thereby given us an epistemological lesson with bearings on problems far beyond the

domain of physical science. It may therefore be convenient to start our discussion with a brief account of this development.

It would carry us too far to recall in detail how, with the elimination of mythical cosmological ideas and arguments referring to the purpose for our own actions, a consistent scheme of mechanics was built up on the basis of Galileo's pioneering work and reached such completion through Newton's mastery. Above all, the principles of Newtonian mechanics meant a far-reaching clarification of the problem of cause and effect by permitting, from the state of a physical system defined at a given instant by measurable quantities, the prediction of its state at any subsequent time. It is well known how a deterministic or causal account of this kind led to the mechanical conception of nature and came to stand as an ideal of scientific explanation in all domains of knowledge, irrespective of the way knowledge is obtained. In this connection, therefore, it is important that the study of wider fields of physical experience has revealed the necessity of a closer consideration of the observational problem.

Within its large field of application, classical mechanics presents an objective description in the sense that it is based on a well-defined use of pictures and ideas referring to the events of daily life. Still, however rational the idealizations used in Newtonian mechanics might appear, they actually went far beyond the range of experience to which our elementary concepts are adapted. Thus, the adequate use of the very notions of absolute space and time is inherently connected with the practically instantaneous propagation of light, which allows us to locate the bodies around us independently of their velocities and to arrange events in a unique time sequence. However, the attempt to develop a consistent account of electromagnetic and optical phenomena revealed that observers moving relative to each other with large velocities will coordinate events differently. Not only may such observers take a different view of shapes and positions of rigid bodies, but events at separate points of space which to one observer appear as simultaneous may be judged by another as occurring at different times.

Far from giving rise to confusion and complication, the exploration of the extent to which the account of physical phenomena depends on the standpoint of the observer proved an invaluable guide in tracing general physical laws common to all observers. Retaining the idea of determinism, but relying only on relations between unambiguous measurements referring ultimately to coincidences of events, Einstein succeeded in remoulding and generalizing the whole edifice of classical physics and in lending to our world picture a unity surpassing all previous expectations. In the general theory of relativity, the description is based on a curved four-dimensional space-time metric which automatically accounts for gravitational effects and the singular role of the speed of light signals representing an upper limit for any consistent use of the physical concept of velocity. The introduction of such unfamiliar but well-defined mathematical abstractions in no way implies ambiguity but rather offers an instructive illustration of how a widening of the conceptual framework affords the appropriate means of eliminating subjective elements and enlarging the scope of objective description.

New, unsuspected aspects of the observational problem were disclosed by the exploration of the atomic constitution of matter. As is well known, the idea of a limited divisibility of substances, introduced to explain the persistence of their characteristic properties in spite of the variety of natural phenomena, goes back to antiquity. Still, almost to our day, such views were regarded as essentially hypothetical in the sense that they seemed inaccessible to direct confirmation by observation because of the coarseness of our sense organs and tools, themselves composed of innumerable atoms. Nevertheless, with the great progress in chemistry and physics in the last centuries, atomic ideas proved increasingly fruitful. In particular, the direct application of classical mechanics to the interaction of atoms and molecules during their incessant motions led to a general understanding of the principles of thermodynamics.

In this century, the study of newly discovered properties of matter such as natural radioactivity has convincingly confirmed the foundations of atomic theory. In particular, through the development of amplification devices, it has been possible to study phenomena essentially dependent on single atoms, and even to obtain extensive knowledge of the structure of atomic systems. The first step was the recognition of the electron as a common constituent of all substances, and an essential completion of our ideas of atomic constitution was obtained by Rutherford's discovery of the atomic nucleus which contains within an extremely small volume almost the whole mass of the atom. The invariability of the properties of the elements in ordinary physical and chemical processes is directly explained by the circumstance that in such processes, although the electron binding may be largely influenced, the nucleus remains unaltered. With his demonstration of the transmutability of atomic nuclei by more

powerful agencies, Rutherford, however, opened a quite new field of research, often referred to as modern alchemy, which, as is well known, was eventually to lead to the possibility of releasing immense amounts of energy stored in atomic nuclei.

Although many fundamental properties of matter were explained by the simple picture of the atom, it was evident from the beginning that classical ideas of mechanics and electromagnetism did not suffice to account for the essential stability of atomic structures, as exhibited by the specific properties of the elements. However, a clue to the elucidation of this problem was afforded by the discovery of the universal quantum of action to which Planck was led in the first year of our century by his penetrating analysis of the laws of thermal radiation. This discovery revealed in atomic processes a feature of wholeness quite foreign to the mechanical conception of nature, and made it evident that the classical physical theories are idealizations valid only in the description of phenomena in the analysis of which all actions are sufficiently large to permit the neglect of the quantum. While this condition is amply fulfilled in phenomena on the ordinary scale, we meet in atomic phenomena regularities of quite a new kind, defying deterministic pictorial description.

A rational generalization of classical physics, allowing for the existence of the quantum but retaining the unambiguous interpretation of the experimental evidence defining the inertial mass and electric charge of the electron and the nucleus, presented a very difficult task. By concerted efforts of a whole generation of theoretical physicists, a consistent and, within a wide scope, exhaustive description of atomic phenomena was, however, gradually developed. This description makes use of a mathematical formalism in which the variables in the classical physical theories are replaced by symbols subject to a non-commutable algorism involving Planck's constant. Owing to the very character of such mathematical abstractions, the formalism does not allow pictorial interpretation on accustomed lines, but aims directly at establishing relations between observations obtained under well-defined conditions. Corresponding to the circumstance that different individual quantum processes may take place in a given experimental arrangement, these relations are of an inherently statistic character.

By means of the quantum mechanical formalism, a detailed account of an immense amount of experimental evidence regarding the physical and chemical properties of matter has been achieved. Moreover, by adapting the formalism to the exigencies of relativistic invariance, it has been possible, within wide limits, to order the rapidly growing new knowledge concerning the properties of elementary particles and the constitution of atomic nuclei. Notwithstanding the astounding power of quantum mechanics, the radical departure from accustomed physical explanation, and especially the renunciation of the very idea of determinism, has given rise to doubts in the minds of many physicists and philosophers as to whether we are here dealing with a temporary expedient or are confronted with an irrevocable step as regards objective description. The clarification of this problem has actually demanded a radical revision of the fundamentals to the description and comprehension of physical experience.

In this context, we must recognize above all that, even when the phenomena transcend the scope of classical physical theories, the account of the experimental arrangement and the recording of observations must be given in plain language, suitably supplemented by technical physical terminology. This is a clear logical demand, since the very word "experiment" refers to a situation where we can tell others what we have done and what we have learned. However, the fundamental difference with respect to the analysis of phenomena in classical and in quantum physics is that in the former the interaction between the objects and the measuring instruments may be neglected or compensated for, while in the latter this interaction forms an integral part of the phenomena. The essential wholeness of a proper quantum phenomenon finds indeed logical expression in the circumstance that any attempt at its well-defined subdivision would require a change in the experimental arrangement incompatible with the appearance of the phenomenon itself.

In particular, the impossibility of a separate control of the interaction between the atomic objects and the instruments indispensable for the definition of the experimental conditions prevents the unrestricted combination of space-time coordination and dynamical conservation laws on which the deterministic description in classical physics rests. In fact, any unambiguous use of the concepts of space and time refers to an experimental arrangement involving a transfer of momentum and energy, uncontrollable in principle, to fixed scales and synchronized clocks which are required for the definition of the reference frame. Conversely, the account of phenomena which are characterized by the laws of conservation of momentum and energy involves in principle a renunciation of detailed space-time coordination. These circumstances find quantitative expression in Heisenberg's indeterminacy relations which specify the reciprocal latitude for the fixation of kinematical and dynamical variables in the definition of the state of a physical system. In accordance with the character of the quantum mechanical formalism, such relations cannot, however, be interpreted in terms of attributes of objects referring to classical pictures, but we are here dealing with the mutually exclusive conditions for the unambiguous use of the very concepts of space and time on the one hand, and of dynamical conservation laws on the other.

In this context, one sometimes speaks of "disturbance of phenomena by observation" or "creation of physical attributes to atomic objects by measurements." Such phrases, however, are apt to cause confusion, since words like phenomena and observation, just as attributes and measurements, are here used in a way incompatible with common language and practical definition. On the lines of objective description, it is indeed more appropriate to use the word phenomenon to refer only to observations obtained under circumstances whose description includes an account of the whole experimental arrangement. In such terminology, the observational problem in quantum physics is deprived of any special intricacy and we are, moreover, directly reminded that every atomic phenomenon is closed in the sense that its observation is based on registrations obtained by means of suitable amplification devices with irreversible functioning such as, for example, permanent marks on a photographic plate, caused by the penetration of electrons into the emulsion. In this connection, it is important to realize that the quantum-mechanical formalism permits well-defined applications referring only to such closed phenomena. Also in this respect it represents a rational generalization of classical physics in which every stage of the course of events is described by measurable quantities.

The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangements for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude. The circumstance that, in general, one and the same experimental arrangement may yield different recordings is sometimes picturesquely described as a "choice of nature" between such possibilities. Needless to say, such a phrase implies no allusion to a personification of nature, but simply points to the impossibility of ascertaining on accustomed lines directives for the course of a closed indivisible phenomenon. Here, logical approach cannot go beyond the deduction of the relative probabilities for the appearance of the individual phenomena under given experimental conditions. In this respect, quantum mechanics presents a consistent generalization of deterministic mechanical description which it embraces as an asymptotic limit in the case of physical phenomena on a scale sufficiently large to allow the neglect of the quantum of action.

A most conspicuous characteristic of atomic physics is the novel relationship between phenomena observed under experimental conditions demanding different elementary concepts for their description. Indeed, however contrasting such experiences might appear when attempting to picture a course of atomic processes on classical lines, they have to be considered as complementary in the sense that they represent equally essential knowledge about atomic systems and together exhaust this knowledge. The notion of complementarity does in no way involve a departure from our position as detached observers of nature, but must be regarded as the logical expression of our situation as regards objective description in this field of experience. The recognition that the interaction between the measuring tools and the physical systems under investigation constitutes an integral part of quantum phenomena has not only revealed an unsuspected limitation of the mechanical conception of nature, as characterized by attribution of separate properties to physical systems, but has forced us, in the ordering of experience, to pay proper attention to the conditions of observation.

Returning to the much debated question of what has to be demanded of a physical explanation, one must keep in mind that classical mechanics had already implied the renunciation of a cause for uniform motion and furthermore that relativity theory has taught us how arguments of invariance and equivalence must be treated as categories of rational explanation. Similarly, in the complementary description of quantum physics, we have to do with a further self-consistent generalization which permits the inclusion of regularities decisive for the account of fundamental properties of matter, but which transcends the scope of deterministic description. The history of physical science thus demonstrates how the exploration of ever wider fields of experience, in revealing unsuspected limitations of accustomed ideas, indicates new ways of restoring logical order. As we shall now proceed to show, the epistemological lesson contained in the development of atomic physics reminds us of similar situations with respect to the description and comprehension of experience far beyond the borders of physical science, and allows us to trace common features promoting the search for unity of knowledge.

The first problem with which we are confronted when leaving the proper domain of physics is the question of the place of living organisms in the description of natural phenomena. Originally, no

Returning to the general epistemological lesson which atomic physics has given us, we must in the first place realize that the closed processes studied in quantum physics are not directly analogous to biological functions for the maintenance of which a continual exchange of matter and energy between the organism and the environments is required. Moreover, any experimental arrangement which would permit control of such functions to the extent demanded for their well-defined description in physical terms would be prohibitive to the free display of life. This very circumstance, however, suggests an attitude to the problem of organic life providing a more appropriate balance between a mechanistic and a finalistic approach. In fact, just as the quantum of action appears in the account of atomic phenomena as an element for which an explanation is neither possible nor required, the notion of life is elementary in biological science where, in the existence and evolution of living organisms, we are concerned with manifestations of possibilities in that nature to which we belong rather than with the outcome of experiments which we can ourselves perform. Actually, we must recognize that the requirements of objective description, in tendency at least, are fulfilled by the characteristic complementary way in which arguments based on the full resources of physical and chemical science, and concepts directly referring to the integrity of the organism transcending the scope of these sciences, are practically used in biological research. The main point is that only by renouncing an explanation of life in the ordinary sense do we gain a possibility of taking into account its characteristics.

Of course, in biology just as in physics, we retain our position as detached observers, and the question is only that of the different conditions for the logical comprehension of experience. This applies also to the study of the innate and conditioned behaviour of animals and man to which psychological concepts readily lend themselves. Even in an allegedly behaviouristic approach, it is hardly possible to avoid such concepts, and the very idea of consciousness presents itself when we deal with behaviour of so high a degree of complexity that its description virtually involves introspection on the part of the individual organism. We have here to do with mutually exclusive applications of the words instinct and reason, illustrated by the degree to which instinctive behaviour is suppressed in human societies. Although we meet in trying to account for the state of our mind ever greater difficulties as regards observational detachment, it is still possible to uphold the requirements of objective description to a great extent even in human psychology. In this

connection, it is interesting to note that, while in the early stages of physical science one could directly rely on such features of the events of daily life which permitted a simple causal account, an essentially complementary description of the content of our mind has been used since the origin of languages. In fact, the rich terminology adapted to such communication does not point to an unbroken course of events, but rather to mutually exclusive experiences characterized by different separations between the content on which attention is focused and the background indicated by the word ourselves.

An especially striking example is offered by the relationship between situations in which we ponder on the motives for our actions and in which we experience a feeling of volition. In normal life, such shifting of the separation is more or less intuitively recognized, but symptoms characterized as "confusion of the egos," which may lead to dissolution of the personality, are well known in psychiatry. The use of apparently contrasting attributes referring to equally important aspects of the human mind presents indeed a remarkable analogy to the situation in atomic physics, where complementary phenomena for their definition demand different elementary concepts. Above all, the circumstance that the very word "conscious" refers to experiences capable of being retained in the memory suggests a comparison between conscious experiences and physical observations. In such an analogy, the impossibility of providing an unambiguous content to the idea of subconsciousness corresponds to the impossibility of pictorial interpretation of the quantum-mechanical formalism. Incidentally, psychoanalytical treatment of neuroses may be said to restore balance in the content of the memory of the patient by bringing him new conscious experience, rather than by helping him to fathom the abysses of his subconsciousness.

From a biological point of view, we can only interpret the characteristics of psychical phenomena by concluding that every conscious experience corresponds to a residual impression in the organism, amounting to an irreversible recording in the nervous system of the outcome of processes which are not open to introspection and hardly adapted to exhaustive definition by mechanistic approach. Certainly, such recordings in which the interplay of numerous nerve cells is involved are essentially different from the permanent structures in any single cells of the organism which are connected with genetic reproduction. From a finalistic point of view, however, we may stress not only the usefulness of permanent recordings in their influence on our reactions to subsequent stimuli, but equally the importance that later generations are not encumbered by the actual experiences of individuals but rely only on the reproduction of such properties of the organism as have proved serviceable for the collection and utilization of knowledge. In any attempt to pursue the enquiry we must, of course, be prepared to meet increasing difficulties at every step, and it is suggestive that the simple concepts of physical science lose their immediate applicability to an ever higher degree the more we approach the features of living organisms related to the characteristics of our mind.

To illustrate the argument, we may briefly refer to the old problem of free will. From what has already been said it is evident that the word volition is indispensable to an exhaustive description of psychical phenomena, but the problem is how far we can speak about freedom to act according to our possibilities. As long as unrestricted deterministic views are taken, the idea of such freedom is of course excluded. However, the general lesson of atomic physics, and in particular of the limited scope of mechanistic description of biological phenomena, suggests that the ability of organisms to adjust themselves to environment includes the power of selecting the most appropriate way to this purpose. Because it is impossible to judge such questions on a purely physical basis, it is most important to recognize that psychological experience may offer more pertinent information on the problems. The decisive point is that, if we attempt to predict what another person will decide to do in a given situation, not only must we strive to know his whole background, including the story of his life in all respects which may have contributed to form his character, but we must realize that what we are ultimately aiming at is to put ourselves in his place. Of course, it is impossible to say whether a person wants to do something because he believes he can, or whether he can because he will, but it is hardly disputable that we have the feeling of, so-to-speak, being able to make the best out of the circumstance. From the point of view of objective description, nothing can here be added or taken away, and in this sense we may both practically and logically speak of freedom of will in a way which leaves the proper latitude for the use of words like responsibility and hope, which themselves are as little definable separately as other words indispensable to human communication.

Such considerations point to the epistemological implications of the lesson regarding our observational position, which the development of physical science has impressed upon us. In return for the renunciation of accustomed demands on explanation, it offers a logical means of comprehending wider fields of experience, necessitating proper attention to the placing of the object-subject separation.

Since, in philosophical literature, reference is sometimes made to different levels of objectivity or subjectivity or even of reality, it may be stressed that the notion of an ultimate subject as well as conceptions like realism and idealism find no place in objective description as we have defined it; but this circumstance of course does not imply any limitation of the scope of the enquiry with which we are concerned.

Having touched upon some of the problems in science which relate to the unity of knowledge, I shall turn to the further question raised in our programme, whether there is a poetical or spiritual or cultural truth distinct from scientific truth. With all the reluctance of a scientist to enter into such fields, I shall venture, with an attitude similar to that indicated in the preceding, to comment on this question. Taking up the argument of the relation between our means of expression and the field of experience with which we are concerned, we are indeed directly confronted with the relationship of science and art. The enrichment which art can give us originates in its power to remind us of harmonies beyond the grasp of systematic analysis. Literary, pictorial and musical art may be said to form a sequence of modes of expression, where the ever more extensive renunciation of definition, characteristic of scientific communication, leaves fantasy a freer display. In particular, in poetry this purpose is achieved by the juxtaposition of words related to shifting observational situations, thereby emotionally uniting manifold aspects of human knowledge.

Notwithstanding the inspiration required in all work of art, it may not be irreverent to remark that even at the climax of his work the artist relies on the common human foundation on which we stand. In particular, we must realize that a word like improvisation, which comes so readily to the tongue when speaking of artistic achievements, points to a feature essential to all communication. Not only are we in ordinary conversation more or less unaware of the verbal expressions we are going to choose in communicating what is on our minds, but even in written papers, where we have the possibility of reconsidering every word, the question whether to let it stand or change it demands for its answer a final decision essentially equivalent to an improvisation. Incidentally, in the balance between seriousness and humour, characteristic of all truly artistic achievements, we are reminded of complementary aspects conspicuous in children's play and tion, modern development of science has, however, created a new basis for the use of such words as knowledge and belief. Above all, the recognition of inherent limitations in the notion of causality has offered a frame in which the idea of universal predestination is replaced by the concept of natural evolution. With respect to the organization of human societies, we may particularly stress that description of the position of the individual within his community presents typically complementary aspects related to the shifting border between the appreciation of values and the background on which they are judged. Surely, every stable human society demands fair play specified in judicial rules, but at the same time, life without attachment to family and friends would obviously be deprived of some of its most precious values. Still, though the closest possible combination of justice and charity presents a common goal in all cultures, it must be recognized that any occasion which calls for the strict application of law has no room for the display of charity and that, conversely, benevolence and compassion may conflict with all ideas of justice. This point, in many religions mythically illustrated by the fight between deities personifying such ideals, is stressed in old Oriental philosophy in the admonition never to forget as we search for harmony in human life that on the scene of existence we are ourselves actors as well as spectators.

In comparing different cultures resting on traditions fostered by historical events, we meet with the difficulty of appreciating the culture of one nation on the background of traditions of another. In this respect, the relation between national cultures has sometimes been described as complementary, although this word cannot here be taken in the strict sense in which it is used in atomic physics or in psychological analysis, where we are dealing with invariable characteristics of our situation. In fact, not only has contact between nations often resulted in the fusion of cultures retaining valuable elements of national traditions, but anthropological research is steadily becoming a most important source for illuminating common features of cultural developments. Indeed, the problem of unity of knowledge can hardly be separated from the striving for universal understanding as a means of elevating human culture.

In concluding this address, I feel that I ought to apologize for speaking on such general topics with so much reference to the special field of knowledge represented by physical science. I have tried, however, to indicate a general attitude suggested by the serious lesson we have in our day received in this field and which to me appears of importance for the problem of unity of knowledge. This attitude may be summarized by the endeavour to achieve a harmonious comprehension of ever wider aspects of our situation, recognizing that no experience is definable without a logical frame and that any apparent disharmony can be removed only by an appropriate widening of the conceptual framework.

fruitful way to focus the problem ever more sharply. On this occasion, of course, it will not be possible to deal in detail with individual contributions, but as a background for the following considerations I shall remind you briefly of some of the main features of the development.

While Planck cautiously limited himself to statistical arguments and emphasized the difficulties of abandoning the classical foundations in the detailed description of nature, Einstein daringly pointed to the necessity of taking the quantum of action into account in individual atomic phenomena. In the same year that he so harmoniously completed the framework of classical physics by establishing the theory of relativity, he showed that the description of observations on photoelectric effects requires that the transmission of energy to each of the electrons expelled from the substances corresponds to the absorption of a so-called quantum of radiation. Since the idea of waves is indispensable to the account of the propagation of light, there could be no question of simply replacing it with a corpuscular description, and one was therefore confronted with a peculiar dilemma whose solution was to require a thorough analysis of the scope of pictorial concepts.

As is well known, this question was further accentuated by Rutherford's discovery of the atomic nucleus which, despite its minuteness, contains almost the whole mass of the atom and whose electrical charge corresponds to the number of electrons in the neutral atom. This gave a simple picture of the atom which immediately suggested the application of mechanical and electromagnetic ideas. Yet, it was clear that, according to classical physical principles, no configuration of electrical particles could possess the stability necessary to the explanation of the physical and chemical properties of atoms. In particular, according to classical electromagnetic theory, every motion of the electrons around the atomic nucleus would produce a continual radiation of energy implying a rapid contraction of the system until the electrons became united with the nucleus into a neutral particle of dimensions vanishingly small relative to those which must be ascribed to atoms. However, in the hitherto entirely incomprehensible empirical laws for the line spectra of the elements was found a hint as to the decisive importance of the quantum of action for the stability and radiative reactions of the atom.

The point of departure became here the so-called quantum postulate, according to which every change in the energy of an atom is the result of a complete transition between two of its stationary states. By assuming further that all atomic radiative reactions involve the emission or absorption of a single light quantum, the energy values of the stationary states could be determined from the spectra. It was evident that no explanation of the indivisibility of the transition processes, or their appearance under given conditions, could be given within the framework of deterministic description. However, it proved possible to obtain a survey of the electron bindings in the atom, which reflected many of the properties of substances, with the aid of the so-called correspondence principle. On the basis of a comparison with the classically expected course of the processes, directives were sought for a statistical generalization of the description compatible with the quantum postulate. Still, it became more and more clear that, in order to obtain a consistent account of atomic phenomena, it was necessary to renounce even more the use of pictures and that a radical reformulation of the whole description was needed to provide room for all features implied by the quantum of action.

The solution which was reached as a result of the ingenious contributions of many of the most eminent theoretical physicists of our time was surprisingly simple. As in the formulation of relativity theory, adequate tools were found in highly developed mathematical abstractions. The quantities which in classical physics are used to describe the state of a system are replaced in quantum-mechanical formalism by symbolic operators whose commutability is limited by rules containing the quantum. This implies that quantities such as positional coordinates and corresponding momentum components of particles cannot simultaneously be ascribed definite values. In this way, the statistical character of the formalism is displayed as a natural generalization of the description of classical physics. In addition, this generalization permitted a consequent formulation of the regularities which limit the individuality of identical particles and which, like the quantum itself, cannot be expressed in terms of usual physical pictures.

By means of the methods of quantum mechanics it was possible to account for a very large amount of the experimental evidence on the physical and chemical properties of substances. Not only was the binding of electrons in atoms and molecules clarified in detail, but a deep insight was also obtained into the constitution and reactions of atomic nuclei. In this connection, we may mention that the probability laws for spontaneous radioactive transmutations have been harmoniously incorporated into the statistical quantum-mechanical description. Also the understanding of the properties of the new elementary particles, which have been observed in recent years in the study of transmutations of atomic nuclei at high energies, has been subject to continual progress resulting from the adaption of the formalism to the invariance requirements of relativity theory. Still, we are here confronted with new problems whose solution obviously demands further abstractions suited to combine the quantum of action with the elementary electric charge.

In spite of the fruitfulness of quantum mechanics within such a wide domain of experience, the renunciation of accustomed demands on physical explanation has caused many physicists and philosophers to doubt that we are here dealing with an exhaustive description of atomic phenomena. In particular, the view has been expressed that the statistical mode of description must be regarded as a temporary expedient which, in principle, ought to be replaceable by a deterministic description. The thorough discussion of this question has, however, led to that clarification of our position as observers in atomic physics which has given us the epistemological lesson referred to in the beginning of this lecture.

As the goal of science is to augment and order our experience, every analysis of the conditions of human knowledge must rest on considerations of the character and scope of our means of communication. Our basis is, of course, the language developed for orientation in our surroundings and for the organization of human communities. However, the increase of experience has repeatedly raised questions as to the sufficiency of the concepts and ideas incorporated in daily language. Because of the relative simplicity of physical problems, they are especially suited to investigate the use of our means of communication. Indeed, the development of atomic physics has taught us how, without leaving common language, it is possible to create a framework sufficiently wide for an exhaustive description of new experience.

In this connection, it is imperative to realize that in every account of physical experience one must describe both experimental conditions and observations by the same means of communication as one used in classical physics. In the analysis of single atomic particles, this is made possible by irreversible amplification effects—such as a spot on a photographic plate left by the impact of an electron, or an electric discharge created in a counter device—and the observations concern only where and when the particle is registered on the plate or its energy on arrival at the counter. Of course, this information presupposes knowledge of the position of the photographic plate relative to the other parts of the experimental arrangement, such as regulating diaphragms and shutters defining space-time coordination or electrified and magnetized bodies which determine the external force fields acting on the particle and permit energy measurements. The experimental conditions can be varied in many ways, but the point is that in each case we must be able to communicate to others what we have done and what we have learned, and that therefore the functioning of the measuring instruments must be described within the framework of classical physical ideas.

As all measurements thus concern bodies sufficiently heavy to permit the quantum to be neglected in their description, there is, strictly speaking, no new observational problem in atomic physics. The amplification of atomic effects, which makes it possible to base the account on measurable quantities and which gives the phenomena a peculiar closed character, only emphasizes the irreversibility characteristic of the very concept of observation. While, within the frame of classical physics, there is no difference in principle between the description of the measuring instruments and the objects under investigation, the situation is essentially different when we study quantum phenomena, since the quantum of action imposes restrictions on the description of the state of the systems by means of space-time coordinates and momentum-energy quantities. Since the deterministic description of classical physics rests on the assumption of an unrestricted compatibility of space-time coordination and the dynamical conservation laws, we are obviously confronted here with the problem of whether, as regards atomic objects, such a description can be fully retained.

The role of the interaction between objects and measuring instruments in the description of quantum phenomena was found to be especially important for the clarification of this main point. Thus, as stressed by Heisenberg, the locating of an object in a limited space-time domain involves, according to quantum mechanics, an exchange of momentum and energy between instrument and object which is the greater the smaller the domain chosen. It was therefore of the utmost importance to investigate the extent to which the interaction entailed in observation can be taken into account separately in the description of phenomena. This question has been the focus of much discussion, and there have appeared many proposals which aim at the complete control of all interactions. In such considerations, however, due regard is not taken to the fact that the very account of the functioning of measuring instruments involves that any interwas fixed, room is provided for a wider description through the recognition that the consequent use of our concepts requires different placings of such a separation.

Without attempting any exhaustive definition of organic life, we may say that a living organism is characterized by its integrity and adaptability, which implies that a description of the internal functions of an organism and its reaction to external stimuli often requires the word purposeful, which is foreign to physics and chemistry. Although the results of atomic physics have found a multitude of applications in biophysics and biochemistry, the closed individual quantum phenomena exhibit, of course, no feature suggesting the notion of life. As we have seen, the description of atomic phenomena, exhaustive within a wide domain of experience, is based on the free use of such measuring instruments as are necessary to proper application of the elementary concepts. In a living organism, however, such a distinction between the measuring instruments and the objects under investigation can hardly be fully carried through, and we must be prepared that every experimental arrangement whose aim is a description of the functioning of the organism, which is well defined in the sense of atomic physics, will be incompatible with the display of life.

In biological research, references to features of wholeness and purposeful reactions of organisms are used together with the increasingly detailed information on structure and regulatory processes that has resulted in such great progress not least in medicine. We have here to do with a practical approach to a field where the means of expression used for the description of its various aspects refer to mutually exclusive conditions of observation. In this connection, it must be realized that the attitudes termed mechanistic and finalistic are not contradictory points of view, but rather exhibit a complementary relationship which is connected with our position as observers of nature. To avoid misunderstanding, however, it is essential to note that—in contrast to the account of atomic regularities—a description of organic life and an evaluation of its possibilities of development cannot aim at completeness, but only at sufficient width of the conceptual framework.

In the account of psychical experiences, we meet conditions of observation and corresponding means of expression still further removed from the terminology of physics. Quite apart from the extent to which the use of words like instinct and reason in the description of animal behaviour is necessary and justifiable, the word consciousness, applied to oneself as well as to others, is indis-