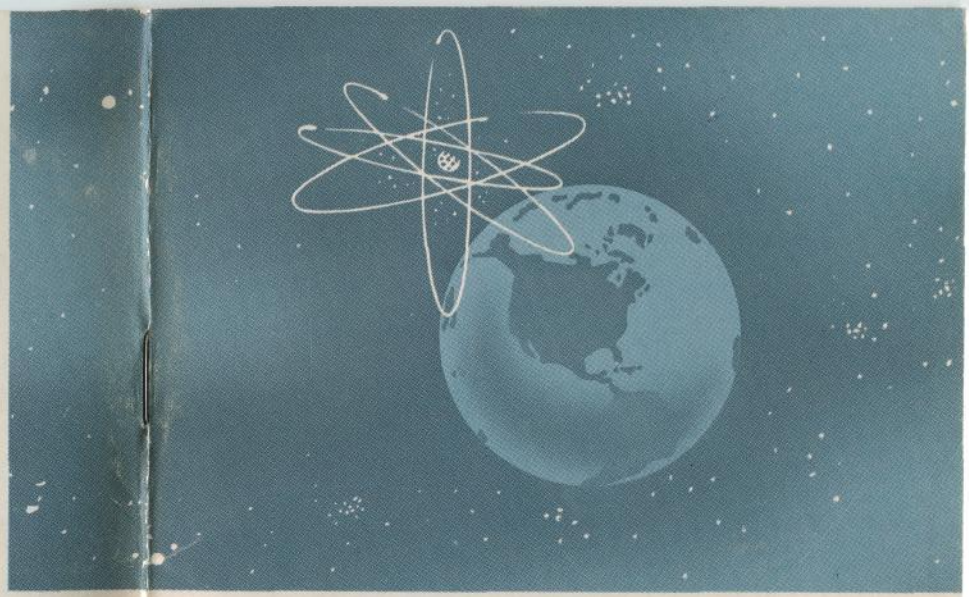

ATOMS AND HUMAN KNOWLEDGE

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Niels Bohr

FRONTIERS OF SCIENCE FOUNDATION OF OKLAHOMA, INC.

Atoms and Human Knowledge

A Public Lecture By

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Delivered on December 13, 1957,
in Holmberg Hall, Norman, Oklahoma,
under the Auspices of the
University of Oklahoma Public Lectures Committee and the
Frontiers of Science Foundation of Oklahoma, Inc.

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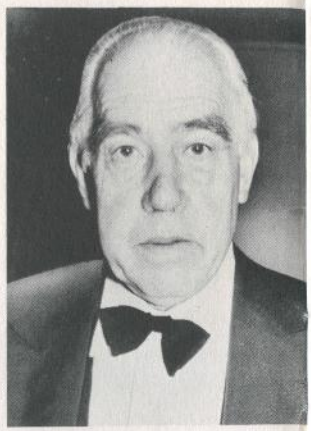

Since 1913, when he published his epoch-making theory of the hydrogen atom, Niels Bohr has been the leading pioneer in atomic physics. He retired from his professorship at the University of Copenhagen in 1956, but continued to serve as director of the Institute of Theoretical Physics which he has created at Copenhagen and made into one of the foremost centers for international scientific cooperation. He is chairman of the Danish Atomic Energy Commission, president of the Royal Danish Academy, etc.

For his great contributions to science Bohr has received virtually all the honors open to a scientist. He received the Nobel Prize in 1922 and the Atoms for Peace Award in 1957. He has been awarded the Guldberg, Hugh, Oersted, Barnard, Mateucci, Franklin, Faraday, Planck, Copley, and Bohr medals. Some 25 universities have honored him with doctor's degrees, and more than 60 scientific societies have elected him to honorary or regular membership. He has been decorated by several governments, and the Danish King has made him a Knight of the Elephant, an honor normally reserved for royalty.

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This biographical sketch and the transcriptions of Professor Bohr's address were prepared by Dr. J. Rud Nielsen, Research Professor of Physics, The University of Oklahoma.

Ladies and gentlemen! I am deeply moved by your warm welcome and by the kind words of my old friend and your distinguished physicist, Mr. Jens Rud Nielsen. It is a great honor for me to speak to you at this great University of Oklahoma, where such vigorous and enthusiastic endeavors in education and scientific research are taking place. It is a very great pleasure for my wife and me to come back here, after the visit of twenty years ago, to see old friends and to see how the activities of this University are developing. This morning I had the great pleasure of seeing in your physics department many-sided researches in atomic physics which play, or will play, a very important role in technology.

Tonight I shall not try to tell you anything new about atomic physics, but with the theme for this lecture, "Atoms and Human Knowledge",* I want to describe how we in this new field of experience, the explorational world of atoms—where, so to speak we wander in an unknown land on paths hitherto untrod by man—have got a very forceful reminder of our position as observers of that nature of which we ourselves are part.

In order to give you an impression of what this new lesson teaches us, I want to remind you of the development of the great edifice which, until most recently, has been the basis for all technology and which we usually refer to as classical physics. To develop this has been, in itself, a great and truly human endeavor. It is not so that in physics we merely record measurements and are able to order them or put them together directly by means of the notions with which we are equipped from orientation in everyday life. Rather, it has been a continual

* This text was transcribed from magnetic tape recording. It has not been corrected by Professor Bohr.

endeavor through the years to develop human concepts or views suited to the ordering and comprehension of our increasing experience. As everyone knows, this has been a long task. In ancient Greece, where, to the admiration of later generations, a spirited effort was made to erect science on well-established, clearly formulated, logical principles, and where wonderful contributions were made to mathematics which were to become the foundations for later developments, it was not found simple or easy to separate one's self from such experiences as the exertion required for the motion of our bodies or even from the motives for the actions which these motions serve. It was as long as two thousand years later, at the time of the Renaissance, that it became possible for Galileo to liberate himself and renounce any explanation of motion itself, taking uniform motion, instead, as something elementary and asking only for the cause of changes in motion in terms of forces. Out of this grew, as you know, the science of classical mechanics, completed by the genius of Newton. The description thus achieved was a so-called deterministic description. This means that it proved possible, from a knowledge of the state of a physical system as defined by the positions and motions of its parts, together with a knowledge of the forces between these parts, to calculate or predict the state of the system at any later time. This great achievement, the foremost expression of which was Newton's explanation of Kepler's laws governing the motions of the planets around the sun and of the satellites around the planets, made an overwhelming impression at the time. This kind of description, therefore, came to stand as the ideal for scientific explanation.

But what we have learned in the exploration of the new field of atomic physics is that most of the phenomena we meet there cannot be pictured in this way: they defy any casual, deterministic description. The starting point was the discovery of an element of wholeness, so to speak, in the physical processes, a feature going far beyond the old doctrine of the restricted divisibility of matter. This element is called the universal quantum of action. It was discovered by Max Planck in the first year of this century and came to inaugurate a whole new epoch in physics and natural philosophy. We came to understand that the ordinary laws of physics, i.e, classical mechanics and electrodynamics, are idealizations that can only be applied in the analysis of phenomena in which the action involved at every stage is so large compared to the quantum that the latter can be completely disregarded.

This condition is amply fulfilled by experience on the ordinary scale, but for phenomena that depend on individual atoms we need entirely new physical laws. Now, what could one do in this situation? I can say at once that it proved possible, by the most active co-operation of a whole generation of experimental and theoretical physicists, to achieve a generalization of classical physics called quantum mechanics, or quantum physics, which helps us in expressing these laws. But this new kind of description is in principle a statistical one, and this fact has given rise to a great deal of discussion. The question is whether we are really dealing with something that represents an irrevocable step in the description of nature or merely with an expediency that we can give up later to achieve a deterministic description. This problem has been essentially (to my mind, fully) clarified by a radical revision of the very foundations for the use of our most elementary physical concepts.

We have to ask ourselves: "How do we communicate physical experience at all?" It is clear that, even if we are quite beyond the scope of classical physics, we can only speak about experience obtained under experimental conditions described in the ordinary way. By an experiment, we must understand a situation in which we can tell others what we have done and what we have learned. That actually means that what every physicist does—and he couldn't do anything else—is to find a condition or experimental arrangement under which a phenomenon occurs and then study it with the aid of such heavy measureing instruments that he can completely disregard the quantum of action.

What observations can we make? Observations are only the marks left on the bodies used as measuring instruments after their interaction with the atomic objects, such as the spot on a photographic plate developed after the impact of an electron. Now, so far we have described everything in the ordinary manner; but how are we to analyze the phenomena? Here we find that in the atomic field, where the quantum of action is essential for the phenomena, the interaction between the measuring instrument and the object plays an essential part. The crucial point is that this part cannot be separated from the phenomena. It is in no way possible to control it separately, since in describing and accounting for the measuring instruments we must neglect the quantum of action. This means that we have lost the basis for a deterministic description. The deterministic description in Newtonian mechanics rests entirely on a combination of the co-ordination, or location, of objects in space and time and the application of such laws as those of the conservation of energy and momentum which allow us to join together, so to speak, the single links of the chain of events. But now, in the field of quantum phenomena, when we have any unambiguous information about atomic objects expressed as location in space or in time, we understand that an experiment has been carried out in which there occurred an exchange of energy and momentum between the measuring instruments, such as fixed scales or synchronized clocks, and the atomic objects, an exchange which, in principle, cannot be controlled. On the other hand, in the description of many other properties of atoms, we make extensive use of the conservation of energy and momentum. But for such phenomena we must renounce a detailed description in space and time. This is the essence of the lesson, that two kinds of concepts which are equally important in the description of experience, and which classical theory thought could be combined unrestrictedly, cannot be so combined. If, in atomic physics, phenomena are observed under different experimental conditions and are described by different physical concepts, they cannot be combined into a simple picture. If the attempt is made, we get apparent contradictions. Such phenomena we call complementary to each other, in the sense that each of them offers unambiguous information about the atomic objects under observation. Together they exhaust the knowledge about the objects that can be defined in human words or concepts.

The lesson, to state it more philosophically, is this: we have learned that, in this simple field of atomic physics, we have to pay attention to the conditions under which experience is obtained, and to the conditions under which the words we use can have precise meaning.

But the fact that, in many other fields of human interest, we meet situations requiring similar caution

or attention is a general lesson from human experience. It is thus not a new thing, but just because we have learned this lesson in such a simple field as atomic physics—so far removed from the aspects of life where human aspirations and passions play their part—it may be helpful to apply it to other fields.

I would like to say a few words first about the old question of the position of living organisms among the other physical objects. At the time of the great triumphs of classical mechanics, organisms were often compared to machines, and to certain good purpose, although it could not be a complete description. Today we know that, to account for the properties of living organisms, we must have essential recourse to what we have learned in atomic physics. It is quite clear that very complicated molecular structures of great stability are responsible for the hereditary properties of the species. However, it is quite impossible to understand their stability on the basis of classical physics. Through quantum mechanics, on the other hand, this is possible. Next, in order to give just one more simple example, the empirical laws for the production of mutations by the influence of penetrating radiations are exactly the same as the laws describing the reactions between radiation and atoms and molecules which we study in atomic physics, but these laws have aspects quite different from what would be expected from classical physics.

Now, in this field of biology, great progress is taking place as a consequence of the advances in atomic physics. We may call this a mechanistic approach, because quantum mechanics is, after all, a rational generalization of classical mechanics. This approach holds very great promise and probably will have no limitations; but the question is: "What bearing does it have on the old problem of explaining life?" Here we must realize, first of all, that "life" is not a word that finds any application in physics. We find no reason to describe the phenomena we deal with in classical physics in terms of life, and exactly the same is true of atomic physics. Life is, in a sense, an irreducible element in biology, just as the quantum of action is now an element in physical science; and, at any rate for the quantum of action, the essential fact is that no explanation can possibly be given for it on the basis of classical physical ideas.

Biologists use the word "life" to remind us of such properties of living organisms as their self-regulation, their adaptability to environment, and so on. Now, the lesson we have learned in atomic physics strongly suggests that such different approaches as the mechanistic and the so-called finalistic are in no way contradictory to each other. They are, rather, expressions for complementary situations of observation where we either try to study details or think of the organism as a whole.

These remarks should not be taken to imply that physicists can directly be of help in developing biology. However, they point to an attitude which, may contribute to a better understanding among various groups of biologists by urging them to think of how words are actually used.

I would like to go on to something very different from physics, to the way we describe the state of our mind; what we call psychic conscious experience. Here we have developed a very rich vocabulary, by means of which we are able to communicate, even to pour out, information to one another. This is important when a man tries to say that he is dissatisfied or that he is contented. Now, all such words as thought, sentiment, volition, conscience, hope, and so on, do not, of course, refer to physical features.

Pairs of such words point to mutually exclusive situations, and the complementary use of words in this field has been common since the beginning of civilization. For example, a situation which calls for a description of our feeling of volition and a situation demanding that we ponder on the motives for our actions have quite different conscious contents. We pay attention to different objects in these two situations and make different separations of these objects from the background from which we, so to speak, judge them and which we loosely call our "self". In general, just as different phenomena in atomic physics require different experimental arrangements for their definition and observation, so the various psychic experiences are characterized by different placements of the separation between the content on which attention is focused and the background indicated by the word "self."

To point out how the lesson we have learned in physics may be helpful, I should like to recount a humorous tale from Danish literature "The Adventures of a Danish Student". This student has a very open mind and also lays himself open to all kinds of adventure. He has two cousins. One is very practical—what you might call dry—and the other is very philosophical. Now, far along in the tale, this cousin makes all kinds of trouble for himself and demands much forbearance for the plight he is in. His practical cousin comes to visit him and talks to him about how his position has completely deteriorated, and explains to him that it is absolutely necessary to do something; he must, as it is spoken of here in America, "look for a job." And everything is accordingly arranged for him. The next day he is to go to a neighboring mansion and get a position as teacher of children, to which he agrees. Then, after some weeks, the practical cousin comes back and finds that things have gone from bad to worse and that absolutely nothing can stop it. The erring cousin says: "I am very sorry, but it is impossible for me, for I have become confused about my different selves. You can so easily speak about me, but I must think of the self that controls me, and as soon as I do that I am equally aware that there is another self that controls and thinks of the self who controls what you call me, and if I start on this line of thought, my trouble becomes worse and worse. If I try to get out of it in any way, I get a terrible headache and have to give everything up".

Now, of course, the whole thing is meant by the writer to describe something very general, the different aspects of any human being. The author has made quite clear and has expressed very beautifully a situation in which all of us may find ourselves. Every healthy child has the possibility of living a normal life; but in case of certain diseases, as the psychiatrist well knows, it runs the risk of a splitting of its personality.

I would now like to say a few words about the old discussion of the freedom of the will. This, of course, is not related in any way to physics. Moreover, though attempts have been made through the ages, it is quite impossible to relate this problem to determinism; for a rigorous deterministic approach leaves no room for the concept of free will. On the other hand, it is clear that, like many other commonly used words, the word freedom is quite necessary to describe the richness of conscious life. Now, what do we use it for? In some situations we like to say that we have the feeling that it is possible for us, so to speak, to make the best of things. Speaking very loosely, it is simply a problem of cause; it is not pos-

sible to say whether we have the feeling that we are going to do something because we have the feeling that we can, or whether we can only because we will.

The problem is this, to see that we use the words "free will" to describe our situation in just as clear a manner as we use such words as "responsibility", "hope", and the like, all of which cannot be applied or defined unambiguously, except on the basis of the situations in which they are used.

I might get still further away from physics for a moment and say a few words about what we call ethical values. These are words that are very far from classical physics and equally far from quantum physics. Various philosophies, or philosphical schools, sometimes say, not out of cynicism but for definite reasons and in all honesty, that we must avoid evaluations or value judgments. But this is simpler said than done, for if there should be (and I don't think there are) philosophical schools that say that we must avoid the use of the words "good" and "bad", I think they would be tempted to say that it is good philosophy to do so.

But let us for a moment go right into the matter and ask how such words as "justice" and "charity" are actually used. We know, first of all, that they are necessary in speaking of human conditions in all stable societies that demand provisions for fair play. They get incorporated in judicial rules and become the law of the land, as, in this country, Oliver Wendell Holmes has so wonderfully explained and made clear in his book on the common law. On the other hand, human life would be deprived of much beauty and richness if we could not speak of sympathy, friendship, love, and so on.

It is clear that in all cultures the attempt is made to combine these two things, justice and charity, to the utmost extent. On the other hand, it is also clear that in a situation where there is a clear basis for the unambiguous use of the word "justice" after these rules, in such a situation the word "charity" would find no place whatever. But it is equally true, of course, as has been emphasized by great writers and philosophers, that compassion and good will can bring any of us into conflict with our ideals of justice. Now, the point that I wish to emphasize is that here we have two words that can be combined to a very large extent, as space-time description and conservation laws can be combined in classical physics, while for the finer and very varied regularities of atomic physics they must be used in a complementary manner. To my mind, the words charity and justice must be used in a complementary manner in many situations in which we express the richness of life and emphasize human values.

I want to emphasize that what we have learned in physics arose from a situation where we could not neglect the interaction between the measuring instrument and the object. In psychology, we meet a quite similar situation involving the decision as to where to draw the separation line between subject and object. A similar state of affairs is inherent in social problems, where we have to do with the relationship of the individual and the community to which he belongs, a relationship that is very rich and many-sided, and where again, different words correspond to different situations.

Before I close I should like to say a few words about the comparison of human cultures. I am not thinking directly of the difficulties we are having in the world today which we surely must hope to overcome; but I am thinking of the kind of experiences ethnographers have on expeditions to peoples who

have lived for a long time in comparative isolation, say, on one of the beautiful islands in the Pacific Ocean. What they find, as everybody knows, are traditions and customs very different from what we are used to, so different that it appears as a great surprise to us that under such conditions there can exist a certain harmony within the population, as these explorers find to be the case. Now, when we attempt to compare cultures, we may be tempted to think that the differences between them are analogous to the different ways in which different observers co-ordinate and describe physical phenomena, ways which have been made so clear in the theory of relativity. But there is a great and fundamental difference. In fact, with the aid of the theory of relativity—through which Albert Einstein succeeded in giving physics great unity and discovered new physical laws common for all observers—however differently various observers may describe experience, any of them can foresee how the other observers will co-ordinate experience. On the other hand, if we compare human cultures the situation is different, because every culture contains an element of complacency. This is not something to deplore or be critical about, for it is quite analogous to the instinct of self-preservation found in any living organism. However, this complacency makes it very difficult, if not impossible, to appreciate the traditions of one culture on the basis of the traditions of another culture. One may be inclined to think that there is such a mutual exclusion among cultures that they are complementary to one another, as has sometimes been claimed; but there is a very great difference between the logical and necessary exclusion that holds for the use of concepts in atomic physics and in psychology and the relationship of cultures to one another, because cultures are only mutually exclusive as long as they are isolated. By intercourse, cultures can develop and change; cultures can flow together and merge, as we know so well from history, and progress can be attained thereby.

I want to say just a few words about how important it is today to promote intercourse among nations. We must understand that the situation into which the progress of science has brought us, with very great new promises for the promotion of human welfare, and at the same time the grave dangers resulting from the increase of our mastery of the forces of nature, is similar to the situations brought about by previous increases in knowledge and abilities, in that it places upon us a greater responsibility. At present, we find ourselves in a situation that constitutes a most forceful challenge to civilization. Nevertheless, this situation holds out a hope that is quite unique in some ways because, quite apart from all present difficulties, we must clearly realize now that there cannot be another great war without human suicide. When we think about how, through the long history of civilization, every conflict so far has been settled by armed force, we have in some ways greater promises today for a peaceful future. The problem is how to go about securing peace; and that is, of course, very difficult to say. But the first point I wish to mention is that the present situation is a radically new one to mankind and certainly demands a novel approach, just as in science, when we met new problems it was necessary time after time to modify our viewpoints and approaches. None of us underrates the difficulties, but the question we must ask ourselves is, what resources do we have? And I should like to say that the resources, and therefore the responsibilities, should be greatest

in countries like your great country, where through happy historical developments there is so large a freedom for the individual, and where it is so much easier to speak openly with everyone about all possible procedures than in countries where unhappily such freedom does not exist in temporary (we hope) epochs of dictatorship.

Another point I would like to make is that it ought to be the best omen for the future that we are dealing with the results of a development that arose from purely scientific endeavors, having as their sole aim the augmentation of our knowledge and understanding of that nature of which we are part. The very fact that this development was brought about by close international co-operation strongly emphasizes the importance of the closest possible international co-operation for the achievement of a peaceful world. At any rate, such co-operation is essential in science, if peace is to be secured.

I know that much of what I have said in this lecture may sound superficial, but by pointing to something that is quite common to all human beings, I hope modestly that what I have said may lead to better understanding. I believe that, however difficult the problems are at the moment, the goal where every nation can attain prominence only by the help it can offer others and by what it can contribute to common human culture may be nearer today than it has ever been in the history of mankind.

It has been a great honor and pleasure for me to speak at the University of Oklahoma, where the question of the education of the younger generation is considered so seriously and where education in our day can mean not only education for citizenship in a great country but education for the service in the great cause of all mankind.