"Physicists have now known sin."
—ROBERT OPPENHEIMER

INTERVIEW

DAVID BOHM

DAVID Joseph Bohm, who retired last year as Professor of Theoretical Physics at Birkbeck College, University of London, is one of the most distinguished physicists and philosophers of science of our era.

He did his doctoral research work with Robert Oppenheimer at the University of California, Berkeley, and later worked in the University of Princeton, New Jersey. His early research on electron plasma in metals is widely recognised as an outstanding work in solid state physics.

Then onwards he concentrated on making fundamental contributions concerning the foundational problems of quantum mechanics. He interacted with Einstein and began challenging the orthodox interpretation of quantum mechanics. Bohm's greatest role has been that of án iconoclast, one who has struggled relentlessly to motivate quantum physicists to critically question the conceptual basis of their theory.

Bohm's was an illustrious and eventful career. He was connected with the Manhattan Project to make the first atom bomb and got involved in controversial investigations—a spin-off of the Oppenheimer trial during the McCarthy period in the United States. The leitmotif of Bohm's life is best conveyed through the following words of his wife, Sarah: "When I first met Dave, it struck me that here was a tremendous courage in looking at things honestly, whatever the consequences."

Bohm, 69, now lives in London and is Emeritus Professor at the University of London.

Here is an exclusive interview taken by Dr. Dipankar Home for SCIENCE TODAY just before Prof. Bohm was going to address the historic International Conference on Fifty Years of the Einstein-Bohr Debate on Quantum Mechanics held at Urbino, Italy.

ST: Prof. Bohm, could you please give us a brief account of your initiation into the study of physics and the type of problems you investigated in the early stage of your research career?
Bohm: I got interested in science when I read a science fiction story at the age of 8. Then, in the fourth grade, we were given an astronomy book. That aroused my interest in the vast order and regularity which could be found in the unsuspected size of the universe. My interest developed further when I started going to the library. I gradually turned to the philosophical significance of the subject, like the question of the nature of the universe. It appeared that physics might be relevant to it.

My graduate work was with Prof. Robert Oppenheimer at Berkeley, California. During the Second World War, I worked on various projects in the radiation laboratory at Berkeley. They were mainly concerned with electric arcs for the production of uranium ions for the isotope separation project. This was part of the Manhattan Project. We also worked on the theory of plasma.

This work on plasmas interested me very much, not only from the practical point of view, but also philosophically, because it represented a system which behaved like a whole. That is, the plasma tended to regenerate itself. This I called "the tendency to establish the stability of collective behaviour". I was interested in the relationship between the individual particles and the collective behaviour.

ST: So you moved on to work on electron plasmas in metals which threw much light on the significance of the role of collective excitations.
Bohm: You see, this work was the continuation of the work on gaseous plasmas. At that time, plasma in a magnetic field was a new subject. We analysed the diffusion of ions in a magnetic field and discovered some new and interesting features. These findings have renewed importance now in view of the attempts to make fusion reactors—more specifically, in the understanding of how to contain the plasma.

When I went to Princeton University after the war, I thought of extending this idea to electrons in a metal. Thus, I was led to consider electrons in a metal to be a plasma. The problem required quantum mechanical treatment. One then discovered that not only are there electron plasma waves, which were indeed later verified experimentally, but also that the plasma surrounds each positive ion with a screening cloud. So that although the electrons have a long-range interaction to begin with, this interaction is neutralised in the environment of the plasma, and the electrons behave as if under a short-range interaction. This realisation was crucial in understanding the properties of electrons in a metal, for example, scattering, resistivity, etc.

ST: After that work, I believe, you became more interested in the foundations of physics.
Bohm: Yes. I became specially interested in the meaning of the quantum theory. I had written a book trying to explain the quantum theory from what I regarded as Niels Bohr's point of view. When I finished the book, I felt I still didn't understand, and I began to think it over.

He gave me the impression of possessing tremendous energy and cheerfulness. He did not give the impression of having any sense of authority. It was very easy to forget that he was Einstein.

I had sent copies of this book to various physicists, including Pauli, Bohr and Einstein. Pauli sent an enthusiastic response, but Bohr did not reply. Einstein, also at Princeton, phoned me and said he would like to have a talk with me about the book. He felt that the book explained the quantum theory as well as could be done, but he still wasn't satisfied.

ST: Which particular aspect wasn't he happy with?
Bohm: Of course, the indeterminism of the quantum theory was one thing. His fundamental disagreement concerned the questions raised by the Einstein-Podolsky-Rosen (EPR) thought experiment and the criteria of reality.

ST: What about the question of locality?
Bohm: Well, we didn't discuss this question, though it was always at the back of his mind. An analysis of the EPR hypothetical experiment led Einstein to conclude that quantum mechanics cannot describe the elements of physical reality, and is therefore incomplete. He felt that quantum mechanics was correct statistically, but it did not provide the correct individual description of the elements of reality. We discussed the problem and what could be done about it. He felt that quantum mechanics was certainly inadequate and one should seek a more complete theory.

ST: Did Einstein have a hidden variable theory in mind?
Bohm: Not necessarily. The words "hidden variable" have created a lot of confusion. You see, we always explain what is visible by what is not visible anyway. Any new variable will not be visible for a time, but they reveal themselves through what is visible.

He didn't have any specific notion of how to explain the quantum theory. He hoped that relativity, with its non-linear equations, extended to include electromagnetism and other fields might also have complex turbulent motion in the background. In this way, he aspired to explain the quantum properties of matter, but he did not develop the idea very far.

ST: Your discussion with Einstein was just a few years before his death. What was his state of mind at that time?
Bohm: He gave me the impression of possessing tremendous energy and cheerfulness. He did not give the impression of having any sense of authority. It was very easy to forget that he was Einstein.

ST: In the later years of his life, Einstein was cut off from the mainstream of physics. How did it affect him?
Bohm: He was cut off on his own choice, but I don't think it affected him that badly. He would have preferred not to be cut off, but he felt that the mainstream of physics was not very deep. He wanted to do something more fundamental and felt that since he had no insecurities and was taken care of, he could do it. He didn't feel that the conventional approach of a

typical physicist was really right. He believed that an almost unique theory could be found with very little reference to experiment. Indeed, this is how he obtained general relativity.

ST: Was this Einstein's viewpoint in the later years of his life?
Bohm: Yes. I once wrote to him, saying that I felt we needed to look carefully at all the new results of atomic and particle physics. He said he knew this was the usual point of view, but it wasn't his.

ST: It seems he preferred to rely mainly on theoretical speculations and theoretical insights..
Bohm: Mostly insights. He felt that a physicist should have the free play of concepts, which you may call speculation, but it had to be guided by good intuition as well as by careful attention to those facts of experience that are relevant; those things which give rise to general principles.

ST: You studied physics with Oppenheimer. What impressions do you have of him?
Bohm: He was brilliant in a broad range of subjects. However, many people agree that he lacked the ability to do very much really original. He was very good at grasping the essence of what other people were saying and at bringing their ideas together. For this reason, he made an excellent director of the Manhattan Project at Los Alámos, which built the atom bomb (fission device). He did an extraordinary job. I can see, from having been his graduate student and having seen him in operation in the Princeton Institute for Advanced Study, that this was his strength—to be able to coordinate what other physicists were doing.

ST: During your association with Oppenheimer, did he discuss with you his involvement with the atom bomb project?
Bohm: We never discussed this directly. When Oppenheimer came back to America from his studies in Germany, he was regarded as the leading American theoretical physicist because he was so sharp and bright. He started by doing research, but gradually it seemed that he wasn't doing so much original work, but was concentrating on building up a school and inspiring students to do good work. He actually did build up a school with very good students. Then he got interested in politics because of Hitler. He felt that it was most important to combat the menace posed by Hitler; he was convinced that the western civilisation would be destroyed if Hitler won. So when the Manhattan Project started, he felt that the effective way to combat Hitler would be to fabricate the atom bomb, because he was genuinely apprehensive that Hitler would get it first. He was accepted on the bomb project despite objections (because of his pro-communist slant) by the security people. At Los Alamos, he proved to be an extremely capable organiser and leader. His ability to comprehend a complex array of information enabled him to hold the whole project literally in his mind. So I think his role was crucial in making that project successful.

Oppenheimer was accepted on the bomb project despite objections (because of his pro-communist slant) by the security people

ST: But don't you think that when Germany surrendered, the dropping of the atom bomb could have been avoided if people like Oppenheimer were really keen to stop it?
Bohm: Oppenheimer had a different way of looking at it. By that time the whole structure of bureaucracy and organisation had gained so much momentum that you couldn't have stopped it. And also, most scientists believed that it was necessary to save both American and Japanese lives by ending the war as quickly as possible. Besides, at that time nobody realised the full implications of the bomb. We merely thought it as a bigger and more effective bomb.

ST: Was that also Oppenheimer's impression?
Bohm: At least, that's the impression I had, and also most people around me. Oppenheimer might have understood it a little better, because he was closer to the top. Anyway, nobody really knew about the dangers of the radioactive fallout. Perhaps, they had a better idea after the tests at Alamogordo. But Oppenheimer had a further argument saying that it was important that the weapon be brought out in the open, rather than be kept as a secret weapon. It was necessary that the whole world knew about it.

ST: You mean in the form of this bombing?
Bohm: Well, Dipankar, you see, at that point of time it didn't seem worse than the fire-bombing of Tokyo. Actually, if you see pictures of the destruction caused in Tokyo by ordinary fire-bombing, these do not look all that different. People were killed on a vast scale by being deprived of oxygen and so on. It was only after the atom bomb was dropped on Hiroshima that people began to see that it had such hitherto unsuspected devastating implications.

ST: How did Oppenheimer react after the bomb was dropped?
Bohm: I don't know if he ever commented on it. You see, one reason why he was attacked politically in America was that he opposed the hydrogen bomb. He opposed it both for technical and humanitarian reasons. If he had not opposed the hydrogen bomb he would not have got into so much trouble. So you can see where his sympathies lay. He was accused of being a communist agent because of that. On the other hand, there were others among American scientists who felt the hydrogen bomb (fusion device) had to be made because they were afraid of Soviet Russia. As it turned out, the Russians developed the atom bomb soon after the Americans did. These American scientists apprehended grave consequences if Russia had the hydrogen bomb and America did not. It is very difficult to make a clear judgement on such issues.

ST: Do you think Oppenheimer's infamous trial was part of the larger scale of witch-hunting that was going on during the McCarthy period?
Bohm: The McCarthy period created

Continued on page 48

Continued from page 27

an atmosphere in which this was inevitable. But I think trouble came to him particularly because he opposed the hydrogen bomb; otherwise he would have escaped it. Moreover he offended a number of people. He could be very rude in his approach. He apparently did it with some important military people who became his enemies.

***ST:** In his trial, Oppenheimer was supported by many eminent scientists. Also, the evidence against him on his links with the Soviet Union was not very convincing.*
Bohm: There was no strong evidence. The way Edward Teller put it was that he didn't think Oppenheimer was disloyal to the U S , but he felt that under the circumstances, Oppenheimer couldn't put his whole energy into developing the hydrogen bomb because of his outlook and his sympathies with the Left and so on. But the support of all other scientists didn't weigh against attacks from the military and the political people and particularly from Teller.

***ST:** A certain personal animosity perhaps?*
Bohm: Partly that, yes. There's no doubt that there was always animosity. But it was partly a genuine disagreement, in the sense that Teller believed Oppenheimer should have supported the hydrogen bomb. Oppenheimer didn't encourage people to go and work at Los Alamos on the hydrogen bomb. Perhaps, Oppenheimer felt that the hydrogen bomb was such an ominous thing that he was reluctant to pursue it.

***ST:** Was Oppenheimer frustrated about the fact that he could not foresee the effects of the atom bomb?*
Bohm: He saw that it would be far-reaching, but he didn't foresee the way it would go. He thought in the beginning that this bomb would cause America to share it with Russia and they would all get together to control the energy. He found it went just the other way and the whole thing turned very disappointing for him.

***ST:** So this, perhaps, is the reason why he must have felt some degree of responsibility for the dropping of the bomb on Hiroshima and Nagasaki?*
Bohm: Yes, there is his famous statment that "physicists have now known sin". I'm ssure that he felt responsible although at that time I think very few scientists would have felt otherwise. Einstein and Bohr were both against it, but as it turned out, that had little effect. I heard Freeman Dyson saying that there was a sort of 'Faustian element' in Oppenheimer's attitude towards the bomb. If you remember, Faust made a pact with the devil to obtain power. I recollect, at that time, the physicists had a feeling of ecstasy, having released all that mighty power. Military men, politicians and industrialists didn't believe that the physicists could do it. Ernest 0. Lawrence told me that when he was watching the bomb go off in Alamogordo, New Mexico, General Groves (the Commander-in-Charge) suddenly shouted, "By God, the Long Hairs have done it". In other words, he never believed that the physicists could really do something like that. There was such tremendous scepticism about intellectuals like physicists that the physicists desperately wanted to show their prowess.

In regions smaller than 10^{-33} cm, ordinary notions of time and space cannot hold because the whole metric is so indeterminate that we cannot distinguish between the past and the future. I think people are approaching this limit

***ST:** It is surprising that the physicists didn't anticipate the radiation hazards and the long-term effects.*
Bohm: This wasn't on anybody's mind at all! It was only later that people came to think that it was much more serious than what they had thought.

***ST:** Would you like to say something about the unfortunate circumstances which forced you to leave the U.S.A. after your work at Princeton?*
Bohm: A year or so after I arrived at Princeton, I was called before the Un-American Activities Committee of the House of Representatives. They were investigating the so-called communists, but I was not clear what they were trying to do. They wanted me to give testimony about some people I had known at Berkeley, whether they were communists or not. After legal advice, I decided to use the 5th Amendment, which gives the right not to testify if your testimony may incriminate you. The law then was such that if your testimony could connect you with communism, it would be incriminating. This was the basis of the argument.

At first, nothing happened. There was a lot of publicity, but it died down. I continued my work in Princeton but, just two years later, I was indicted for the contempt of Congress. We had a trial, but while I was waiting for the trial there was a Supreme Court decision settling the right not to testify on the basis of incrimination and, therefore, I was acquitted when my trial came up. But then I found that I could not get a job in America. It was the beginning of the McCarthy era.

***ST:** What were the factors, you think, responsible for the kind of trial involving you?*
Bohm: There were no charges levelled against me. They wanted me to give testimony, which I felt was better not to give, in the sense that I felt that such a testimony would merely start a kind of witch-hunt, which would be of no real value. There was a widespread anti-communist feeling. I think this trend was heightened by the Korean war. I had some communist friends, but you see, I didn't testify.

***ST:** Now, coming back to physics, most physicists accept quantum mechanics* per se *uncritically but you believe there are genuine difficulties in the conventional approach of understanding quantum mechanics. Could you please explain the essence of your approach, in terms of the quantum potential that you have been developing since 1951?*
Bohm: A key aspect which I discussed with Einstein was whether quantum mechanics would enable us to discuss reality independent of the act of observation. That requires us to make it clear what is meant by reality. At present, this is not clear since it all seems to be dependent on the act of

measurement. I developed the quantum potential interpretation which tries to remedy the incompleteness of quantum mechanics by fusing the concepts of particle and wave together, rather than just sticking to one of them. This new ontological basis for the quantum theory assumes that the electron is a particle accompanied always by a wave satisfying Schrödinger's equation. This wave determines what we call the quantum potential, which has qualitatively new features that account for the difference between the classical theory and the quantum theory. A particularly striking feature is that in a many-body system, the quantum potential depends on the overall quantum state in a way that, unlike classical potential, it cannot be expressed as a pre-assigned interaction among the particles. This is what I mean by the new quality of quantum wholeness whose deeper implications we have tried to clarify. I think more work needs to be done on the field theory and on the relativistic approaches using the quantum potential model. At present, it provides a reasonable approach towards understanding the queer features of quantum mechanics such as non-locality but eventually one should try to get some deeper understanding of the origin of the quantum potential.

ST: It appears that all the standard quantum mechanical results can be reproduced from the quantum potential interpretation. Are there any new predictions from your model?
Bohm: Not the way it's done. There are no new predictions because it is a new interpretation given to the same theory. At this stage, we say that it enables you to comprehend what is going on, which may make new progress possible. De Broglie had proposed part of this concept in 1927 at the Solvay Congress, but it was rejected. This was partly because he couldn't deal with the many-body problem, partly because of the positivistic bias at the time along with the fact that Einstein did not like it. Later I showed that the many-body problem could be adequately dealt with using this new approach.

ST: What prompted Einstein to object to this idea?
Bohm: Einstein never stated his objections clearly; I think he must have sensed that it would involve non-locality. He felt that it was too cheap, that is, just putting particle and wave together was too simplistic. He wished that something deeper should have come out of it. He may have been right but, in my view, in the absence of deeper ideas, it's better to have this than none at all.

ST: Your book Quantum Theory *(Prentice Hall, 1951) is considered to be a standard treatise on the subject. How do you now feel about this book? Do you propose to revise it?*
Bohm: To revise this book would be as much work as to write another one. If I were to write the book again, I would write it from another point of view.

ST: How did Einstein react to the spin version of his celebrated thought experiment (the EPR example) which you first proposed in your book?
Bohm: He saw it and he thought it was good.

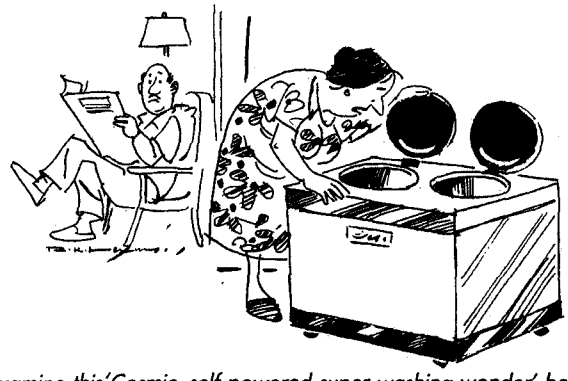
ST: How do you visualise the next 60 years of quantum mechanics?
Bohm: I guess that quantum mechanics is going to be limited in some way. The Planck length, which links together the gravitational constant, the speed of light and Planck's constant, is, in my view, the limit of all three theories—the quantum theory, the relativity theory and the gravitational theory. Beyond this limit, something entirely new must emerge, some new notion of time and space. In regions smaller than 10^{-33} cm, ordinary notions of time and space cannot hold because the whole metric is so indeterminate that we cannot distinguish between the past and the future. I think people are approaching this limit, in some sense, with the Grand Unified Theories in particle physics.

ST: What about the present state of the unification of quantum physics with gravity?
Bohm: That's not very clear. There are some physicists who doubt whether quantum mechanics should be applied to gravity, but I think that probably it should be. My own feeling is that the present attempt at quantising gravitational theory is something like quantising hydrodynamics. They start with quantum mechanics, take the classical limit and requantise. It may be heuristically useful, but not clear. I think gravity is like the hydrodynamical approximation to something else, which has to do with the new physics near 10^{-33} cm.

ST: In retrospect, looking at your vast experience and the eminent physicists with whom you interacted, who have particularly influenced you?
Bohm: In each period, there was a different person. When I was at Berkeley, I talked a lot with Weinberg and he got me interested in complementarity and philosophical problems. Oppenheimer had also a tremendous effect at that time. Later, Einstein had a profound influence. Just talking to people has been important. The point is to interact with people and share ideas. My ability to collaborate with Basil Hiley at Birkbeck College had an extremely important effect on what I did over the past many years.

ST: How do you prefer to relax?
Bohm: I like to walk a great deal, but since I've had a cardiac bypass operation, I must moderate that. I read, talk with people, listen to music by Beethoven and Mozart. I prefer to read philosophy from time to time.

ST: What would be your cardinal advice to young physicists?
Bohm: I think it's most important to remain open-minded and not to get stuck in prejudices. ST



Did you examine this 'Cosmic, self-powered super washing wonder', before buying? It contains two plastic buckets, a cake of soap and a wooden washing board!