Niels Bohr, the man

His mode of doing physics, "man to man" as in a tennis match, his insights into quantum theory and indeterminacy, and his work for an open world were all infused by his principle of complementarity.

John Archibald Wheeler

The fall of wartime 1944. Connecticut Avenue in downtown Washington. A broad sidewalk. One physicist from the du Pont plant at Hanford, Washington, producer of plutonium, walking alongside two from Los Alamos, customer for that plutonium. From Los Alamos, Aage Bohr, the son, and Niels Bohr, the father: an immensely impressive figure, widely regarded as the world's most responsible man of science. A few days before, thanks to the friendly offices of Supreme Court Justice Felix Frankfurter, the deeply concerned Bohr had had his long and historic discussion with President Franklin D. Roosevelt on weapons control, the higher politics of international relations in the coming nuclear age and the ideal of the open world. "How can such a man as I," Bohr said early in that long walk, "speak about these issues to the leader of such a country in the midst of such a war? But I put it simply to him as man to man; what other way is there?"

"I put it to him as man to man"! That phrase epitomizes Bohr's way of life as well as his way of doing physics. Public statements were not for him, nor were press conferences, nor were winged phrases to catch the public eye. No. His way of doing physics was man to man. His way of making headway on any great issue was man to man. His effectiveness derived not from publicity, but from its direct opposite, man-to-man dialog, private persuasion, the hold of his eyes and voice and reasoning on his partner in colloquy.

A special sense of judgment Bohr certainly had, and a marvelous physical insight, but above all a unique gift for making progress through dialog. And what dialog! What wonderful mixture of jokes and optimism and utmost seriousness! What issue of physics would be taken up in any given year at Bohr's institute as it was in the old days, in that modest building, in that stucco structure, smaller than many a house? Bohr distilled the central issue out of dialog with those who were themselves distillers of issues, former collaborators and special visitors. He knew that nobody can be anybody without somebodies around. Among the somebodies—for one extended period or another—were Paul Dirac, Rudolf Peierls and E. J. Williams of Britain, Hendrik Casimir, Paul Ehrenfest and Hans Kramers of the Netherlands, Werner Heisenberg and Lise Meitner of Germany, Léon Rosenfeld of Belgium, Wolfgang Pauli of Switzerland, Vladimir Alexandrovitch Fock, George Gamow and Lev Landau of the Soviet Union, Oskar Klein of Sweden, Yoshio Nishina of Japan, and John Slater and L. H. Thomas of the United States.

The single-hearted attention that Bohr gave to such a colleague showed nowhere better than in the way the two men walked up and down outside the Institute. They might share a less private discussion in the upstairs Institute lunchroom to which so many members brought the open-faced sandwiches—smørrebrød—purchased down the street. However, soon the talk would focus again more sharply on the issue that had been, or was in the course of being, "smoked out." Bohr would take the visitor away to his office, often carrying along his "right-hand man" of the moment—Rosenfeld or E. J. Williams, for example, in 1934–35. Bohr went round and round the table as he talked or joked, expostulated or reflected, his whole soul taken up in the action. He stopped to make an especially strong point—or to listen briefly. His words were forceful. His voice was soft. His glance was piercing as he looked up from time to time and stared into one's eyes. His mood changed from moment to moment as dictated by the discussion itself: for making a point, "How could one possibly believe. . . ." or "There is not the slightest evidence that. . . ." If in doubt, his head tipped to one side as he spoke to one position; to the other, as he spoke to the opposite position.

Physics as tennis

Explanation was never dry pedagogy, but a one-man tennis match in which Bohr hit the ball from one side of the court, then ran to the other fast enough to hit it back—the more volleys, the more enjoyable the game: "Such-and-such an effect leads one to expect thus-and-so. . . . Indeed one does see thus-and-such, but then so-and-so observed such-and-such. . . . That finding put us in immense difficulty. Just at this point so-and-so pointed out that the proper formulation of the principle is not what we thought, but thus-and-thus. . . . This discovery brought the whole subject into order. But then so-and-so realized that this extended prin-

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Niels Bohr, standing in the Carlsberg mansion's garden, in 1955.

ciple stands in absolute contradiction to the stability of such-and-such.... This discrepancy convinced us that we were absolutely lost. But just today we find that the new formulation itself is really complete nonsense.... What fools we have all been! We have only to recognize such-and-such and we see at last that absolutely everything has to be exactly as it is."

From time to time, to make a point or lighten the atmosphere there would come a joke. A favorite of Bohr was the definition of a "great truth" as "a truth whose opposite is also a great truth."

Of all ways to tell the visitor of some new finding at the Institute, and convince him of it, and to tell him how to convince others, it would be difficult to imagine a single way at the same time more modest and more effective than this "explanation-by-tennis"; but for those who were not just visiting, it was only a warm-up for the real tennis match. In it the colleague himself knocked the ball back and forth with Bohr. The spirit might have been the game for the game's sake, but the excitement came from expectation of the unexpected. The best witness to the level of the dialog was the level of the participants, from Kramers to Heisenberg and from Peierls to Pauli. How else could a man keep his serve in such an encounter except to make his own point of greatest concern?

Sometimes a week or two would go by without a meeting. When it came, perhaps three or four of us would gather with Bohr in his office or another room to discuss some then worrisome point. To bring about a seminar it took a visitor, perhaps an experimental physicist and former col-

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Intense discussion with Werner Heisenberg (center) and Wolfgang Pauli, in the lunchroom of Bohr's institute in Copenhagen.

Congress at Bohr's institute in 1936. These seminars were often the starting point of an intense effort to solve a current problem in theoretical physics—with Bohr alternately taking both sides of an issue. Only rarely did the seminars conclude with dull finality: "It was an interesting seminar."

laborator from Poland, or a new and important paper reported by someone at the Institute, perhaps Carl Jacobsen, Christian Møller or Rosenfeld. The attendance in 1934–35 ranged from one to two dozen. The language was usually German, occasionally English.

The joy was to have something that "wouldn't fit." The central idea of the Institute was clear, "No progress without a paradox." Most seminars were successful in the sense that Bohr broke in halfway through or sooner to solve the puzzle or explain the central point at issue. He would get to his feet and, reflecting as he kept talking and pacing up and down before the blackboard, encourage himself by saying every now and then, "Now it comes, now it comes." Suddenly it really would come, and he would give the explanation to the group as another tennis match. It was more reminiscent of soccer, however, where he had played with a leading team, to see the way he plunged into the middle of things, found that central point, seized on it and delivered it with great force to all assembled. Only rarely was it that the worst happened: Nothing came up that surprised anyone, and Bohr had to utter those dreaded words, "It was an interesting seminar."

Usually the new issue became a focal point for discussion in the next days. Those days could almost have been numbered odd and even. One day was a day of building. "If so-and-so is true, such-and-such follows. That will give us the chance to understand thus-and-so. That means it will be absolutely central to measure this-and-this cross section. Then we will be able to predict such-and-such with great assurance." No criticism. That was reserved for the next day. If at its end anything survived, that battle-tested core became the starting point of yet another day of building—and so on, up to a conclusion that could be played out as a complete tennis match.

The principle behind this all-yes drive one day, all-no drive the next, is familiar in everyday life. We have lost our keys. But was it at home—or at the office? We will have little success in finding them by prowling the ground halfway between the two locations! We know we have to put all our effort into searching at the one place, then all our enthusiasm into searching at the other!

Was it the secret of Bohr's success in discovery to believe in one idea one hundred percent one day and work on it with all the force of his being? And another day to adopt with equal single-mindedness the directly opposite view?

Who ever saw Niels Bohr make progess with an idea except in dialog or dictation or sudden revelation out of the depths of the subconscious? Always the end desired was a harmonious account of a wide range of experience. For this purpose he kept a continuous, slow fire under about 15 topics. They ranged from the angular momentum of light to dispersion relations for reaction cross sections in the continuum and from stopping power to superconductivity. He stored preliminary drafts of papers on each in a little cabinet in his office, just off the Pompeian court of the mansion at Carlsberg, where he did his dictation on any issue of importance.

The great hero of a long war bears on his breast not only the splendid medals of great victories, but also a long array of ribbons, each standing for some lesser engagement won by virtue of his enterprise. Nothing, except Bohr's modesty, keeps us from thinking in imagination of his chest, too, similarly decorated for all time by his grateful colleagues.

The medals, ribbons, sculpture

The newcomer to the world of physics soon learns of Bohr's glittering stars, but has little conception how long his array of ribbons is. The stellar list gives only a faint conception of the immense list of pregnant ideas that he contributed—from the theory of diamagnetism and the quasiradiation theory of stopping power to the ideas behind the Thomas precession and the Zeeman effect, and from "the Pauli principle before the Pauli principle" and the predictions that led to the discovery of halfnium to the explanation of the Ramsauer scattering of slow electrons by atoms and the contributions of U^{235} and U^{238} to the slow- and fast-neutron fission of uranium, to cite a very few of them.

And what now about the shining medals? What happy encapsulation of his very greatest discoveries and concerns can we find? Stroll, shall we, about the Princeton campus? Visit one great sculpture after another in the impressive outdoor collection of monu-

mental art given by the Putnam family! Come at length, in the courtyard of the physics building, upon that beautiful bronze piece by Antoine Pevsner, "Construction in the Third and Fourth Dimension," dedicated to the memory of Niels Bohr. At its base, on the north side, incised in black granite, we read, "Niels Bohr 1885–1962." On the east side, we read, "Elucidator of the structure of the atom and the structure of the nucleus." On the west, we find inscribed, "Author of the principle of complementarity," and we see the famous yin–yang symbol of the Orient and the Latin words, *Contraria sunt complementa*: They epitomize the central idea of modern quantum theory, complementarity. On the south, we read words out of Bohr's famous June 1950 "Open Letter to the United Nations." There he had at last departed from his practice of private advocacy and had spoken publicly for the principle of an open world. "The goal to be put before everything else," he said, "is an open world where each nation can assert itself solely by the extent to which it can contribute to the common culture and help others with experience and resources." The letter then concludes:

> Any widening of the borders of our knowledge imposes an increased responsibility on individuals and nations through the possibilities it gives for shaping the conditions of human life. The forceful admonition in this respect which we have received in our time cannot be left unheeded and should hardly fail in resulting in common understanding of the seriousness of the challenge with which our whole civilization is faced.... The efforts of all supporters of international co-operation, individuals as well as nations, will be needed to create in all countries an opinion to voice, with ever increasing clarity and strength, the demand for an open world.

Atomic structure, nuclear structure

Star number one, medal number one, is Bohr's theory of atomic stability. It is wrong to symbolize the central concept by that widespread logo of our era, a nucleus encircled by ellipses. Elliptic orbits were the last detail to concern Bohr. He grappled day after day, week after week, in those months of work at Ernest Rutherford's Manchester, with a far deeper issue. What keeps matter from collapsing? That great collection of positive and negative electric charges that constitutes a "solid body": Why doesn't it fall together and disappear in a microscopic fraction of a second? How can *anything* exist?

We find many a wild idea of how nature prevents this "electric collapse" in that premier journal of physics of the 1910s, the *Philosophical Magazine*. Give up Coulomb's law for the force between charged particles? Or abandon the familiar expression for the radiation of energy by an accelerated charge? Who hesitated at such suggestions? In contrast to those who made these and other radical proposals, Bohr was a daring conservative: conservative against postulating any change in the battle-tested laws of physics, but in the application of them, daring.

Bohr did not give up the inverse-square force between electron and nucleus, as did J. J. Thomson. He did not try to claim that a charged particle will circulate in orbit without radiation. But he did insist that the quantum must be as essential to the Rutherford atom as it is to the Planck heat radiation. Immediate confirmation that this was the right way to think he found in the very simplest dimensional arguments about atomic sizes and the energy of binding of electrons. Having made clear to himself this wonderful point of the centrality of the quantum, Bohr could go on to the next issue, the spectroscopic evidence on hydrogen, ready to appreciate this message as no one before ever had. The circular and elliptic orbits came at the end of this explanation, not at the beginning. (See the article by John Heilbron, page 28.)

Bohr's very industry on the atom almost kept his findings from the world. We are mistaken if we think of the clarification of the hydrogen atom as the be-all and end-all of his labors at Rutherford's Manchester center. Week after week went by, and still Bohr held off from any publication. Rutherford's expostulations grew stronger. Bohr protested: "But nobody will believe me unless I can explain every atom and every molecule." Rutherford was quick to reply, "Bohr, you explain hydrogen and you explain helium and everybody will believe all the rest."

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Ernest Rutherford with Bohr, and (in front) Margrethe Bohr, Rosa Oliphant and Mary Rutherford. (Photo by Mark Oliphant)

Rutherford, it is well known, did not trust theoretical men. "When a young man in my laboratory uses the word 'universe,' " he once thundered, "I tell him it is time for him to leave." "But how does it come," he was asked on another occasion, "that you trust Bohr?" "Oh," was the response, "but he's a football player!"

We recall that Bohr's original semiclassical theory did not even succeed in explaining the spectrum of helium. Nevertheless, it took less than ten years after his original publication for his general concept of the atom to sweep the field.

The failure of the theory to predict correctly the spectrum of neutral helium was redeemed in part by its triumph in identifying and explaining the slightly shifted spectrum of ionized helium and by the subsequent, more precise spectroscopic confirmation of this diagnosis. However, it meant much more for the world's acceptance of the new atomic theory that it made sense and gave reasonable results for the structure of atoms all the way up and down the periodic table.

Few there are today who know the immense toil on atomic theory in the Copenhagen of the late 1910s and early 1920s. It gave us, essentially correctly, and before the advent of wave mechanics and Hartree fields, such concepts as the screening number and the self-consistent atomic field, and the order of building of the elements. Bohr was never content with pioneering a new domain of physics. He had the doggedness and sense of order to insist that the new idea be tested and exploited to the full to provide a completely harmonious account of a whole domain of experience. It is no wonder that Einstein wrote of him that he "has the highest form of musicality in the sphere of science."

Bohr took immense care, and showed a unique ability, to make statements that repay intensive study: repay, because they combine maximum emphasis on what is known and maximum circumspection about what is unknown. Nowhere does this unique ability show earlier, with greater force, than in Bohr's first paper, in 1913, on the structure of the atom:

> The principal assumptions used are:
> (1) That the dynamic equilibrium of the systems in the stationary states can be discussed by help of the ordinary mechanics, while the passing of the systems between different stationary states cannot be treated on that basis.
> (2) That the latter process is followed by the emission of a *homogeneous* radiation, for which the relation between the frequency and the amount of energy emitted is the one given by Planck's theory.

The same ability to sort the known from the unknown, and to tread along the line between them without overstepping it, shows in star number two, his pioneering contributions, sung and unsung, to our understanding of nuclear structure and nuclear reactions, a story too long to be told here.

Indeterminism, complementarity

Bohr's sound judgment of what should be considered as known and sure foundation to stand and build upon, and what should be circumnavigated as unknown, shines nowhere with greater brilliance than in star number three. If modern quantum theory is the overarching principle of 20th-century physics, then Bohr's principle of complementarity is its shining keystone.

With our detecting devices, complementarity tells us, we can ask one question of nature, such as the position of an electron, or a complementary question, such as the momentum of that electron; but nature is so built that the asking of the one question automatically excludes us from asking at the same time, in the same connection, the complementary question.

Complementarity had a place in almost every Bohr discussion. When he received the Danish equivalent of a knighthood, the Order of the Elephant, and was required to supply a heraldic motto, he made it *Contraria sunt complementa*.

Werner Heisenberg, on his last visit to the United States before his death, remarked how—right after the time of his own paper on the principle of indeterminism—he was out sailing with Bohr and was explaining to their sailing partner, Niels Bjerrum, the contents of the article. After hearing him out Bjerrum turned to Bohr and said, "But Niels, this is what you have been telling me ever since you were a boy."

Bohr's own deeper formulation of the central content of quantum theory, complementarity—subsequently to be widened by him to stress the elemen-

Memorial statue, dedicated to Niels Bohr, by Antoine Pevsner. This statue stands in the courtyard of Jadwin Hall at Princeton University; the four sides of the base carry the inscriptions reproduced here. (Photo by Robert P. Matthews.)

tary quantum phenomenon, brought to a close, as he put it, by an irreversible act of amplification—he put forward only some months later, at the Como conference of September 1927 and the following Solvay congress. On 11 November, after that second meeting, in Brussels, Paul Ehrenfest wrote to his Leyden colleagues, Samuel Goudsmit, George Uhlenbeck and Gerhard Dieke, that "Brussels-Solvay was fine! Lorentz, Planck, Einstein, Bohr, Heisenberg, Kramers, Pauli, Dirac, Fowler, Brillouin, Bragg, Compton, Langmuir, Schrödinger, [Born], de Broglie, Curie, Wilson, Richardson, Knudsen, Debye and I. BOHR towering completely over everybody. At first not understood at all,... then step by step defeating everybody.

"Naturally," Ehrenfest continues in his letter, "once again the awful Bohr incantation terminology. Impossible for anybody else to summarize. (Poor Lorentz as interpreter between the British and the French who were absolutely unable to understand each other. Summarizing Bohr. And Bohr responding with polite despair.) (Every night at 1 am Bohr came into my room just to say ONE SINGLE WORD to me, until 3 am.) It was delightful for me to be present during the conversations between Bohr and Einstein. Like a game of chess. Einstein all the time with new examples. In a certain sense a sort of Perpetuum Mobile of the second kind to break the UNCERTAINTY RELATION. Bohr from out of philosophical smoke clouds constantly searching for the tools to crush one example after the other. Einstein like a jack-in-the-box: jumping out fresh every morning. Oh, that was priceless. But I am almost without reservation pro Bohr and contra Einstein. His attitude to Bohr," Ehrenfest confessed, "is now exactly like the attitude of the defenders of absolute simultaneity towards him."

Einstein continued unconvinced, and in a letter to Schrödinger the spring of the following year wrote, "The Heisenberg–Bohr soothing philosophy—or religion?—is so cleverly concocted that for the present it offers the believers a soft pillow of repose from which they are not so easily chased away. Let us therefore let them rest."

Einstein was not to be satisfied, then or to the day of his death. He performed a service for the whole community by drawing together the embers of discontent with quantum theory into a flame that could be seen and struggled with.

Bohr, true as always to his man-to-man way of doing physics, took the initiative time and time again, year after year, to seek out Einstein, to probe his deep-down reluctance to accept complementarity, and to try, by bringing new clarity, to bring agreement. A discussion between them, always friendly, and punctuated now and then by a joke, was also deadly serious. If Einstein—that Einstein who taught us in 1905 that "God plays dice"—if Einstein by 1927 could joke, "God does not play dice," Bohr could reply, "Einstein, stop telling God what to do." If Einstein could object, "If a person, such as a mouse, observes the universe, does that change the state of the universe?" and could protest that quantum theory is incompatible with any reasonable idea of reality, Bohr could reply that that idea of reality is too limited. Only by seeking out and facing up to every objection of importance put up by anyone anywhere did Bohr give quantum theory that battle-tested status that it holds today: foundation stone in the century to come, surely, for a still-greater advance—conceivably even, some today dare to hope, that all-encompassing view of the great plan of existence that mankind has always sought.

The demand for an Open World

We come now to the fourth battle medal, the fourth star, the final inscription at the base of the Pevsner sculpture, Bohr's concept of the "Open World."

What turnabout had taken place in six years in his thinking about nuclear weapons? In 1944 it had been his hope that man-to-man private discussions between Churchill, Roosevelt and Stalin could result in an agreement between the great powers for control of A-bombs before the secret of their existence burst upon an unprepared world. Control of the new devices, he believed, should be the first step in establishing openness among nations. Subsequent developments convinced him that the order had to be reversed:

Third Washington Conference on Theoretical Physics, 18 February 1937. Among the participants are: Hans Bethe (front row, center), I. I. Rabi (just behind Bethe), Bohr, George Gamow (behind and to right of Bohr), Felix Bloch (far right), Wheeler (behind Gamow), Gregory Breit (behind Wheeler), Merle Tuve (back row, far left), Eugene Wigner (in front of Tuve), James Franck (third right from Tuve), Wendell Furry (just in front of Franck) and Edward Teller (just right of Furry, partly hidden).

not first control, then openness; but first openness between nations as a prerequisite for control of nuclear weapons.

The reasoning behind this conclusion he makes clear in the very letter itself that he sent to the United Nations from Copenhagen on 9 June 1950, a few days before the totally unexpected invasion of South Korea by North Korea. "The very fact," Bohr reasons, "that knowledge is in itself the basis for civilization points directly to openness as a way to overcome the present crisis. . . . Full mutual openness, only, can effectively promote confidence and guarantee common security."

What events had immediately preceded Bohr's open letter to the United Nations? Nine months before its sending had come the explosion of the first Soviet A-bomb. Seven months before Bohr wrote the letter, the world had learned of Klaus Fuchs and the secrets of atomic and hydrogen bombs that he had given to the Soviets. Then had come a debate, first in official circles, then in the press, month by month more intense, whether the West should push the construction of a hydrogen bomb. The controversy had culminated in Harry Truman's forthright order, "Go ahead." A visitor staying at that time in the house of Bohr in Copenhagen, and deeply troubled through the night whether to put aside his own research and accept the urgent call to go to Los Alamos, will never forget the impact of Bohr's words over breakfast, "Do you imagine for one moment that Europe would now be free of Soviet control if it were not for the atomic bomb?" Incentive enough there was in these developments for Bohr to conceive and write his famous letter. Still more incentive there surely would have been for the world to pay attention to it if everyone could have foreseen that the first Soviet H-bomb explosion would come only nine months after the first (1 November 1952) Western H-bomb explosion!

We are seeing today the beginnings of a battle for the minds and hearts of men everywhere. In that battle, no weapon of the democracies is more powerful than the ideal of the open world. As Bohr himself put it in his June 1950 open letter

> Such a stand would . . . appeal to people all over the world, fighting for fundamental human rights, and would greatly strengthen the moral position of all supporters of genuine international cooperation. At the same time, those reluctant to enter on the course proposed would have been brought into a position difficult to maintain since such opposition would amount to a confession of lack of confidence in the strength of their own cause when laid open to the world.

Industry and sense of responsibility

How can one know Bohr, the man, unless one conceives in imagination the hours, days and months that he devoted to developing first the doctrine of control, then the principle of the open world; the leaders with whom he conferred; his many wartime crossings of the Atlantic—Europe to America on empty troop ships, America to Europe by flying boat—and the draft paper after draft paper that he prepared? Bohr brought a combination of total humility and total commitment to the political requirements for peace. He brought a total humility and total commitment to every question of principle in physics. That spirit of the man is best to be seen in some of his favorite words, from Theodor Fontane:

> Gaben, wer hatte sie nicht
> Talent, Spielzeug für Kinder
> Erst der Ernst macht den Mann
> Erst der Fleiss das Genie;

or, in translation:

> Gifts? Who hasn't?
> Talent? Toy for children!
> Commitment, only, makes the man;
> Only diligence, genius.

We think of Bohr's industry in the cause of peace and the open world as we look at the words on the south side of the Pevsner sculpture. As we turn to the east side we recall again his labors—and achievements—in magnificently elucidating the structure of the nucleus and the structure of the atom. Finally, when we take leave of the glowing bronze shape, we see again on its western side that yin–yang symbol of the faith that guided this industry, that achieved these discoveries, and that made him the master thinker of quantum theory, our help in decades past, our hope in time to come, deepest subject in all of science, the faith that he distilled into the motto, *Contraria sunt complementa*. What we take to be contradictions are not contradictions, he tells us; they are complementary insights. Each gives part of the story. Our picture of the truth is not complete without both. Complementarity, in this sense, he considered a guide to human problems of such universal use that it should be taught to every child in secondary school.

No great human issue left Bohr indifferent. From the rise in expectations of the humblest inhabitant of a Third World country to the plight of blacks in some parts of the United States, and from the Achilles heel of gangster governments to the mutual enrichment of diverse cultures, every broad issue that combined importance for the world with "do-ability" was the subject of deep thought and intense conversation with everyone who cared, from king to cleaning woman and from ambassador to fellow scientist.

Bohr was a great scientist. He was a great citizen of Denmark, of the World. He was a great human being.

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