

# Great Connections Come Alive: Bohr, Ehrenfest and Einstein

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On an occasion like this an appropriate scriptural text cannot be out of place, and which text could be more appropriate than this one from Ecclesiasticus: "Let us now praise famous men, and our fathers that begat us. The Lord manifested in them great glory, even his mighty powers from the beginning." Praising our great predecessors fulfills a deep human need, but one might question whether it is a historian's task. Perhaps one measure of the greatness of those we would praise is the degree to which such praise is indeed compatible with the professional obligations of the historian. I have no doubts on that score today.

Commemorating a great scientist of the past normally means celebrating his work—exploring what it has meant to the development of his subject and how it has opened new aspects of the world to our understanding. That, very properly, is what we have been doing at this symposium to celebrate Niels Bohr's centennial. We have been acting in the spirit of what Einstein wrote when Isaac Newton's tercentenary was being celebrated in 1942: "To think of him is to think of his work." [1] I would not want to take issue with the truth of Einstein's remark, but when we apply it to Bohr, or to Einstein himself, this truth becomes a "deep truth." Let me remind you that "deep truth" is a term that acquired a very specific meaning in Bohr's Copenhagen. In contrast to a truth, which is a statement whose opposite is clearly false, a "deep truth" is a statement whose opposite also contains deep truth. Surely when we think of Bohr's work, or of Einstein's, we must think of the men themselves. Their stature as human beings is comparable to the stature of their contributions to science. Their greatness as men is realized and embodied in the way they lived their lives in science. Of how many distinguished scientists could it be said: "However great a scientist he was, he was even a rarer phenomenon as a noble character"? [2] How many could be described as men "whom it is good to have known and consoling to contemplate"? [3] These words were used about Bohr and Einstein, respectively, but could have been applied to either.

These two lives, remarkable enough individually, were linked in an equally remarkable way. Bohr and Einstein knew each other for thirty-five years, but met only infrequently. What we know about the ways in which they shared their concerns for the fundamental issues of physics comes in large part from the

wonderful essay Bohr wrote for Einstein's 70th birthday, his "Discussion with Einstein on Epistemological Problems in Atomic Physics" [4]. Written after a quarter of a century of their profound searching into the depths of quantum physics, Bohr's essay necessarily laid stress on the nature of their disagreement on fundamental issues. By doing so he wanted to emphasize how strongly he had been influenced by Einstein's critical attitude, and how positive an influence his occasional meetings with Einstein had been on the development and clarification of Bohr's own position. He did not, perhaps unfortunately, sufficiently convey to his readers the warm personal ties that bound the two men.

It would be natural to assume that we could supplement Bohr's essay and learn more about the nature of that friendship by studying the Bohr-Einstein correspondence. We find, however, only a handful of letters exchanged over the years. These are impressive and interesting, to be sure, but they do not give us the detailed record of developing ideas and personal interactions we might have hoped to find. The communication between Bohr and Einstein, indeed the close intellectual and emotional ties that bound them, involved a third man, Paul Ehrenfest, who played an essential role in their relationship.

It may not be too much to say that Ehrenfest himself was one of the strongest links between his two great friends. His rich and extensive correspondence with them and with others presents us with a fresh and lively picture of Bohr and Einstein as they appeared to an unusually perceptive contemporary of their own generation. Ehrenfest did not change physics as his two close friends did—and no one knew that better or felt it more keenly than he—but he was in his own way as extraordinary a human being. "Passionately preoccupied with the development and destiny of men," as Einstein wrote of him, "his relations with his friends played a far greater role in Ehrenfest's life than is the case with most men." [5] Fortunately for us, as it was for him, Bohr and Einstein were two of these friends.

Bohr came to know Ehrenfest before he met Einstein. Perhaps surprisingly, it was Bohr who took the first step toward Ehrenfest by writing to him in the spring of 1918. To see why it happened this way and at this particular time we must have a look at the background of their first encounter. Bohr was thirty-two at the time he wrote, and had been professor of theoretical physics at Copenhagen for two years. His name was already known to physicists everywhere for his brilliantly successful theory of the hydrogen atom and its spectrum [6]. This novel combination of the quantum ideas of Planck and Einstein with Rutherford's nuclear atom depended crucially for its success on Bohr's bold departure from all past theories of the emission of light. According to Bohr, the frequency of the light emitted by an atom was not the frequency with which anything in the atom actually moved. The audacity of this step was, however, balanced by Bohr's careful concern to show that his new way of determining the frequencies emitted did correspond to the classical results in the limit of long wave lengths. In undertaking to write "On the Constitution of Atoms and Molecules", as Bohr did in 1913, he knew that he would be exploring a domain new to theoretical physics, a domain dominated by the remarkable stability of these small structures [7]. He knew too that the novelty of this domain demanded constant attention to the guides provided by successful past

explorations of more familiar regions of experience, together with a mastery of the phenomena continually being found along the way.

The famous trilogy of papers of 1913 was followed by several more during the next couple of years, but since 1915 Bohr had not published anything. Not that he had been idle. It was in the first years after his return from Manchester to take up his professorship at Copenhagen that J. Rud Nielsen was struck by

“... the speed with which he moved. He would come into the yard, pushing his bicycle, faster than anybody else. He was an incessant worker and seemed always to be in a hurry. Serenity and pipe-smoking came much later.” [8]

Bohr had much to keep him busy then, including his teaching and the early planning for the new institute of theoretical physics whose construction was approved by the university faculty in 1917 [9]. But his greatest efforts went into his own research.

During the war much progress was made on the quantum theory and its application to atomic spectra. Bohr followed this closely, and continually reviewed and revised his own thinking in the light of what he learned. But despite his admiration for the elegant new mathematical methods introduced in Arnold Sommerfeld's papers—of which Bohr said “I do not think that I have ever enjoyed the reading of anything more than I enjoyed the study of them” [10]—Bohr went on searching for something deeper. He recognized, as others did, that “many difficulties of fundamental nature” remained unsolved, but he was especially aware of the basis reason for this fact: “it has not been possible hitherto to replace these [classical] ideas by others forming an equally consistent and developed structure.” And that structure was Bohr's goal.

He worked on a long paper that would try to unify what had been done so far, would bring out the assumptions underlying the existing theory, and perhaps “throw light on the outstanding difficulties by trying to trace the analogy between the quantum theory and the ordinary theory of radiation as closely as possible” [11]. In this work where the correspondence principle was developed, Bohr made important use of Einstein's new quantum theory of radiation and of Ehrenfest's principle of adiabatic invariance. He was one of the first to grasp the significance of Ehrenfest's work, and the adiabatic principle had been part of Bohr's set of working concepts for several years before 1918 [12]. Since this principle provided a criterion for finding some results of classical physics that would “stand unshaken in the midst of the world of radiation phenomena whose anti-classical quantum character stood out ever more inexorably,” as Ehrenfest would write later [13], Bohr found it especially attractive. He renamed it the “principle of mechanical transformability” to emphasize its connection with the necessary stability of the stationary states of a quantum system.

When Bohr finally had copies of the first part of his long paper in hand—he now saw it as the first of four parts—what could be more natural than to send one to Ehrenfest. He had not met Ehrenfest, but he did have some sense of what he was like through his conversations with Hans Kramers. Kramers had left Holland at the age of 22 after several years of study at Leiden, made his way to Copenhagen in 1916, and became Bohr's valued assistant, the first research student of the new

professor. Bohr's letter to Ehrenfest reported his pleasure in Kramers' progress, as well as discussing the value he placed on Ehrenfest's own work and explaining his changed terminology [14].

Ehrenfest received Bohr's letter and paper at a peculiar moment in his life [15]. He had moved to Leiden in 1912 to follow Lorentz in the chair of theoretical physics at its university. This prized position came to Ehrenfest at the early age of thirty-two, but he had already lived and worked in Göttingen and St. Petersburg, as well as in his native Vienna, which he detested. From the moment of his arrival in Leiden Ehrenfest had thrown himself into the creation of a genuine scientific community. His efforts succeeded quickly, and Lorentz noted with warm approval that Ehrenfest "had gotten the students talking." He also pursued his own ideas on a variety of physical problems, and strove valiantly to keep up with his close friend Einstein's work on the general theory of relativity, discussing it often with Lorentz. Some months before Bohr wrote to him, however, Ehrenfest had become fascinated by the problem of economic equilibrium [16]. He had put aside his work in physics and devoted all his energy to trying to develop the parallels between economics and thermodynamics. About the time he received Bohr's letter, Ehrenfest wrote Einstein that he was still "miles away from all of physics." He knew he would return eventually "full of remorse and ready to mend [his] ways," but for the moment physics had lost its charm [17]. His return to physics came much sooner than Ehrenfest expected.

Bohr's letter and his paper, "On the Quantum Theory of Line-Spectra" apparently succeeded in breaking the spell that mathematical economics had cast over Ehrenfest. There is some irony in this. Ehrenfest had not been one of those who instantly grasped the significance of Bohr's 1913 papers, who saw as Einstein had that it was an "enormous achievement" and "one of the greatest discoveries" [18]. On the contrary, in a letter to Lorentz written in August 1913 Ehrenfest commented: "Bohr's work on the quantum theory of the Balmer formula (in the *Phil. Mag.*) has driven me to despair. If this is the way to reach the goal, I must give up doing physics." [19] He had not changed his mind three years later, when he wrote to Sommerfeld to congratulate him on his theory of the hydrogen fine structure:

"Even though I consider it horrible that this success will help the preliminary, but still completely monstrous, Bohr model on to new triumphs, I nevertheless heartily wish physics at Munich further successes along this path." [20]

Ehrenfest had begun to change his mind when he saw the connections between the adiabatic principle and Bohr's theory, and encouraged his student Jan Burgers to write his dissertation on "the Rutherford-Bohr model of the atom" [21]. By the time Bohr's letter reached him, Ehrenfest was ready to receive it.

His reply indicated how very pleased he was to find that Bohr had given the adiabatic principle such a major place in his work, and that Bohr even appreciated Ehrenfest's point about the adiabatic invariance of the statistical weights assigned to the stationary states. "Oh, if you only knew how much aggravation I had until I managed to convince anyone that there was a problem here," he wrote. Ehrenfest was also happy to learn that Kramers was working so effectively. He liked Kramers very much and appreciated his ability, but Ehrenfest had been concerned about one

thing: “He always does only what comes easily to him at the time—nothing ever seems to seize him in such a way that he has even a little feeling of real urgency about it.” [22] Ehrenfest always had to feel that his students were possessed by their work before he was convinced they had a genuine vocation for physics.

Bohr had closed his letter with the hope that he would be able to come to Holland and meet Ehrenfest when the war was over. Ehrenfest responded in kind, in his own lively way. “I impatiently await the day when you enter our house as our guest.” And then he added a remark that showed how highly he had come to think of Bohr: “I hope that Einstein can also be with us then.” Within a few days Ehrenfest was back to physics, jotting down notes and questions on the quantum theory, ideas for further development prompted by his study of Bohr’s paper.

Ehrenfest wasted no time in arranging for Bohr to visit Holland. There was to be a meeting of Dutch scientists in April 1919, and in January Ehrenfest invited Bohr to take part, urging him to spend weeks rather than days in Holland, to stay with the Ehrenfests “for as long as you can stand it” in their chaotic household, and promising once again to try to get Einstein there at the same time [23]. Bohr probably had no way of knowing that Ehrenfest was hoping to provide him with the greatest gift he could imagine by trying to arrange for him to meet Einstein. Ehrenfest had compared his friend’s last visit to Leiden in 1916 with a marvelous concert, composed entirely of the finest music, a concert whose “echoes, that go on resounding inside you afterwards” offer as much satisfaction as the event itself. For Ehrenfest, Einstein was not only one of the “wonders of Nature” for his intellectual gifts, but also

“a marvelous interweaving of simplicity and subtlety, of strength and tenderness, of honesty and humor, or profundity and serenity (a somewhat melancholy serenity, to be sure).” [24]

While Ehrenfest, like Yeats, loved to “have the new friend, meet the old,” he did not offer to share Einstein unless he felt his gift would be properly appreciated.

Bohr’s visit to the Netherlands in the spring of 1919 was a great success, even though Einstein could not be there, regretfully declining despite his “intense wish” to meet Bohr, “that man of magnificent intuitive gifts” [25]. Bohr lectured at Leiden in English, the language in which he had published almost all his scientific work up to then. Ehrenfest had assured him that this would be no problem since all Dutch scientists spoke the language well. Ehrenfest did not, however, as he made clear when he introduced Bohr:

“Please allow me to welcome our honored guest, Professor Bohr, in the German language. I could, of course, do this in English, but then, to my great regret, it would be totally unintelligible, and this might be considered unsuitable.” [26]

His introductory remarks also showed that he had already learned something essential about Bohr. Ehrenfest expressed his conviction that this personal encounter with Bohr would give Dutch physicists “a much deeper sympathetic understanding of his ideas” than could be obtained by the mere study of his publications. He had now decided that Bohr’s ideas were not only well worth understanding, but

could be understood, despite the almost impenetrable form in which they sometimes appeared in the journals. Perhaps Kramers had told him of how one learned by working with Bohr day after day; perhaps Ehrenfest had now seen this for himself after only a few days in Bohr's presence. In any case he knew that Bohr in person was quite different from Bohr in print.

He devoted himself to making sure that Bohr's visit was a happy and fruitful one, introducing Bohr to the physicists of the Netherlands and making sure there was time for their unhurried talk, but also seeing to it that Bohr did not become exhausted by rushing from one conversation to another [27]. Ehrenfest knew how essential it was for a man like Bohr to have tranquil hours and days when he could be alone with his thoughts. He and Bohr had much to talk about together—from the current problems of the quantum theory to the Icelandic sagas, from the stages of a child's development to the difference between genuine physicists and the others. Their exchanges ranged over heaven and earth as Ehrenfest showed his new friend the treasures of the Dutch museums and the brilliant colors of the bulb fields [28].

Bohr was deeply moved by this encounter, calling it "a most wonderful time of the greatest intellectual enrichment." He tried to say how much this friendship meant but found that difficult. He then added,

"Dear Ehrenfest, you do not know how miserable and stupid I feel when writing this letter. I am sitting and thinking of all what you have told me about so very many different things, and whatever I think of I feel that I have learned so much from you which will be of great importance for me; but, at the same time, I miss so much to express my feeling of happiness over your friendship and of thankfulness for the confidence and sympathy you have shown me. I find myself so utterly incapable of finding words for it." [29]

The many-layered emotional and intellectual response evoked in Bohr by this meeting with Ehrenfest did not fade away after his return to Copenhagen. In a long letter written at the end of October 1919, Bohr returned to some of the matters they had discussed, and especially to some of the non-scientific issues. His comments in the middle of his letter on the problems of expressing certain kinds of ideas are worth quoting:

"Dear Ehrenfest, writing to you I feel so poor, not only in what I am thinking, but especially in means of expression. Although of course in general I express myself freer in English than in German I feel, when I want to enter on a question of finer sentiments, if possible a still greater poverty in English than in German, because in such matters it is the choice of the words and not their grammatical use which is essential, and in this respect the German words can almost always be got by direct transcription of the corresponding Danish word, while it is not so in English. Therefore, although I am happy being allowed to write to you in English, you must take what I write not as an image of what I like to say, but as a picture in which I am bound to restrict myself to use the limited number of colors given by my poor collection of English words." [30]

At another point in this letter Bohr used another metaphor to illustrate the "utter deficiency of our means of realizing and discussing ideas of 'irrational character'".

"You will see how right I am in trying beforehand to excuse my poor means of

expression, and you may take the foolishness I write, and the inadequate words I use, as disconnected ‘Anschläge’ on a musical instrument, where the only contents of the words are the chains of ideas and sentiments they automatically produce by reflex, just as you listen to the tunes produced by the instrument in harmonious connection with the original tone.”

During that same month of October 1919 Einstein paid his first post-war visit to Ehrenfest in Leiden. This visit came at a high moment in Einstein’s life, only a few weeks after he learned that the English eclipse expedition had confirmed the correctness of his predicted value for the gravitational deflection of light by the sun. To Einstein these two weeks spent with Ehrenfest were “really a beautiful and tranquil time”, a time that confirmed the importance of their friendship. “I know that it is good for both of us,” he wrote “and that each of us feels less of a stranger in this world because of the other.” [31]

Just as Ehrenfest had wanted to share Einstein with Bohr, he now was keen on sharing Bohr with Einstein and evidently sang the praises of his new friend. On his return to Berlin Einstein wrote that he was now going “to bury himself” in Bohr’s papers. “You have shown me that there is a man of profound vision behind them, one in whom great connections come alive.” [31] Since we know that Bohr remembered how, even as a child, he had liked “to dream of great interrelationships,” we can imagine how pleased he would have been to know that he was being characterized in this way [32].

Some six months later Bohr lectured to the German Physical Society in Berlin, speaking “On the Series Spectra of the Elements” [33]. It was on this occasion that Bohr finally met Einstein. For well over a decade, ever since the days when he was working on his doctoral thesis, Einstein had been a major presence in his intellectual life. From Einstein’s papers he had learned the indispensable role of the energy quantum in individual atomic events, the inevitability of energy quantization in accounting for thermal radiation, and the close connections between the essential features of his own atomic theory and the equilibrium of matter and radiation. No matter what Einstein was like as a person, meeting him would have been a major event in Bohr’s life. Nine years earlier, when he met J.J. Thomson soon after his arrival in Cambridge, Bohr had written to his brother Harald: “You should know what it was for me to talk to such a man.” [34] The prospect of a meeting with Einstein would have seemed even more momentous in Bohr’s mind, particularly after all he must have heard from Ehrenfest. Though Einstein was only six years older than he, Bohr would always see him as one of the grand masters, as if he were of another generation.

Bohr and Einstein hit it off as well as Ehrenfest hoped they would. In his first letter to Einstein, Bohr wrote:

“To meet you and talk with you was one of the greatest experiences I have ever had, and I cannot say how grateful I am for all the kindness with which you met me on my visit to Berlin... You don’t know how very stimulating it was for me to have the long awaited opportunity to hear directly your views on the questions that I have been working on. I will never forget our conversations on the way from Dahlem to your house...” [35]

Einstein, not usually given to emotional expression, was even warmer:

“Rarely in life has a person given me such joy by his mere presence as you have. Now I understand why Ehrenfest is so fond of you. I am now studying your great papers, and while doing this I have the pleasure—whenever I get stuck somewhere—of seeing your friendly youthful face before me, smiling and explaining. I have learned much from you, especially how you confront scientific matters.” [36]

Two weeks later Einstein was in Leiden telling Ehrenfest “with extraordinary warmth” about his meeting with Bohr. Ehrenfest’s reaction came in a card to Bohr saying: “When will I have both of you here together some time.” [37] That dream of Ehrenfest’s would not be realized for several years.

The meetings of Bohr, Ehrenfest and Einstein did continue, but as pairwise encounters. Einstein made a brief lecture tour in June 1920 speaking in Oslo and then in Copenhagen. His visits to both cities were major news events, drawing admiring crowds, and extensive coverage by the press [38]. For Einstein the best part of his trip was the hours he spent with Bohr, as he reported to Lorentz [39].

In April 1921 the first of the post-war Solvay Conferences was held in Brussels. All three men had been invited and planned to go. “I am looking forward to the new year more than I can say,” Bohr wrote to Ehrenfest in November 1920, “especially because it will bring me into personal contact with you and Einstein again; we shall all really meet together for the first time in Brussels . . .” [40] It did not happen that way. Einstein changed his plans, withdrawing from the Solvay meeting in order to go to the United States with Chaim Weizmann on a fund-raising expedition for the new Hebrew University in Jerusalem [41]. And at the last minute Bohr, too, found it impossible to go to Brussels. The years of intense scientific work, together with the great strain of planning and supervising every detail of his new Institute for Theoretical Physics, officially opened in March 1921, finally caught up with him [42]. About a week before the Solvay meeting was to begin Bohr had to withdraw; his doctor had ordered several weeks of complete rest [43].

His friends had been concerned for months about the extent to which Bohr was overworked. Since the previous August Ehrenfest had been urging Bohr to give up everything that was not absolutely essential, and in particular to cancel his plans to attend the Solvay meeting and give the review he had promised of the quantum theory of atomic structure:

“You understand that it is sad for me to lose this opportunity to see you and Einstein together, but I *still* advise you to do it. In any event decline to lecture—just come for the discussions!” [44]

At the end of December, Ehrenfest offered to help Bohr with the review he persisted in trying to write. This had been Lorentz’s suggestion [45] and Ehrenfest put it forward diffidently, emphasizing (by triply underlining the phrase) that he would do it only if Bohr wanted him to [46]. There was one real difficulty that had to be faced: the two men wrote in utterly different styles. The more Bohr worked over his manuscripts, the more complicated they became in their successive versions. As he understood a subject better and saw more deeply into its details and difficulties, he tried harder to qualify his remarks so that no shade of meaning, no



subtle difference between situations, could be overlooked by the reader. Bohr seemed to fear oversimplification more than anything else, and exerted all his efforts to avoid giving an illusion of clarity at the expense of suppressing some feature of the situation that did not fit into a simple pattern. As Pauli once wrote: "He knew well what he wished *not* to say when he strove in long sentences to express himself in his scientific papers." [47] Ehrenfest's way of dealing with physics was completely different. He tried always to seek out the one essential feature of a situation, sharpening the statement of a problem as much as possible—even pushing it into paradoxical form if he could—so that the solution could then appear with devastating clarity. He worked like a caricaturist, capturing the defining traits at the expense of all else.

Under these circumstances Ehrenfest proposed that all he could do to help Bohr would be to prepare a short manuscript composed of a series of propositions distilled from Bohr's papers. He feared, of course, that Bohr would not find anyone else's words an adequate expression of his ideas. "I would gladly adapt myself to your genetic way of thinking," Ehrenfest wrote "but I would still ultimately have to assert (or at least inquire into) a thesis, a proposition; it is inevitable that a few dogmatically hardened bones get stuck into the genetic mollusk." [46]

The printed proceedings of the Third Solvay Conference included both Bohr's draft of the first part of his promised report and Ehrenfest's brief distillation of the propositions that seemed to him to constitute Bohr's correspondence principle [48] that principle which appeared to some like a "somewhat mystical magic wand, which did not act outside Copenhagen", as Kramers once put it [49]. Although Ehrenfest made no attempt to deal with the complexities as Bohr would have, his article ends with remarks that express the spirit of Bohr's approach. Ehrenfest thought the deepest significance of the correspondence principle was that it seemed to come closer than anything else to that future theory, whose very outline was not yet apparent, which would be capable of handling the problems of radiation. For that reason it would be premature, he felt, to try to codify the current version of the principle just so that it could be applied more conveniently. One should accept its tentative nature, leaving it open to change. Ehrenfest had realized that Bohr was struggling to formulate a language for describing the new domain of experience provided by atomic physics, and he accepted Bohr's view that this struggle demanded its own methods. When he ended the text for the published version of his Solvay report this way, Ehrenfest might have been remembering some words that Bohr had recently written to him:

"Throughout this year, ever since the moment when I came upon the first traces of this conceptual structure, I haven't really been in a position until now to try to think things through in an orderly way. 'Think through' is a phrase that applies very badly in this domain where nothing is fixed and where everything really depends only on a feeling for harmony. But you don't know what great joy I have had recently, apart from some hours of doubt, and I should like so much to give you an impression of it, since you have had so much complaining and bother from me." [50]

By the end of June 1921 Bohr had recovered his strength and was making plans for the future. These included making an occasion to see Ehrenfest again, an occasion that would help to make up for the missed opportunity in Brussels. Bohr

invited Ehrenfest to come to Copenhagen at his convenience, to lecture or not, if he preferred just to lead some discussions. Money was available to cover travel costs, and both Ehrenfests would be made welcome at the Bohr home in the Institute. “I don’t need to tell you what an event it would be for all the Copenhagen physicists, and what a joy it would be for me and my wife.” [51]

Ehrenfest had been looking forward to such a visit for a long time, but Bohr’s letter stirred up mixed emotions. After days of staring at the letter sitting there at his desk and chewing on his pen, Ehrenfest finally poured out his feelings. First his “jubilation” at the opportunity to see Bohr and especially on his own home ground. “It was *splendid* to get your letter. But almost immediately thereafter gray depression and doubt crept in again.” All of Ehrenfest’s old self-doubt was revived. “What can *I* lecture on in Copenhagen? What would I know that Kramers, for example, doesn’t know much better and couldn’t say much better than I?” He also felt guilty because the same money could be better used to invite one of the many deserving physicists from the conquered nations (he listed no fewer than 17 of them!). But after going through a long litany of reasons why he should not accept, Ehrenfest did recognize what he could contribute by his visit:

“You see, I might really be useful for discussing subjects you propose, because it really isn’t totally useless for you to have to present your thoughts and conjectures to a listener who is tolerably critical, quick to understand, and anxious to learn. And I can, finally, also give lectures for other people (not for you!) if you make clear to me what you want from me. ... Dear, dear Bohr, I really would like so terribly much to be with you again.” [52]

Bohr was, of course, really anxious to have Ehrenfest and not some more or less worthy substitute. He knew his friend well enough to see past the self-doubt that tormented Ehrenfest, that peerless lecturer whom Einstein would call “the best teacher in our profession whom I have ever known” [53]. After many reassurances to this effect [54], Ehrenfest did finally make his trip to Copenhagen, the first of many, in December 1921. We know his reactions from a postcard he sent to Einstein after three weeks in Denmark:

“It is marvelously beautiful here—everything! He is a prodigious physicist. I sound to myself like a badly told joke when I open my mouth in his presence. A lecture of his will appear shortly in the *Zeitschrift für Physik* (the manuscript goes off tomorrow), in which he explains how he has now deciphered the structure of *all* the atoms. It is something tremendous, both methodologically and for its results. ... I felt so happy in Bohr’s house, happier than I have been in a long time. ... If only my poor wife weren’t so miserably stuck at home, I would be completely joyful now and would wish for nothing more than to be Bohr’s assistant.” [55]

Ehrenfest described his impressions of Bohr in much more detail in a long letter he wrote to Lorentz after his return to Leiden. Best of all had been the possibility of talking to Bohr again and again about his work:

“To be sure, this is certainly not easy to do. In the first place he was overloaded with proof-reading, which he does in a completely grotesque way, because he incessantly changes everything, making fundamental changes again and again—even in the galley proofs! In the second place it’s hopeless to put one individual question to him. He

reacts to that like a very rapidly spinning top, ‘completely transversely.’ His brother Harald consoled me by saying... ‘If Niels tells me something, I absolutely don’t understand for 59 minutes what he is talking about and what he is driving at, but in the 60th minute light suddenly dawns, and then I see that everything he had said before was really necessary.’ I eventually chose this procedure too: ask and then listen patiently and attentively to whatever follows, but just don’t come back to the question. In this way I learned an enormous amount but had hardly a tenth of my questions answered. Nothing is more impossible for him than to say ‘yes, yes’ or ‘no, no.’ If one grasps him with the yes-or-no tongs, he becomes very *wretched* like a caged bird.

He is a very, very great scientist. His way of developing the quantum theory is really very different from that represented by Sommerfeld’s book, for example. Thank God! His work is permeated by the conviction that we have just touched the *beginning* of an essentially *new* physics. His model of the atom is an extraordinarily symbolic symbol for him. At the same time he has a very powerful feeling for which features of the symbol should be taken inexorably seriously and which he may plainly ignore or at least treat very lightheartedly. (He once said in conversation, quite naively and not trying to be ‘witty’: ‘Oh no, I can’t believe that. That is much too concrete for it to be real; that is only formal.’)

Ehrenfest summed up his very lengthy report to Lorentz on Bohr and his work by writing:

“What I find so liberating in Bohr is that one can *think* again instead of just calculating.” [56]

On November 10, 1922 the Royal Swedish Academy of Sciences announced its choices for the Nobel prizes in physics. Since the Academy had deferred awarding the physics prize in 1921, it could now announce two winners: the prize for 1921 went to Einstein, and that for 1922 to Bohr. The very next day Bohr wrote to Einstein. His letter contained the following striking passage:

“To me it was the greatest honor and joy ... that I should be considered at the awarding of the prizes at the same time as you. I know how little I have deserved this, but I should like to say that I have felt it as the greatest good fortune that—quite apart from your great contribution to the world of human thought—the fundamental contribution that you have made to the more special field in which I work should be recognized and also quite publicly, just as the contributions of Rutherford and Planck were, before I was considered for such an honor.” [57]

Bohr’s letter finally caught up with Einstein in Japan, and Einstein’s answer was just as remarkable:

“I can say without exaggeration, that it pleased me as much as the Nobel prize. I find especially delightful your fears that you might have received the prize before me—that is genuinely ‘Bohrish’. Your new investigations of the atom have accompanied me on the trip, and they have even increased my love for your intellect.” [58]

This brief exchange tells us a great deal about the ways in which these two thought and felt about each other. Einstein had already put his view of Bohr as a physicist on the record earlier that year when he proposed to the Academy of

Sciences at Berlin that Bohr be elected as a corresponding member. His recommendation referred to “the rare blend of boldness and careful consideration” in Bohr as a scientific thinker, to his “intuitive grasp of hidden things and his keen critical sense.” “With all his knowledge of details,” Einstein wrote “his gaze is steadily directed to the underlying principle. He is unquestionably one of the greatest discoverers of our age in the field of science.” [59]

In December 1925 Ehrenfest’s dream of having Bohr and Einstein in Leiden together finally came true. The occasion was the golden anniversary of Lorentz’s doctorate, an event that the Dutch scientific community wanted to celebrate in proper style [60]. Einstein, who loved and revered Lorentz as he did no other human being, had of course agreed to be present [61]. Bohr, who had received an official invitation in April, apparently did not decide to attend until he learned from Ehrenfest early in September that Einstein would be there. To be able to spend a week with Einstein was a treat that Bohr could not pass by. Ehrenfest was delighted with Bohr’s sudden decision, and wrote at once to Einstein:

“Bohr is now struggling mightily with the problems of quanta and he needs to talk about his ideas with you more than with anyone else. It is so important to him to know to what extent you have run into the same deep difficulties as he has. I know that no man alive has seen so deeply as you two into the real abysses of the quantum theory, and that no one else but you two really sees what completely radical new concepts are needed.” [62]

Ehrenfest asked both his friends to give him unconditional authority to ensure their isolation. He continued,

“I believe that you two could not remain so isolated in either Berlin or Copenhagen as in my house, in case I obtain the necessary authority from you to arrange it. . . . You realize what a great experience it would be for me to hear the two of you discussing the quantum riddles, but you can rely on me to leave you by yourselves almost all the time. I am especially interested in what will come of the discussion between you and Bohr concerning the experiments that you are always thinking up on the boundary between waves and particles. While I expect that you two will feel quite similarly about the general puzzles, some fruitful conflict might develop between you concerning this special area.” [62]

Einstein answered at once, “with what was for him a completely unheard of speed,” as Ehrenfest described it to Bohr [63]. He granted Ehrenfest the requested power of attorney for isolation, looked forward with great anticipation to seeing Bohr, but also commented on one substantial aspect of Ehrenfest’s letter:

“I am no longer thinking up experiments about the boundary between waves and particles; I believe that this was a mistaken effort. One will probably never arrive at a reasonable theory by an inductive route, though I also believe that quite basic experiments like those of Stern and Gerlach and Geiger and Bothe can seriously help.” [64]

When he wrote to Bohr about his forthcoming visit, Ehrenfest was full of advice. He wanted Bohr to stay in his home; he and Einstein could have the two little rooms upstairs, where they would have the privilege of smoking, a privilege limited to those guests rooms and perhaps to those special guests.

“I urgently request that you bring no sort of writing work with you. It would really be a sin to spoil this opportunity—this rare opportunity to peer for once with Einstein into the furthest depths of physics that are accessible at present to anyone’s gaze. And you would certainly, and at the same time uselessly, spoil it for yourself, if you were to bring such work with you.” [63]

Ehrenfest painted an appealing picture of what Bohr could expect—quiet chats while strolling along the canals of Leiden, or on the nearby beaches, free from all interruption, on calm, sunny days. And with Einstein, that “wonderfully deep and good man”, who has “suffered much and who feels the sorrow in the world” [63].

This meeting took place at one of the crucial times in the turbulent history of the quantum theory. Earlier in 1925 several experiments had quickly ruled out the Bohr–Kramers–Slater theory, a theory which had tried to eliminate the light quantum from physics, even at the expense of abandoning the exact validity of the laws of conservation of energy and momentum [65]. Although Kramers successfully used some features of the abandoned theory in his work on dispersion, Bohr recognized that an even more fundamental change in the conceptual basis of physics had become necessary. In April he had written to Rutherford referring to “our present theoretical troubles” which he found to be “of an alarming character indeed” [66]. He was now prepared to consider “a radical departure from an ordinary space–time description” in discussing atomic events [67]. “We must take recourse to symbolic analogies of a still higher degree than before,” Bohr wrote to Max Born at the beginning of May. “Just lately I have been racking my brains trying to imagine such analogies.” [68] It was a time when Bohr and his co-workers were occasionally “close to despair” [69]. He was indeed anxious to talk to Einstein about the paradoxical and tormenting problems of the wave-particle duality of radiation, the duality that Einstein had been wrestling with for two decades.

Einstein’s concern with duality had deepened during the past year. Struck by S.N. Bose’s new and intriguing derivation of the Planck law for black-body radiation, Einstein had applied the same statistical arguments to a gas of material particles. When he analyzed the statistical fluctuations implied by the distribution law for this gas (the Bose–Einstein distribution), Einstein found the same dual structure that he had first traced for radiation at least as early as 1909. Just at this time he had been reading an interesting thesis sent him from Paris by Paul Langevin. The thesis was by Louis de Broglie, and Einstein saw new support for de Broglie’s matter waves in the fluctuation properties of the Bose–Einstein gas. Perhaps matter showed the same kind of duality as radiation. It was an idea that could be put to experimental test, and Einstein was eager to have this done [70].

There were other weighty matters to discuss, foremost among them the new matrix mechanics begun by Heisenberg, and just applied to the problem of the hydrogen atom with brilliant success by Pauli [71]. Only days before departing for Leiden Bohr had learned of Pauli’s “wonderful results” [72]. “I do not know whether to congratulate him or you the most,” he wrote to Heisenberg [73]. Bohr, like Pauli, was convinced that Heisenberg’s work marked a new stage of “wonderful progress as regards the development of the rational quantum mechanics.” [74]

Also brand new and crying out for discussion was the proposal of the spinning electron, just published by two of Ehrenfest’s students, George Uhlenbeck and

Samuel Goudsmit. This was strongly opposed by Pauli, who had already dissuaded Ralph Kronig from publishing similar ideas almost a year earlier. Bohr, too, was skeptical about spin at first since he saw no reason why this spin should be coupled to the orbital angular momentum of the electron [75].

The question of the electron spin was the first subject discussed by Bohr and Einstein. A few months later Bohr wrote:

“Einstein asked the very first moment I saw him what I believed about the spinning electron. Upon my question about the cause of the necessary mutual coupling between the spin axis and the orbital motion, he explained that this coupling was an immediate consequence of the theory of relativity. This remark acted as a complete revelation to me, and I have never since faltered in my conviction that we at last were at the end of our sorrows.” [76]

Most of the conversation must have dealt with the problems of radiation. Bohr reported to Slater that as a result of his long discussion with Einstein in Leiden he now believed there was agreement on the general ideas, and that Einstein was no longer searching for contradictions between the wave theory and light quanta [77]. Perhaps the “fruitful conflict” on this issue that Ehrenfest had looked forward to did not take place at Leiden. It would certainly take place at later meetings.

For Bohr the time in Leiden was “a wonderful experience”, and his conversations with Einstein were “a greater pleasure and more instructive than I can say.” [78]

There would be several more occasions when all three met together, most notably at the 1927 Solvay Conference. By this time it was clear that Bohr and Einstein did not “feel quite similarly about the general puzzles.” [79] In a long letter to his students Ehrenfest described the nature of their discussions at the meeting in Brussels:

“Bohr towering completely over everybody. At first not understood at all... then step by step defeating everybody. Naturally, once again the awful Bohrish conjuring terminology. Impossible for anyone else to summarize. (Poor Lorentz as interpreter between the English and the French who were absolutely unable to understand each other. Summarizing Bohr, and Bohr reacting with polite despair.) Every night Bohr came to my room at 1 a.m. to say ‘just one single word’ to me, until 3 a.m. It was splendid for me to be present at the dialogues between Bohr and Einstein. Like a game of chess. Einstein always with new examples. Something like perpetual motion devices of the second kind, but to violate the uncertainty relations. Bohr always searching, out of a dark cloud of philosophical smoke, to find the tools to shatter example after example. Einstein like a jack-in-the-box: jumping out again fresh every morning. Oh, that was priceless. But I am almost without reservation pro-Bohr and contra-Einstein. He is now behaving toward Bohr exactly the way the defenders of absolute simultaneity behaved toward him.” [80]

Despite his definite statements in the last two sentences, Ehrenfest did not find it possible to be simply “pro-Bohr and contra-Einstein.” Bohr’s own account of these conversations at the Solvay meeting contains a comment on this point:

“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." [81]

The deep differences in the views of his two close friends were painful for Ehrenfest to bear, and he did what he could to promote mutual understanding between them. In September 1931 he tried to arrange another meeting in a letter addressed to both men:

"Now I am naturally very, very anxious to have you, Einstein, here when Bohr is here. I cannot begin to tell you both how important it would be to me to hear you two discussing the current state of physics in a *tranquil* conversation. I have already confessed to you that I oscillate like a pith ball between the plates of a condenser when I go from one of you two to the other. What I want to accomplish most of all is that Bohr gets to see quite clearly how completely you, Einstein, know and understand his ideas and efforts and nevertheless consider it fully justified to continue searching for the 'genuine' nonlinear microscopic differential equations. I know very well, Einstein, that you have no trace of the urge to propagandize in your soul, and therefore can feel little incentive for such a discussion. For me, however, it is enormously important to see as sharply as possible up to what point you are both forced to think alike, and where your freedom for a parting of the ways begins. I promise not to interrupt you at all. I do hope, though, that I would be able to help a little bit now and then because I am so very familiar with your two extremely different ways of speaking, and Bohr's terrible clouds of politeness are a major hindrance to communication if they aren't vigorously blown away from time to time." [82]

I have deliberately limited my discussion to the first years of the Bohr–Ehrenfest–Einstein relationships, the years in which those remarkable friendships were formed. The warm understanding and strong bonds of sympathy established then between Bohr and Einstein sustained them through another thirty years of occasional meetings and deepening differences in their views on physics. Without this solid base of friendship the Bohr–Einstein dialogue might not have continued to be a model of civilized disagreement over fundamental scientific issues. Without Ehrenfest's catalytic role that friendship of Bohr and Einstein might never have achieved its full strength. Each of the three men felt revived, cheered and refreshed after contact with any of the others. Each felt, as Einstein had once written to Bohr, that the mere presence of the others was a source of joy. Perhaps after all, as Lionel Trilling once suggested, "truth is the expression, not of intellect, nor even ... of will, but of love." [83]

### *Acknowledgement*

Unpublished letters by Bohr are quoted by permission of Professor Aage Bohr. Unpublished letters by Ehrenfest are quoted by permission of the Ehrenfest family. Unpublished letters by Einstein are quoted by permission of the Hebrew University of Jerusalem.

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