euresis journal

euresis Association for the Promotion of the Scientific Endeavour

Volume 2
Winter 2012

journal homepage
www.euresisjournal.org

Niels Bohr and His Physics Institute An Example of Creativity and Creative Inspiration in Science

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Abstract

Today's physics students chiefly remember Niels Bohr for two contributions to their field; the first is his 1913 model of the atom, in which he created a bridge between the quantum and the classical worlds for the sub-microscopic regime. The second contribution, more nebulous in their minds, is his involvement in quantum mechanics' interpretation.

Bohr's formulation of atomic structure made use of the experimental discovery by Ernest Rutherford that the atom was essentially a great void with a tiny massive nucleus in its center, the phrases a "fly in the cathedral" or a "gnat in Albert Hall" sometimes used to convey to the general public the relative sizes of the nucleus and the atom. A better, though less picturesque, analogy is our Solar System with the nucleus replaced by our own Sun. Bohr joined Rutherford's picture of the atom with two notions from quantum theory. The first was Max Planck's revolutionary 1900 conjecture that energy was emitted and absorbed in discrete "*quanta*" and the second Albert Einstein's brilliant 1905 insight that light or more generally electromagnetic radiation has a dual nature, manifested as both waves and particles, the latter coming to be known as *photons*.

Bohr' s picture departed radically from classical physics by having electrons circling the nucleus emit or absorb energy only when they moved from one orbit to another whereas, according to the rules of classical physics, circling electrons would be expected to radiate continuously. Another major departure from classical physics was the introduction of the notion that only certain orbits are allowed for electron motion, their size determined by quantum rules. The so-called Bohr atom explained many puzzling features in atomic behavior, with a particularly dramatic fit to experimental information gleaned from the study of hydrogen and ionized helium, atoms with only a single electron. Bohr also found the necessary connection to classical theory for very large orbits through what he called the Correspondence Principle.

The dramatic success of the Bohr theory in explaining a variety of phenomena made it clear that certain of its elements had to be true. On the other hand its failure in other cases, e.g. many electron atoms, made it equally clear that much more was needed before one had a satisfactory quantum theory of matter. This became the central problem in physics for the next dozen years, one in which Bohr played a central role both as a leader and a teacher. Its denouement began in 1925-26 with the brilliant insights of Werner Heisenberg and Erwin Schrodinger that produced respectively matrix mechanics and wave mechanics, quickly shown to be equivalent. Satisfactory calculations could be performed with either's set of rules, but the meaning of what came to be called quantum mechanics proved elusive.

Now once again Bohr played a crucial role. He and Heisenberg, with frequent input from Wolfgang Pauli, produced "The Copenhagen Interpretation of Quantum Mechanics" during the course of sustained all-day working sessions that lasted for much of 1927. Its two pillars are Heisenberg's Uncertainty and Bohr's Complementarity Principles, though I believe both the names of Bohr and Heisenberg could reasonably be attached to either of the principles. The one places limits on simultaneous measurements of e.g. an electron's position and momentum (can be related to its velocity) while the other maintains that the very same electron can be detected in either its particle or wave form but not in both at the same time. This impossibility is tied to the Uncertainty Principle. Particle and wave are terms we use to describe the results of experiments.

This formulation of quantum mechanics, though almost universally used, was never fully accepted by some of the subject's pioneers, including most famously Bohr's very good friend, Einstein. The thirty-year debate between the two of them on the subject, never fully resolved, has become one of the legends of physics.

In his third decade of research Bohr pioneered the modern concept of the atom's nucleus as a compound system, to be studied as a whole rather than as simply the sum of its constituents, a notion that helped pave the way to understanding phenomena such as nuclear fission. Among other first insights attributed to Bohr, a notable one for the future of nuclear physics and ultimately of nuclear weapons, was the realization that fission does not occur in all of uranium, but only in its comparatively rare isotope, uranium 235.

These achievements would have been enough to place Bohr in the pantheon of great twentieth century scientists, but there is another aspect to both his life and work that is often forgotten because it has not left a record in physics textbooks. It concerns his direct personal influence, probably unmatched by anyone else in physics.

The words from those who knew him and came under his influence reflect this love and admiration. There is an obvious common thread in all these recollections. The great American physicist John Wheeler, who spent more than a year at Bohr's Institute in the 1930s, and worked directly with him, put it this way [1].

> *Nothing has done more to convince me that there once existed friends of mankind with the human wisdom of Confucius and Buddha, Jesus and Pericles, Erasmus and Lincoln than walks and talks under the beech trees of Klampenborg Forest with Niels Bohr.*

Otto Frisch, who together with his aunt Lise Meitner discovered the possibility that nuclei could undergo fission, remembered sitting with other young physicists by Bohr's side after dinner as an inspiring experience [2].

> *Here, I felt, was Socrates come to life, tossing us challenges in his gentle way, lifting each argument to a higher plane, drawing wisdom out of us which we didn't know we had, and of course we hadn't.*

Arriving in Copenhagen after a journey of a day and a half from the Netherlands, the then twenty-year old Hendrik Casimir saw his mentor Paul Ehrenfest suddenly become quiet, then pensively turn to him and say [3],

> *Now you are going to know Niels Bohr and that is the most important thing to happen in the life of a young physicist.*

What did Bohr do to have such an influence on the young physicists around him? Why did Heisenberg write in his obituary for Bohr that [4]

> *Bohr's influence on the physics and physicists of our century was greater than that of anyone else, even than that of Albert Einstein*

Why did Sir George Thomson, who confirmed the wave nature of particles, write [1]

> *Bohr's Influence on science is only partially expressed in his published work. He led science through the most fundamental change of attitude it has made since Galileo and Newton, by the greatness of his intellect and the wisdom of his judgments. But quite apart from their unbounded admiration for his achievements, the scientists of all nations felt for him an affection which has perhaps never been equaled. What he was counted for even more than what he had done.*

The questions for this essay are what was it in Bohr's *persona*, in his achievements and in his interactions with others that led so many to describe him in such tones, how did it come about and what does this tell us about the role an individual may have in promoting scientific creativity? There is perhaps no better place to start than by taking Heisenberg's statement as a starting point. Comparing Bohr to Einstein, there is little question that the latter was a greater scientist, one like only Newton for the breadth and depth of his ideas. Einstein was also immensely admired, but by physicists and by the general public, albeit somewhat from a distance. Nowhere does one find the kind of statement about him that one readily encounters in Bohr stories.

The distinguished physicist Abraham Pais, who knew both Bohr and Einstein well, and wrote wonderful biographies of each, has contrasted the many features of their lives. Two great differences stand out. The first is attachment to a country, alternatively described as a sense of being rooted. Einstein had very little of that. Born in Germany, he seems to have never felt much attachment to that country in his youth, choosing to pursue his university studies in Switzerland and later acquire citizenship there, famously working in the Bern patent office. However he resumed his German citizenship when, after a stint as a professor in Prague, he took up a post in Berlin. The dual citizenship he then held led to many curious and sometimes humorous situations such as the one at the Nobel Prize ceremony when he was due to accept the 1921 Physics Prize. Since Einstein was away in Japan, it was given for him to the German Ambassador to Sweden, who then consigned it in Berlin to the Swiss Ambassador to Germany who in turn gave it to Einstein. Emphasizing this double tie, Einstein would quip

> *if relativity is right the Germans will say I am German and the Swiss will say I am Swiss whereas if it is wrong the Swiss will say I am German and the Germans will say I am a Jew.*

However neither tie was very strong, characterising himself as a bird of passage. Einstein left Germany for good as soon as Hitler came to power in 1933. Moving shortly after that to the United States, he became a citizen of his new country, never returning to the Europe he had left behind.

By contrast Bohr was deeply tied to his native Denmark. No other place could or would ever be home for him. He traveled widely, but even the most tempting of offers could not draw him away from there. He vacillated briefly when in 1923 he was offered a professorship in Cambridge England at triple his Danish salary. He would have had little or no teaching duties and be together with his very good friend Rutherford (Bohr even named one of his sons Ernest), but in the end his ties to Denmark were too strong. He simply would not break them. True happiness lay in Copenhagen or near there, in the simple country house with a thatched roof that he bought in 1924.

Denmark gave much to Bohr in return in the forms of support and appreciation. The Carlsberg brewing family had left a mansion for use by the country's leading citizen in science, literature or the arts during his or her lifetime. When the previous occupant, the philosopher Harald Hoffding, died in 1932, Bohr was chosen as the next occupant. The family entertained a great deal there; symbolically their first guests were Lord and Lady Rutherford (he had been made a Lord the year before). By the 1930s Bohr was so well known in Demark that, as the Dutch physicist Casimir recounted, a letter from his parents addressed simply to Hendrik Casimir c/o Niels Bohr, Denmark arrived without delay.

The other great difference between Bohr and Einstein was in the way they worked. Though both were social beings, interacting readily with others, Einstein's deepest thoughts were pursued in solitude. He had an upstairs study in his Berlin home where he was not to be disturbed, nothing was to be touched; he would descend for meals when he felt like doing so. In later years at the Institute for Advanced Study, he remained a revered but distant figure, seldom coming to seminars or participating in meetings. By contrast, Bohr developed his thoughts while interacting with others. As John Wheeler, who knew him well, put it [1],

> *I never saw Niels Bohr make progress with an idea except in dialogue 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 slow fire under about fifteen topics.*

Bohr's day-to-day research was almost never conducted alone. In the company of a younger physicist, he would examine and re-examine a topic, turning it over in his probing mind, always searching for clarity but keenly aware of possible contradictions. As he used to say "*A great truth is one whose opposite is also a great truth.*" The preparation of manuscripts was often an excruciating process, as sentences were written and then rewritten the next day and then once again the day after. Though it could be painful the young physicists who helped him also felt it gave them a unique entry to the workings of one of physics' great minds.

It should also be mentioned at this point that Bohr was fortunate, in a way Einstein was not, to have at all stages of his life an extraordinarily happy family. His loving parents recognized and helped develop his talents. His one-year younger brother Harald, a distinguished mathematician, was from childhood on his best friend. Most importantly of all, he had a long and happy marriage. His wife Margrethe features prominently at all steps of Bohr's adult life, continually smoothing the way for him. It clearly was a very happy union, but it was also a marriage of those times, one in which Margrethe made sure that Niels always had time for his long talks with disciples, for his weeklong cross-country ski trips, for his hikes along the Danish shore with physicists, for his sailing trips. Her regal presence was always felt, eliminating all domestic obstacles, smiling despite the concerns that must have come with the raising of their six young boys.

Assisted by all this good fortune, Bohr brought together in one creation the strands of his desire to contribute to science, to aid others, to enhance the culture of Denmark and to assist both him and the young in furthering their thoughts in physics. This was how it came about.

With the publication in 1913 of his model of the atom, it was clear that this 28 year-old Dane was the emerging leader in combining the new knowledge of the atom with the basic tenets of quantum theory. Newly married, he wished to settle in Denmark and pursue his studies, but there was no appropriate university position for him. In 1914 he therefore accepted a post in Manchester, England where Rutherford presided. Two years later, his home country now aware that they might lose him permanently, created a professorship in theoretical physics. Bohr returned to Copenhagen, the initial occupant of the newly created chair.

That year he also received a letter from a young Dutchman named Hendrik Kramers, who was working toward his doctorate in Leiden, but wanted to know if he could visit Bohr. Their meeting went very well and Kramers wound up spending the next ten years in Copenhagen, leaving finally only because he had been offered a professorship in Utrecht. Kramers was a brilliant physicist in his own right, widely knowledgeable, cultured, and conversant in many languages. He would turn out to be the ideal complement to Bohr during the coming decade. At first he and Bohr shared no more than a tiny office, but almost immediately upon taking up his post, Bohr began planning for something greater, an institute that would welcome young physicists from around the world. In early 1917 he petitioned the university for funds to build an *Institut for teoretisk Fysik*, outlining in his proposal both the scope of such an undertaking and its desirability. He also underlined that the state of affairs in atomic physics was now such that it had become necessary for theorists to provide guidance to experimenters in their work. In other words the heretofore-accepted plan of experiments leading theory might be reversed in this situation. Recognizing the importance of theorists and experimentalists working together, Bohr also began thinking of having an experimental physics component in the new institute. In order to advance his dream of having in Copenhagen a community of physicists where young visitors from abroad could stay anywhere from days to years, Bohr worked hard to raise the necessary funds. He was, after all, trying to create something that was new and untried. Physics was very fortunate that he was a man of immense mental and physical energy, as well as being apparently selfless in a very deep way.

Raising the funds was not easy task, particularly in light of the post World War I financial depression, but Bohr was tireless, engaged in all parts of the planning and building. Some of the financing came from private sources, inspired by the young man's zeal and earnestness. The land was bought, construction began and in March 1921, the *Universitets Institut for teoretisk Fysik* was inaugurated. Completely exhausted, Bohr had to postpone a much-anticipated set of seven lectures he was scheduled to deliver in Gottingen, Germany's great center of learning in mathematics and physics and could not attend the 1921 Solvay Conference held in Brussels that fall. But he recovered quickly and was soon off running again.

The following year, 1922, was a triumphal one for Bohr in every sense. He had published by then a series of papers in which he seemed able to explain many of the puzzling features of the Periodic Table of Elements by judicious use of his Correspondence Principle, a technique he devised for connecting the classical and quantum atomic worlds. But the way he obtained the results puzzled most readers. As Kramers [1] described it

> *Many physicists abroad thought, at the time of the appearance of Bohr's theory of the periodic system, that it was extensively supported by unpublished calculations which dealt in detail with the structure of the individual atoms, whereas the truth was, in fact, that Bohr had created and elaborated with a divine glance a synthesis between results of a spectroscopical nature and of a chemical nature.*

The dominant German schools led by Arnold Sommerfeld in Munich and Max Born in Gottingen proceeded in a more formal way, first setting up the equations that a problem seemed to demand, solving them and finally analyzing the solutions. Bohr's method, on the other hand, relied on intuition and judicious search of experimental data for hints on how to proceed. The difference of the two approaches became clear during the course of his Gottingen lectures; it inspired the young with a particularly strong influence on two students of Sommerfeld, both destined for greatness in the world of physics. Their names were Wolfgang Pauli and Werner Heisenberg. As Heisenberg would later say [4]

> *We had all of us learned Bohr's theory from Sommerfeld and knew what it was all about. But it sounded quite different from Bohr's own lips.*

The lectures were held on beautiful late spring days in June. Physicists had come from all over Germany and some even from neighboring countries to hear them. Elders brought their very best students with them; rooms were found for them to sleep in. At the end of the third lecture, Heisenberg stood up and asked Bohr some pointed questions about what he had just said. The Dane, grasping that this was no ordinary twenty-year old youth, asked Heisenberg to come for a walk with him in the Gottingen hills. The walk lasted three hours, during which the two discovered how much they had in common in the way they thought about physics. Bohr recognized the young man's brilliance and Heisenberg was flattered by the attention. He was also struck by the new vision of how to approach the deepest problems in physics. Many years later Heisenberg [4] reminisced how "that walk was to have profound repercussions on my scientific career, or perhaps, it is more correct to say that my real scientific career only began that afternoon".

At the end of the walk, Bohr invited the young man to spend some time with him in Copenhagen, where they would have more time to talk about these matters. A year and a half passed before Heisenberg had completed all his required studies and could come. When he did arrive, Bohr was very busy, the head of a growing research team and the father of five young sons, but within a few days he asked Heisenberg to come for a three-day walk with him. They would bring whatever they needed in rucksacks- the important thing was that they would be able to really get to know one another. A bond was forged during that time, one that would be crucial two years later when Bohr and Heisenberg would work together for a year at formulating the interpretation of quantum mechanics.

The Gottingen meting was also a turning point for Pauli. This brilliant, precocious man was a year half older than Heisenberg but already well known for a review article on relativity. It had amazed the physics community, including Einstein, for its thoroughness and the depths of its insights. He had perhaps the sharpest mind of all the major contributors to quantum mechanics, making him the perfect foil to the more original Heisenberg, his old friend from Munich school days. Pauli also went to Copenhagen and remained a close friend and critical analyzer of Bohr's thoughts for the rest of his life. He too gained from Bohr the confidence to trust his conclusions even if they could not be proved mathematically in a rigorous fashion. Within two years Pauli had arrived at the Exclusion Principle, one of the backbones of quantum theory.

The year of 1922 came to an end with another triumph for Bohr, being awarded the Physics Nobel Prize. The ceremony was capped by yet another demonstration of his insight into the structure of matter. Bohr had from the beginning tried to ensure that his Copenhagen Institute would have an experimental wing, judiciously choosing an old Manchester friend, George von Hevesy to head it when it was established. One of the first experiments Bohr suggested was to search for the still undiscovered element 72 in the periodic table in zirconium samples since according to his calculations the two elements should have similar properties. Von Hevesy, working together with Dirk Coster, a young Dutch physicist, succeeded in isolating the new element only days before the 1922 Physics Prize was to be awarded, enabling Bohr to make the announcement at the conclusion of his acceptance speech. Its properties were exactly what Bohr had predicted. The element was given the name *hafnium*, Hafniae meaning harbour and being the old Latin name for the city of Copenhagen. (Many years later, the artificially produced transuranic element 107 would be named *Bohrium*.)

By 1924 the original *Universitets Institut for teoretisk Fysik* had become insufficient. It was a three-story building with a lecture hall, a library and office space on the first two floors. The Bohr family, originally living on the third floor, but now numbering five sons, clearly needed more room. Plans began for two more buildings, one of which would house the Bohrs and the other a dedicated experimental facility. Originally grants from the government and two Danish foundations, the Carlsberg and the Rask-Oersted, had provided most of the necessary funds and they continued to support Bohr, but he now began to look abroad as well. His greatest success came from the new emerging economic power, the United States. In 1923 John D. Rockefeller founded the International Education Board, which fifteen years later would become part of the Rockefeller Foundation. During that same year Bohr paid his first visit to the United States. Having received the Physics Nobel Prize the year before, Bohr was recognized as a commanding intellectual figure even though he was not yet forty. In November of 1923, he made a compelling presentation to the IEB, after which his Institute was awarded $40,000, the first grant awarded by the IEB to a physics research institute. Danish providers and the City of Copenhagen rapidly met the IEB's condition that funds for buildings and instruments would be provided only if additional grants from other sources were obtained.

Though some of the young physicists arriving in Copenhagen came with funds from their own home countries, the two largest sources of support were the Danish Rask-Oersted Foundation and the IEB, which in 1924 instituted a set of one-year fellowships. Commonly known as Rockefeller Foundation Fellowships, these were designated for young researchers in the natural sciences. Of the more than sixty young visitors who stayed at the Institute for substantial periods of time during the 1920s, thirteen came with funds from the former and fifteen with funds from the latter. Wolfgang Pauli was in the first group and Werner Heisenberg in the second.

By 1926 the new buildings were ready. Once the Bohr family moved to the adjacent villa, some of the space freed on the third floor of the old building was converted into a small apartment for a special guest. Werner Heisenberg, befriended by Bohr four years earlier was the first to occupy it. The great physics breakthrough in quantum theory had just occurred with not one, but two formulations. The first achieved in the summer of 1925 by Heisenberg, was known as matrix mechanics and the second, developed independently in early 1926 by Erwin Schrodinger, was called wave mechanics. Quickly shown to be equivalent in their capacity to solve problems, their reception in the physics community was nevertheless very different for wave mechanics employed familiar mathematical techniques while matrix mechanics seemed opaque by comparison.

Heisenberg, feeling brushed aside by physicists rushing to embrace Schrodinger's formulation and rejecting his, appealed to Bohr for assistance. He did this in large part because he felt that neither he nor Schrodinger had arrived at a satisfactory understanding of the theories they were proposing. Schrodinger disagreed, as did most of the physics community, but Bohr sided with Heisenberg. He had been thinking along the same lines and now invited his young German friend to join him in seeing if they could reach a correct understanding. So began what would turn out to be a year of work for the two of them. The discussions would spill over into the night for Bohr would often walk over to Heisenberg's adjacent apartment after dinner to mull over some thoughts that had occurred to him.

The outcome of their labor was first presented by Bohr in the early fall of 1927 at a conference on Lake Como commemorating the hundredth anniversary of Volta's death and shortly afterwards in Brussels at the Fifth Solvay Conference. The audiences, at first baffled, were slowly by and large won over, many of them reluctantly. One can see this from an editor's preface to Bohr's lecture [1], as published by *Nature* in April 1928"….

> *The strange conflict that has been waged between the wave theory of light and the quantum hypothesis has resulted in a remarkable dilemma. But now we have a parallel dilemma, for a material particle exhibits some of the attributes of wave motion. Can these apparently contradictory views be reconciled? According to Bohr, the pictures should not be viewed as contradictory, but complementary……*
>
> *It must be confessed that the new quantum mechanics is far from satisfying the requirements of the layman, who seeks to clothe his conceptions in figurative language. Indeed its originators hold that such symbolic representation is inherently impossible. It is earnestly to be hoped that this is not the last word on the subject and that they may yet be successful in expressing the quantum postulate in picturesque form.*

Though perhaps not the last word on the subject, Bohr's formulation continues to hold. Bohr's rebuttal of Einstein and others criticism at the Solvay Conference in 1927 further heightened both his own and the Copenhagen Institute's reputation. All young theoretical physicists now wanted to go there. It was hard to obtain the necessary financial resources but, juggling funds from several sources, Bohr managed to maintain a certain degree of freedom for extraordinary efforts and made use of this freedom wisely. He shielded, as much as possible, his young collaborators from any concerns regarding funding. One of them later reminisced "But you never asked Bohr where he got the money from." [5].

The story of George Gamow, later the founder of Big-Bang cosmology, illustrates how he used this freedom. Gamow first arrived in Denmark in 1928. He was educated or perhaps more correctly educated himself with two friends in Saint Petersburg because none of the professors were up to date on the developments in quantum theory. Twenty-four years old at the time of his arrival in Western Europe, he was the first young Russian physicist to come there for, Russia, ravaged by World War I and the Revolution was still greatly impoverished. His arrival in the West had been made possible by a grant that allowed him to spend three months in Gottingen. While there he made an important discovery, one that would turn out to be the first application of the new quantum mechanics to the atom's nucleus. He had shown how these new techniques could explain many of the important features of how a heavy nucleus decays by the emission of so-called alpha particles.

When his three months were over, he was supposed to return to Saint Petersburg. He decided to do so via Copenhagen. Arriving there, he went immediately to the Bohr Institute, which he had heard of, asking the secretary in broken German if he could speak to Bohr. The reply was that the professor was very busy and could not see him until next week, but on learning that Gamow could only stay one day in Copenhagen, she fetched him. Bohr talked for a while to the young Russian. Realizing immediately the importance of the work and discovering that Gamow had funds for only one day in Denmark, Bohr asked him if he would like to stay for a year if he, Bohr, was to provide a stipend. The answer by an astounded Gamow was of course an enthusiastic yes.

However Bohr did more for Gamow than simply provide funds for a year in Copenhagen. Realizing that the research would be of interest to Rutherford as well, he arranged for Gamow to go to Cambridge for a visit, writing Rutherford to pay attention to what the young man was saying and Bohr then proceeded to help him obtain a Rockefeller Foundation Fellowship to spend a year in Cambridge when his Copenhagen stay was over. After that, he invited Gamow back to Copenhagen for a third year away from Russia. At that point, returning to Russia in order to renew his passport, Gamow was detained because of growing unfriendliness of Stalin toward the West. Two years later, again with assistance from Bohr, he managed to return to the West. He never went back to Russia. We can speculate on what Gamow's career might have been without Bohr's benign intervention at multiple points, but it almost surely would have suffered by comparison to what it actually was.

Gamow's arrival in Copenhagen coincided with another novel idea of Bohr's about how to stimulate creative new thinking in physics. By now the Institute had been functioning for more than a half dozen years, with many young physicists coming and going. Wouldn't it be interesting to gather them back on a yearly basis for a week of free ranging discussions? There would be no set agenda, no published proceedings, no formality. Bohr realized that many of the old Copenhagen residents now had commitments to teaching, but if the meeting was held during Easter vacation, they might be able to come. Furthermore he would tell them to feel free to bring along a particularly bright student if they wanted to. This would expose the very young to the *Copenhagen Spirit*. Deciding this could be helpful, Bohr wrote to many of his physicist friends, encouraging them to come. And they did! Starting in 1929, a new Copenhagen tradition was established.

Gamow, already well known for his love of pranks, made a special contribution to the meeting, introducing the notion that it would include either an afternoon or evening skit written, produced and acted by the youngest in attendance, a performance during which the young would make fun, sometimes not too gently of their elders. This would help emphasize the idea that they were all there together to exchange ideas without consideration of age or rank. One year, 1932, the theme was a parody of Goethe's *Faust*, with one young physicist playing Bohr/Lord and another Pauli/Mephistopheles, each vying for the possession of Ehrenfest/Faust's soul. Another year, one in which the Bohrs had taken a trip around the world, the skit was a takeoff on Jules Verne's *Around the World in Eighty Days* with the protagonist being Phileas Foggy instead of Phileas Fogg, a reference to Bohr's soft voice.

That year, 1932, marked many remarkable shifts, almost all prompted by new and exciting experimental findings. The discovery of the positron, the electron's anti-particle, showed the essential correctness of Dirac's theory joining special relativity and quantum mechanics and accelerated the drive toward a quantum theory of fields that could account for both the creation and annihilation of particles. The Institute's also began a subtle shift in its activities, away from atomic to nuclear physics. Another of that year's discoveries, the nucleus' missing component, the neutron, prompted this change. Puzzles regarding the nature of the forces within the nucleus, seemingly wrong statistical behavior and mysteries of atomic weight all began to be resolved. At the same time, technical innovations that would soon alter the field began to take place. In the later spring of 1932, Cockroft and Walton achieved the first artificially induced nuclear disintegration, and within a few months Ernest Lawrence, six thousand miles away, reproduced their results with a new kind of machine that he had built, the cyclotron.

The Bohr Institute, which always rightly prided itself as being a place where the young would come together to work on whatever they found interesting, was responding to these new challenges with Bohr, vigorous as ever, leading the charge. Questions such as how should one think of a large compound nucleus began to be bandied about. Did it perhaps have some properties resembling those of a drop of liquid? These all came to the foreground in the late winter of 1938, when Lise Meitner and her nephew Otto Frisch realized that Otto Han and Fritz Strassman's experiments of bombarding uranium with neutrons were to be interpreted as the splitting of a uranium nucleus into two comparable fragments. The tests that confirmed this result directly were performed by Frisch at the Bohr Institute, another reflection of Bohr's success in building up an experimental part of the Institute.

Experimental physics wasn't the only part of the Institute that had been built up over the years. The mark of a scientific institution that is successful over a long period of time is its ability to change as new fields emerge rather than to continue refining previous results. Bohr was eager to respond to the new challenges provided this could be done in a smooth way without destroying what had already been achieved. One new subject was biology, not altogether unfamiliar to him since Bohr's father had been a prominent physiologist and he had therefore grown up accustomed to discussions of the subject. But starting in the late 1920s his interest in the subject was renewed, prompted by his thinking about complementarity. Could one describe the structure of a living object or did the detailing of its components necessarily lead to the end of life? This was of course a larger philosophical question as well, propounded by him in a well-known 1932 lecture on the subject of "Light and Life". Perhaps its most important outcome was to inspire a 26 year-old Copenhagen postdoctoral fellow named Max Delbruck to follow it up by turning to biology as a career. Delbruck in turn went on to become one of the founders of modern molecular biology, recreating at both the California Institute of Technology and at the Cold Spring Harbor Laboratory on Long Island a Copenhagen-like spirit of adventure and informality, much like the one he had admired as a young physicist.

But Bohr did much more than simply consider the extension of the notion of complementarity to physics. He began to envision a parallel track for the Institute, perhaps finding a way to extend to biology the freewheeling discussions that were the essence of the Copenhagen Spirit in physics. He made it a point in his travels of meeting with biologists, attempting to gain some insight into what sort of activities would best suit the workings of the Institute. He also hosted some small conferences that might touch on the relation between biology and physics, even though biologists viewed these efforts with some distrust. Bohr's endeavors were also encouraged by the Rockefeller Foundation's promise of support, though they were more interested in a real experimental biology program than in the sort of philosophical considerations that Bohr had put forth. There was also a natural connection to the Copenhagen laboratory of August Krogh, a Copenhagen researcher who had been a student and then co-worker of Bohr's father. Winner of the 1920 Nobel Prize in Medicine and Physiology, Krogh had considerable prestige of his own.

One life sciences program at the Bohr Institute did have considerable success, probably in large part because it straddled the borders between physics, chemistry and biology. George von Hevesy, the old friend of Bohr we mentioned earlier, directed it. They two had met in 1911 in Manchester, young men, one a theorist and the other an experimentalist, working together in Rutherford's laboratory. They remained close from then on. Von Hevesy joined Bohr in Copenhagen after World War I and remained there for the next six years, leaving to accept a professorship in Freiburg, but in 1934 he came back to Copenhagen to advance his research program of using radioactive isotopes as indicators of biological change.

There were other reasons as well for his move. Von Hevesy was repelled by the emergence of the Nazis in Germany, but also, as he wrote to a friend [6]

> *Most people do not grow any more when they have reached the age of forty, but Bohr's fantastic personality develops more and more…..*
> *If one has the chance to live near such a unique person, one should not live anywhere else*

Von Hevesy's first paper on the subject of radioactive isotopes as indicators in biology was a 1935 letter to *Nature* written in collaboration with Bohr's old friend, the doctor Ole Chievitz. It makes use of radioactive phosphorous to characterize the uptake of phosphorous in various organs of the body. By 1937, Von Hevesy was essentially devoting all his energy to a wide variety of problems using these techniques in both animal and plant studies. This work would eventually lead to his being awarded the 1943 Chemistry Nobel Prize.

The program that von Hevesy had envisioned joined nicely with possibilities for expanding the role of experiment at the Bohr Institute. The development of high voltage sources that had led to Cockroft and Walton's success and in particular Lawrence's cyclotron had opened up new possibilities for nuclear physics research. Bohr, encouraged by foundation support, now began to plan for building a cyclotron in Copenhagen. Such a machine could be used for nuclear physics experiments, but it could also be employed to produce the radioactive isotopes that von Hevesy was using and, as an additional benefit, could produce X-rays for the treatment of cancer patients.

Bohr received funding from the Rockefeller Foundation, the Carlsberg Foundation and the Thrige Foundation. But he also needed technical expertise. In March 1937, on his round-the world-trip, he visited Berkeley and arranged with Lawrence that one of the Californian's best aides, Lawrence Laslett, would come to Copenhagen and help them build the cyclotron. Laslett arrived in September 1937. The Copenhagen cyclotron started working in November 1938. It was the second in Western Europe, the first being one built in Cambridge at the Cavendish Laboratory. A series of experiments then began, including little more than a year later an exploration of how a uranium nucleus could split into two pieces when bombarded with neutrons. Otto Frisch asked a biologist visiting the Institute if there was a term in biology for a bacterium breaking into two pieces. He was told that the expression was *nuclear fission*.

But soon after that the research activities were severely curtailed by the outbreak of World War II in 1939 and the German occupation of Denmark the following year. The rise to power in Germany of the Nazi Party in early 1933 had presented Bohr with new challenges as he tried to help Jewish refugee physicists find a new home. On the 7th of April of 1933, less than three months after Hitler had become Germany's Chancellor, a ruling was passed, colloquially known as the *Beamtengesetz*. It allowed German scholars to be dismissed from their university positions on the basis of politics or race. Exceptions were to be made for those who had served as soldiers in World War I, but e.g. James Franck chose not to avail himself of this clause. Franck, a close friend of Bohr's was the head of the experimental physics program in Gottingen as well as being the 1925 Physics Nobel Prize winner for his work confirming many of the key aspects of Bohr's atomic theory. Max Born, the head of Gottingen's Theoretical Physics Institute, also left Germany at this point, as did most of his institute co-workers. Gottingen, up to that point Germany's most active center of research in quantum theory, essentially ceased to exist as a force in frontier physics.

Copenhagen, already a magnet for the subject, now became even more important as refugees sought a haven of tranquility, while they searched for positions elsewhere in the world. James Franck came in 1934, leaving in 1936 for a professorship in the United States at Johns Hopkins University. Nor did Bohr simply provide a stepping-stone for transients; with his extensive contacts everywhere and his great reputation for honesty, he actively sought placements for friends, protégés and those in need. Franck's prestige was such that he could obtain a position abroad without help from Bohr, but the same was not true for the young. Though not stated as such, part of the purpose for Bohr's six- month trip around the world in early 1937 was undoubtedly to help young and not-so young physicists find positions. As e.g. Viki Weisskopf, later Institute professor at MIT and Director General of CERN remembered "I had come to Copenhagen to work with Bohr….He has influenced my life enormously and from the beginning he made the most profound impression on me. He was my intellectual father" [7]. Weisskopf first arrived in Copenhagen in 1932. In 1937 he was back, now a refugee. Bohr found him a position at the University of Rochester, one of many helped by Bohr this way.

Soon Bohr would himself become a refugee. After the German Army occupied Denmark, it was only a matter of time before Bohr, whose mother was Jewish, would be threatened with deportation. He and his wife Margrethe, warned of imminent arrest, fled on the night of September 29, 1943. A small fishing boat carried them to a larger vessel that took them to Sweden. He then went directly to Stockholm to intercede with Swedish authorities, including an audience with the King, on behalf of Danish Jews. A week after arriving in Sweden he was flown to England and eventually to the United States. While there he made several trips, to Los Alamos, gave some technical advice but mainly acted to inspire the young physicists with hope that the development of nuclear weapons might serve the prospects of world disarmament, ushering in a new era of openness and cooperation. Most of the next two years were taken up with a shuttle diplomacy, including interviews with both Churchill and Roosvelt, to advance these prospects.

As soon as the war was over, Bohr returned to Copenhagen, arriving there on August 25, 1945. The next morning he rode his bicycle to the Institute and, on the 7th of October, celebrated his 60th birthday, back in his homeland. In the following years Bohr continued his work for world peace but did not neglect science. He played a key role in the development of CERN, the European Center for Nuclear Research; Copenhagen hosted its theory group for five years, from the inception of CERN in 1952 until completion of its accelerator in 1957, at which point the group moved to Geneva. Concurrently the Scandinavian countries banded together to create a theoretical physics institute in Copenhagen. The *Nordisk Institut for Theoretisk Atomfisik*, or Nordita. It is still in existence and still an active research center. Bohr was the first chairman of the governing board.

He died in his sleep in 1962.

References

Niels Bohr Collected Works has been issued in thirteen volumes, appearing between 1972 and 2006. Originally envisioned by Bohr's collaborator Leon Rosenfeld as a collection, the complete set has now been printed as such by Elsevier Publishing under the guidance of Editor-in-Chief Finn Aaserud [5]. The volumes are obviously an invaluable source of information about both Niels Bohr and the evolution of his institute. The best biography, certainly the most comprehensive, of Niels Bohr is the one by Abraham Pai [8]. Finn Aaaserud's book [5] is a particularly valuable source of information regarding institutional support of Bohr's Institute and the role this support played in influencing the direction of research.

1 French, A. and P.J. Kennedy 1985, Niels Bohr: A Centenary Volume (Harvard University Press: Cambridge, Mass.)
2 Frisch, O. 1979, What Little I Remember (Cambridge University Press: Cambridge, U.K.)
3 Casimir, H. 1983, Haphazard Reality – A Half Century of Physics (Harper and Row: New York)
4 Heisenberg, W. 1985, *Gesammelte Werke*, ed. W. Blum (Piper Verlag, Munich). See also W. Heisenberg, 1971, Physics and Beyond – Encounters and Conversations (Harper and Row: New York).
5 Aaserud, F. 1990, Redirecting Science, Niels Bohr, Philanthropy and the Rise of Nuclear Physics (Cambridge University Press: Cambridge, U.K.) See also, A. Pais, 1990 Niels Bohr's Times, in Physics, Filosofia e Politica (Clarendon Press: Oxford, U.K.)
6 Levi, H. 1985, Gorge de Hevesy (Rhodos Press: Copenhagen)
7 Weisskopf, V. 1991, The Joy of Insight: Passion of a Physicist (Basic Books: New York.)

8 Pais, A. 1982, Subtle is the Lord: The Science and Life of Albert Einstein (Oxford University Press: New York.). See also A. Pais, 1986, Inward Bound; Of Matter and Forces in the Physical World (Oxford University Press: New York.)