(This is a talk given before the opening show of "Copenhagen", at The Morris Performing Art Center, South Bend, IN on March 1, 2000)

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I am not aware of any theatrical play in recent memory, or movie, or TV series, for that matter, that is so intensely loaded with scientific content, and nevertheless so incredibly successful as Michael Frayn's 'Copenhagen'. The spectacular success of the play in London, New York and Berlin came as a shock to Michael Frayn himself (yes, you guessed it, the author and various directors thought it's wiser to test things out in smaller cities before bringing the play to Metropolitan South Bend). In March 2000, Michael Frayn was scratching his head and shifting his eyeglasses constantly as he confessed to the following in front of a huge, jam-packed auditorium [**quote**]: *"As I sat in front of my word processor four or five years ago, struggling with this intractable massive material, struggling to understand the outline of the physics involved, struggling to understand the history of the period, struggling to find some shape of what I wanted to say, I lost all faith that the play was ever going to be produced. It seemed to me that I was writing it for my own benefit, that noone was ever going to put on this incredibly abstract remote piece, and even if anyone did, the idea that anyone would come and see it certainly never occured to me."* [**end quote]**. Well, as his science goes, Mr. Frayn is definitely too modest. It turns out, that before releasing the play, he asked Balazs Gyorffy, a theoretical physics professor at Bristol University in England, to read through the play and look for eventual mistakes. Professor Gyorffy told me that there wasn't really anything he had to iron out. Mr. Frayn did a fantastic job at capturing more than just the outline of very sublte physics ideas behind the play.

What is the reason behind 'Copenhagen's spectacular success? The accurate science it uses is just part of its success story. As I tried to understand the 'Copenhagen' phenomenon, I realized that the best insights into this came not from historians or scientists, but from those who approached the issue from theatrical perspective. Michael Blakemore, the first director of the play, said: [**quote] "***The audience need not understand the science in its complete detail. It's initially about the bomb, but it's also about a profound alteration these scientists suggested that we look at reality"*. Kurt Dempster, founder of the Ensemble Studio Theatre in New York, said the following [**quote**], "*Copenhagen is a play that should be seen by anyone who wants to understand our recent past. This play is bremming with ideas, characters, discoveries and events that changed the world forever. In the intimacy that only theatre can give, Michael Frayn takes us to the private world of Werner Heisenberg, Niels and Margarethe Bohr at a legendary meeting when our collective destiny was being decided. Did you ever see the 360 degrees panoramic shot of ground zero at Nagasaki? It's devastation as far as the eye can see... Have you ever thought of what the world would be if Hitler had won, and that could be London or New York? If you see 'Copenhagen', you will be provoked, challanged, wonderfully entertained and perhaps educated in the most theatrical way."* [**end quote].**

But who is Margarette and Niels Bohr, and Werner Heisenberg? It's not at all simple for me to give you an adequate account within the microscopic time frame I have for this talk. What should I tell you first, that both Bohr and Heisenberg are Nobel Prize winners? So what? There are so many Nobel Prize winners around us nowadays. Any science graduate student studying at a major US university will run into several of them. These people develop a beautiful new theory or discover a new particle, and a few decades later their kid wakes them up in the middle of an October night, saying "Dad, there is a weird guy on the phone, who says he's calling from Stockholm". And then there are the very, very few, who also have to wait quite some time, because the Nobel Prize Committee members get into a yearly fight about **which particular** groundbreaking work of their prolific career should they recognize. Among these are Albert Einstein, Hans Bethe, Richard Feynman, and yes, Niels Bohr and Werner Heisenberg.

Imagine now, that it is the very beginning of the year 1913. Albert Einstein describes in the following way his own struggle during this period [**quote]** "*Every attempt I made to reconcile these [quantum] effects with the basics of theoretical physics, resulted in perfect failure. As if the ground slipped away from under my feet, and there was not a single solid piece of land I could build on."* By the end of the summer of 1913, however, the scientific community had a very pleasant surprise. There was someone, who had a clue. It was not the by then world famous Einstein, wasn't even the great Rutherford. It was a twenty-eight year old Dane called Niels

Hendrik David Bohr. At that time he was just recently married to his beloved wife, Margarette, who is also featured in the play. They will spend over fifty years together. Unquestionably, Margarette was Bohr's best friend and strongest supporter, without whom he would probably have not made it through some very difficult times. Margarette also had the incredible patience of typing up all the 30 different version of each and every paper Bohr wrote – and he wrote about 200 papers during his career.

In his paper published on July of 1913, (which was only his fourth publication), he gave not one, but *two* derivations for the spectrum of the hydrogen atom, a problem that resisted solution for three decades by that time! He postulated the existence of a few stable electronic orbits around the nucleus, and proposed a planetary model of the atom, in analogy with the Solar system, where the nucleus played the role of the Sun, and the electrons were the planets. Very quickly, this result turned him into a world figure in science. It started a still unparalleled revolution in physics, and the leader of this revolution became and remained Niels Bohr. In his memoirs written in 1949, Einstein writes "*That this insecure and contradictory foundation was sufficient to enable a man of Bohr's unique instict and tact to discover the major laws of the spectral lines and of the electron shells of the atoms together with their significance for chemistry appeared to me like a miracle – and appears to me as a miracle even today. This is the highest form of musicality in the sphere of thought".***[end quote]**

Bohr went on to receive the Nobel Prize for this work in 1922. However, this was just the beginning of an unparalleled career spanning over a half a century, and another of his most important contribution, the establishment of the complementarity principle, had yet to come. Indeed, only a year after receiving the Nobel prize, Bohr realized, that the classical physics textbooks so many were ready to abandon, should be kept, after all. He said in 1923 already: "*Every description of natural processes must be based on ideas which have been introduced and defined by the classical theory".* It is also important to note here, that Niels Bohr established and successfully raised funds for the Institute for Theoretical Physics in Copenhagen, which now bears his name. The Institute became arguably the most successful physics research institute of all times, hosting at one time or another almost every important researcher in the physical sciences. Bohr became the "intellectual organizer", the "guiding spirit" of the quantum revolution, and his institute the very location of the revolution itself. Professor Kurt Gottfried of Cornell University, the author of one of the best presently used textbooks on quantum mechanics, was also a member of the Institute in the nineteen fifties, and knew Bohr personally. From the anecdotes and stories Professor Gottfried told me about him, it is clear Neils Bohr had a good sense of humor, a warm personality which made him a true and effective supporter of young talents. Bohr himself was not off limits when jokes were made at the Institute. Apparently, sometimes during intense concentration, he spoke so softly, mumbled so slowly that people had serious difficulty understanding him. They used to say that Dr. Bohr is not only a physics, but a language genius as well, as he indeed spoke about a half a dozen languages. The only problem was, they said jokingly, that one never knew which one of the many languages he was actually speaking. At any rate, nobody questions his leading role in making sense of the many achievements of the quantum revolution, in developing the tight framework applicable to any quantom problem. This framework became known as the Copenhagen interpretation.

One of the towering figures among the Institute's frequent visitors was Bohr's young protegé, Werner Karl Heisenberg – the third character in the play. He earned his PhD at an incredibly young age of 21. While still a graduate student, he immersed himself so deeply into the monumental task of providing a firm mathematical framework for describing quantum processes, that he totally ignored studying experimental physics. Ironically, his ignorance of experimental techniques almost costed him his doctorate and followed him throughout his career. During his thesis defense, in front of luminaries like great theoretical physicist Arnold Sommerfeld and the famous experimentalist Wilhelm Wien, he proved unable to derive the magnifying power of rather simple optical instruments like the microscope. The scandal culminated when Professor Wien asked him to explain how a battery works – he could not answer that either. Sommerfeld knew by then quite well how extraordinarily talented theoretician Heisenberg was. He gave him the highest possible grade, to compensate somehow for Wien's choice: the lowest possible grade (that is, an F). This is the main reason Heisenberg got his doctorate on that day.

In retrospect, the young Heisenberg's gamble to devote all his intellectual capabilities to comprehend theoretical physics payed off very well. The breakthrough came in 1925. By that time Heisenberg spent several wonderful months at - well, where else but - in Bohr's Institute in Copenhagen. It was a period of a starting friendship and intense collaboration between Bohr and Heisenberg. But Heisenberg also mentioned in his letters from that period several nasty scientific conflicts with his Danish mentor. Experimental evidence was mounting,

that there is something wrong with Bohr's celebrated planetary model of the atom, and there was no easy way out. Heisenberg realized that failure of the model is fundamental, and it cannot be remedied by incremental changes. He zeroed in on the notion of electronic orbits, a concept that was at the heart of Bohr's original theory. In a letter written in 1925, Heisenberg said: "*All of my meagre efforts go toward killing off and suitably replacing the concept of the orbital path which one cannot observe*". And he duly did so: He was barely 23 in the first half of 1925, when he discovered quantum mechanics. He stated the ambitious requirement, that the new theory must be [**quote] "***founded exclusively upon relationships between quantities which are in principle observable"*. For about two months Heisenberg worked on a manuscript, which he then sent off for publication without mentioning a word to Niels Bohr. When Bohr finally saw the manuscript, he immediate realized that Heisenberg [**quote] "***had taken a step probably of extraorinary proportion*".

Two years later, the events almost repeated themselves: soon after Bohr left Copenhagen for a tript to Norway, Heisenberg made another landmark discovery. He realized that in fact there is an even deeper reason why the notion of electronic orbit must be disposed of [**quote]: "***you can say, well, this orbit is really not a complete orbit. Actually, at every moment the electron has only an inaccurate position and an inaccurate velocity, and between these two inaccuracies there is this uncertainty relation"*[**end quote]**.** He again was afraid of Bohr, and kept quiet until the manuscript was complete. His fear was well founded: while Bohr embraced the central idea of the paper, he quickly found a fundamental mistake in the example Heisenberg chose to illustrate his new principle. It is quite ironic, that this example actually involved a microscope! Again, Heisenberg's worse nightmare about optical intruments during his PhD exam were back to haunt him. Eventually, the paper was corrected, published, and the new principle presented in there became widely known as the uncertainty principle. In the next couple years, despite of all these minor collisions, Bohr and Heisenberg worked very successfully together, and developed a close friendship.

In 1933 Heisenberg was awarded the Nobel Prize in Physics. Hans Bethe, the Nobel Prize winning leader of the theory division of the Manhattan project, gave us a lecture in 1992 at Cornell University. When the issue of how important Heisenberg's discovery of quantum mechanics was, he simply told us [quote] "*We do not know of a single case when quantum mechanics failed"[end quote]*. Given that Heisenberg's quantum mechanics has been under the most intense scrutiny in the history of science - tested by tens of thousands of researchers, in hunderds of thousands of different experiments and calculations – I would suggest there are very few theories with a similar track record. Bethe also told us, jokingly, that he believes Heisenberg's uncertainly principle got some bad press: [quote] "*Many people believe that the uncertainty principle has made everything uncertain. It's quite the opposite. Without the uncertainty principle there could not exist any atoms, there could not be any certainty in the behavior of matter. So it is in fact a certainty principle."*

1933 was also the year when Germany elected Adolf Hitler as chancellor. The Nobel Prize immediately made Heisenberg a man of great stature in Germany, and drew upon himself the uncomfortable watchful eye of the Nazi leadership. As the war approached, the sweeping historical events gradually took control over the scientific activity of both Bohr and Heisenberg. In contrast to many other leading figures of the quantum revolution, Heisenberg opted to stay in Nazi Germany during the second World War. His activities during this period, especially his leadership of the (fortunately failed) German atomic bomb project remains highly controversial even today. There is much debate about what he did, and what he did not do. The most controversial event, which is also the central event in Michael Frayn's play, is Heisenberg's visit to German occupied Copenhagen in October, 1941. He met with Bohr and something went terribly wrong, which suddenly ended their long friendship. While Heisenberg stated his version of events several times after the war, no official statement came from Bohr. The debate among historians is raging for more than half a century as to what had actually occured.

It was not an accident that Hans Bethe was talking about Heisenberg in 1992. It was the year when the British government declassified the so-called Farm Hall transcripts. These are transcripts of secretly recorded private conversations between Heisenberg and nine other German scientists, arrested at the end of WWII war by an Allied science intelligence unit, and held for six months at an English country manor, Farm Hall, near Cambridge. In 1990 I met one of the members of the Science Intelligence unit who interrogated Heisenberg, and who later wrote the introduction to the Farm Hall documents. By then everyone knew about Sir Charles Frank's encounter with Heisenberg in 1945. However, he never **ever** revealed even the slightest detail about these meetings. When asked directly whether he indeed interrogated the members of the German atomic bomb project, he would calmly reply: "sure I did, I had lunch with them". Sir Charles' charm offensive during the six months detension of

Heisenberg and his teammates was very deliberate and effective in making the German team feel safe and unsuspecting. In fact, Heisenberg is caught on tape asked by somebody if he believes whether they are being recorded. Heisenberg replied “no, they wouldn’t do that, the British are gentlemen!”.

Why did the Farm Hall transcripts create such an excitement after their release in 1992? Because, after close to four decades of silence, they promised new insight into what happened with Heisenberg during the war. Historians, again, are still fighting over the interpretation of the transcripts. Mr. Frayn decided instead to summon the spirits of Heisenberg, Niels and Margarette Bohr for a final attempt to find a common ground. It is quite amazing that in some sense he succeeded in making Niels Bohr speak from beyond his grave. The excitement and interest created by the play put tremendous pressure on the members of the Bohr family to release the letters that Niels Bohr wrote but never sent to Heisenberg about their ill-fated meeting in 1941. They finally released the documets less then two weeks ago. Will these documents end the debate? I don’t think so. One thing for sure: they made ‘Copenhagen’, the play, even more interesting. Thank you for your attention.

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