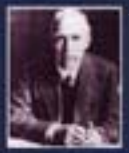
NUCLEAR FAMILY: NIELS and MARGRETHE BOHR

"Bohr is the first scientist who also makes an impression as a human being…he is not just a physicist but much more." —*Werner Heisenberg on his first meeting with Niels Bohr*



The Danish physicist **Niels Bohr** was at the forefront of understanding the discipline that would come to be known as **quantum mechanics**. Niels Bohr was born in Copenhagen on October 7, 1885. His father, Christian Bohr, was a professor of Physiology and his mother, Ellen Adler, was from a prominent Jewish family. His home life was very content, and he was particularly close to his brother the mathematician Harald Bohr. After Bohr received his Ph.D. at the University of Copenhagen, he spent a brief and unhappy period as a student under J.J. Thompson at Cambridge. Bohr studied physics with **Ernest Rutherford** at the University of Manchester where he developed his model of the atom and proposed the idea that an electron in an atom releases a photon as it drops from a higher energy state to a lower one. It was his friendship with Rutherford that would be the model for Bohr's own working relationship with the students he would mentor later in Copenhagen.

"It was not luck, rather deep insight, which led him to find in young years his wife, who, as we all know, had such a decisive role in making his whole scientific and personal activity possible and harmonious." —*Richard Courant describing Niels Bohr's marriage to Margrethe Nørlund*

In 1912, Bohr married **Margrethe Nørlund**, however, he postponed his honeymoon a week to finish his paper on the atom. The Bohrs marriage was remarkable not only because of Margrethe's patience with Niels' passion for physics, but also because of her own intelligence and interest. Although she had no training in physics, she typed Bohr's papers and hosted the numerous physicists that would visit their home. She was familiar with the language of physics and Bohr respected her opinion in everything. Their marriage produced six sons and weathered the tragic loss of two of them. **Christian Bohr**, the eldest was just seventeen when he drowned in a tragic sailing accident. His family had hoped Christian would be a poet. **Harald Bohr** suffered brain damage from meningitis early in his childhood. Never well, Harald had to be institutionalized. He died by the age of ten.

In 1920, Bohr became head of the newly formed **Institute for Theoretical Physics at the University of Copenhagen**. He received the 1922 Nobel Prize in physics "for his services in the investigation of the structure of atoms and of the radiation emanating from them." Bohr enjoyed working with other physicists and brought many of the finest minds in physics to work at his Institute in Copenhagen. Bohr was often instrumental in securing the funding the students needed to stay in Copenhagen. The Carlsberg Brewery offered fellowships to many student physicists. The young physicists who came to Copenhagen not only spent time at the institute but also were frequent visitors in Bohr's home in Copenhagen and their summer home in Tisvilde.

In September 1943, the Bohrs fled Copenhagen to escape deportation because of Niels Bohr's Jewish heritage. They escaped in a fishing boat to Sweden. In February 1944, Bohr and his son Aage arrived in **Los Alamos** to work on the **Manhattan Project**. After the war, he returned to Copenhagen and resumed his work at the Institute. He died in Copenhagen in 1962.

"Bohr fathered many scientific 'children.' Almost every country in the world has physicists who proudly say, 'I used to work with Bohr.'" —*George Gamow*

Photos (clockwise from top): Niels Bohr, 1935; Bohr talking with Werner Heisenberg; Bohr and Margrethe Nørlund, engaged; the Germans occupy the Institute for Theoretical Physics; Niels and Margrethe Bohr later in life.

PHYSICS and POLITICS

1885—October 7, **Niels Bohr** is born.

1895—J. J. Thompson discovers the **electron**, a negatively charged sub-atomic particle.

1896—First Nobel Prizes established.

1900—Max Planck discovers heat energy is found in discrete packets or **quanta**.

1901—December 5, **Werner Heisenberg** is born.

1905—Albert Einstein realizes that light has to be understood not only as waves but also as quantum particles, later known as photons. (A)

1910—Ernest Rutherford shows that electrons move around a **nucleus** (in orbitals) where the mass of the atom is concentrated.

1913—Niels Bohr discovers quantum theory applies to matter. Orbits of electrons in atoms are limited to certain whole number possibilities. (The Bohr Model of the atom.)

1914—June 28, Archduke Ferdinand assassinated in Sarajevo.

1914—August 1, military movements begin in Europe; **World War I begins**.

1915—Albert Einstein postulates **General Theory of Relativity**.

1918—November 11, Germany surrenders and World War I ends.

1920—Niels Bohr becomes head of the Institute for Theoretical Physics established for him at the University of Copenhagen.

1922—June, Niels Bohr meets Werner Heisenberg after Heisenberg challenges him during a lecture series in Göttingen.

1922—December 11, **Niels Bohr receives the Nobel Prize** in Physics for his work on the structure of atoms.

1922—**Benito Mussolini marches into Rome** and forms Fascist government. (B)

1924—September, Werner Heisenberg becomes a research fellow at Niels Bohr's institute in Copenhagen.

1924—Louie de Broglie in Paris suggests that, just as radiation can be treated as particles, so the particles of matter can be treated as a wave formation.

1925—Werner Heisenberg abandons electron orbits as unobservable, and completes his paper on Quantum Mechanics.

1925—Max Born finds a mathematical formulation in matrices for the movement of electrons in terms of absorption and emission of light.

1926—Erwin Schrödinger finds the mathematical **Wave Equation** solution and proves that wave and matrix mechanics are mathematically equivalent.

1927—March 23, Werner Heisenberg submits his paper demonstrating that all statements about the movement of a particle are governed by the **Uncertainty Principle**: the more accurately you know its position, the less accurately you know its velocity and vice versa.

1927—September, Volta Conference at Lake Como where Niels Bohr and Werner Heisenberg defend the Copenhagen Interpretation of Quantum Mechanics.

1927—October, Werner Heisenberg is appointed Professor of Theoretical Physics at Leipzig and leaves Copenhagen.

1928—Niels Bohr relates Werner Heisenberg's particle theory and Erwin Schrödinger's wave theory by the **Complementarity Principle**, according to which the behavior of an electron can be understood completely only by descriptions in both wave and particle form. Uncertainty with Complementarity become established as the pillars of the Copenhagen Interpretation of quantum mechanics.

1929—October, New York stock market crashes. **The Great Depression begins.** (C)

1930—Niels Bohr and Albert Einstein debate the Uncertainty Relationship at the 6th Solvay Conference.

1931—August, Ernest Lawrence and M. Stanley Livingston develop the first cyclotron, for smashing atoms, at the University of California, Berkeley.

1932—February, James Chadwick discovers the neutron, a particle that can be used to study the nucleus because it has no electrical charge.

1932—Werner Heisenberg begins using the **neutron** to apply quantum mechanics to the structure of the nucleus.

1933—January 30, **Adolf Hitler comes to power in Germany** as Chancellor. (D)

1933—April 7, German-Jewish professors and civil servants are fired from their posts.

1933—December 11, **Werner Heisenberg receives the Nobel Prize** in Physics (for 1932) for his work on quantum mechanics.

1934—Enrico Fermi in Rome bombards uranium with neutrons and produces an unidentified radioactive substance. (E)

1936—January 29, Werner Heisenberg and theoretical physics are attacked in a Nazi Party newspaper.

1937—July 15, Werner Heisenberg and other physicists are attacked in an SS newspaper.

1937—Niels Bohr explains the properties of the nucleus by analogy with a drop of liquid.

1938—July 21, **Heinrich Himmler exonerates Werner Heisenberg of SS charges**.

1939—Lise Meitner and Otto Frisch in Sweden apply Bohr's liquid drop model to the uranium nucleus and realize that it has turned into barium under bombardment by splitting in two, releasing a huge quantity of energy **(Fission)**. (F)

1939—Niels Bohr and John Wheeler at Princeton realize that fission also produces free neutrons. These neutrons are moving too fast to fission other nuclei in U-238, the isotope which makes up 99% of natural uranium, and will fission only the nuclei of the U-235 isotope, which constitutes less that 1% of it.

1939—Frédéric Joliot in Paris and Enrico Fermi in New York demonstrate the release of two or more free neutrons with each fission, which proves the possibility of a chain reaction in pure U-235.

1939—May, Niels Bohr organizes assistance for fleeing German-Jewish scientists.

1939—August, Albert Einstein writes letter to President Roosevelt about the possibility of a German nuclear weapons program.

1939—September 1, **World War II begins** when Germany invades Poland.

1939—September 26, Werner Heisenberg joins fission research project in Berlin.

1940—April 9, **Germany invades and occupies Denmark**.

1940—Otto Frisch and Rudolf Peierls in Birmingham calculate the minimum amount of U-235 needed to sustain a chain reaction **(the U-235 Fission Rate)**. Their calculation is actually too low but will encourage the scientists working on an atomic bomb.

1941—January, Glenn Seaborg and associates at the University of California, Berkeley discover **plutonium**, a man-made heavy metal ideal for use in nuclear weapons.

1941—Werner Heisenberg is appointed Professor of Physics at the University of Berlin and named director of its Kaiser Wilhelm Institute for Physics.

1941—Spring, Leipzig uranium pile shows first neutron multiplication.

1941—**September 15–22, Werner Heisenberg visits Niels Bohr in Copenhagen.**

1941—December 7, Japan attacks **Pearl Harbor**; the United States enters the war. (G)

1941—December 8, the first prisoners are gassed at Chelmno death camp near Lødz, Poland.

1942—Nazi death camps at Auschwitz, Birkenau, Treblinka, Sobibor, Belzec, Majdanek-Lublin begin mass murder of Jews in gas chambers.

1942—September, the Allied atomic bomb program known as the **Manhattan Project** begins under director Colonel Leslie R. Groves.

1942—February 26, Heisenberg presents lecture to Reich officials on energy acquisition from nuclear fission after the army withdraws most of it's funding.

1942—June 4, **meeting between Werner Heisenberg and Albert Speer** on Nuclear research.

1942—December 2, Enrico Fermi in Chicago achieves the **First Self-Sustaining Nuclear Chain Reaction**.

1943—March, J. Robert Oppenheimer arrives as director of the new atomic lab at **Los Alamos**, New Mexico.

1943—September 28, German attaché Georg F. Duckwitz leaks the SS order to deport 8,000 Danish Jews on October 1, 1943, to Danish Social Democrat Hans Hedtoft. Hedtoft warns Danish Jewish leaders C.B. Henriques and Marcus Melchior. With the help of Danish citizens, more than 7,500 Jews reached safety; 481 were deported to Theresienstadt. 51 deportees died by the end of the war.

1943—September, Niels Bohr and his family escape Denmark in a fishing boat before the planned Nazi deportation.

1944—February, Niels Bohr and his son Aage arrive in Los Alamos, New Mexico to work on the atomic bomb.

1944—June, Danish Red Cross officials inspect Theresienstadt to ascertain condition of Danish Jews.

1944—June 6, **D-day**, Normandy invasion by Allied forces. (H)

1945—The Allied advance in Germany halts the German atomic program.

1945—May 3, Werner Heisenberg arrested by U.S. forces at his home in Urfeld, Germany.

1945—May 8, Germany surrenders; war over in Europe; German scientists detained.

1945—July–December, **Werner Heisenberg and other German scientists are held at Farm Hall** in England.

1945—July 16, **Trinity Test** of an atomic weapon near Alamogordo, New Mexico.

1945—**August 6, the first atomic bomb, "Little Boy" is dropped on Hiroshima.** (I)

1945—**August 9, the second atomic bomb, "Fat Man" is dropped on Nagasaki.** (J)

1945—August 10, Japan surrenders. (K)

1946—January 3, Werner Heisenberg returns to Germany after internment at Farm Hall in England.

1947—**Werner Heisenberg visits Niels Bohr in Copenhagen again.**

1949—Werner Heisenberg visits America; many American physicists avoid meeting him.

1956—Werner Heisenberg's account of the 1941 meeting with Bohr is published in Robert Jungk's book *Brighter Than a Thousand Suns*.

1957—Bohr reads Heisenberg's account of the 1941 meeting and drafts a response which he does not send.

1962—November 18, Niels Bohr dies in Copenhagen.

1976—February 1, Werner Heisenberg dies of cancer in his home in Munich.

1984—Margrethe Bohr dies in Copenhagen.

1995—Nuclear Non-Proliferation Treaty ratified by 135 nations including the U.S.

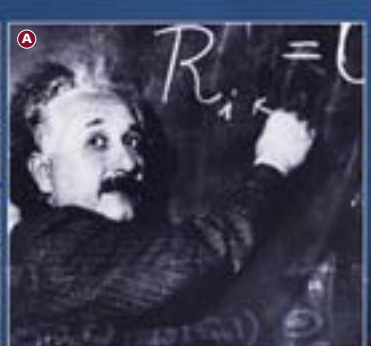
2002—Bohr family publishes Niels Bohr's 1957 response to Werner Heisenberg's account of the1941 meeting, as a result of public interest sparked by Michael Frayn's play *Copenhagen*.

TIMELINE COLOR KEY

Key Dates in Physics

Key Dates in Politics

Physics and Politics Collide



THE UNCERTAIN HISTORY of WERNER HEISENBERG

"Every word or concept, clear as it may seem to be, has only a limited range of applicability."
—Heisenberg, Physics and Philosophy, *1963*

In 1924, a young German physicist named **Werner Heisenberg** came to Copenhagen to work with Niels Bohr. Heisenberg was born December 5, 1901, into an upwardly mobile and academic family. His father, August Heisenberg, was a professor of Classical Greek; his mother, Annie Wecklein, was the daughter of a teacher and school administrator. Werner Heisenberg studied physics at first at Göttingen, then Munich under Max Born. He won the Nobel Prize in physics in 1932 for his work on quantum mechanics. Heisenberg and Bohr's collaboration resulted in the **Uncertainty Principle**, **Complementarity** and the **Copenhagen Interpretation** of the new field of **Quantum Mechanics**, which they presented and defended at the 1927 Volta Conference at Lake Como.

Heisenberg has been much criticized for his decision to remain in Germany during World War II in spite of the fact that he had offers from several universities outside Germany. The decision to remain could not have been an easy one. Heisenberg and theoretical physics were attacked in 1936 and 1937 in the Nazi party newspaper and the SS newspaper respectively. Heisenberg was interrogated at the Prinz Albrecht Strasse but was not exonerated until 1938.

Heisenberg's 1941 Visit to Copenhagen

In September or October 1941 (the accounts vary), Heisenberg went to Denmark, which had been under German Occupation since April 9, 1940. While in Copenhagen, Heisenberg visited his former mentor and friend **Niels Bohr**. The dispute and uncertainty over exactly what was said during this visit, what Heisenberg's intentions were, and the irresistible explanations for Heisenberg's behavior put forth by myriad scientists and biographers, form the historical basis for Frayn's play.

In 1947, Heisenberg returned to visit Bohr in Copenhagen with his British custodial escort **Ronald Fraser**, but his attempt to reconstruct their 1941 conversation proved disastrous. Heisenberg said of their second meeting, "we both came to feel that it would be better to stop disturbing the spirits of the past." Heisenberg gave several explanations for his 1941 visit to different people. The one that most angered Bohr appeared in **Robert Jungk's book *Brighter Than A Thousand Suns*** where Jungk quotes Heisenberg as suggesting that he was attempting to undermine the German atomic program. Bohr was angered by this statement and drafted several letters to Heisenberg on the matter, but never sent them.

In 1942, concern over Heisenberg's potential contribution to a German atomic bomb was sufficient for some in Allied intelligence to suggest kidnapping Heisenberg. However, the plot was never executed. In 1945, as Germany capitulated, Heisenberg and other German scientists were taken into custody by the Allies. In spite of one American general's claim that it would be easier to kill the scientists, they were taken instead to **Farm Hall** in England. The Allies were not only concerned about the secrecy of their own atomic bomb project, but they were also beginning to have concerns about the Russians. In part, the scientists were removed to protect them from falling into Soviet hands.

Heisenberg ultimately returned to Germany and did rebuild German physics at the **Max Planck Institute** formerly the Kaiser Wilhelm Institute. However, he never escaped the shadow of having worked for the Nazi regime. When he visited America in 1949, many physicists avoided meeting him. Until his death in Munich in 1976, Heisenberg faced question about the German atomic project.

"I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair, and when at the end of the discussion I went alone for a walk in the neighboring park I repeated to myself again and again the question: "Can nature possibly be as absurd as it seemed to us in these atomic experiments?" —Werner Heisenberg on his preparations with Bohr for the 1927 Como Conference

Photos: Werner Heisenberg (left); Farm Hall, England (above).

"The relationship between two people is the most important thing in our existence. At this central point from which derive happiness and unhappiness to the highest degree, one should not make any unnecessary mistakes." —Werner Heisenberg in an unsent letter to a family member quoted by Jochen Heisenberg

THE RESCUE of DANISH JEWS

"There is no Jewish question in Denmark."
—Foreign Minister Erik Scavenius to the German Hermann Göring in autumn, 1941.

German troops invade.

A remarkable and little known piece of history amidst the atrocities of World War II is the story of the rescue of the vast majority of **Denmark's Jewish population**. Denmark was invaded by Germany on April 4, 1940. The Danish army was no match for the German army. To save further bloodshed, the Danish government capitulated with little fighting. During the early years of the German occupation, the Danish Jews were not removed for fear of upsetting the Danish government, which still controlled many aspects of daily life. However, as the war moved on, acts of sabotage perpetrated by the Danish resistance proved successful and relations with the German occupiers deteriorated. The Danish government resigned on August 28, 1943.

AN ASTONISHING ESCAPE

On September 28, 1943, SS officer, **Werner Best** received Hitler's order to deport Denmark's approximately 8,000 Danish Jews on October 1, 1943, at 10:00 pm—Rosh Hashanah—the Jewish New Year. Best confided the information to German diplomat **Georg Dukwitz** who told the Danish Social Democrat **Hans Hedtoft** who, in turn, warned Jewish leaders. On September 29, 1934, **Rabbi Marcus Melchior** told his congregation of the planned removal of Danish Jews and urged them to go into hiding. Most Danish Jews were hidden for a time then made the dangerous ocean-crossing in small fishing boats from the Danish island of **Zealand (Sjaelland)** to Sweden where they were offered asylum. Nearly one-fifth of Danish Jews escaped via the fishing port **Gilleleje**. Of the Jewish population, only about 481 were captured by the Nazis. Most of these were sent to Theresienstadt in Czechoslovakia. 51 of those deported had died by the end of the war.

The hiding and transport of nearly 7,500 Danish Jews required the coordinated efforts and secrecy of numerous ordinary Danes. The Jewish population was hidden in hospitals, schools, mental institutions, churches and ordinary homes. **Dr. Kosten** and the staff of the **Bispebjerg Hospital** housed hundreds of Jews before their escape. Copies of the Torah from Rabbi Melchior's congregation were hidden in the crypt of nearby Trinity Church. Many fishing vessels added hidden compartments to avoid Nazi inspection. When the Nazi's began using dogs to detect hidden passengers, chemists in Sweden prepared handkerchiefs soaked in rabbit's blood and cocaine. The rabbit's blood was to attract the dog and the cocaine would temporarily impair the dog's sense of smell.

Danish King Christian X.

SEPARATING FACT AND FOLKLORE

Even before the war, Denmark's response to the Anti-Semitism in Germany was felt in the person of **Danish King Christian X**. On April 12, 1933, he attended a service in honor of the one hundredth anniversary of the Copenhagen Synagogue even though a boycott against Jews had already been declared in Germany. The stories that King Christian and other Danes wore gold stars on their garments to prevent the identification of Jews are not true. Since the race laws were never enforced in Denmark, Danish Jews were never forced to wear the stars. However, accounts of Danish officials calling Jewish-sounding names in the phonebook to warn them of the impending deportation are based in fact. After the war, when Jewish families returned to Denmark, they discovered their homes had been cared for. The looting that occurred elsewhere in Europe was virtually non-existent in Denmark.

Werner Best (left); Georg Dukwitz (right).

Gilleleje Harbor.

"We stayed very low on the floor. We heard there were German patrols outside. We saw flashlights going through the windows." —Leif Wasserman's recollection of the boat ride to Sweden

THE MANHATTAN PROJECT: FROM THEORY to BOMB

"In the course of the last four months it has been made probable—through the work of Joliot in France as well as Fermi and Szilard in America—that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. It now appears almost certain that this could be achieved in the immediate future. This new phenomenon would also lead to the construction of bombs." —Albert Einstein in his August 2, 1939 letter to President Roosevelt

BEGINNINGS OF THE BOMB

The amazing progress theoretical physicists had made in understanding the atom reached a graphic and tangible display in the atomic bomb. In 1939, **Albert Einstein** wrote his famous letter to Roosevelt warning of the potential for creating a weapon based on a **nuclear chain reaction**. After the end of World War II, Einstein would publicly regret the letter saying, "I could burn my fingers that I wrote that first letter to Roosevelt." Hungarian Jewish refugees, **Leo Szilard**, **Edward Teller** and **Eugene Wigner** asked Einstein to write a letter to Roosevelt warning him of the possibility that Hitler might use a weapon that used the incredible energy released in nuclear fission. By October 9, 1941, Roosevelt had authorized atomic weapon development. Also in 1941, **Otto Frisch** and **Fritz Peierls** estimated that a very small amount of fissionable U-235 (an isotope of uranium) could produce an explosion equivalent to several thousand tons of TNT. The bombing of Pearl Harbor on December 7, 1941, had also motivated the American atomic bomb project. In 1942, plants to separate U-235 were built at **Oak Ridge, Tennessee** and **Hanford, Washington**. At the same time scientists were also working on the possibility of using plutonium in an atomic weapon.

General Leslie Groves was deputy chief of construction for the Army Corps of Engineers. He had overseen the building of the Pentagon. Initially, Groves did not want to take charge of the weapons program, however in 1942 he assumed control and called the atomic bomb project the **Manhattan District** after the location of the project's headquarters. Head of Scientific Research for the Manhattan Project was **Robert Oppenheimer**. By 1945, the project employed over 130,000 people and cost more than $2 million dollars (the equivalent of $20 billion in 2004).

Ironically, many of the scientists who would work on the Manhattan Project were European Jews who had fled the Nazis. **Niels Bohr** and his son Aage joined the Manhattan Project in 1944. Bohr has been characterized as serving mainly as a "scientific father confessor" to the scientists, clarifying their problems with the atomic bomb and offering possible approaches that might be taken during his time at Los Alamos.

DESTROYER OF WORLDS

On July 16, 1945, the **Trinity** test of the first plutonium bomb was held near **Alamogordo, New Mexico**. It was named Trinity, Oppenheimer later claimed for a John Donne poem. On August 6, 1945, the uranium bomb known as "little boy" was dropped on **Hiroshima**. Three days later, on August 9, a second plutonium bomb, called "fat man" was dropped on **Nagasaki** as the planned target Kokura was covered by clouds. Japan surrendered on August 10, 1945. Over 230,000 people died immediately at Hiroshima or in the days and weeks that followed because of radiation poisoning. It is believed that approximately 100,000 people died because of the Nagasaki bomb. 270,000 people in Japan today are still living with the side effects of the atomic bombs. It was the first and only time nuclear bombs had been used on human targets.

Photos (clockwise from top): Enrico Fermi; Los Alamos Laboratory; Robert Oppenheimer; atomic mushroom cloud over Nagasaki, August 9, 1945; Hiroshima following the atomic bombing; "Jumbo" at Trinity test site; General Leslie Groves.

"We knew the world would not be the same. A few people laughed, a few people cried, most people were silent. I remembered the line from the Hindu scripture, the Bhagavad-Gita. Vishnu is trying to persuade the Prince that he should do his duty and to impress him takes on his multi-armed form and says, 'Now, I am become Death, the destroyer of worlds.' I suppose we all thought that one way or another." —Robert Oppenheimer

QUANTUM LEAP: THE RAPID PROGRESS of EARLY 20th CENTURY PHYSICS

"Anyone who is not shocked by quantum theory has not understood a single word." —*Niels Bohr*

Pictured at the 1930 Copenhagen Conference (front row, left to right): Oskar Klein, Niels Bohr, Werner Heisenberg, Wolfgang Pauli, Lev Landau and Hendrik Kramers.

Many people alive today have grown up with both the **atom** and the **atomic bomb**. It is difficult to imagine the world into which Bohr and Heisenberg embarked, in beginning to visualize the unseen world of the atom. Prior to the 20th Century, physics had been based on **Newton's laws**. The **electron** was not discovered until 1895. The new understanding of the atom that physicists reached in the 1930s and 1940s was lightning fast by comparison with the centuries that preceded it.

QUANTUM MECHANICS

The branch of physics that deals with the motion of bodies (a ball, a train, a drop of water) is called **mechanics**. Classical or **Newtonian Mechanics** describes the motion of objects in the observable world. **Quantum Mechanics** is the branch of physics that was developed by physicists when they discovered that Newtonian Mechanics could not adequately describe the motion of bodies on atomic and subatomic levels. In 1900, **Max Planck** discovered that heat energy is not continuous (like a wave) but exists in discrete packets or quanta (like a particle), and that all transmissions of energy are made in these units. In 1905, Albert Einstein discovered that light, too, must be thought of not just as waves but also as quantum particles. By 1913, **Niels Bohr** discovered that quantum theory applies not just to energy but to matter as well. Bohr used his understanding of quanta to create his model of the atom. **The Bohr Model of the Atom** is the one many of us were taught in school; with the nucleus sitting in the center like the sun and electrons moving like planets in orbits around the nucleus. Out of his work with Rutherford, Bohr realized that electrons in an atom exist at certain energy levels, which he described as orbits. By applying quantum theory to the atom, Bohr explained how the number of electrons in an atom is limited to certain whole number possibilities. The Bohr model of the atom was ultimately supplanted by the quantum theory of the atom, as orbits may incorrectly imply that an electron has an unchanging pathway. Electrons are still imagined as moving around an atom, but the model is more like an electron cloud with mathematical probabilities of finding an electron in various places around the nucleus of an atom.

"The opposite of a correct statement is a false statement. But the opposite of a profound truth may well be another profound truth." —*Niels Bohr*

HEISENBERG'S UNCERTAINTY PRINCIPLE

Heisenberg succinctly described his **Uncertainty Principle**, "The more accurately you know the position of a particle the less accurately you know its velocity and vice versa." Sometimes referred to as the "**indeterminacy principle**," it expresses the limitations of simultaneously measuring the position and the momentum of a particle. One common metaphor for understanding the Uncertainty Principle is photography. Rather than particles, imagine bullets. If you photograph a speeding bullet, you could have a picture of a blurry bullet and you might be able to calculate its velocity from the blurriness in the image, but you would not know its exact position. Alternately, you could have a photo of a bullet suspended in air from which you could determine where the bullet was but not how fast it was moving when it was photographed.

COMPLEMENTARITY

Complementarity describes **wave-particle duality**, in which different measurements (experiments) done on a system reveal it to have both wave-like and particle-like properties depending on the experiment. A system can behave as a particle or a wave but never as both at the same time. Bohr discovered complementarity as an adjunct to Heisenberg's Uncertainty Principle. Bohr noted that the principle of complementarity "implies the impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear."

SCHRÖDINGER'S CAT

Theoretical physicists regularly work by proposing a "**Gedankenexperiment**," a thought experiment, to sort out the answer to a difficult question. One such famous experiment was proposed by **Erwin Schrödinger**. A cat is placed in a box with a radioactive isotope, a Geiger counter, a hammer, and a vial of cyanide. Each hour there is a 50-50 chance the isotope will decay, registering on the Geiger counter, and causing the hammer to break the vial of cyanide and poison the cat. Is the cat in the box dead or alive? Intuitively we would say the cat must be dead or alive. However, on average, the cat is half alive and half dead, and in physics the cat is both alive and dead until the box is opened. When the box is opened the act of observing then changes the state of the cat to being either alive or dead. The dual state of the cat can be described as a wave function, which collapses when the observer opens the box.