TimeLine Theatre Company

COPENHAGEN

by **Michael Frayn**
directed by **Louis Contey**

STUDY GUIDE

BY MAREN ROBINSON, DRAMATURG

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MICHAEL FRAYN AND THE *COPENHAGEN* EFFECT

About the Author:

Michael Frayn is an award-winning playwright, novelist, journalist and translator. Born September 8, 1933, Frayn read Philosophy at Emmanuel College, Cambridge. He worked as a journalist for *The Guardian* and *The Observer*. Frayn, who acted as a Russian interpreter during his military service, has translated numerous works by Chekhov. His novels include: *The Tin Men*, *The Russian Interpreter*, *Towards the Edge of Morning*, *A Landing on the Sun*, *Headlong* (short-listed for the Booker Prize) and *Spies* (winner of the Whitebread Novel Award). In the theatre, Frayn is perhaps best known for his play *Noises Off*, a comedy about the on and off-stage drama in producing a farce. He is also the author of other plays including: *Alphabetical Order*, *Clouds*, *Make or Break*, *The Benefactors* and *Democracy*, which recently ran on Broadway. *Copenhagen* received the *Olivier*, the 1998 *Evening Standard* Award for Best Play of the Year, the 1998 Outer Critics' Circle and Drama Desk Awards for Best New Play, the 1999 Prix Molière for Best New Play and the 2000 Tony Award for Best Play. He lives in London with his wife Claire Tomalin, a biographer and critic.

About the Play:

"What is so refreshing about an artistic interpretation of the historical event of the Copenhagen visit is that it approaches the truth as a multifaceted and ultimately delicate construct, and that we learn to respect it as such, doubts and all." – Jochen Heisenberg, Werner Heisenberg's son, on Michael Frayn's *Copenhagen*

The attention given to Michael Frayn's imagined meeting between the Bohrs and Heisenberg went well beyond the normal theatre accolades. It also sparked renewed interest in the physics, the history and the ethics of a bygone event. Frayn himself was astonished at the way the play gripped the public imagination.

Michael Frayn was invited to be among the lecturers at a 1999 Seminar at the Niels Bohr Institute. As a result of the interest in the play, the Bohr estate released the drafts of the letter Bohr wrote (but never sent) to Heisenberg about their 1941 meeting after becoming angered by the account given in Robert Jungk's book *Brighter Than A Thousand Suns*. Werner Heisenberg's son, Jochen Heisenberg, has been asked to give his opinion on his father's reasons for visiting Copenhagen in 1941. Historians have criticized Frayn for being too soft on Bohr or neglecting the contributions of other physicists in the development of quantum mechanics.

Because of this interest actor David Burke, who performed in the London production, was able to perpetuate on Frayn an elaborate practical joke in which he had a friend claim to be in possession of papers written and hidden by Heisenberg during his internment at Farm Hall. All the while the actor was forging damaged documents designed to tantalize Frayn with possible details about Heisenberg.

Public interest in the play extends beyond the merely historical. Frayn's background in philosophy draws him to ask the big questions: how humans experience our own existence, how we can understand our own behavior and the behavior of others, and what is our ethical responsibility in our interaction with others. These larger questions take on great resonance against the backdrop of Nazi Germany and the atomic bomb, but are no less important in our current lives.

About the People:

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

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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

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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 who 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, the eldest was just 17 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 age 10.

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

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Movie Westerns: A Thought Experiment

For Bohr, any event could become a thought problem. George Gamow, in his book, *Thirty Years that Shook Physics,* says that Bohr loved movie Westerns. He always took his students along to the movies with him to have them explain the plot complications. After one Western, he began to argue with Gamow and some other students about why the good cowboy always shoots the bad guy even though the bad guy always draws his gun first. Bohr theorized that the hero was quicker because he responded on instinct and was not delayed by having to decide when to shoot. To test the hypothesis Gamow bought cap pistols and Bohr spent an afternoon at the Institute shooting his students.

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.

"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

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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.

"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

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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.

THE CONTEXT: TIMELINE OF KEY EVENTS IN 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.
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 Copenhagen University.
1922 June, Niels Bohr meets Werner Heisenberg after Heisenberg challenges him during a lecture series in Göttingen.
1922 December 11, **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.
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.**
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.

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.

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**).

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 (t**he 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.

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 its 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, Robert J. Oppenheimer arrives as director of the new atomic lab at **Los Alamos.**
1943 September 28, German attaché Georg F. Dukwitz leaks the SS order to deport 8,000 Danish Jews on October1, 1943, to Danish Social Democrat Hans Hedtoft. Hedtoft warns Danish Jewish leaders C.B. Henriques and Marcus Melichor. 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 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.
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, NM.
1945 August 6, the first atomic bomb, "Little Boy" is dropped on Hiroshima, Japan.
1945 August 9, the second atomic bomb, "Fat Man" is dropped on Nagasaki, Japan.
1945 August 10, Japan surrenders.
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.*

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

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 p.m. – 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, 1943, 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.

"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 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.

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.

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

Many people alive today have grown up with both the atom and the atom 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. Erwin Schrödinger proposed one such famous experiment. 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 to 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.

Double slit experiment

Light is shown through a panel that contains two slits. The light on the opposite side of the panel appears in bands of light and dark indicating the interference of waves that have passed through the two slits and supporting the wave-like nature of light. Thomas Young first did the double slit experiment in 1805 to determine whether light was composed of particles or waves traveling through ether. It was revived as a “Gedankenexperiment” or thought experiment in quantum mechanics. By the 1920s, quantum physicists had already shown that light interacts with matter in discrete quantum packets. So the thought experiment asked what would happen if a single photon of light was aimed at the two slits and hit a sensitive surface on the other side. If just one slit in the panel is open, the photon hits on the sensitive surface will pile up in the same general location if the experiment is repeated. If both slits are open and the experiment is repeated, the pattern of bands will appear. Since the photons are being sent through the slits one at a time, this suggests that they could not be "interfering" with each other. To resolve this problem, modern quantum mechanics postulates probability waves that indicate the likelihood of finding a particle in a particular place. These probability waves provide the interference that ordinary waves would supply.

Particle or Wave: Wave-Particle Duality

Since subatomic particles exhibit characteristics of both waves and particles, a phenomenon known as the wave-particle duality. The terminology of quantum mechanics can be tricky. Sometimes subatomic particles may be referred to as subatomic systems in an effort to avoid the word "particle" when it may not be accurate for the circumstances. Wave-particle duality is a key concept of quantum mechanics. It holds that light and matter can exhibit the properties of both waves and particles. This was contrary to the understanding of classical mechanics in which something was either a wave or a particle, but not both. This is part of what made quantum mechanics such a giant shift in the prevailing thinking that had dominated physics for hundreds of years.

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 more than 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.

"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

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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. More than 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.

BIOGRAPHIES

Notable Physicists and Colleagues of Niels Bohr and Werner Heisenberg

Max Born	December 11, 1882 – January 5, 1970. A German of Jewish descent, he fled German in 1933 and took a post at Cambridge. He was awarded a Nobel Prize in 1954 for his probability density function for Schrödinger's Equation of Quantum Mechanics. He was also the grandfather of Olivia Newton John.
Hendrik Casimir	July 15, 1909 – May 4, 2000. A Dutch physicist, in 1948 he predicted the quantum mechanical attraction between conducting plates, now known as the Casimir Effect.

James Chadwick	October 20, 1891 – July 24, 1974. The British physicist studied under Ernest Rutherford. He received the Nobel Prize for his discovery of the neutron, which has no electrical charge. The discovery of the neutron was necessary for studies that would lead to fission and the atomic bomb. He worked on the Manhattan Project.
Louis de Broglie	August 15, 1892 – March 19, 1987. The Seventh Duc de Broglie, the French physicist won the Nobel Prize in Physics in 1929 for his development of wave mechanics, which included wave-particle duality based on the work of Albert Einstein and Max Plank.
Paul Dirac	August 8, 1902 – October 20, 1984. The British born Dirac is known for developing a version of Quantum Mechanics that incorporated both Werner Heisenberg's Matrix Mechanics and Erwin Schrödinger's Wave Mechanics. His *Principles of Quantum Mechanics* became a standard textbook.
Paul Ehrenfest	January 18, 1880 – September 25, 1933. Ehrenfest was an Austrian-Jewish physicist. In spite of vital contributions to the understanding of quantum mechanics, Ehrenfest suffered from low self-esteem and doubts about his ability to keep up in the quickly changing world of physics. He shot his son, who had Down's syndrome, before shooting and killing himself. His suicide note was addressed to Niels Bohr and Albert Einstein (both of whom he held in great affection), among other physicists.
Albert Einstein	March 14, 1879 – April 18, 1955. German-born scientist of Jewish descent, Einstein is one of the most well-known and well-regarded physicists of the 20th Century. He proposed both the Special and General Theories of Relativity, wrote a paper on Brownian Motion and made contributions to Quantum Mechanics and Cosmology. He received the 1921 Nobel Prize for his explanation of the photoelectric effect.
Enrico Fermi	September 29, 1901 – November 28, 1954. The Italian-born physicist received a Nobel Prize in Physics for his discovery of new radioactive elements and related nuclear reactions brought about by slow neutrons. Fermi left for America to avoid the Italian anti-Semitic laws that could affect his Jewish wife and children. He continued his work on fission in the United States and ultimately worked on the Manhattan Project developing the first atomic bomb.
Siegfried Flugge	The first physicist to calculate a critical mass for U-235 with Francis Perrin. He also authored a book entitled *Practical Quantum Mechanics.*
Otto Frisch	October 1, 1904 – September 22, 1979. Nephew of Lise Meitner, the Austrian-British physicist. He studied with Niels Bohr in Copenhagen. While visiting his aunt in Sweden in 1938 they worked to explain Otto Hahn and Fritz Strassman's discovery that uranium bombarded with neutrons produced barium. They coined the term

"fission." With Rudolph Peierls in Birmingham, Frisch estimated it would require a very small critical mass to create an explosion using Uranium-235.

George Gamow — March 4, 1904 – August 18, 1968. The Ukrainian scientist studied in Göttingen and later in Copenhagen with Niels Bohr. He worked on numerous projects but is perhaps best remembered as a popularizer of physics with his accessible books for the general public. He settled in the United States after fleeing increasing oppression in the Soviet Union.

Samuel Goudsmit — July 11, 1902 – December 4, 1978. Although he received his Ph.D. in Germany, Goudsmit spent much of his career in the United States. From 1944–1946, he was Chief of Scientific Intelligence for the ALSOS Mission, which included investigating the German atomic project. He is most well known for the discovery of "spin" with George Uhlenbeck.

Otto Hahn — March 8, 1879 – July 28, 1968. The German chemist received the 1944 Nobel Prize in chemistry for his work, but was unable to attend the ceremony as the British government was detaining him for his work on the German atomic project. He had worked earlier on the bombardment of uranium with neutrons with Lise Meitner until she fled Germany. He has been criticized for downplaying Meitner's role in his research.

Friedrich Houtermanns — January 22, 1903 – March 1, 1966.The Polish physicist made contributions to numerous areas of physics. He worked with George Gamow on stellar physics.

Fédéric Joliot — March 19, 1900 – August 14, 1958. The French physicist was an assistant to Marie Curie, and ultimately married her daughter Irène in 1926, after which they both changed their names to Joliot-Curie. He and his wife received the 1935 Nobel Prize in chemistry "in recognition of their synthesis of new radioactive elements."

Pascual Jordan — October 18, 1902 – July 31, 1980. German physicist Jordan was also involved in the development of quantum mechanics, specifically quantum field theory. After 1933, he was a Nazi party member, but at the same time wrote a book on the history of physics crediting the contributions of Jewish physicists.

Oskar Klein — September 15, 1894 – February 5, 1977. The son of a Swedish Rabbi, Klein was also a student of Niels Bohr. Between 1918 and the early 1920s, he would divide his time between Stockholm and Copenhagen. In 1923, he took a post at the University of Michigan. He is known for the Klein-Gordon Equation, the first relativistic wave equation.

Hendrik Kramers	December 17, 1894 – April 24,1952. The Dutch physicist was an assistant to Bohr for almost ten years and would remain a close family friend. Margrethe Bohr would recall his musical skill. Kramer's Law is a formula he derived explaining the opacity of material inside a star.
Lev Landau	January 22, 1908 – April 1, 1968. A Russian physicist, he received the Nobel Prize in Physics in 1962 for his theories of condensed matter. He worked on superconductivity and quantum electrodynamics as well as particle physics.
Max von Laue	October 9, 1879 – April 24, 1960. The German physicist who figured out how to measure X-rays by the diffraction of crystals for which he received the 1914 Nobel Prize in Physics. He was a student of Max Planck.
Lise Meitner	November 7, 1878 – October 27, 1968. An Austrian-Jew, Meitner studied with Otto Hahn and Max Planck. She collaborated closely with Hahn, a chemist, on the study of radioactivity. When Austria was annexed by Germany in 1938, Meitner was forced to flee to Sweden where she and her nephew Otto Frisch helped explain the process they would call "nuclear fission".
Christian Møller	1904 – 1980. Møller was a Danish-born physicist and student of Niels Bohr. He was the director of CERN (The European Center for Nuclear Research) Theoretical Study Group from 1954-1957 and the Secretary of the Royal Danish Academy of Sciences from 1959-1980. He is known for the Møller scattering equation from his study of the collision of two electrons.
Robert Oppenheimer	April 22, 1904 – February 18, 1967. The American physicist of German-Jewish extraction became the scientific director of the Manhattan Project. During the Cold War, he was called before the House Un-American Activities Committee and his security clearance was stripped because of his Communist sympathies. Edward Teller testified against him during the hearings.
Wolfgang Pauli	April 25, 1900 – December 15, 1958. Swiss-Austrian Physicist known for his work on Spin. He studied in Göttingen under Max Born and at the Institute for Theoretic Physics in Copenhagen under Niels Bohr. He postulated the neutrino and, in 1945, received the Nobel Prize for the Pauli exclusion principle, which states that no two electrons could exist in the same quantum state. He was also known for accidentally breaking lab equipment.

Rudolph Peierls	June 5, 1907 – September 19, 1995. Peierls studied under Werner Heisenberg and Wolfgang Pauli. A German Jew, he moved to Birmingham when Hitler came to power. With Otto Frisch, he calculated the critical mass of Uranium-235 needed to create an atomic explosion. Their paper sparked American and British interest and helped lead to the Manhattan Project.
Francis Perrin	1901 – 1992. In 1939, the French physicist helped establish the possibility of nuclear chain reactions and nuclear energy production. He was later French high commissioner for atomic energy.
Max Planck	April 23, 1858 – October 4, 1947. The German physicist Planck is often considered to be the father of Quantum Mechanics. He is most well known for his realization that electromagnetic energy could only be emitted in quantized form from which he derived what is known as Planck's Constant. He was awarded the Nobel Prize in physics in 1918 for this discovery.
Stefan Rozental	A Polish-Jewish physicist Rozental, was an assistant and close collaborator of Niels Bohr. He also worked for Heisenberg for a time. He was often asked to give recollections of both Bohr and Heisenberg. He edited his fellow physicists' recollections of Niels Bohr for a memorial volume published in Bohr's honor in 1967.
Ernest Rutherford	August 30, 1871 – October 19, 1937. The New Zealand-born physicist is often known as the father of nuclear physics. He pioneered the orbital model of the atom. He had a great friendship with his student Niels Bohr, and they collaborated closely on Bohr's own understanding of atomic orbits.
Erwin Schrödinger	August 12, 1887 – January 4, 1961. The Austrian physicist received a Nobel Prize in 1933 for the Schrödinger Equation on Wave Mechanics. He fled Germany in 1938 after his dismissal at the University of Graz because of his open opposition to the Nazi government. He is famous for a thought problem known as Schrödinger's Cat.
Arnold Sommerfeld	December 5, 1868 – April 26, 1951. German physicist who instructed both Werner Heisenberg and Wolfgang Pauli. His work also helped further the acceptance of Einstein's Special Theory of Relativity.
Otto Stern	February 17, 1888 – August 17, 1969.A German experimental physicist who resigned his post at the University of Hamburg in 1933 and took a position at the Carnegie Institute of Technology. He received a Nobel Prize for physics in 1943.
Fritz Strassman	February 22, 1902 – April 22, 1980. A German Chemist, who collaborated with Lise Meitner and Otto Hahn on the discovery of nuclear fission in uranium.

Leo Szilard	February 11, 1898 – May 30, 1964. A Jewish-Hungarian physicist, Szilard along with Edward Teller and Eugene Wigner, asked Albert Einstein to write a letter to President Roosevelt warning him of the possibility of an atomic weapon. He helped Fermi construct the first reactor to achieve a self-sustaining nuclear reaction in Chicago in 1942. He went on to work on the Manhattan Project where he would argue against the bomb’s use on human targets.
Edward Teller	January 15, 1908 – September 9, 2003. Teller was a Hungarian-Jewish physicist. He received his Ph.D. under Werner Heisenberg at the University of Leipzig. He also studied under Niels Bohr. He worked on the Manhattan Project and became known as “the father of the hydrogen bomb” which he helped to develop for the U.S. government during the Cold War. He also testified against Robert Oppenheimer before the House Un-American Activities Committee.
J. J. Thompson	December 18, 1856 – August 30, 1940. The British physicist who discovered the electron, for which he was awarded the Nobel Prize in 1906. Ernest Rutherford was one of his students as was Bohr at a later time. In spite of his own revolutionary discovery, Thompson had a rather narrow view of the atom and disagreed with Bohr, who left him to work with Rutherford.
George Uhlenbeck	December 6, 1900 – October 31, 1988. The Indonesian-born physicist introduced the concept of electron spin with Samuel Goudsmit for which they received the Max Planck medal.
Victor Weisskopf	September 19, 1908 – April 22, 2002. An Austrian-American physicist. He worked on the Manhattan Project but later would work against the proliferation of nuclear weapons.
Carl von Weizsäcker	Born June 28, 1912, he is a German physicist and philosopher. He worked on the German atomic project with Werner Heisenberg and was detained with him at Farm Hall. His father was the diplomat Ernst von Weisäcker and his brother, Richard, would later become the president of Germany. For a time, he served as director of the Max Plank Institute. Later in his life, he would turn to finding connections between religion and science.
Eugene Wigner	November 17, 1902 – January 1, 1995. A Hungarian-Jewish physicist and mathematician, he received the Nobel Prize in Physics in 1963. Along with fellow émigrés Leo Szilard and Edward Teller, he urged the creation of the Manhattan Project and worked on the atomic bomb.

GLOSSARY OF KEY TERMS IN *COPENHAGEN*

The Atom

Atom	An atom is a submicroscopic structure found in all matter. Originally from the Greek, it was believed to be the smallest indivisible particle of matter; however, research soon proved that there are smaller subatomic particles. An atom contains a nucleus of positively charged protons and non-electrically charged neutrons at its core. Most of the mass of an atom is contained in its nucleus. Smaller negatively charged electrons are found around the nucleus. Atoms are classified by their atomic number, the number of protons in the nucleus. Niels Bohr, working under Ernest Rutherford, postulated an atom with orbitals in which the electrons moved around a nucleus. An electron had to exist in one of the orbitals and when an excited electron dropped to a lower orbital the energy emitted was a specific quantum amount. Now electrons are perceived as existing in a cloud, that is, the probability of finding an electron at a certain point around the nucleus. Sometimes the area that electrons occupy is referred to as an electron shell.
Proton	A proton is a positively charged subatomic particle it has about 1836 times the mass of an electron. Ernest Rutherford discovered the proton in 1918. The proton with neutrons makes up the nucleus of an atom and the number of protons determines which element the atom is. The proton itself is made up of smaller subatomic particles not discussed in *Copenhagen*.
Neutron	The neutron is a subatomic particle that has a slightly larger mass than a proton and no electrical charge. Together with electrons, neutrons make up the nucleus of an atom. An atom may have a different number of neutrons and remain the same element; it has the same atomic number. If its atomic mass changes however and it is known as an isotope. Carbon-12 has 6 protons and 6 neutrons, but carbon-14 had 6 protons and 8 neutrons. Carbon-14 is an isotope.
Electron	Electrons are negatively charged subatomic particles that move around the nucleus of an atom. Electrons determine how atoms interact with each other and determine the chemical properties of an element. Electricity is created by moving electrons.
Photon	A photon is considered an elementary particle. It is a quantum of energy. It exhibits the characteristics of both a wave and a particle. Light is composed from a large quantity of photons. A very high-energy photon is called a gamma ray.

Nuclear Science

Isotope	Isotopes are forms of a chemical element that have the same atomic number but a different atomic mass. The atomic mass is different because there are additional neutrons in the nucleus of the atom. The atomic number of an isotope remains the same because the number of protons remains the same. The number attached to the element indicates the additional neutrons. Uranium-238 and uranium-235 are isotopes. Isotopes occur in nature as a percentage of the element.
Uranium-235	Uranium-235 is an isotope of uranium that differs from uranium-238 in its ability to cause a rapidly expanding fission chain reaction. A uranium nucleus that absorbs a neutron splits into two new nuclei. It then releases two or three more neutrons, which, in turn, can fission other nuclei. In a nuclear reactor, the reaction is slowed down by control rods made of an element that absorbs neutrons such as cadmium, boron or hafnium. In a nuclear bomb, the reaction is uncontrolled and the energy release creates a nuclear explosion. Only .72% of natural uranium is uranium-235.
Uranium-238	Uranium-238 is the most commonly occurring isotope of uranium. When a neutron hits uranium-238 it becomes the unstable uranium-239, which decays into another element known as neptunium-239, which ultimately decays into plutonium-239. Uranium-238 is important because it impedes fission. For use in a weapon, minimizing the amount of uranium-238 is ideal. However, in a nuclear reactor uranium-238 is best to breed plutonium.
Plutonium	Plutonium is a radioactive metallic element that is used in most modern nuclear weapons. The most important of its isotopes is plutonium-239. Plutonium is desirable in nuclear weapons because the critical mass for a nuclear explosion is between 10-16 kilograms, a sphere about ten centimeters in diameter. Detonation of plutonium will create an explosion of about 20 kilotons per kilogram of plutonium. Almost all plutonium is manufactured from uranium.
Fission	Fission is a nuclear process, which means it occurs in the nucleus of an atom. When the nucleus of an atom absorbs a neutron and the atom splits into two more, smaller nuclei and some by products such as free neutrons and photons occur.
Cadmium	Cadmium is a metallic element that is useful in nuclear reactors for its ability to absorb neutrons and thus slow a chain reaction. Cadmium and its compounds are extremely toxic to the human body.
Heavy Water	Heavy water is chemically the same as H_20. However, the atoms of hydrogen are of the heavy isotope deuterium. In deuterium, the nucleus contains a neutron in addition to the single proton that would be found in the nucleus of hydrogen. For this reason, it is also known as deuterium oxide. Heavy water is used in some nuclear reactors as a neutron moderator. It slows neutrons so they can react with the uranium in the reactor.

Nuclear Pile	A nuclear pile is another term for a nuclear reactor, a device in which nuclear reactions can be controlled and sustained. It was called a pile because of the layering of a fissile element such as uranium with a control element such as cadmium. Enrico Fermi and Leo Szilard were the first to create such a nuclear reactor at the University of Chicago.
Chain reaction	A nuclear chain reaction takes place when more than one nuclear reaction is caused by another nuclear reaction leading to an exponential increase in nuclear reactions. In fission, a chain reaction occurs when the neutrons released by the fission of an atom of an element in turn strike other nuclei and fission them.
Critical Mass	Critical mass is the mass of a fissile material required for a sustained nuclear reaction
Slow Neutron	Slow neutrons, also called thermal neutrons, are often used in fission because they are more easily absorbed by atomic nuclei.
Fast Neutrons	Fast neutrons are so-called to distinguish them from slow neutrons. They are the neutrons produced by nuclear fission and have higher kinetic energy. In reactors, neutron moderators are used to slow down fast neutrons.

COPENHAGEN **DISCUSSION QUESTIONS**

About the Play

1. Frayn repeats the mention of Elsinore and the deaths of Christian and Harald Bohr. Why does he do this and how does it contribute to the themes of the play?

2. Frayn studied philosophy and worked as a journalist, but he is not a physicist. How does his background influence the questions he has his characters ask about human nature?

3. The play is based on real incidents and real people. How does the dramatization of historical figures help illuminate the history?

4. In 1999 Michael Frayn was invited to speak to physicists at a conference at the Niels Bohr Institute because of *Copenhagen*. How does the play help an audience understand the physics?

5. Heisenberg's Uncertainty Principle serves a metaphorical and structural function in the play. How does Frayn use the concept of uncertainty throughout the play?

About the Production

1. The set makes dramatic use of plastic walls that are both present and seem to disappear. What is the effect of the set in the context of the play?

2. Because of the plastic walls, light is both reflected by and diffused through the walls. How does the lighting help set the mood for the play?

3. The play refers to specific pieces of music; the word silence is also repeated. How does the music or lack of music affect the emotional content of the play?

COPENHAGEN ADDITIONAL RESOURCES

Niels Bohr

Pais, Abraham. *Niels Bohr's Times,* Clarendon Press, Oxford 1991

Rozental, S. Ed. *Niels Bohr: His Life and Work as Seen by His Friends and Colleagues*, North Holland Publishing Co, New York, 1964.

Werner Heisenberg

Cassidy, David. *Uncertainty: The Life and Science of Werner Heisenberg*, W.H. Freeman and Co., New York, 1992.

Powers, Thomas. *Heisenberg's War*, Knopf, 1993

Physics

Gamow, George. *Thirty Years That Shook Physics*, Dover, New York, 1966.

Zukav, Gary. *The Dancing Wu Li Masters*, HarperCollins, New York, 1979.

The Plight of Danish Jews

Levine, Ellen. *Darkness Over Denmark*, Holiday House, New York, 2000.

Yahil, Leni. *The Rescue of Danish Jewry*, Jewish Publication Society of America, Philadelphia, 1969.

General History

Bernstein, Jeremy. *Hitler's Uranium Club, the Secret Recordings at Farm Hall*, American Institute of Physics, New York, 1996.

Jungk, Robert. *Brighter Than a Thousand Suns,* Harvest, New York, 1970.

Frank, Sir Charles. Intro. *Operation Epsilon: The Farm Hall Transcripts,* University of California Press, Berkeley, 1993.

Medawar, Jean and David Pyke. *Hitler's Gift: The True Story of Scientists Expelled by the Nazi Regime*, Arcade Publishing, New York, 2000.

Szasz, Ferenc Morton. *The Day the Sun Rose Twice*, University of New Mexico Press. Albuquerque, 1984.

COPENHAGEN INTERNET RESOURCES

On Michael Frayn and *Copenhagen*

http://www.bbc.co.uk/bbcfour/cinema/features/copenhagen.shtml
http://www.pbs.org/hollywoodpresents/copenhagen/id/id_play_1.html
http://www.nbi.dk/NBA/files/sem/copintro.html (1999 lecture at the Niels Bohr Institute)

Werner Heisenberg

http://www.aip.org/history/heisenberg/p01.htm
http://nobelprize.org/physics/laureates/1932/heisenberg-bio.html
http://www.bbc.co.uk/bbcfour/audiointerviews/profilepages/heisenbergw1.shtml
http://www.pbs.org/wgbh/aso/databank/entries/bpheis.html
http://www.haigerloch.de/stadt/atomkeller/heisenberg.html

A Portion of the Farm Hall Transcripts after the news of the bomb

http://www.aip.org/history/heisenberg/p11a.htm

Niels Bohr

http://www.nba.nbi.dk/
http://nobelprize.org/physics/laureates/1922/bohr-bio.html
http://www.pbs.org/wgbh/aso/databank/entries/bpbohr.html
http://www.aip.org/history/nblbro.htm
http://www.nbi.dk/cgi-bin/search-nba
https://store.aip.org/OA_HTML/esva_advsrch_results.jsp

Drafts of letters Bohr never sent to Heisenberg re: the 1941 visit.

http://www.nbi.dk/NBA/papers/docs/cover.html

German Invasion of Denmark/ The Rescue of Danish Jews

http://www.auschwitz.dk/docu/Occupation.htm
http://fcit.coedu.usf.edu/holocaust/MAPS/map010.htm
http://en.wikipedia.org/wiki/Rescue_of_the_Danish_Jews

Heisenberg's Uncertainty Principle

http://en.wikipedia.org/wiki/Uncertainty_principle
http://www.aip.org/history/heisenberg/p08.htm
http://www.bbc.co.uk/dna/h2g2/A408638
http://www.onthemedia.org/otm061005.html

Complementarity

http://en.wikipedia.org/wiki/Complementarity_%28physics%29
http://www.upscale.utoronto.ca/GeneralInterest/Harrison/Complementarity/CompCopen.html

Schrödinger's Cat

http://en.wikipedia.org/wiki/Schrodinger%27s_cat

The Copenhagen Interpretation of Quantum Mechanics

http://www.benbest.com/science/quantum.html
http://www.aip.org/history/heisenberg/p09.htm

The Atom

http://en.wikipedia.org/wiki/Atom
http://www.pbs.org/wgbh/aso/databank/entries/dp13at.html
http://en.wikipedia.org/wiki/Bohr_model

Classical Mechanics

http://en.wikipedia.org/wiki/Classical_mechanics

Quantum Mechanics

http://en.wikipedia.org/wiki/Quantum_mechanics
http://www.spaceandmotion.com/Physics-Niels-Bohr.htm

The Manhattan Project and the Atomic Bomb

http://www.lanl.gov/history/index.shtml
http://www.lanl.gov/history/road/birthofmodernphysics.shtml

Einstein's 1939 Letter to Roosevelt

http://www.dannen.com/ae-fdr.html
http://hypertextbook.com/eworld/einstein.shtml

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Special thanks are due to the Niels Bohr Archive at the American Institute of Physics for the generous loan of two unpublished transcripts of conversations with Margrethe Bohr.