Copenhagen

by Michael Frayn

Background Information

THE NATIONAL ARTS CENTRE ENGLISH THEATRE
PROGRAMMES FOR STUDENT AUDIENCES
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NATIONAL ARTS CENTRE
CENTRE NATIONAL DES ARTS

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Section 1 - A Theatregoer's Primer of Quantum Mechanics

a quantum: a minute "energy packet" or particle of electromagnetic radiation.

quanta: many quantum.

classical (Newtonian) mechanics: the branch of physics based principally on the theories of Isaac Newton, 1642-1727. The system is very successful in predicting the behaviour of particles, pendulums, machines, etc., but fails to describe how matter interacts with matter on the incredibly small scale of the subatomic or the incredibly large scale of astromony.

relativity: the branch of physics developed by Albert Einstein that describes the behaviour of very massive and very fast phenomena like planets and light.

quantum mechanics: the branch of physics that describes the behaviour of matter and electromagnetic radiation at the subatomic level.

a photon: a quantum of light.

an electron: a subatomic particle with a negative electrical charge.

mesons: a class of subatomic particles that hold nucleons together in the nucleus.

neutron: a subatomic particle with no electrical charge located in the nucleus.

a cyclotron: a machine for accelerating subatomic particles.

nuclear fission: the splitting of an atom into two or more parts, which releases a very large amount of energy. This can occur very quickly as in an atomic bomb, or in a more controlled manner allowing the energy to be captured for useful purposes, as in the nuclear reactors used to generate electricity.

wave-particle duality: the central paradox of quantum physics -- at the level of the atom, both matter and radiation can behave sometimes like waves and sometimes like particles.

the Bohr Principle of Complementarity: theory put forward by Niels Bohr in 1928 to explain the wave-particle duality of light. The wave and particle characteristics of subatomic phenomena complement each other. Both aspects are necessary to our understanding of these phenomena, but only one aspect can be observed at a time.

the Heisenberg uncertainty principle: theory put forward by Werner Heisenberg in 1927. It is impossible to determine the position and momentum of a subatomic particle at the same time because the very process of observation changes crucial aspects of the particle so observed.

the Copenhagen Interpretation: the first consistent formulation of quantum mechanics, combining Bohr's work on complementarity, Heisenberg's on uncertainty, and Max Born's probability-based re-interpretaion of Schrödinger's wave theory; it is named for the city in which Niels Bohr ran an influential physics institute.

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Section 1 - A Theatregoer's Primer of Quantum Mechanics
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Schrödinger's cat: a thought experiment devised by Erwin Schrödinger (1887-1961) to point up the irrationality of the strange notions about reality which quantum mechanics makes possible.

Imagine a cat in a closed, soundproof box. Also in the box, imagine a device that can release a poisonous gas that would kill the cat instantly. The release mechanism for the gas is hooked up to a radioactive material and will be triggered by the decay of that material. After one hour, there is a fifty-fifty chance that the radioactive material has decayed. That means there's also a fifty-fifty chance that the cat is still alive.

Or at least that's what it would mean in a world governed by the certainties of classical physics. Because the box is designed to totally prevent your being able to hear or see any evidence of the cat's presence, the only way to know for sure if the cat is dead or alive is to open the box and take a look. Intuition and life-experience suggest that the unseen cat in the box must be either one or the other.

According to the quantum mechanics of the Copenhagen Interpretation, however, the cat in the box *doesn't exist* until the moment someone opens the box and observes it! If we understand what we can know about the cat's condition in the same way quantum mechanics explains what we can know about subatomic particles, our act of observation actually causes reality to manifest in the form we observe, as opposed to any other possible form. So, just as wave-particle duality is resolved in quantum mechanics by suggesting that only when the scientist's gaze "collapses the wavefunction" is the Universe forced to choose between a particle or a wave, Schrödinger's cat-in-a-box will be in limbo, both alive and dead, until an act of observation calls one possibility into being instead of the other.

Section 2 - The Race for the Bomb

1931 -- Harold C. Urey discovers deuterium (heavy hydrogen) which is present in all natural hydrogen compounds including water. He later contributes to Uranium 235 isotope separation, which is to be a key ingredient of the atomic bomb.

1932 -- James Chadwick proves the existence of neutrons. Not being repelled by similarly charged particles, the neutron made an ideal "bullet" for bombarding other nuclei to create a nuclear fission reaction.

January 1933 -- Adolph Hitler becomes chancellor of Germany. Due to anti-Semitism and Nazi repression, many prominent scientists flee central Europe, including Albert Einstein.

September 1933 -- Hungarian physicist Leo Szilard realizes that "if we could find an element which is split by neutrons, and which would emit two neutrons when it absorbs one, such an element would sustain a nuclear reaction."

1934 -- Enrico Fermi of Italy irradiates uranium with neutrons and unknowingly achieves the world's first nuclear fission.

June/July 1934 -- Leo Szilard files a patent application for the atomic bomb. The patent described the concept of using neutron induced chain reactions to create explosions.

December 1938 -- Otto Hahn, Fritz Strassman and Lise Meitner produce uraninum nuclear fission at Germany's Kaiser Wilhelm Institute.

January 1939 -- Otto Hahn and Fritz Strassmann in Berlin announce the discovery of uranium fission. The observations are given their correct interpretation in a February 11 paper by Lise Meitner and Otto Frisch.

February 1939 -- Robert Oppenheimer speculates in a letter that a chain reaction in a 10-centimeter cube of uranium deuteride "might very well blow itself to hell."

March 1939 -- Fermi describes the recent fission experiments and their implication that uranium could be a potent energy source or explosive to a group of U.S. military officials in Washington.

April 1939 -- Paul Harteck and Wilhelm Groth in Hamburg inform German Army Weapons about uranium fission, saying it may make possible powerful explosives.

SEPTEMBER 1, 1939 – THE GERMAN ARMY INVADES POLAND; WWII BEGINS.

September 16, 1939 -- German Army Weapons recruits scientists for a wartime uranium project. The meeting organizers are Kurt Diebner and his assistant, Erich Bagge, both Nazi party members.
Later that month Diebner convenes a second Army Weapons conference on uranium fission, including Heisenberg, Weizsäcker, Harteck and Hahn. Heisenberg discusses a possible uranium reactor, noting that with sufficiently enriched uranium it will explode.
The fission program will be headquartered in the new Kaiser Wilhelm Institute of Physics (KWI) in Berlin-Dahlem. Fission research is made a secret of the state, and publication of scientific results is suppressed. Germany has a military nuclear-fission project.

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Section 2 - The Race for the Bomb (continued)

December 1939 -- Heisenberg submits the first part of a report to German Army Weapons, concluding that the surest way to a reactor for energy production is enrichment of U^{235} in uranium, also the only method of producing explosives "several orders of magnitude more powerful than the strongest explosives yet known."

1940 -- The University of California begins building a giant cyclotron under the direction of Ernest O. Lawrence.

May 1940 -- German troops in Norway seize control of the world's only heavy water production facility and step up production to supply the German fission program.

June 1940 -- Harteck reports on a uranium oxide-dry ice reactor. His 185 kilograms of uranium is inadequate for neutron multiplication, but Heisenberg's group in Dahlem refuses to share more of the available uranium; Heisenberg's Leipzig project has first claim on available heavy water.

July 1940 -- Weizsäcker in a secret report to Army Weapons proposes that reactors can be used to create neptunium for the construction of atomic bombs.

October 1940 -- A new fission-research laboratory is completed at the KWI; Heisenberg commutes between reactor experiments in Berlin and Leipzig.

March 1941 -- Heisenberg and the Berlin-Dahlem team report on their first reactor experiments with layers of uranium oxide and paraffin in a cylindrical tank. The results are negative, and Heisenberg concludes that heavy water must be used.

June 22, 1941 – Germany invades the Soviet Union.

September 1941 -- Heisenberg meets with Niels Bohr in Nazi-occupied Copenhagen and brings up nuclear fission research. Heisenberg later describes the meeting as an attempt to seek advice while Bohr sees it as a hostile approach. In Copenhagen Heisenberg and Weizsäcker lecture at a Nazi propaganda institute.

December 1941 -- The head of Army Weapons Research orders a review of the uranium project. Declaring the army can no longer support projects that will not yield results in the foreseeable future, he considers cancellation of support for fission research.

December 8, 1941 — The United States declares war on Japan one day after the bombing of Pearl Harbor.

December 1941 -- President Roosevelt allocates $2 billion to the Manhattan Engineering District to build the atomic bomb.

January 1942 -- Heisenberg and collaborators report to Army Weapons on reactor experiment B-III. Still without heavy water, the reactor uses paraffin and uranium powder and produces no neutron multiplication.

September, 1942 -- Colonel Leslie Groves is promoted to Brigadier-General and put in charge of the Manhattan Project. He recruits J. Robert Oppenheimer as Scientific Director.

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Section 2 - The Race for the Bomb (continued)

February 1942 -- The Reich Research Council holds a conference in Berlin to promote uranium research to an audience of Nazi leaders. Heisenberg explains how a successful reactor might be used in submarines, that U235 can be used to make a bomb and that a reactor could generate plutonium. No critical-mass figure is given, but a mass of tons is implied.

March 1942 -- Albert Speer places the German economy on a war footing. Projects that do not promise short-term results are eliminated or down-graded in priority.

April 1942 -- The Leipzig L-IV reactor demonstrates neutron generation of 13 percent. Heisenberg predicts this design could be critical with 5 metric tons of heavy water and 10 tons of solid uranium metal. The reactor is destroyed by fire in June. Heisenberg leaves for Berlin, and reactor research ceases in Leipzig.

June 1942 -- A secret meeting is held in Dahlem including War Minister Speer and leading nuclear scientists. Heisenberg describes atomic bombs as possible but not in the near future. Speer approves all the scientists' requests, including a bomb-resistant bunker for a large reactor, but the project receives the lowest priority that allows it to proceed.

July 1942 -- Heisenberg becomes acting head of the KWI in Dahlem and begins planning a series of large reactor experiments involving as much of Germany's uranium and heavy water as possible. The uranium metal plates of his design prove difficult to manufacture as well as ineffective; while awaiting delivery he turns to other research.

December 1942 -- At the University of Chicago, in a squash court under Stagg Field, Enrico Fermi and his team produce the world's first controlled and self-sustained nuclear fission reaction.

November 1943 -- The U.S. Military begin remodeling the B-52 bomber for delivery of the A-bomb.

MAY 1945 – GERMANY SURRENDERS. THE WAR IN EUROPE IS OVER.

July 1945 -- Trinity Test at Alamogordo, New Mexico. The A-bomb explodes with an 18,000 ton TNT equivalence.

AUGUST 6 AND 9, 1945 – "LITTLE BOY" EXPLODES OVER HIROSHIMA, KILLING OVER 100,000 PEOPLE. THREE DAYS LATER, "FAT MAN" EXPLODES OVER NAGASAKI, KILLING OVER 75,000. JAPAN SURRENDERS SOON AFTER.

Compiled from Doug Prouty's "The Race to Build the Atomic Bomb: A Resource for Teachers and Students", Contra Costa County Office of Education, at http://www.cccoe.k12.ca.us/abomb/ and the archives of *American Scientist, the Magazine of Sigma Xi* (The Scientific Research Society) at http://www.americanscientist.org/articles/96articles/Logan-table2.html

Section 3 - Brief Biographical Details on the Bohrs, Heisenberg and Other Important Historical Figures

I. Niels Bohr

Noble prize-winning Danish physicist born in Copenhagen, Denmark, in 1885. As the head of the Institute for Theoretical Physics at the University of Copenhagen (1920-1962), Bohr was one of the founding fathers of quantum mechanics. Bohr was the academic mentor and personal friend of Werner Heisenberg; their combined efforts resulted in a logical interpretation of the physical meaning of quantum mechanics known as the Copenhagen Interpretation. Conflicting allegiances during WWII severely strained their friendship.

Bohr married Margrethe Norlund in 1912. They had six children, all sons, but Harald and Christian, the eldest, were lost, Christian in 1934, thrown overboard in a storm during a sailing excursion with his father and two family friends. Bohr's mother was Jewish, which put him and his family in danger of Nazi persecution. He actively aided the emigration of other physicists from pre-war Germany, and protected Jews in Nazi-occupied Denmark until 1943, when he and his family were forced to flee. They escaped to Sweden in a fishing boat.

As an émigré to America, Bohr assisted Manhattan Project scientists with the development of the atomic bomb. But even as early as 1944 Bohr expressed his reservations about the destructive potential of nuclear energy, taking an active role in advocating for the control of nuclear weapons by petitioning Winston Churchill and Franklin D. Roosevelt. Both leaders rejected Bohr's recommendations. Bohr was the first person to receive an Atoms for Peace Award as a result of his post-war efforts to promote the responsible use of nuclear research. Niels Bohr died in 1962.

II. Margrethe Bohr

The daughter of a pharmacist, Margrethe Norlund was born in 1890 and grew up in a small Danish town fifty miles from Copenhagen. She met Niels Bohr in 1910 while she was studying to become a French teacher. They married in 1912. The union produced six sons, two of whom, tragically, were lost.

Margrethe Bohr assisted her brilliant husband in his work, acting as a sounding board, dictation-taker, typist and editor to produce the many drafts of his scientific papers. A close friend of the family once observed that Margrethe had "a decisive role in making Niels' whole scientific and personal activity possible and harmonious."

Margrethe Bohr passed away in 1984. She was 95. She is buried in Copenhagen with her husband.

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Section 3 - Brief Biographical Details on the Bohrs, Heisenberg and Other Important Historical Figures (continued)

III. Werner Heisenberg

Werner Heisenberg, creator of the famous Heisenberg Uncertainty Principle, was born in Würzburg, Germany, in 1901. At the age of 23, Heisenberg put forward his theory of quantum mechanics that addressed problems associated with the Bohr-Rutherford model of the atom. He received the Nobel Prize for Physics for this work in 1932.

In 1926 Heisenberg won a position as a lecturer in theoretical physics at the University of Copenhagen and began a remarkably fruitful collaboration with Niels Bohr that resulted in the Copenhagen Interpretation of Quantum Mechanics. Heisenberg returned to Germany a year later to accept a position at the University of Leipzig; at 26, he was the youngest full professor in Germany. He married Elizabeth Schumacher in 1937. They had seven children.

The onset of WWII put Heisenberg in a difficult position. He was a German patriot actively involved with youth groups like the "New Boy Scouts" that sought to regenerate the noble spirit of Germany after the devastation it had suffered in WWI. Professionally, he initially resisted the Nazi's attempts to impose their vision of "purity" on German academic life, but chose to remain in Germany when many other scientists chose to leave during the 1930s. Heisenberg later maintained that his desire to preserve whatever he could of Germany's scientific heritage compelled him to stay behind along with his colleague Max Planck.

When war broke out in 1939, Heisenberg was made the director of the German atomic bomb project, which ended in failure in 1942. After the war he and his colleagues on the project were imprisoned at Farm Hall in England for six months and their conversations were secretly recorded. Returning to Germany after his release, Heisenberg established the new Max Planck Institute out of the ashes of the former Kaiser Wilhelm Institute for Physics. He continued to work and lecture in a variety of positions in West Germany and frequently represented his country abroad. He died in 1976.

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Section 3 - Brief Biographical Details on the Bohrs, Heisenberg and Other Important Historical Figures (continued)

IV. German Atomic Scientists Imprisoned with Heisenberg at Farm Hall

Dr. Kurt Diebner, the German army's expert on nuclear physics, commissioner for Norwegian heavy water production, and deputy head of the German atomic project.
Dr. Eric Bagge, a physicist at the Leipzig Institute of Theoretical Physics.
Professor Otto Hahn, a radio-chemist from the Kaiser-Wilhelm Institute of Chemistry in Berlin-Dahlem (ultimately the Max Planck Institute), who received the 1944 Nobel Prize for Chemistry.
Professor Max von Laue, a nuclear physicist at the Kaiser-Wilhelm Institute, and the 1914 recipient of the Nobel Prize for Physics.
Professor Carl F. von Weizsäcker, a theoretical physicist at the Kaiser-Wilhelm Institute.
Professor Paul Hartek, a physical chemist from Hamburg and the driving force behind much of German atomic research.
Professor Walter Gerlach, a professor from the Institute of Physics in Munich with a background in German torpedo work, who was appointed to the physics section of the Reich Research Council.
Dr. Karl Wirtz, a physicist at the KWI.
Dr. Horst Korsching, a physicist and uranium separation expert working in Berlin.

Source: Stanley Goldberg and Thomas Powers' "Declassified files reopen 'Nazi bomb' debate", The Bulletin of the Atomic Scientists at http://www.thebulletin.org/issues/1992/s92/s92.goldberg.html

V. Other Major Figures Mentioned in *Copenhagen*

Max Planck (1858-1947): discovered quanta; the publication of his findings in 1900 is viewed as the beginning of quantum mechanics.

Arnold Sommerfeld (1868-1951): worked with Bohr on a new model of the atom that included non-circular orbits.

Lise Meitner (1878-1968): provided a theoretical description of the process of nuclear fission, along with Otto Frisch. Forced to flee Germany in 1938.

Albert Einstein (1879-1955): created the theory of relativity and won the Nobel Prize in 1921 for work on the photoelectric effect. He fled Germany soon after Hitler came to power.

Max Born (1882-1970): collaborated extensively with Bohr on the Copenhagen Interpretation of quantum mechanics that revolutionized scientific thinking by putting an end to the absolute rule of determinism.

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Section 3 - Brief Biographical Details on the Bohrs, Heisenberg and Other Important Historical Figures (continued)

V. Other Major Figures Mentioned in *Copenhagen* (continued)

Erwin Schrödinger (1887-1961): developed his famous wave equation in an attempt to circumvent the random nature of "quantum leaps" associated with Bohr's model of the atom. Ultimately, Schrödinger's wave equation and Heisenberg's matrix mechanics were proven to be equivalent.

James Chadwick (1891-1974): discovered the neutron in 1932 and received the Nobel Prize for this discovery in 1935. He was the key scientist of the British atomic bomb program.

Louis de Broglie (1892-1987): put forward the important idea in his 1924 doctoral thesis that electrons had properties of both waves and particles.

Irene Joliot-Curie (1897-1956): conducted critical experiments in radioactivity along with her husband Fredric Joliot, including how one atomic element can be changed into another through exposure to radiation.

Leo Szilard (1898-1964): credited with the idea of using a chain reaction to construct an atomic bomb. Left Hungary for the U.S. in the 1930s.

Wolfgang Pauli (1900-1958): most famous for the Pauli Exclusion Principle, which states that no two particles can occupy the same "quantum state".

George Uhlenbeck (1900-1988): discovered and explained electron spin along with Samuel Goudsmit.

P. M. A. Dirac (1901-1984): formulated relativistic quantum physics by applying Einstein's ideas to quantum theory. He shared a Nobel Prize with Erwin Schrödinger in 1933.

Enrico Fermi (1901-1954): did important work on artificial transmutations of radioactive elements in his native Italy. Fled to the U.S. to escape growing anti-Semitism in Italy (his wife was Jewish) where he made significant contributions to the Manhattan Project.

Sam Goudsmit (1902-1978): discovered and explained electron spin along with George Uhlenbeck. He was also the leader of the Allies' mission to investigate the status of the Nazi bomb program after WWII.

Fritz Houtermans (1903-1966): worked with George Gamow and others on alpha particle decay and absorption; pointed out the possibility of initiating chain reactions with neutrons as early as 1932. Fled Nazi occupied Germany in 1933.

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Section 3 - Brief Biographical Details on the Bohrs, Heisenberg and Other Important Historical Figures (continued)

V. Other Major Figures Mentioned in *Copenhagen* (continued)

George Gamow (1904-1968): first to propose the liquid drop model of the atomic nucleus later used by Bohr to explain fission. His significant contributions to astrophysics included work on the big bang theory.

Christian Møller (1904-1981): contributed to atomic and nuclear theory, but best known for his work on relativity.

J. Robert Oppenheimer (1904-1967): head of the American atomic bomb program.

Rudolph Peierls (1907-1995): derived the dispersion formula for nuclear reactions with P. G. L. Kapur. Fled Germany in 1933 and later worked for the British atomic bomb program.

Victor Weisskopf (1908-): major figure in theoretical physics, especially in nuclear and elementary particle physics. He emigrated from Europe to the U.S. in 1937 and later worked at Los Alamos on the development of the atomic bomb.

Edward Teller (1908-): worked on the Manhattan Project at Los Alamos in the Theoretical Physics Division.

Hendrik Casimir (1909-): made important fundamental contributions to applied mathematics, theoretical physics and low temperature physics.

Sources: *IS 364: The Atomic Era*, "Great Names of the Atomic Era" at "Biographies of Persons in *Copenhagen*" compiled by Harry Lustig at http://www.siue.edu/~jpogats/IS364/IS364PDF/GreatNames.pdfhttp://web.gc.cuny.edu/ashp/nml/copenhagen/CopenhagenCharacters.doc

Section 4 - Sources and Resources

The following websites and books were invaluable sources of the information in this document:

1. An excellent review of two relevant books--*Hitler's Uranium Club: the Secret Recordings at Farm Hall* by Jeremy Bernstein, AIP Press, Woodbury, New York, 1996, ISBN 1-56396-258-6 and *Heisenberg and the Nazi Atomic Bomb Project: a Study in German Culture* by Paul Laurence Rose, University of California Press, Berkeley, 1998, ISBN 0-520-21077-8 is available on the web at http://www.aps.org/units/fps/roct00.html

2. *IS 364: The Atomic Era*, "Great Names of the Atomic Era" at http://www.siue.edu/~jpogats/IS364/IS364PDF/GreatNames.pdf

3. "Biographies of Persons in *Copenhagen*" compiled by Harry Lustig at http://web.gc.cuny.edu/ashp/nml/copenhagen/CopenhagenCharacters.doc

4. An excerpt from the Farm Hall transcripts is available at http://www.aip.org/history/heisenberg/p11a.htm

5. An article by Stanley Goldberg and Thomas Powers on the significance of the Farm Hall transcripts, "Declassified files re-open 'Nazi bomb' debate" is available at http://www.thebulletin.org/issues/1992/s92/s92.goldberg.html

6. The Contra Costa County's Office of Education offers an excellent educational website called "The Race to Build the Atomic Bomb" , written by Doug Prouty, at http://www.cccoe.k12.ca.us/abomb/

7. Information on the chronology of the German bomb project can be found at the Archives of *American Scientist, the Magazine of Sigma Xi* (The Scientific Research Society) at http://www.americanscientist.org/articles/96articles/Logan-table2.html

8. An excellent review page on *Copenhagen* with several useful links is at http://www.complete-review.com/reviews/fraynm/cophagen.htm

Some Books Recommended by Playwright Michael Frayn

Thomas Powers, *Heisenberg's War* (Cape, 1993)

David Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg* (Freedman, 1992)

Abraham Pais, *Niels Bohr's Times* (OUP, 1991)

Werner Heisenberg, *Physics and Beyond* (Harper & Row, 1971)

Operation Epsilon, the Farm Hall Transcripts, introduced by Sir Charles Frank (Institute of Physics Publishing, 1993)