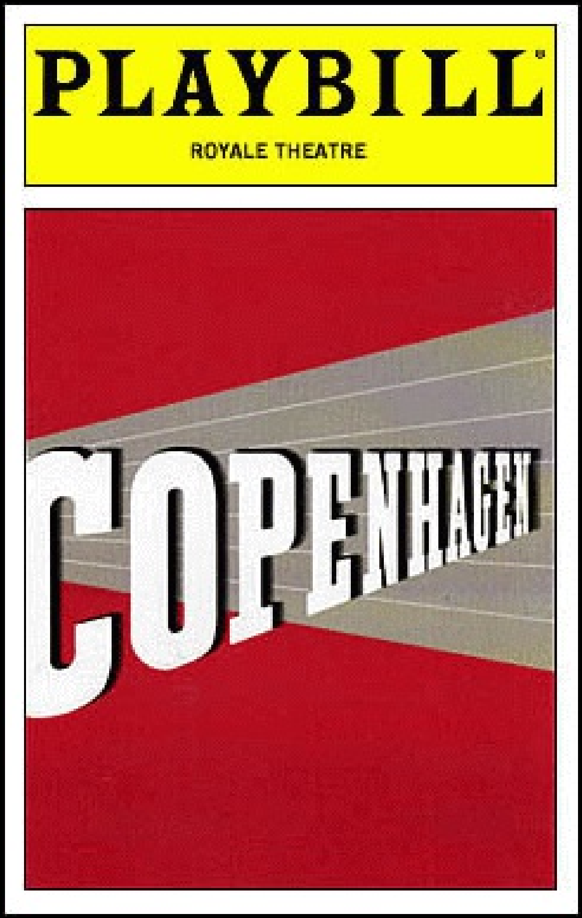
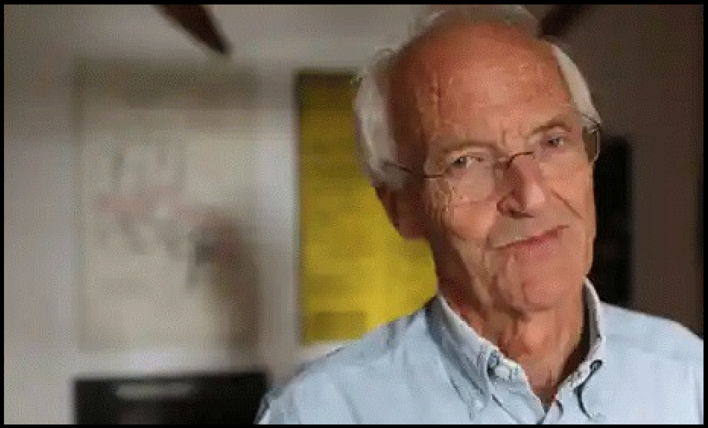
Copenhagen

Copenhagen





Michael Frayn (1933-)

London Premiere 1998

New York Premiere 2000

Copenhagen

Michael Blakemore’s 1998 staging of “Copenhagen,” with David Burke, Sara Kestelman and Matthew Marsh

Niels Bohr (1885-1962)

1885 – Born, Copenhagen
1903-1911 – University of Copenhagen
1911-1912 – Research at Cambridge and Manchester
1912 – Marries Margrethe Nørlund
1912-1914 – Lecturer at Copenhagen
1913 – Bohr Model of the Atom
1914-1916 – Reader at Manchester
1916-1962 – Professor of Theoretical Physics, Copenhagen
1921 – Director of the Institute for Theoretical Physics, Copenhagen
1922 – Nobel Prize in Physics
1927 – Complementarity Principle
1934 – Death of Christian Bohr
1941 – Meeting with Heisenberg
1943 – Bohr Flees Denmark
1943-1945 – Los Alamos
1962 – Died, Copenhagen

Margrethe (Nørlund)Bohr (1890-1984)

1885 – Born, Slagelse, Denmark
1909-1910 – Zahle's School for Female Specialist
Teachers, Copenhagen
1910-1911 – Hospitalization
1912 – Marries Niels Bohr
1943 – Flees Denmark
1943-1945 – Exile in Sweden
1984 – Died, Copenhagen

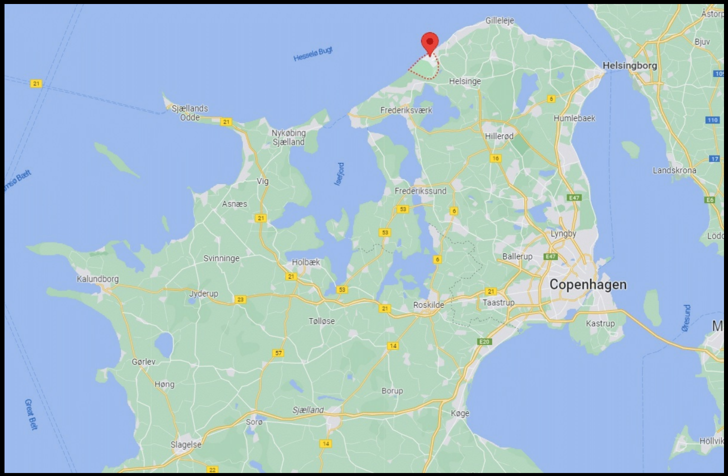
Werner Heisenberg (1901-1976)

1901 – Born, Würzburg
1919 – Member of the Freikorps, Munich
1920-1923 – Studies Physics at Munich and Göttingen
1923 – Ph.D., Munich
1924-1927 – Lecturer at Göttingen
1924-1925 – Research with Bohr in Copenhagen
1925 – Matrix Mechanics
1926-1927 – Lecturer and Assistant to Bohr, Copenhagen
1927 – Uncertainty Principle
1927 – Professor of Theoretical Physics, Leipzig
1932 – Nobel Prize in Physics
1939-1945 – German Atomic Bomb Project
1945-1946 – Internment at Farm Hall
1946-1958 – Director, Max Planck Institute for for Physics, Göttingen
1958-1970 – Director, Max Planck Institure for Physics and Astrophysics, Munich
1976 – Died, Munich

Carlsberg

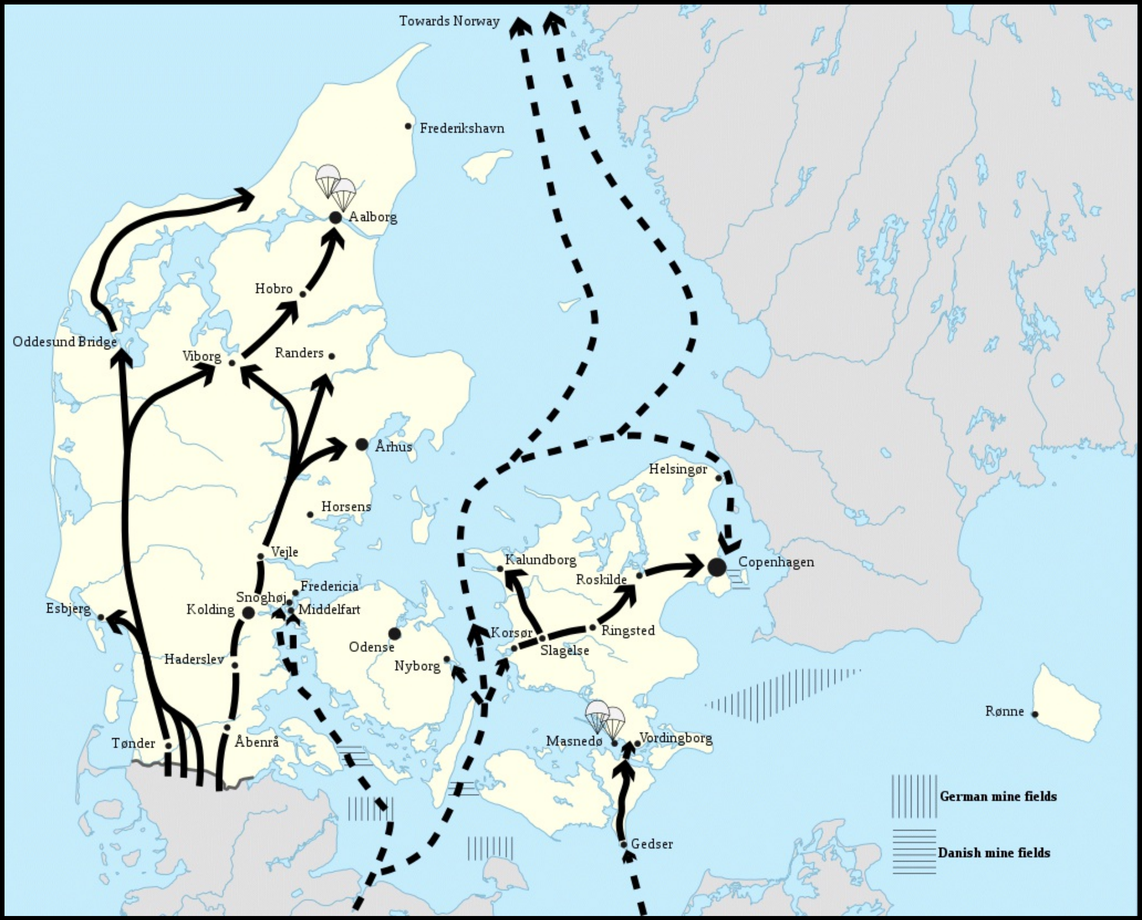
Niels and Margrethe at the Carlsberg House

Tisvilde (Bohrs' Summer House)



Niels and Margrethe at Tisvilde

German Occupation of Denmark



April 9, 1940

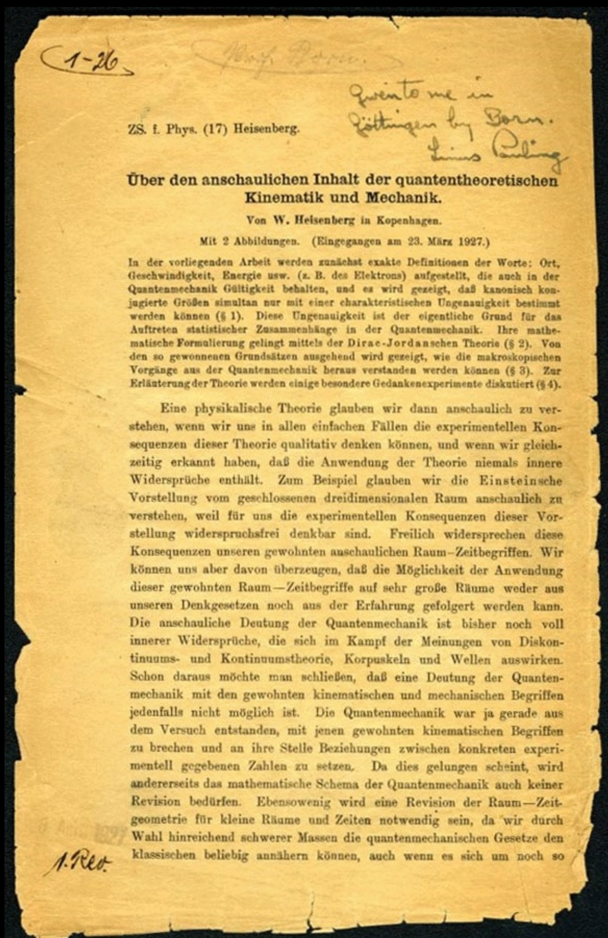
German Occupation of Denmark

Martial Law Declared,
August 29, 1943

German Occupation of Denmark

Rescue of the Danish
Jews, October 1943

The Uncertainty Principle



1-26

Given to me in Göttingen by Born. Linus Pauling

ZS. f. Phys. (17) Heisenberg.

Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik.

Von W. Heisenberg in Kopenhagen.

Mit 2 Abbildungen. (Eingegangen am 23. März 1927.)

In der vorliegenden Arbeit werden zunächst exakte Definitionen der Worte: Ort, Geschwindigkeit, Energie usw. (z. B. des Elektrons) aufgestellt, die auch in der Quantenmechanik Gültigkeit behalten, und es wird gezeigt, daß kanonisch konjugierte Größen simultan nur mit einer charakteristischen Ungenauigkeit bestimmt werden können (§ 1). Diese Ungenauigkeit ist der eigentliche Grund für das Auftreten statistischer Zusammenhänge in der Quantenmechanik. Ihre mathematische Formulierung gelingt mittels der Dirac-Jordanschen Theorie (§ 2). Von den so gewonnenen Grundsätzen ausgehend wird gezeigt, wie die makroskopischen Vorgänge aus der Quantenmechanik heraus verstanden werden können (§ 3). Zur Erläuterung der Theorie werden einige besondere Gedankenexperimente diskutiert (§ 4).

Eine physikalische Theorie glauben wir dann anschaulich zu verstehen, wenn wir uns in allen einfachen Fällen die experimentellen Konsequenzen dieser Theorie qualitativ denken können, und wenn wir gleichzeitig erkannt haben, daß die Anwendung der Theorie niemals innere Widersprüche enthält. Zum Beispiel glauben wir die Einsteinsche Vorstellung vom geschlossenen dreidimensionalen Raum anschaulich zu verstehen, weil für uns die experimentellen Konsequenzen dieser Vorstellung widerspruchsfrei denkbar sind. Freilich widersprechen diese Konsequenzen unseren gewohnten anschaulichen Raum-Zeitbegriffen. Wir können uns aber davon überzeugen, daß die Möglichkeit der Anwendung dieser gewohnten Raum—Zeitbegriffe auf sehr große Räume weder aus unseren Denkgesetzen noch aus der Erfahrung gefolgert werden kann. Die anschauliche Deutung der Quantenmechanik ist bisher noch voll innerer Widersprüche, die sich im Kampf der Meinungen von Diskontinuums- und Kontinuumstheorie, Korpuskeln und Wellen auswirken. Schon daraus möchte man schließen, daß eine Deutung der Quantenmechanik mit den gewohnten kinematischen und mechanischen Begriffen jedenfalls nicht möglich ist. Die Quantenmechanik war ja gerade aus dem Versuch entstanden, mit jenen gewohnten kinematischen Begriffen zu brechen und an ihre Stelle Beziehungen zwischen konkreten experimentell gegebenen Zahlen zu setzen. Da dies gelungen scheint, wird andererseits das mathematische Schema der Quantenmechanik auch keiner Revision bedürfen. Ebensowenig wird eine Revision der Raum—Zeitgeometrie für kleine Räume und Zeiten notwendig sein, da wir durch Wahl hinreichend schwerer Massen die quantenmechanischen Gesetze den klassischen beliebig annähern können, auch wenn es sich um noch so

1. Rev.

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

x is position

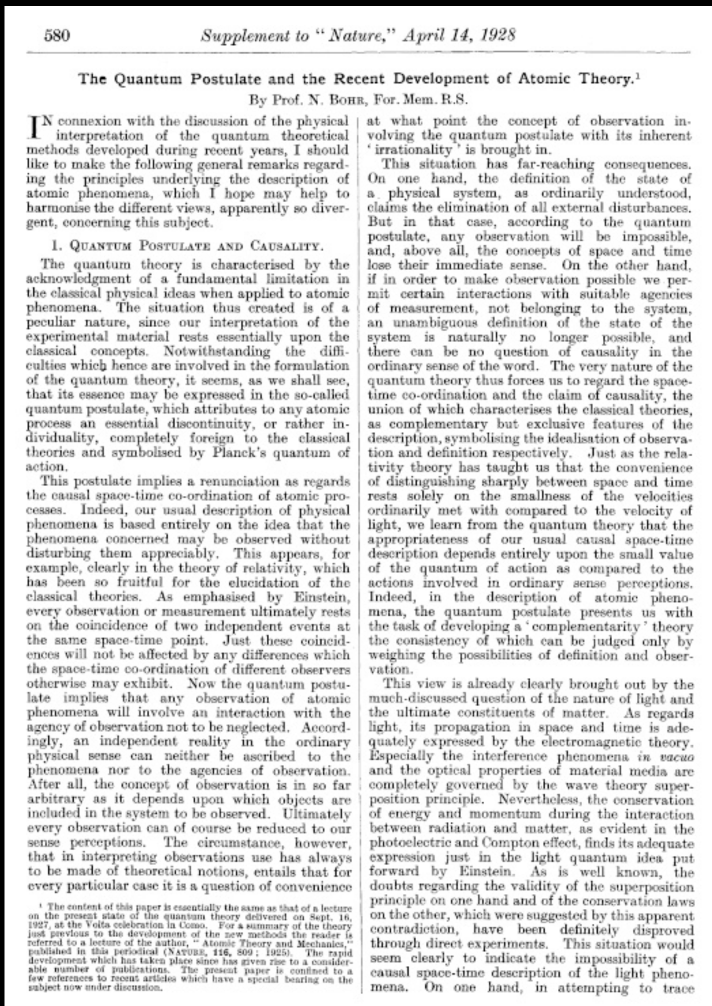
p is momentm

E is energy

t is time

h is Planck's constant

The Complementarity Principle



580 *Supplement to "Nature," April 14, 1928*

The Quantum Postulate and the Recent Development of Atomic Theory.[1]

By Prof. N. Bohr, For. Mem. R.S.

IN connexion with the discussion of the physical interpretation of the quantum theoretical methods developed during recent years, I should like to make the following general remarks regarding the principles underlying the description of atomic phenomena, which I hope may help to harmonise the different views, apparently so divergent, concerning this subject.

1. Quantum Postulate and Causality.

The quantum theory is characterised by the acknowledgment of a fundamental limitation in the classical physical ideas when applied to atomic phenomena. The situation thus created is of a peculiar nature, since our interpretation of the experimental material rests essentially upon the classical concepts. Notwithstanding the difficulties which hence are involved in the formulation of the quantum theory, it seems, as we shall see, that its essence may be expressed in the so-called quantum postulate, which attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories and symbolised by Planck's quantum of action.

This postulate implies a renunciation as regards the causal space-time co-ordination of atomic processes. Indeed, our usual description of physical phenomena is based entirely on the idea that the phenomena concerned may be observed without disturbing them appreciably. This appears, for example, clearly in the theory of relativity, which has been so fruitful for the elucidation of the classical theories. As emphasised by Einstein, every observation or measurement ultimately rests on the coincidence of two independent events at the same space-time point. Just these coincidences will not be affected by any differences which the space-time co-ordination of different observers otherwise may exhibit. Now the quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation. After all, the concept of observation is in so far arbitrary as it depends upon which objects are included in the system to be observed. Ultimately every observation can of course be reduced to our sense perceptions. The circumstance, however, that in interpreting observations use has always to be made of theoretical notions, entails that for every particular case it is a question of convenience at what point the concept of observation involving the quantum postulate with its inherent 'irrationality' is brought in.

This situation has far-reaching consequences. On one hand, the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case, according to the quantum postulate, any observation will be impossible, and, above all, the concepts of space and time lose their immediate sense. On the other hand, if in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word. The very nature of the quantum theory thus forces us to regard the space-time co-ordination and the claim of causality, the union of which characterises the classical theories, as complementary but exclusive features of the description, symbolising the idealisation of observation and definition respectively. Just as the relativity theory has taught us that the convenience of distinguishing sharply between space and time rests solely on the smallness of the velocities ordinarily met with compared to the velocity of light, we learn from the quantum theory that the appropriateness of our usual causal space-time description depends entirely upon the small value of the quantum of action as compared to the actions involved in ordinary sense perceptions. Indeed, in the description of atomic phenomena, the quantum postulate presents us with the task of developing a 'complementarity' theory the consistency of which can be judged only by weighing the possibilities of definition and observation.

This view is already clearly brought out by the much-discussed question of the nature of light and the ultimate constituents of matter. As regards light, its propagation in space and time is adequately expressed by the electromagnetic theory. Especially the interference phenomena *in vacuo* and the optical properties of material media are completely governed by the wave theory superposition principle. Nevertheless, the conservation of energy and momentum during the interaction between radiation and matter, as evident in the photoelectric and Compton effect, finds its adequate expression just in the light quantum idea put forward by Einstein. As is well known, the doubts regarding the validity of the superposition principle on one hand and of the conservation laws on the other, which were suggested by this apparent contradiction, have been definitely disproved through direct experiments. This situation would seem clearly to indicate the impossibility of a causal space-time description of the light phenomena. On one hand, in attempting to trace

[1] The content of this paper is essentially the same as that of a lecture on the present state of the quantum theory delivered on Sept. 16, 1927, at the Volta celebration in Como. For a summary of the theory just previous to the development of the new methods the reader is referred to a lecture of the author, "Atomic Theory and Mechanics," published in this periodical (Nature, 116, 809; 1925). The rapid development which has taken place since has given rise to a considerable number of publications. The present paper is confined to a few references to recent articles which have a special bearing on the subject now under discussion.

Two properties of a system are said to be complementary to one another if both are necessary for a complete representation of the system but the two cannot be realized simultaneously. Such complementarity is a generic feature of the the quantum world.