

Essay review

Heisenberg and the German bomb

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Reviews of *Copenhagen*. By MICHAEL FRAYN. (Methuen Drama, 1998.) Pp. 116. UK£6.99 (pbk). ISBN 0 413 72490 5. Scope: play. Level: non-specialist. Also published by (Anchor Books, 2000.) Pp. 135. US\$12.00 (pbk). ISBN 0 385 72079 3. *Hitler's Uranium Club: The Secret Recordings at Farm Hall*. Annotated by JEREMY BERNSTEIN. (Copernicus Press, 2001.) Pp. xxx + 384. US\$20.00 (pbk). ISBN 0 387 95089 3. Scope: Text. Level: non-specialist.

Michael Frayn's drama *Copenhagen*, dealing with the 1941 meeting between Werner Heisenberg and Niels Bohr, received enthusiastic reviews when it opened at London's National Theatre in May 1998. It ran in repertory there until late January, 1999, transferring to the Duchess Theatre in London's West End, where it presented eight performances per week to large audiences until April, 2001. A New York company also performed eight times per week at Broadway's Royale Theater from January 2000 to April 2001. A touring company is now performing the play at cities around the US. The play has been translated and performed in (to my knowledge) French, German and the Scandinavian languages. The number of seats (mostly filled) for these presentations is at least 800 000—surely much larger than the number of physicists who have ever lived. The success of the play as drama is undeniable. Its historical accuracy has been questioned, and it has already been the subject of at least two conferences. The accuracy of its presentation of physics and the scientific/philosophical ideas around which it has been structured have received less discussion. These matters are the subject of the present review.

First, however, a brief description of the play and its historical context. The play is set in the living room of Niels and Margrethe Bohr in Copenhagen. The three characters in the play, long-dead, are the Bohrs and Werner Heisenberg, recalling Heisenberg's visit to German-occu-

ried Denmark in September 1941. Since September 1939, the month the Second World War began, Heisenberg has been involved with the *Uranverein*, 'Hitler's Uranium Club' of Bernstein's title. At the time of the visit, Germany occupied or controlled most of Europe. Its army had invaded the USSR the previous June and had not yet suffered its first reverses. Heisenberg made no secret of his belief in the inevitability and desirability of a German victory in the war and, in fact, visited Denmark (and other occupied countries) under the auspices of a German cultural/propaganda bureau. In the play, as in Heisenberg's later recollections of the visit, he begins his private conversation with his former mentor by asking whether 'as a physicist one had the moral right to work on the practical exploitation of atomic energy'. Bohr, apparently, understood something very threatening in Heisenberg's words. He never publicly detailed his interpretation of the conversation, but several previously private documents, which shed some light on the matter, were released by the Niels Bohr Archive on 6 February 2002. Facsimiles of the original documents and English translations are at the Archive's Web site <http://www.nba.nbi.dk>. I will have more to say about this material below.

There is no doubt that Bohr was a difficult person to communicate with in conversation. I heard him lecture first at a seminar when I was a first-year graduate student. He had a habit of beginning sentences at an audible level, but then speaking more and more softly until the end of the sentence was completely lost (to me, at least). I thought, at the time, that he was also using a Germanic sentence structure, so that all verbs disappeared, but that may not have been the case. I later heard a large public lecture, after which a written text was provided, but that did not help me very much. He evidently believed in the general applicability of the principles of Complementarity and Uncertainty well outside the realm of physics. The play and also Richard Rhodes's *Making of the Atomic Bomb* emphasize his love of paradox. His 1944 meeting with Winston Churchill, also described by Rhodes, was as disastrous as his conversation with Heisenberg.

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Heisenberg's position with regard to development of nuclear energy in Nazi Germany is also disputed. He was certainly not a member of the Nazi party, having been accused by Johannes Stark of being a 'White Jew', a charge he escaped only by the personal intervention of Heinrich Himmler. He did, at times, promote to government officials the idea of a nuclear explosive, but later claimed only to have been interested in a 'Maschine' (reactor). Samuel Goudsmit, in his book *Alsos* maintained that Heisenberg did not understand the difference between a (slow-neutron) nuclear reactor and a (fast-neutron) bomb. I am inclined to agree with Bernstein's assessment that he did, but did not understand either very well. Frayn was much influenced by Thomas Powers's *Heisenberg's War*, which espouses the view that Heisenberg actually opposed (and obstructed) development of a nuclear bomb in Nazi Germany for moral reasons, a view originally asserted by Robert Jungk in his book *Brighter than a Thousand Suns*. Heisenberg does seem to have believed that it would somehow be possible for Germany to win the war but rid itself of Hitler and his henchmen. Those who are interested in what Heisenberg and other German nuclear scientists understood and believed should definitely read the Farm Hall transcripts, now available in an edition extensively annotated by Jeremy Bernstein. *Hitler's Uranium Club* also includes an introduction by David Cassidy, author of the excellent Heisenberg biography *Uncertainty*, a chronology of the German nuclear program, and Bernstein's prologue, which details fission-related work in Germany and the Allied countries. Each edition of Frayn's play contains a postscript which deals with the question 'how much of it is fiction and how much of it is history'. The postscript to the US edition is available online at the Website of one of the conferences referred to above <http://web.gsuc.cuny.edu/ashp/nml/copenhagen>. The US edition of the play also includes 'an outline sketch of the scientific and historical background of the play'.

In Heisenberg's first words in the play he describes himself in a way most jarring to a physicist:

Now we're all dead and gone, yes, and there are only two things the world remembers about me. One is the uncertainty principle, and the other is my mysterious visit to Niels Bohr in Copenhagen in 1941...

On the one hand, we physicists know Heisenberg as one of the inventors of quantum mechanics and quantum field theory (not just the uncertainty principle), who first understood exchange interaction, and who bequeathed us the Heisenberg ferromagnet. His role in the development of quantum mechanics was, perhaps, overstated by the Nobel committee, which awarded him the 1932 prize 'for the creation of quantum mechanics...' The 1933 prize was shared by Schrödinger and Dirac 'for the discovery of new

productive forms of atomic theory'. Thirty-one years later the Nobel committee made amends by awarding the 1954 prize to Max Born 'for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wave function'. Frayn was considerably faster. In the second (US) edition of the play he has Bohr say that the invention of quantum mechanics came 'Mostly out of what he'd been doing with Max Born and Pascual Jordan at Göttingen'. On the other hand, who, except for some historians, knew before Frayn's play about the 1941 meeting?

Let us turn now to some of the physics presented in the play. In Act One's dialogue between Niels Bohr and Heisenberg concerning Bohr's insights of January 1939, the earliest days of nuclear fission, Bohr says:

Natural uranium consists of two isotopes U-238 and U-235. Less than one per cent of it is U-235, and this tiny fraction is the only part of it that's fissionable by *fast* neutrons. [emphasis added]

This seems to me to be badly garbled physics. Only U-235 is fissionable by *slow* neutrons. Bohr's reasoning in arriving at this conclusion is clearly explained in Abraham Pais's *Niels Bohr's Times*. Fission of U-238 by fast neutrons from the D-T reaction provides a significant fraction of the yield in many modern 'staged' nuclear weapons. See, for example Rhodes's *Dark Sun* for more on this point. What natural uranium and, *a fortiori*, pure U-238 will not do is to support a fast neutron chain reaction. An explanation of this appears to be the intention of the following lines, which only continue the confusion.

...238 is not only impossible to fission by fast neutrons—it also absorbs them. So very soon after the chain reaction starts there aren't enough fast neutrons left to fission the 235.

The error concerning fast and slow neutrons and U-238 is repeated in the appended 'outline sketch' mentioned above.

A second area of physics/philosophy emphasized throughout the play involves Complementarity, Uncertainty, the Copenhagen Interpretation and the alleged non-causal character of quantum mechanics. Bohr is sometimes quoted to the effect that 'anyone who is not worried about these matters does not understand them'. David Mermin quotes another eminence who has said that anyone who is not disturbed 'has rocks in his head'. In full knowledge that I am consigning myself to the ranks of the uncomprehending (and unrepentant) cranioliths, I must confess that I am closer to the view that quantum mechanics makes some surprising predictions, and we just have to get used to it. I admit also that I find Bohr's attempts to express the 'philosophical implications' of the quantum world in 'plain

language' only to add to the confusion. If I had to pick a successful effort, from the early days of the field, to put the nature of quantum mechanics 'in plain language' I would choose the first chapter of Dirac's *Quantum Mechanics*. Thus, I find those parts of the play which emphasize 'uncertainty' in human affairs rather muddy.

Finally, some impressions about Heisenberg's role in the German fission effort, his 1941 visit to Copenhagen, and the newly-released Bohr documents: there is no doubt that Heisenberg did hold out to the authorities the possibility of a bomb of 'unimaginable' power, that he knew that this would require *fast* neutrons, that he had not actually solved the corresponding diffusion equation until a week after Hiroshima, and that he did not understand the factors limiting the yield of the fast-neutron blast. Certainly neither he nor anyone else in the German effort ever displayed the seriousness of Robert Serber in his April 1943 lecture to the newly-arrived scientists at Los Alamos:

The object of the project is to produce a *practical military weapon* in the form of a bomb in which the energy is released by a fast neutron chain reaction. . . [emphasis in the *Los Alamos Primer*]

Why was this ardor, so evident on the Allied side, not present in Germany? In the former case, it was certainly driven by knowledge of the evil nature of the Nazi regime, and the fear that it might be first to develop this dangerous new weapon. On the other side, there is no evidence of moral reservations; indeed, an important factor decreasing any feeling of urgency was the arrogant belief that Germany was far ahead in the competition and, initially at least, that the war would be short. This is evident from Goudmit's interrogation of the scientists and from their recorded remarks at Farm Hall, where they discussed selling their expertise, and speculated that the Allied leaders at Potsdam must be concerned with their situation.

The play, and Bernstein, and other commentators have emphasized the different values for the critical mass which Heisenberg quoted at various times. At Farm Hall, in the immediate aftermath of the news of Hiroshima, he makes an estimate which strikes me as reasonable for 'back of the envelope' purposes, but is totally inadequate for serious designs. The problem is that the calculation yields the ratio of the critical radius to the neutron mean free path(s).

Heisenberg took the ratio to be the square root of 80, the number of generations of neutrons to fission completely a significant mass of uranium. The mass, however, depends on the cube of the radius, so a fairly small change in cross-section or the numerical factor makes a huge difference in the critical mass. Frisch and Peierls, who solved the diffusion problem correctly, used an overestimate of the cross-section and obtained too small a critical mass. The correct numerical factor is considerably smaller than the square root of 80, so Heisenberg's method yields too large a mass. In the play, Bohr makes much of the discrepancy between 50 kg and 1 tonne, but the cube root of 20 is not a very large number. Incidentally, the definition of critical mass given by Frayn in his postscript is quite imprecise. He writes, '...critical mass. This is the amount of fissile material (U-235 or plutonium) which is large enough to support an explosive chain reaction, but small enough not to explode spontaneously'. It would be more accurate to say that a *super*-critical mass will support an explosive chain reaction whose growth rate depends on the degree of supercriticality. At exact criticality the growth rate vanishes.

Heisenberg also had a limited understanding of slow-neutron physics, including an erroneous belief that a reactor would be self-stabilizing because of the decrease in cross-section associated with the heating of the neutrons, and a stubborn adherence to an inefficient reactor geometry because it was amenable to calculation.

The newly-released documents were written by Bohr after he read Jungk's book, which includes a letter from Heisenberg to the author giving Heisenberg's recollection of the 1941 meeting in a way that deeply offended Bohr. What Heisenberg remembered saying differed greatly from what Bohr remembered hearing. Bohr's recollections, detailed in the recently-released documents, show that he heard Heisenberg speak of his own two-year effort to develop German nuclear weapons, and that these might prove decisive if the war should last for several more years. I urge interested readers to examine the documents at the Bohr Web site, which also has a link to the second conference about the play *Copenhagen*. Quite apart from any possible miscommunication between the two men (and it is clear that Heisenberg did almost all the talking), it seems to me that Heisenberg had much stronger motives than Bohr to distort his recollection of the event.