

Title: Bohr and Heisenberg: Debate on the Gamma-Ray Microscope

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Abstract:

On March 27th, 1927, Heisenberg published the paper in which he introduced the uncertainty relations through his well-known γ -ray microscope thought experiment. Since then, the debates and commentaries over the origin of the uncertainty relations have continued for a century (see, for instance, Bacciagaluppi and Valentini 2009; Beller 1999; Brown and Redhead 1981; Busch 1990; Hilgevoord and Uffink 1985,2024; Jammer 1974; Uffink 1990).

Going back to 1927 through a selection of letters -- including an unpublished letter from Jordan to Rosenfeld -- this talk aims to add a crucial piece to this century-old puzzle by shedding new light on the differences between Heisenberg and Bohr's conceptual basis of the uncertainty relations. According to the received view, Bohr derives the uncertainty relations from the $\textit{wave-particle duality}$ of light. By contrast, it is commonly stated that Heisenberg based them on the $\textit{discontinuity}$ in the interaction between the electron and the light quantum, i.e., the uncontrollable change resulting from the Compton effect (cf. Camilleri 2009). I will challenge the received view by arguing that: (i) Bohr's derivation of the uncertainty relations fundamentally relies on the use of $\textit{classical concepts}$, consistent with their central role in his broader interpretation of quantum mechanics. (ii) The supposed contrast rooted in the wave-particle duality of light may stem from Heisenberg's 1927 misrepresentation (or misinterpretation) of Bohr's ideas on the γ -ray microscope. This misrepresentation may have influenced the reception of Bohr's interpretation, particularly regarding his ideas on the conceptual justification for the uncertainty relations, and contributed to obscuring the deeper significance of Bohr's complementarity principle - fully comprehensible only in light of (i).

Bohr and Heisenberg: Debate on the γ -Ray Microscope

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October 22, 2025



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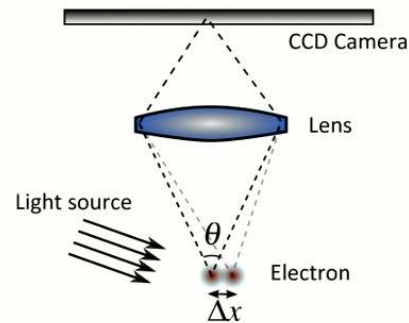
The Birth and the First Steps of the γ -Ray Microscope:

Heisenberg 1927

(The Physical Content of Quantum Kinematics and Mechanics)



At the instant when position is determined – therefore, at the moment when the photon is scattered by the electron – the electron undergoes a discontinuous change in momentum.



The Folklore:

Folklore (1):

About Heisenberg's 1927 picture of the γ -ray microscope.



Particle-focused picture.

Folklore (2):

About the difference(s) with Bohr in 1927/their disagreement.



Discontinuity Vs. Wave-particle duality.

The Aim of the Talk:

I. Pars Destruens:

Questioning **folklore (1)** and **folklore (2)**.

II. Pars Construens:

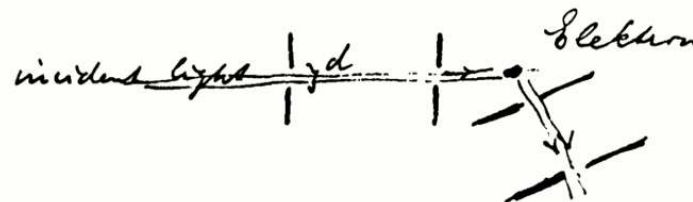
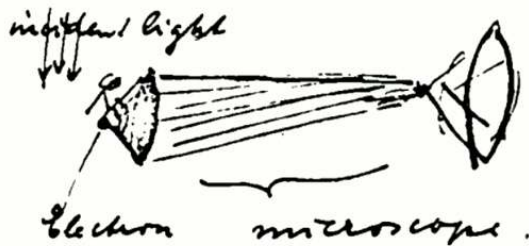
Exploring new questions – and new answers – about the disagreement between Bohr and Heisenberg.

- 1 The Folklore Vs. What Heisenberg's 1927 Picture Might Have Been
- 2 New Question(s) and New Answer(s)

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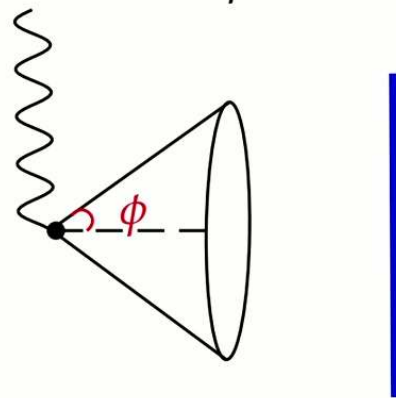
The Letters

- Letter from Jordan to Rosenfeld, 31 December 1927;
- Letter from Heisenberg to Dirac, 27 April 1927.

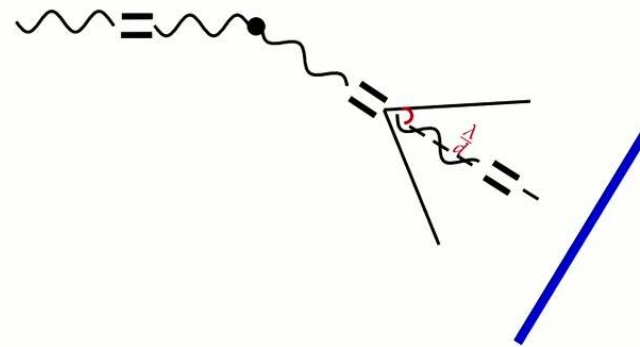


The Reconstruction

Bohr's Derivation
of $\Delta x \Delta p \sim h$



Heisenberg's Derivation
of $\Delta x \Delta p \sim h$



Vs. Folklore

Vs. Folklore (1)

- Wave-like aspect. ✓
- Not merely a corpuscular description.
- No particle-focused picture.

Vs. Folklore (2)

- Wave-like aspect. ✓
- No corpuscular Vs. Wave-like + corpuscular description.
- No discontinuity Vs. Wave-particle duality.

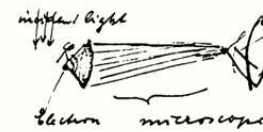
- 1 The Folklore Vs. What Heisenberg's 1927 Picture Might Have Been
- 2 New Question(s) and New Answer(s)**

New Question(s): Are They the Same? What about the disagreement?

Heisenberg's Derivation
of $\Delta x \Delta p \sim h$



Bohr's Derivation
of $\Delta x \Delta p \sim h$



New Question(s): Are They the Same? What about the disagreement?

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$$\Delta x = d$$



Why?



We are measuring the position with the slit.

$$\Delta p = \frac{\lambda}{d} p$$

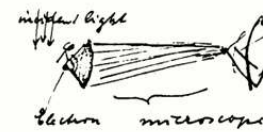


Why?



The measurement of position with the slit **produces** the modification of the beam of light. (Diffraction)

Bohr's Derivation
 of $\Delta x \Delta p \sim h$



$$\Delta x = \frac{\lambda}{\phi}$$



Why?



We are measuring the position with the microscope. (Rayleigh)

$$\Delta p = \phi p$$



Why?



The measurement of position with the microscope **requires** ϕ .

Bohr's Words

*Any measurement which aims at an ordering of the elementary particles in time and space **requires** us to forego a strict account of the exchange of energy and momentum between the particles and the measuring rods and clocks used as a reference system. [...] Such considerations lead immediately to the reciprocal uncertainty relations set up by Heisenberg.*

(Bohr, 1929, The Atomic Theory and the Fundamental Principles underlying the Description of Nature, My emphasis)

Heisenberg's Words

*The electron may also be considered to be a plane de Broglie wave, and it is at once apparent that diffraction phenomena are necessarily **produced** by the slit.*

*(Heisenberg, 1930, *The Physical Principles of the Quantum Theory*, My emphasis)*

It is characteristic of the foregoing discussion that simultaneous use is made of deductions from the corpuscular and wave theories of light, for, on the one hand, we speak of resolving power, and, on the other hand, of

photons and the recoils resulting from their collision with the particle under consideration. This is avoided, in so far as the theory of light is concerned, in the following considerations.

If electrons are made to pass through a slit of width d (Fig. 6), then their co-ordinates in the direction of this width are known at the moment after having passed it with the accuracy $\Delta x = d$. If we assume the momentum in this direction to have been zero before passing through the slit (normal incidence), it would appear that the uncertainty relation is not fulfilled. But the electron may also be considered to be a plane de Broglie wave, and it is at once apparent that diffraction phenomena are necessarily produced by the slit. The emergent beam has a finite angle of divergence α , which is, by the simplest laws of optics,

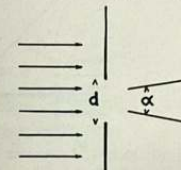


FIG. 6

$$\sin \alpha \sim \frac{\lambda}{d}, \quad (19)$$

where λ is the wave-length of the de Broglie waves. Thus the momentum of the electron parallel to the screen is uncertain, after passing through the slit, by an amount

$$\Delta p = \frac{h}{\lambda} \sin \alpha \quad (20)$$

since h/λ is the momentum of the electron in the direction of the beam. Then, since $\Delta x = d$,

$$\Delta x \Delta p \sim h.$$

In this discussion we have avoided the dual character of light, but have made extensive use of the two theories of the electron.

Rosenfeld – 1971, Commentary on Heisenberg's 1927 Paper

Bohr looked upon such imaginary experiments in a rather different spirit from Heisenberg. [...] Bohr wanted to pursue the epistemological analysis one step further, and in particular to understand the logical nature of the mutual exclusion of the two aspects opposed in the particle-wave dualism.

(Rosenfeld, 1971, Commentary on Heisenberg's 1927 Paper)

Bohr – 1929, Causality and Objectivity

In his well-known paper [...] Heisenberg took the position that the demand for visualizability [...] Can only concern the clarification of its contradiction-free applicability. While I also agree with this viewpoint, at the same time, I believe that recognizing the natural limitations of our conventional ways of visualization [Anschauungsformen] is essential for assessing the given problem.

(Bohr, 1929, Causality and Objectivity)

New Answer(s):

Revision of Bohr-Heisenberg's Difference(s) in 1927

The Hint from the γ -ray Microscope:

H: Wave-like aspect \leftrightarrow *Effect*

B: Wave-like aspect \leftrightarrow *Precondition*

What Heisenberg "Took" from Bohr and What He Did Not:

- Wave-particle duality ✓
(But wave-like aspect \nleftrightarrow Precondition)
- Classical concepts as *Anschauungsformen* ✗

What They Respectively Saw as the "Origin" of the UR:

- B: Complementarity \nrightarrow
(with classical concepts as *Anschauungsformen*)
- H: (?)
I argue with Bohr over the extent to which the relation $p, q \sim h$ has its origin in the wave- or the discontinuity-aspect of qu[antum] m[echanics].
(Heisenberg letter to Pauli, 4 April 1927)

New Answer(s):

Revision of Bohr-Heisenberg's Difference(s) in 1927

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- Wave-particle duality ✓
(But wave-like aspect \nleftrightarrow Precondition)
- Classical concepts as *Anschauungsformen* ✗

What They Respectively Saw as the "Origin" of the UR:

- B: Complementarity \nrightarrow
(with classical concepts as *Anschauungsformen*)
- H: Discontinuity
I argue with Bohr over the extent to which the relation $p, q \sim h$ has its origin in the wave- or the discontinuity-aspect of qu[antum] m[echanics].
(Heisenberg letter to Pauli, 4 April 1927)

Further Developments:

Heisenberg's Role in the Reception of Bohr's Interpretation

*I argue with Bohr over the extent to which the relation $p, q \sim h$ has its origin in the **wave-** or the **discontinuity-aspect** of qu[antum] m[echanics]. Bohr emphasizes that, e.g., in the γ -ray microscope the diffraction of the waves is essential; I emphasize that the theory of light quanta and even the Geiger-Bothe experiment are essential.
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Further Developments

The Broader Meaning of This Research

- The development of a concept: the UR.
- The development of a *dilemma*: the light quanta dilemma.
- The γ -ray microscope as a clue to Heisenberg's and Bohr's distinct approaches to this dilemma (at least in 1927).



- (1) Reconnect the UR with their "historical context", thereby enriching their meaning.
- (2) Further disentangle Bohr from Heisenberg, seeking to clarify the features of Bohr's original interpretation and freeing it from the umbrella term of "The" Copenhagen interpretation.

Thank you!