An invitation to quantum mechanics: phenomena

Christian Wüthrich

http://www.wuthrich.net/

Philosophy of Physics: Quantum Mechanics

Reading

This section is based on the first chapter of our main seminar text:

Tim Maudlin (2019). *Philosophy of Physics: Quantum Theory*. Princeton University Press.

The puzzle of quantum physics

John S Bell (2004, 173)

> *A preliminary account of these notions was entitled 'Quantum field theory without observers, or observables, or measurements, or systems, or apparatus, or wavefunction collapse, or anything like that'. That could suggest to some that the issue in question is a philosophical one. But I insists that my concern is strictly professional. I think that conventional formulations of quantum theory, and of quantum field theory in particular, are unprofessionally vague and ambiguous. Professional theoretical physicists ought to be able to do better.*

John Stuart Bell (^{2}2004). *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: University of Cambridge Press.

A precise physical theory

Tim Maudlin (2019, 4f)

> *A physical theory should contain a physical ontology: What the theory postulates to exist as physically real. And it should also contain dynamics: laws (either deterministic or probabilistic) describing how these physically real entities behave. In a precise physical theory, both the ontology and the dynamics are represented in sharp mathematical terms.*

> *But it is exactly in this sense that the quantum-mechanical prediction-making recipe is not a physical theory. It does not specify what physically exists and how it behaves, but rather give a (slightly vague) procedure for making statistical predictions about the outcomes of experiments.*

A tripartite distinction

Maudlin distinguishes three things:

1. a physical theory,
2. a recipe for making predictions,
3. data or phenomena.

Tim Maudlin (2019, 5f)

> *What is usually called 'quantum theory' is a recipe or prescription, using somewhat vague terms, for making predictions about data. If we are interested in the nature of the physical world, what we want is instead a theory—a precise articulation of what there is and how the physical world behaves, not just in the laboratory but at all places and times. The theory should be able to explain the success of the recipe and thereby also explain the phenomena.*

Experiment 1: The cathode ray tube

The grainy nature of a fading cathode ray: particles?

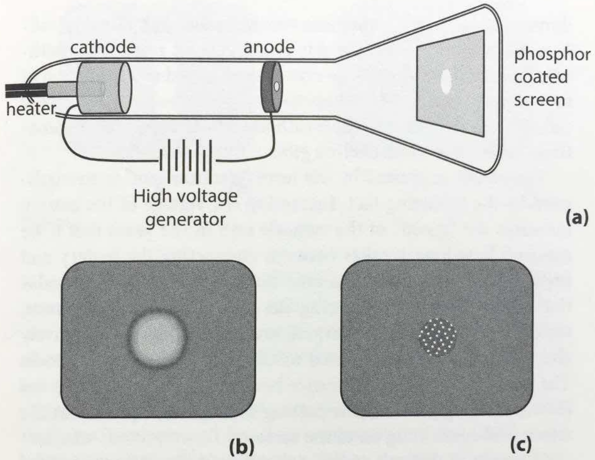


Figure 1

Experiment 2: The single slit

Diffraction at a narrow slit: waves?

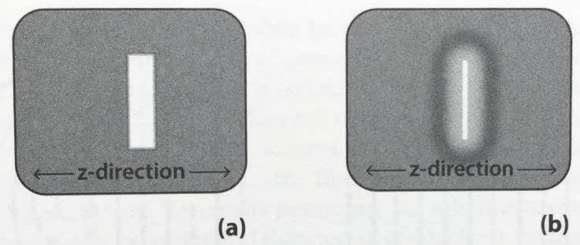


Figure 2

Experiment 2: The single slit

Reducing diffraction through shorter wavelength: wave-particle duality

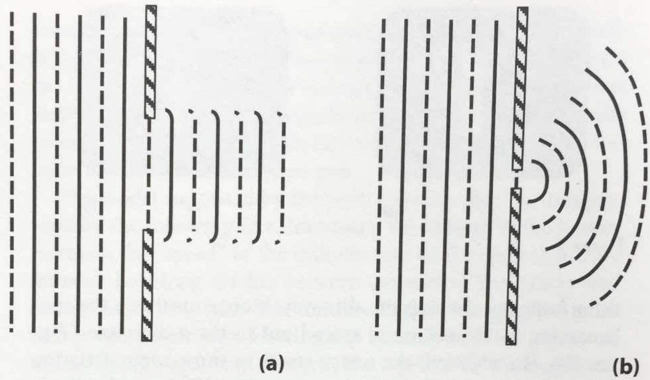


Figure 3

Experiment 3: The double slit

The quantum signature: interference and superposition

Richard Feynman *et al.* (1975, §37-1)

We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. We cannot explain the mystery in the sense of 'explaining' how it works. We will tell you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.

Richard Feynman, Robert Leighton, and Matthew Sands (1975). *The Feynman Lectures of Physics*. Reading, MA: Addison-Wesley.

Experiment 3: The double slit

The quantum signature: crests and troughs

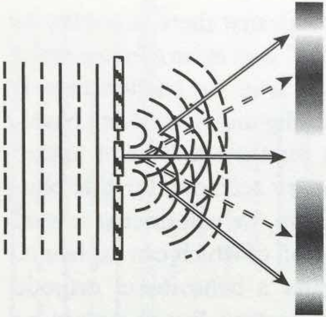


Figure 4

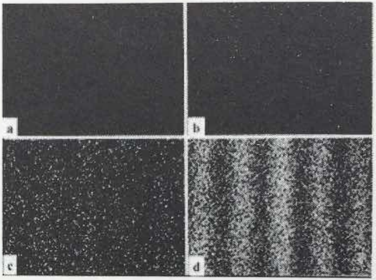


Figure 5. Credit: Reprinted courtesy of the Central Research Laboratory, Hitachi, Ltd., Japan.

Experiment 3: The double slit

How does an individual electron know to form an interference pattern?

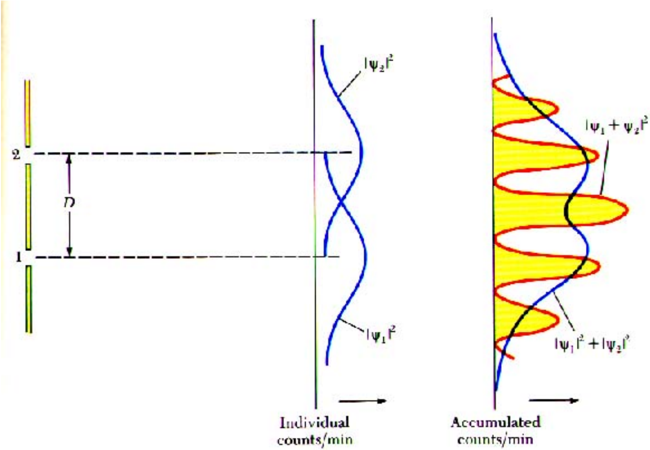


Figure: Interference pattern found in double-slit experiments.

Experiment 4: The double slit with monitoring

The monitoring proton destroys interference

Figure 6

Experiment 5: Spin

The Stern-Gerlach set-up

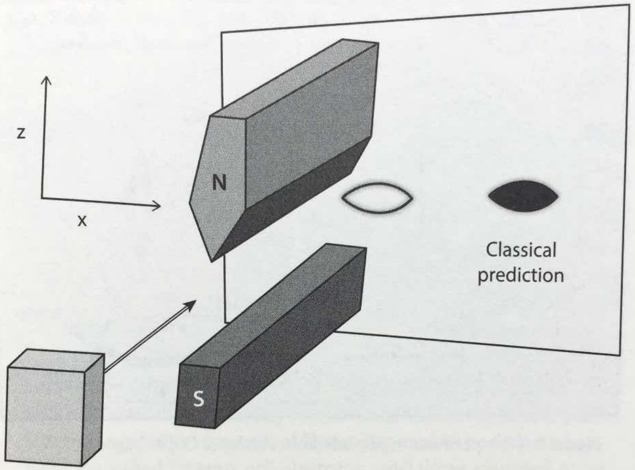


Figure 7

Experiment 5: Spin

Stern-Gerlach: confirmation of the quantization of spin

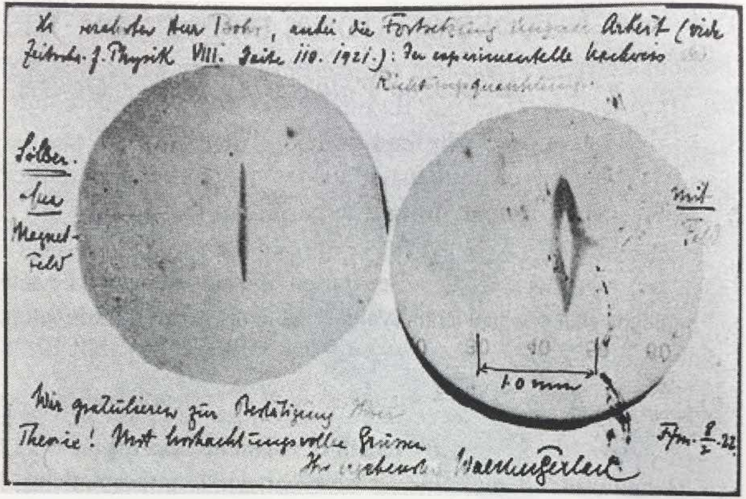


Figure 8. With permission of Niels Bohr Archive, Copenhagen.

Experiment 5: Spin
Combining Stern-Gerlach apparatuses

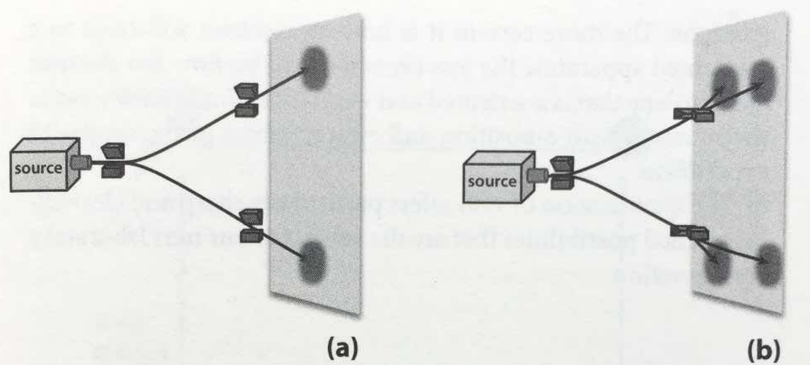


Figure 9

Experiment 6: The (Mach-Zehnder) interferometer

Entangling spin and position

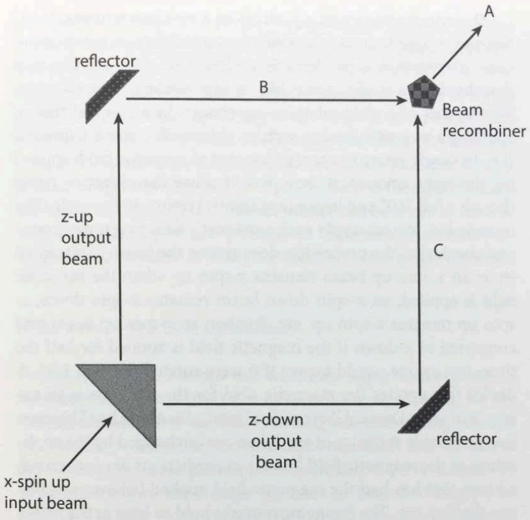


Figure 10

Experiment 7: The EPR experiment

Non-local entanglement, and "spooky action at a distance"

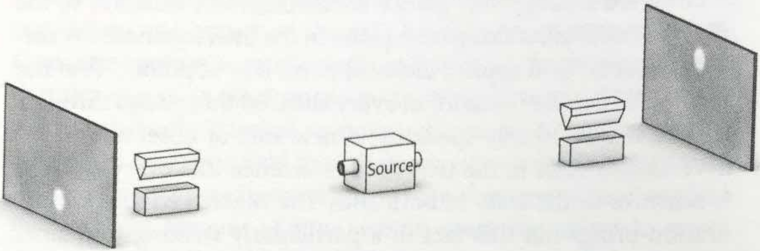


Figure 11

Experiment 8: GHZ/Tests of Bell's inequality

The Greenberger-Horne-Zeilinger experiment

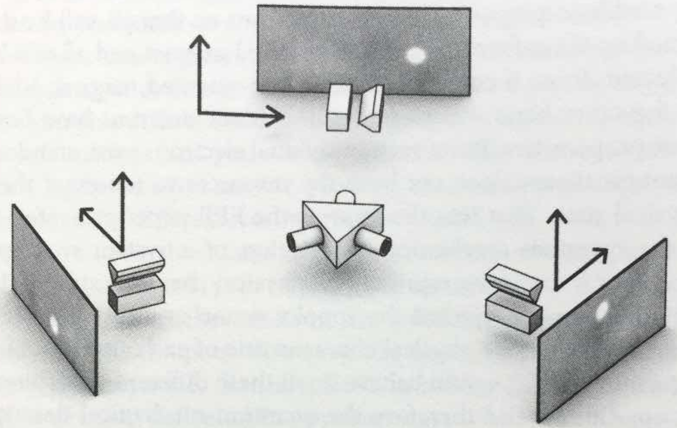


Figure 12

Experiment 8: GHZ/Tests of Bell's inequality

The Greenberger-Horne-Zeilinger experiment

- particles, used as indices: 1, 2, 3
- orientation of magnet: X, Z

⇒ eight possible global experimental configurations: $X_1X_2X_3$, $X_1X_2Z_3$, $X_1Z_2X_3$, $Z_1X_2X_3$, $X_1Z_2Z_3$, $Z_1X_2Z_3$, $Z_1Z_2X_3$, $Z_1Z_2Z_3$

- We are only interested in four: $X_1X_2X_3$, $X_1Z_2Z_3$, $Z_1X_2Z_3$, $Z_1Z_2X_3$

Maudlin (2019, 30f)

> *After many runs of the experiment, we would notice the following unbroken regularities. When the $X_1X_2X_3$ configration obtains [...], then an odd number of the particles (either one or all three) are detected in the 'up' direction. But when any of the other three configurations is chosen, so one magnet is in the x-direction and the other two in the z-direction, an even number of particles (either zero or two) are deflected in the up direction. That is the observed phenomenon.*

Experiment 8: GHZ/Tests of Bell's inequality

The Greenberger-Horne-Zeilinger experiment

- Similarly to the EPR scenario, given an arrangement and two measurement outcomes, we can predict the third with certainty.
- Just as in the EPR scenario, either the outcomes are locally predetermined by the states of the particles, or there must be some spooky action-at-a-distance or some form of non-locality
- There is a simple proof that the outcomes cannot be predetermined...
- Central question: can we prearrange the particle states such the phenomenon described in the Maudlin quote obtains without the particles being sensitive which experiments are carried out on the others?

Experiment 8: GHZ/Tests of Bell's inequality

The Greenberger-Horne-Zeilinger experiment

Maudlin (2019, 32)

In short, we must somehow fill in the circles in Figure 13 with 'up' and 'down', specifying how each particle would react to each of the four global experimental arrangements. There must be an an odd number of 'ups' along the dashed $X_1X_2X_3$ row and an even number of 'ups' along the other three indicated rows.

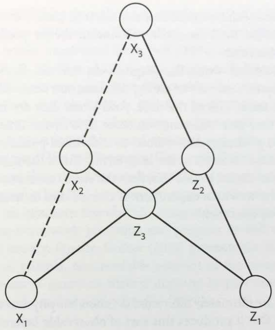


Figure 13

Experiment 8: GHZ/Tests of Bell's inequality

The Greenberger-Horne-Zeilinger experiment

Maudlin (2019, 32)

But it is clear that no specification can meet these requirements. If it could, then adding the total number of ups along all four rows would yield odd + even + even + even = an odd number of ups. However, the entry on each circle would have been counted twice, since each circle lies at the intersection of two rows, Since each circle in counted twice, no matter how we fill in the circles, the total count of all four rows must yield an even number of ups. QED.

Experiment 8: GHZ/Tests of Bell's inequality

The Greenberger-Horne-Zeilinger experiment

Maudlin (2019, 32)

> *[T]he GHZ argument shows that the set of possible reactions cannot be so predetermined in a way that is insensitive to the distant experimental arrangements. We are stuck with the spooky action-at-a-distance that Einstein so abhorred. This is an example of quantum nonlocality.*

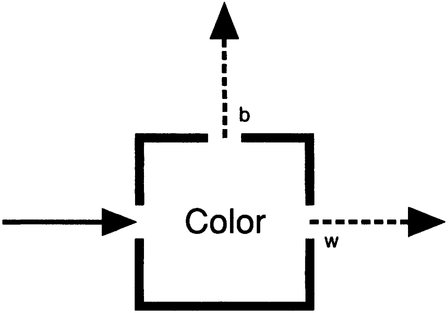
Reading

This section is based on chapter 1 (not assigned) of:

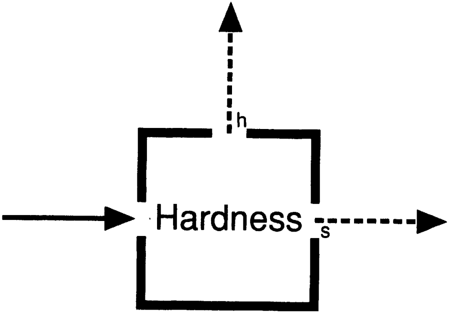
David Z Albert (1992). *Quantum Mechanics and Experience*. Harvard University Press.

Quantum superposition: Setting things up

- electrons with two properties: 'color' (black, white), 'hardness' (soft, hard)
- color box: measuring device with three apertures such that incoming e^- are sorted according to their color



- hardness box: similar device sorting e^- into hard and soft ones



- measurements repeatable: if after measurement, e^- is fed into same type of box without tampering, then same measurement outcome will be observed

- Q: Are properties related, i.e. are there correlations between values of hardness and color of e^-?

⇒ combine boxes to measure correlations

- precisely half of e^- coming out of one aperture of first box come out of each aperture of second box

⇒ no correlations, color (hardness) of e^- entails nothing about its hardness (color)

Three-box experiments

- suppose we have three boxes aligned for subsequent measurement, s.t. the first and third box are of same type as one another, but of different type from second box
- no tampering with e^- between boxes
- e^- going into third box is presumably known to have a particular pair of color and hardness properties (e.g. white and soft)

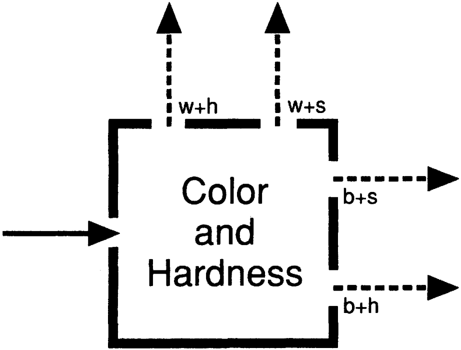
$\Rightarrow$ it seems as if we can predict the outcome of the third measurement

- It turns out that we can't: precisely half of the e^- will come out of each aperture of third box.
- Apparently, presence of middle box itself constitutes some sort of tampering: middle box seems responsible for changing half of e^- since we know that two identical boxes in sequence show a different behaviour.

- Can boxes be built less crudely, can intermediate measurements be refined such as to avoid this? No, we can't even "move the statistics of [...] of disruption even so much as one millionth of one percentage point away from fifty-fifty" (5f), i.e. every device that qualifies as e.g. hardness box will randomize color.
- What is it that determines precisely which e^- have their properties changed by second box and which don't? Let's look for correlations between measurable properties of incoming e^- and their final measurement outcome. But there is absolutely no such correlation... $\Rightarrow$ this question has no answer

Color-and-hardness boxes

- boxes with five apertures, including one for each pair of measurement outcomes



- box like that would have to consist of a color box and a hardness box

⇒ Problem: the second device will randomize e^- with respect to the first measurement

- Albert: "So the task of putting ourselves in a position to say 'the color of this electron is now such-and-such and the hardness of this electron is now such-and-such' seems to be fundamentally beyond our means." (7)

⇒ example of uncertainty principle, since measurements of one of the two incompatible properties disrupts the measurement of the other

Stern-Gerlach experiment

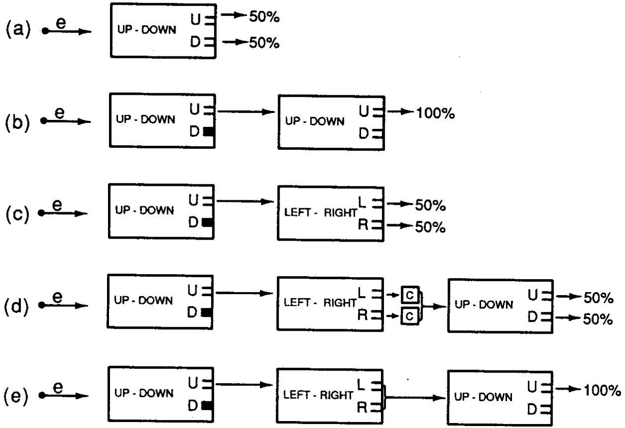
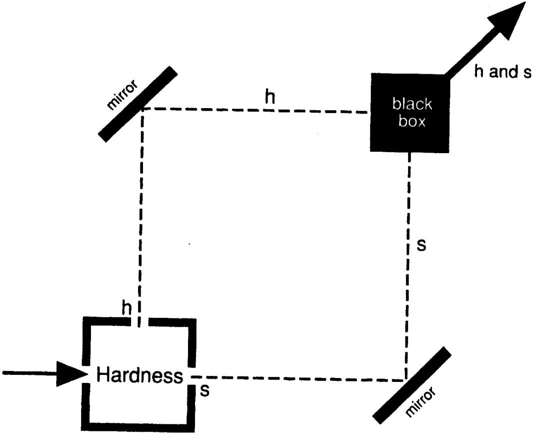


Figure: Stern-Gerlach experiment with 'mixture' (d) and 'superposition' (e) (Sklar, Fig. 4.4)

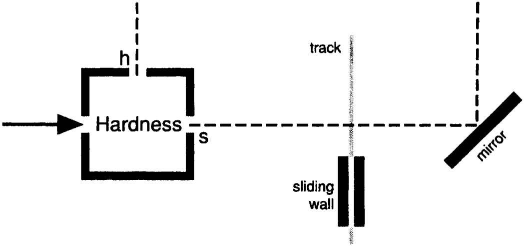
Two-path experiments

- Consider a more complicated device as in Figure 1.4 in Albert:



- Suppose that white e^- is fed into device and we measure its hardness at *h and s*. Expectation: we find half hard and half soft e^-. And this is what we find.
- Suppose that hard e^- is fed into device and then measure its color at *h and s*. Expectation: find half of e^- to be white and half black. And this is what we find.
- Suppose we feed white e^- into device and measure their color at *h and s*. Expectation: half should be found to be white, half black. But this is not at all what we find: all e^- are found to be white!

- Add a sliding wall as in the following figure (Fig. 1.5):



- What happens if we slide wall in?
- Expectation: overall output goes does down 50%; given that all e^- were just found to be white, they should still be so, right?
- But they are not: only half of the e^- are now white, the other half black.

Considering routes of electrons: superposition

Which route does an electron take when wall is out?

- Can it have taken *h*? Apparently not, since these e^- are known to randomize color.
- Can it have taken *s*? No, same reason.
- Can it somehow have taken *both* routes? Apparently not, since whenever we stop experiment and look to see where the e^- is, we find it either on *h* or on *s*.
- Can it have taken *neither* route? No, since if we wall up both routes, nothing goes through.

Electrons in superposition states

We can write these superposition states as follows (for later reference):

$$
\begin{aligned}
|\text{black}\rangle &= \frac{1}{\sqrt{2}}|\text{hard}\rangle + \frac{1}{\sqrt{2}}|\text{soft}\rangle, \\
|\text{white}\rangle &= \frac{1}{\sqrt{2}}|\text{hard}\rangle - \frac{1}{\sqrt{2}}|\text{soft}\rangle, \\
|\text{hard}\rangle &= \frac{1}{\sqrt{2}}|\text{black}\rangle + \frac{1}{\sqrt{2}}|\text{white}\rangle, \\
|\text{soft}\rangle &= \frac{1}{\sqrt{2}}|\text{black}\rangle - \frac{1}{\sqrt{2}}|\text{white}\rangle.
\end{aligned}
$$