Photons We can detect single quanta of light. All we need is a sufficiently sensitive detector (photographic film would work, or a photomultiplier tube) and a low-intensity light source. You will find the light signal comes in little dots, one at a time. These dots appear to arrive randomly, although their distribution is proportional to the intensity of our source.

Randomness is a fundamental aspect of the quantum world.

0.1 Double-slit experiment with electrons

You've seen in PH 21x the double-slit experiment with light. We can do the same thing with electrons, since they are also waves.

$$\psi(x,t) = Ae^{i\overbrace{(k(x - v_{\text{phase}}t))}^{\text{phase}}} \tag{1}$$

The "phase" of an electron wave varies from zero to 2π across one wavelength.

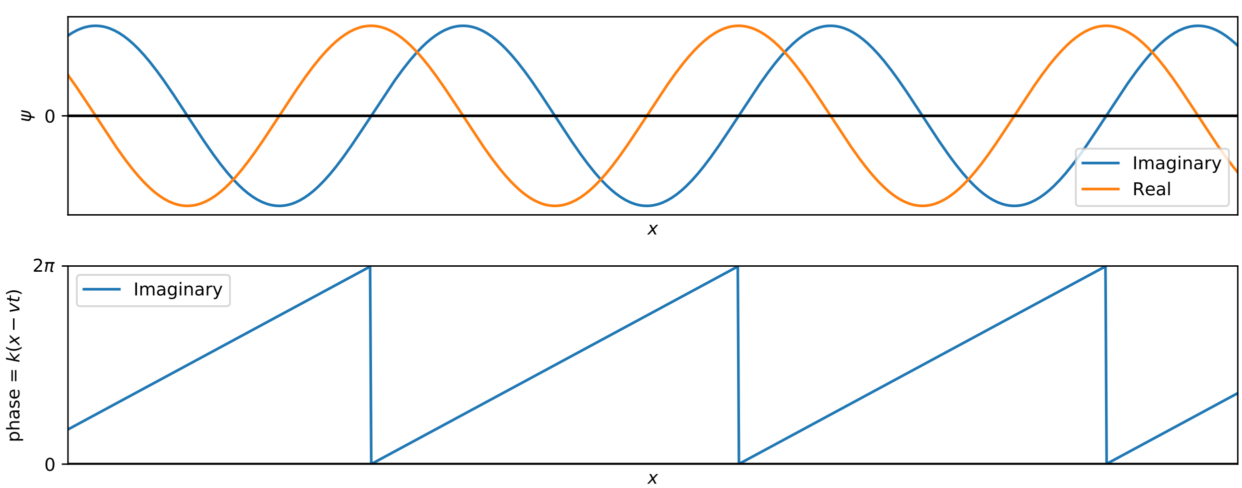

Figure 1: The phase of a wave goes from 0 to 2π over one wavelength.

If we have a line source (like an electron passing through a narrow slit), near the source we expect the surfaces of constant phase to be curved, and to flatten out as we get further away, forming concentric cylinders. Eventually we can approximate it as a "plane wave" with planar wave fronts.

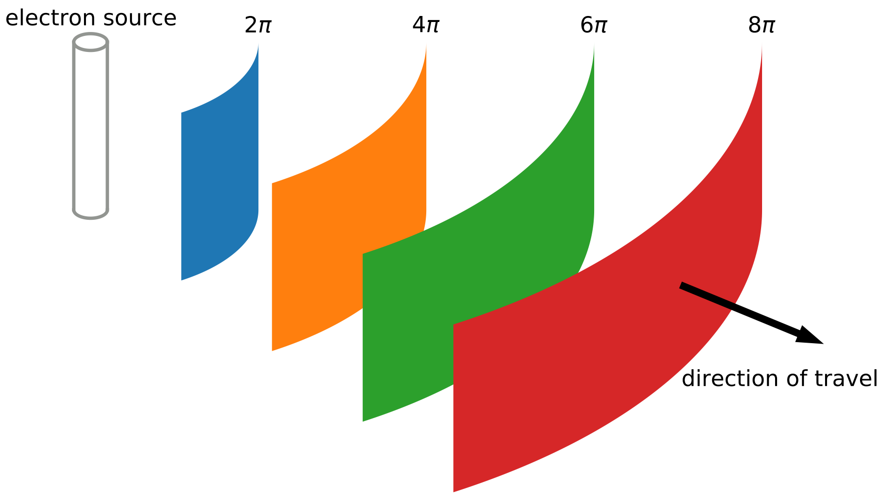

Figure 2: An electron wave flowing away from a cylindrical source. Far away from the source, the waves look like they are flat, and can be viewed as "plane waves."

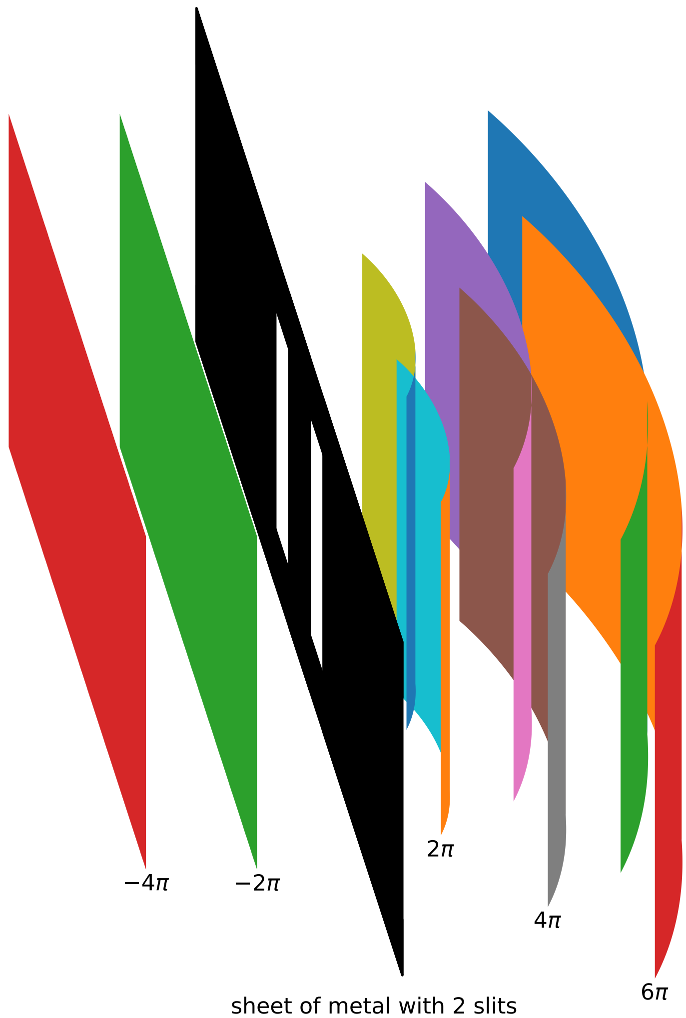

Figure 3: Side-view of a two-slit experiment.

To imagine a double slit experiment, picture an electron plane wave approaching a sheet of metal with two slits in it. Most of the electron wave gets absorbed by the metal, but a small fraction gets through, and forms two new cylindrical outgoing waves on the other side. (Note: if this were light, the picture would not change, except that there would be a polarization we'd have to worry about.)

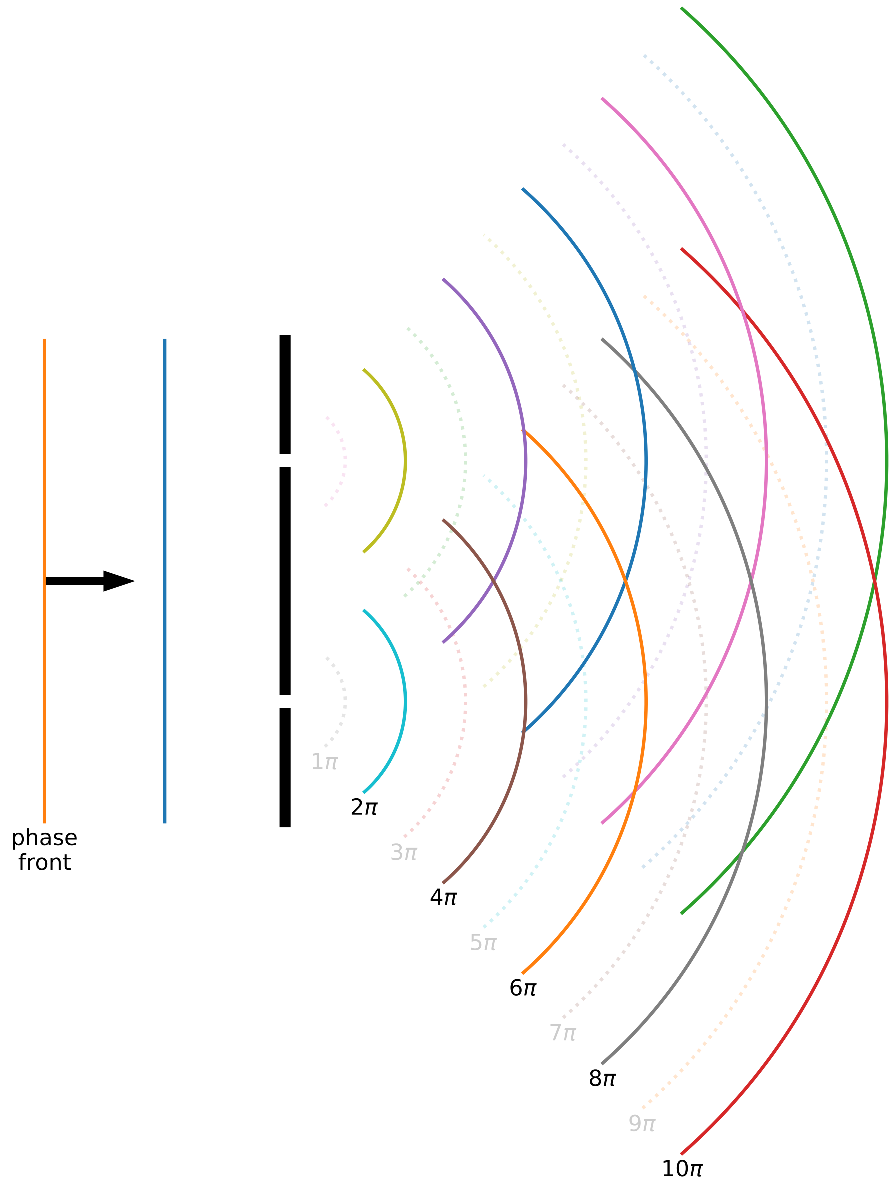

Figure 4: Side-view of a two-slit experiment.

At every point in space we add the real component of $\psi_{\text{path 1}}$ to the real component of $\psi_{\text{path 2}}$, and add the imaginary component of $\psi_{\text{path 1}}$ to the imaginary component of $\psi_{\text{path 2}}$.

The wave picture describes the overall pattern formed on the screen, while the particle picture makes the dots show up at random points on the screen, respecting the pattern predicted by the wave. Both of these are exactly the same as what is observed (and predicted) for light.

Weird thing #1 We must accept that each electron goes through both slits. Otherwise it wouldn't "know" where not to show up on the screen. Hard to accept if you view electrons as particles.

Weird thing #2 Electrons as well as photons have inherent random behavior. "God plays dice."

Weird thing #3 If we put a detector to detect which slit the electron passed through, the probability distribution $|\psi|^2$ will change dramatically.

0.2 Detecting which way an atom fell

Dürr, S., Nonn, T. & Rempe, G. Origin of quantum-mechanical complementarity probed by a 'which-way' experiment in an atom interferometer. *Nature* **395**, 33-37 (1998). `https://paradigms.oregonstate.eduhttps://doi.org/10.1038/25653`

They collected rubidium-85 in a magneto-optical trap. A single atom at a time is then dropped (the trap was turned off) and fell into a beam splitter (which was an optical stanting wave. Eventually another optical standing wave was used to deflect the atoms back together, which resulted in an interference pattern at a detector, i.e. it was a two-slit experiment.

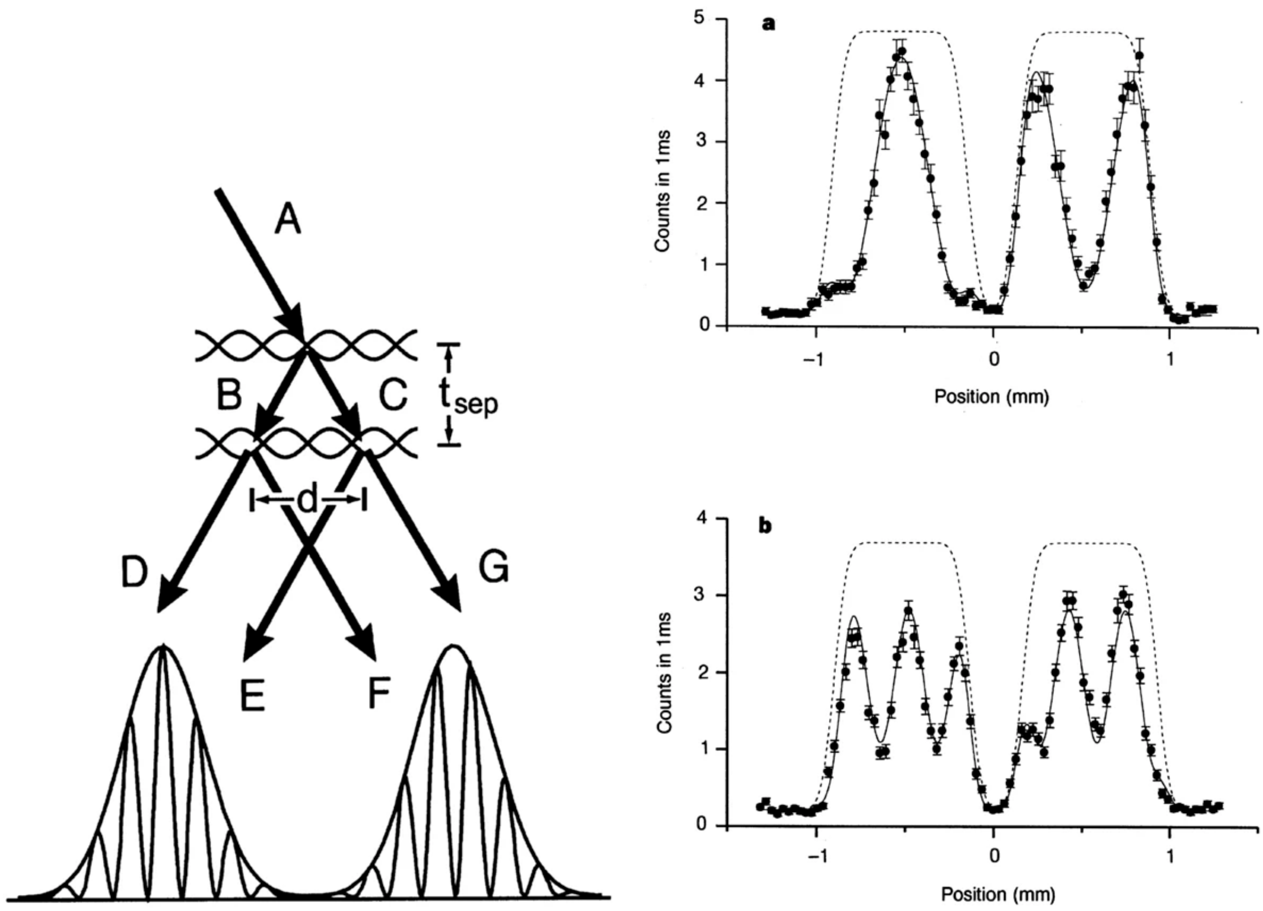

Figure 5: Schematic of the experiment, and the resulting detections for two different slit configurations.

While the two beams were split, they had the option of using a pair of microwave pulses to detect which "slit" the rubidium atom dropped through. These microwave pulses (at 3 GHz frequency) trigger an internal quantum transition in rubidium between the $5^2S_{\frac{1}{2}}$ and $5^2P_{\frac{3}{2}}$ states. Taking this measurement removes the interference patterns, as per the *Weird thing #3* mentioned above.

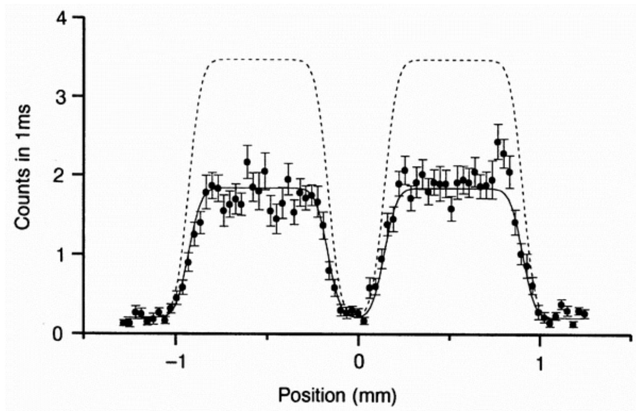

Figure 6: Interference pattern after detecting which way the atom went with 3 GHz microwave pulses.