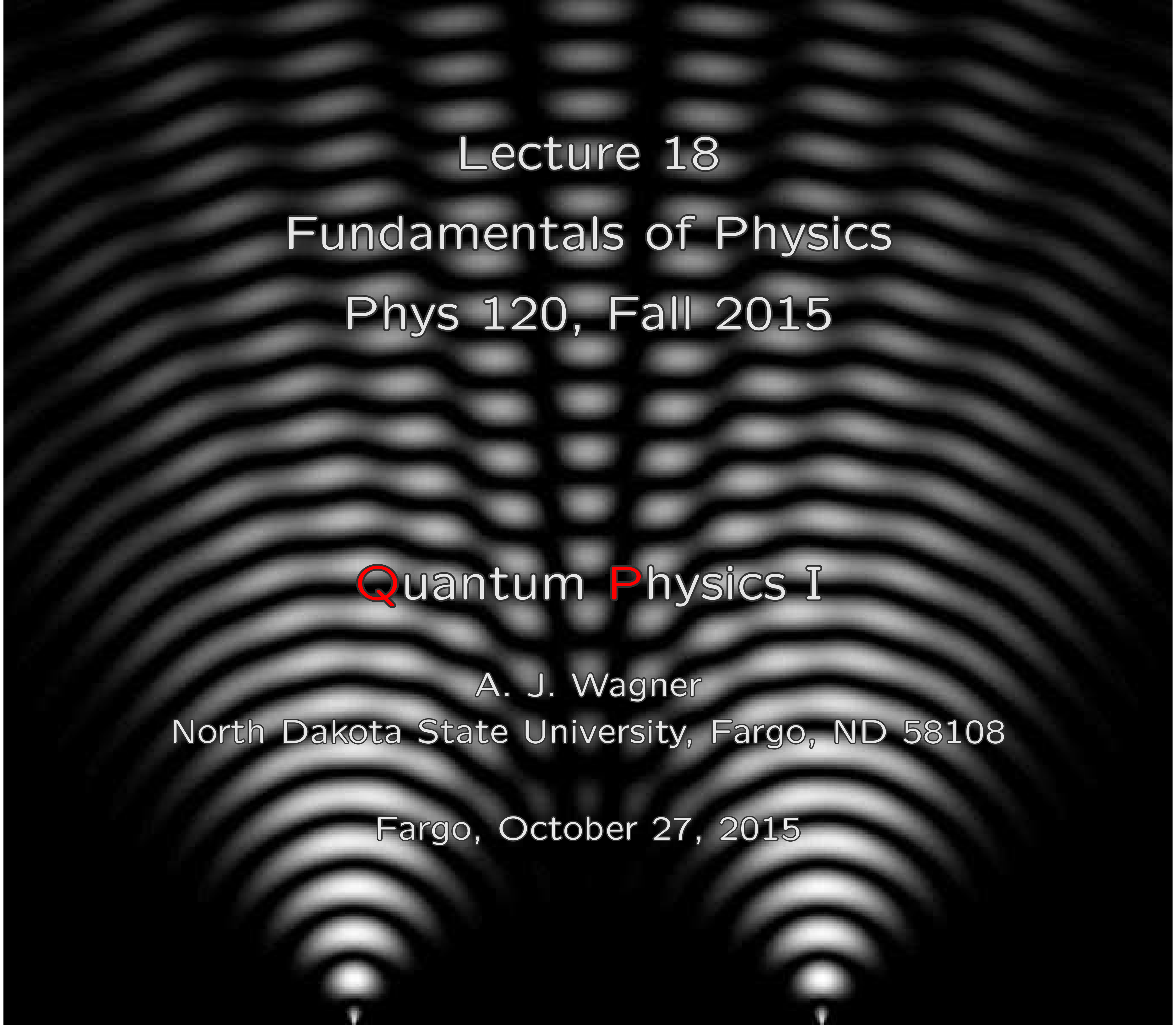

Lecture 18

Fundamentals of Physics

Phys 120, Fall 2015

Quantum Physics I

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Fargo, October 27, 2015

Overview

- Origin of Quantum mechanics
- Radiation has wave and particle properties
- Quantum radiation
- Matter has wave and particle properties
- Quantum Matter
- Nature is non-local and uncertain

The Quantum Idea

Between 1900 and 1930 Physicists began to realize that many fundamental properties in nature are quantized.

Analogy to computation: an analog quantity can take any value, a digital quantity can only take on certain discrete values. If the discretization is small enough, we may not notice the difference. Think of a videogame that shows a rotating objects. The computer, by its digital nature, can only show the object at certain discrete angles, but you will likely not be able to tell the difference.

Similarly macroscopic quantities look like they can take on any value or position, but if you look at objects that are small enough this is no longer true.

WARNING: This subject is another brain teaser where your intuition is about to fail you.

Example: the swing

Suppose you sit on a swing at a playground. If you stop pumping you will gradually slow down, and the height of your swinging will (appear to) continuously decrease. At the same time you will (appear to) continuously loose energy to friction.

If you were much smaller (maybe the size of an atom) you would notice a strange effect: you could only swing with certain discrete amplitudes and you would suddenly switch from one allowed amplitude to another and release a corresponding quantum of energy. The time after which this happens is fundamentally unpredictable*.

This is still true when it is you swinging on a real swing, but the quantums of energy are so small as to make the process appear continuous.

This will seem strange to you because you have been raised in a Western Culture steeped in an Aristotelian/Newtonian worldview. You expect that two identical experiments will have the same outcome. You are about to learn that this is not how reality works.

*Although the *average time is predictable*

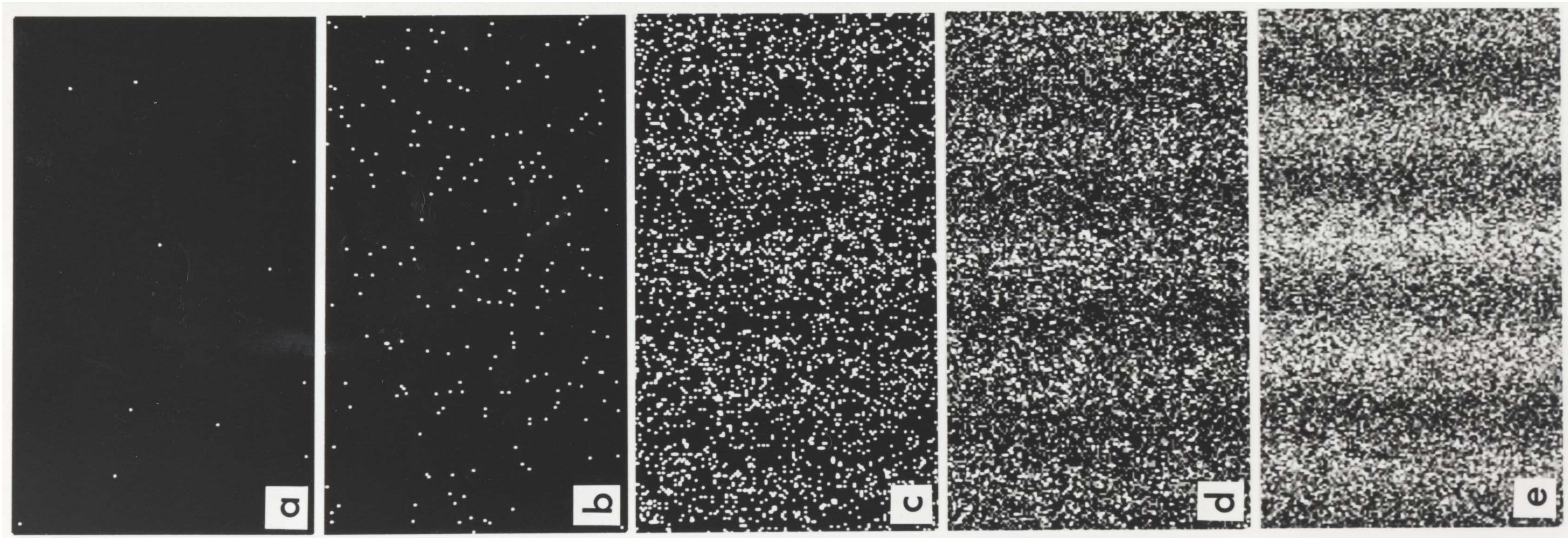
The double slit experiment

Thomas Young
1773-1829
Polymath physician, also helped decipher the Rosetta Stone.

In 1803 Young reported on his landmark observation of interference behind a double slit screen, shattering the prevailing idea promoted by Newton that light consists of light-particles.[a]
We found that the explanation lay in understanding light as electromagnetic waves.
However, when you look at his pattern for light with a very low intensity you notice something strange: The light impacts the screen in discrete events!

[a] His results were generally not believed, but after the French scientist August Fresnel (1788-1827) reproduced his results and published a much extended analysis they were accepted.

Double Slit Results



1) Light is quantized, leading to discrete, particle-like events.
2) The events appear at random positions, but the **probability** for appearing is proportional to The intensity predicted by the wave theory.
3) The Electromagnetic (EM) field is quantized (we don't know why). Yellow light can only take on energies of $0J$, $3.2 \times 10^{-19}J$, $6.4 \times 10^{-19}J$, $9.6 \times 10^{-19}J$, etc.

Quantum Theory of Radiation

Albert Einstein was the first to propose that electromagnetic radiation needs to be quantized.

The Quantum Theory of Radiation
All EM fields are quantized. More specifically, when carrying radiation of frequency f, and the EM field is allowed to have only the following particular values of total energy:

total energy $= 0, hf, 2hf, 3hf, 4hf, 5hf,$ and so on

That is the field's energy must be a simple multiple of the energy increment $E = hf$, where f is the frequency (in herz) of the radiation, and h is a universal constant called **Planck's constant**: $h = 6.6 \times 10^{-34}$ joules per hertz. This quantum is called a **photon**.

Max Planck
(1858-1947)

The mystery of the creation of the dots

Since the EM field is quantized, when the field gets absorbed at the screen it has to do so in an increment of hf. The total, spread out field must loose one quantum of energy instantaneously.

The energy must be deposited at only a single point in the screen, because the screen is made of atoms and, as we will discuss in a later lecture, these atoms are also quantized so that each one must either absorb or not absorb one whole quantum of energy.*

This is the explanation of the particle like behavior of light observed in the previous figure. These energy quanta are called **photons** and are often thought of as microscopic particles of light, even though "particles" may be a misleading word.

Insofar as we can think of photons as particles, they are parcels of EM field that travel at lightspeed and carry an energy hf, where f is the frequency of the oscillating EM field that carries the radiation (note: since their speed is c their restmass must be zero).

But beware: photons are not really particles, otherwise we would not see interference in the double slit experiment!

*This is the basis of spectroscopy that we already mentiond.

Concept check

During the double-slit experiment with light, the region between the slits and the screen contains

a) electrons

b) an EM field

c) photons

d) energy

e) none of the above

Concept check

Radiation made of yellow light, red light, and infrared radiation enters your camera and strikes the photographic film. Which of the three forms of radiation deposits the most energy per photon?

a) Yellow
b) Red
c) Infrared
d) All three deposit the same energy per photon

Quantum Radiation

We don't know why radiation is quantized, or why Planck's constant has a particular value.
Photons strike the screen relatively randomly, but the probability of hitting the bright regions is higher.
The result for many photons is predictable, the result for a single photon is unpredictable.
Once a photon is deposited the whole EM field must "know" about this. This is puzzling in light of a finite lightspeed. This is known as another quantum phenomenon called *nonlocality*.

Concept Check

If Planck's constant were ten times larger than it is, quantum effects would be
a) easier to detect
b) more difficult to detect
c) neither of the above

Concept Check

Suppose the light source is turned on so briefly that only a single quantum of energy passes through the double slit. When it arrives at the screen, this energy is deposited

a) all over the white bands

b) on a small point within the white bands

c) at one small point on the screen, lying directly behind the slit through which the energy passed.

De Broglie's Idea: particles with wave properties

Louis de Broglie
1892 - 1987

In 1923 as a PhD student Luis de Broglie felt that since electromagnetic waves showed particle properties the inverse might also be true. He proposed that particles should also show wavelike properties[a]:

$$\text{wavelength of material particle} = \frac{\text{Planck's constant}}{(\text{particle's mass})(\text{particle's velocity})}$$

$$\lambda = \frac{h}{mv}$$

[a] Planck's formula $E = hf = hc/\lambda$ implies $\lambda = hc/E$. If we now want go generalize this for a particle we get $\lambda = hv/(mv^2/2) = h/mv$

Wavelength of particles

Baseball:

$$\lambda = \frac{6.6 \times 10^{-34} J/hz}{(1kg)(1m/s)} = 6.6 \times 10^{-34} m$$

Electron

$$\lambda \approx 10^{-11} m$$

Two-slit experiment with electrons

How will real particle behave in a two-slit experiment?
Experiments show they behave just like photons!

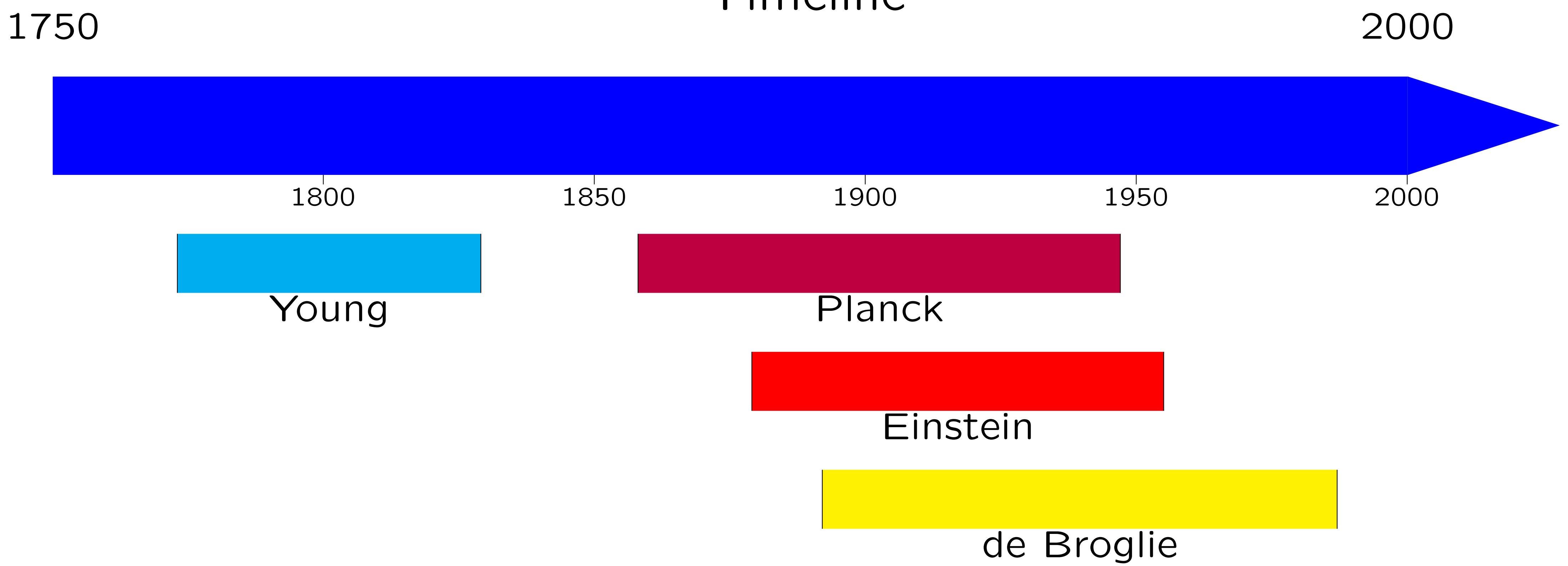
The Quantum Theory of Matter

The Quantum Theory of Matter
A new type of field called a matter field exists in nature. Like EM fields, matter fields are quantized. For example the matter field for electrons is allowed to possess enough energy for either 0 electrons, 1 electron, or 2 electrons and so on. Electrons (and other material particles) exist because matter fields are quantized in just these energy increments.

Concept Check

How is an electron similar to a photon?
a) both contain electric charge
b) both move at lightspeed
c) both impact a tiny point on a viewing screen
d) both are quanta.

Timeline


1750
2000
1800
1850
1900
1950
2000
Young
Planck
Einstein
de Broglie

Summary

- energy is quantized
- the double slit experiment
- Quantum theory of radiation: $E = nhf$
- Events are uncertain/non-deterministic
- Field/particle duality...
- "real" particles act the same way!