"I like relativity and quantum theories
because I don't understand them
and they make me feel as if space shifted about
like a swan that
can't settle,
refusing to sit still and be measured;
and as if the atom were an impulsive thing
always changing its mind."

"Relativity", D.H. Lawrence,
English author (1885-1930)

"In fact, it is often stated that of all the theories proposed in this century, the silliest is quantum theory. Some say that the only thing that quantum theory has going for it, in fact, is that it is unquestionably correct."

Michio Kaku, American theoretical physicist (1947-)

Current Assignments ...

Office hours:
3-4 Tuesdays
& Thursdays

For today
- Read Chapter 12

For Lecture 20
- Read Sections 13.1 - 13.2

Homework #4
- Posted March 7. Due 11:00 AM, Friday, March 22

Writing Assignment #2
- Posted Feb. 28. Due 11:00 AM, Thursday, April 4

Suggested Conceptual Exercises
- Chapter 12: 1,3,5,7,9,11,13,15,17,19,21,23,25,27,29,31,33,35

Tutorial #9
- Homework #3 will be returned

Review of Lecture 18

Textbook, Sections 11.2 - 11.7
- The big bang
- The shape of the universe
- Dark matter and dark energy
- Cosmic inflation *– let's finish this topic*

Cosmic Inflation (Read Sec. 11.7)

- Our present best understanding of the formation of the universe includes a brief period of intense inflation.
  - →The universe is hypothesized to have expanded by a factor of 10^{25} in size in only 10^{-35} sec.
- Doesn't this mean the universe expanded faster than light?
  - →Yes, but this is not a problem! Objects cannot move through space faster than light, but there is no limit on how fast the space itself can expand.
- The distribution of mass in the universe now is due to inflation of small fluctuations.

Cosmic Inflation

- **Question:** Given that energy is conserved and that everything developed from an energy fluctuation having the mass of a dust grain, where did all the mass and energy of the universe come from?
- **Answer:**
  - → The gravitational energy of any isolated lump of matter (e.g., a star or planet) that is held together only by gravity, is negative because work must be done on it to pull it apart.
  - → So the gravitational energy of the universe is enormously negative.
  - → Inflation did not change the net energy of the universe: it created negative (gravitational) and positive (kinetic, radiant, etc.) energy in equal amounts.
  - → The net energy of the universe is still almost zero.

The Evidence for Cosmic Inflation

- It explains today's "lumpy" universe, with stars clumped into galaxies, galaxies into clusters, and clusters into superclusters.
  - → The initial lumpiness was caused by quantum uncertainties that created microscopic lumps.
  - → During inflation, these initial quantum lumps were stretched enormously.
  - → Then gravity further amplified the lumpiness, resulting in the distribution of objects in the universe that seen today.
- It also explains the observed flatness of the universe.
  - → Inflation plus "normal" expansion have stretched the universe so much that its overall curvature is flat.
  - → Inflation both predicts and explains this delicate balance between the open and closed geometries

A Brief History of the Universe

A clickable timeline covering the period from the big bang to the present day

- http://www.pbs.org/deepspace/timeline/

Alternate timeline

- http://physics.lakeheadu.ca/courses/Astro/2330/Cosmology/eras.gif

---

Plan for Lecture 19

Textbook, Chapter 12

- Quantum theory
- The quantization of light
- The quantum theory of radiation
- Matter waves, matter fields
- The quantum theory of matter
- Quantum nonlocality and uncertainty

The Quantum Idea

"Physics is finished, young man. It's a dead-end street."
Advice from Max Planck's teacher ~1880.

- The idea of quantization – that certain properties can only take on certain values – appeared in 1900.
- Quantum physics developed from 1900-1930 and is an area of active research.
- It describes the nature and behavior of matter and radiation, particularly at smallest scales.

→ Well-tested, extremely successful predictions

The Quantum Idea

- Quantum physics has been revolutionary in philosophy as well as in physics.
- The Newtonian universe was deterministic – once you knew where everything was and how it was moving, you could predict future motion precisely.
- Quantum physics introduces an element of randomness – you cannot know the exact position and speed of anything simultaneously, and future motion can be predicted only as a set of probabilities.

Recall from Lecture 10: Young's Double Slit Experiment

- First performed by Thomas Young in 1801.
- Goal was to answer the question of whether light was made of particles (Newton's "corpuscular" theory), or of waves travelling through some ether, just as sound waves travel in air.

Textbook Figure 9.16

Voted #5 in a 2002 poll of "the most beautiful experiments in physics" by Physics World.

L10: Young's Double Slit Experiment

What happened?

Young's two-slit experiment with laser light

- http://www.colorado.edu/physics/2000/applets/twoslitsa.html

The resulting interference pattern supported the wave theory of light.

Light is a wave.*

Textbook Figure 9.17

*for now, stay tuned!

Double Slit Experiment - Dim Light

What happens if the light is very dim?

Textbook
Figure 12.3

© 2010 Pearson Education, Inc.

The pattern builds up as a set of tiny dots.

What Does This Mean?

- It suggests that light consists of tiny particles.
- But we have already shown that light behaves like a wave (because of the interference pattern).

How is this possible?

- Light is a quantized wave.
- It consists of little packets of energy.
- It is the quantized EM field that comes through the slits and interferes at the screen.

The Quantization of Light

- Let's look at yellow light with a frequency of 5×10^{14} Hz.
- It is allowed to have the following energies:

  0 J
  3.2×10^{-19} J
  6.4×10^{-19} J
  9.6×10^{-19} J etc.

Discovered by Max Planck in 1900 when he was studying blackbodies.

- These values are integer multiples of 3.2×10^{-19} J.

The Quantum Theory of Radiation

- All electromagnetic fields are quantized.
- When carrying radiation of frequency f, the EM field is allowed to have only the following particular values of total energy:

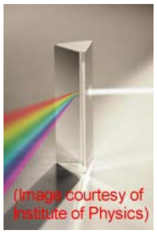
  E = 0, hf, 2 hf, 3 hf, 4 hf, and so on

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

Which of the following colours has the most energy per "energy packet"?

(A) red
(B) yellow
[✓ (C)] violet
(D) all the same
(E) the answer depends on the intensity of the light

$\lambda_{violet} < \lambda_{yellow} < \lambda_{red}$
so
$f_{violet} > f_{yellow} > f_{red}$


(Image courtesy of Institute of Physics)

E = hf, and so the colour with the highest frequency (and shortest wavelength) will have the most energy per energy packet. Of these three colours, this is violet.

Photons

- Photons are the energy packets.
- The energy of a single photon is E = hf.
- They travel at lightspeed (have no mass) and carry energy.
- We sometimes refer to photons as if they are little particles of light.
- This is not really correct - they are energy increments of an EM field.
  → Have wavelike properties & exhibit interference.
- An EM wave is still a wave - but it can only lose energy in units of photons.

Concept Check 4

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

(A) all over the white bands on the screen

[✓ (B)] at one small point within the white bands

(C) at one small point, which could be anywhere on the screen

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

Textbook Figure 12.1

Visualizing the Double Slit Experiment for a Single Photon

View from above: The very dim wave is just as we expect it to be until it impacts the screen. But it only has enough energy to make one photon, which appears somewhere on the screen.

Textbook Figure 12.6

(a) the light (EM field) is emitted

(b) the light approaches the two slits

(c) a portion of the light has passed through the slits

(d) this light approaches the viewing screen

(e) a single impact, a photon, appears on the viewing screen.

At the instant the photon appears, the entire spread-out EM field vanishes or "collapses" to a small point.

The Strange World of Quantum Physics

- Although an EM wave is spread through space, it instantaneously "collapses" when it interacts with an atom. There seems to be no propagation time associated with this.
- The photons appear on the screen in random places, but eventually build up the double-slit interference pattern. How do the photons know where to go?
- Finally, one quantum of light is exceedingly small. Normal lights emit millions of trillions of photons every second – it is impossible to tell if the energy changes by one photon's worth or not!

So far, we have been looking at radiation.

Now let's take a look at matter.

Quantum physics applies to both.

Matter Waves

- Everything is made of radiation and matter.
  - → Until ~1900, physicists believed that radiation was waves and particles were matter.
- Planck showed that radiation has particle-like qualities (1900).
- DeBroglie proposed that matter has wave-like properties (1923) → <u>matter waves</u>
- The wavelength of any mass is defined as

$\boxed{\lambda = h/mv}$ = Planck's constant /(mass)(velocity)

→ $\lambda \approx 10^{-35}$ m for a 1-kg object → very small

→ $\lambda \approx 10^{-11}$ m for an electron → detectable

The Wave Theory of Matter

Every material particle has wave properties with a wavelength equal to h/mv, where m is the particle's mass and v is its velocity.