Atomic Energy

Greece (c. 400 BC)

John Dalton (1766 - 1844)

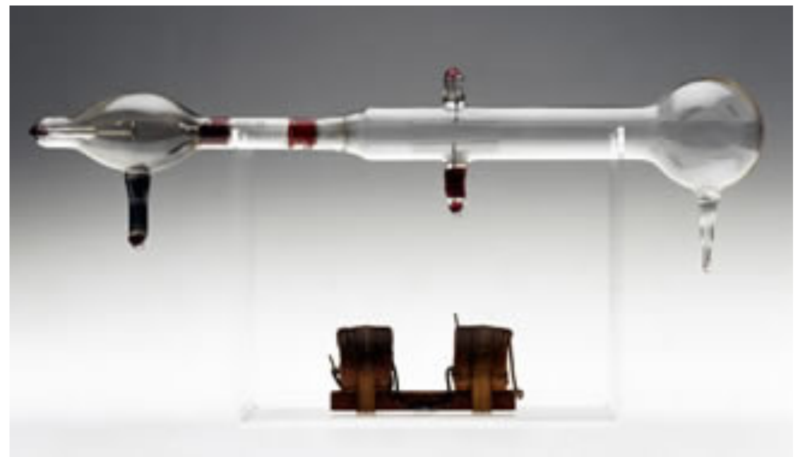
- Discoverer of color blindness
- Stoichiometry – math of how elements combined to form other elements
- Dalton found that oxygen & carbon combined to make 2 compounds (1803)
  - Each had its own particular weight ratio of oxygen to carbon (1.33:1 and 2.66:1)
  - Same amount of carbon, one had exactly twice as much oxygen as the other
- Law of simple multiple proportions

Dalton's Elementary Atomic Theory

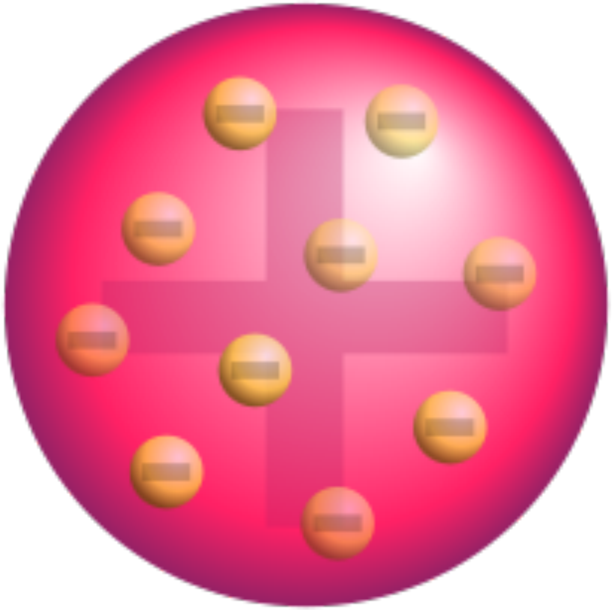
- Elements are made of extremely small particles called atoms
- Atoms of a given element are identical in size, mass, and other properties
- Atoms of different elements differ in size, mass, and other properties
- Atoms cannot be subdivided, created, or destroyed
- Atoms of different elements combine in simple whole-number ratios to form chemical compounds
- In chemical reactions, atoms are combined, separated, or rearranged

J.J. Thomson (1856 - 1940)

What are cathode rays? (1897)

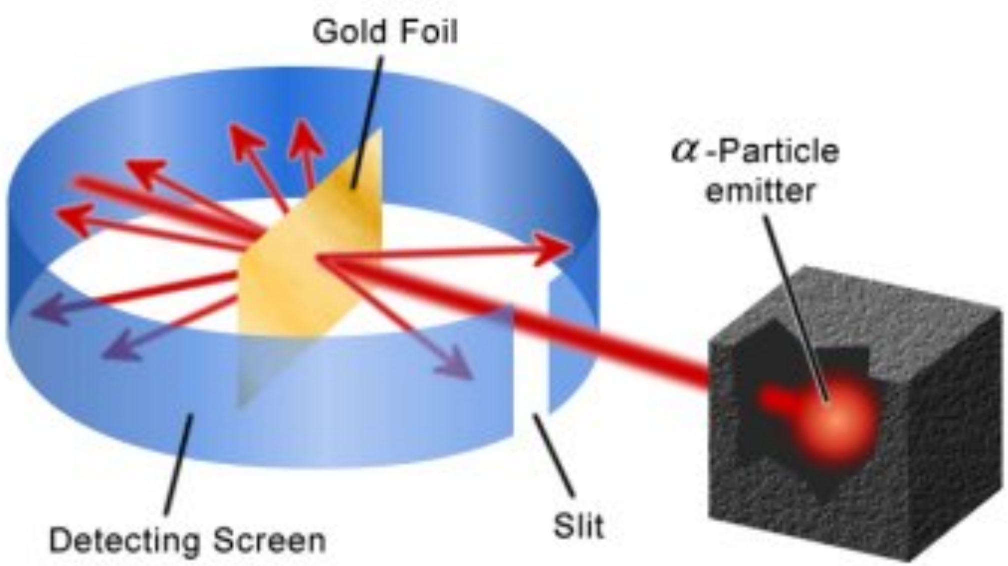


Thomson's Atomic Model



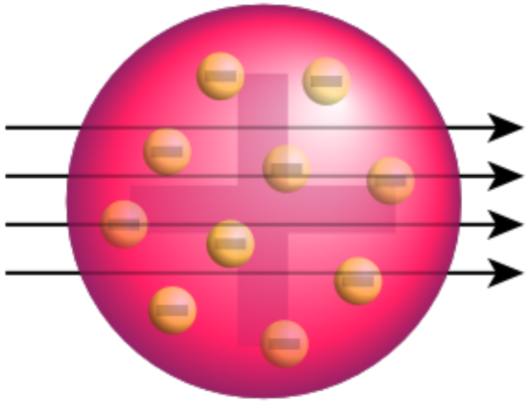
Geiger-Marsden Experiment (1909)

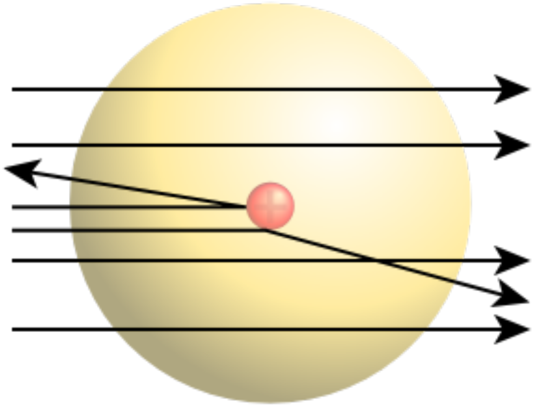
Goal: To measure distribution of charge in atom



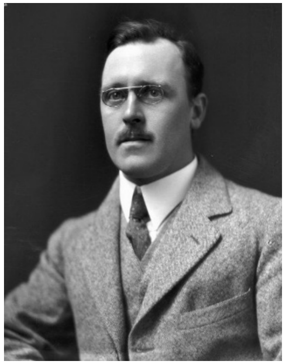
Geiger-Marsden Experiment (1909)

- Most particles did as expected
- Observed a few percentage of α-particles were deflected through angle > 90°
- How can this be true?





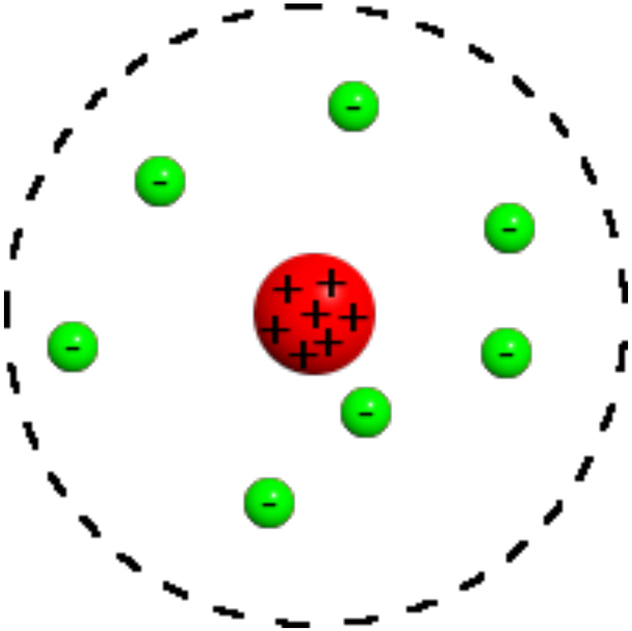
Hans Geiger



Ernest Marsden

Rutherford Model (1911)

- "Plum pudding" model incorrect
- Some α-particles were deflected or reflected
- Many α-particles passed through
- Rutherford's planetary model



Rutherford Model (1911)

Problems with Rutherford's planetary model

1. Electron would lose energy (EM radiation)
2. As electron spirals inward, emission would gradually increase in frequency as orbit got smaller and faster
3. Produce continuous smear, in frequency, of EM radiation
4. Atom has extremely short lifetime (unstable)

Rutherford Model (1911)

Problems with Rutherford's planetary model

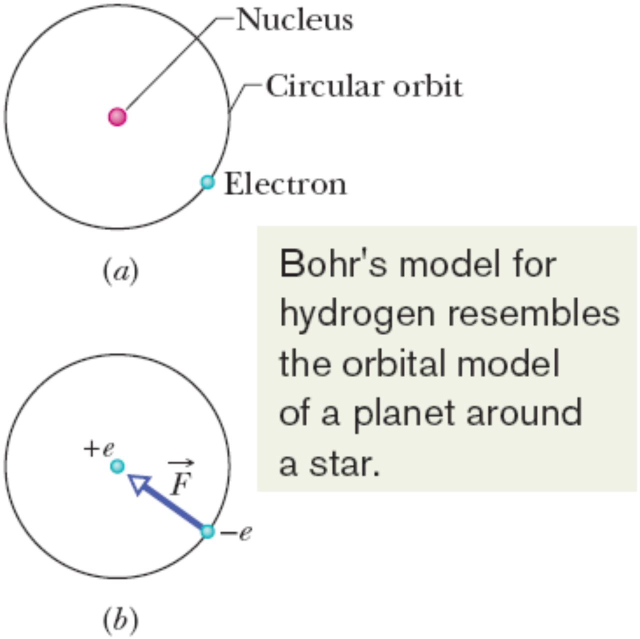
1. Emission spectra of hydrogen is well known by 1908
2. Only discreet lines are seen in the hydrogen spectra

Bohr Model (1913)

- Electrons can only be in certain stable orbits around the nucleus
- Each orbit has an energy associated with it

Explained why atom is stable!

- Only a certain number of electrons can exist in each orbital shell



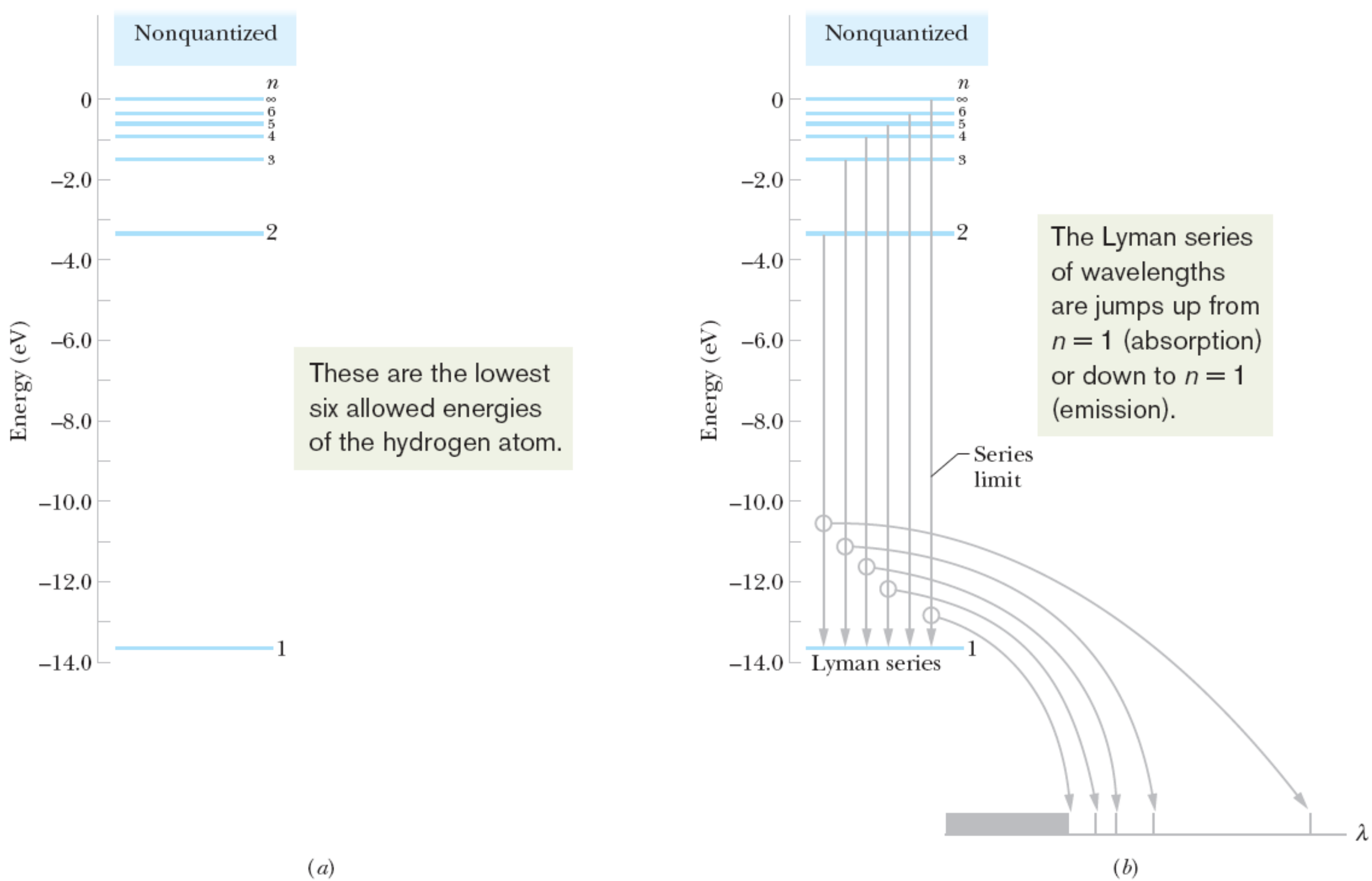
Bohr Model (1913)

- Light emitted/absorbed
  - Emitted when electron jumps from higher orbit to lower orbit
  - Absorbed when it jumps from a lower to higher orbit
  - Energy & frequency of light emitted/absorbed is given by difference between the two orbit energies

Explained why only certain lines are observed in H-spectra!

The Hydrogen Atom

$$E_n = -\frac{2.180 \times 10^{-18}\,\text{J}}{n^2} = -\frac{13.61\,\text{eV}}{n^2}, \quad \text{for } n = 1, 2, 3, \ldots.$$



Example Problem

For the Lyman series, what is energy for the 1, 2, and 3 transitions?

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So for n = 1

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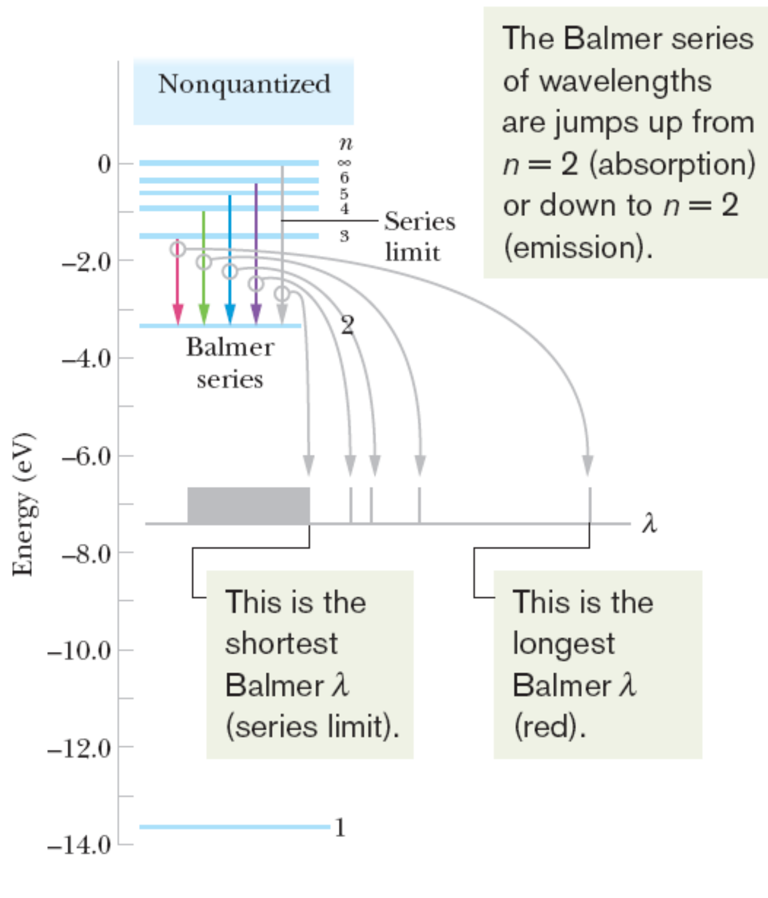
So for n = 2
$E_1 = - 2.180 \times 10^{-18}$ J $/(2)^2$
$E_1 = - 5.45 \times 10^{-17}$ J

So for n = 3
$E_1 = - 2.180 \times 10^{-18}$ J $/(3)^2$
$E_1 = - 2.422 \times 10^{-17}$ J

The Hydrogen Atom



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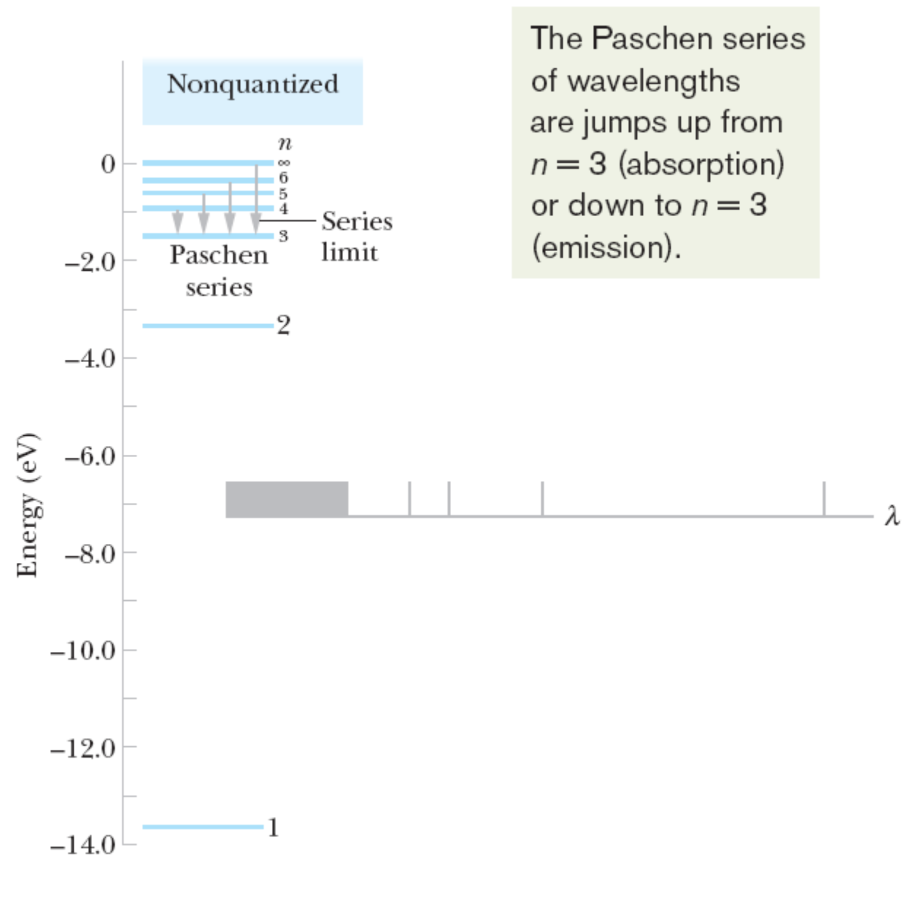


(d)

Quantum numbers and the Hydrogen Atom

Each set of quantum numbers (*n, l,* m_l) identifies the wave function of a particular quantum state. The quantum number *n,* is called the **principal quantum number.** The **orbital quantum number** *l* is a measure of the magnitude of the angular momentum associated with the quantum state. The **orbital magnetic quantum number** m_l is related to the orientation in space of this angular momentum vector.

The restrictions on the values of the quantum numbers for the hydrogen atom, as listed in the table, are not arbitrary but come out of the solution to Schrödinger's equation.

Symbol	Name	Allowed Values
n	Principal quantum number	$1, 2, 3, \ldots$
ℓ	Orbital quantum number	$0, 1, 2, \ldots, n-1$
m_ℓ	Orbital magnetic quantum number	$-\ell, -(\ell-1), \ldots, +(\ell-1), +\ell$

Photons

But notice here we are talking about light that is emitted or absorbed by an atom. In 1905, Einstein proposed that electromagnetic radiation (or simply *light)* is quantized and exists in elementary amounts (quanta) that we now call **photons.**

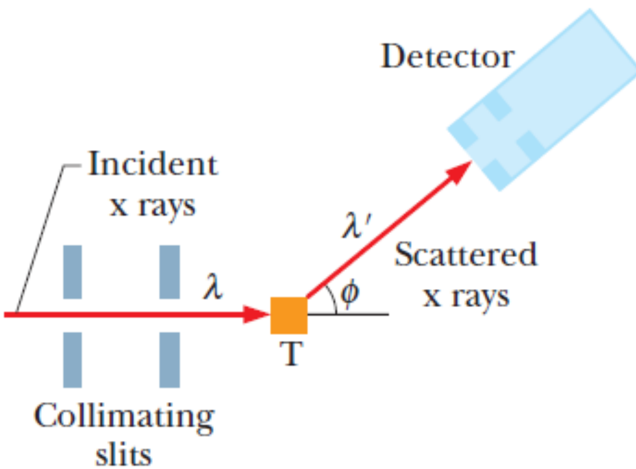
According to that proposal, the quantum of a light wave of frequency f has the energy

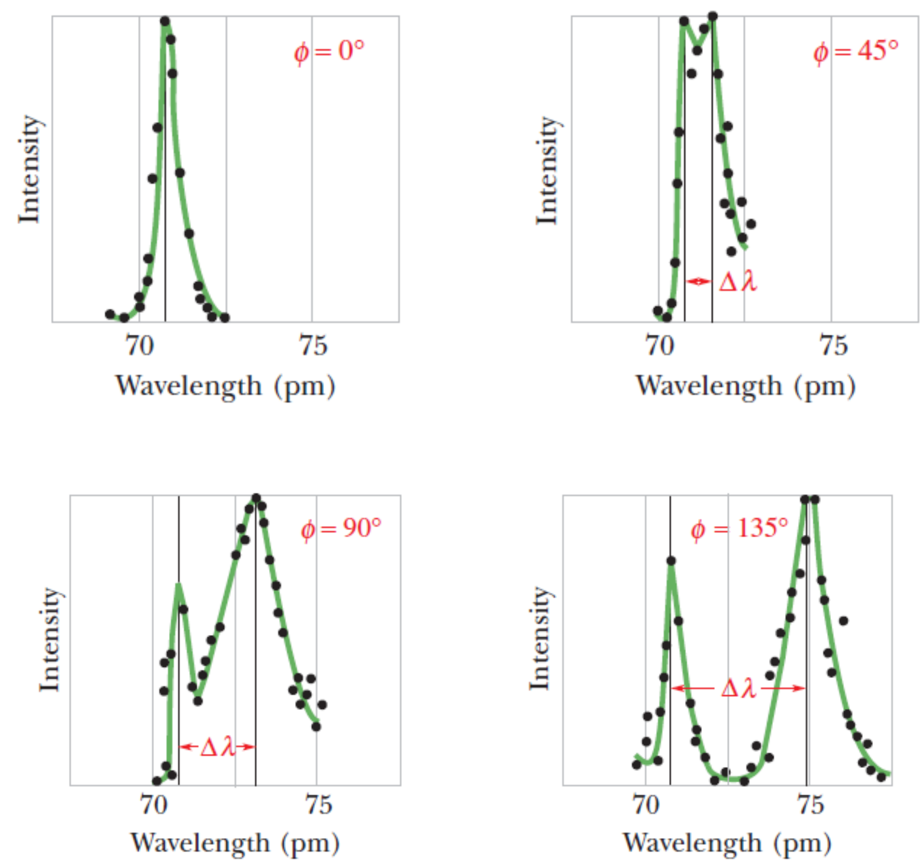
$$E = hf \qquad \text{(photon energy).}$$

Here h is the ***Planck constant,*** which has the value

$$h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s} = 4.14 \times 10^{-15}\ \mathrm{eV \cdot s.}$$

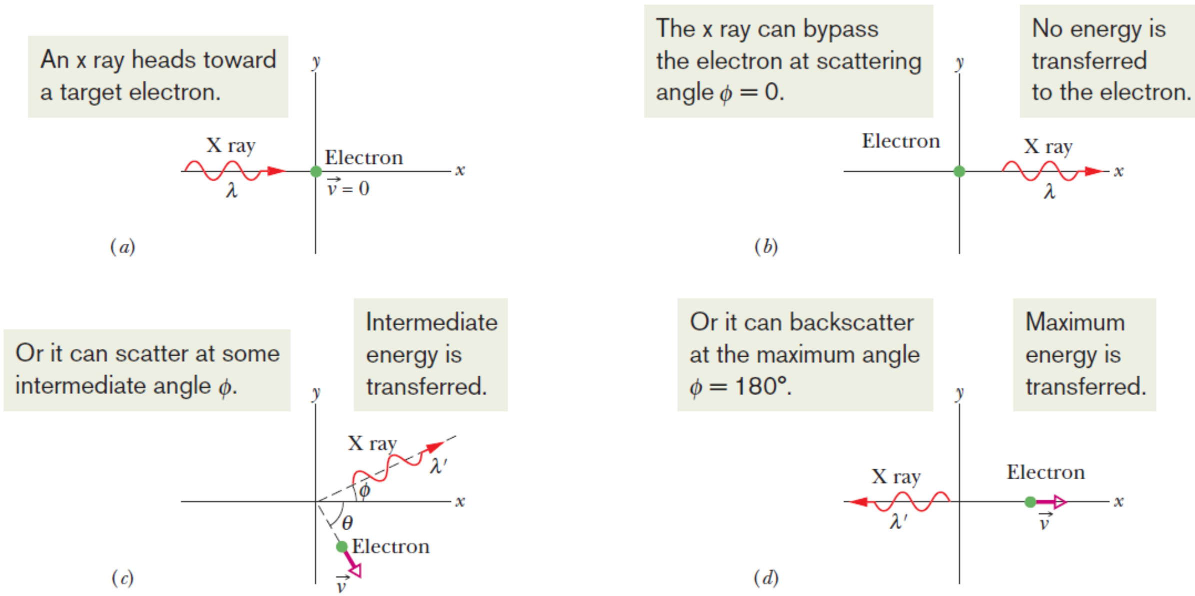
Photon Have Momentum
The Compton Effect





$$p = \frac{hf}{c} = \frac{h}{\lambda} \qquad \text{(photon momentum)}.$$

Photon Have Momentum
The Compton Effect



As a result of the collision, an x ray of wavelength λ' moves off at an angle ϕ and the electron moves off at an angle θ, as shown. Conservation of energy then gives us

$$hf = hf' + K$$

Here *hf* is the energy of the incident x-ray photon, *hf'* is the energy of the scattered x-ray photon, and *K* is the kinetic energy of the recoiling electron. Since the electron may recoil with a speed comparable to that of light, then the Compton shift is defined as:

$$\Delta\lambda = \frac{h}{mc}(1 - \cos\phi) \qquad \text{(Compton shift)}.$$

Example Problem

A sodium vapor lamp emits light at a wavelength of 590 nm. What is the momentum of the photons produced by the light and their frequency? Assume that the speed of light is $c = 3 \times 10^8$ m/s.

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$$h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}$$

Converting the wavelength

$\lambda = 590$ nm $= 590 \times 10^{-9}$ m

So, $p = (6.63 \times 10^{-34}\ \mathrm{J \cdot s}) / (590 \times 10^{-9}\ \mathrm{m}) = 1.12 \times 10^{-27}\ \mathrm{kg \cdot m/s}$

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Based on the equation:

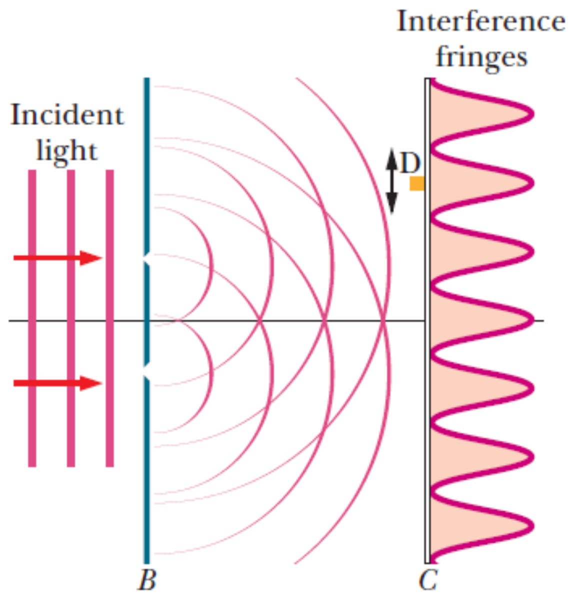
$f/c = 1/\lambda$

Rearranging this equation we see that $f = c/\lambda$

$f = (3 \times 10^8\ \text{m/s}) / (590 \times 10^{-9}\ \text{m}) = 5.08 \times 10^{14}\ \text{Hz}$

Light as a Probability Wave

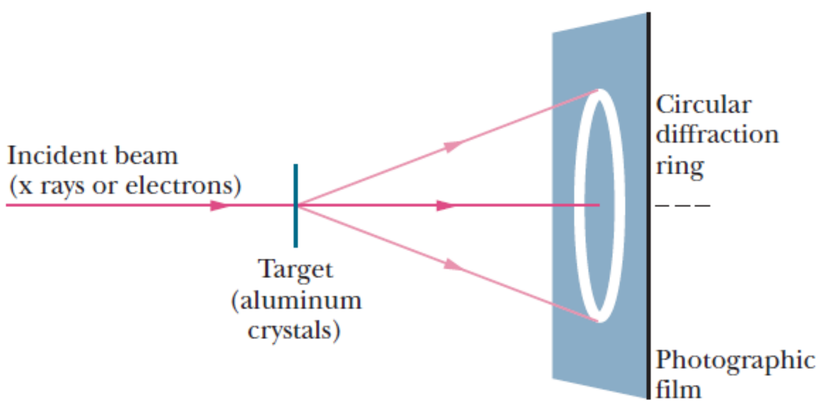
The probability (per unit time interval) that a photon will be detected in any small volume centered on a given point in a light wave is proportional to the square of the amplitude of the wave's electric field vector at that point.



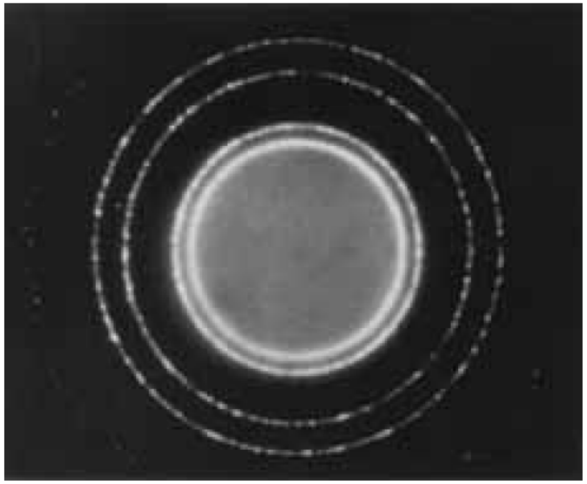
de Broglie Wavelength
Electrons & Matter Waves

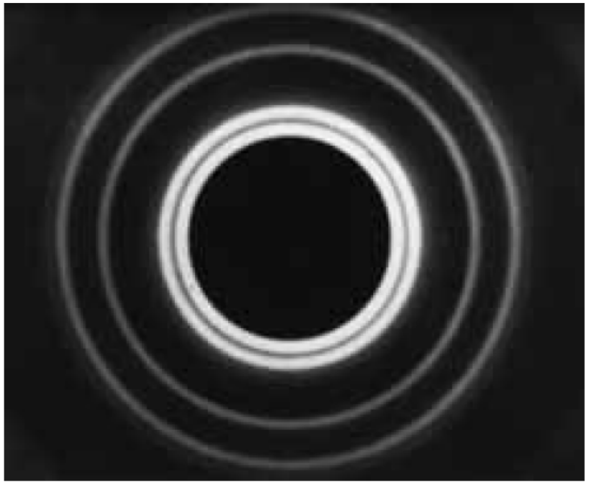
$$\lambda = \frac{h}{p} \qquad \text{(de Broglie wavelength)}$$

de Broglie suggested that $p = h/\lambda$ might apply not only to photons but also to electrons



(*a*)


(*b*)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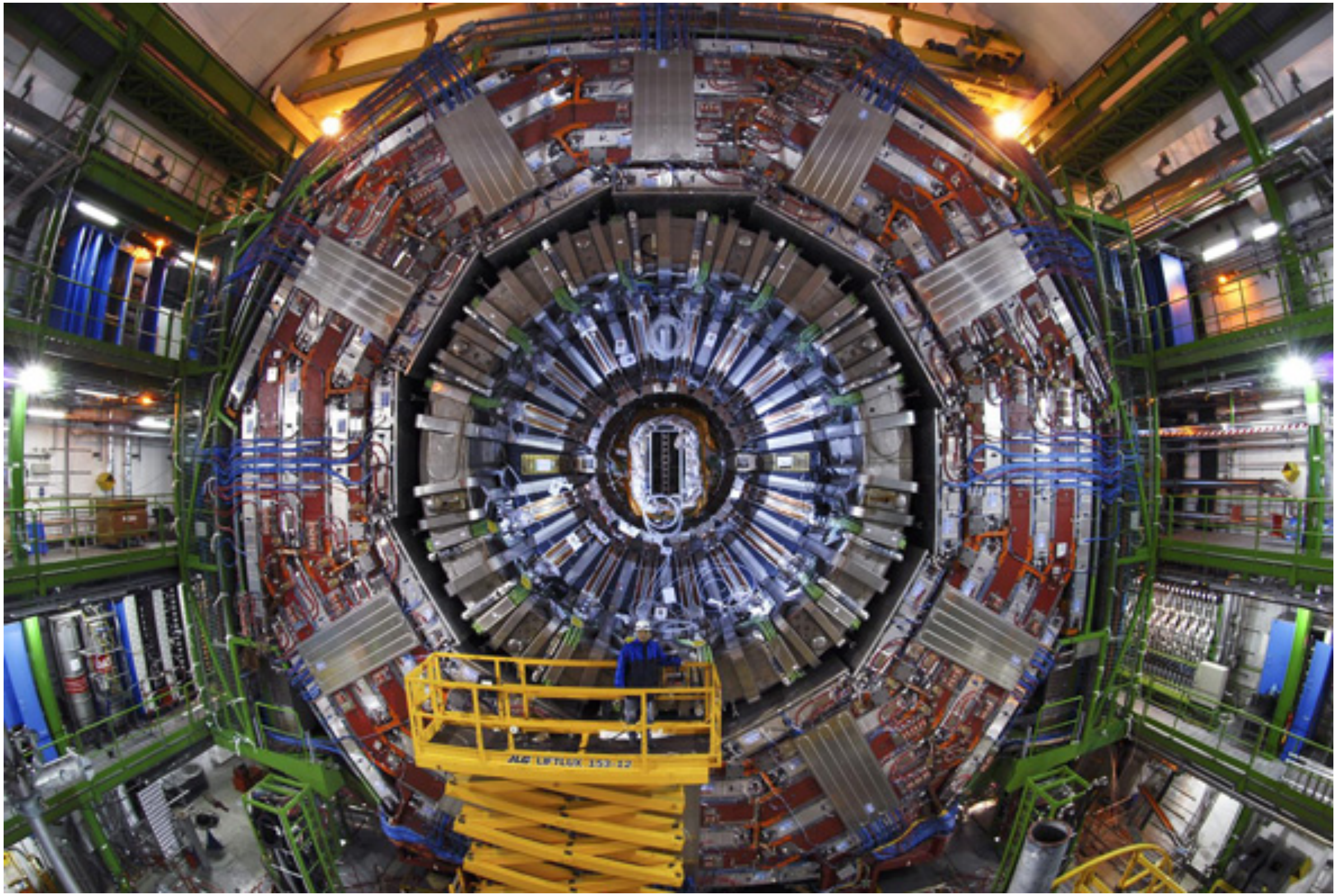
Particles



One of the large particle detectors that comprise the Large Hadron Collider at CERN in Geneva, Switzerland. SOURCE: © CERN

Particles: Fermions and Bosons

Fermions obey the Pauli exclusion principle, which asserts that only a single particle can be assigned to a given quantum state. Bosons *do not* obey this principle. Any number of bosons can occupy a given quantum state.

All particles have an intrinsic angular momentum called spin. The component of spin in any direction (assume the component to be along a *z axis)* is:

$$S_z = m_s\hbar \qquad \text{for } m_s = s, s-1, \ldots, -s, \qquad \hbar \text{ is } h/2\pi,$$

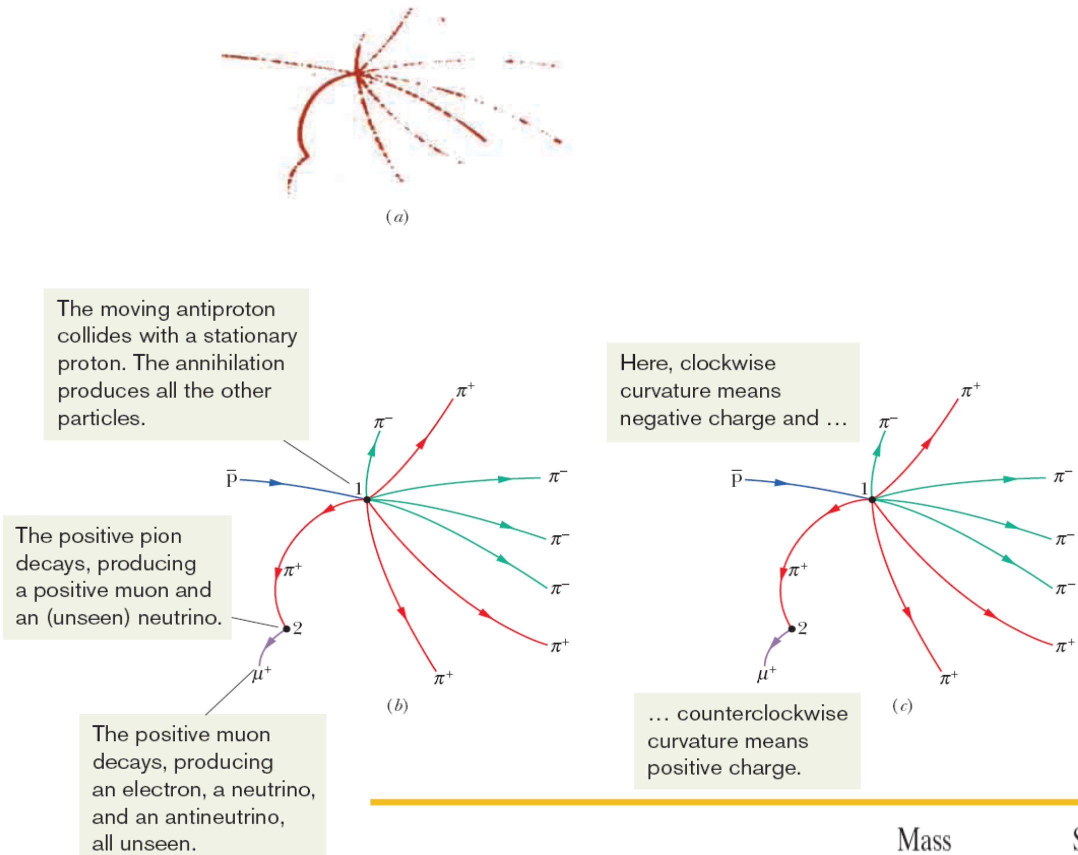
1. Fermions: particles with half-integer spin quantum numbers
2. Bosons: Particles with zero or integer spin quantum numbers
3. Leptons: Particles on which the strong force does not act, leaving the weak force as the dominant force
4. Hadrons: Particles on which the strong force acts
   a. Mesons: hadrons which are also bosons
   b. Baryons: hadrons which are also fermions

Particles

- In 1928 Dirac predicted that the electron *e^-* should have a positively charged counterpart of the same mass and spin
- *Every particle has a corresponding **antiparticle.*** The members of such pairs have the same mass and spin but opposite signs of electric charge (if they are charged) and opposite signs of quantum numbers.
- When a particle meets its antiparticle, the two can *annihilate* each other. The particle and antiparticle disappear, and their combined energies reappear in other forms.
- Antimatter: An assembly of antiparticles, such as an antihydrogen atom

$$e^- + e^+ \rightarrow \gamma + \gamma.$$

Particles in a Bubble Chamber



<u>Decay Process:</u>

1. Proton – Antiproton Annihilation

$$p + \bar{p} \rightarrow 4\pi^+ + 4\pi^-.$$

2. Pion Decay

$$\pi^+ \rightarrow \mu^+ + \nu.$$

3. Muon Decay

$$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}.$$

Particle	Symbol	Charge q	Mass (MeV/c^2)	Spin Quantum Number s	Identity	Mean Life (s)	Antiparticle
Neutrino	ν	0	$\approx 1 \times 10^{-7}$	$\frac{1}{2}$	Lepton	Stable	$\bar{\nu}$
Electron	e^-	-1	0.511	$\frac{1}{2}$	Lepton	Stable	e^+
Muon	μ^-	-1	105.7	$\frac{1}{2}$	Lepton	2.2×10^{-6}	μ^+
Pion	π^+	$+1$	139.6	0	Meson	2.6×10^{-8}	π^-
Proton	p	$+1$	938.3	$\frac{1}{2}$	Baryon	Stable	$\bar{p}$

Particles: Leptons

In all particle interactions, the net lepton number *for each family* is separately conserved.

The Leptons[a]

Family	Particle	Symbol	Mass (MeV/c^2)	Charge q	Antiparticle
Electron	Electron	e^-	0.511	−1	e^+
	Electron neutrino[b]	ν_e	$\approx 1 \times 10^{-7}$	0	$\bar{\nu}_e$
Muon	Muon	μ^-	105.7	−1	μ^+
	Muon neutrino[b]	ν_μ	$\approx 1 \times 10^{-7}$	0	$\bar{\nu}_\mu$
Tau	Tau	τ^-	1777	−1	τ^+
	Tau neutrino[b]	ν_τ	$\approx 1 \times 10^{-7}$	0	$\bar{\nu}_\tau$

[a] All leptons have spin quantum numbers of $\frac{1}{2}$ and are thus fermions.
[b] The neutrino masses have not been well determined.

Particles: Hadrons

Baryons and mesons are hadrons, whose interaction are governed by the strong force. A new quantum can be introduced, called the *baryon number*, *B*. The conservation law of *B* is given as:

To every baryon we assign $B = +1$. To every antibaryon we assign $B = -1$. To all particles of other types we assign $B = 0$. A particle process cannot occur if it changes the net baryon number.

Quark Model

The Quarks[a]

			Quantum Numbers			
Particle	Symbol	Mass (MeV/c^2)	Charge q	Strangeness S	Baryon Number B	Antiparticle
Up	u	5	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\bar{u}$
Down	d	10	$-\frac{1}{3}$	0	$+\frac{1}{3}$	$\bar{d}$
Charm	c	1500	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\bar{c}$
Strange	s	200	$-\frac{1}{3}$	-1	$+\frac{1}{3}$	$\bar{s}$
Top	t	175 000	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\bar{t}$
Bottom	b	4300	$-\frac{1}{3}$	0	$+\frac{1}{3}$	$\bar{b}$

[a] All quarks (including antiquarks) have spin $\frac{1}{2}$ and thus are fermions. The quantum numbers q, S, and B for each antiquark are the negatives of those for the corresponding quark.

Basic Forces and Messenger Particles

Electromagnetic Forces:

- At the atomic level, Coulomb's Law explains the electromagnetic force that two electrons exert on each other.
- At a deeper level, this interaction is described by ***quantum electrodynamics (QED).*** It is assumed that each electron senses the presence of the other by exchanging photons with it.
- These photons, called ***virtual photons***, cannot be detected since they are emitted by one electron and absorbed by the other a very short time later. These are also called *messenger particles.*
- If a stationary electron emits a photon and remains itself unchanged, energy is not conserved. The principle of conservation of energy is saved, by the uncertainty principle, written in the form

$$\Delta E \cdot \Delta t \approx \hbar.$$

- When electron *A* emits a virtual photon, the overdraw in energy is quickly set right when that electron receives a virtual photon from electron *B*, within a time frame given by the above relation.

Basic Forces and Messenger Particles

The Weak Force:

A theory of the weak force, which acts on all particles, was developed by analogy with the theory of the electromagnetic force.

The messenger particles that transmit the weak force between particles, however, are not (massless) photons but massive particles, identified by the symbols W and Z.

The theory was so successful that it revealed the electromagnetic force and the weak force as being different aspects of a single ***electroweak force***.

Particle	Charge	Mass
W	$\pm e$	80.4 GeV/c^2
Z	0	91.2 GeV/c^2

Basic Forces and Messenger Particles

The Strong Force:

The messenger particles in this case are massless, and are called ***gluons*.**

The theory assumes that each “flavor” of quark comes in three varieties, labeled *red, yellow, and blue.* Thus, there are three up quarks, one of each color, and so on. The antiquarks also come in three colors, which we call *antired, antiyellow, and antiblue.*

The force acting between quarks is called a ***color force*** and the underlying theory is called ***quantum chromodynamics (QCD).***

Apparently, quarks can be assembled only in combinations that are *color-neutral.*

The color force not only acts to bind together quarks as baryons and mesons, but it also acts between such particles, in which case it has traditionally been called the strong force. Hence, not only does the color force bind together quarks to form protons and neutrons, but it also binds together the protons and neutrons to form nuclei.

Basic Forces and Messenger Particles

- *Einstein's Dream:*

- The unification of the fundamental forces of nature into a single force occupied Einstein's attention for much of his later life.

- The weak force has been successfully combined with electromagnetism so that they may be jointly viewed as aspects of a single *electroweak force.*

- The *grand unification theories (GUTs)* attempt to add the strong force to this combination, and are being pursued actively.

- Theories that seek to add gravity, sometimes called *theories of everything (TOE),* are at an encouraging but speculative stage at this time.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

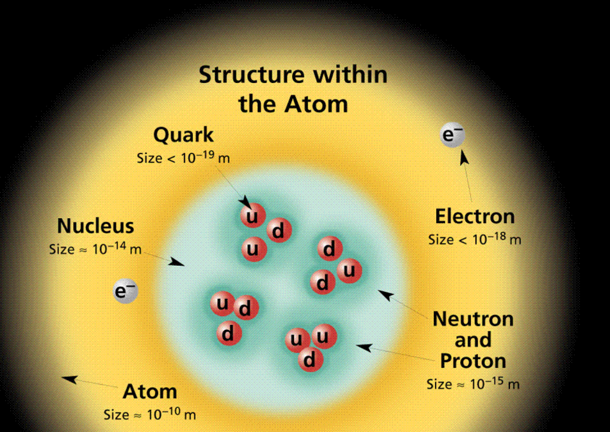
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

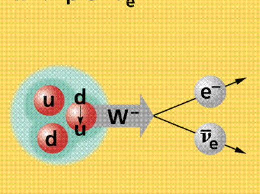
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

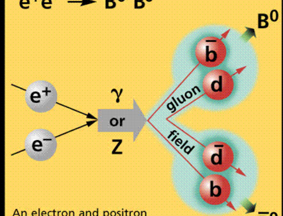
These diagrams are an artist's conception of physical processes. They are *not* exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^- \,\bar{\nu}_e$



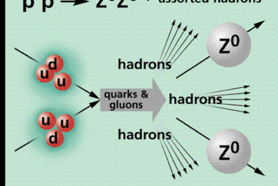
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\,\bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B⁰ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
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