Particle Physics: History of Particle Physics

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Week 2: September 23, 2017
Columbia University Science Honors Program

Course policies

- **Attendance record counts**

  - Up to four absences

  - Lateness or leaving early counts as half-absence

  - Send email notifications of all absences to shpattendance@columbia.edu.

- Please, no cell phones during class

- **Please, ask questions!**

- Lecture materials

  https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

Schedule

Month	Day	Lecture	Teacher
September	16	Introduction	José
	23	History of Particle Physics	José
	30	No classes -- Yom Kippur	-
October	7	Special Relativity	Inês
	14	Quantum Mechanics	Inês
	21	Experimental Methods	Cris
	28	The Standard Model - Overview	Cris
November	4	The Standard Model - Limitations	Cris
	11	Neutrino Theory	José
	18	Neutrino Experiment	José
	25	No classes -- Thanksgiving	-
December	2	LHC and Experiments	Inês
	9	The Higgs Boson and Beyond	Inês
	16	Particle Cosmology	Cris

History of Particle Physics

Late 1800's – Early 2000's:

Discoveries of Standard Model particles,
particle properties,
realization of fundamental symmetries,
experimental triumphs,
but also a lot of puzzles, frustration, confusion…

From Classical Physics…
…to Modern Physics…
…and Particle Physics today
(Standard Model)

Late 1800's

Atoms (from Greek $άτομος$ = non-divisible) were thought to be fundamental constituents of matter.

Chemists and physicists were classifying the known (and yet-to-be discovered) elements according to their chemical properties.

But trends in the periodic table suggest some underlying atomic structure: i.e., atoms are composites of smaller, more "fundamental" particles that determine chemical behavior.

Periodic Table of the Elements

© www.elementsdatabase.com

■ hydrogen
■ alkali metals
■ alkali earth metals
■ transition metals

■ poor metals
■ nonmetals
■ noble gases
■ rare earth metals

Mendeleev's 1869 periodic table

D. Mendeleev

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ,

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.
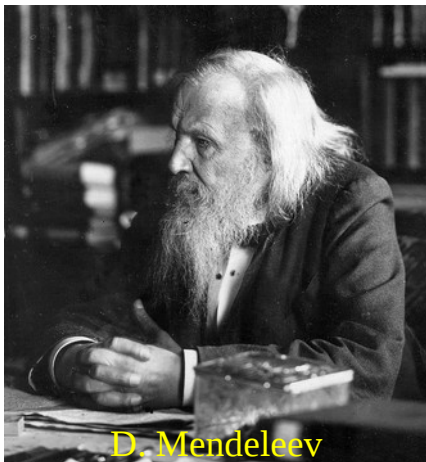
		Ti=50	Zr=90	?=180.
		V=51	Nb=94	Ta=182.
		Cr=52	Mo=96	W=186.
		Mn=55	Rh=104,4	Pt=197,1.
		Fe=56	Ru=104,4	Ir=198.
		Ni=Co=59	Pd=106,6	Os=199.
H=1		Cu=63,4	Ag=108	Hg=200.
Be= 9,4 Mg=24	Zn=65,2	Cd=112
B=11 Al=27,3	?=68	Ur=116	Au=197?
C=12 Si=28	?=70	Sn=118
N=14 P=31	As=75	Sb=122	Bi=210?
O=16 S=32	Se=79,4	Te=128?
F=19 Cl=35,5	Br=80	I=127
Li=7 Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
Ca=40	Sr=87,6	Ba=137	Pb=207.
?=45	Ce=92
?Er=56	La=94
?Yt=60	Di=95
?In=75,6	Th=118?

Д. Менделѣевъ

Mendeleev's Periodic Table summarizes patterns in the electro-chemical properties of the elements. In the 1800's, scientists used these patterns to search for "missing" elements.
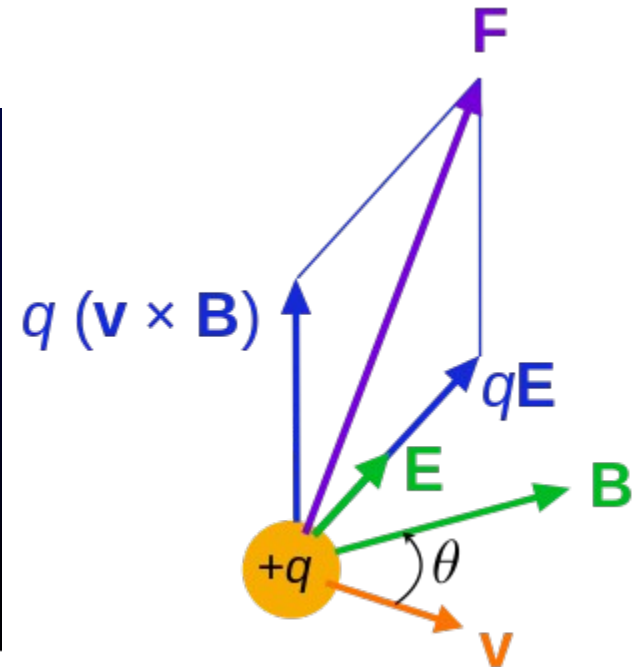
6

Key concept: Lorentz Force

$$\vec{F} = q \, (\vec{v} \times \vec{B} + \vec{E})$$

Charge of the particle

Velocity of the particle

Magnetic field

Electric field

$q \, (\mathbf{v} \times \mathbf{B})$

$q\mathbf{E}$

F

E

B

V

θ

+q

Physics during the 1890's

New, unstable elements (radioactive) were being investigated by M. Curie, P. Curie, H. Becquerel, E. Rutherford, et al.

Radioactivity: describes the emission of particles from atomic nuclei as a result of nuclear instability. The fact that atoms seemed to spontaneously split apart also suggests they are not fundamental particles.
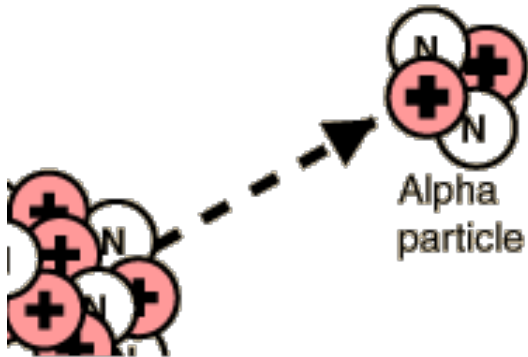
At the time, it was known that unstable elements tended to emit three types of particles, which were differentiated by their electric charge:
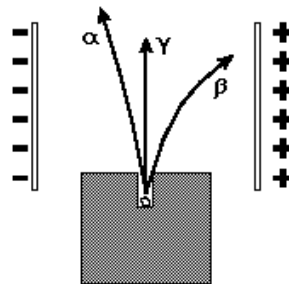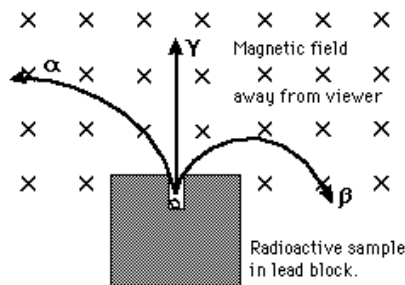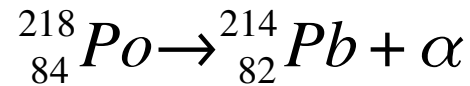

Pierre and Marie Curie

1) Alpha particles (α):   +2 electric charge;   about 4x proton mass
2) Beta particles (β):   -1 electric charge; about 1/1800 proton mass
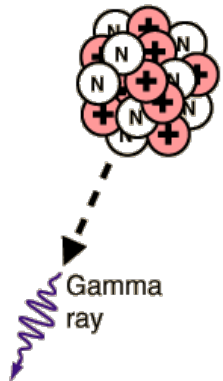**3) Gamma particles (γ):** electrically neutral
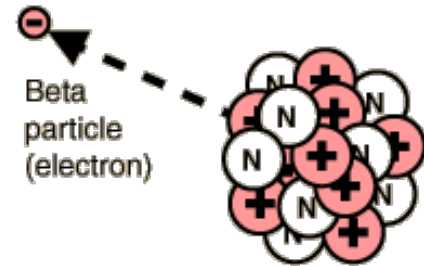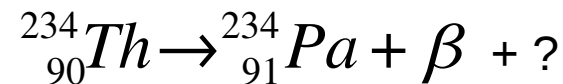
Radioactivity

The **α-particle**, as it turns out, is just He^{+2}, the nucleus of a helium atom.
It is emitted in decays like:

$$^{218}_{84}Po \rightarrow ^{214}_{82}Pb + \alpha$$

The **β-particle** is an electron (not known until 1897). A β-decay example:

$$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + \beta + ?$$

The **γ-particles** are photons, emitted in such decays as:

$$^{137}Ba^{*} \rightarrow ^{137}Ba + \gamma$$

Alpha particle

Beta particle (electron)

Gamma ray

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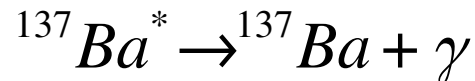
The Early Years (1897-1932)

1897: Discovery of the electron

Discovery of the electron (1897)

□ For a number of years, scientists had generated "cathode rays" by heating filaments inside gas-filled tubes and applying an electric field.

- Recall: we know cathode rays have electric charge, because they can be deflected by magnetic fields.
- Question: are cathode rays some kind of charged fluid, or are they made of charged particles (like ions)?

J. J. Thompson

Image: NobelPrize.org

□ In 1897, J.J. Thomson attempted a measurement of the charge/mass ratio of cathode rays to see if they were particles.

Discovery of the electron (1897)
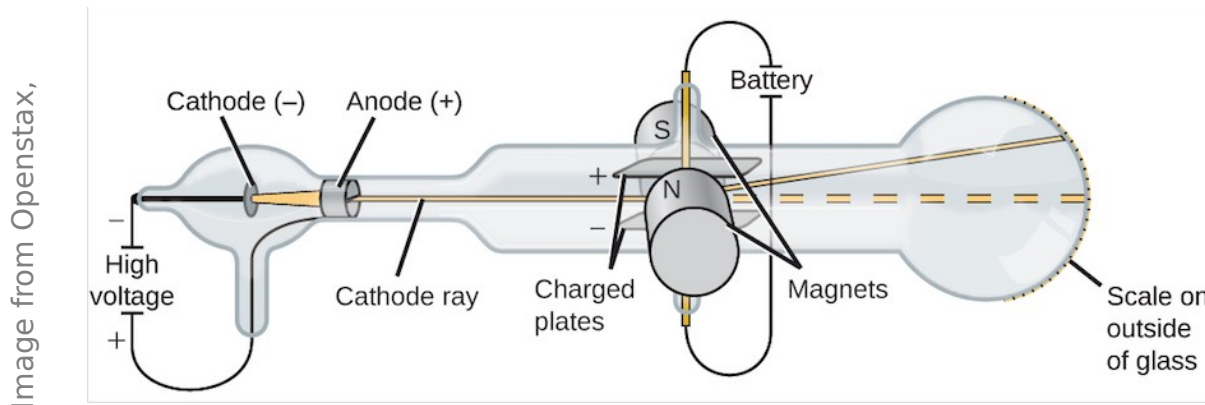
- Put a cathode ray into a known electric or magnetic field.
- Measure the cathode ray's deflection.
- If cathode rays are composed of discrete charges, their deflection should be consistent with the Lorentz Force Law:

Image from Openstax,

$$\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right)$$

Thompson's cathode ray tube

Demo of a cathode ray tube

https://youtu.be/FWwSBCA6xgY

Discovery of the electron (1897)

- Thomson found that cathode ray deflections were indeed consistent with the Lorentz Force, and could be particles ("corpuscles") after all.
- The charge to mass ratio e/m was significantly larger than for any known ion (over 1000x e/m of hydrogen). This could mean two things:

  (1) The charge e was very big.

  (2) The mass m was very small.
- Independent measurements of e suggested that, in fact, cathode rays were composed of extremely light, negatively charged particles.
- Thomson called his corpuscle's charge the electron (from the Greek $ἤλεκτρον$ = "amber"); eventually, this term was applied to the particles themselves, whose mass is:

m_e= 0.511MeV/c^2

Discovery of the electron (1897)

- Thomson correctly believed that electrons were fundamental components of atoms (e.g., responsible for chemical behavior).

- Because atoms are electrically neutral, he surmised that the negatively charged point-like electrons must be embedded in a "gel" of positive charge such that the entire atom is neutral.

- Thomson: electrons are contained in an atom like "plums in a pudding".

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scientific multimedia

positively charged "paste"

localized electron (negative charge)
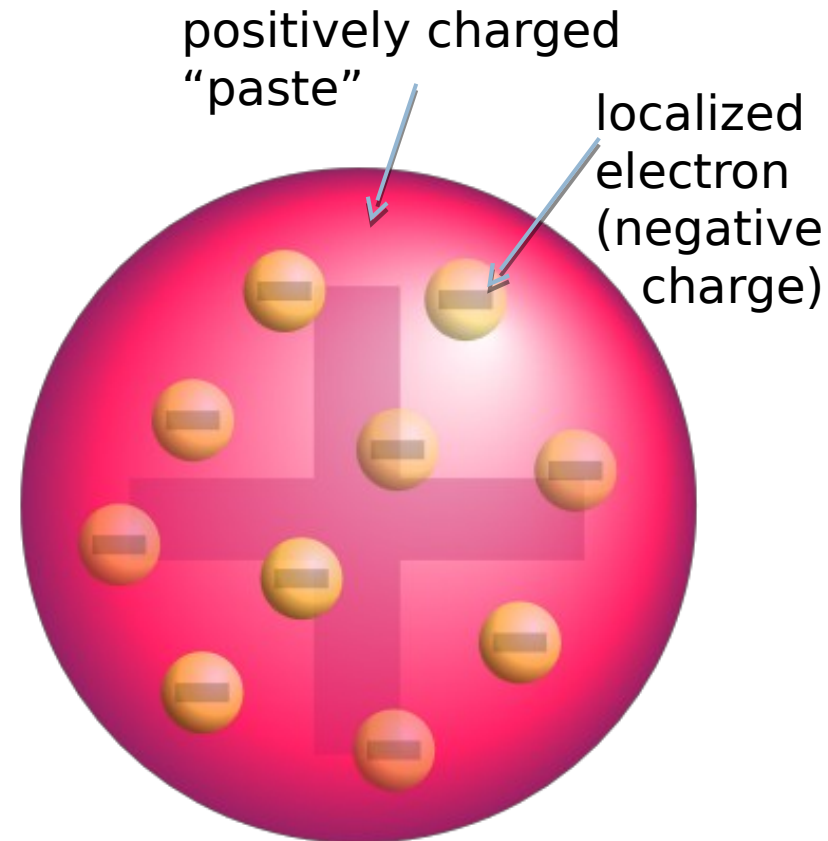
Thomson's plum-pudding model of the atom

Image: greenanswers.com

DIY (if you have an old TV...)

- The physics behind J. J. Thompson experiment is the same as in a CRT TV.

Source: http://www2.physics.ox.ac.uk/accelerate/resources/demonstrations/cathode-ray-tube

1911: Discovery of the atomic nucleus

The Rutherford Experiment

E. Rutherford
Image: NobelPrize.org
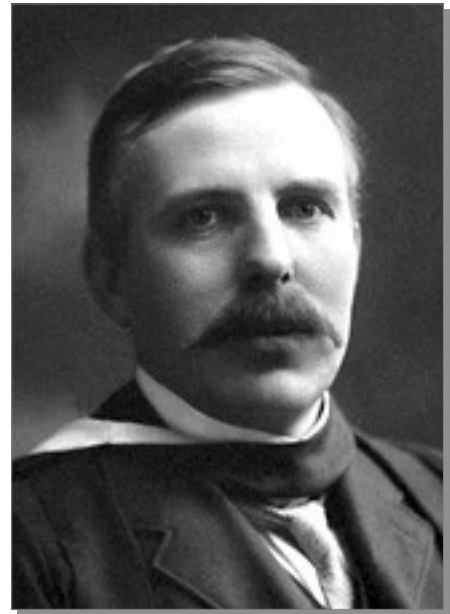
□ Test of Thompson's theory of atomic structure (1909-1913):
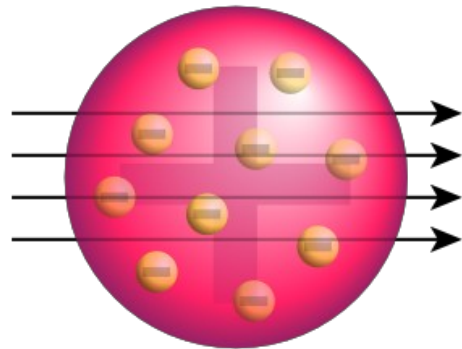
Thompson's model of atom
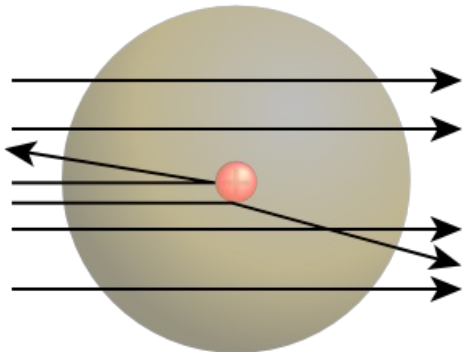
Rutherford's model of atom

Scattering two particles and measuring the deflection gives information about particle structure and interaction.

Image: Wikipedia.org

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The Rutherford Experiment

□ Gold foil experiment:

▪Most a-particles were not scattered at all, but a few were scattered through angles of 90° or more!

Lead block containing an alpha particle emitting source

Alpha particle deflected at a large angle

Beam of alpha particles

Gold foil

Zinc sulfide coated screen

Most alpha particles pass through the foil with little or no deflection

Alpha particle deflected at a small angle

$$N(\theta) \propto \sin^{-4}(\theta/2)$$

Geiger and Marsden's data points

Theoretical scattering of one point charge off another

Rutherford formula

Scattered alpha particles

10^7 10^6 10^5 10^4 10^3 10^2 10

0° 20° 40° 60° 80° 100° 120° 140°

Scattering angle

The Rutherford Experiment

□ Gold foil experiment:

Image: highered.mcgraw-hill.com

Lead block containing
an alpha particle
emitting source

Alpha particle
deflected at a
large angle

Beam of
alpha particles

Gold foil

Most alpha particles
pass through the foil
with little or no
deflection

Alpha particle
deflected at a
small angle

Zinc sulfide
coated screen
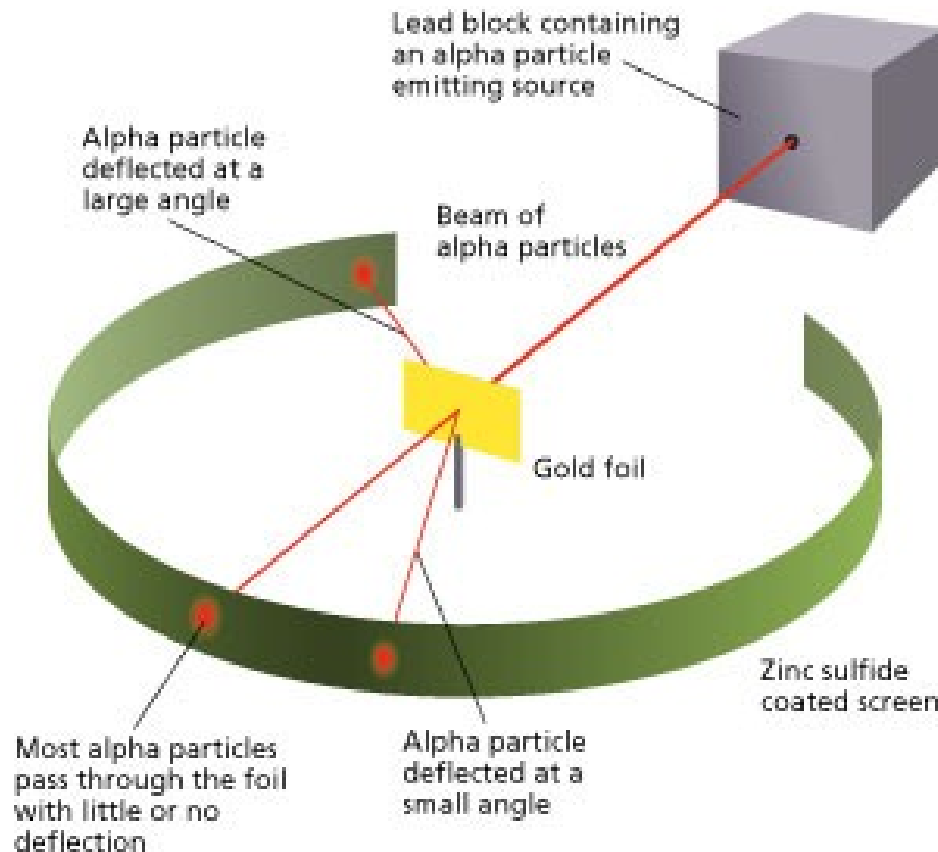
▪Most a-particles were not scattered at all, but a few were scattered through angles of 90° or more!

▪Rutherford: large-angle scattering is exactly consistent with Coulomb repulsion of **two small, dense objects**.

▪Conclusion: scattered particle beam is evidence of a dense, compact, positively-charged structure (located at the center of the atom).

# Discovery of the nucleus (1911)
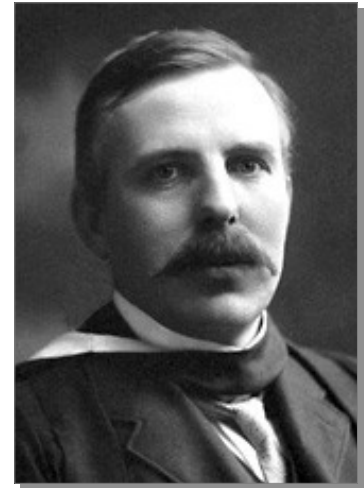
E. Rutherford
Image: NobelPrize.org

□ Rutherford's efforts formed one of the truly great experiments of modern physics.

□ He quickly understood that he discovered a new nuclear model of the atom, saying of the result:

"It was quite the most incredible event that ever happened to me in my life. It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

□ In a later experiment (1919), he identified the nucleus of the hydrogen atom as an elementary particle present in all other nuclei; he called it the proton (from Greek $\pi\rho\acute{\omega}\tau o\varsigma$ = "first").

The Bohr atom (1914)

- New atomic model:
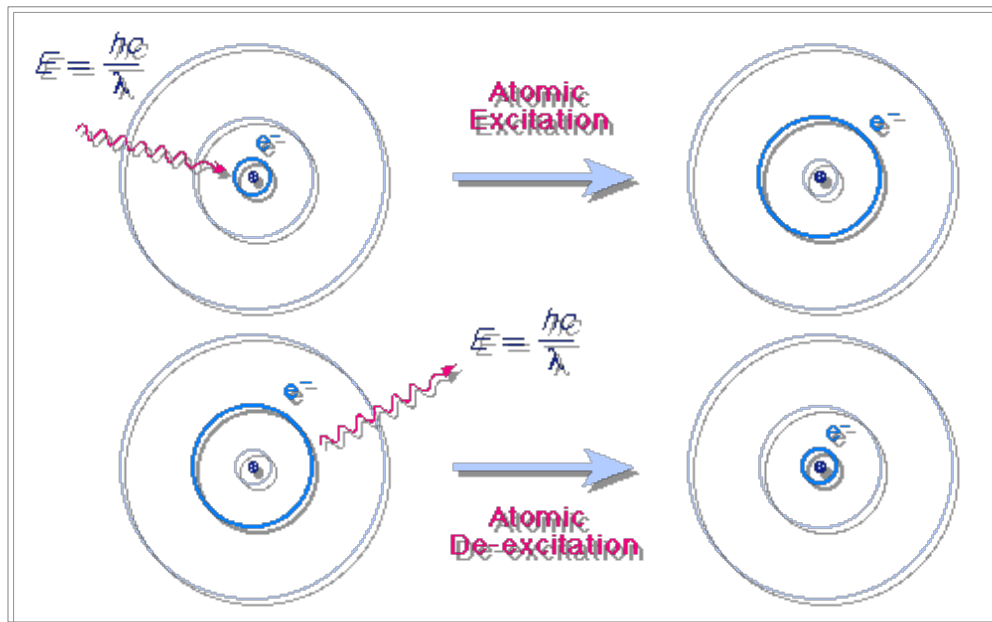 localized positive charge and electron "cloud"
- Also results from spectroscopy:
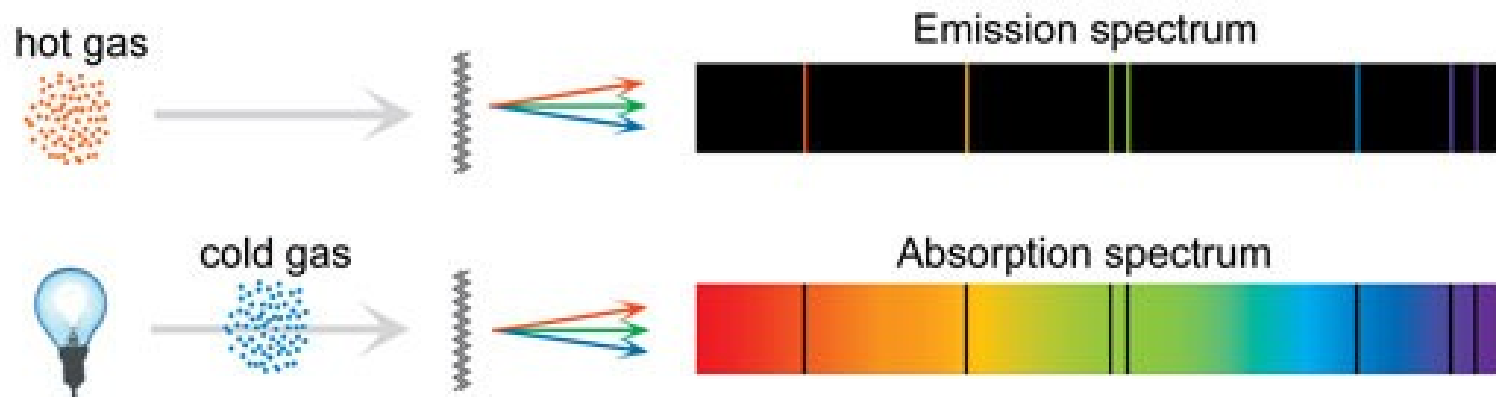
The Bohr atom (1914)

- New atomic model:
  localized positive charge and electron "cloud"
- Also results from spectroscopy:

When you excite a gas, it emits radiation in certain discrete wavelengths (spectral lines) according to Balmer's formula:

$$\frac{1}{\lambda} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

The Bohr atom (1914)

N. Bohr

- In 1914, N. Bohr developed a simple atomic model that perfectly explained the phenomenon of spectral lines.
- The three main ideas behind Bohr's semi-classical *ansatz (educated guess):*

1) The electron moves in uniform circular motion, with the centripetal force provided by its Coulomb attraction to the nucleus:

$$F_{centripetal} = m_e \frac{v^2}{r} = \frac{e^2}{r^2} = F_{Coulomb}$$

2) The angular momentum of the electron in its orbit is quantized, satisfying the constraint:
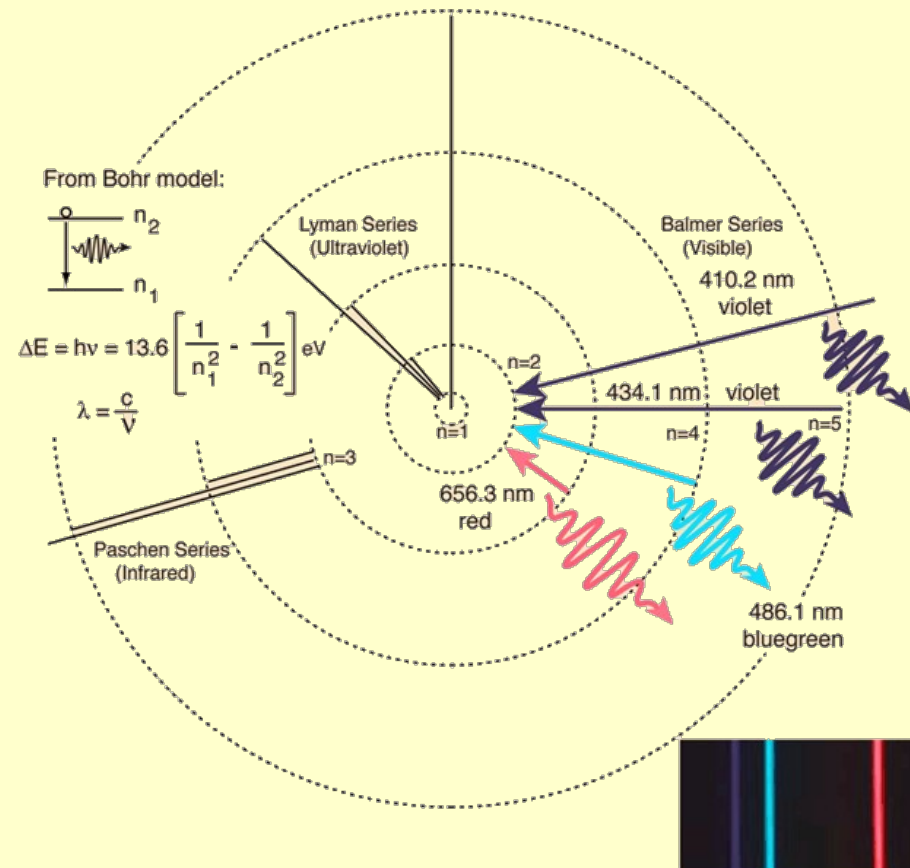
$$m_e v r = n\hbar, \quad n \text{ is an integer}$$

3) Therefore, the electron can have only a discrete spectrum of allowed energies:

$$E = \frac{1}{2} m_e v^2 - \frac{e^2}{r} = -\frac{1}{n^2} \left(\frac{m_e e^4}{2\hbar^2} \right)$$

The Bohr hydrogen model

- In the context of the Bohr model, the discrete spectra seen in atomic spectroscopy makes perfect sense.

- The electron occupies discrete orbits in the hydrogen atom.

- When hydrogen is excited in an electric field, the electron jumps into a higher energy orbit.

- Eventually, the electron will return to a lower energy state. Once this happens, light must be emitted to conserve the energy of the whole system.

Emission spectrum of the hydrogen atom.

From Bohr model:

$$\Delta E = h\nu = 13.6 \left[\frac{1}{n_1^2} - \frac{1}{n_2^2} \right] eV$$

$$\lambda = \frac{c}{\nu}$$

Lyman Series (Ultraviolet)

Balmer Series (Visible)

410.2 nm violet

434.1 nm violet

656.3 nm red

486.1 nm bluegreen

Paschen Series (Infrared)

Discovery of the neutron (1932)

J. Chadwick
Image: NobelPrize.org

□ In the Bohr atomic model, atoms consisted of just protons and electrons.

□ However, there was a major problem: most elements were heavier than they should have been.
(He charge is +2e, but weighs $4m_p$;
Li charge +3e, but weighs $7m_p$; etc.)

□ To account for the missing mass in heavier elements, nuclei had to contain other particles comparable in mass to the proton (1 GeV/c^2) but with no electric charge.

□ The mysterious massive, neutral particle inside atomic nuclei eluded detection until 1932, when J. Chadwick observed the neutron in an α-Be scattering experiment.

End of an Era (1897-1932)

- 1927: **New Wrinkle…
  Antimatter**

- P. Dirac attempted to combine quantum mechanics with the relativistic energy formula:

$$E^2 - (pc)^2 = (mc^2)^2$$

- PROBLEM: the theory allows both positive and negative energy solutions!

$$E_+ = +\sqrt{p^2 c^2 + m^2 c^4}$$
$$E_- = -\sqrt{p^2 c^2 + m^2 c^4}$$

- Dirac's interpretation: the positive solutions are ordinary particles; the negative solutions are anti-matter.

- But was anti-matter real, or just a mathematical artifact?

P. Dirac
Image: NobelPrize.org

Discovery of antimatter (1932)

- In 1932, C. Anderson observed the anti-electron (positron), validating Dirac's theory.

- Feynman's explanation of negative energies: they are the positive energy states of anti-particles!

- Anti-matter is a universal feature of quantum field theory; all particles have matching anti-particles.

- Anti-particles have the same mass as their particle partners, but opposite quantum numbers (charge, lepton number, etc.)

X B

FIG. 1. A 63 million volt positron ($H\rho=2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho=7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Discovery of the positron in a cloud chamber
by C. Anderson
Phys. Rev. 43, 491 – Published 15 March 1933

Notation: Particle: e^-, p
Antiparticle: e^+, $\bar{p}$

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Meanwhile… (1900-1924)

- A new particle, the **field quantum**

- The discovery of the **photon**, the *quantum* of the electromagnetic field, marked a major departure from classical physics.

- As with the developing picture of the atom, it took several decades (and several incontrovertible experiments) before physicists accepted the existence of the photon.

- But before we get into that, let's talk about what classical physics actually had to say about electromagnetism.

Classical electrodynamics

- Work by J.C. Maxwell in the mid/late 1800s: the EM field could be understood in terms of four equations:

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$
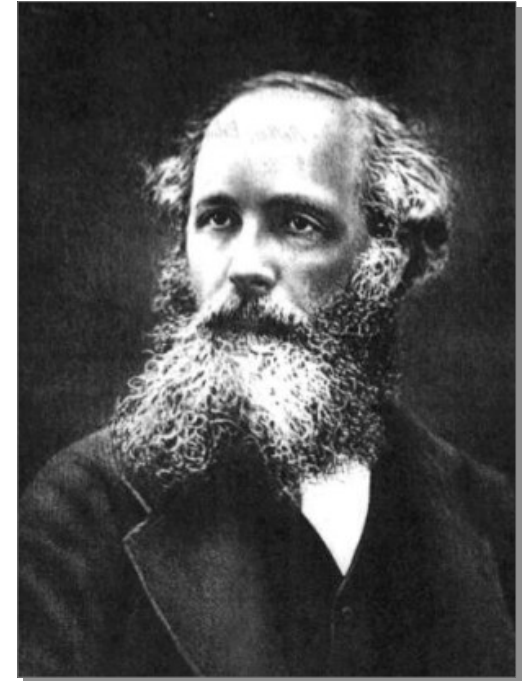
J.C. Maxwell
The University of York

- These are Maxwell's equations in the vacuum, relating the electric and magnetic field.

Classical Electrodynamics

- Gauss's law: the electric flux leaving a volume is proportional to the charge inside.
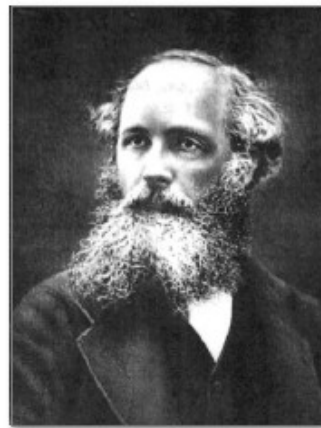- Gauss's law for magnetism: there are no magnetic monopoles; the total magnetic flux through a closed surface is zero.
- Faraday's law of induction: the voltage induced in a closed circuit is proportional to the rate of change of the magnetic flux it encloses.
- Ampere's circuital law: the magnetic field induced around a closed loop is proportional to the electric current plus displacement current.

And it came to pass that...

$$\oint \mathbf{E} \cdot d\mathbf{A} = q/\epsilon_0$$

Gauss' law for electricity

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

Gauss' law for magnetism

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

Faraday's law

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i$$

Ampere-Maxwell law

and there was $\mathcal{L}ight!$

©2006 Instant Attitudes

Classical electrodynamics

- Maxwell's equations predict self-propagating, transverse electric & magnetic (electromagnetic) waves, aka light, which travel at speed $c=3\times10^8$m/s and have frequency $f=c/\lambda$

Electromagnetic waves transport energy through empty space, stored in the propagating electric and magnetic fields.

λ

Electric field variation

Magnetic field variation is perpendicular to electric field.

Magnetic field variation

A single-frequency electromagnetic wave exhibits a sinusoidal variation of electric and magnetic fields in space.

33
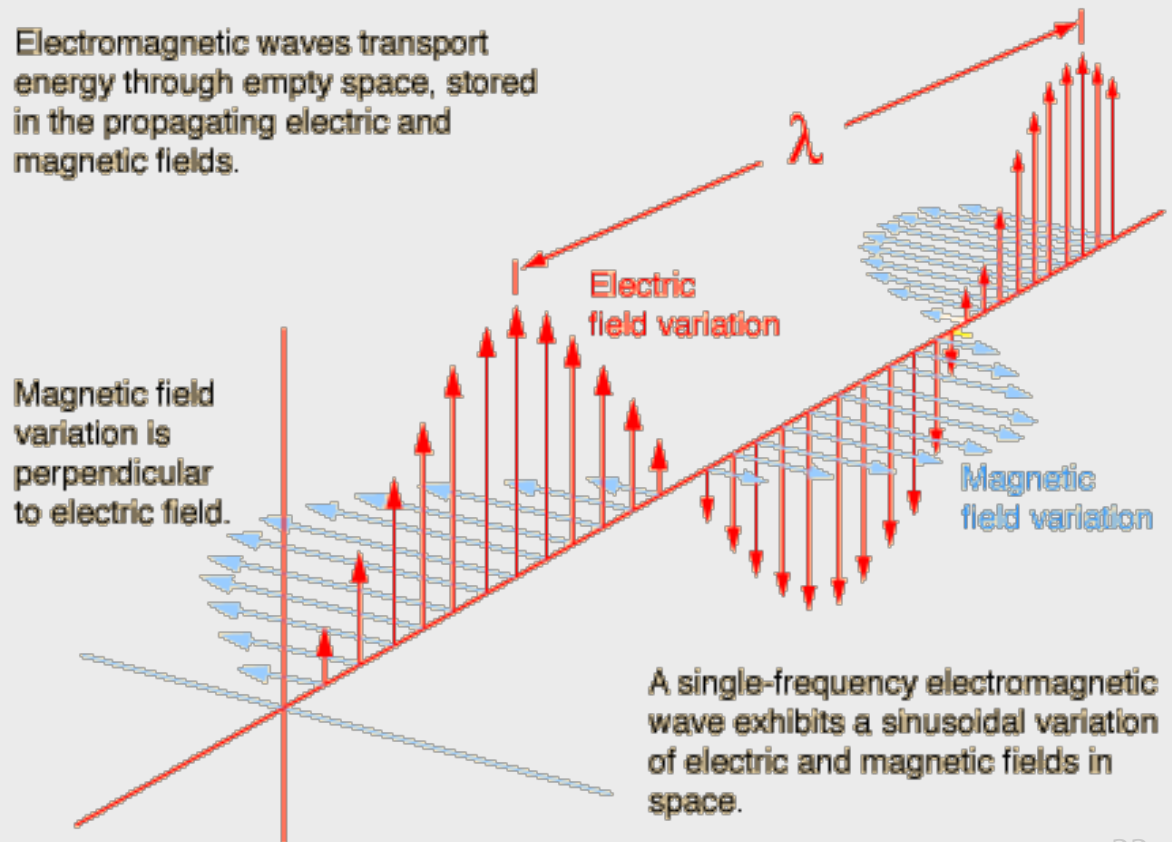
Classical electrodynamics

- A beautiful theory…
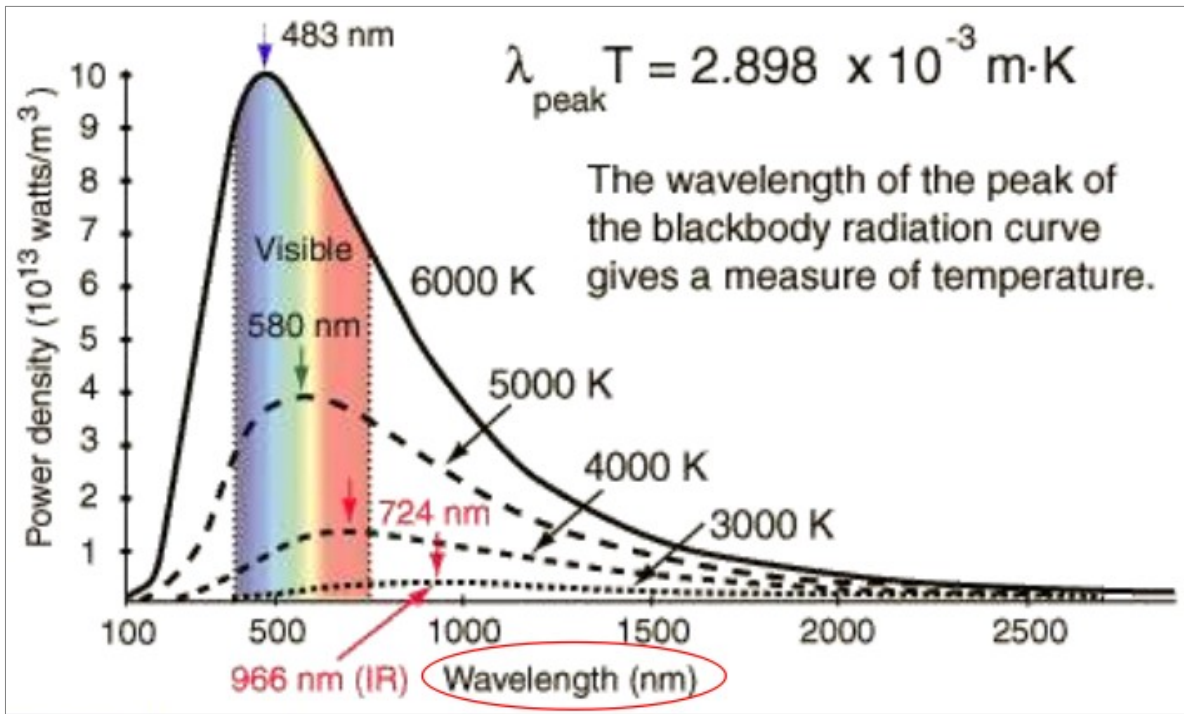
  The implications of the Maxwell Equations – namely, the appearance of electromagnetic fields to observers in different inertial reference frames – inspired scientists (Poincaré, Einstein) to develop special relativity.

- But, when trying to explain thermal radiation (light emitted by hot objects), the theory completely fails!

Failure of classical electrodynamics

The wavelength of the peak of the blackbody radiation curve gives a measure of temperature.

$$\lambda_{peak} T = 2.898 \times 10^{-3} \, \text{m·K}$$

- When light is emitted by hot objects, the intensity of the light always varies continuously with the wavelength –unlike atomic spectra –and the spectrum has a characteristic shape. Examples of blackbodies: stars, light filaments, toaster coils, the universe itself!

- This so-called blackbody spectrum (or Planck spectrum) always peaks at a wavelength that depends on the surface temperature of the object.
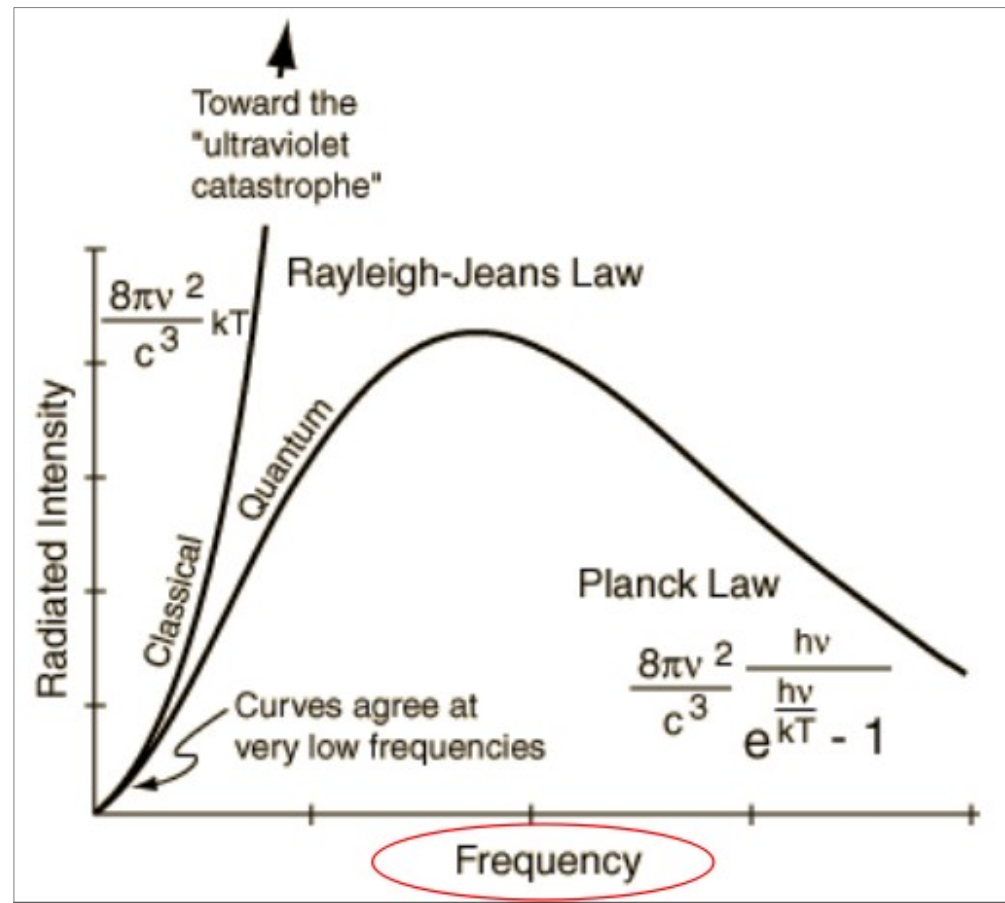
Failure of classical electrodynamics

□ "Ultraviolet catastrophe"

- A study of blackbody radiation with classical E&M and statistical mechanics (the Rayleigh-Jeans Law) predicts that the emitted intensity varies with frequency and temperature as:

$$I_{\nu}(T) \propto \frac{k_B T}{c^3} \nu^2$$

- This means that as the light frequency increases into the UV, the intensity becomes infinite!
- This nonsensical answer was such an embarrassment for the theory that physicists called it the "ultraviolet catastrophe".

Toward the "ultraviolet catastrophe"

$\frac{8\pi \nu^2}{c^3} kT$ Rayleigh-Jeans Law

Quantum

Classical

Radiated Intensity

Planck Law

$\frac{8\pi \nu^2}{c^3} \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$

Curves agree at very low frequencies

Frequency

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Planck's solution: light quanta

- In 1900, using arguments from statistical mechanics (the theory of bodies in thermal equilibrium), M. Planck derived a theoretical curve that fit the blackbody spectrum perfectly*:

$$I_\nu(T) \propto \frac{h}{c^3} \frac{\nu^3}{e^{h\nu/k_B T} - 1}$$

- *However, to get this result, Planck had to assume that thermal radiation is quantized; that is, it's emitted in little "packets" of energy, photons, proportional to the frequency ν:*

$$E = h\nu$$

- *The quantity h, called Planck's constant, was determined from the fit to the blackbody spectrum. It turned out to be a fundamental constant of nature, and has the value:*

$$h = 4.1357 \times 10^{-15} \text{ eV} \cdot \text{s}$$

Are photons real?

□ In order to explain blackbody emission spectra, Planck needed to assume that thermal radiation is emitted in bundles whose energy comes in integral multiples of $h\nu$.

□ This suggested that light could actually be quantized (it's a particle). But most of the experimental evidence (and Maxwell's Equations) at the time said that light is a wave.

M. Planck
NobelPrize.org

□ So **is light a particle, or a wave?** BOTH! As it turns out, light can behave like a particle if you are performing the right kind of experiment!

□ At first, Planck did not really believe in the light quantum, and most physicists did not accept its existence until faced with undeniable evidence from two phenomena:
1) The photoelectric effect
2) Compton scattering
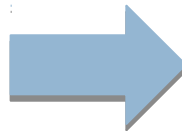
Evidence for particle nature of light

Photoelectric effect (1905)
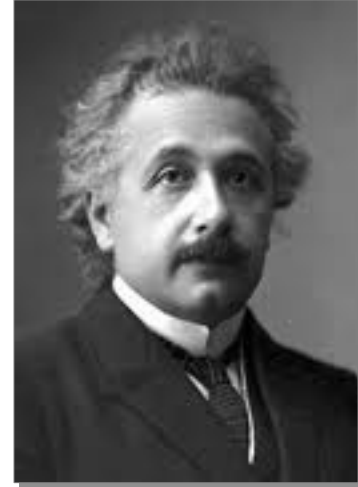
A. Einstein
NobelPrize.org

- In the 1800's, it was discovered that shining light onto certain metals liberated electrons from the surface.
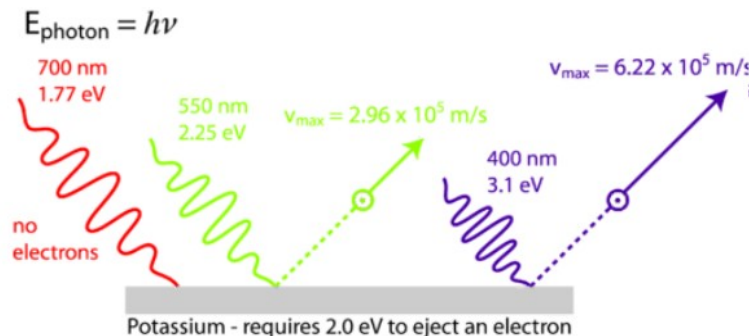
  Experiments on this photoelectric effect showed odd results:
  1) Increasing the intensity of the light increased the number of electrons, but not the maximum kinetic energy of the electrons.
  2) Red light did not liberate electrons, no matter how intense it was!
  3) Weak violet light liberated few electrons, but their maximum kinetic energy was greater than that for more intense long-wavelength beams!

- In 1905, A. Einstein showed that these results made perfect sense in the context of quantization of the EM field, where photon energy is proportional to frequency. If photons of energy E=hν strike electrons in the surface of the metal, the freed electrons have a kinetic energy:

$$K = h\nu - \phi$$

- The work function ϕ is a constant that depends on the metal.

$E_{photon} = h\nu$

700 nm
1.77 eV

550 nm
2.25 eV $v_{max} = 2.96 \times 10^5$ m/s

$v_{max} = 6.22 \times 10^5$ m/s

400 nm
3.1 eV

no electrons

Potassium - requires 2.0 eV to eject an electron

Compton scattering (1923)

Compton scattering

Recoil electron

$p_e = \dfrac{\sqrt{E^2 - (m_e c^2)^2}}{c}$

Incident photon λ_i

Target electron at rest

ϕ

θ

$p_i = \dfrac{E_i}{c} = \dfrac{h\upsilon_i}{c} = \dfrac{h}{\lambda_i}$

$p_f = \dfrac{E_f}{c} = \dfrac{h\upsilon_f}{c} = \dfrac{h}{\lambda_f}$

Scattered photon

λ_f

$\lambda_f - \lambda_i = \Delta\lambda = \dfrac{h}{m_0 c}(1 - \cos\theta)$
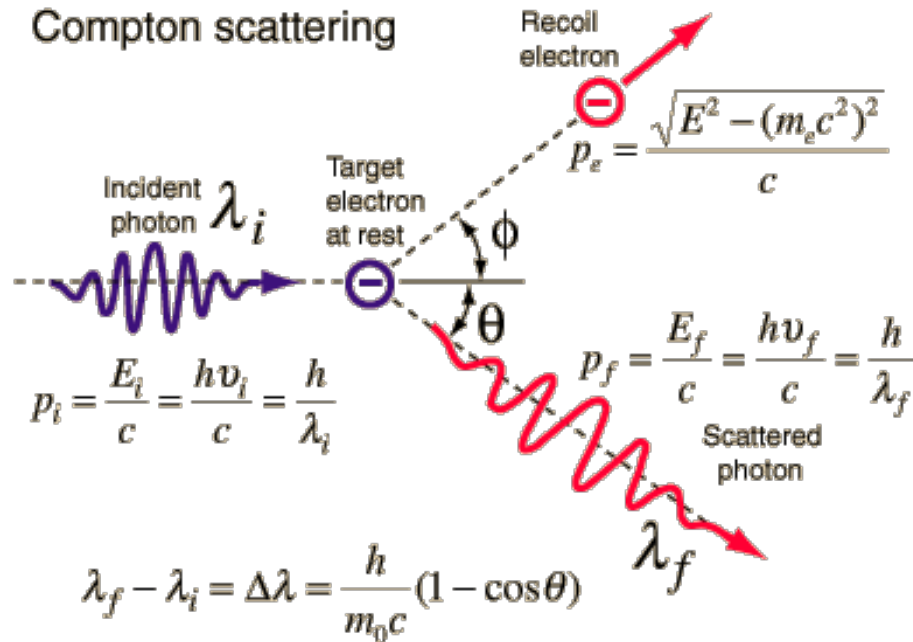
A. H. Compton
NobelPrize.org

- In 1923, A.H. Compton found that light scattered from a particle at rest is shifted in wavelength.

- There is *no way* to derive this formula if you assume light is a wave, but if you treat the incoming light beam like a particle with energy E=hν, Compton's formula drops right out!

- Hence, the Compton Effect proved to be the decisive evidence in favor of the quantization of the EM field into photons.

When is field quantization important (observable)?

- Even on the atomic scale, quantization of the EM field is a tiny effect

- In a bound state (like H = proton + electron), huge numbers of photons are streaming back and forth, effectively "smoothing out" the EM field in the atom.

- Only in elementary particle processes involving single photons (Compton scattering, photoelectric effect) does field quantization become important.

On to the particle zoo (1932-1960)

Field quantization in nuclear physics

□ Field quantization, once accepted for the electromagnetic field, was quickly applied to other calculations.

□ One was the physics of the atomic nucleus, which gets very complicated after hydrogen.

- QUESTION: How are protons in heavy atoms bound inside the 1 fm "box" of the nucleus?

- Shouldn't the electrostatic repulsion of the protons blow the nucleus apart?
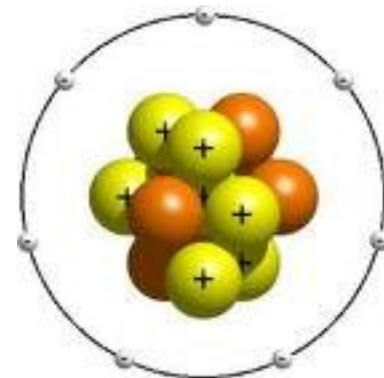
Nuclear force model (1934)

- Evidently, some force is holding the nucleus together: the "strong force."
- Inside the nucleus, the strong force has to overwhelm the EM force, but outside, on the atomic scale, it should have almost no effect.
- How to accomplish this? Assume the strong force has a very short range, falling off rapidly to zero for distances greater than 1 fm.
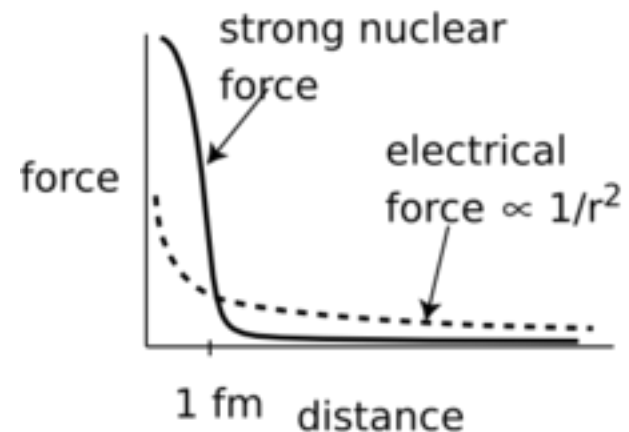- H. Yukawa: force may vary as:

H. Yukawa
Image: NobelPrize.org

$$F_{\text{strong}} \propto -\frac{1}{r^2} e^{-r/a}$$

where a ~ 1 fm is the range.

44

Quantization of the nuclear field

□ Yukawa's Model: the proton and neutron are attracted to each other by some sort of field, just like the electron is attracted to the proton by the electromagnetic field.

□ The nuclear field should be quantized; that is, it is mediated by an exchanged quantum, as the electromagnetic field is mediated by the photon. So, there should exist a new, detectable particle!

□ An interesting issue: because the range of the nuclear field is so small, the exchanged quantum of the strong force must be massive (this is due to the Uncertainty Principle –next slide and later…).

□ Yukawa calculated the mass of the strong mediator, and found it to be about $300m_e$, or $m_p/6$.

□ Because its mass fell between that of the proton and electron, he called it a *meson* (Greek = "middle-weight"), distinguished from the electron (*lepton* = "light-weight") and the neutron and proton (*baryon* = "heavy-weight").

Estimate of Yukawa meson mass

□ When two protons in a nucleus exchange a meson (mass m), they temporarily violate energy conservation.

□ The Heisenberg Uncertainty Principle says this is OK, as long as the amount of energy borrowed (ΔE) is "paid back" in a time (Δt) such that: $\Delta E \, \Delta t \geq \hbar / 2$; with $\hbar = h / 2\pi$

□ In this case, we need to "borrow" an energy $\Delta E = mc^2$ long enough for the meson to make it across the nucleus from one proton to another.

□ Since the meson will probably travel at some substantial fraction of the speed of light, the time it takes to cross the nucleus is roughly: $\Delta t = r_0 / c, \quad r_0 \approx 1 \text{ fm}$

□ So, the meson mass is around: $m \geq \hbar / (2 \, r_0 \, c) \approx 100 \text{ MeV}/c^2$

Discovery of Yukawa's meson?

- In 1937, two groups studying cosmic ray air showers found particles of approximately the mass predicted by Yukawa.
- Did this confirm Yukawa's theory of strong interactions?
- Not exactly… it turned out that the particles observed by cosmic ray physicists had the wrong lifetimes (much too long: ~ 2 μs) and masses (a little too light: ~ 100 MeV/c^2).
- By 1947, physicists realized that the cosmic ray particles were not the expected nuclear meson, but rather a completely unexpected elementary particle: the μ ("muon").
- Theorists were not happy. Rabi: "Who ordered that?"
- About the same time, other short-lived particles known as pions (π) were also discovered.

Particle spectrum extends…

- Proton, electron, neutron
- Photon
- Muon
- Pions
- + antiparticles

+Neutrinos…

$$n \rightarrow p + e^- + \,?$$

W. Pauli
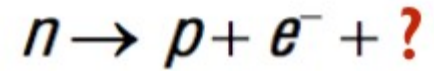
☐ Postulated to save conservation of energy!
- In the study of radioactive decays (esp. β-decay), physicists found that many reactions appeared to violate energy conservation.
- Option 1 (Bohr): nuclear decays do actually violate energy conservation.
- Option 2 (W. Pauli): the missing energy is carried off by another neutral particle which hadn't been detected (as of 1930).
- In 1932, E. Fermi incorporated Pauli's idea into his theory of nuclear decays. He called the missing particles *neutrinos* ("little neutral ones").
- Major assumption: neutrinos almost never interact with ordinary matter, except in decays.

E. Fermi

Discovery of neutrinos (1950s)

- By introducing neutrinos (symbol ν) to radioactive decay, conservation of energy was restored. Decay reactions started to look like this:

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

$$\pi \rightarrow \mu + \nu$$

$$\mu \rightarrow e + 2\nu$$

- By 1950, there was compelling theoretical evidence for neutrinos, but no neutrino had ever been experimentally isolated.
- Finally, in the mid-1950s, C. Cowan and F. Reines came up with a method to directly detect neutrinos using "inverse" β-decay:

$$\bar{\nu} + p \rightarrow n + e^+$$

- **A difficult experiment:** Cowan and Reines set up a large water tank outside a commercial nuclear reactor, expecting to see evidence of the above reaction only 2 to 3 times per hour (which they did). Conclusion: (anti) neutrinos (ν's) exist.   =
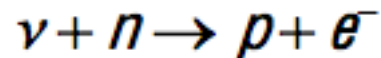

C. Cowan and F. Reines

Image: CUA

Antineutrinos?

- Because all particles have anti-particles, physicists assumed that neutrinos must have corresponding **anti-neutrinos**.
- But does anything distinguish a neutrino from an anti-neutrino?
- From the results of Cowan and Reines, the reaction below must occur:

$$\nu + n \rightarrow p + e^-$$

- If anti-neutrinos are the same as neutrinos, the anti-neutrino version of this reaction must also occur:

$$\bar{\nu} + n \rightarrow p + e^-$$
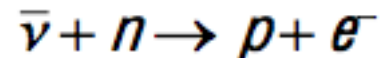
- In fact, in the late1950s, R. Davis and D.S. Harmer found that the **anti-neutrino reaction does not occur**. Therefore, something is different about the anti-neutrino that forbids the process. But what?

A new conservation law

- A rule of thumb (R. Feynman): a reaction will be observed unless it is expressly forbidden by a conservation law.

- So what conservation law does the anti-neutrino reaction violate? Conservation of energy and electric charge are obeyed, so it must be something else.

- In 1953, E.J. Konopinski and H.M. Mahmoud proposed the existence of **a new quantum number** that explained why certain reactions worked while others did not.

- They assigned a **lepton number** L = +1 to the electron, muon, and neutrino, and L = -1 to the positron, antimuon, and antineutrino. All other particles got L = 0. In any reaction, this lepton number had to be conserved!

Lepton number conservation

- To apply conservation of lepton number, just add up the lepton numbers on each side of the reaction and see if they agree.
- The neutrino reaction occurs because:

$$\nu + n \rightarrow p + e^-$$

$$L : 1 + 0 = 0 + 1$$

- The antineutrino reaction doesn't occur because:

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

$$L : -1 + 0 \neq 0 + 1$$

- In view of lepton number conservation, the charged pion and muon decays should actually be written:

$$\pi^+ \rightarrow \mu^+ + \nu \qquad \mu^+ \rightarrow e^+ + \nu + \bar{\nu}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu} \qquad \mu^- \rightarrow e^- + \nu + \bar{\nu}$$

Lepton FLAVOR number conservation

□ Experimentally, the following reaction (though it obeys energy, charge, and lepton number conservation) never occurs:

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

□ Why? Apparently, the absence of this reaction suggests a law of conservation of "mu-ness," but that alone wouldn't explain why muons can decay like this:

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

□ Conclusion: something about the ν's in the second reaction makes it occur.

□ The Answer: there are two kinds of neutrinos: one associated with the electron ($\bar{\nu}_e$) and one with the muon (ν_μ).

□ Therefore, we now have an electron number L_e and a muon number L_μ to account for all forbidden and allowed processes. Lepton conservation becomes electron number and muon number conservation.

Decays and lepton flavor conservation

□ In the context of L_e and L_μ conservation, we can now account for all forbidden and allowed decays…

$$n \rightarrow p + e^- + \bar{\nu}_e \qquad L_e : 0 = 0 + 1 - 1$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad L_\mu : 0 = -1 + 1$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad L_\mu : 0 = +1 - 1$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \begin{array}{l} L_e : 0 = -1 + 1 + 0 \\ L_\mu : -1 = 0 + 0 - 1 \end{array}$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \qquad \begin{array}{l} L_e : 0 = +1 - 1 + 0 \\ L_\mu : +1 = 0 + 0 + 1 \end{array}$$

□ Note how all of the decays conserve charge and energy as well as lepton flavor.

Particle spectrum extends...

- Proton, electron, neutron
- Photon
- Muon
- Pions
- + antiparticles
- + neutrinos
- + strange particles

Discovery of strange particles (1947)

- By 1947, the catalog of elementary particles consisted of the p, n, π, μ, e, and the ν (and the anti-particles). The overall scheme seemed pretty simple.

- However, at the end of that year, a new neutral particle was discovered: the K^0 ("*kaon*"):
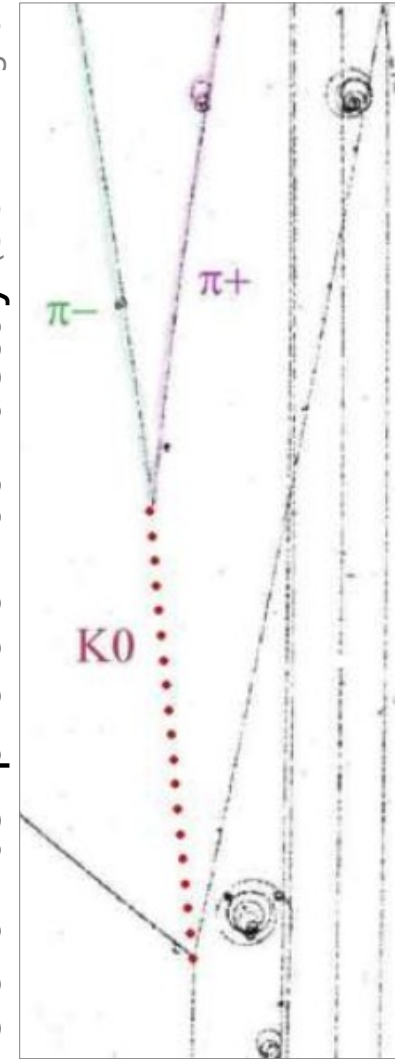
$$K^0 \rightarrow \pi^+ + \pi^-$$

- In 1949, a charged kaon was found:

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

- The K's behaved somewhat like heavy π's, so they were classified as mesons ("mass roughly between the proton and electron mass").

- Over the next two decades, many more mesons were discovered: the η, the φ, the ω, the ρ's, etc.

Bubble chamber photo of kaon decay (U of Birmingham)

More strange particles (1950)

- In 1950, C. Anderson observed another particle that looked like the K, but decayed via the reaction:

$$\Lambda \rightarrow p + \pi^-$$

- The Λ is heavier than the proton, making it a baryon like the p and n.
- Over the next decade, as particle accelerators started to increase in energy, many more (increasingly heavy) baryons were discovered: the Σ's, the Ξ's, the Δ's, etc.
- Struggling to fit new particles into existing theories, physicists viewed the growing groups of mesons and baryons with increasing dismay:

  When Nobel prizes were first awarded in 1901, physicists knew something of just two objects which are now called "elementary particles": the electron and the proton…. I have heard it said that "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine."
  -W. Lamb, Nobel Prize Acceptance Speech, 1955

A new conservation law

□ QUESTION: Experiments in the 1950s showed that there were many unstable baryons, but the proton was not one of them. Why didn't the proton decay?

$$p \rightarrow e^+ + \gamma$$

□ In 1938, Stückelberg proposed an explanation of the proton's stability. The method is familiar: he introduced a new quantum number, and assumed that it was conserved in all interactions.

□ The new quantum number, often written A, is called the baryon number. The baryons get A=+1, and the antibaryons get A=-1; all other particles get A=0.

□ Baryon number conservation explains why β-decay works, and p-decay does not:

$$n \rightarrow p + e^- + \bar{\nu}_e, \qquad A: 1 = 1 + 0 + 0$$
$$p \rightarrow e^+ + \gamma, \qquad A: 1 = 0 + 0$$

□ NOTE: no known reaction seems to conserve meson number, so we don't have to worry about conservation of mesons.

Yet another quantum number (S)

- "Strange" Behavior: The new mesons and baryons discovered during the 1950s all had the following properties:
  1) They are produced on short timescales (10^{-23}s)
  2) But they decay relatively slowly (10^{-10}s)

- This suggests the force causing their production (strong force) differs from the force causing their decay (weak force).

- In 1953, M. Gell-Mann and K. Nishijima introduced a new quantum number, strangeness (S), to explain this behavior.

- According to this scheme, strangeness is conserved in strong interactions, but not conserved (violated) in weak decays.

- IMPORTANT POINT: In addition, particles with non-zero S are always produced in pairs –no interaction produces just one strange particle.

Conservation of strangeness

□ A p-π collision may produce the following products; here S is conserved:

$$\pi^- + p \rightarrow \begin{cases} K^+ + \Sigma^- \\ K^0 + \Sigma^0 \\ K^0 + \Lambda \end{cases}$$
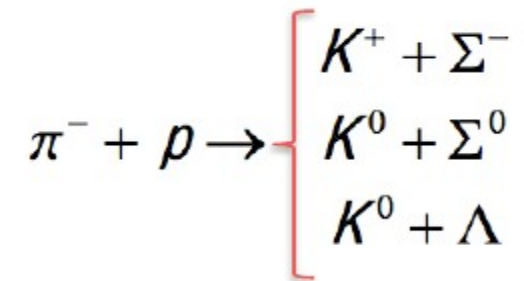
□ The K's have S=+1, the Σ's and Λ have S=-1, and the π, p, and n have S=0.

□ When these particles decay, S is not conserved: $\Lambda \rightarrow p + \pi^-$

$$\Sigma^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$
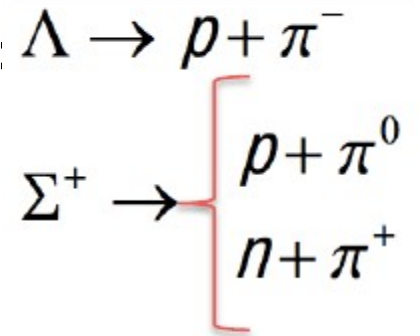
□ Strong processes conserve S; weak processes do not!

Summary of particle zoo (1960)

- Leptons: e, μ, ν_e, ν_μ. Lightest particles. Lepton flavor number is conserved in all interactions.

- Mesons: $\pi, \eta, \phi, \omega, \rho$, … Middle-weight particles. There is no conserved "meson number".

- Baryons: p, n, Σ, Ξ, Λ, … Heaviest particles. Baryon number A is always conserved. Strangeness S is conserved sometimes (strong interactions) but not always (weak decays).

- The point: things seemed like **a real mess!** No one knew how to predict particle properties. New conservation laws were invented to explain reactions.

Quark Era (1960-1978)

The Eightfold Way

M. Gell-Mann
Image: NobelPrize.org

☐ Finally, in 1961, Gell-Mann brought some order to the chaos by developing a systematic ordering of the elementary particles.

☐ He noticed that if he plotted the mesons and baryons on a grid of strangeness S vs. charge Q, geometrical patterns emerged.
The lightest mesons and baryons fit into hexagonal arrays:

Baryon Octet

Meson Nonet

Images: physics.fsu.edu

The Eightfold Way
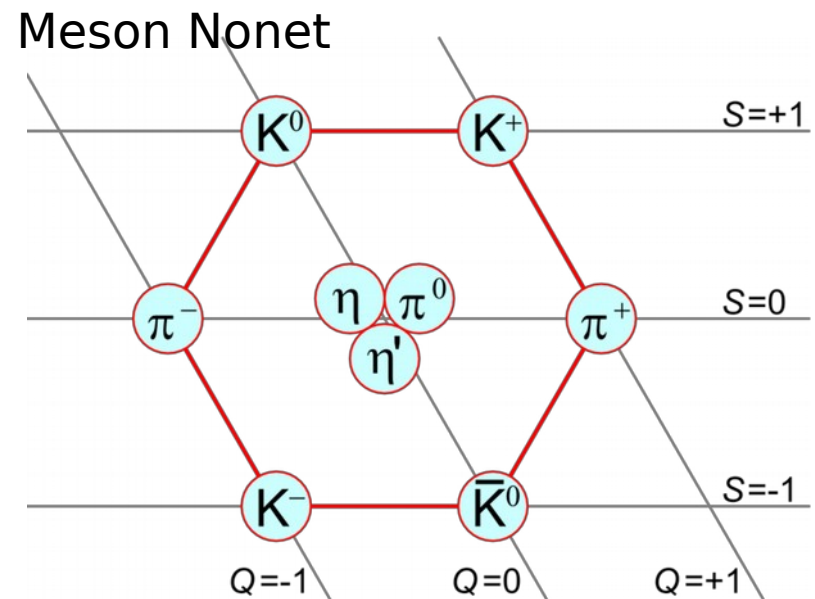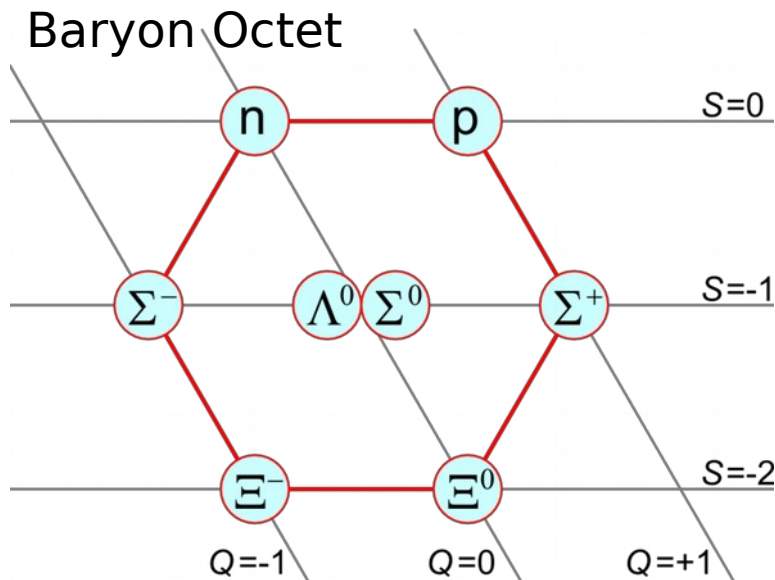
M. Gell-Mann
Image: NobelPrize.org
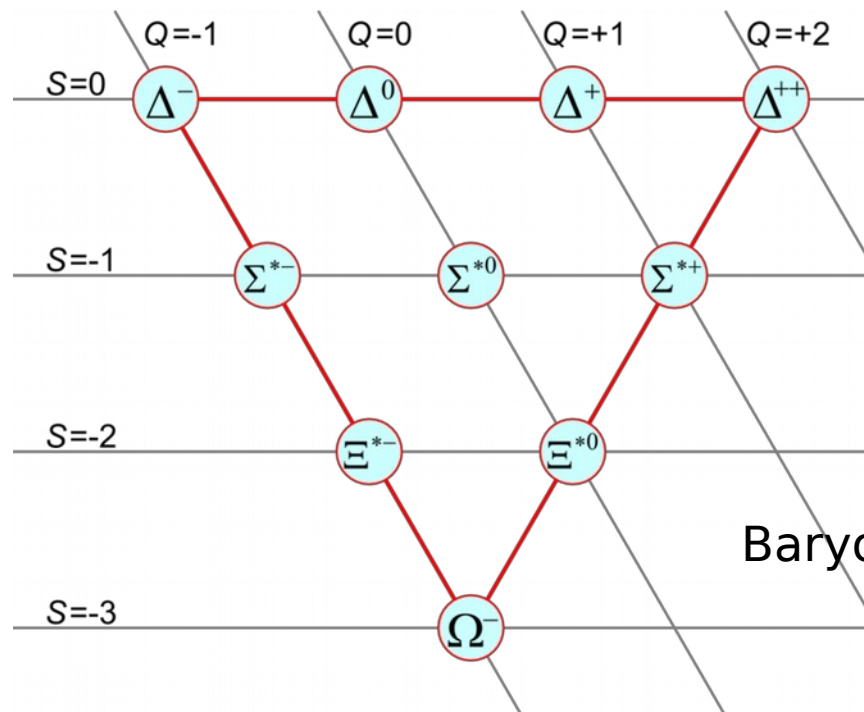
- ☐ Gell-Mann called his organizational scheme the "Eightfold Way".

- ☐ Note that other figures were allowed in this system, like a triangular array incorporating 10 of the heavier baryons.

Baryon Decuplet

Prediction of new baryons (1964)

- Like the Periodic Table of the elements, the Eightfold Way yields simple relations between the hadrons.

- Gell-Mann/Okubo mass formula: relates masses of the members of the baryon octet:

$$2\left(m_{p/n} + m_{\Xi}\right) = 3m_{\Lambda} + m_{\Sigma}$$

- Similarly, a mass formula for the baryon decuplet:

$$M_{\Delta} - M_{\Sigma^*} = M_{\Sigma^*} - M_{\Xi^*} = M_{\Xi^*} - M_{\Omega}$$

- **KEY POINT: In 1963, the Ω^- was not yet observed. Gell-Mann used the Eightfold Way to predict its mass, charge, and strangeness.**
In 1964, the Ω^- was found, and had exactly the properties predicted!
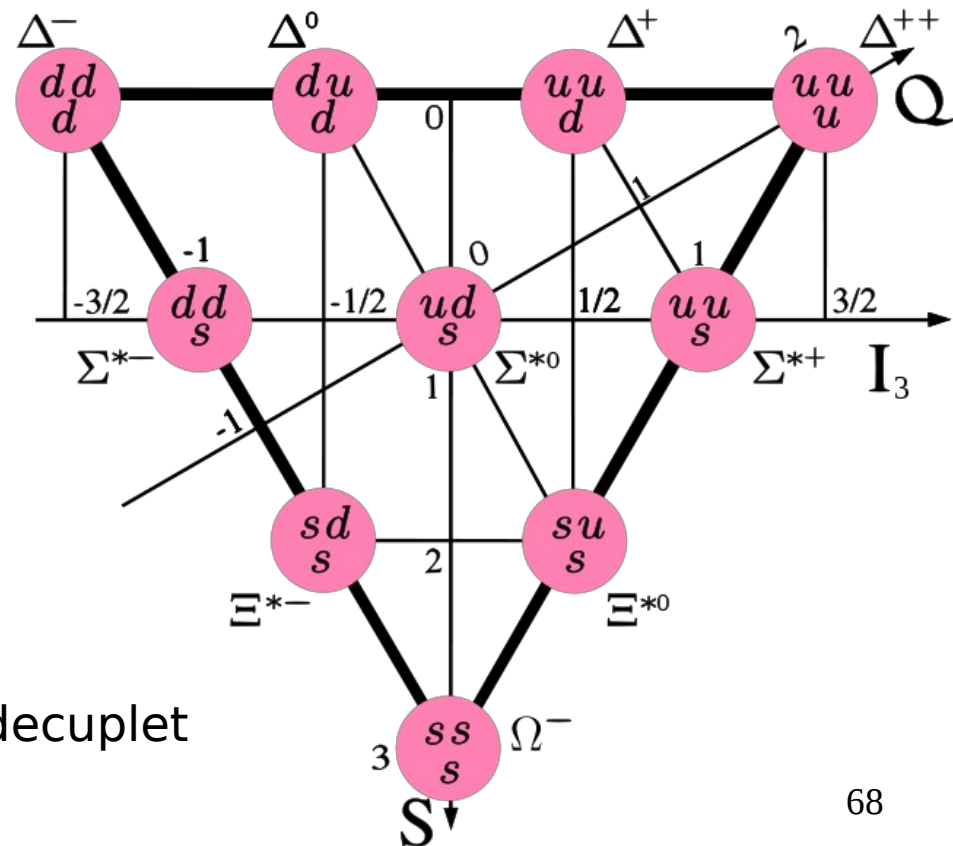
The quark model (1964)

- The patterns of the Eightfold Way evoke the periodicities of the Table of the Elements.

- In 1964, Gell-Mann and G. Zweig proposed an explanation for the structure in the hadron multiplets: all hadrons are composed of even more fundamental constituents, called *quarks.*

- *According to their quark scheme, quarks came in three types, or "flavors":*
  up (u), down (d), and strange (s).

- *To get the right hadronic properties, Gell-Mann gave his quarks fractional electric charge:*

Quark Flavor	Charge (Q)	Strangeness (S)
Up: u	2/3	0
Down: d	-1/3	0
Strange: s	-1/3	-1

The quark model (1964)

- The quark model has the following conditions:
  1) Baryons are composed of three quarks; antibaryons are composed of three antiquarks.
  2) Mesons are composed of quark-antiquark pairs.

- Using these rules, the hadronic multiplets are easily constructed...

Baryon decuplet

The quark model (1964)

- NOTE: quarks have never actually been directly observed! There is no such thing as a free quark (more on this later…). However, scattering experiments show evidence of hadrons having a substructure (analogous to Rutherford scattering of atoms).

The quark model (1964)

- Until the mid-1970s, most physicists did not accept quarks as real particles.
- Then, in 1974, two experimental groups discovered a neutral, extremely heavy meson called the J/ψ.
- The J/ψ had a lifetime about 1000 times longer than other hadrons in its mass range.
- The J/ψ was understood to be a bound state of a new quark-antiquark pair. This new quark was called **charm** (c) (and the quark-antiquark state is sometimes called "charmonium").
- We have since discovered the <u>bottom</u> (beauty) quark, in 1977, and the <u>top</u> (truth) quark, in 1995.

The quark model: btw...

symmetry**breaking**
extra dimensions of particle physics
A joint Fermilab/SLAC publication

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VIEW CURRENT

Belle experiment makes exotic discovery

January 11, 2012 | 4:29 am

The Belle Experiment at KEK laboratory in Japan has discovered two unexpected new types of hadrons. Hadrons are composite particles made up of quarks, the smallest known components of matter.

These new particles are thought to contain at least four quarks, making them exotic hadrons — hadrons that do not fit the quark model originally developed in 1961.

The Belle experiment discovered a new type of exotic hadron. Image: KEK

The B Factory experiment at KEK previously discovered exotic hadrons containing charm quarks. With this new finding, the Belle experiment has identified the first of this type of exotic hadrons discovered to contain bottom quarks, the second-heaviest type of quarks among the six known types of quarks. The particles, termed Zb, contain both one bottom quark and one anti-bottom quark.
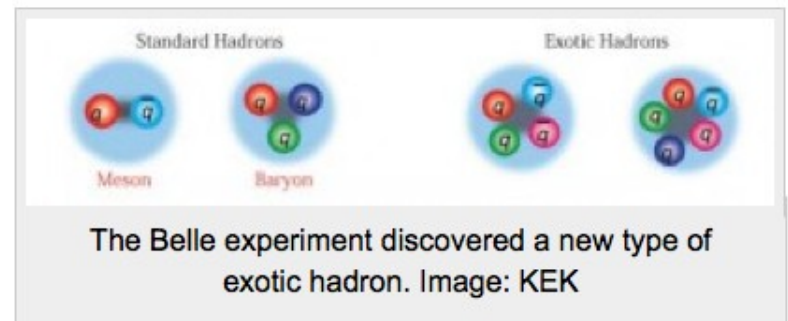
Standard Model (1978-present)

Not covered today

- 1964: Higgs mechanism proposed → 11th lecture.

- 1975: discovery of a third lepton (tau).

- Development of the theory of the strong force (Quantum ChromoDynamics).

  - 1979: observation of the effects of the mediator of the strong force (gluon).

- Development of the theory of the weak force and unification with the electromagnetism.

  - 1983: discovery of the mediators of the weak force: W^+, W^-, Z^0

  → 6th lecture.

- History of neutrino oscillations → 8th and 9th lectures.

- 2012: discovery of the Higgs boson → 11th lecture.

The Standard Model now

- The Ultimate Periodic Table?