From electrons to quarks -- 1st part: the development of Particle Physics

Outline:

● What is particle physics -- why do it?
● Early days - atoms, electron, proton
● Models of the atom - Thomson, Rutherford, Bohr
● Cosmic rays
● Detectors - scintillators, cloud chamber, emulsion, bubble chamber, spark chamber
● More particles: neutron, positron
● Muon, pion
● Kaon - “strange particles”

● Webpages of interest
  ■ http://www-d0.fnal.gov (Fermilab homepage)
  ■ http://sg1.hep.fsu.edu/~wahl/Quarknet/index.html (has links to many particle physics sites)
  ■ http://www.fnal.gov/pub/tour.html (Fermilab particle physics tour)
  ■ http://ParticleAdventure.org/ (Lawrence Berkeley Lab.)
  ■ http://www.cern.ch (CERN -- European Laboratory for Particle Physics)
What is particle physics?

- Particle physics or high energy physics
  - is looking for the *smallest constituents of matter* (the “ultimate building blocks”) and for the *fundamental forces* between them;
  - aim is to find *description in terms of the smallest number of particles and forces* (“interactions”)

- At given length scale, it is useful to describe matter in terms of specific set of constituents which can be treated as *fundamental*; at shorter length scale, these fundamental constituents may turn out to consist of smaller parts (be “*composite*”)

- Concept of “smallest building block” changes in time:
  - in 19th century, atoms were considered smallest building blocks,
  - early 20th century research: electrons, protons, neutrons;
  - now evidence that nucleons have substructure - quarks;
  - going down the size ladder: atoms -- nuclei -- nucleons -- quarks -- preons, strings ??... ???
WHY CAN'T WE SEE ATOMS?

- "seeing an object"
  - = detecting light that has been reflected off the object's surface
- light = electromagnetic wave;
- "visible light" = those electromagnetic waves that our eyes can detect
- "wavelength" of e.m. wave (distance between two successive crests) determines "color" of light
- wave hardly influenced by object if size of object is much smaller than wavelength
- wavelength of visible light: between $4 \times 10^{-7}$ m (violet) and $7 \times 10^{-7}$ m (red);
- diameter of atoms: $10^{-10}$ m
- generalize meaning of seeing:
  - seeing is to detect effect due to the presence of an object
- quantum theory $\Rightarrow$ "particle waves", with wavelength $\propto 1/(m \nu)$
- use accelerated (charged) particles as probe, can "tune" wavelength by choosing mass m and changing velocity $\nu$
- this method is used in electron microscope, as well as in "scattering experiments" in nuclear and particle physics
Particle physics  
(High Energy Physics)

- **Goal:**
  - To understand matter and energy at smallest scale

- **Why?**
  - To understand more organized forms of matter
  - To understand the origin and destiny of the universe.

- **Basic questions:**
  - Are there irreducible building blocks?
    - Are there few or infinitely many?
    - What are they?
    - What are their properties?
  - What is mass?
  - What is charge?
  - What is flavor?
  - How do the building blocks interact?
  - Why are there 3 forces?
    - gravity, electroweak, strong
    - (or are there more?)
Electron

- **Cathode rays:**
  - During 2nd half of 19th century, many physicists (Geissler, Crookes, Hittorf,..) do experiments with “discharge tubes”, i.e. evacuated glass tubes with “electrodes” at ends, electric field between them (HV)
  - Development of better pumps and better glass blowing techniques - improved tubes (better vacuum)
  - 1869: discharge mediated by rays emitted from negative electrode (“cathode”)
  - rays called “glow rays”, later “cathode rays”
  - study of cathode rays by many physicists - find
    - cathode rays appear to be particles
    - cast shadow of opaque body
    - deflected by magnetic field
    - negative charge
Electron, cont’d

- Hertz, Hallwachs, Lenard (1887 - 1894): “photoelectric effect”:
  - UV light incident on metal surface causes negative particle to be emitted from surface

- 1895: Wilhelm Röntgen (1845-1923) (Würzburg)
  - Uses discharge tubes designed by Hittorf and Lenard (but improved pump) to verify Hertz’ and Lenard’s experiments
  - Discovers X-rays -- forget about cathode rays!

- 1897: three experiments measuring e/m, all with improved vacuum:
  - Emil Wiechert (1861-1928) (Königsberg)
    - Measures e/m – value similar to that obtained by Lorentz
    - Assuming value for charge = that of H ion, concludes that “charge carrying entity is about 2000 times smaller than H atom”
    - Cathode rays part of atom?
    - Study was his PhD thesis, published in obscure journal – largely ignored
  - Walther Kaufmann (1871-1947) (Berlin)
    - Obtains similar value for e/m, points out discrepancy, but no explanation
  - Wilhelm Wien (Aachen)
    - Obtains same e/m; method similar to method used later in mass spectroscopy
  - J. J. Thomson
Röntgen and X-rays:

Hand of Anna Röntgen

From Life magazine, 6 April 1896
1897: Joseph John Thomson (1856-1940) (Cambridge)

- Improves on tube built by Perrin with Faraday cup to verify Perrin’s result of negative charge
- Conclude that cathode rays are negatively charged “corpuscles”
- Then designs other tube with electric deflection plates inside tube, for e/m measurement
- Result for e/m in agreement with that obtained by Lorentz, Wiechert, Kaufmann, Wien
- Bold conclusion: “we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter... is of one and the same kind; this matter being the substance from which all the chemical elements are built up.”
WHAT IS INSIDE AN ATOM?

- J.J. Thomson’s model:
  - “Plum pudding or raisin cake model”
    - atom = sphere of positive charge (diameter \(\approx 10^{-10} \text{ m}\)),
    - with electrons embedded in it, evenly distributed (like raisins in cake)
    - i.e. electrons are part of atom, can be kicked out of it – atom no more indivisible!

![Diagram of atom with electrons and positively charged particle cloud]
Geiger & Marsden's scattering experiment

- **Geiger, Marsden, 1906 - 1911** (interpreted by Rutherford, 1911)
  - get particles from radioactive source
  - make “beam” of particles using “collimators” (lead plates with holes in them, holes aligned in straight line)
  - bombard foils of gold, silver, copper with beam
  - measure scattering angles of particles with scintillating screen (ZnS).
Geiger – Marsden apparatus
Geiger, Marsden, Rutherford expt.
result:

- most particles only slightly deflected (i.e. by small angles), but some by large angles - even backward
- measured angular distribution of scattered particles did not agree with expectations from Thomson model (only small angles expected),
- but did agree with that expected from scattering on small, dense positively charged nucleus with diameter < $10^{-14}$ m, surrounded by electrons at $\approx 10^{-10}$ m

Maximum deflection from entire electron cloud of a gold atom < 0.02°.
• **RUTHERFORD MODEL OF ATOM:**
  (“planetary model of atom”)
  - positive charge concentrated in nucleus (<10^{-14} m);
  - negative electrons in orbit around nucleus at distance \( \approx 10^{-10} \) m;
  - electrons bound to nucleus by Coulomb force.

Rutherford’s "Planetary" Model of the atom
problem with Rutherford atom:

- electron in orbit around nucleus is accelerated (centripetal acceleration to change direction of velocity);
- according to theory of electromagnetism (Maxwell's equations), accelerated electron emits electromagnetic radiation (frequency = revolution frequency);
- electron loses energy by radiation $\Rightarrow$ orbit decays,
- changing revolution frequency $\Rightarrow$ continuous emission spectrum (no line spectra), and atoms would be unstable (lifetime $\approx 10^{-10}$ s).

$\Rightarrow$ we would not exist to think about this!!

- This problem later solved by Quantum Mechanics
De Broglie, Bohr model
Proton

● “Canal rays”
  ■ 1886: Eugen Goldstein observes in a cathode-ray tube (in addition to the cathode ray) radiation that travels in the opposite direction - away from the anode; --- called “canal rays” because they get out of tube through holes (canals) bored in the cathode;
  ■ 1898: Wilhelm Wien studies canal rays; concludes that they are the positive equivalent of the negatively-charged cathode rays. Measures their deviation by magnetic and electric fields -- concludes that they are composed of positively-charged particles heavier than electrons.
  ■ 1912: Wilhelm Wien shows that canal rays can lose their electric charge by collision with atoms in tube

● Positive charge in nucleus (1900 – 1920)
  ■ Atom must contain something with positive charge to compensate for negative charge of electron
  ■ Canal rays from tubes with hydrogen found to be lighter than others
  ■ Rutherford atom: positive charge in nucleus
  ■ 1912 – 1920: in many nuclear transmutations, hydrogen nuclei emitted - eventually called protons
  ■ comparing nuclear masses to charges, it was realized that the positive charge of any nucleus could be accounted for by an integer number of hydrogen nuclei -- protons
Canal rays

“Canal Rays” (protons)
Beta decay

\[ \beta \text{ decay} \quad n \rightarrow p + e^- + \bar{\nu}_e \]

- \(\beta\) decay changes a neutron into a proton
- Only observed the electron and the recoiling nucleus
  - "non-conservation" of energy
- Pauli predicted a light, neutral, feebly interacting particle (1930)
  - the neutrino
- Although accepted since it "fit" so well, not actually observed initiating interactions until 1956-1958 (Cowan and Reines)
Cosmic rays

- Discovered by Victor Hess (1912)
- Observations on mountains and in balloon: intensity of cosmic radiation increases with height above surface of Earth - must come from “outer space”
- Much of cosmic radiation from sun (rather low energy protons)
- Very high energy radiation from outside solar system, but probably from within galaxy
Detectors

- Detectors
  - use characteristic effects from interaction of particle with matter to detect, identify and/or measure properties of particle; has “transducer” to translate direct effect into observable/recordable (e.g. electrical) signal
  - example: *our eye is a photon detector*; (photons = light “quanta” = packets of light)
  - "seeing" is performing a photon scattering experiment:
    - light source provides photons
    - photons hit object of our interest -- some absorbed, some scattered, reflected
    - some of scattered/reflected photons make it into eye; focused onto retina;
    - photons detected by sensors in retina (photoreceptors -- rods and cones)
    - transduced into electrical signal (nerve pulse)
    - amplified when needed
    - transmitted to brain for processing and interpretation
Interaction of particles with matter

- when passing through matter,
  - particles interact with the electrons and/or nuclei of the medium;
  - this interaction can be weak, electromagnetic or strong interaction, depending on the kind of particle; its effects can be used to detect the particles;

- possible interactions and effects in passage of particles through matter:
  - **excitation** of atoms or molecules (e.m. int.):
    - charged particles can excite an atom or molecule (i.e. lift electron to higher energy state);
    - subsequent de-excitation leads to emission of photons;
  - **ionization** (e.m. int.)
    - electrons liberated from atom or molecule, can be collected, and charge is detected
  - **Cherenkov radiation** (e.m. int.):
    - if particle's speed is higher than speed of light in the medium, e.m. radiation is emitted -- “Cherenkov light” or Cherenkov radiation, which can be detected;
    - amount of light and angle of emission depend on particle velocity;
Interaction of particles with matter, cont’d

- **transition radiation** (e.m. int.):
  - when a charged particle crosses the boundary between two media with different speeds of light (different “refractive index”), e.m. radiation is emitted -- “transition radiation”
  - amount of radiation grows with (energy/mass);

- **bremsstrahlung** (= braking radiation) (e.m. int.):
  - when charged particle's velocity changes, e.m. radiation is emitted;
  - due to interaction with nuclei, particles deflected and slowed down emit bremsstrahlung;
  - effect stronger, the bigger (energy/mass) ⇒ electrons with high energy most strongly affected;

- **pair production** (e.m. int.):
  - by interaction with e.m. field of nucleus, photons can convert into electron-positron pairs

- **electromagnetic shower** (e.m. int.):
  - high energy electrons and photons can cause “electromagnetic shower” by successive bremsstrahlung and pair production

- **hadron production** (strong int.):
  - strongly interacting particles can produce new particles by strong interaction, which in turn can produce particles,... “hadronic shower”
Scintillation counter

- **Scintillation counter:**
  - energy liberated in de-excitation and capture of ionization electrons emitted as light - “scintillation light”
  - light channeled to photomultiplier in light guide (e.g. piece of lucite or optical fibers);
  - scintillating materials: certain crystals (e.g. NaI), transparent plastics with doping (fluors and wavelength shifters)
Photomultiplier tubes convert small light signal (even single photon) into detectable charge (current pulse). Photons liberate electrons from photocathode. Electrons “multiplied” in several (6 to 14) stages by ionization and acceleration in high electric field between “dynodes”, with gain $\approx 10^4$ to $10^{10}$. Photocathode and dynodes made from material with low ionization energy. Photocathodes: thin layer of semiconductor made e.g. from Sb (antimony) plus one or more alkali metals, deposited on glass or quartz. Dynodes: alkali or alkaline earth metal oxide deposited on metal, e.g. BeO on Cu (gives high secondary emission).
Spark chamber

- gas volume with metal plates (electrodes); filled with gas (noble gas, e.g. argon)
- charged particle in gas $\Rightarrow$ ionization $\Rightarrow$ electrons liberated; $\Rightarrow$ string of electron - ion pairs along particle path
- passage of particle through “trigger counters” (scintillation counters) triggers HV
- HV between electrodes $\Rightarrow$ strong electric field;
- electrons accelerated in electric field $\Rightarrow$ can liberate other electrons by ionization which in turn are accelerated and ionize $\Rightarrow$ “avalanche of electrons”, eventually formation of plasma between electrodes along particle path;
- gas conductive along particle path $\Rightarrow$ electric breakdown $\Rightarrow$ discharge $\Rightarrow$ spark
- HV turned off to avoid discharge in whole gas volume
Parts of sparkchamber setup

- Scintillation Counter, S1
- Photo-tube 1
- Discriminator 1
- High Voltage Supply
- Trigger Unit
- Coincidence Unit
- Cosmic Ray
- Scintillation Counter, S2
- Photo-tube 2
- Discriminator 2
What we see in spark chamber
Geiger-Müller counter:

- metallic tube with thin wire in center, filled with gas, HV between wall (-, “cathode”) and central wire (+, “anode”); ⇒ strong electric field near wire;
- charged particle in gas ⇒ ionization ⇒ electrons liberated;
- electrons accelerated in electric field ⇒ liberate other electrons by ionization which in turn are accelerated and ionize ⇒ “avalanche of electrons”; avalanche becomes so big that all of gas ionized ⇒ plasma formation ⇒ discharge
- gas is usually noble gas (e.g. argon), with some additives e.g. carbon dioxide, methane, isobutane,..) as “quenchers”;

Geiger Counter Principles
Cloud chamber

- Container filled with gas (e.g. air), plus vapor close to its dew point (saturated)
- Passage of charged particle $\Rightarrow$ ionization;
- Ions form seeds for condensation $\Rightarrow$ condensation takes place along path of particle $\Rightarrow$ path of particle becomes visible as chain of droplets
Positron

- Positron (anti-electron)
  - Predicted by Dirac (1928) -- needed for relativistic quantum mechanics
  - Existence of antiparticles doubled the number of known particles!!

- Positron track going upward through lead plate
  - Photographed by Carl Anderson (August 2, 1932), while photographing cosmic-ray tracks in a cloud chamber
  - Particle moving upward, as determined by the increase in curvature of the top half of the track after it passed through the lead plate,
  - And curving to the left, meaning its charge is positive.
Anderson and his cloud chamber
Neutron

- **Bothe + Becker (1930):**
  - Some light elements (e.g. Be), when bombarded with alpha particles, emit neutral radiation, "penetrating"- gamma?

- **Curie-Joliot and Joliot (1932):**
  - This radiation from Be and B able to eject protons from material containing hydrogen

- **Chadwick (1932)**
  - Doubts interpretation of this radiation as gamma
  - Performs new experiments; protons ejected not only from hydrogen, but also from other light elements;
  - Measures energy of ejected protons (by measuring their range),
  - Results not compatible with assumption that unknown radiation consists of gamma radiation (contradiction with energy-momentum conservation), but are compatible with assumption of neutral particles with mass approximately equal to that of proton - calls it "neutron"
  - Neutron assumed to be “proton and electron in close association”
Chadwick's experiment

**Fig. 1.**

- Po source
- Be
- Target material
- To pump
- To amplifier → Oscillograph
- Vacuum
- Nucleus of Po
- Neutrons or alpha particles
- Target material
- Number of particles
- Range in equivalent cm of air

**Fig. 2.**
More particles: Pion, Muon,

- **1935**: Yukawa predicts the pion as carrier of a new, strong (nuclear) force - the force which holds the nucleus together
- **1937**: muon is observed in cosmic rays (Carl Anderson, Seth Neddermeyer) - first mistaken for Yukawa’s particle
Bubble chamber

- bubble chamber
  - Vessel, filled (e.g.) with liquid hydrogen at a temperature above the normal boiling point but held under a pressure of about 10 atmospheres by a large piston to prevent boiling.
  - When particles have passed, and possibly interacted in the chamber, the piston is moved to reduce the pressure, allowing bubbles to develop along particle tracks.
  - After about 3 milliseconds have elapsed for bubbles to grow, tracks are photographed using flash photography. Several cameras provide stereo views of the tracks.
  - The piston is then moved back to recompress the liquid and collapse the bubbles before boiling can occur.
- Invented by Glaser in 1952 (when he was drinking beer)
- $\bar{p} p \rightarrow p \bar{n} K^0 K^- \pi^+ \pi^- \pi^0$
- $\bar{n} + p \rightarrow 3$ pions
- $\pi^0 \rightarrow \gamma \gamma, \gamma \rightarrow e^+ e^-$
- $K^0 \rightarrow \pi^+ \pi^-$
Kaons

- **First observation of Kaons:**
  - Cloud chamber exposed to cosmic rays
  - Experiment done by Clifford Butler and George Rochester at Manchester
  - Left picture: neutral Kaon decay (1946)
  - Right picture: charged Kaon decay into muon and neutrino

- Kaons first called “V” particles
- Called “strange” because they behaved differently from others
“Strange particles”

- Kaon: discovered 1947; first called “V” particles

K⁰ production and decay in a bubble chamber
Particle physics experiments

• Particle physics experiments:
  ■ collide particles to
    ◆ produce new particles
    ◆ reveal their internal structure and laws of their interactions by observing regularities, measuring cross sections,...
  ■ colliding particles need to have high energy
    ◆ to make objects of large mass
    ◆ to resolve structure at small distances
  ■ to study structure of small objects:
    ◆ need probe with short wavelength: use particles with high momentum to get short wavelength
    ◆ remember de Broglie wavelength of a particle \( \lambda = \frac{h}{p} \)
  ■ in particle physics, mass-energy equivalence plays an important role; in collisions, *kinetic energy* converted into *mass energy*;
    ◆ relation between kinetic energy \( K \), total energy \( E \) and momentum \( p \):
      \[
      E = K + mc^2 = \sqrt{(pc)^2 + (mc^2)c^2}
      \]
About Units

● **Energy - electron-volt**
  - 1 electron-volt = kinetic energy of an electron when moving through potential difference of 1 Volt;
    - 1 eV = 1.6 × 10^{-19} Joules = 2.1 × 10^{-6} W·s
    - 1 kW·hr = 3.6 × 10^6 Joules = 2.25 × 10^{25} eV

● **mass - eV/c^2**
  - 1 eV/c^2 = 1.78 × 10^{-36} kg
  - electron mass = 0.511 MeV/c^2
  - proton mass = 938 MeV/c^2
  - professor’s mass (80 kg) ≈ 4.5 × 10^{37} eV/c^2

● **momentum - eV/c**:
  - 1 eV/c = 5.3 × 10^{-28} kg m/s
  - momentum of baseball at 80 mi/hr
    ≈ 5.29 kgm/s ≈ 9.9 × 10^{27} eV/c
How to do a particle physics experiment

- **Outline of experiment:**
  - get particles (e.g. protons, antiprotons,...)
  - accelerate them
  - throw them against each other
  - observe and record what happens
  - analyse and interpret the data

- **Ingredients needed:**
  - particle source
  - accelerator and aiming device
  - detector
  - trigger (decide what to record)
  - recording device
  - many people to:
    - design, build, test, operate accelerator
    - design, build, test, calibrate, operate, and understand detector
    - analyze data
  - lots of money to pay for all of this
How to get high energy collisions

- Need $E_{\text{com}}$ to be large enough to
  - allow high momentum transfer (probe small distances)
  - produce heavy objects (top quarks, Higgs boson)
  - e.g. top quark production: $e^+e^- \rightarrow t\bar{t}$,
    $q\bar{q} \rightarrow t\bar{t}$, $gg \rightarrow t\bar{t}$, ...

- Shoot particle beam on a target (“fixed target”):
  - $E_{\text{com}} = 2\sqrt{Emc^2} \sim 20 \text{ GeV}$ for $E = 100 \text{ GeV}$,
    $m = 1 \text{ GeV}/c^2$

- Collide two particle beams (“collider”:
  - $E_{\text{com}} = 2E \sim 200 \text{ GeV}$ for $E = 100 \text{ GeV}$
How to make qq collisions, cont’d

- However, quarks are not found free in nature!
- But (anti)quarks are elements of (anti)protons.
- So, if we collide protons and anti-protons we should get some qq collisions.

Proton structure functions give the probability that a single quark (or gluon) carries a fraction \( x \) of the proton momentum (which is 900 GeV/c at the Tevatron)
Accelerator

**Accelerators:**
- Use electric fields to accelerate particles, magnetic fields to steer and focus the beams.
- **Synchrotron:** Particle beams kept in circular orbit by magnetic field; at every turn, particles “kicked” by electric field in accelerating station.
- **Fixed target operation:** Particle beam extracted from synchrotron, steered onto a target.
- **Collider operation:** Accelerate bunches of protons and antiprotons moving in opposite direction in same ring; make them collide at certain places where detectors are installed.
Fermilab accelerator complex