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?

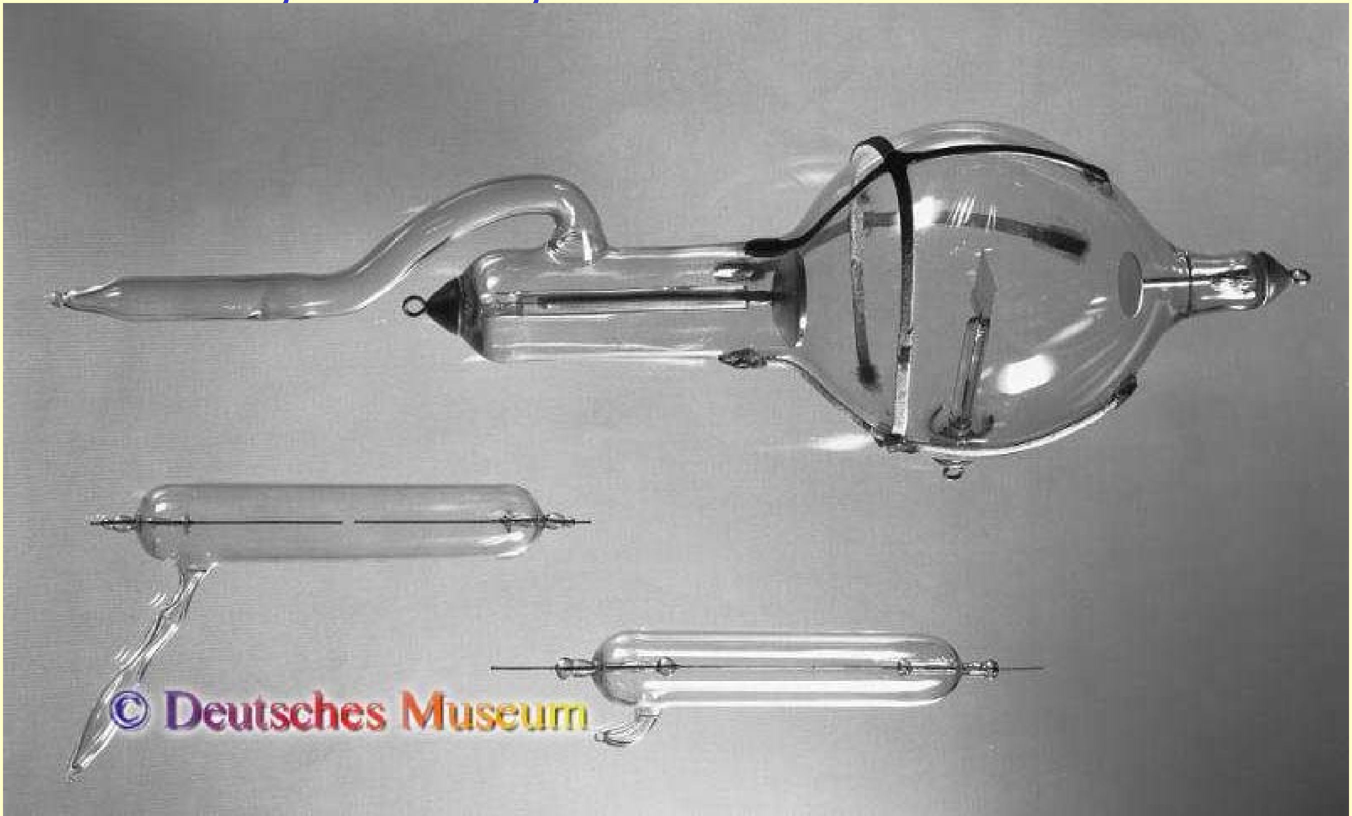
- "seeing an object"
  - = detecting light that has been reflected off the object's surface
- light = electromagnetic wave;
- "visible light"= those electromagnetic waves that our eyes can detect
- "wavelength" of e.m. wave (distance between two successive crests) determines "color" of light
- wave hardly influenced by object if size of object is much smaller than wavelength
- wavelength of visible light:
  between 4×10^{-7} m (violet) and 7×10^{-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 $\propto 1/(m\ v)$
- use accelerated (charged) particles as probe, can "tune" wavelength by choosing mass m and changing velocity v
- 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

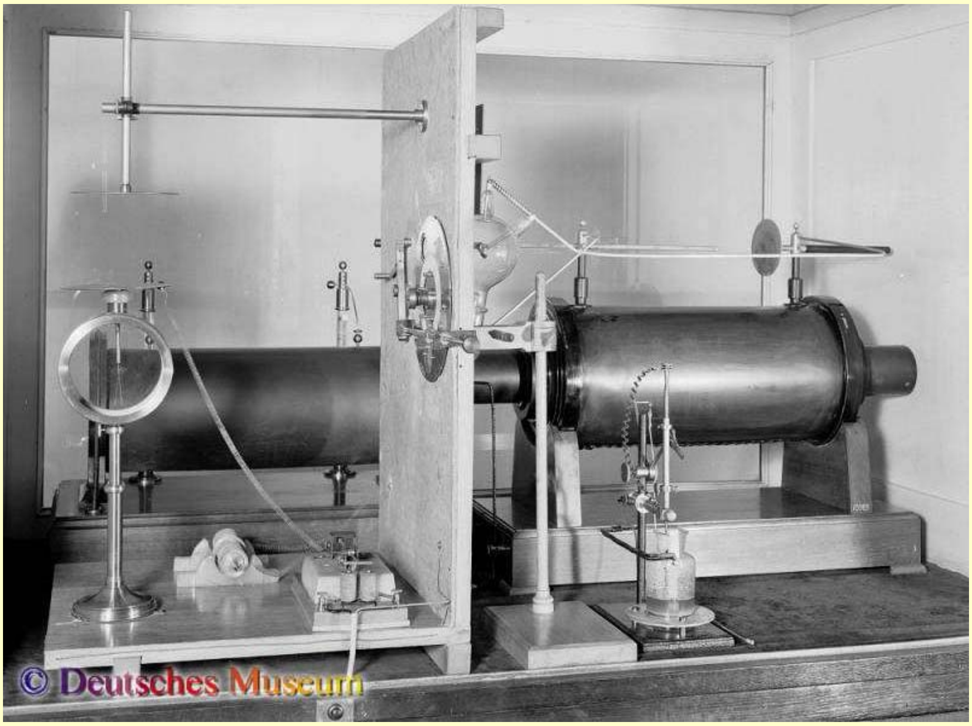
- Cathode rays:
  - During 2nd half of 19th century, many physicists (Geissler, Crookes, Hittorf,..) do experiments with "discharge tubes", i.e. evqcuated glass tubes with "electrodes" at ends, electric field between them (HV)
  - Development of better pumps and better glass blowing techniques – improved 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

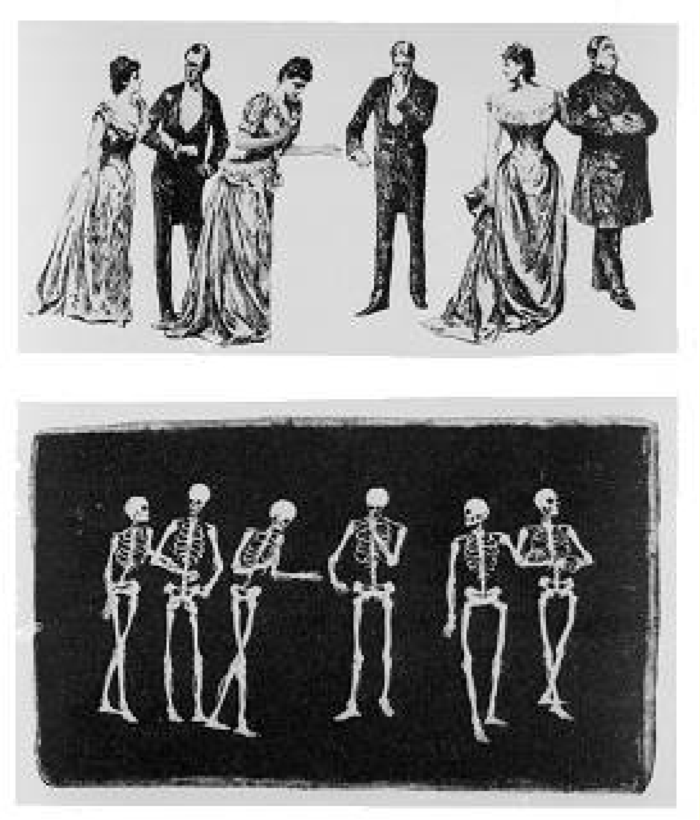


Electron, cont'd

- 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:



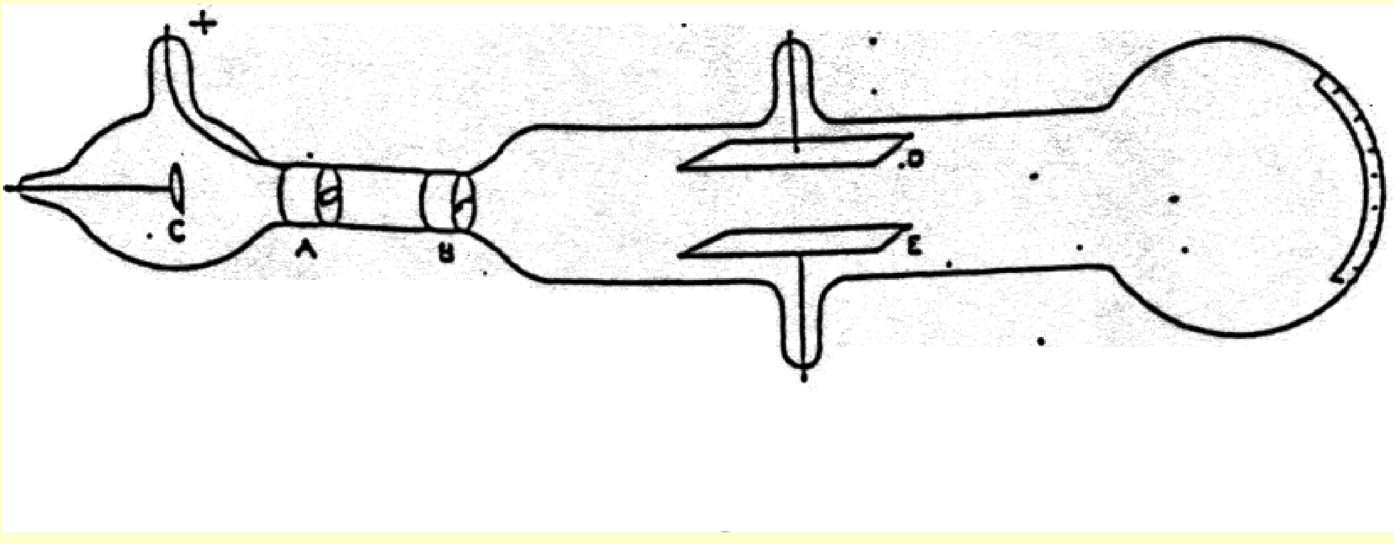


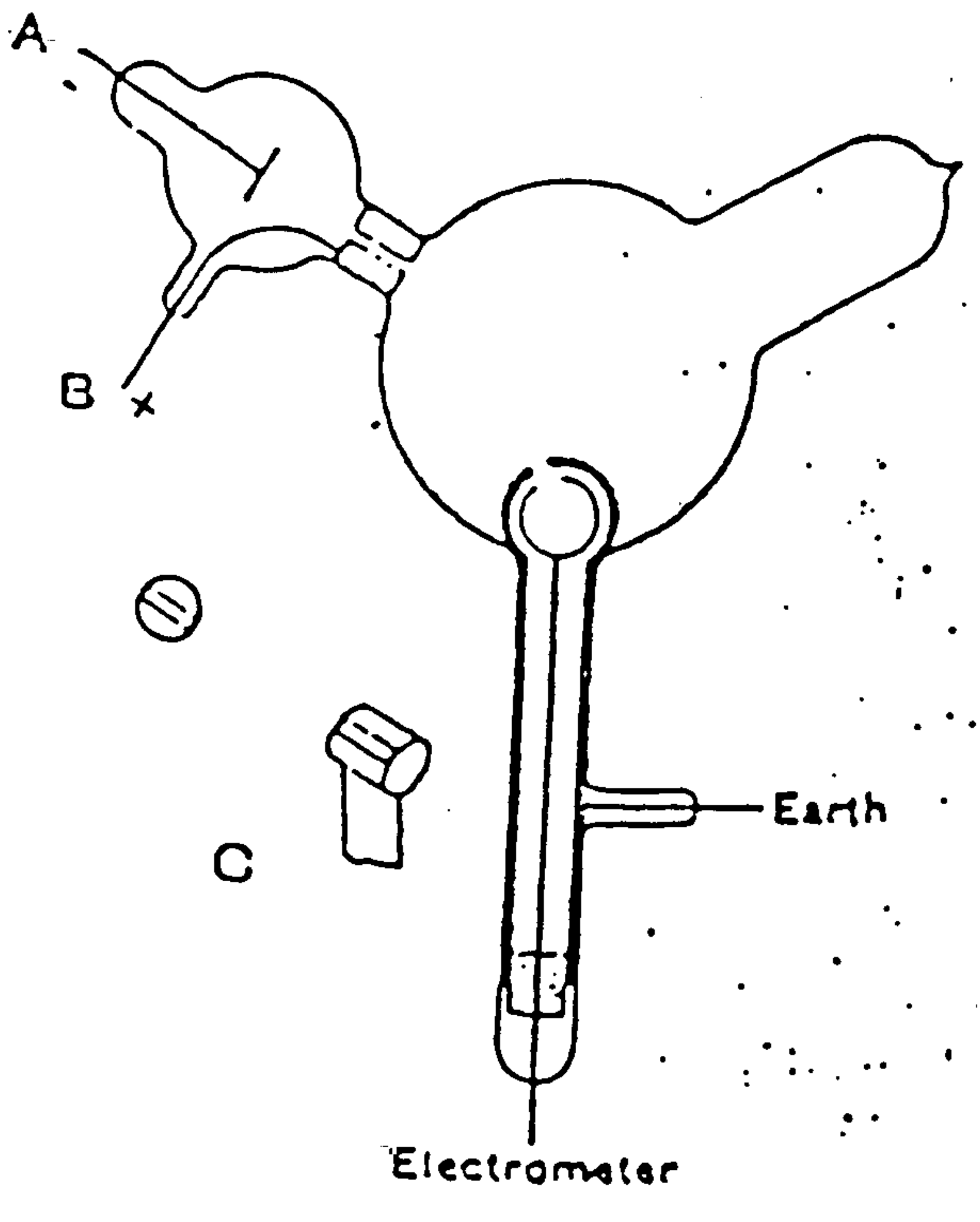
Hand of Anna Röntgen

From Life magazine,6 April 1896

1897: Joseph John Thomson (1856-1940) (Cambridge)

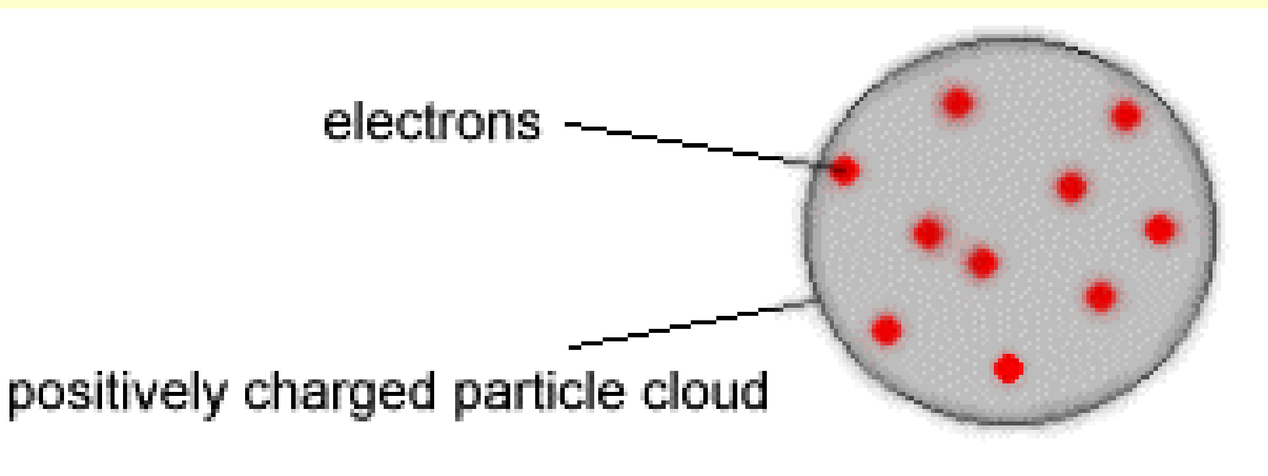
- Improves on tube built by Perrin with Faraday cup to verify Perrin's result of negative charge
- Conclude that cathode rays are negatively charged "corpuscles"
- Then designs other tube with electric deflection plates inside tube, for e/m measurement
- Result for e/m in agreement with that obtained 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."




A
-
B
+
C
Earth
Electrometer

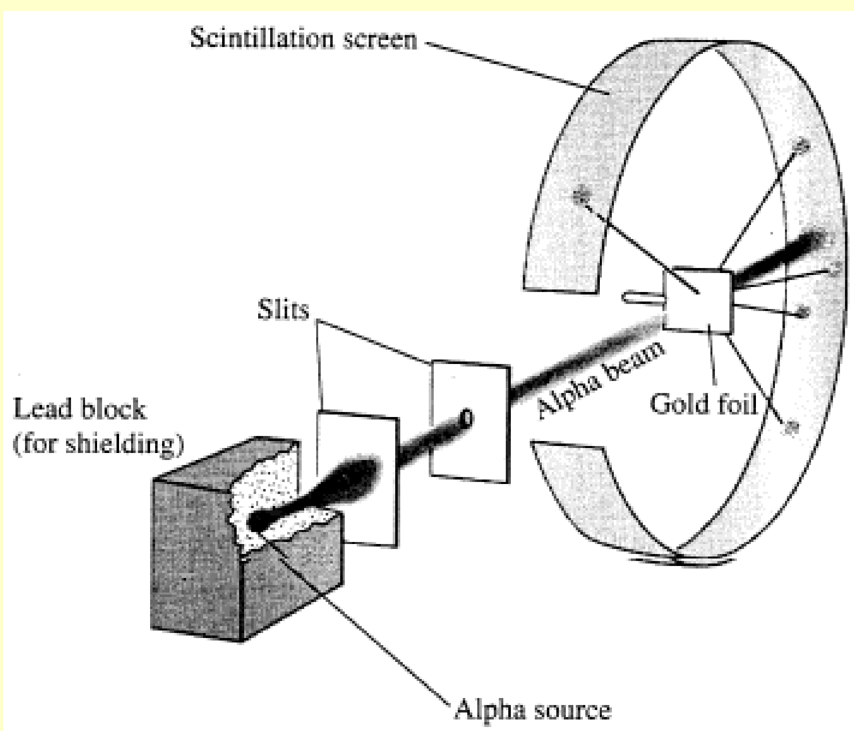
WHAT IS INSIDE AN ATOM?

- J.J. Thomson's model:
  - "Plum pudding or raisin cake model"
    - atom = sphere of positive charge (diameter $\approx 10^{-10}$ 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!

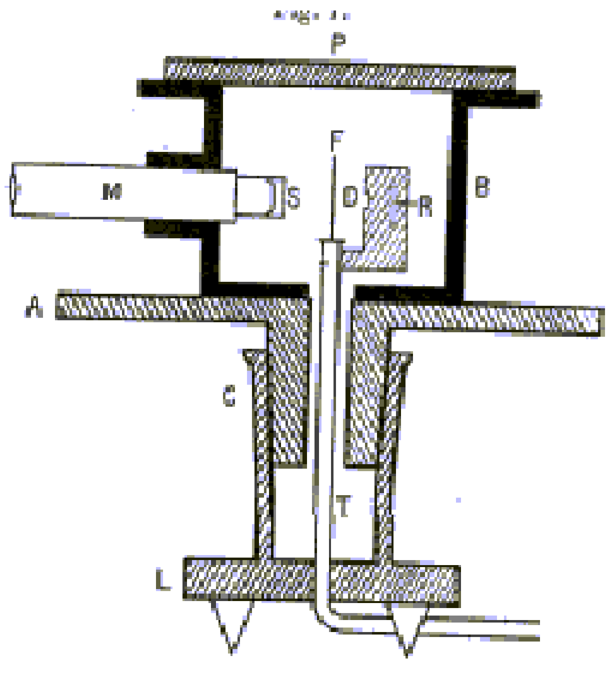


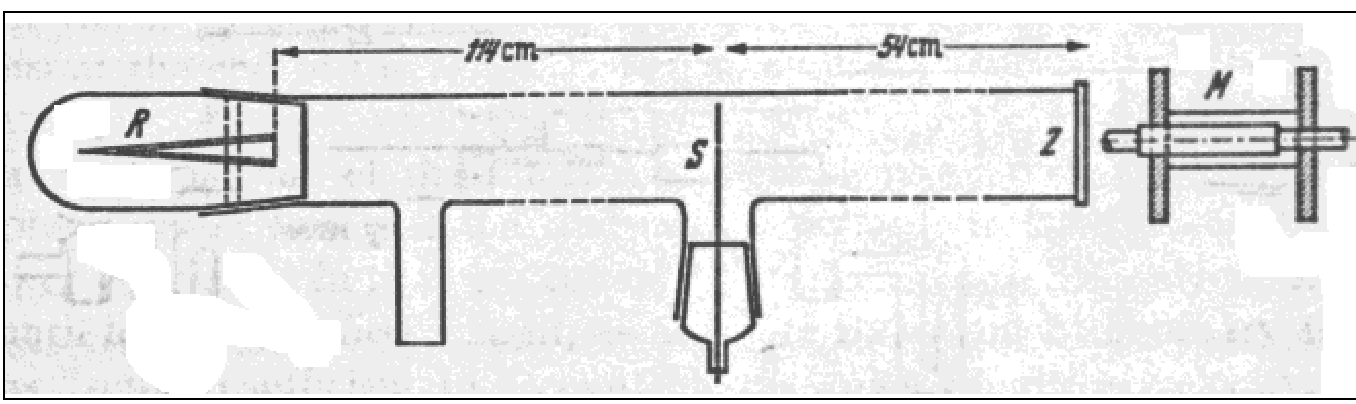
Geiger & Marsden's scattering experiment

- 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) .

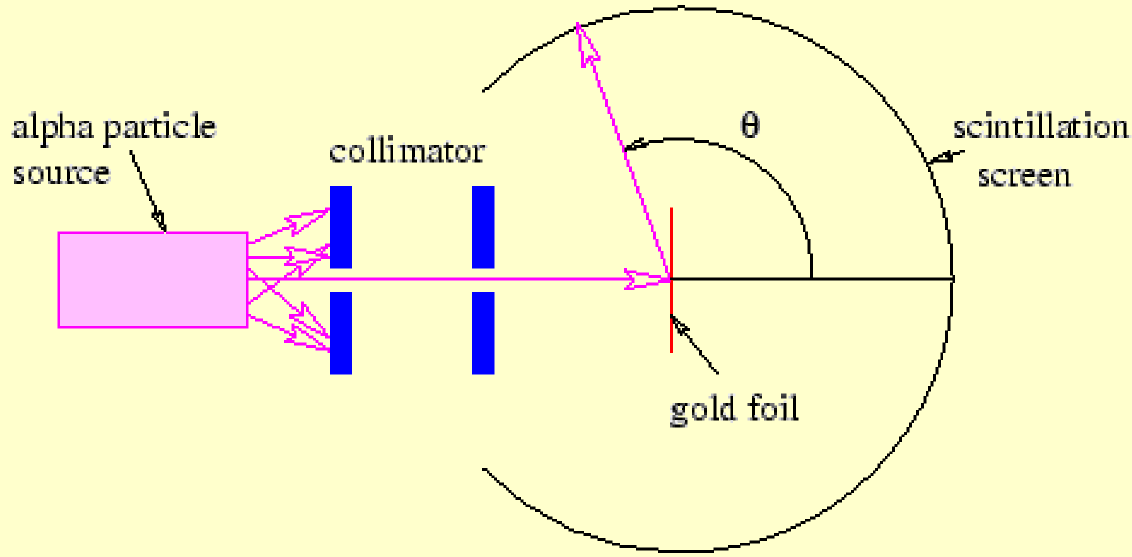


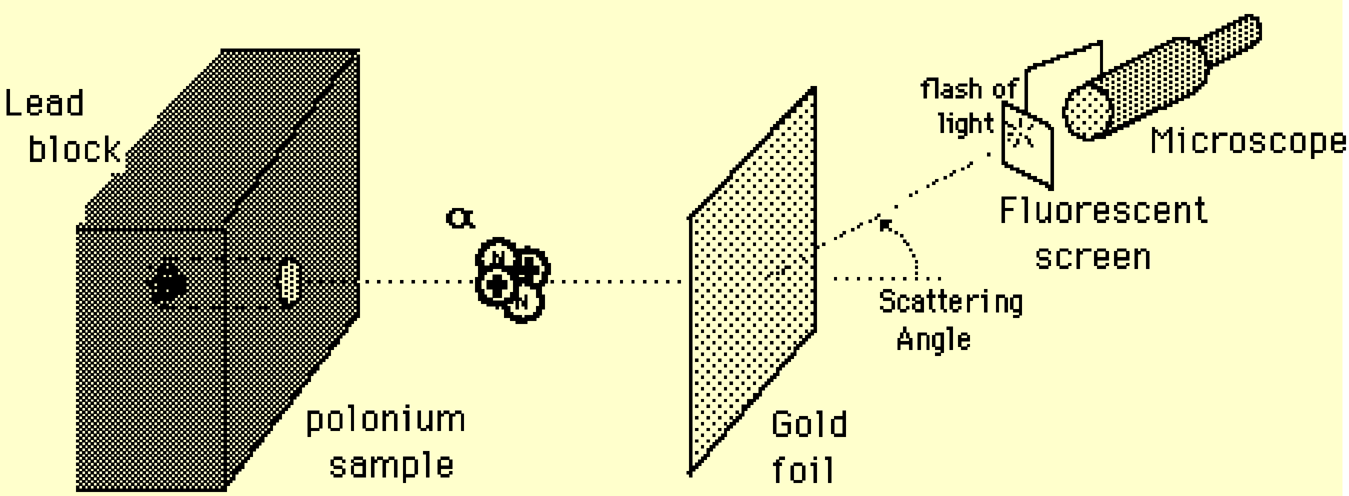
Geiger - Marsden apparatus





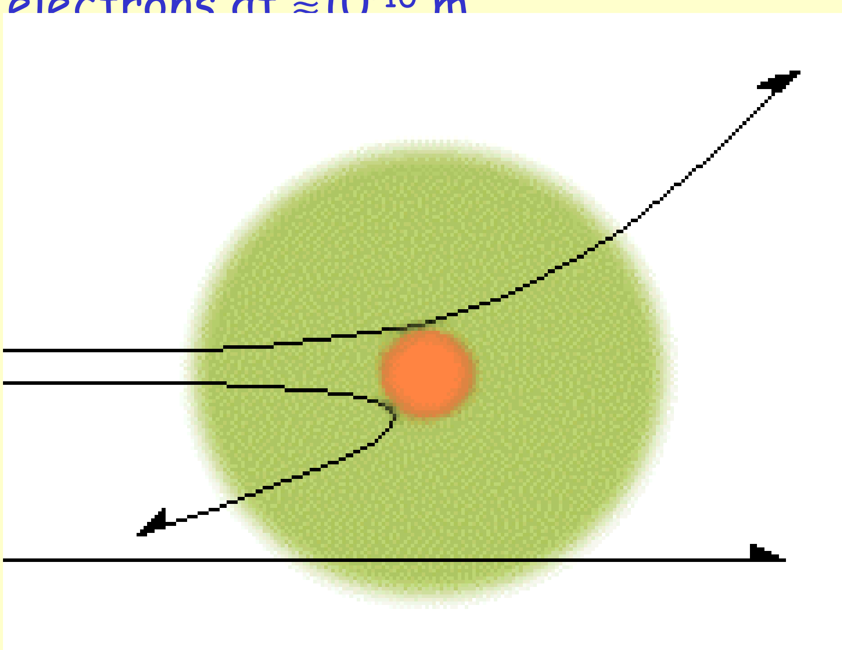
Geiger, Marsden, Rutherford expt.

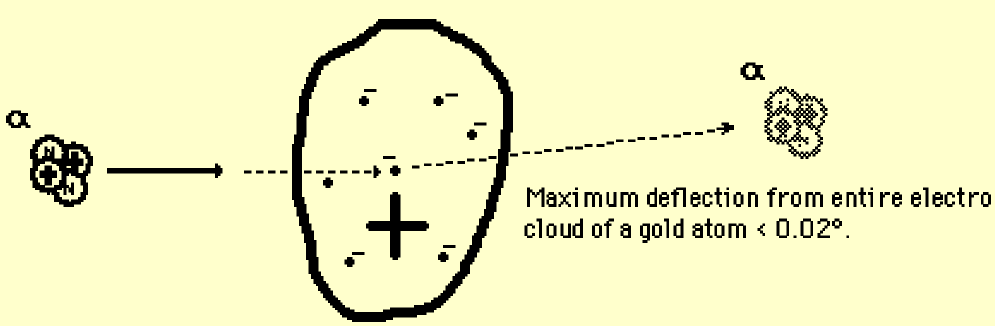




Geiger Marsden experiment: result

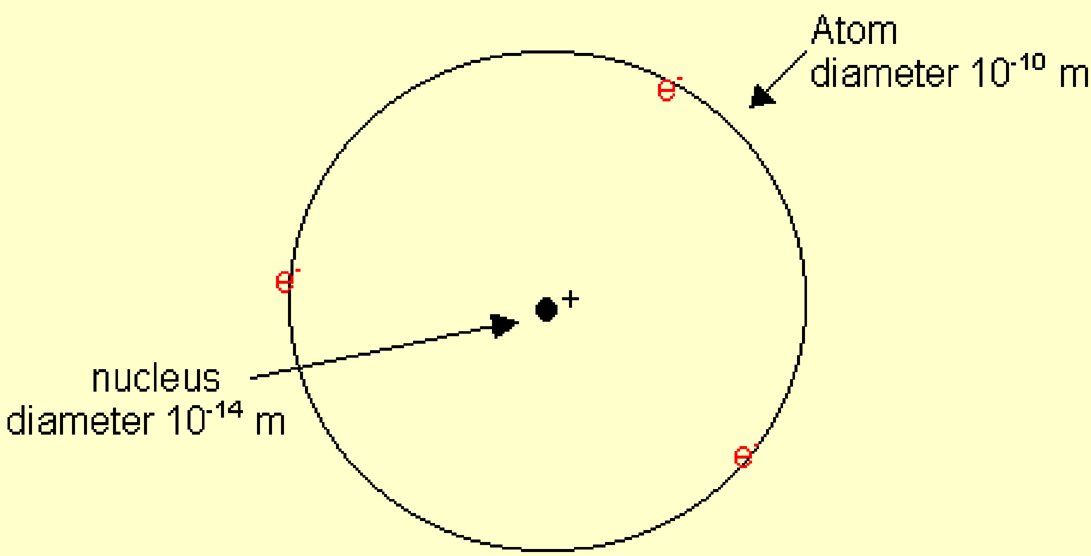
- **result:**
  - most particles only slightly deflected (i.e. by small angles), but some by large angles - even backward
  - measured angular distribution of scattered particles did not agree with expectations from Thomson model (only small angles expected),
  - but did agree with that expected from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



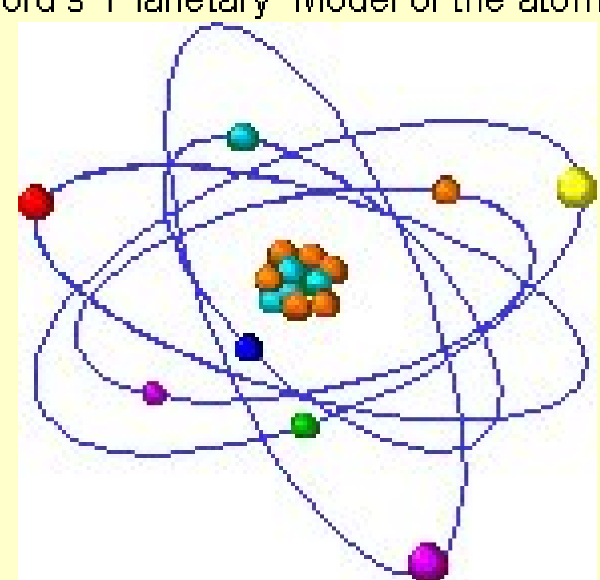


Rutherford model

- RUTHERFORD MODEL OF ATOM:
  ("planetary model of atom")
  - positive charge concentrated in nucleus (<10^{-14} m);
  - negative electrons in orbit around nucleus at distance ≈10^{-10} m;
  - electrons bound to nucleus by Coulomb force.



Rutherford's "Planetary" Model of the atom



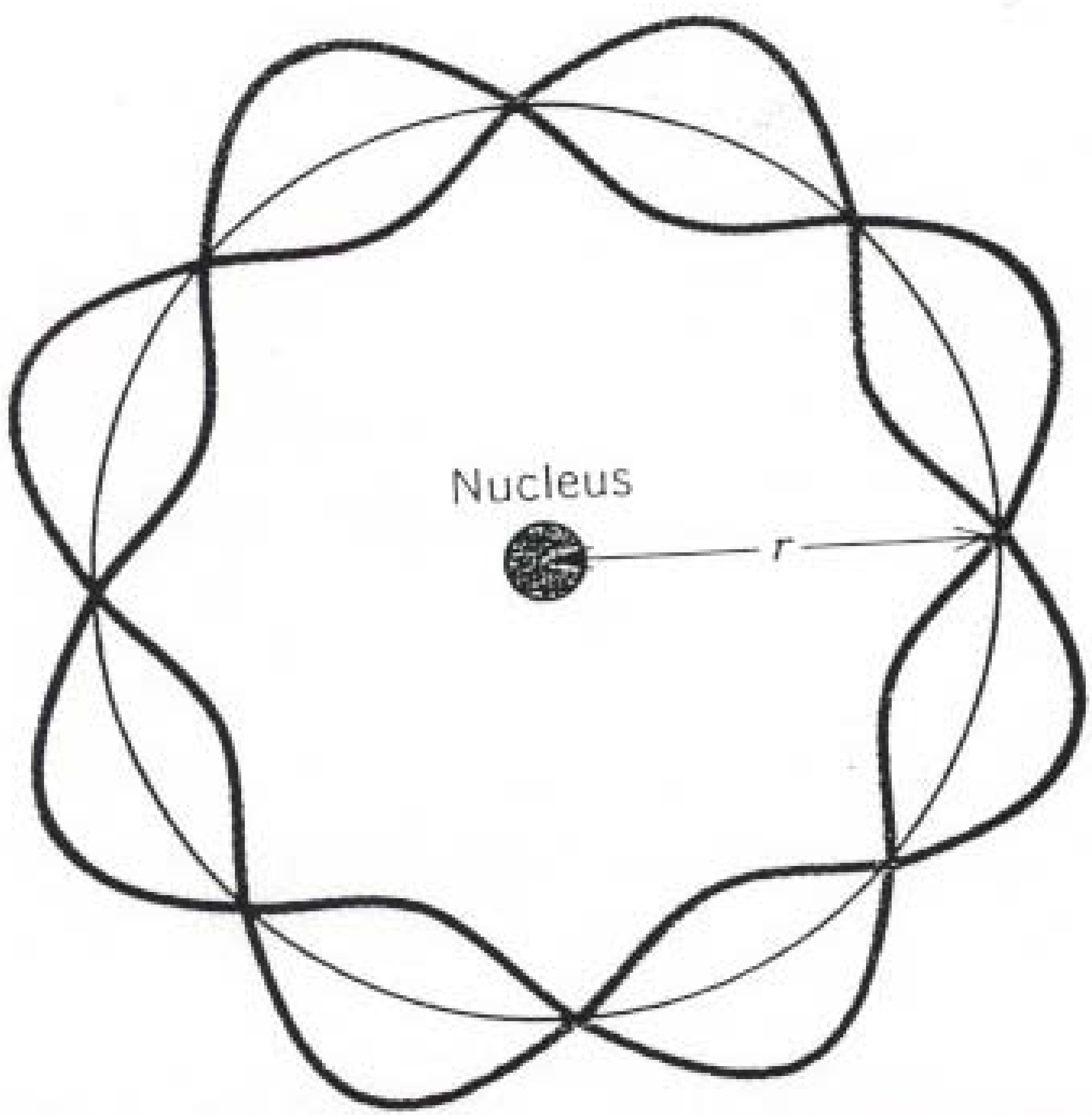
problem with Rutherford atom:

- 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*

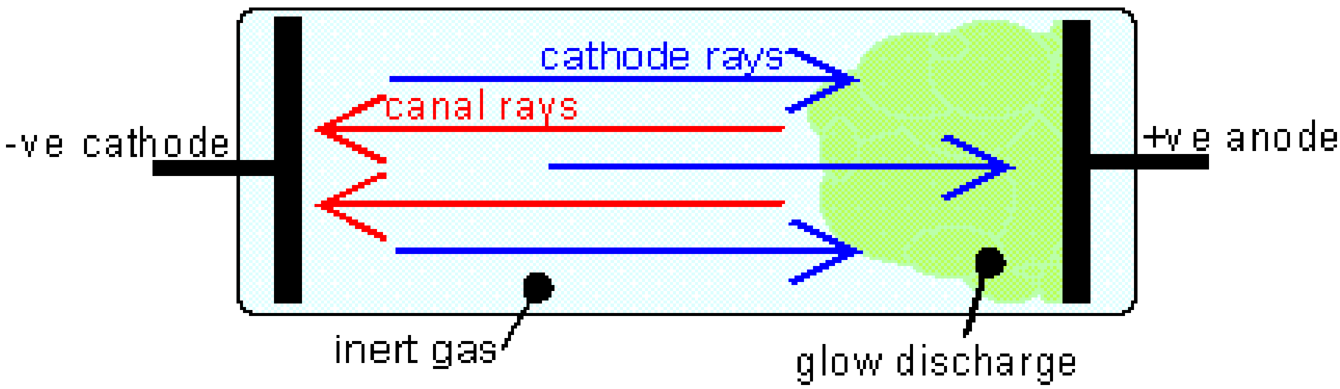
De Broglie, Bohr model

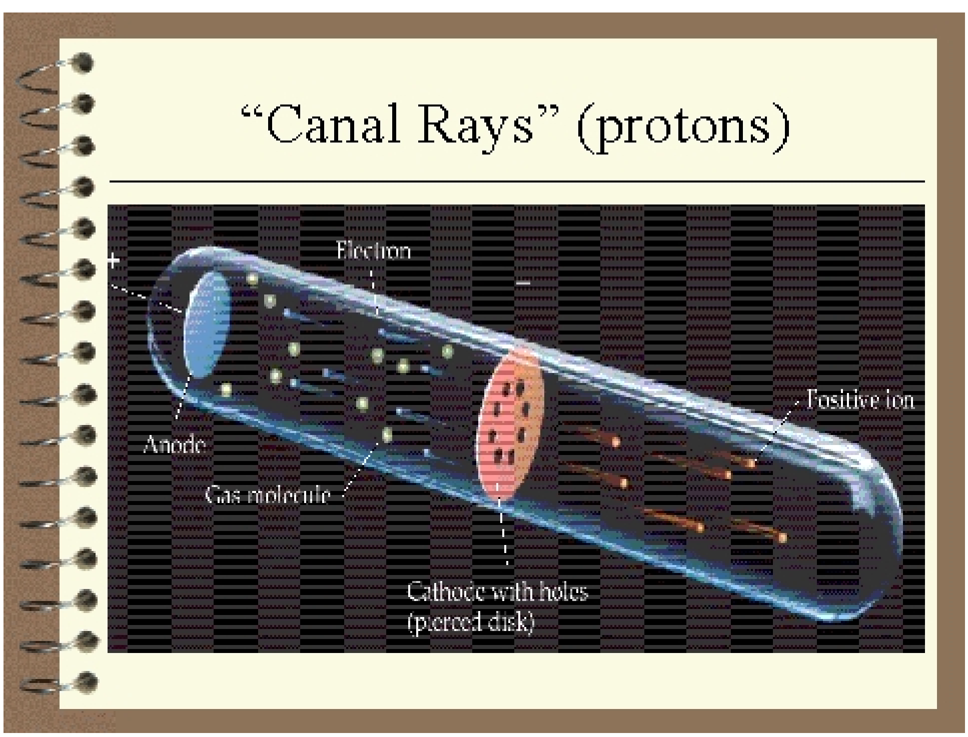


Proton

- "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

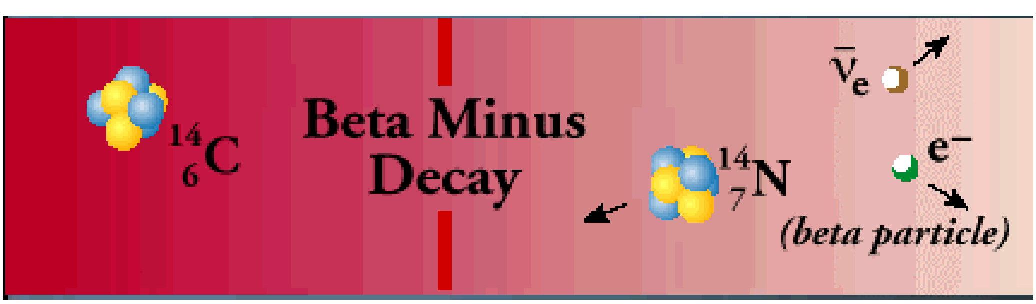

cathode rays
canal rays
-ve cathode
+ve anode
inert gas
glow discharge


"Canal Rays" (protons)
+
−
Electron
Anode
Gas molecule
Positive ion
Cathode with holes
(pierced disk)

Beta decay

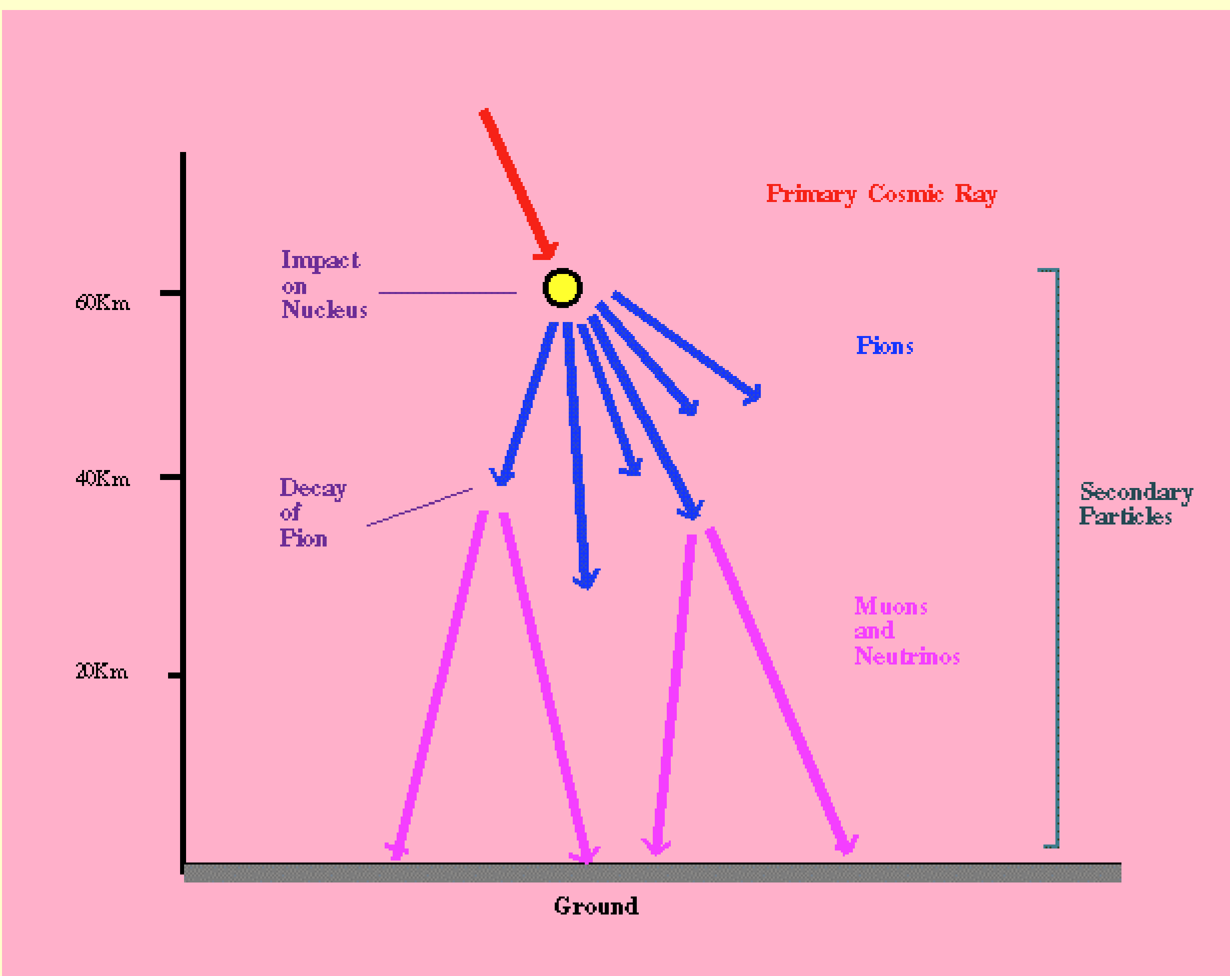
β decay $\quad n \rightarrow p + e^- + \bar{\nu}_e$

- β 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)



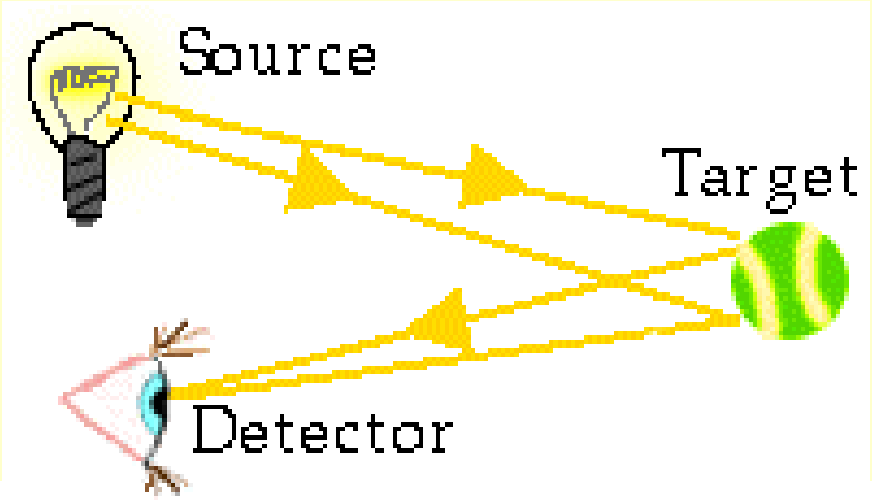
Cosmic rays

- 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

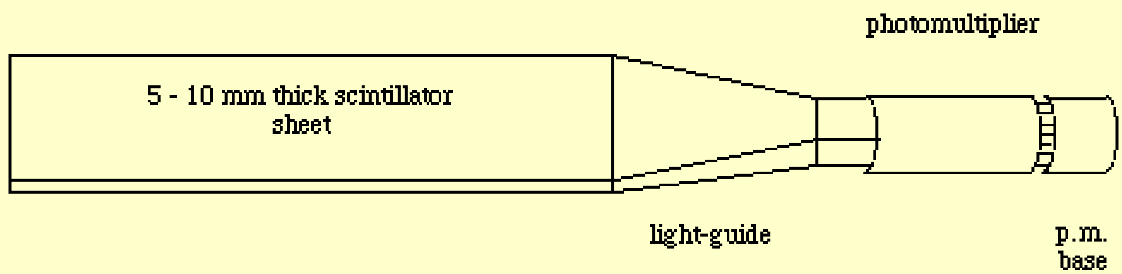
- when passing through matter,
  - particles interact with the electrons and/or nuclei of the medium;
  - this interaction can be *weak*, *electromagnetic* or *strong interaction*, depending on the kind of particle; its effects can be used to detect the particles;
- possible interactions and effects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

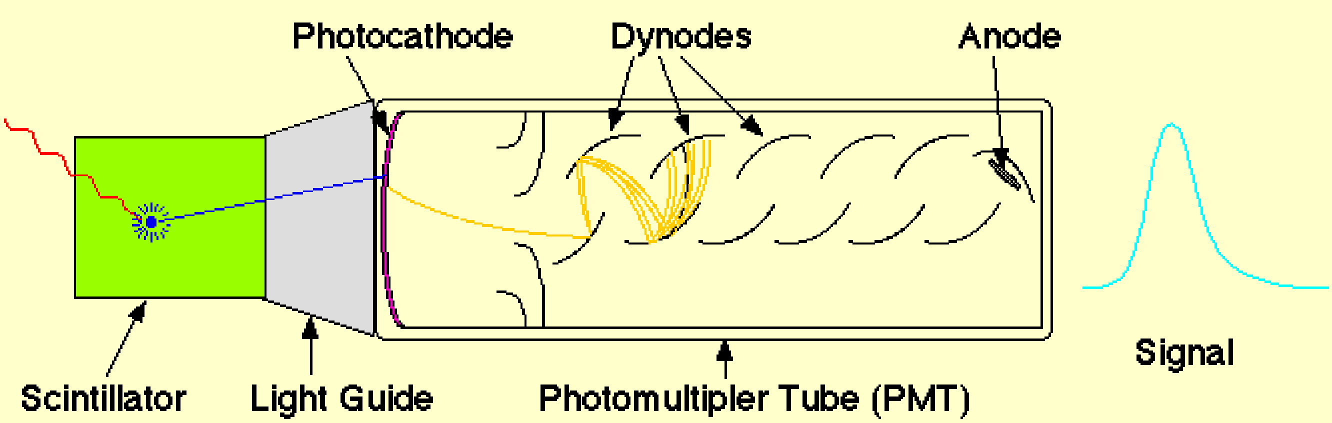
Interaction of particles with matter, cont'd

- **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) $\Rightarrow$ 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

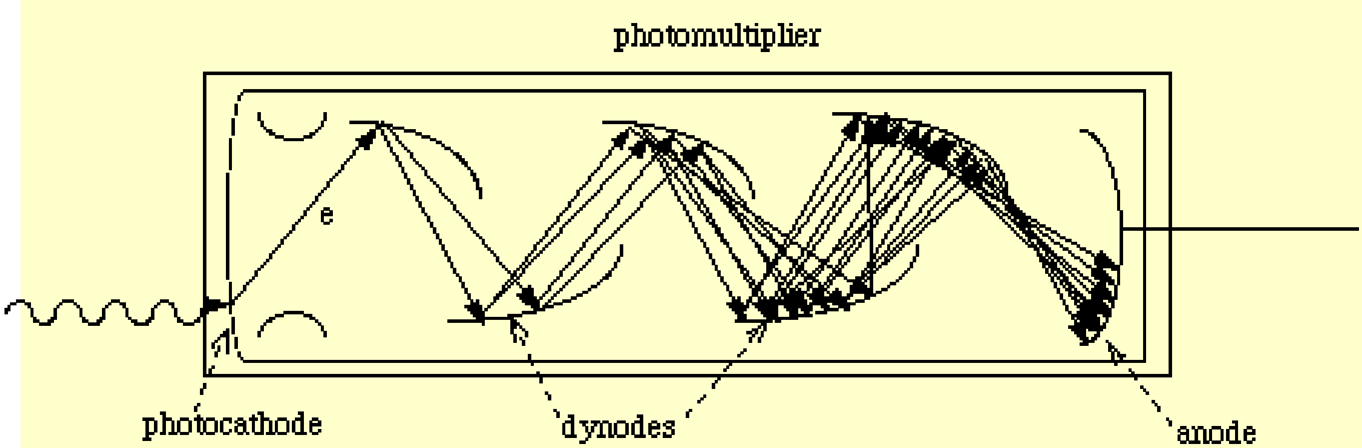
- Scintillation counter:
  - energy liberated in de-excitation and capture of ionization electrons emitted as light - “scintillation light”
  - light channeled to photomultiplier in light guide (e.g. piece of lucite or optical fibers);
  - scintillating materials: certain crystals (e.g. NaI), transparent plastics with doping (fluors and wavelength shifters)





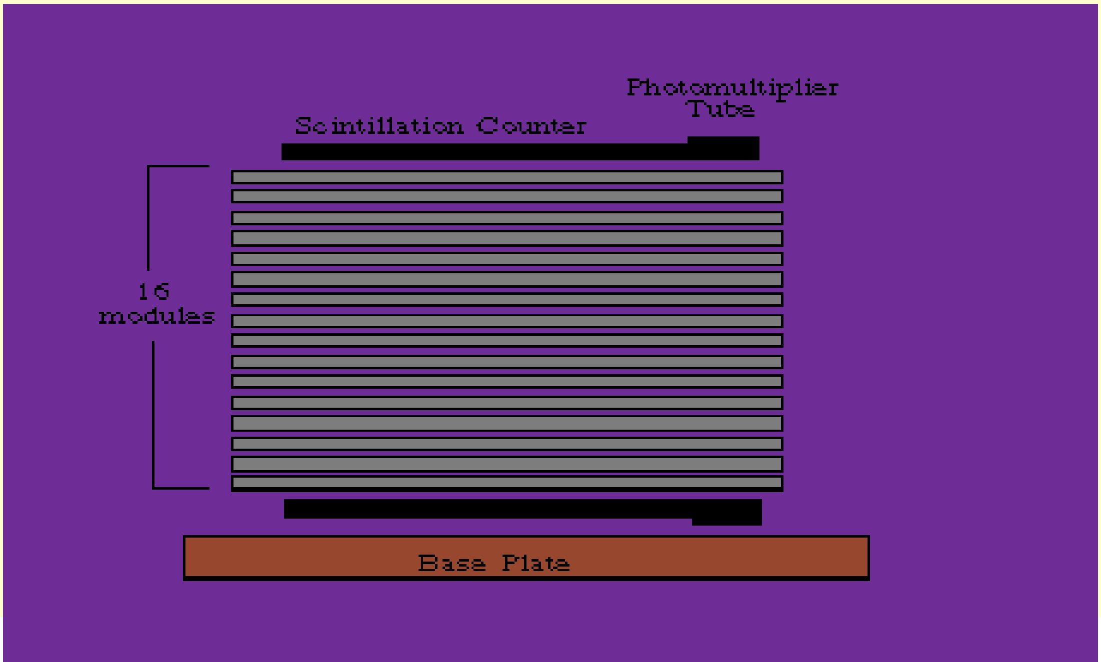
Photomultiplier

- 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);

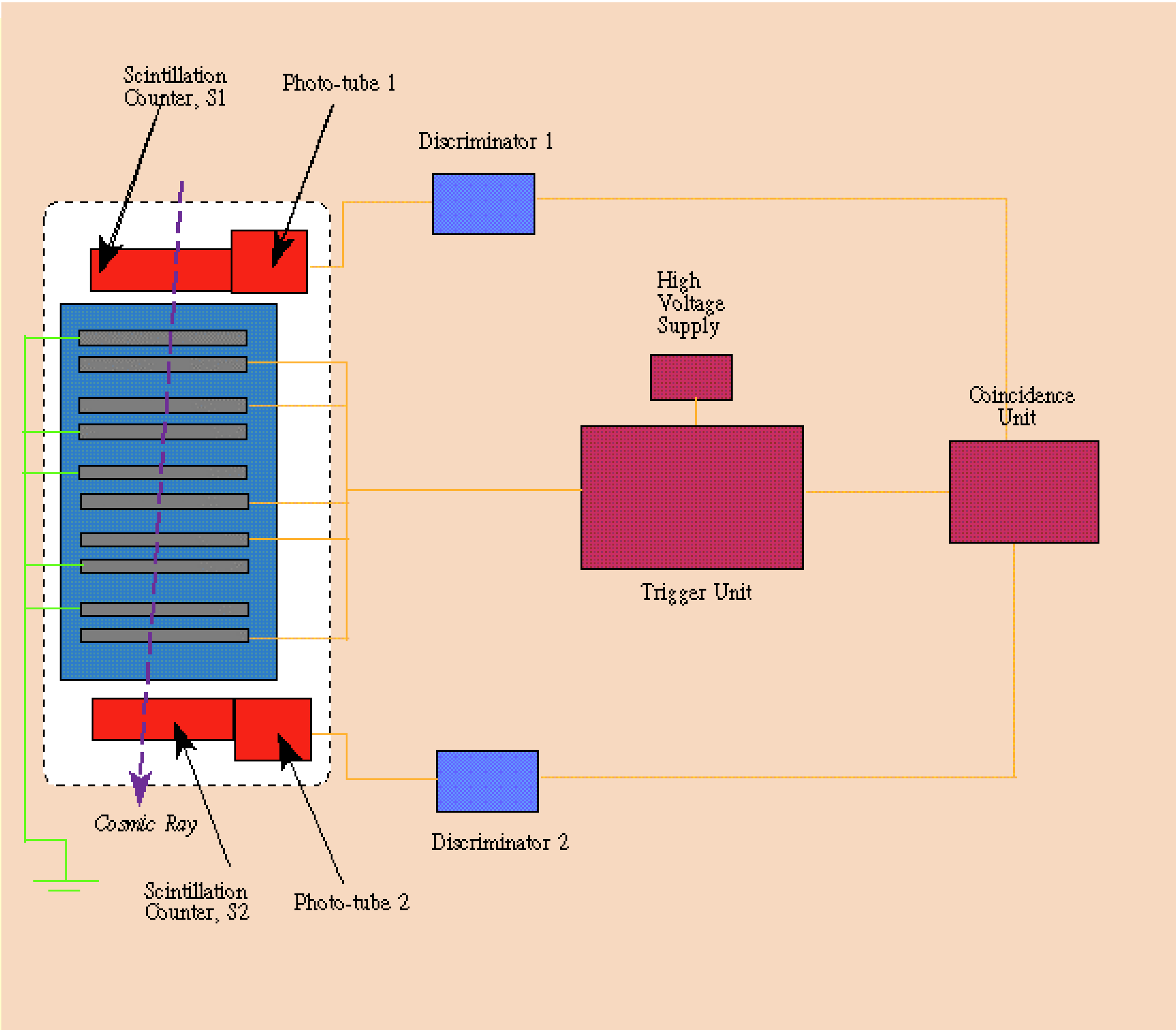


Spark chamber

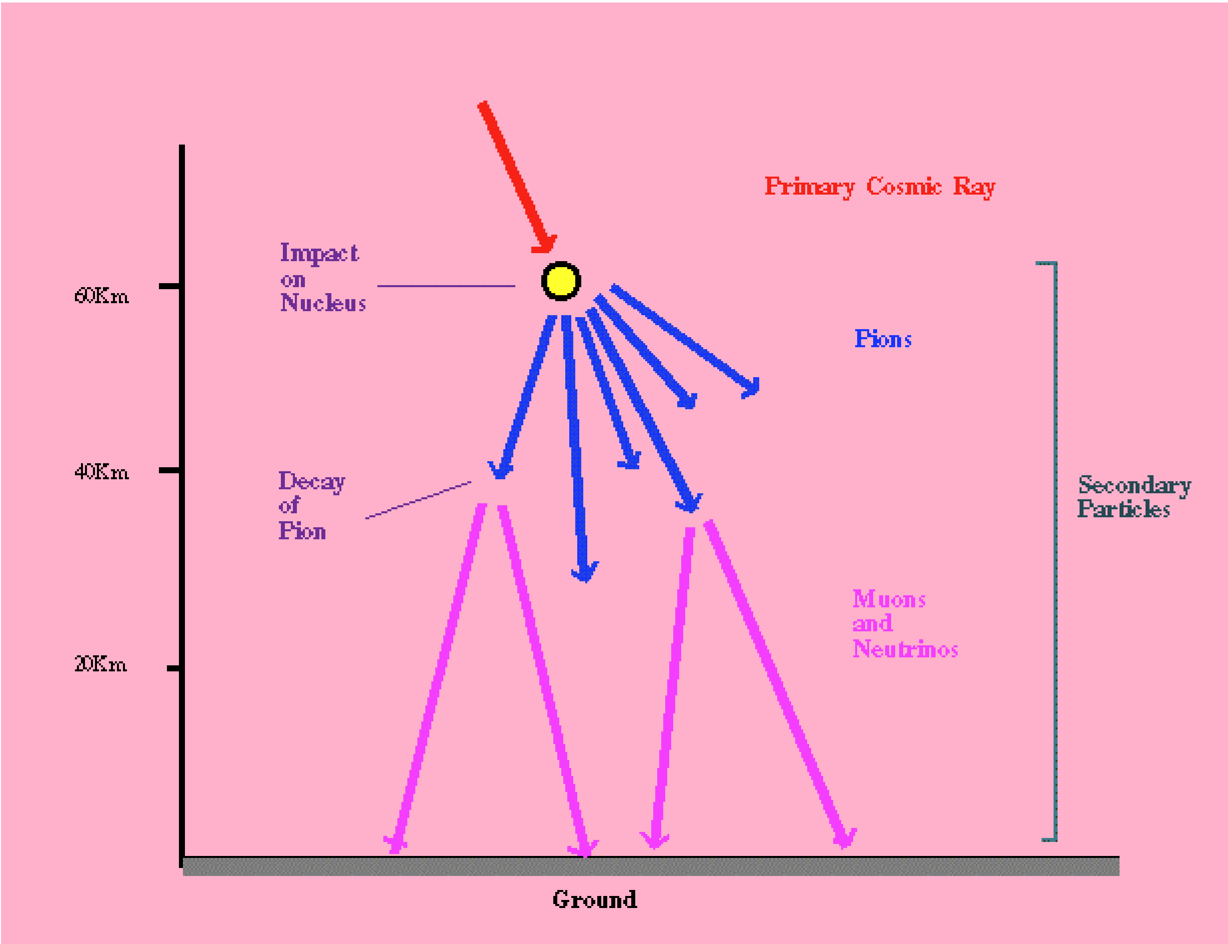
- gas volume with metal plates (electrodes); filled with gas (noble gas, e.g. argon)
- charged particle in gas ⇒ ionization ⇒ electrons liberated; ⇒ string of electron - ion pairs along particle path
- passage of particle through "trigger counters" (scintillation counters) triggers HV
- HV between electrodes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

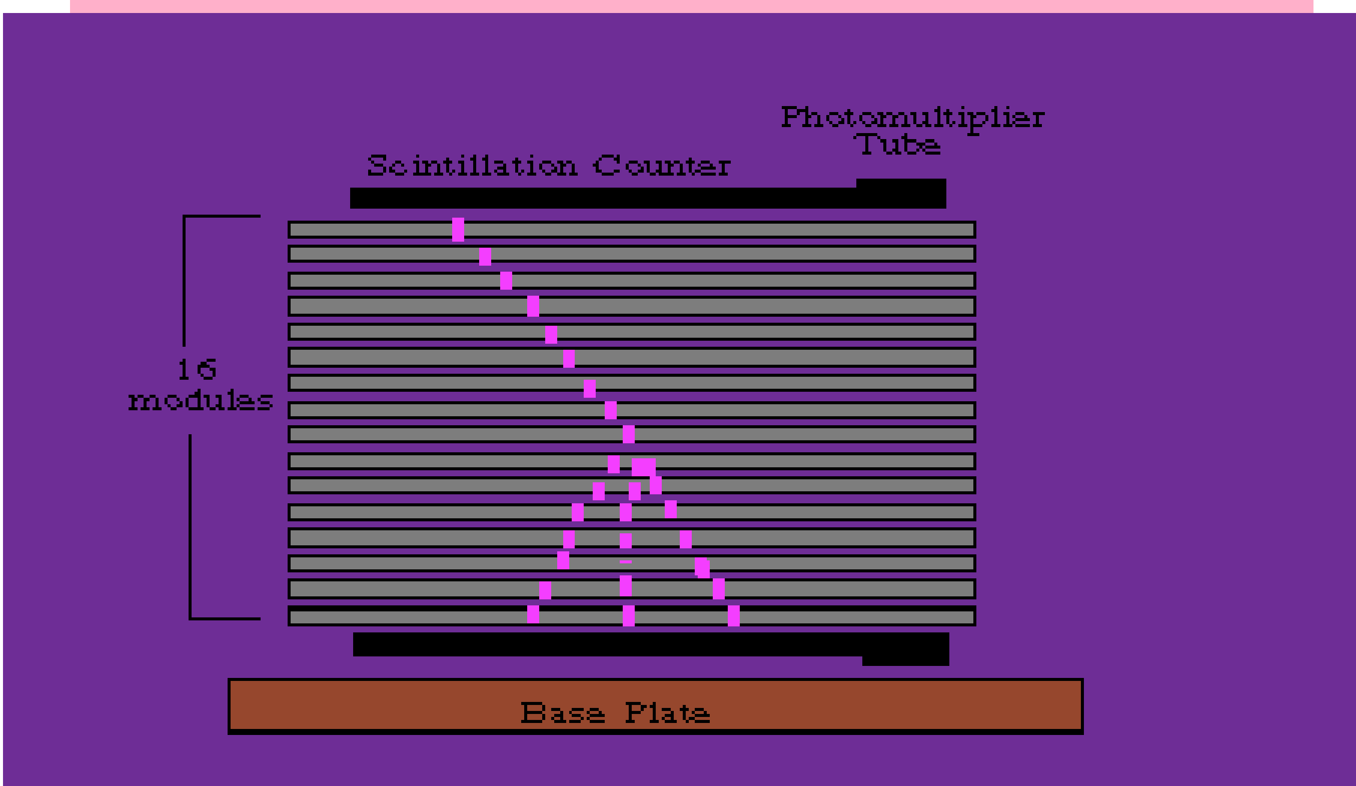


Parts of sparkchamber setup



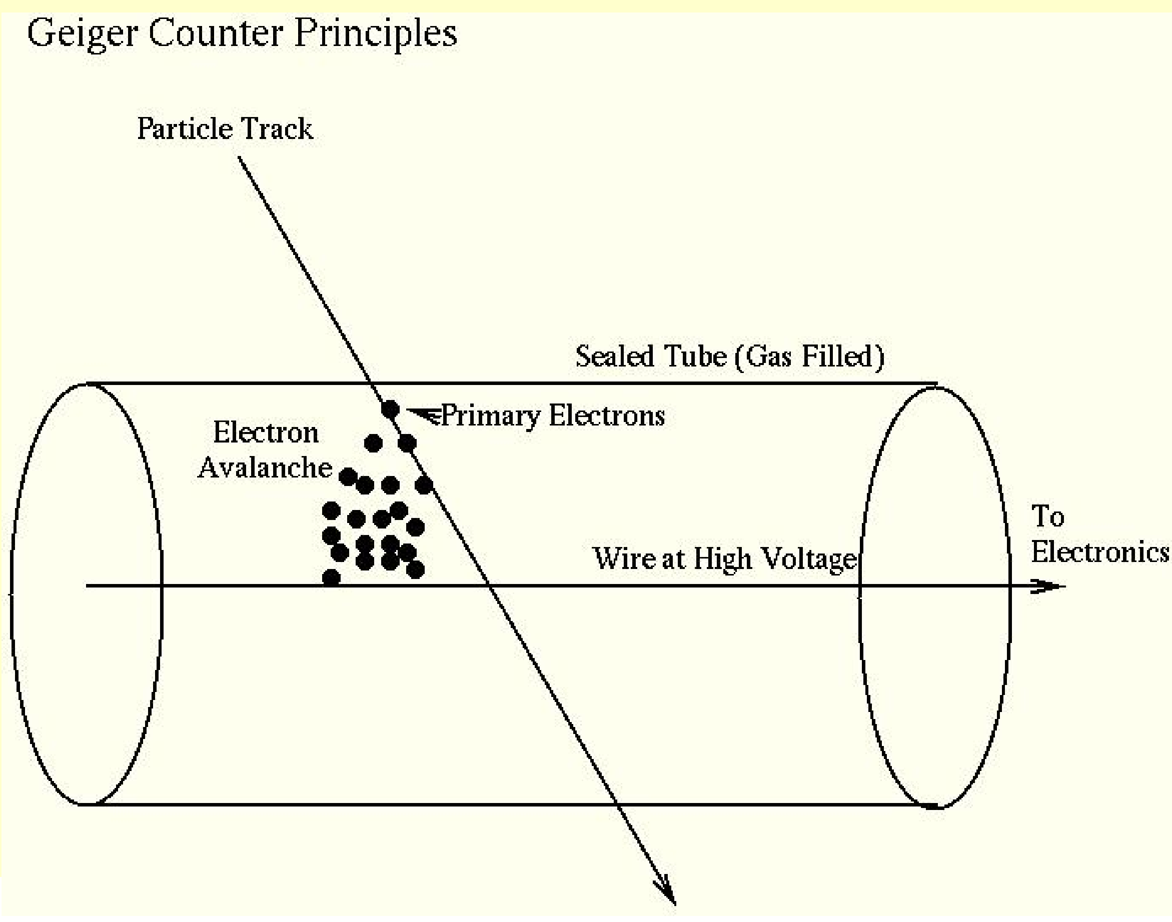
What we see in spark chamber





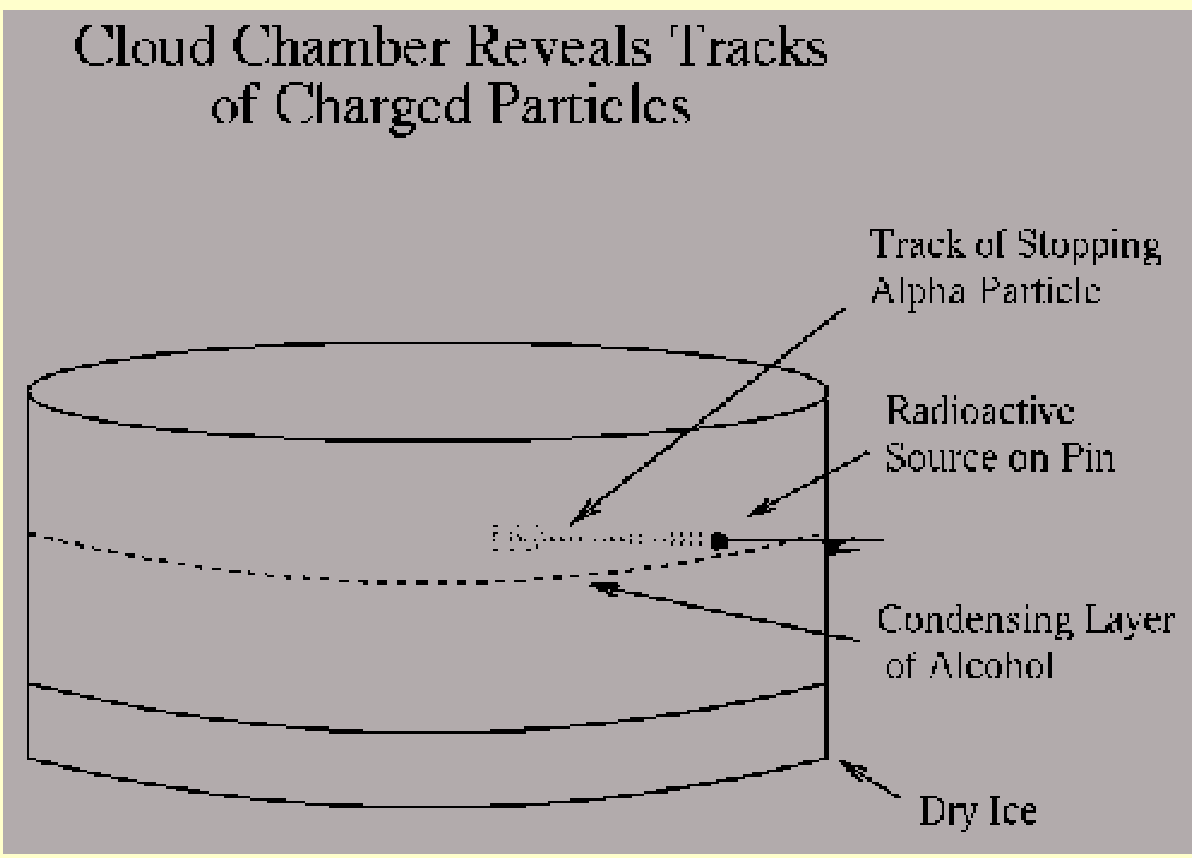
Geiger-Müller counter:

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



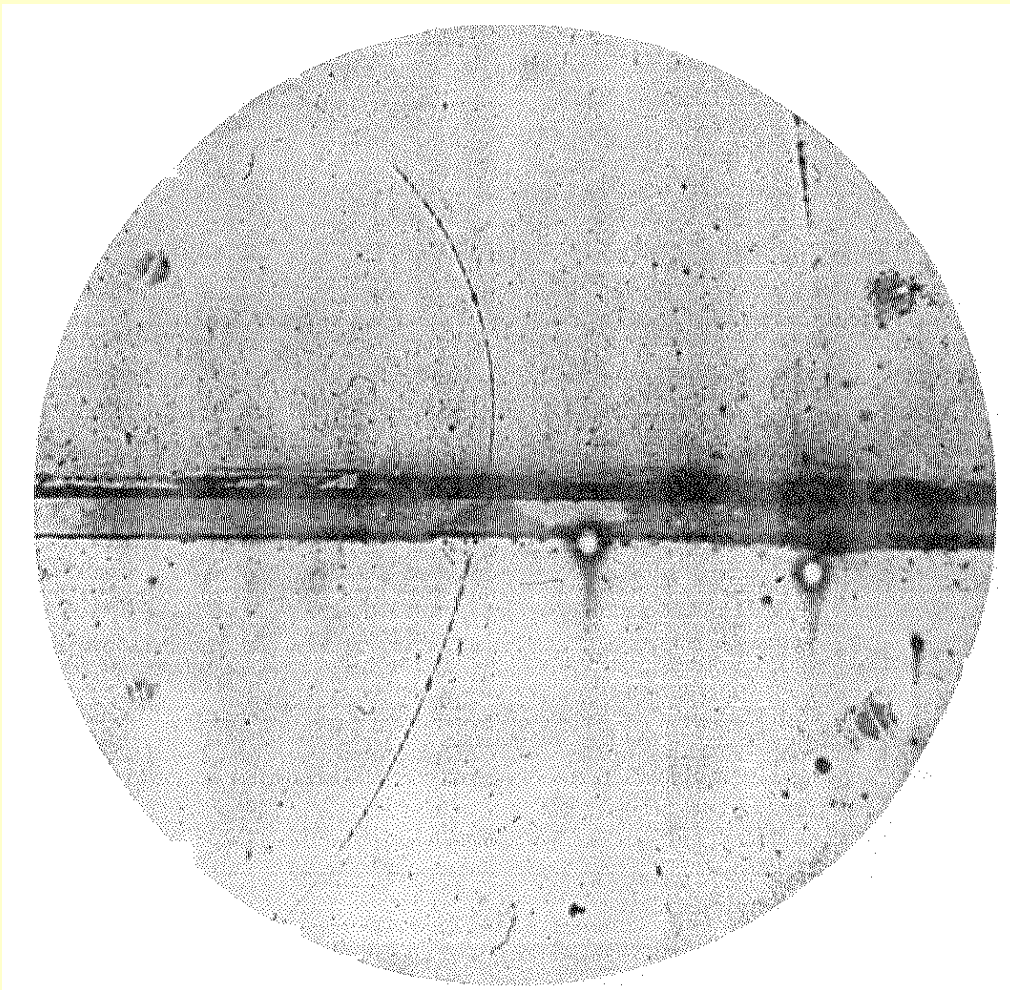
Cloud chamber

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



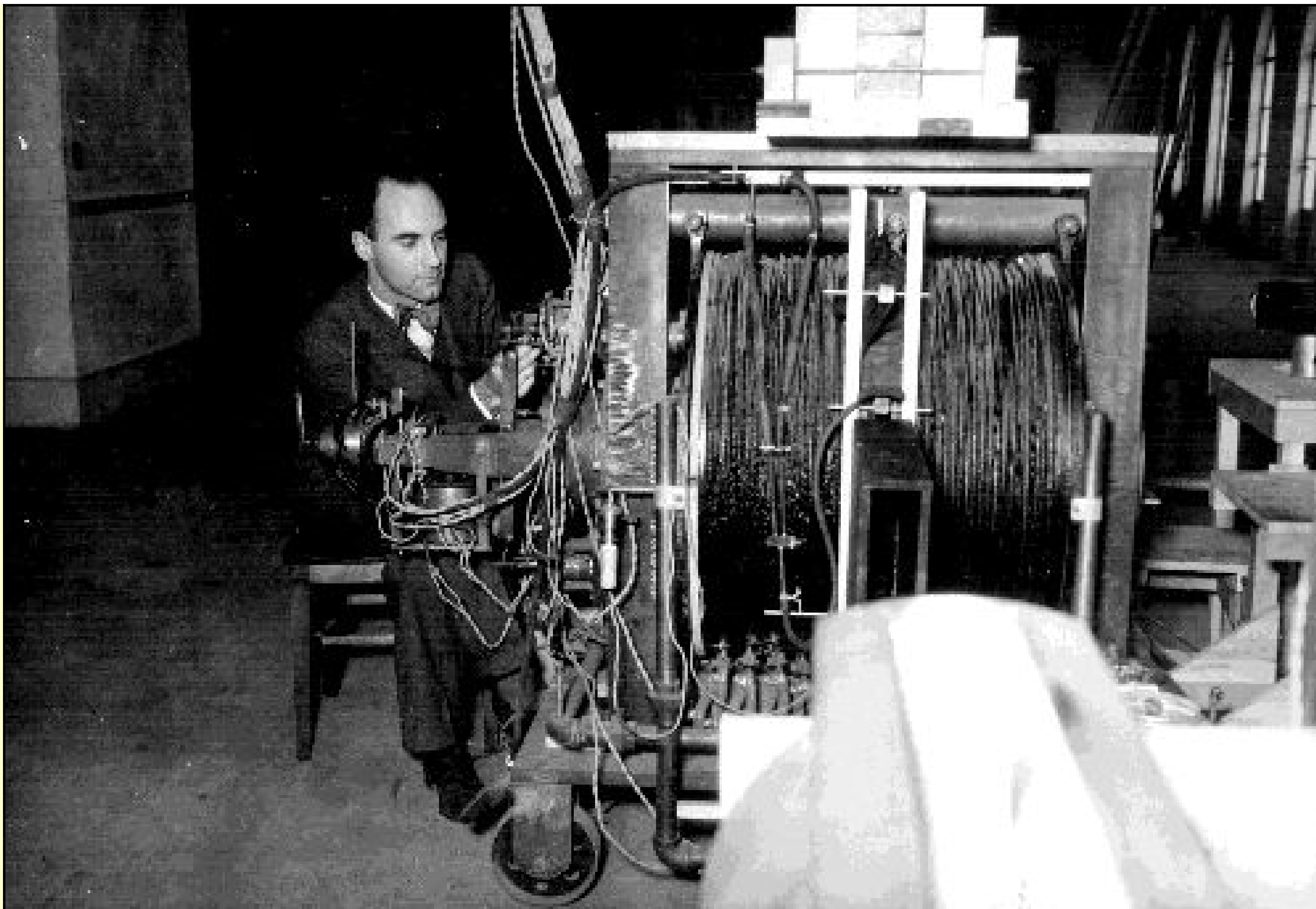
Positron

- 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 mesuring 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

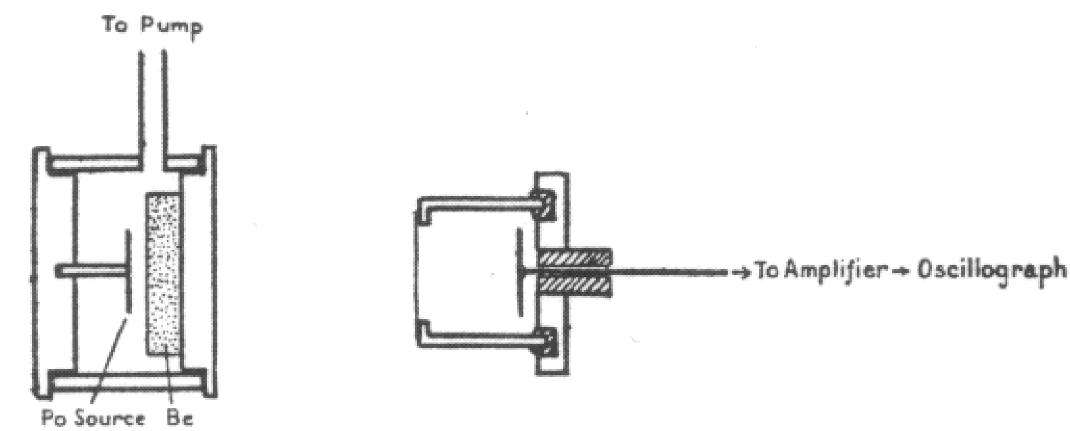
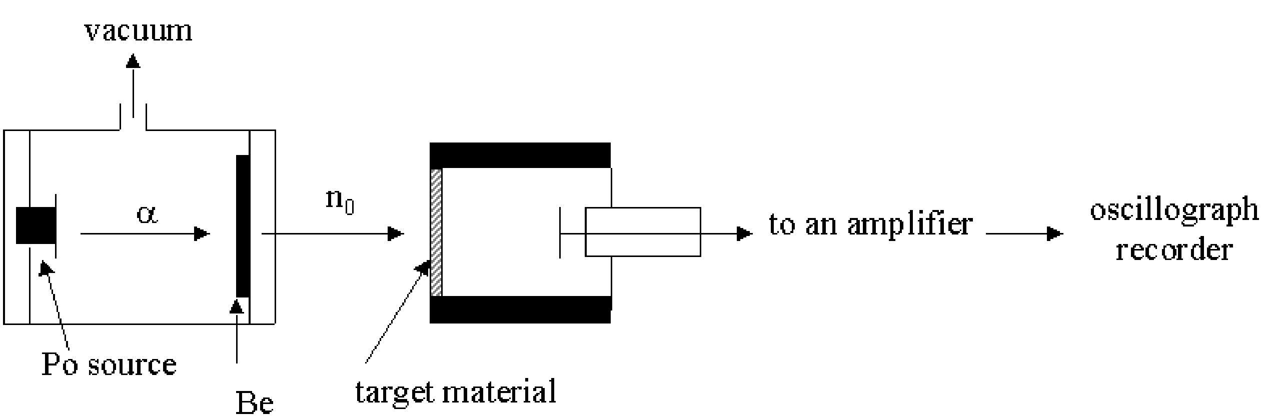


FIG. 1.



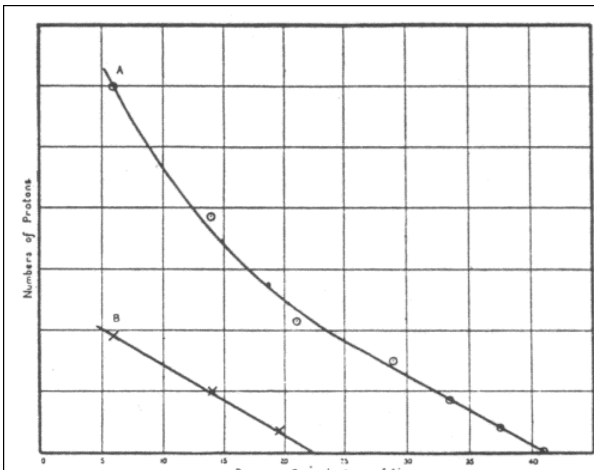
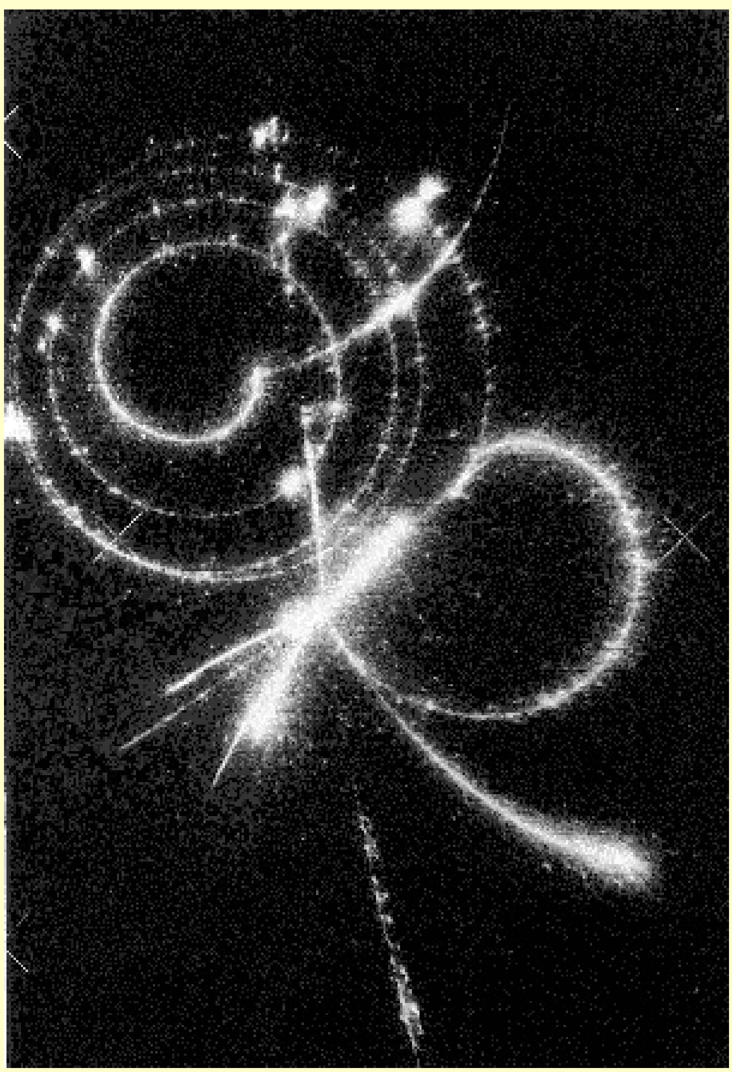


FIG. 2.

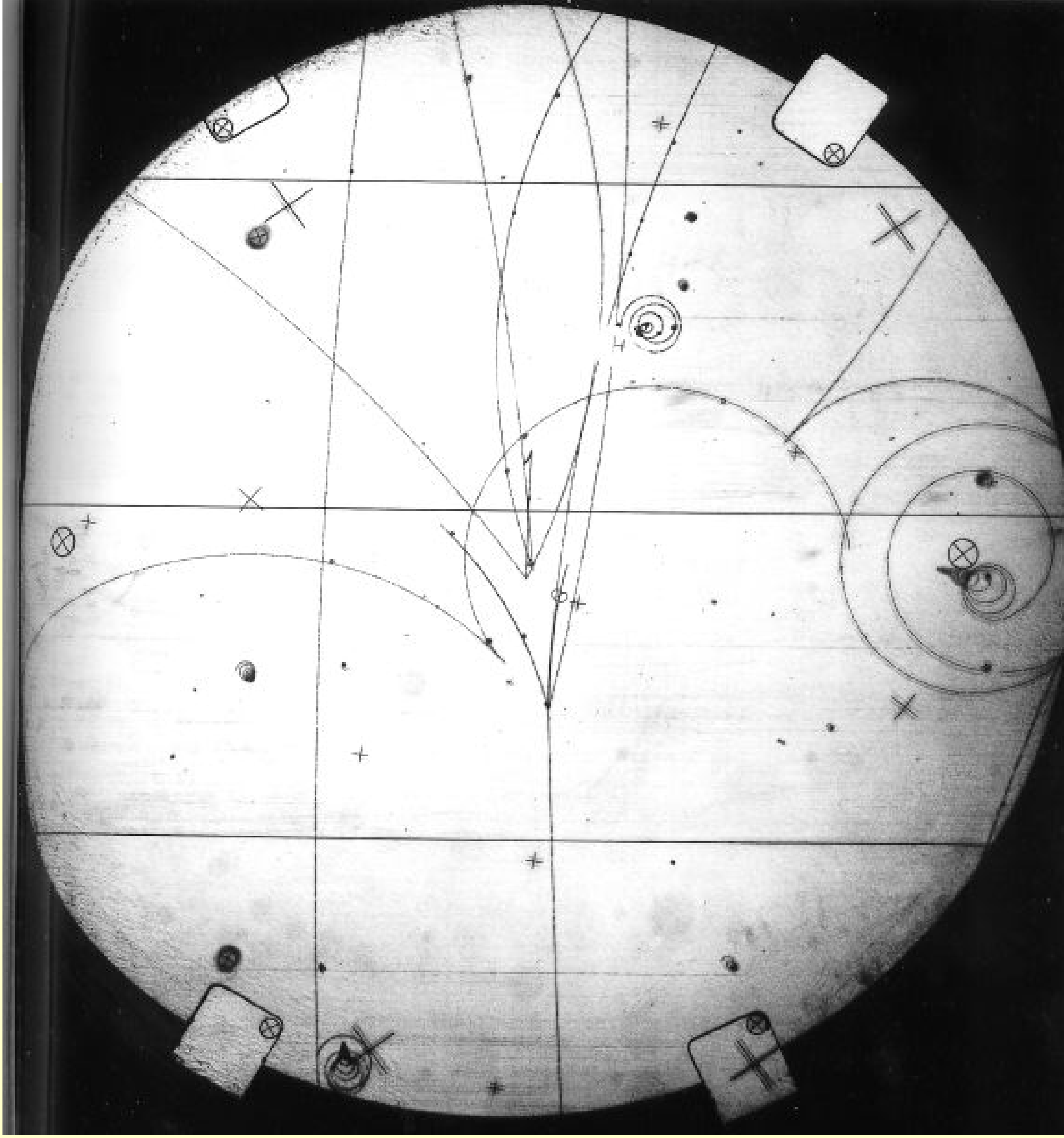
More particles: Pion, Muon,

- 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

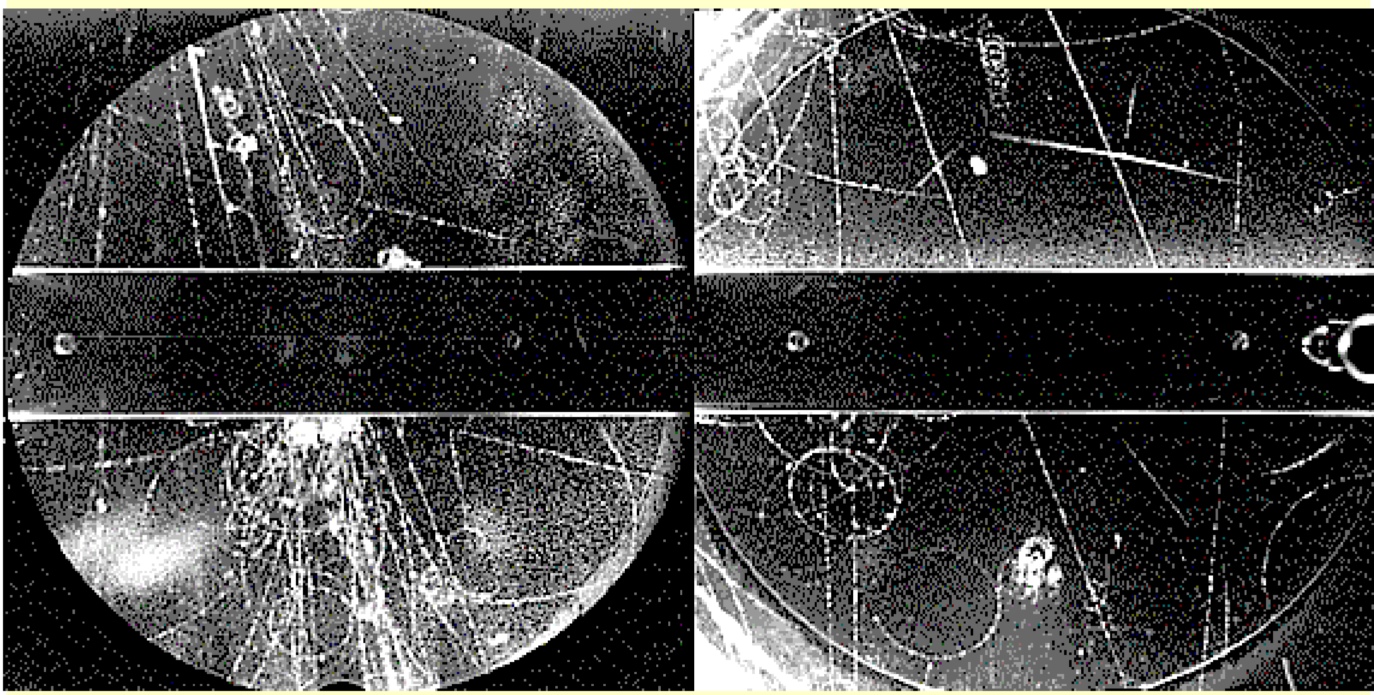
- bubble chamber
  - Vessel, filled (e.g.)with liquid hydrogen at a temperature above the normal boiling point but held under a pressure of about 10 atmospheres by a large piston to prevent boiling.
  - When particles have passed, and possibly interacted in the chamber, the piston is moved to reduce 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)



- pbar p $\rightarrow$ p nbar K^0 K^- π^+ π^- π^0
- nbar + p $\rightarrow$ 3 pions
- $\pi^0 \rightarrow \gamma\gamma$, $\gamma \rightarrow e^+ e^-$
- $K^0 \rightarrow \pi^+ \pi^-$

Kaons

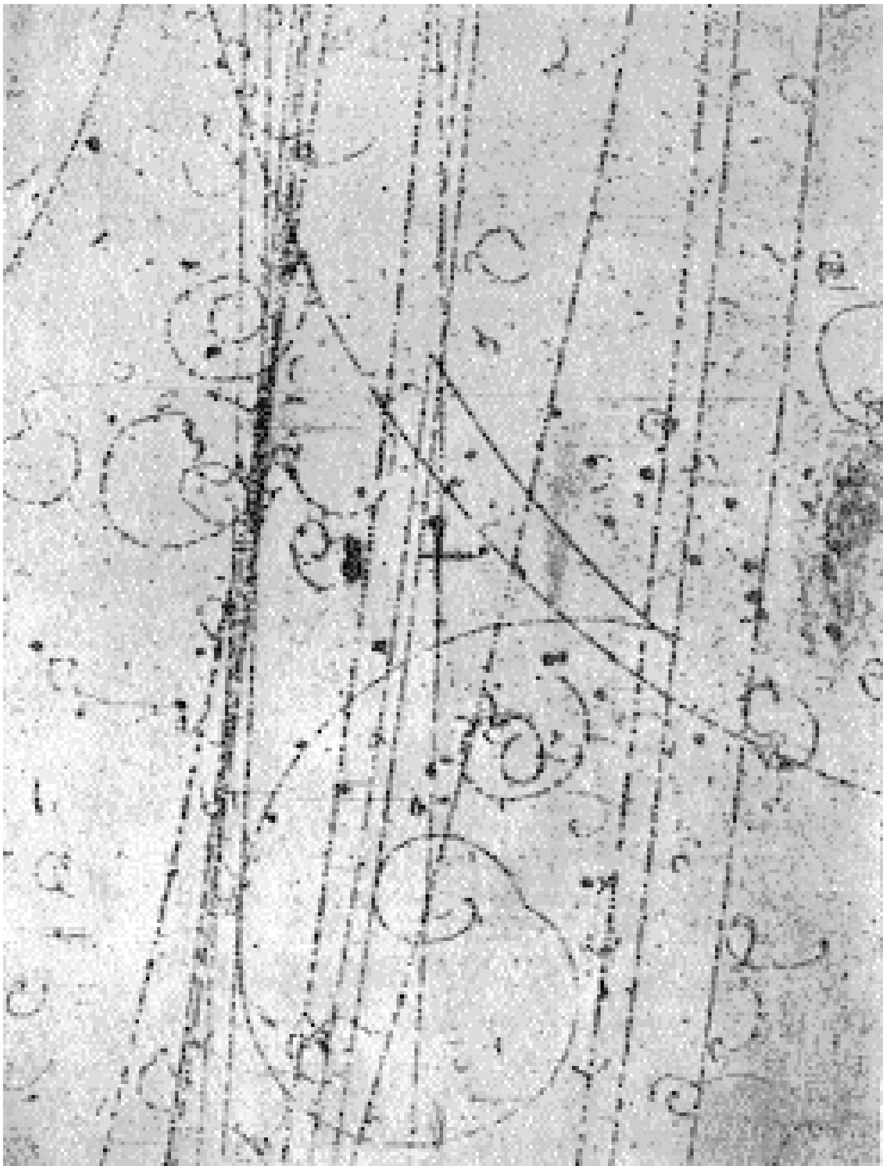
- First observation of Kaons:
  - Cloud chamber exposed to cosmic rays
  - Experiment done by Clifford Butler and George Rochester at Manchester
  - Left picture: neutral Kaon decay (1946)
  - Right picture: charged Kaon decay into muon and neutrino

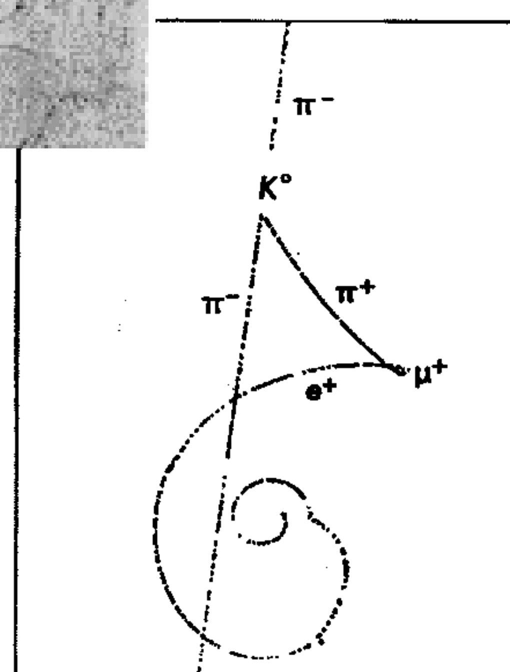


  - Kaons first called "V" particles
  - Called "strange" because they behaved differently from others

“Strange particles”

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





K^0 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 $\lambda = h/p$
  - 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) $\approx$ 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
      $\approx$ 5.29 kgm/s $\approx$ 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

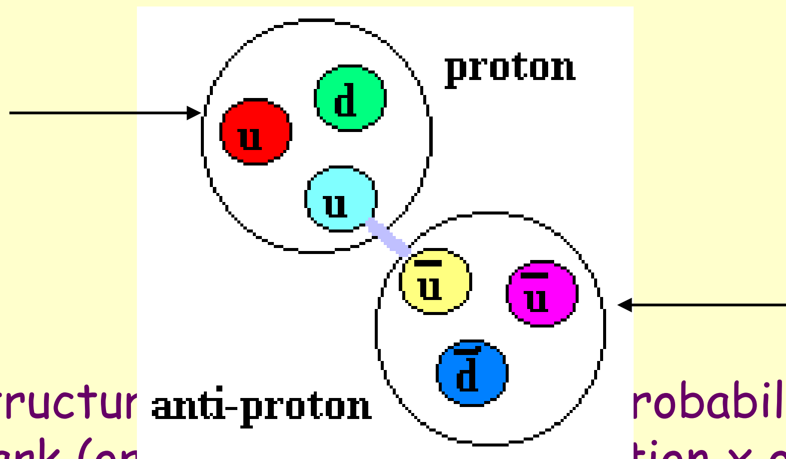
How to get high energy collisions

- Need E_{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: $e^+e^- \to t\bar{t}$, $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$, …
- Shoot particle beam on a target ("fixed target"):
  - $E_{com} = 2\sqrt{Emc^2} \sim 20$ GeV for $E = 100$ GeV, $m = 1$ GeV/c^2

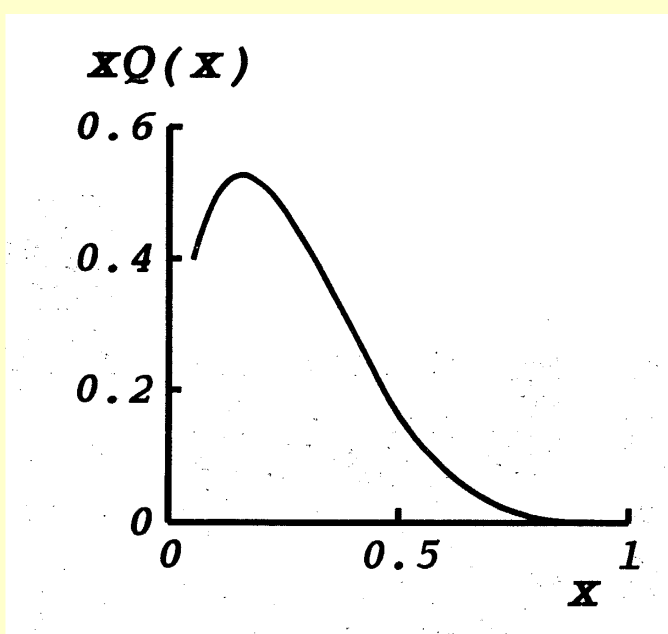
- Collide two particle beams ("collider :
  - $E_{com} = 2E \sim 200$ GeV for $E = 100$ GeV

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.

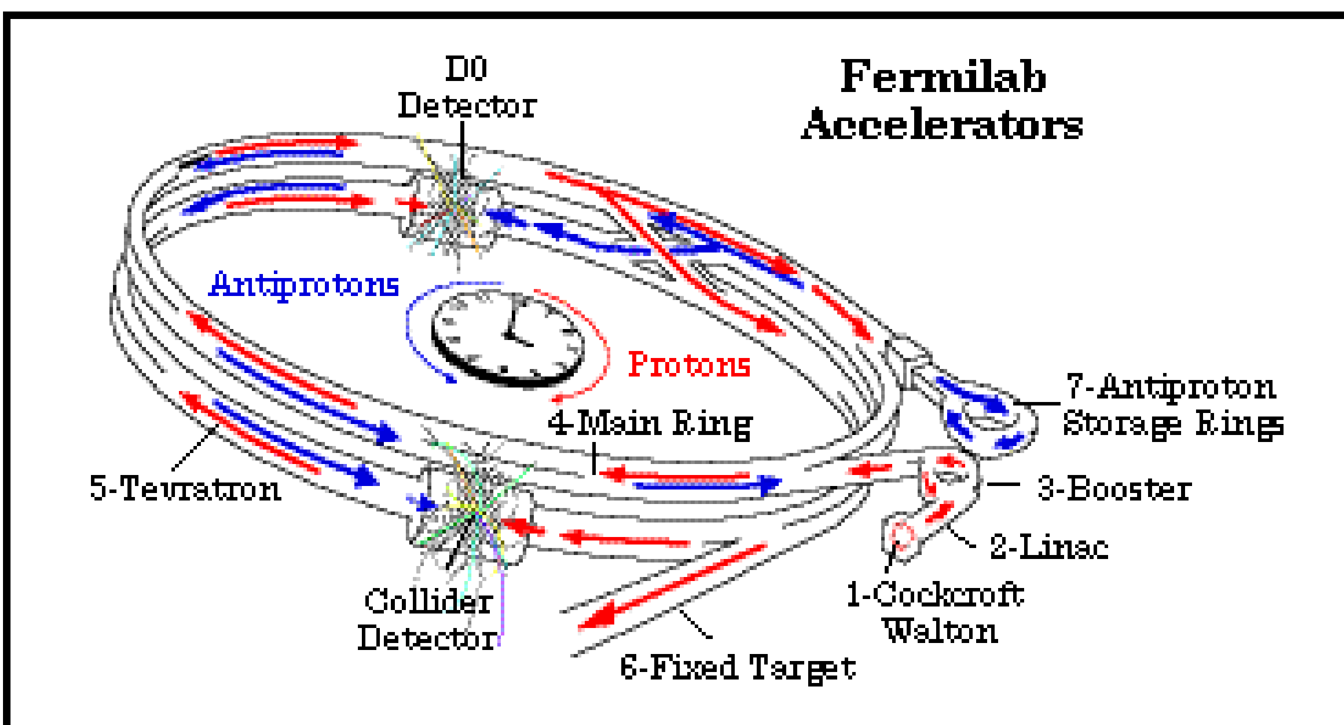


- Proton structur … robability that a single quark (or … ction x of the proton momentum (which is 900 GeV/c at the Tevatron)



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