INTRODUCTION TO PARTICLE PHYSICS PHYS 5380

Recommended reading:

Elementary level

D.H. Perkins, ***Introduction to High Energy Physics***

Medium Level

David Griffith, ***Introduction to Elementary Particles***

Advanced

F. Halzen and A. Martin, ***Quarks and Leptons***

Gordon Kane, ***Modern Elementary Particle Physics, updated edition***

Experimental techniques

Konrad Kleinknecht, ***Detectors for Particle Radiation***

R. Stroynowski, Fall 2016

Textbooks
** first choice*

Elementary level (general)

**Donald Perkins, Introduction to High Energy Physics*
Cindy Schwartz, The subatomic ZOO
R.M. Barnett, H. Muhry and H. Quinn, The Charm of Strange Quarks

Medium Level (theory)

L. Okun, Leptons and Quarks
C. D. Coughlan and J. E. Dodd, The ideas of particle physics
**David Griffith, Introduction to Elementary Particles*
Martinus Veltman, Facts and Mysteries in Elementary Particle Physics

Advanced (theory)

Abraham Seiden, Particle Physics, a comprehensive introduction
F. Halzen and A. Martin, Quarks and Leptons
K. Gottfried and V. Weiskopf, Concepts of Particle Physics
** Gordon L. Kane: "Modern Elementary Particle Physics: Updated Edition"*
Chris Quigg, Gauge Theories of Strong, Weak and Electromagnetic Interactions
Bjorken and Drell, Quantum Field Theory
Kerson Huang, Quarks, Leptons and Gauge Fields
B.R. Martin and G. Shaw, Particle Physics
W.N. Cottingham and D.A. Greenwood, An Introduction to the Standard Model of Particle Physics
Byron P. Roe, Particle Physics at the New Millenium

Experimental techniques

** Richard Fernow, Introduction to experimental particle physics*
Bruno Rossi, High Energy Physics
Konrad Kleinknecht, Detectors for Particle Radiation
Klaus Grupen and Boris Shwartz: "Particle Detectors"
Claude Leroy and Pier-Giorgio Rancoita: "Principles of Radiation Intercations In Matter And Detection (3rd Edition)

Syllabus

Aug 22 (Mon)	*Introduction, historical perspective, discovery of the electron, nucleus and neutron*
Aug 24(Wed)	“
Aug 26(Fri)	*Quantum mechanics and relativity, particle –wave duality*
Aug 29(Mon)	*Neutrino*
Aug 31(Wed)	“
Sep 2(Fri)	*Forces and interactions*
***Sep 5(Mon)**	***LABOR DAY – no class***
Sep 7(Wed)	*Particle ZOO: Leptons(electrons, muons, neutrinos), quarks (pions, kaons, resonances), bosons - carrier of the force*
Sep 9(Fri)	**“**
Sep 12(Mon)	“
Sep 14(Wed)	*Symmetries, conservation laws and quantum numbers: E-p, charge, angular momentum, parity, isospin, G-parity, lepton number, baryon number, flavor, charge conjugation*
Sep 16(Fri)	“
Sep 19(Mon)	“
Sep 21(Wed)	*Static quark model, relativistic kinematics, lab-vs-cm*
Sep 23(Fri)	*Dynamics, DIS, parton model*
Sep 26(Mon)	“
Sep 28(Wed)	*CP violation, CKM matrix*
Sep 30(Fri)	*Weak interactions, the Standard Model, neutrino mixing*
Oct 3(Mon)	“
Oct 5(Wed)	*Higgs*
Oct 7(Fri)	*Astrophysics connection (composition of the universe, dark matter, dark energy)*
**Oct 10(Mon)*	***FALL BREAK – no class***
Oct 12(Wed)	*Astrophysics questions*
Oct 14(Fri)	*Feynman diagrams*
Oct 17(Mon)	“
Oct 19(Wed)	*Particle detectors: charged particles: ionization (emulsion, cloud and bubble chambers, wire chambers - spark, proportional, drift chambers), limitations on momentum measurements: Energy loss: Bethe-Bloch, dE/dx, radiation length, bremstrahlung, Coulomb scattering, position in space*
Oct 21(Fri)	*Photon detection*
Oct 24(Mon)	*Calorimetry*
Oct 26(Wed)	*Particle detectors: neutrals: decays of pi0, Ks, Lambda, photon conversions, neutron interactions*
Oct 28(Fri)	*Scintillators, fibers*
Oct 31(Mon)	*Particle identification: TOF, Cerenkov light, dE/dx, muons*
Nov 2(Wed)	*Readout electronics, trigger, solid state trackers, radiation damage*
Nov 4(Fri)	*Particle detectors – neutrinos*
Nov 7(Mon)	*Detector systems, ATLAS*
Nov 9(Wed)	*Particle acceleration techniques: electrostatic, RF; cyclotron, synchrotron, linacs, storage rings*

Nov 11(Fri)	*Student Presentation*
Nov 14(Mon)	*Student Presentation*
Nov 16(Wed)	*Student Presentation*
Nov 18(Fri)	*Student Presentation*
Nov 21(Mon)	*Student Presentation*
***Nov 23(Wed)**	**Thanksgiving – no class**
***Nov 25(Fri)**	**Thanksgiving – no class**
Nov 28(Mon)	*Student Presentation*
Nov 30(Wed)	*Student Presentation*
Dec 2(Fri)	*Student Presentation*
Dec 5(Mon)	*Open questions, Grand Unification, Supersymmetry, superstrings*

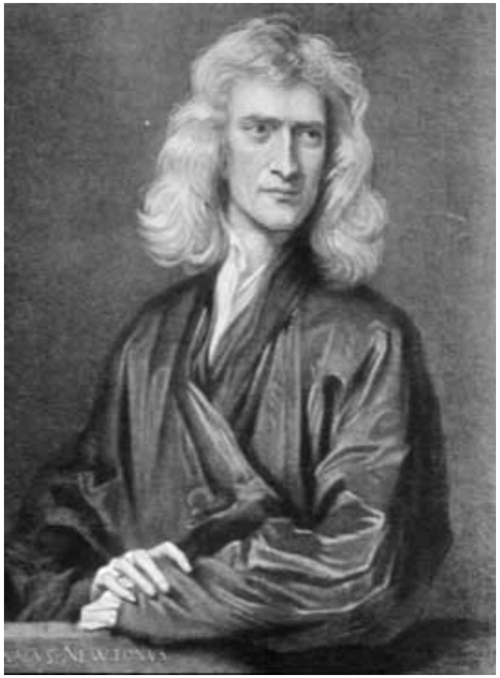
Tentative subjects for seminar presentations

Dark matter
Magnetic monopole
Neutrino Oscillations/Dune
Gravitational waves/LIGO
CP violations
Higgs boson
Supersymmetry
Antimatter
Dark energy

Grading

Homework 40%, Presentation – 40%, class participation – 20%

Isaack Newton

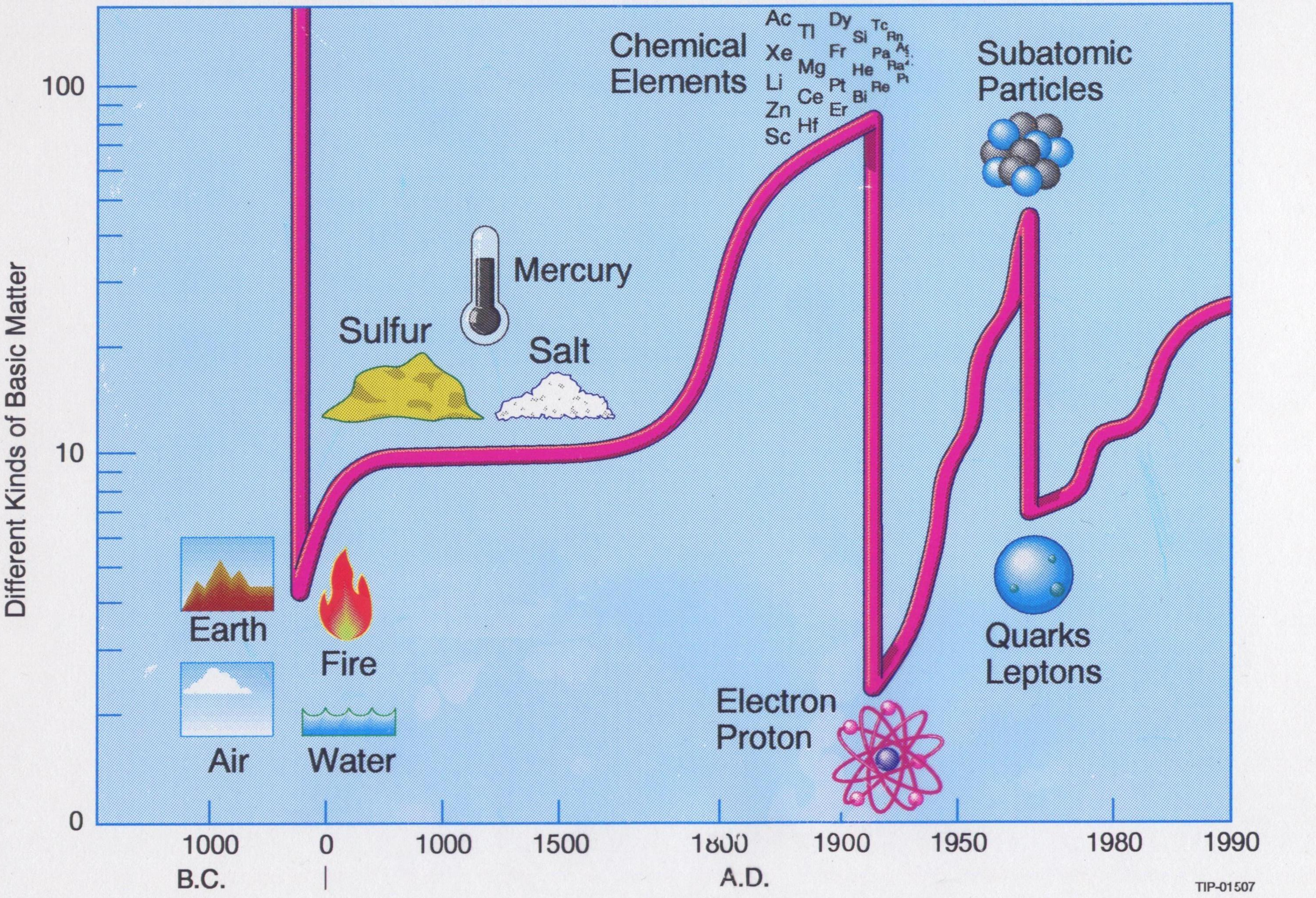


From a portrait by Kneller in 1689

Optics (1680)

"Now the smallest Particles of Matter may cohere by the strongest Attractions and compose bigger Particles of weaker Virtue. There are therefore Agents of Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out."

History of Elementary Particles



The “elementary particles” at the end of the 19th century:

The Atoms of the 92 Elements

f

1. Hydrogen
2. Helium
3. Lithium

....

....

92. Uranium

Mass $M_H \approx 1.7 \times 10^{-24}$ g

increasing mass

Mass $\approx 238\, M_H$

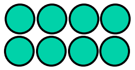
Estimate of a typical atomic radius

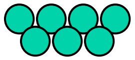
Number of atoms /cm^3: $$n = \frac{N_A}{A}\rho$$

$N_A \approx 6 \times 10^{23}\ \mathrm{mol}^{-1}$ (Avogadro constant)
A: molar mass
r: density

Atomic volume: $$V = \frac{4}{3}\pi R^3$$

Packing fraction: $f \approx 0.52 — 0.74$





$$R = \left(\frac{f}{(4/3)\pi n}\right)^{1/3}$$

Example: Iron ($A = 55.8$ g; $\rho = 7.87$ g cm^{-3})

$$R = (1.1 \div 1.3) \times 10^{-8}\ \text{cm}$$

1894 – 1897: Discovery of the electron

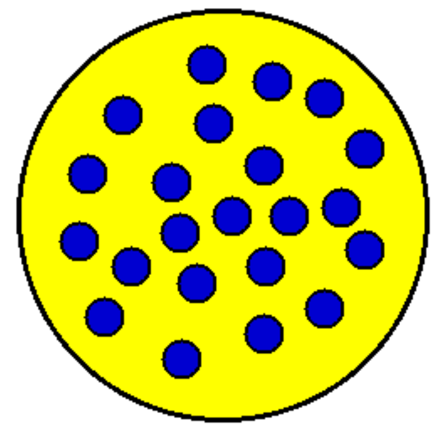
J.J. Thomson

Study of "cathode rays": electric current in tubes at very low gas pressure ("glow discharge")
→Current carried by particles

Measurement of the electron mass: $m_e \approx M_H/1836$

"Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?" (J.J. Thomson)
"What good is it for?" (Queen Victoria)

➡ ATOMS ARE NOT ELEMENTARY



Thomson's atomic model (plum pudding):

- Sphere with uniform positive charge distribution
- Radius ~ 10^{-10} m
- Electrons with negative electric charge embedded in the sphere

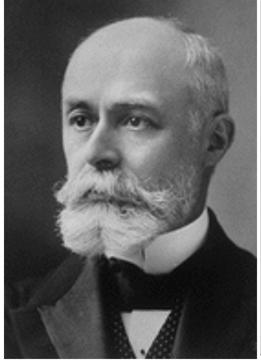
1896: Discovery of natural radioactivity

(Henri Becquerel, Maria Skłodowska-Curie)

α – heavy, charged, β – light, charged, γ - neutral

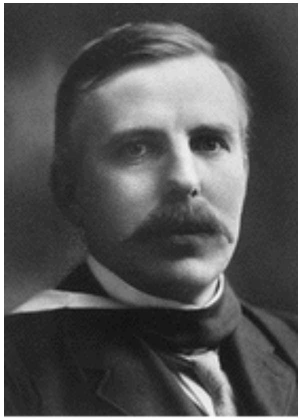
1909−13: Rutherford's scattering experiments

Discovery of the atomic nucleus

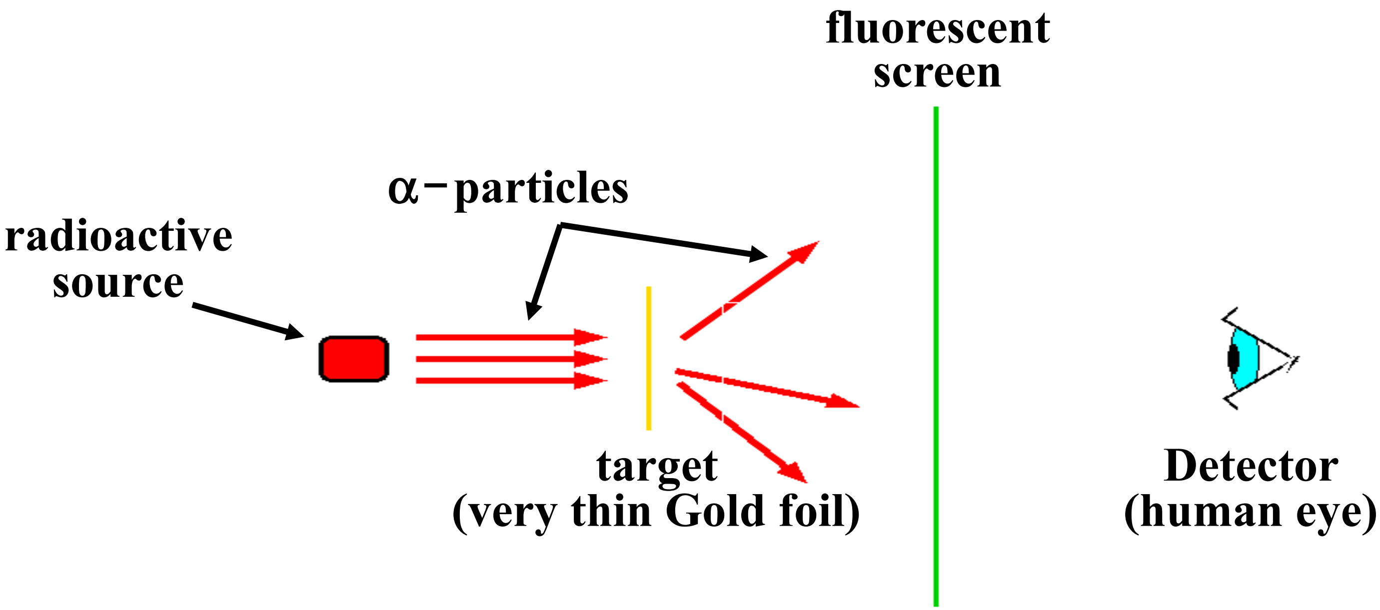


Henri Becquerel

Maria Curie



Ernest Rutherford

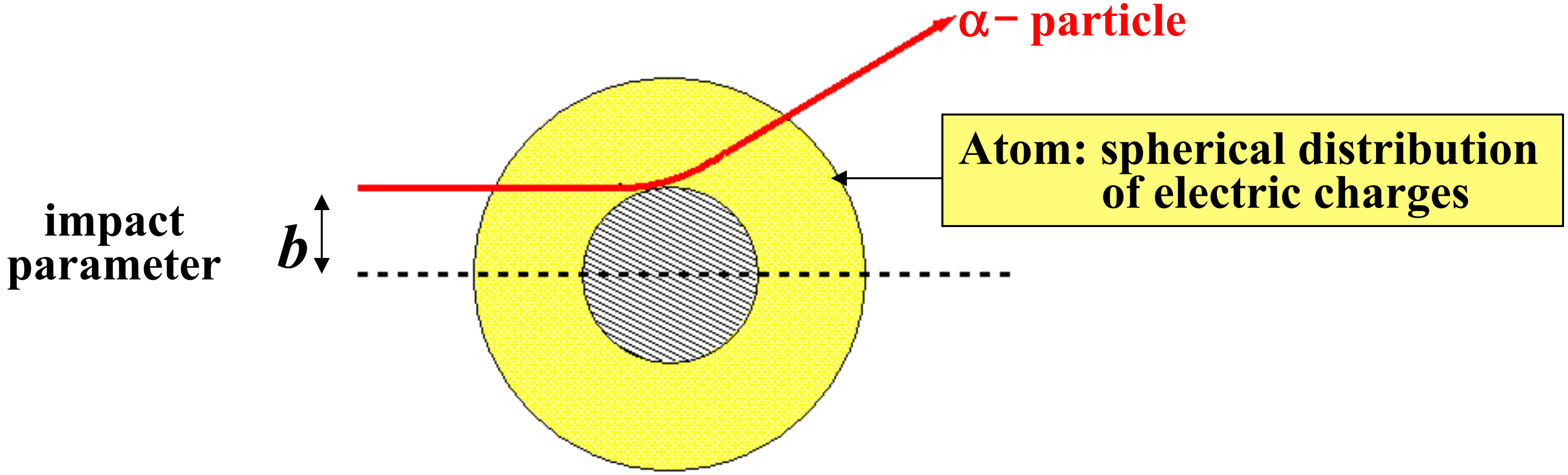


α−particles: nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes

Typical α – particle velocity $\approx 0.05\,c$ (c : speed of light)

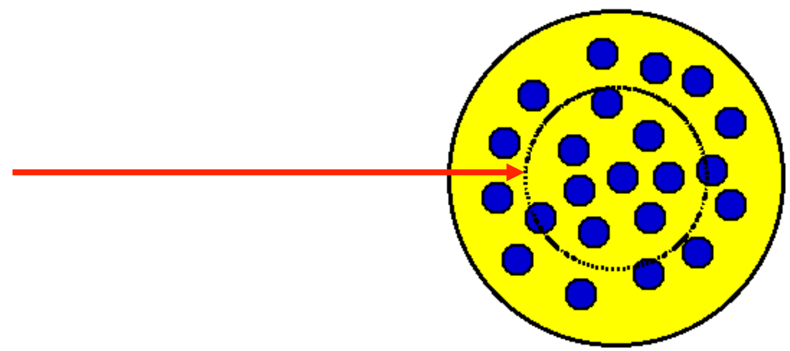
Expectations for α – atom scattering

α – atom scattering at low energies is dominated by Coulomb interaction



α – particles with impact parameter = *b* "see" only electric charge within sphere of radius = *b* (Gauss theorem for forces proportional to r^{-2})

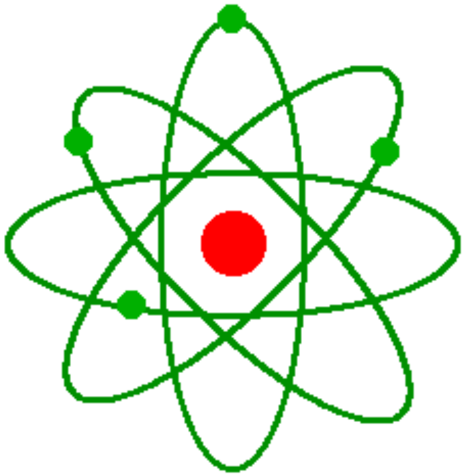
For Thomson's atomic model the electric charge "seen" by the α – particle is zero, independent of impact parameter



→ no significant scattering at large angles is expected

Rutherford's observation:

significant scattering of α – particles at large angles, consistent with scattering expected for a sphere of radius ≈ few x 10^{-15} m and electric charge = Ze, with Z = 79 (atomic number of gold) and e = |charge of the electron|



→ **an atom consists of a positively charged nucleus surrounded by a cloud of electrons**

Nuclear radius ≈ 10^{-15} m ≈ 10^{-5} × atomic radius

Mass of the nucleus ≈ mass of the atom
(to a fraction of 1‰)

First (wrong) ideas about nuclear structure (before 1932)

Observations

- **Mass values of light nuclei ≈ multiples of proton mass (to few %) (proton ≅ nucleus of the hydrogen atom)**
- **β decay: spontaneous emission of electrons by some radioactive nuclei**

Hypothesis: the atomic nucleus is a system of protons and electrons strongly bound together

Nucleus of the atom with atomic number Z and mass number A: a bound system of A protons and $(A - Z)$ electrons

Total electric charge of the nucleus = $[A - (A - Z)]e = Z\,e$

Problem with this model:

- **Too many protons in the nucleus (need electrons in the nucleus to balance the charge) e.g., M(He) ~ 4 × M(H) but there are only 2 orbital electrons**
- **Chemical isotopes have different masses**
- **Quantum mechanics – hyperfine splitting of Nitrogen spectral lines indicates angular momentum (spin) of N nucleus = 1**
  Electron, proton spin = ½ħ (measured)
  N(A = 14, Z = 7): 14 protons + 7 electrons = 21 spin ½ particles

DISCOVERY OF THE NEUTRON (Chadwick, 1932)

James Chadwick

Neutron: a particle with mass ≈ proton mass but with zero electric charge

Solution to the nuclear structure problem:

Nucleus with atomic number *Z* and mass number *A*: a bound system of *Z* protons and (*A* – *Z*) neutrons

Nitrogen anomaly: no problem if neutron spin = ½ħ

Nitrogen nucleus (A = 14, Z = 7): 7 protons, 7 neutrons = 14 spin ½ particles

=> **total spin has integer value**

Should observe new type of radiation (neutrons) resulting from the bombarding of Be with α particles

Neutron source in Chadwick's experiments: a ^{210}Po radioactive source (5 MeV α – particles) mixed with Beryllium powder => emission of electrically neutral radiation capable of traversing several centimeters of Pb:

$$\underbrace{{}^{4}\mathrm{He}_{2}}_{\alpha\text{ - particle}} + {}^{9}\mathrm{Be}_{4} \rightarrow {}^{12}\mathrm{C}_{6} + \text{neutron}$$

How do we detect neutral particles?

• **Passage of charged particles through matter**

Interaction with atomic electrons

→ **ionization**
(neutral atom –> ion$^+$ + free electron)

→ **excitation of atomic energy levels**
(de-excitation –> photon emission)

Interaction with atomic nucleus

→ **inelastic collisions**
(many secondary particles)

→ **elastic collisions**
(recoil nucleus)

Probability of interaction with nucleus is much smaller than probability of interaction with atomic electron.

•Size of the electron shell/size of the nucleus ~ 10^5

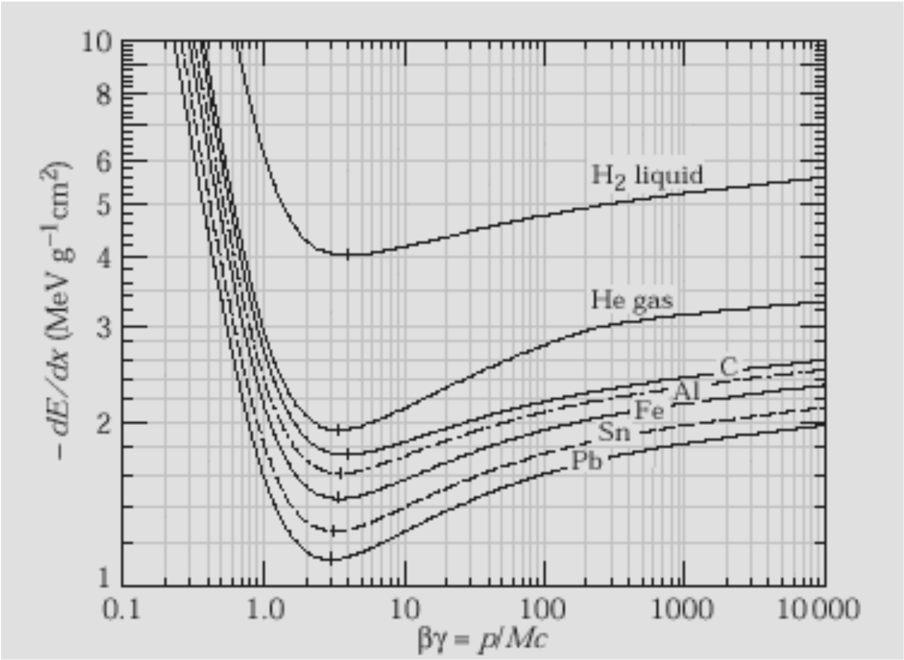
•Range of electromagnetic force/range of strong force ~ ∞

Energy loss

Ionization + excitation of atomic energy levels → energy loss

Mean energy loss rate – *dE* /*dx*

- **proportional to (electric charge)^2 of incident particle**
- **for a given material, function only of incident particle velocity**
- **typical value at minimum:**
  $-dE/dx = 1 – 2$ **MeV /(g cm^{-2})**



NOTE: traversed thickness (*dx*) is given in g /cm^2 to be independent of material density (for variable density materials, such as gases)
→ multiply *dE* /*dx* by density (g/cm^3) to obtain *dE* /*dx* in MeV/cm

Range of passage of charged particle through matter

Residual range of a charged particle with initial energy E_0 that is losing energy only by ionization and atomic excitation:

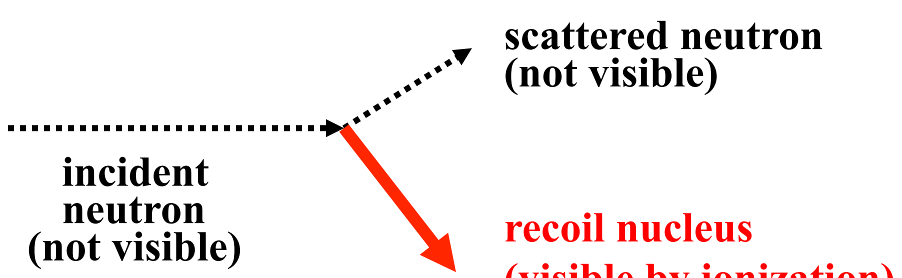
$$R = \int_0^R dx = \int_{E_0}^{Mc^2} \frac{1}{dE/dx} dE = MF(\mathrm{v})$$

$\boldsymbol{M}$**:** particle rest mass
v: initial velocity
$E_0 = Mc^2 / \sqrt{1-(\mathrm{v}/c)^2}$

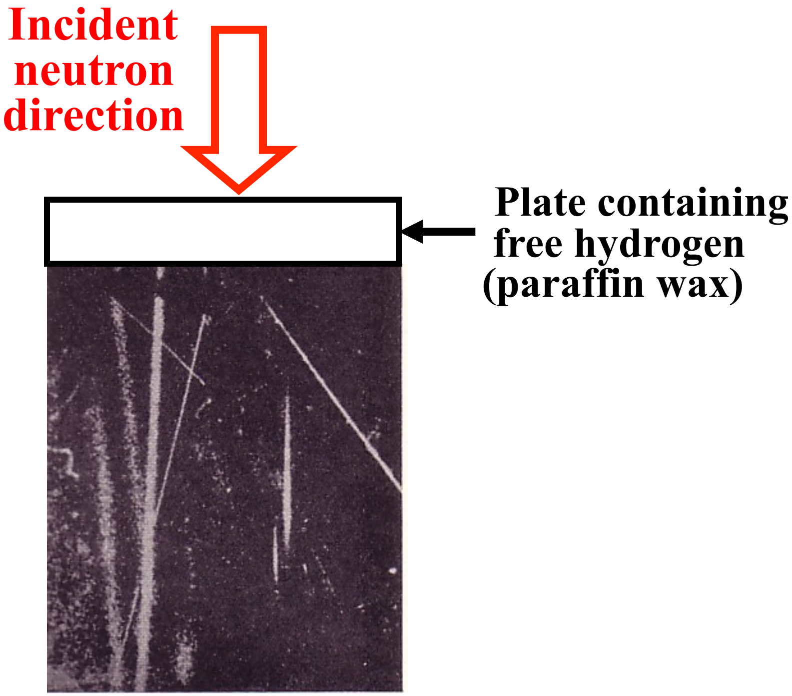
=> the measurement of R for a particle of known rest mass M is a measurement of the initial velocity

Passage of neutral particles through matter: no interaction with atomic electrons
=> detection possible only in case of collisions producing charged particles

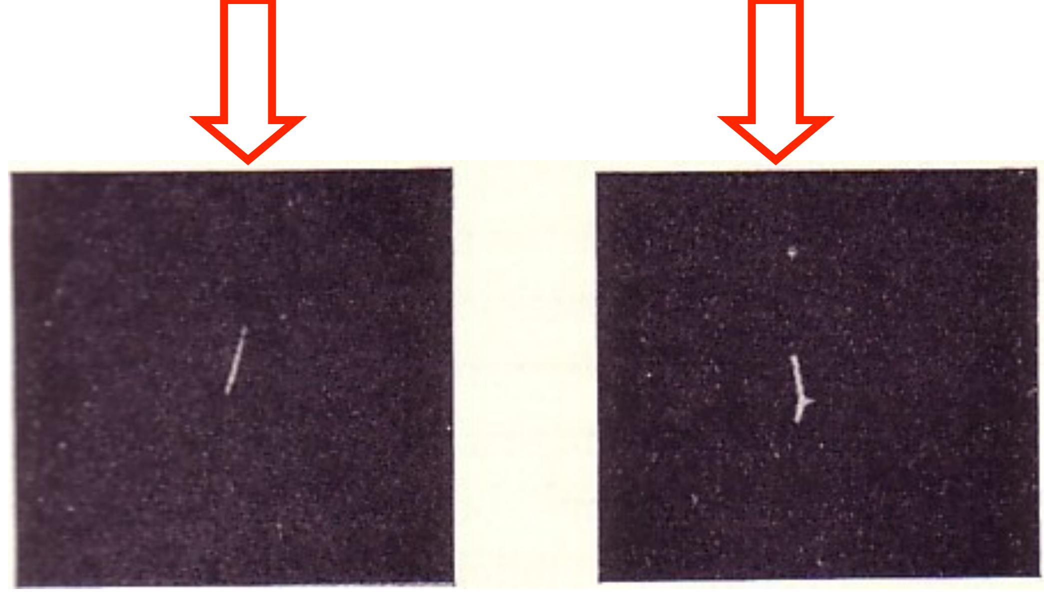
Neutron discovery:
observation and measurement of nuclear recoils in an "expansion chamber" filled with Nitrogen at atmospheric pressure



An old gaseous detector based on an expanding vapour; ionization acts as seed for the formation of liquid drops. Tracks can be photographed as strings of droplets



proton tracks ejected from paraffin wax



Recoiling Nitrogen nuclei

Assume that incident neutral radiation consists of particles of mass m moving with velocities $v < V_{max}$

Determine max. velocity of recoil protons (U_p) and Nitrogen nuclei (U_N) from max. observed range

$$U_p = \frac{2m}{m + m_p} V_{max} \qquad U_N = \frac{2m}{m + m_N} V_{max}$$

(From non-relativistic energy-momentum conservation
m_p: proton mass; m_N: Nitrogen nucleus mass)

$$\Rightarrow \quad \frac{U_p}{U_N} = \frac{m + m_N}{m + m_p}$$

From measured ratio U_p / U_N and known values of m_p, m_N determine neutron mass: $m = m_n \approx m_p$

Present mass values : $m_p = 938.272 \text{ MeV}/c^2$ $\qquad m_n = 939.565 \text{ MeV}/c^2$