# 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***

**Richard Fernow, Introduction to experimental particle physics**

**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 21(Mon)* | *Solar eclipse* |
| *Aug 23 (Wed)* | *Introduction, historical perspective, discovery of the electron, nucleus and neutron* |
| *Aug 25 (Fri)* | *Quantum mechanics and relativity, particle –wave duality* |
| *Aug 28 (Mon)* | “ |
| *Aug 30 (Wed)* | “ |
| *Sep 1 (Fri)* | *Forces and interactions* |
| *Sep 4 (Mon)* | ***LABOR DAY – no class*** |
| *Sep 6 (Wed)* | *Particle ZOO: Leptons(electrons, muons, neutrinos) quarks (pions, kaons, resonances) bosons - carrier of the force* |
| *Sep 8 (Fri)* | “ |
| *Sep 11 (Mon)* | “ |
| *Sep 13 (Wed)* | *Symmetries, conservation laws and quantum numbers: E-p, charge, angular momentum, parity, isospin, G-parity, lepton number, baryon number, flavor, charge conjugation* |
| *Sep 15 (Fri)* | “ |
| *Sep 18 (Mon)* | “ |
| *Sep 20 (Wed)* | *Static quark model, relativistic kinematics, lab-vs-cm* |
| *Sep 22 (Fri)* | *Dynamics, DIS, parton model* |
| *Sep 25 (Mon)* | “ |
| *Sep 27 (Wed)* | *CP violation, CKM matrix* |
| *Sep 29 (Fri)* | *Weak interactions, the Standard Model, neutrino mixing* |
| *Oct 2 (Mon)* | “ |
| *Oct 4 (Wed)* | *Higgs* |
| *Oct 6 (Fri)* | “ |
| *Oct 9 (Mon)* | ***FALL BREAK – no class*** |
| *Oct 11 (Wed)* | *Feynman diagrams – graphic representation* |
| *Oct 13 (Fri)* | *Feynman diagrams* |
| *Oct 16 (Mon)* | *Astrophysics questions* |

| | | |
|---|---|---|
| *Oct 18 (Wed)* | *Astrophysics connection (composition of the universe, dark matter, dark energy)* | |
| *Oct 20 (Fri)* | *Particle detectors: charged particles: ionization (emulsion, cloud and bubble chambers, wire, spark, proportional, drift chambers) Limitations on momentum measurements: Energy loss: Bethe-Bloch, dE/dx, radiation length, bremstrahlung, Coulomb scattering, position in space* | |
| *Oct 23 (Mon)* | *Silicon detectors* | |
| *Oct 25 (Wed)* | *Neutrinos* | |
| *Oct 27 (Fri)* | *Particle detectors: scintillators, fibers,*<br>*neutrals: decays of pi0, Ks, Lambda, photon conversions, neutron interactions* | |
| *Oct 30 (Mon)* | *Calorimetry* | |
| *Nov 1 (Wed)* | *Particle identification: TOF, Cerenkov light, dE/dx, muons* | |
| *Nov 3 (Fri)* | *Readout electronics, trigger* | |
| *Nov 5 (Fri)* | *Particle detectors – neutrinos* | |
| | | *Review* |
| *Nov 6 (Mon)* | *Student lecture 1* | *Oct.30* |
| *Nov 8 (Wed)* | *Student lecture 2* | *Nov. 2* |
| *Nov 10 (Fri)* | *Student lecture 3* | |
| *Nov 13 (Mon)* | *Student lecture 4* | *Nov. 6* |
| *Nov 15 (Wed)* | *Student lecture 5* | *Nov. 9* |
| *Nov 17 (Fri)* | *Student lecture 6* | *Nov.11* |
| *Nov 20 (Mon)* | *Student lecture 7* | *Nov.14* |
| ***Nov 24 (Fri)*** | ***Thanksgiving – no class*** | |
| *Nov 27 (Mon)* | *Computing for particle physics* | |
| *Nov 29 (Wed)* | *Monte Carlo techniques* | |
| *Dec 1 (Fri)* | *Statistics* | |
| *Dec 4(Mon)* | *Future of particle physics: Grand Unification, superstrings, Future machines proton-proton HL-LHC, neutrino Dune, e+e- NLC, CEPC* | |

***Subjects for seminar presentations***

*Particle physics:* *magnetic monopole, neutrino oscillations, CP violation, Higgs boson. antimatter, supersymmetry, lepton mixing, quark mixing*

*Astroparticle physics:* *dark matter, dark energy, gravitational waves*

*Machines and detectors:* *application of particle beams in medicine*
*application of photon beams in medicine*

***Grading***

*Homework 40%, Presentation – 40%, class and seminars participation – 20%*

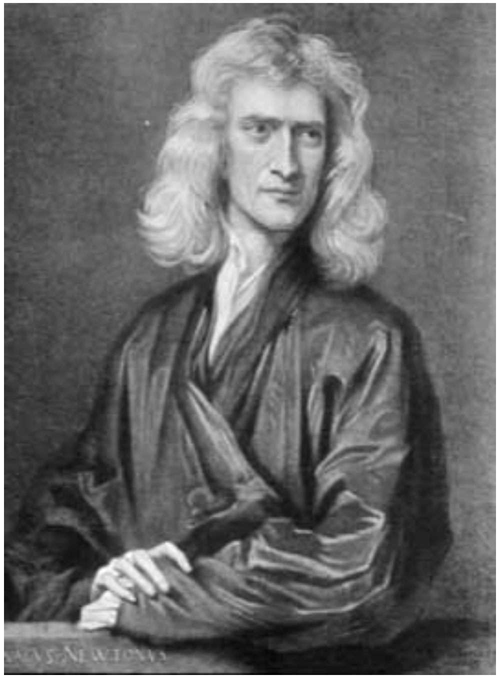
*Grading of seminar presentations will be done in collaboration with the audience.*
*Sample grading sheet:*
*Rate the following aspects in the range of 1 to 10 with 10 being best:*
*Introduction of the topic. Is the subject important to physics?*
*Organization and logic of the talk:*
*Transparencies: was the presentation clear? what was missing?*
*Questions: was the speaker able to answer questions?*
*What element of this presentation would you lie to see expanded further*

***Disability Accommodations**: Students needing academic accommodations for a disability must first register with Disability Accommodations & Success Strategies (DASS). Students can call 214-768-1470 or visit http://www.smu.edu/Provost/ALEC/DASS to begin the process. Once registered, students should then schedule an appointment with the professor as early in the semester as possible, present a DASS Accommodation Letter, and make appropriate arrangements. Please note that accommodations are not retroactive and require advance notice to implement.*

· ***Religious Observance**: Religiously observant students wishing to be absent on holidays that require missing class should notify their professors in writing at the beginning of the semester, and should discuss with them, in advance, acceptable ways of making up any work missed because of the absence. (See University Policy No. 1.9.)*

· ***Excused Absences for University Extracurricular Activities**: Students participating in an officially sanctioned, scheduled University extracurricular activity should be given the opportunity to make up class assignments or other graded assignments missed as a result of their participation. It is the responsibility of the student to make arrangements with the instructor prior to any missed scheduled examination or other missed assignment for making up the work. (University Undergraduate Catalogue)*

# 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."***

# Motivations

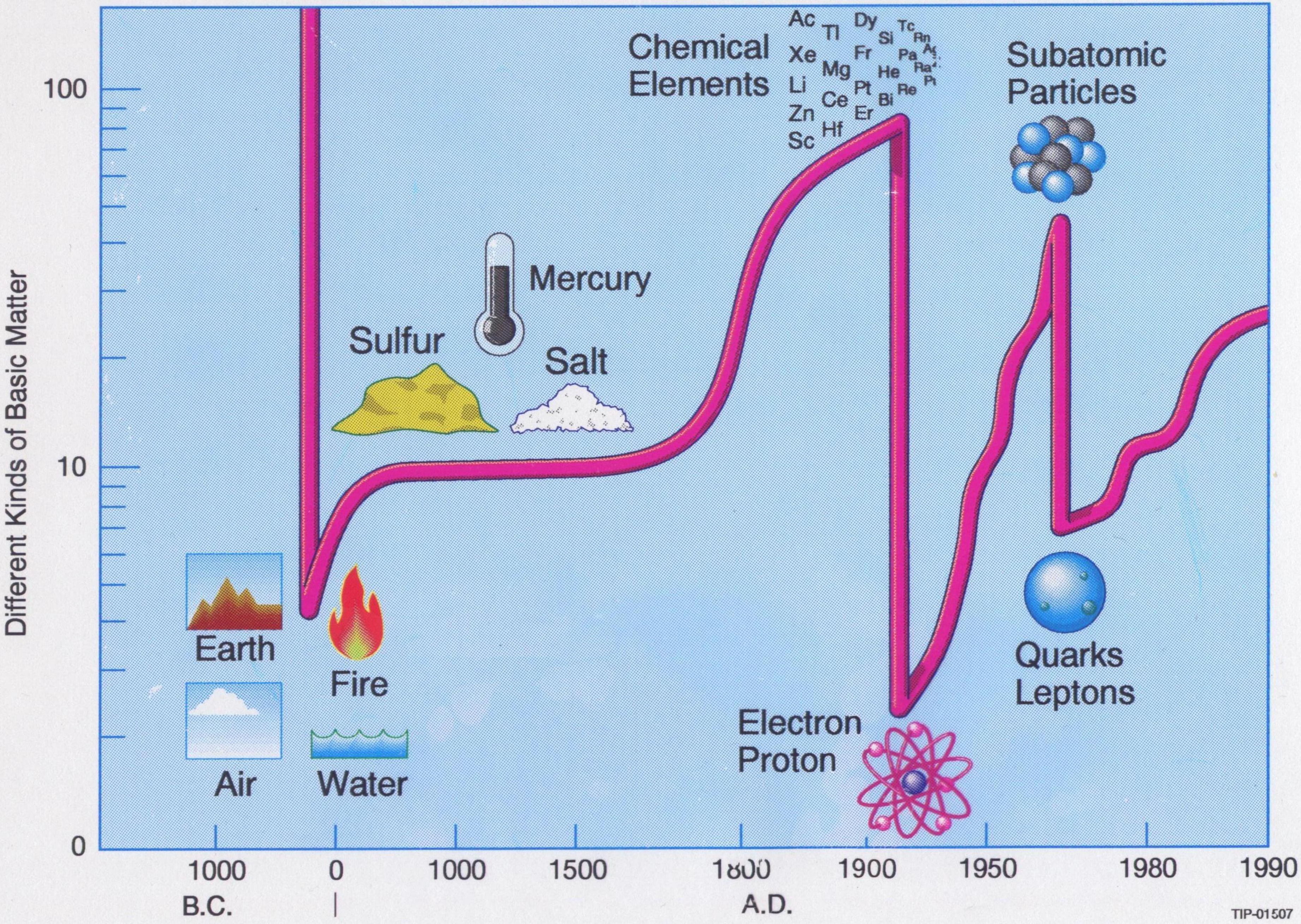
**Historical** − what are the smallest constituents of matter ?

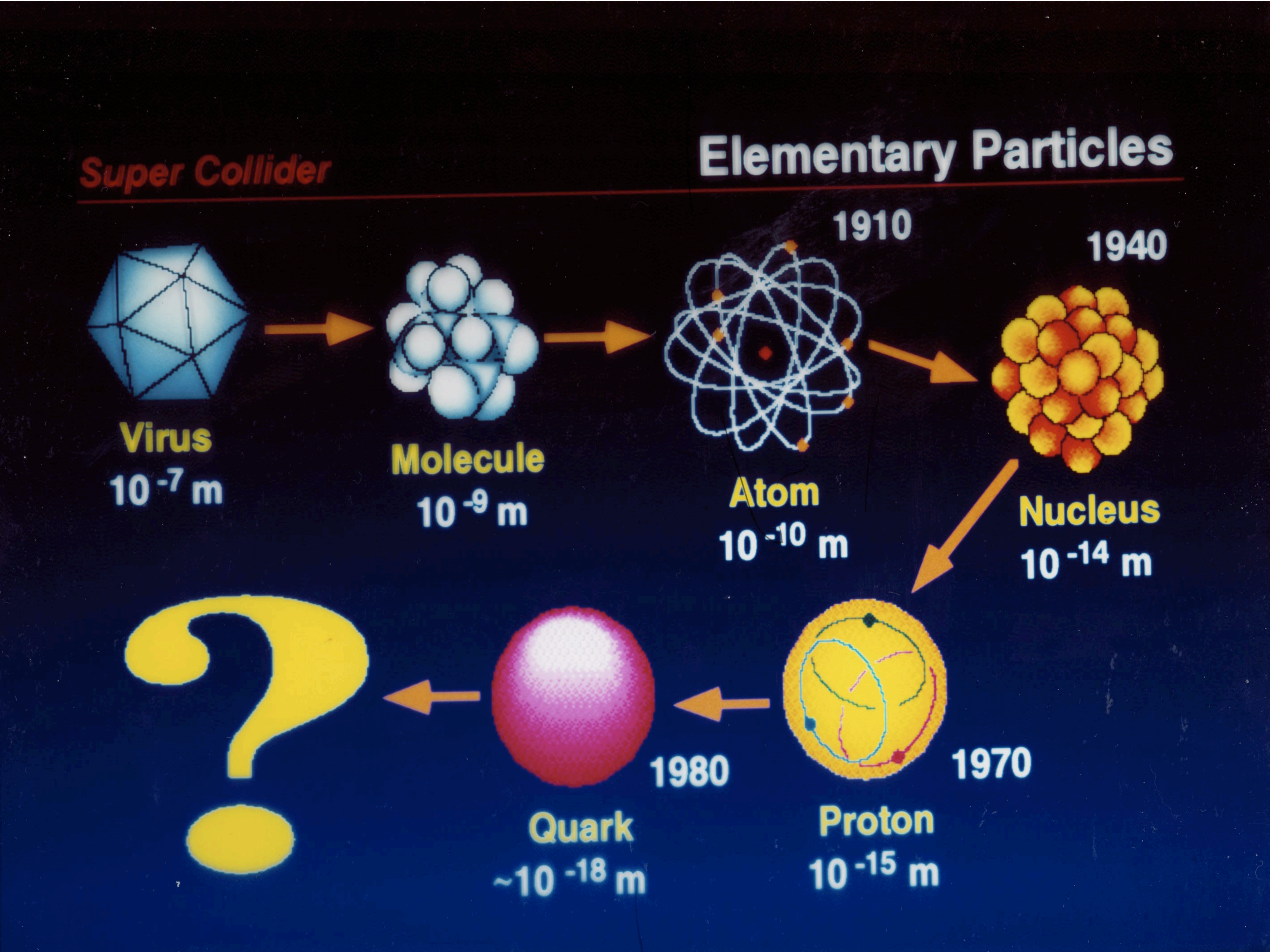
**A brief history of matter**

- $5^{th}$ Century BCE Greek PhilosophersLeucippus and his pupil Democritus postulated that all matter is made up from the indivisible components (atmos − cannot be cut).
  The idea of change is an illusion. Atoms can pack and scatter differently creating all forms found in nature.
- Long break of ~22 centuries included such giants as Copernicus, Gallileo and others addressing mostly gravitational effects
- $17^{th}$ century − Boyle, Newton, Dalton, Lavoisier, Volta - beginning of scientific thought and experimentation
- End of $19^{th}$ century − discovery of electrons and $\alpha,\beta,\gamma$ rays
- $20^{th}$ century − discovery of components of atoms, elementary particles and their structure (quarks and leptons)

Did we peeled the last layer of the onion?

# History of Elementary Particles




Super Collider
Elementary Particles
Virus
$10^{-7}$ m
Molecule
$10^{-9}$ m
1910
Atom
$10^{-10}$ m
1940
Nucleus
$10^{-14}$ m
1970
Proton
$10^{-15}$ m
1980
Quark
~$10^{-18}$ m
?

# Motivations 21st century

- Identification of fundamental forces of nature:
gravity, electromagnetism, weak and strong interactions
led to the development of the Standard Model fully confirmed
by the discovery of the Higgs Boson in 2012. This model, we believe,
to be applicable at ay scale ranging from smallest −particle level
to largest − galactic and universe level.
- The theoretical framework that allows us to ask new questions:
  - How the universe was created ?
  - Can we explain/describe observations ?
  - How does it evolve with time ?
- Notice the underlying arrogant assumptions that we know everything
about the structure of matter and that we understand all mechanisms
of the interactions at the fundamental level.
- Future − search for deviations from what we expect both at the
smallest scale of elementary particles and at cosmic scale.

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

## The Atoms of the 92 Elements

$f$ → 1. Hydrogen, 2. Helium

1. Hydrogen
2. Helium
3. Lithium

............

............

92. Uranium

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

increasing mass

Mass $\approx 238\, M_H$

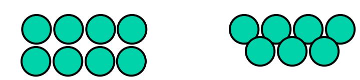
## Estimate of a typical atomic radius

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

$N_A \approx 6 \times 10^{23}$ 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$^{-3}$)

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

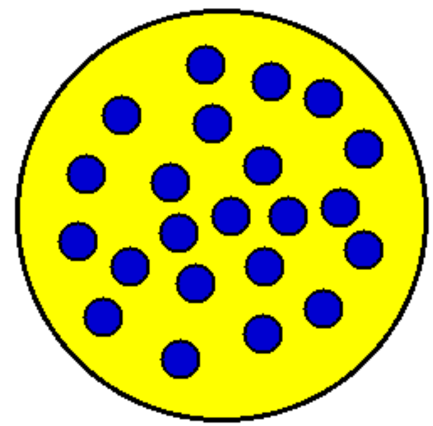
**→Current carried by particles**

**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

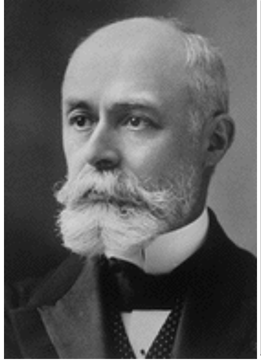
1896: Discovery of natural radioactivity

(Henri Becquerel, Maria Skłodowska-Curie)

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

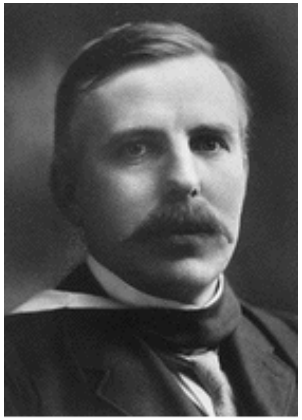
1909−13: Rutherford's scattering experiments

Discovery of the atomic nucleus

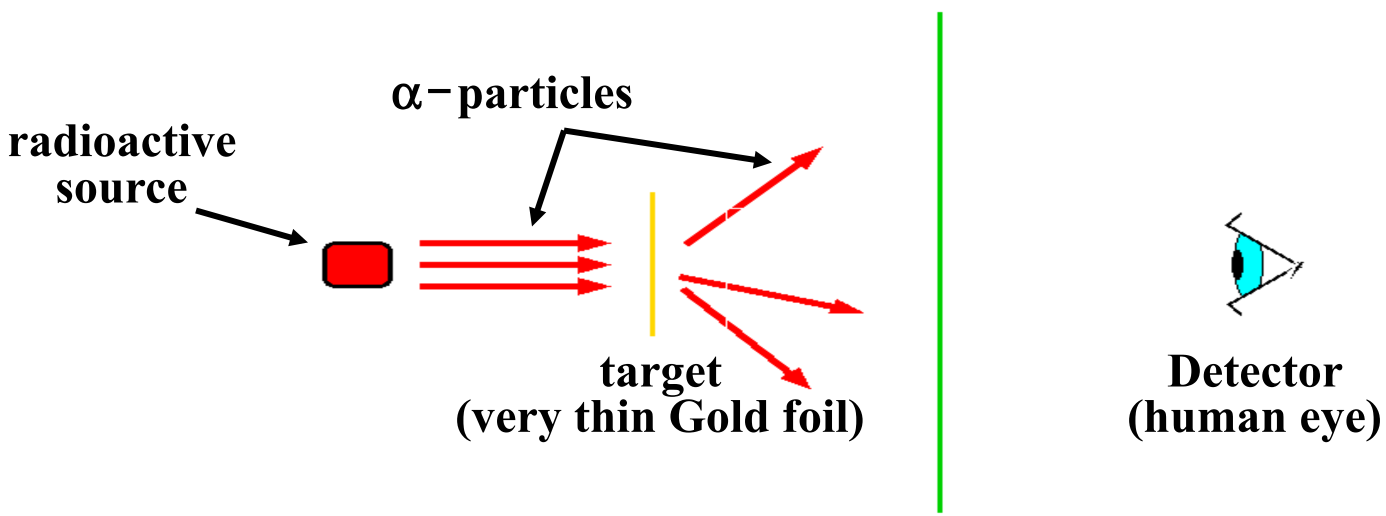


Henri Becquerel

Maria Curie



Ernest Rutherford

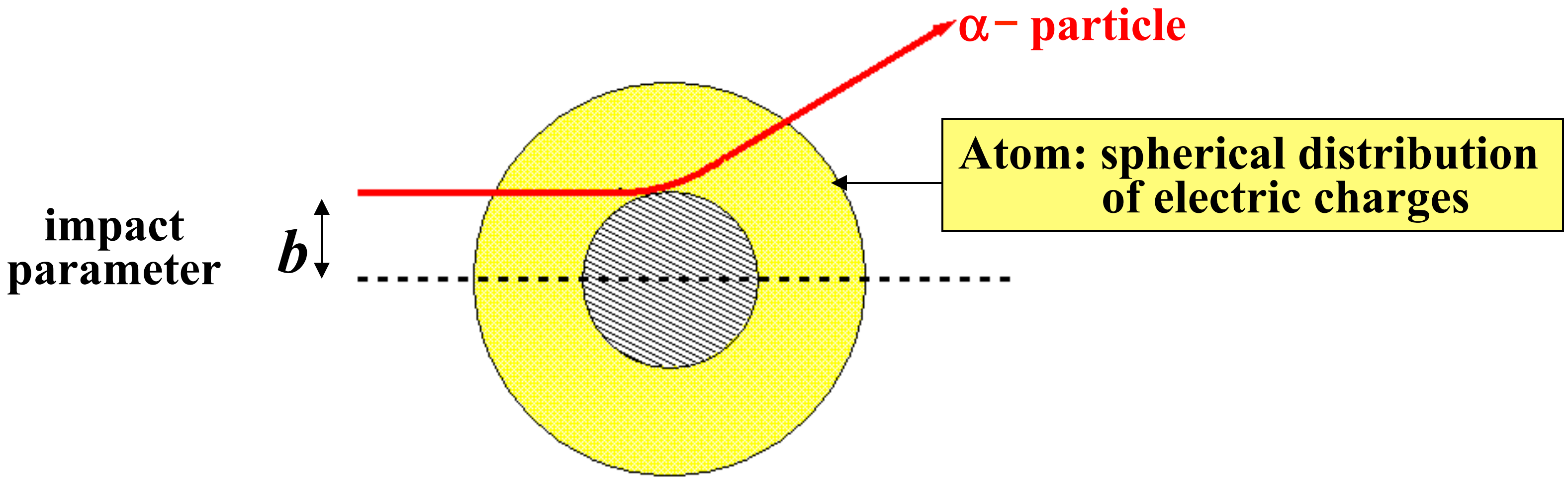



α−particles: nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes

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

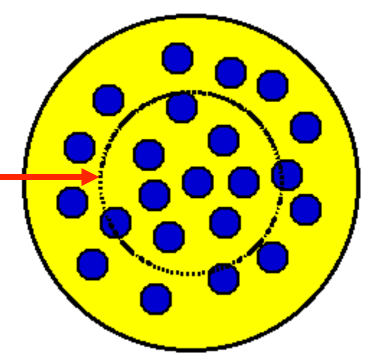
# Expectations for α – atom scattering

**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 $r^{-2}$)**

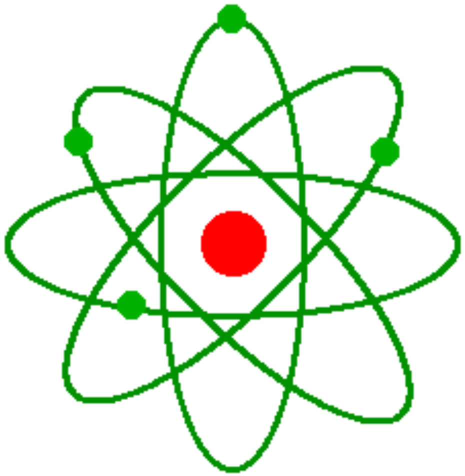
**For Thomson's atomic model the electric charge "seen" by the α – particle is zero, independent of impact parameter**



→ 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‰ )

*Atom is mainly empty space*

# 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:**

$$^4He_2 + {}^9Be_4 \rightarrow {}^{12}C_6 + \text{neutron}$$

↑ **α** - particle

# 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,
if energetically allowed)

→ **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 ~ $10^5$**

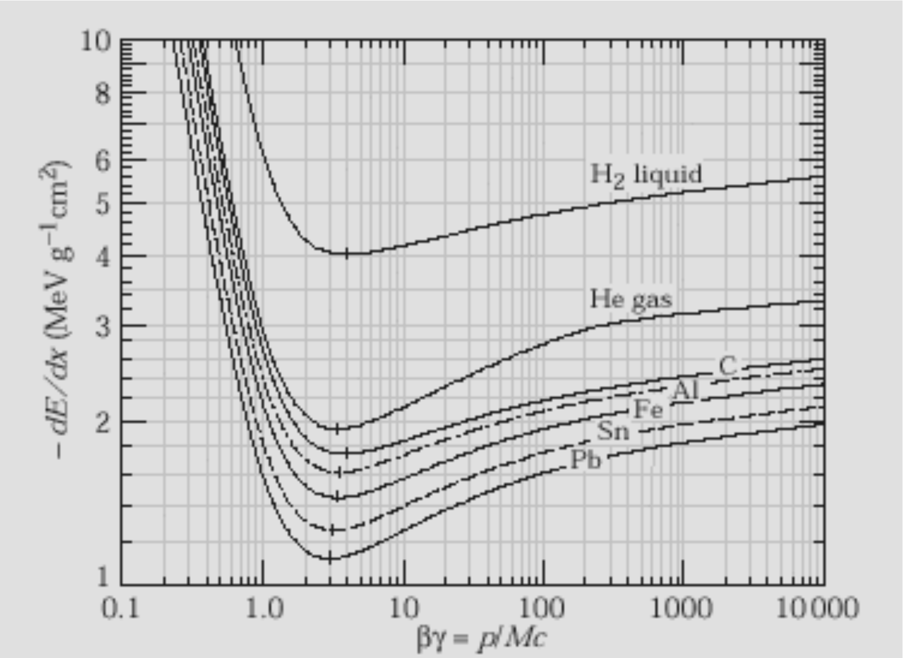
• **Range of electromagnetic force/range of strong force ~ ∞**

# 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:**

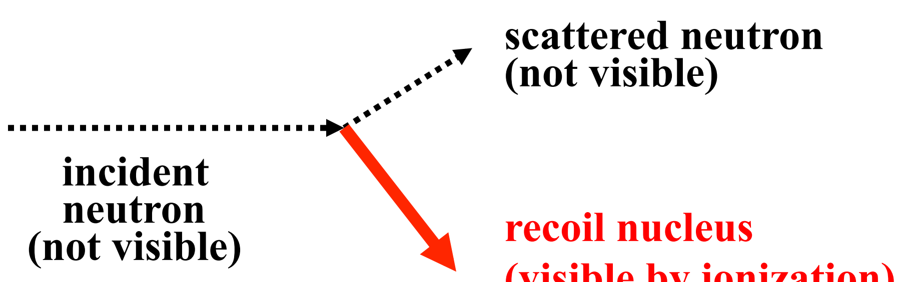
$$R = \int_0^R dx = \int_{E_0}^{Mc^2} \frac{1}{dE/dx} dE = MF(\mathrm{v})$$

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

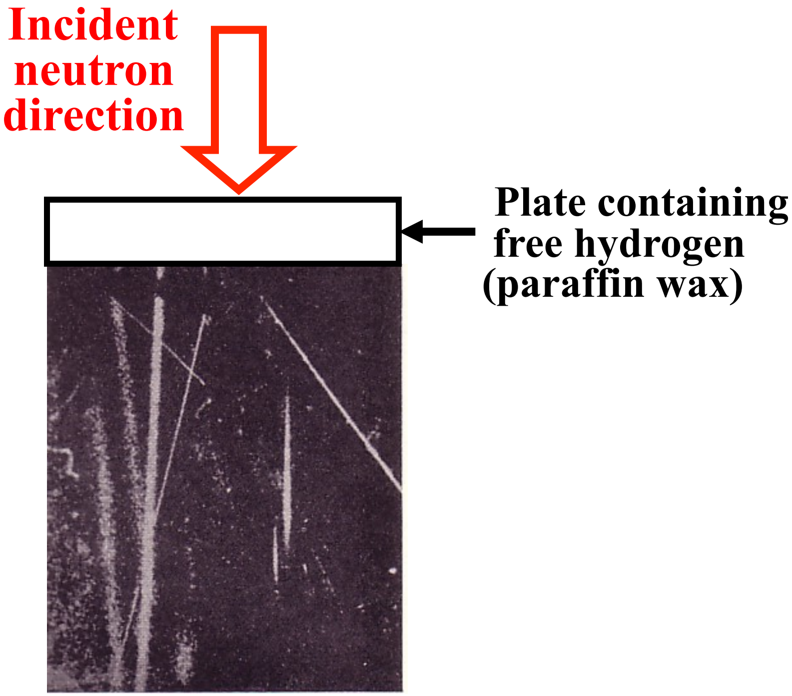
**=> the measurement of R for a particle of known rest mass M is a measurement of the initial velocity**

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

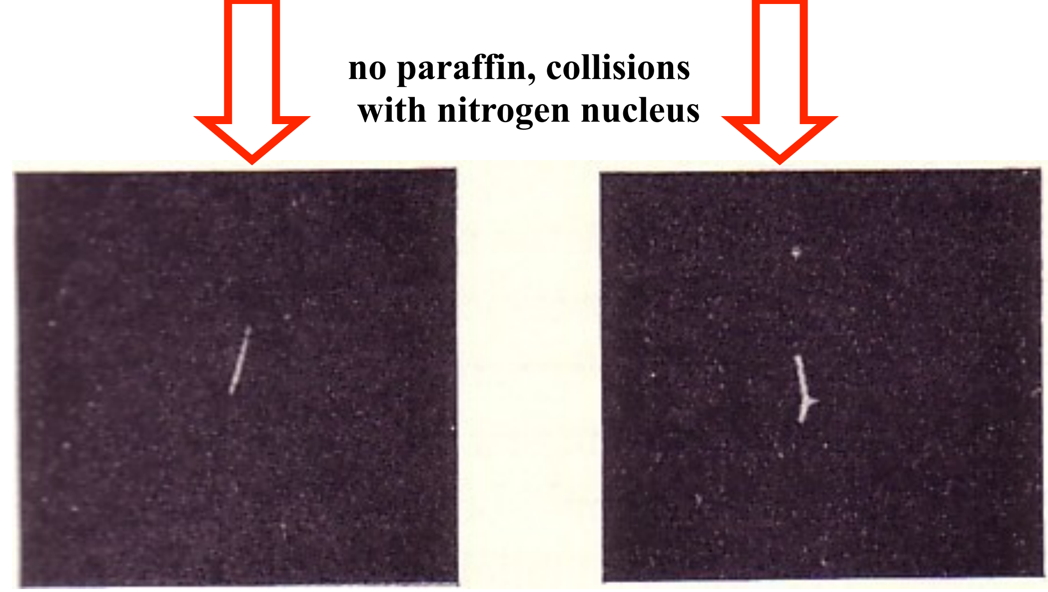
**Chadwick's neutron discovery:**
**observation and measurement of nuclear recoils in an "expansion chamber" filled with Nitrogen at atmospheric pressure**




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




Collision with paraffin produces protons




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 :** $m_p = 938.272\ \mathrm{MeV}/c^2$ $\qquad m_n = 939.565\ \mathrm{MeV}/c^2$