Particle Detectors

Lecture 1
07/03/18

a.a. 2017-2018

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The Course

- 42 hours, 21 lectures.
- Time Table:
  - Wednesday 9-11, aula informatica
  - Friday 9-11, aula B
- The slides are available at:
- http://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/rivelatori1718/ typically one or two days after the lecture in PDF format

Reception

- Available any time, better on appointment.
- e-mail: emanuele.fiandrini@pg.infn.it

(rough) PROGRAM

- **Introduction** (few definitions, a bit of rel cinematics, cross sections,…)
- **Particle's interactions with matter**
  - Ionisation energy loss
  - Photon-matter interactions
  - Multiple scattering
  - Interaction length
  - Electromagnetic and hadronic showers
  - Cherenkov and transition radiation
  - Nuclear recoil, scintillation,…
- **Particle detectors**
  - General properties of particle detectors
  - Gas and solid state tracking and position detectors
  - Organic and inorganic scintillators, photomultipliers, scintillating fibers
  - Calorimetry: homogeneous and sampling calorimeters
  - Particle identification: dE/dx measurements, time of flight, Cerenkov and transition radiation detectors
- **Detector systems: integration/combination of detectors (→ experimental apparatus)**
  - **CMS, AMS, NA62,… seminars from researchers of our department**

Some warnings

- This is the only course on particle detectors you will attend during your path to degree
- **The material of the lectures is huge, but it will give you just some basic information on the most popular particle detectors (Far to be complete!)**
- We will use and combine many different topics (classical mechanics and electromagnetism, atomic and nuclear physics, some QED and QCD, special relativity, statistics, electronics,…
- Therefore the course is **hard**
- **Try to study each lectures as they are given**

Final exam

- Final exam is **oral**
- **It is made with a seminar** (45-60 min, max 30-35 slides) from each of you on a real experiment, taking data or proposed, as CMS, AMS, NA62, FERMI…I'll ask you how that stuff works…

BIBLIOGRAPHY

Some available (*) at http://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/rivelatori1718/bibliografia/

- * C. Grupen, Particle Detectors, Cambridge University Press, 1996
- * R. Fernow, Introduction to Experimental Particle Physics, Cambridge University Press, 1992
- * W.R.Leo, Tecniques for Nuclear and Particle Physics Experiments, Springer Verlang, 1994
- * Glenn F. Knoll , Radiation Detection and Measurement, 3rd ed - (Wiley, 2000)
- Dan Green, The Physics of Particle Detectors, Cambridge University Press,2000
- Konrad Kleinknecht, Detectors for Particle Radiation, Cambridge U.K.
- Blum & Rolandi, Particle Detection with Drift Chambers, Springer Verlang, 1994

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PAPERS:

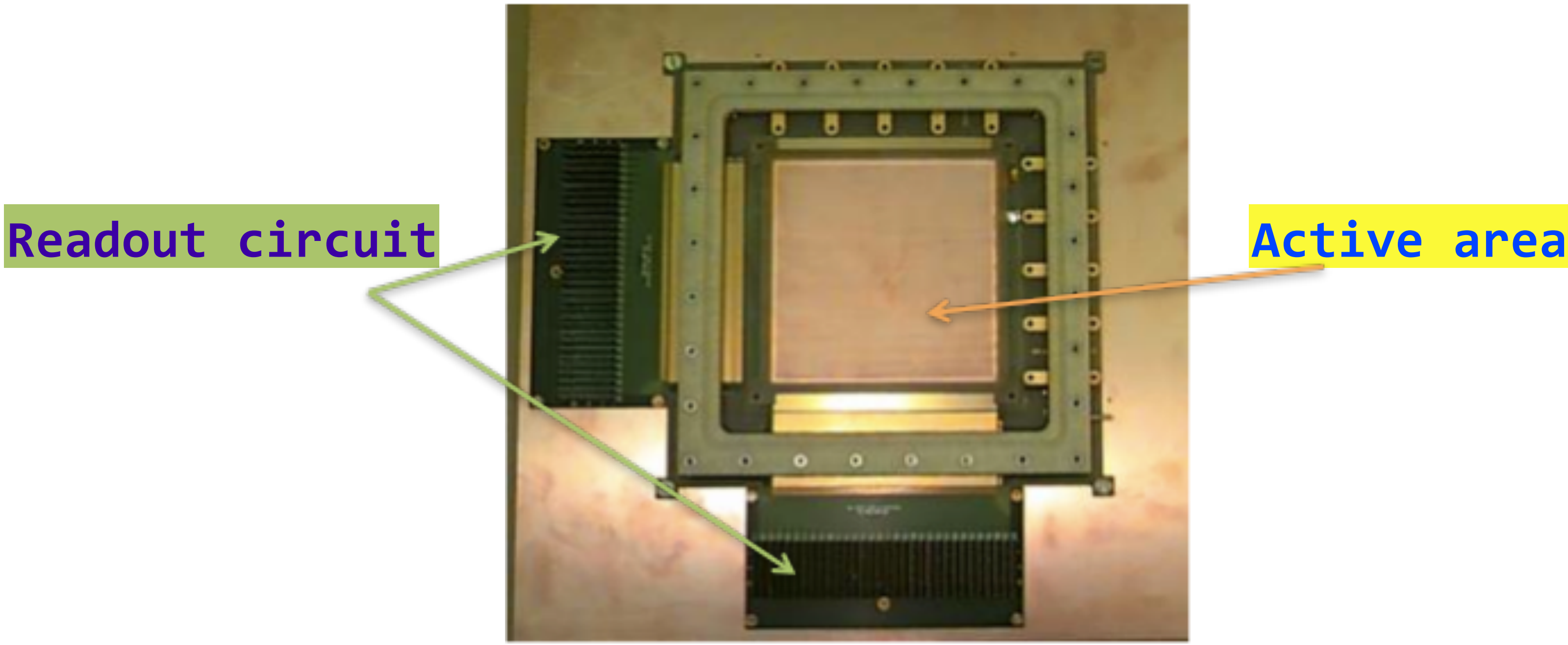
- Experimental Tecniques in High Energy Physics, T.Ferbel (editore),World Scientific, 1991
- Instrumentation in High Energy Physics, F.Sauli (Editore), World Scientific, 1992

OTHERS:

- Particle data Book (Phys. Rev. D)
- R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/Briefbook
- Proceedings of conferences (Vienna VCI, Elba, IEEE)
- Introduction to radiation detectors and electronics (Helmut Spieler, Lecture Notes – Physics 198,Spring semester 1999- UC Berkeley) http://www-physics.lbl.gov/~spieler/physics_198_notes_1999/index.html

What is a particle detector?

In experimental physics, a particle detector or radiation detector is an instrument used to detect, to track and to identify elementary particles by measuring one or more properties of them



Particle detectors are devices producing an observable signal when they are crossed by a particle. Usually they are made by an active element (such that there is some interaction with the particle) and by a readout system ("forming" the signal and sending it to the data acquisition chain)

What is a particle detector?

General Principle: All the particles, crossing a slab of matter, lose a fraction of their energy in the material with some probability by some physical process.

- Charged Particles: inelastic collisions on atomic electrons hit along the trajectory;
- All the hadrons (charged and neutral) by nuclear reactions on the nuclei hit along the trajectory;
- Electrons emit braking radiation (bremsstrahlung), charged particles may emit cherenkov and transition radiation
- Photons may be scattered inelastically or not (ie Thomson/ Compton scattering), absorbed (photoelectric eff.), convereted pairs e^+ e^-, depending on the photon energy

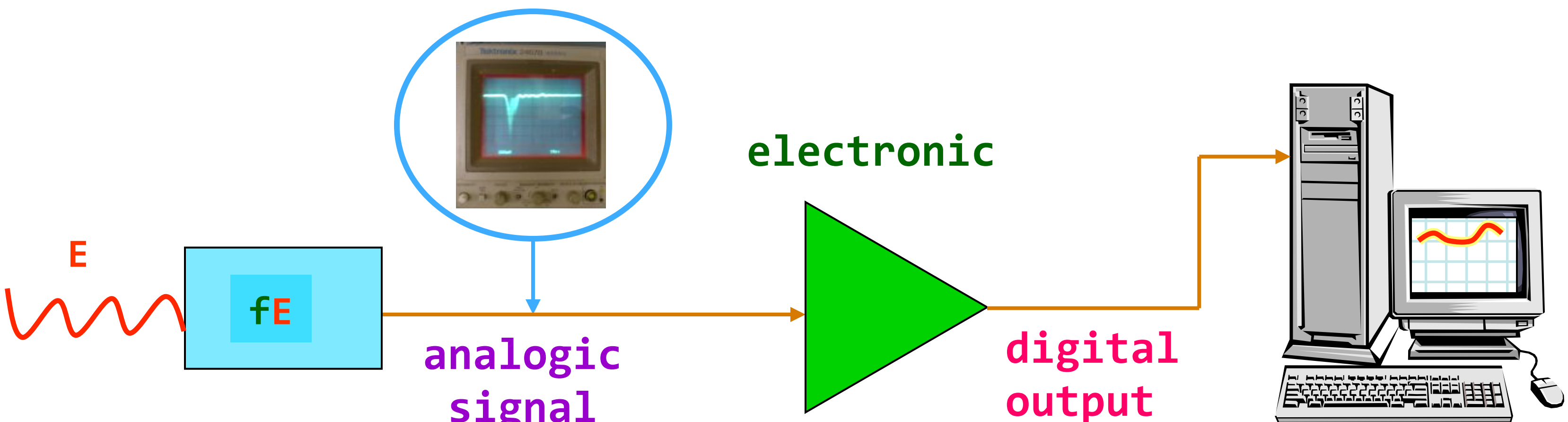
What is a particle detector?

- The basic operation principle of ALL the detectors is to convert the energy lost in the active part in a “concrete signal” that can be “measured” (current, voltage, light, heat,...).
- Different tecniques, materials and arrangements depending on the particle type to detect, on the energy range, speed, on the particle rate,…
- For example, a photon detector must be inevitably different from a muon detector.
- The “signal” depends on some cinematic or dynamic “property” of the particle (eg energy, velocity, linear momentum p, charge, mass...) which is being detected.
- “Universal” detectors, sensitive to all the particles over all the range of their “properties” DO NOT exist

What is a particle detector?

General operation principle of a detector:
Particle with energy E → transfer of energy fE (f ≤ 1) to the detector → conversion in a accessible, measurable form of energy (light, current, voltage, heat,...)

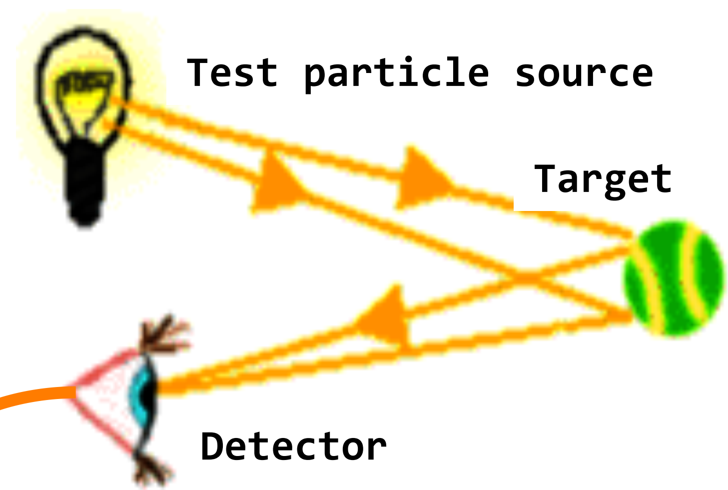
Modern detectors are essentially electrical: fE converted in electrical pulses → needed electronic circuitry to form the signal

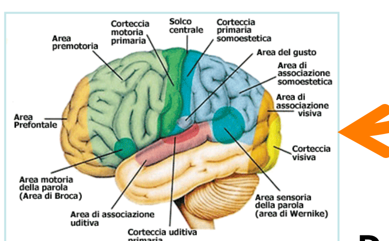


Which is the more familiar detector?

Human eye (as any other eye) is a particle detector: photons

- ❑ Light beam
- ❑ target
- ❑ detector
- ❑ Data processing

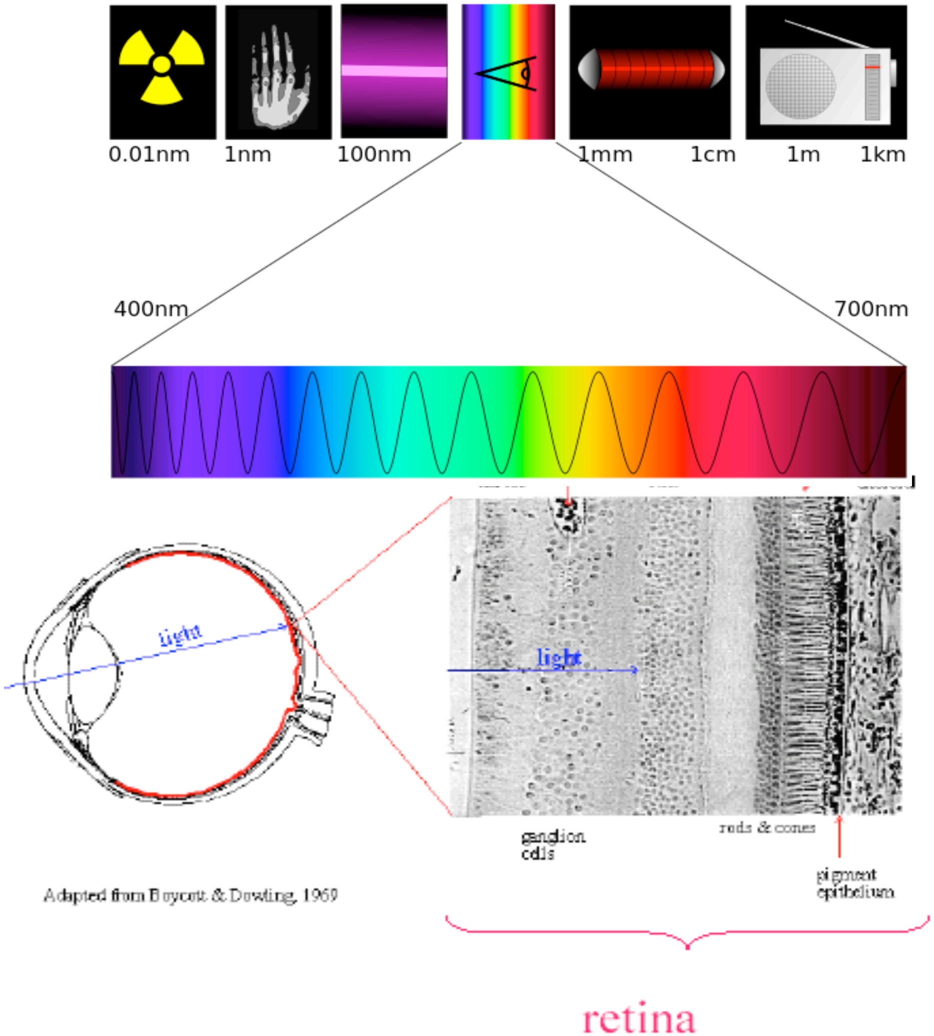




Data processing

The oldest detector of photons… built billions of times

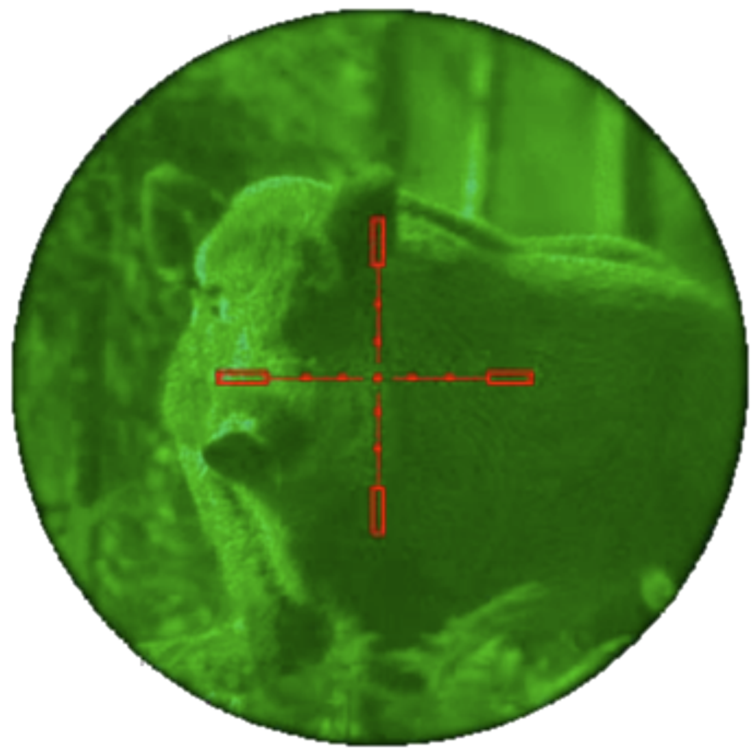
- **High sensitivity to photon in a well defined frequency range**
- **Good spatial resolution**
- **Adaptative optics for photon focalization**
- **Large dynamic range (1:10^{14}) + threshold automatic matching**
- **Energy discrimination (wave length)**
- **Rather slow (acquisition speed + analysis ~10 Hz)**



Other ways to “see”?

Ex.: by subtraction

Ex.: infrared



Electromagnetic emission from a body

At a temperature of 37 C (~310 K), the emission is peaked in infrared.

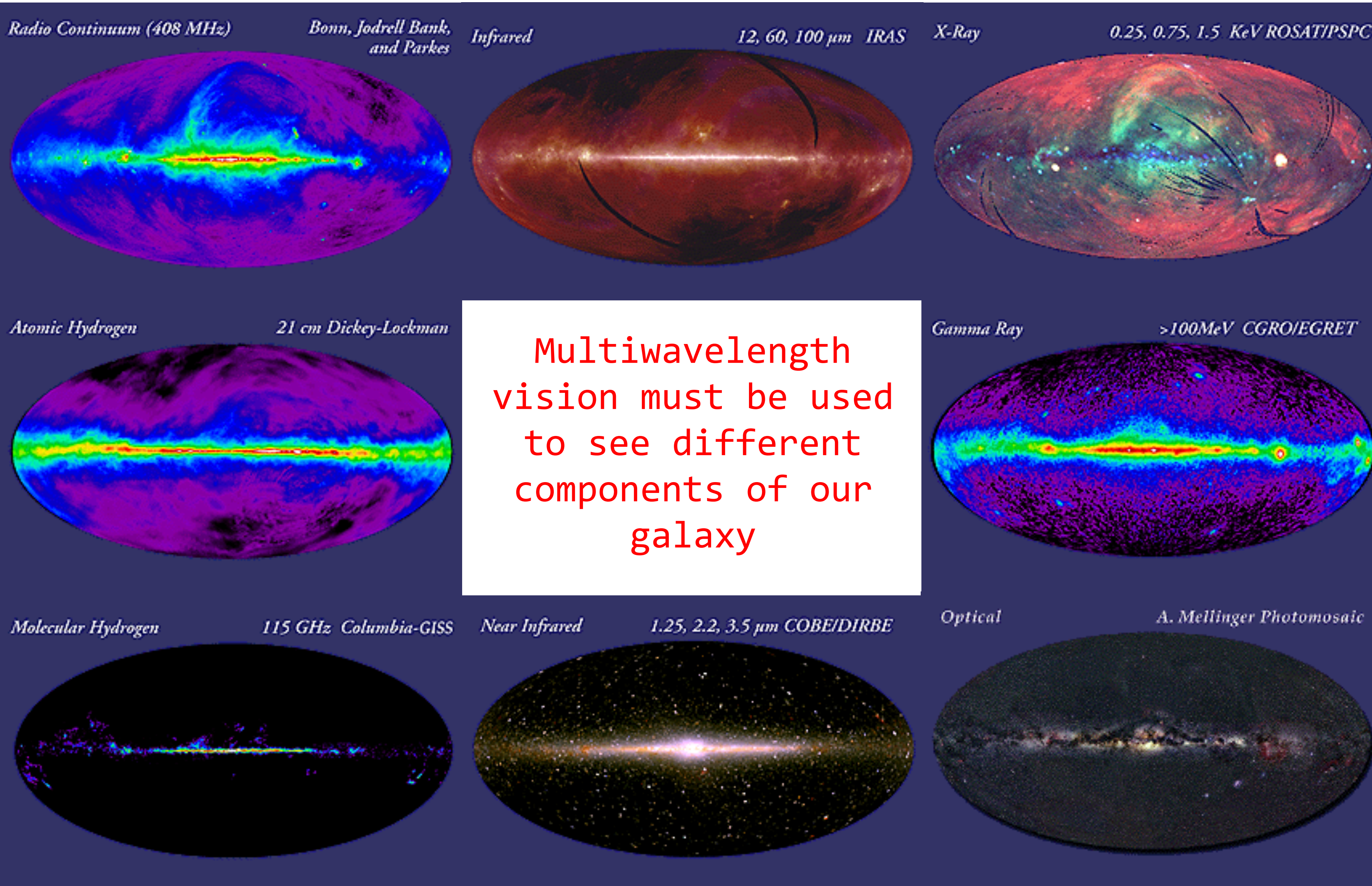
Most of matter is “transparent” to IR

Other ways to “see”?

“energetic” light (X rays)

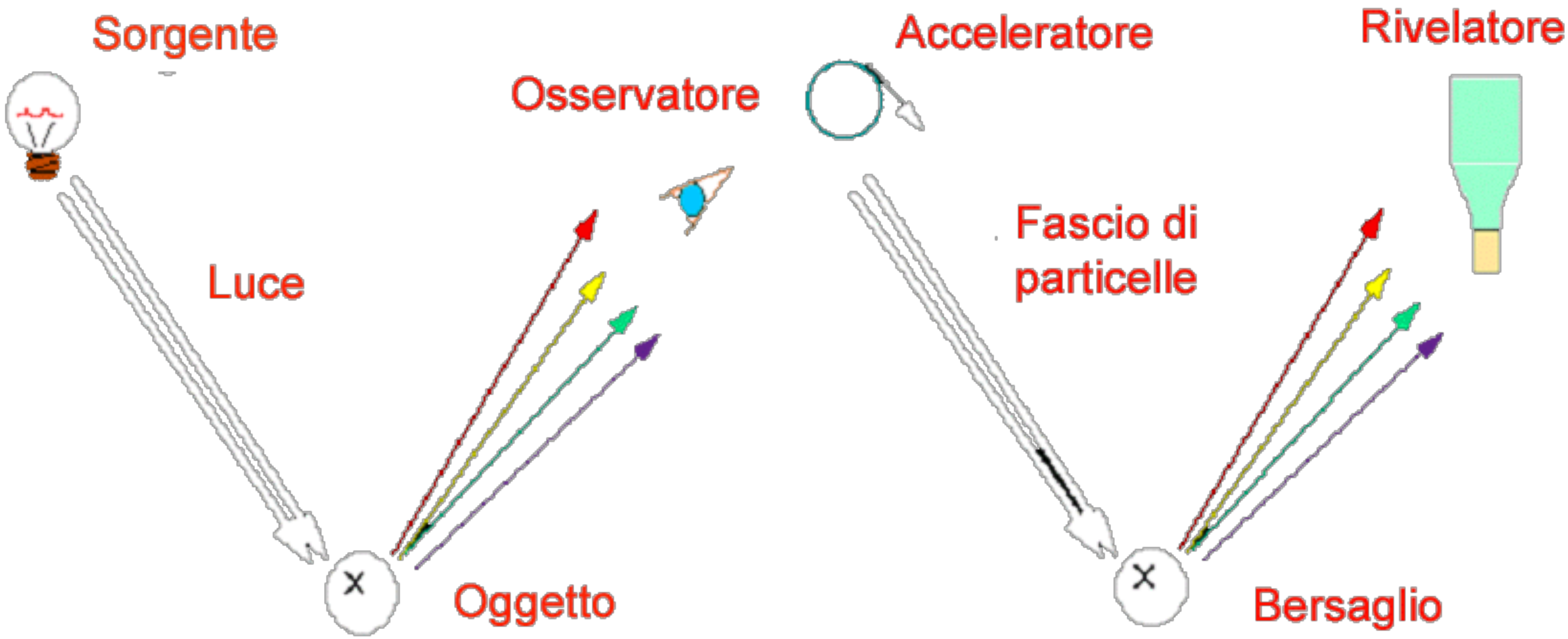
Ultrasounds

Why X rays and ultrasounds are used, instead of “light”?



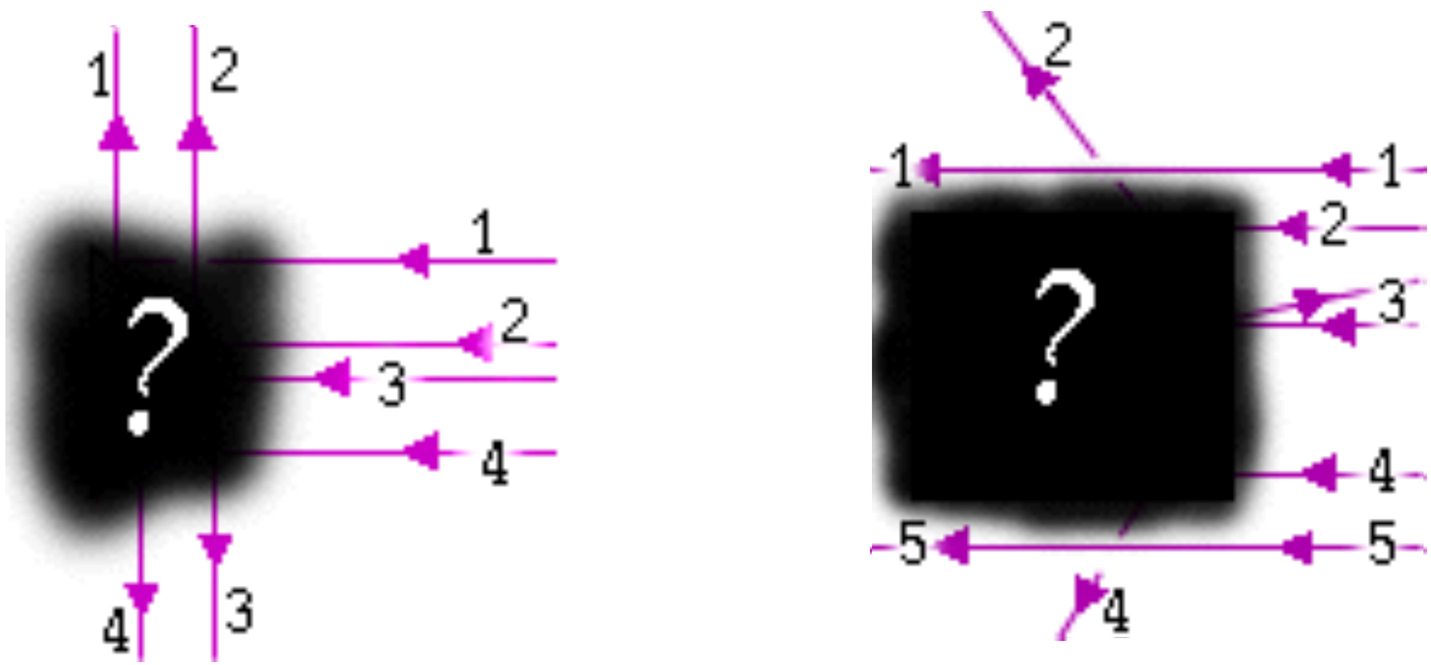
Multiwavelength vision must be used to see different components of our galaxy

We "see" the subatomic matter because we hit it with particles produced by sources (as the accelerators or radioactive decays) which scatter or produce new particles that reach the detectors

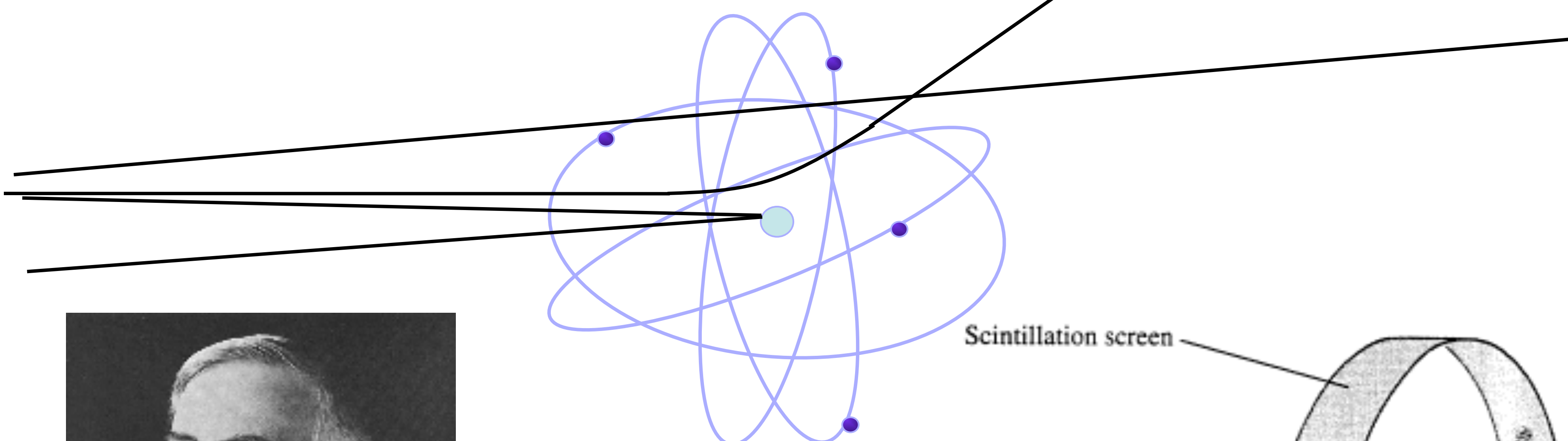


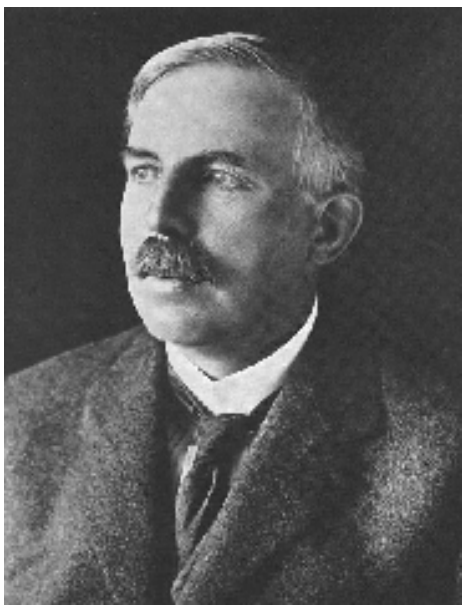
So, the first necessary condition to "see" a particle is that it reaches the detector.
The second is that some known interaction occurs between the incident particle and the detector material

For instance, the way that incident particles are scattered off by targets can reveal details of the target particles

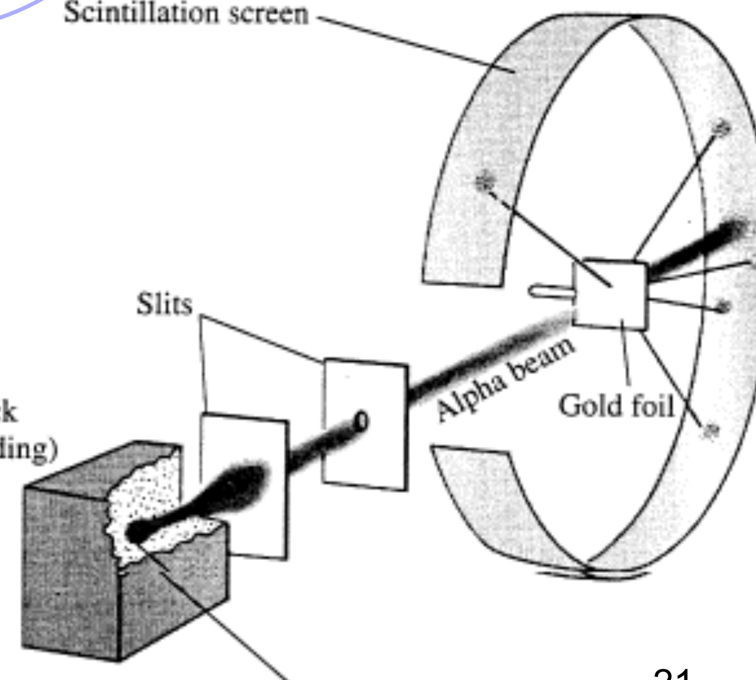


Ex: Rutherford’s atomic model





Ernest Rutherford
1909



Photographic Plates

Use of photographic paper as detector
➠ Detection of photons / x-rays

W. C. Röntgen, 1895
Discovery of the 'X-Strahlen'

Photographic paper/film

e.g. AgBr / AgCl

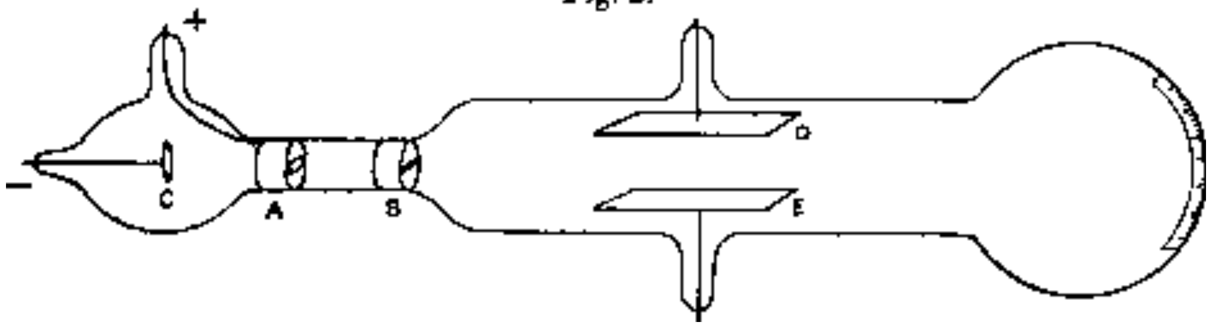
AgBr + 'energy'
➠ metallic Ag (blackening)

+ Very good spatial resolution
+ Good dynamic range
- No online recording
- No time resolution

Cathodic ray tube

J. Plücker 1858 ➠ J.J. Thomson 1897

Fig. 2.



Phosphorence light reveals the impact point

accelerator

manipulation
By E or B field

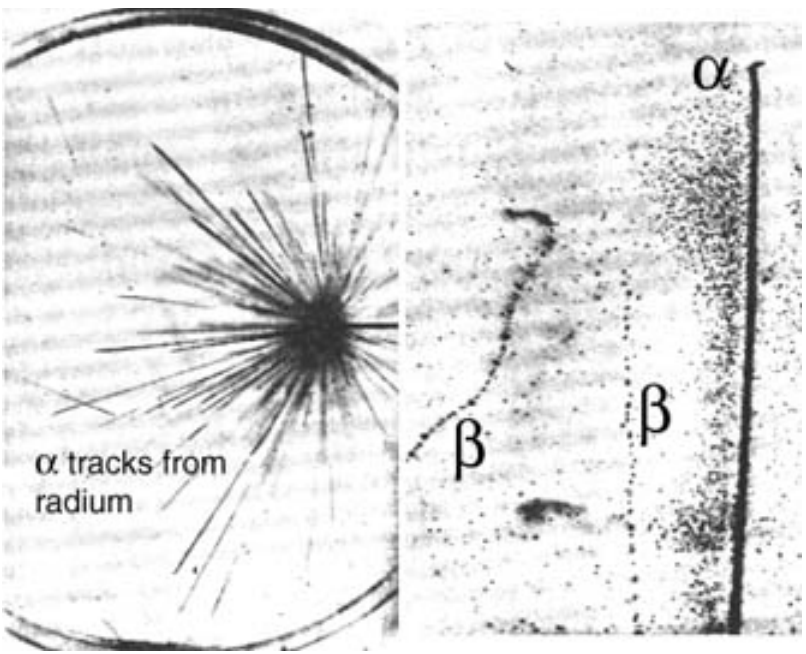
detector

From: J.J. Thomson: Cathode Rays.
***Philosophical Magazine*, 44, 293 (1897).**

"… The rays from the cathode C pass through a slit in the anode A, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit in another earth-connected metal plug B, they travel between two parallel aluminium plates about 5 cm. long by 2 broad and at a distance of 1.5 cm. apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflexion of this patch…."

C. T. R. Wilson,
1912, Cloud chamber

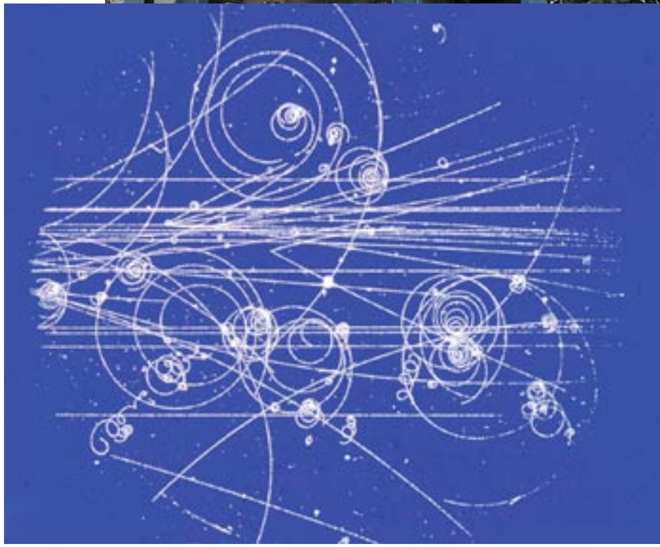
First tracking detector



The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a super-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle's path.

Bubble chamber

- The **Big European Bubble Chamber** (**BEBC**) is a piece of equipment formerly used to study weak interactions at CERN. BEBC was installed at CERN in the early 1970s. It is a stainless-steel vessel which was filled with 35 cubic metres of liquid deuterium, D_2 or a H/Ne mixture, whose sensitivity was regulated by means of a piston weighing 2 tonnes. During each expansion, charged particles left trails of bubbles as they passed through it. It has since been decommissioned and is now on display at CERN's Microcosm museum.
- The BEBC project was launched in 1966 by France and Germany. It was surrounded by a 3.5 T superconducting solenoid magnet. In 1973, it began operation at the Proton Synchrotron (PS). From 1977 to 1984, it was operated in the West Area neutrino beam line of the Super Proton Synchrotron (SPS), where it was exposed to neutrino and hadron beams at higher energies of up to 450 GeV. By the end of its active life in 1984, BEBC had delivered a total of 6.3 million photographs to 22 experiments devoted to neutrino or hadron physics. Around 600 scientists from some fifty laboratories throughout the world had taken part in analysing the 3000 km of film it had produced. (from wikipedia)

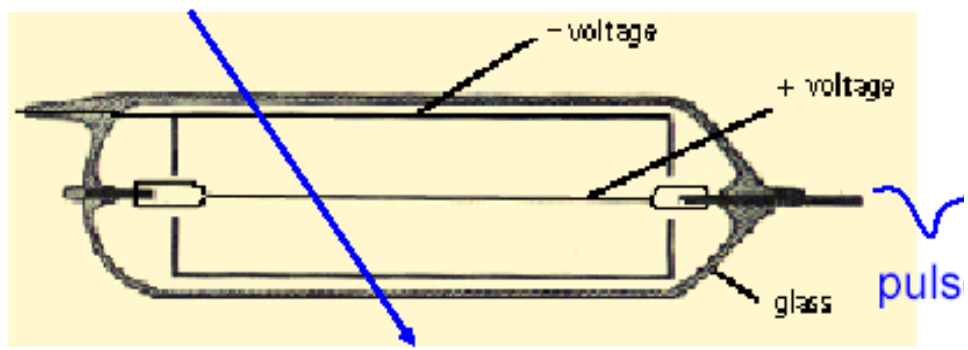


http://cerncourier.com/cws/article/cern/28742

Geiger-Muller

The "first" electrical detector ever built

E. Rutherford 1909 H. Geiger



The Geiger counter, later further developed and then called Geiger-Müller counter

Electrical signal reveals the passage of a charged particle

First electrical signal from a particle

Some numbers

- **Masses**

– Electron (e)	~0.5 MeV	J/Ψ	3.2 GeV
– Muon (μ)	~105 Mev	B	10 GeV
– Pion (π)	~140 MeV	W,Z0	80.4, 91 GeV
– Proton and neutron (p,n)	~938 MeV	H0	125 GeV
– τ lepton	1.73 GeV	top quark	173 GeV
– Photon and neutrino(γ,ν)	~0. MeV		

- **Lengths**
  - 1 μm (10^{-6} m) - spatial resolution of track apparatus
  - 1 nm (10^{-9} m) - green wave length (~500nm)
  - 1 Å (10^{-10} m) - atomic dimensions
  - 1 f (10^{-15} m) - nuclear dimensions

Remembering the uncertainty principle **$\Delta x \cdot \Delta(pc) = (h/2\pi)\, c$ →**

- to resolve an atom (~Å 10^{-10}m) need energies ~KeV
- To resolve a nucleus (~f 10^{-15}m) need energies ≥200 MeV
- to distinguish partons in protons need energies ~GeV

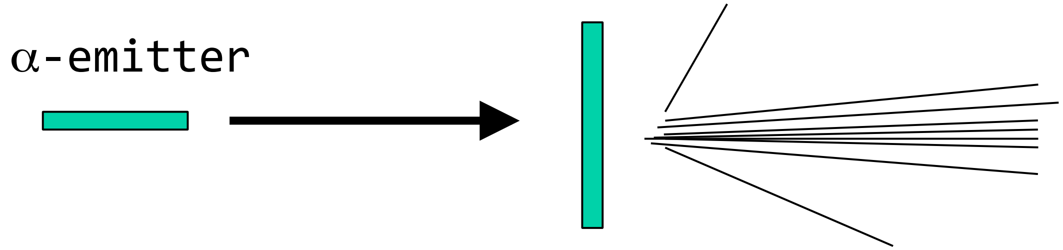
- **Times**
  - 1 μs (10^{-6} s) drift of 5 cm of an e- in a gas (drift chambers), ~μ meson lifetime
  - 1 ns (10^{-9} s) a photon travels 30 cm in 1 ns (in vacuum)
  - 1 ps (10^{-12} s) B meson lifetime

Relativistic kinematics (few recalls)

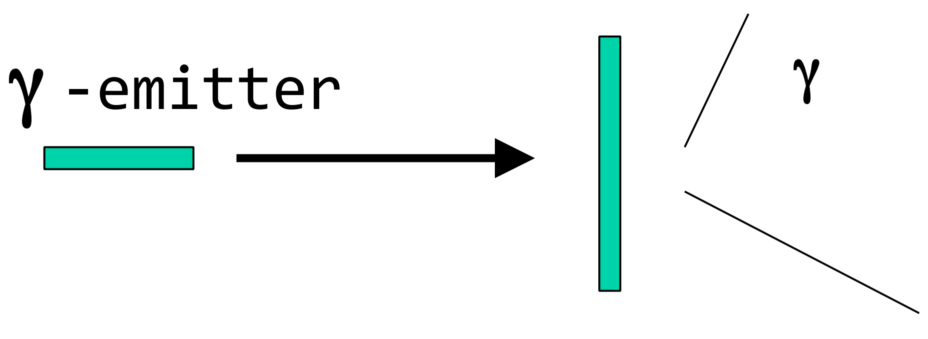
- Relativity describes *particle* behaviour at
  - high speed (close to speed of light)
  - i.e. high energy (compared with particle rest mass)
- Quantum mechanics describes behaviour of *waves* (or *fields*)
  - Probabilistic interpretation for individual particles
- Often need *both* to analyse results of particle experiments

Relativistic kinematics

- Alpha particle scattering from nuclei:
  - Rest mass of alpha = 3.7 GeV
  - Typical energy ~ 10 MeV
  - Can treat classically (fortunately for Rutherford!)



- Compton scattering of γ from electron:
  - Rest mass of γ = 0 eV
  - Rest mass of electron = 511 keV
  - Typical energy of γ ~ few MeV, up to tens MeV
  - Need to use both relativity and QM



Relativistic Kinematics

- Lorentz transformations define the principle of relativity:

$$\begin{cases} x' = \gamma(x - \beta(ct)) \\ ct' = \gamma(ct - \beta x) \end{cases}$$

$$\beta = \upsilon / c$$

$$\begin{cases} (E'/c) = \gamma((E/c) - \beta p) \\ p' = \gamma(p - \beta(E/c)) \end{cases}$$

$$\gamma = 1/\sqrt{1-\beta^2}$$

Lorentz factor or Lorentz boost

Relativistic Kinematics

- Extension of "normal" 3-vector e.g.
  - 4-Position: $x^{\mu} = (ct, \underline{x})$
  - 4-Velocity: $v^{\mu} = (\gamma c, \gamma \underline{v})$
  - 4-Momentum: $p^{\mu} = mv^{\mu} = (\gamma mc, \gamma m\underline{v}) = (E/c, \underline{p})$
  - Have time-like component (scalar) and space-like component (vector)

Relativistic Kinematics

- Length of a 3-vector doesn't change under rotations in (three-) space:

  $x^2 + y^2 + z^2 = x'^2 + y'^2 + z'^2 = \text{constant}$

- Lorentz 4-vectors are such that their "length" (magnitude) does not change under Lorentz transformation:

$$x^\mu x_\mu = x`^\mu x`_\mu = x_0^2 - (x_1^2 + x_2^2 + x_3^2) = \text{constant}$$

$X_0 = ct$

Relativistic Kinematics 4-vectors

The components of the momentum and energy 4-vector, *p*, are given by:

$$p = (E, p_x, p_y, p_z) \text{ or } p = (E, \vec{p}) \text{ or } p = (E, \boldsymbol{p}) \text{ with } c = 1$$

The length of the 4-vector is given by:

$$m_o^2 = E^2 - \vec{p}^{\,2} = E^2 - p_x^2 - p_y^2 - p_z^2$$

A particle is said to be "on the mass shell" if m_0=rest mass

This relationship is true in ALL reference frames (lab, center of mass,…) because it is a Lorentz invariant.

A 4-vector with length L^2 is classified as follows:

- Time like if $L^2 > 0$
- Space like if $L^2 < 0$
- Light like if $L^2 = 0$ (think photon!)

Relativistic Kinematics

In HEP the particles (e.g. protons, pions, electrons) we are concerned with are usually moving at speeds close to the speed of light.
The classical relationship for the kinetic energy of the particle in terms of its mass and velocity is not valid:

Kinetic Energy $\neq 1/2\ mv^2$

Thus we must use *special relativity* to describe the energies and momenta of the particles. The total energy (E=rest + kinetic) of a particle with rest mass, m_o, is:

$$E=m_0c^2+T \quad \Longleftrightarrow \quad E = mc^2 = \frac{m_o c^2}{\sqrt{1-(v/c)^2}} = \gamma m_o c^2$$

Here v is its speed, c = speed of light. The total momentum, p, of a particle with rest mass, m_o, is:

$$\vec{p} = m\vec{v} = \frac{m_o \vec{v}}{\sqrt{1-(v/c)^2}} = \gamma m_o \vec{v}$$

We can also relate the total energy, E, to a particle's total momentum, p:

$$E^2 = (cp)^2 + (m_o c^2)^2$$

Energy, momentum and mass

$$E^2 = p^2c^2 + m^2c^4$$

$$E = \gamma mc^2 \qquad p = \beta\gamma mc$$

$$\gamma = E/mc^2 \qquad \beta = pc/E$$

Energies (momenta) are classified as follows:

$\gamma \sim 1$ non relativistic

$\gamma > 1$ relativistic

$\gamma >> 1$ ultrarelativistic (in this case K~E, E=cp)

N.B. In the following sometimes we will use "natural units" h=c=1

Lorentz Invariant Vs. Conserved quantity

With a Lorentz Invariant you get the same number in two different reference systems (it is a scalar).

Let E_L and p_L be energy and momentum measured in LAB frame

Let E_{cm} and p_{cm} be energy and momentum measured in center of mass frame

Then: $E^2_{cm} - p^2_{cm} = E^2_L - p^2_L$

Since (E, p) is a Lorentz invariant (as long as both are measured in same system)

With a conserved quantity you get the same number in the same reference system but at a different time.

Let p_{iL}=initial momentum in lab (before collision)

Let p_{fL}=final momentum in lab (after collision)

Let p_{icm}=initial momentum in CM (before collision)

Let p_{fcm}=final momentum in CM (after collision)

Momentum conservation says:

$p_{iL} = p_{fL}$ AND $p_{icm} = p_{fcm}$ BUT NOT $p_{iL} = p_{fcm}$

Relativistic Kinematics 4-vectors

We can also manipulate 4-vectors using contravariant/covariant (up/down) notation: $m_0^2 = p_u p^u = g_{uv} p^v p^u$

In this notation g_{uv} is the metric tensor of Minkowsky spacetime and is given (e.g.) by:

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Thus the (scalar) product of two 4-vectors (a, b) is given by:

$$ab = a_\mu b^\mu = \sum_{\mu=0}^{3} \sum_{\nu=0}^{3} g_{\mu\nu} a^\nu b^\mu \equiv g_{\mu\nu} a^\nu b^\mu = a^o b^o - a^1 b^1 - a^2 b^2 - a^3 b^3$$

The sum of two 4-vectors is also a 4-vector.

The length of the sum of the 4-vectors of two particles (1,2) is:

$$p_1 + p_2 = (E_1 + E_2, \vec{p}_1 + \vec{p}_2)$$

$$(p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$$(p_1 + p_2)^2 = E_1^2 + E_2^2 + 2E_1 E_2 - \vec{p}_1^{\,2} - \vec{p}_2^{\,2} - 2\vec{p}_1 \bullet \vec{p}_2$$

$$(p_1 + p_2)^2 = m_1^2 + m_2^2 + 2(E_1 E_2 - |\vec{p}_1||\vec{p}_2|\cos\theta) \equiv m_{12}^2$$

m_{12} is called the invariant mass or effective mass

θ=angle between particles, m_1, m_2 are rest masses

Relativistic Kinematics 4-vectors

Example: Consider a proton at rest in the lab frame and an antiproton with 10GeV/c of momentum also in the lab frame.
What is the energy of the antiproton in the lab frame?
Since the rest energy of a particle is a Lorentz invariant we can make us of:

$$m_o^2 = E^2 - \vec{p}^{\,2}$$

c=1

For an antiproton the rest mass, m_0, = 938 MeV/c^2. We can re-write the above as:

$$E = \sqrt{\vec{p}^{\,2} + m_o^{\,2}} = \sqrt{10^2 + 0.938^2} = 10.044\,\text{GeV}$$

Thus at high energies ($E \gg m_0c^2$) $E \approx |p|$.

How fast is the anti-proton moving in the lab frame ?
We need to remember the energy/momentum relationship between the rest frame (particle at rest) of the anti-proton and the lab frame:

$$E_{lab} = \frac{m_0 c^2}{\sqrt{1-(v/c)^2}} = \gamma m_0 c^2 \quad p_{lab} = \frac{m_0 v}{\sqrt{1-(v/c)^2}} = \gamma\beta m_0 c \quad \beta = v/c,\ \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$p_{lab}/E_{lab} = \gamma\beta m_0 c\,/\,\gamma m_0 c^2 = \beta = 10/10.044 = 0.996$$

Thus v = 0.996c (fast!)

Particles and Interactions

Sub nuclear physics studies the components of matter (partons, leptons and gauge bosons) and tries to understand their interactions →

- ❑ Strong Interactions (Relative force at $\sim 10^{-18}$ cm ~ 1)
- ❑ e.m. interactions (" " $\sim 10^{-2}$)
- ❑ Weak Interactions (" " $\sim 10^{-5}$)
- ❑ Gravitational Interactions (" " $\sim 10^{-39}$)

- The gravitational force is not relevant at particle scale since m_p = 938 MeV = 1.67×10^{-27} kg. It is a long range force.
- The weak force responsible for radioactive decays and neutrino interactions) is not very relevant for detectors operation. It is short range.
- The strong force keeps together nucleons (p and n) in the nucleus and partons in nucleons. It is exploited in hadronic calorimeters. This force too is short range.
- The e.m. force keeps together electrons in the atoms. It is long range and for charged particles dominates the interactions down to ~1 f (at shorter distances strong forces dominates).

The electromagnetic interaction is fundamental for detectors physics. Almost all the interactions of elementary particles with detector materials are, at the end, of electromagnetic nature

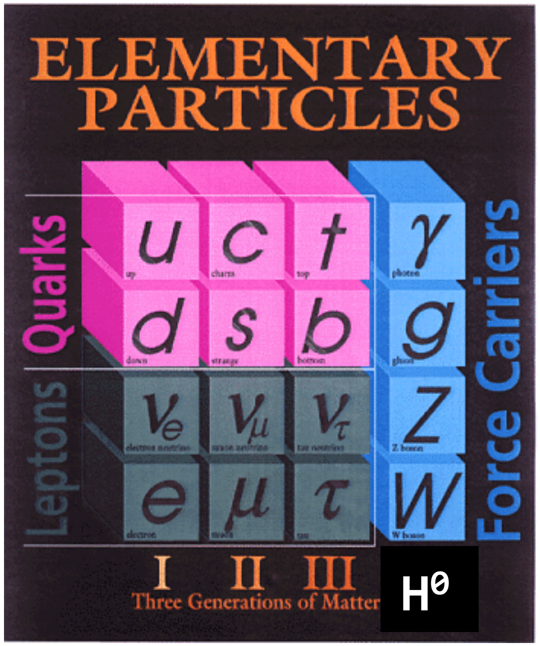
Particles and interactions

Particles are classified according to the forces they are subjected to.

- **Leptons (e, μ, τ) and their neutrinos are not** subjected to strong force. They dont show internal structure → “point-like”
- **Hadrons** feel **strong** force and and divided in **baryons** (half integer spin) and **mesons** (integer spin). Hadrons have an internal structure (quark and gluons).
- Every particle has its antiparticle with the same mass and spin, but opposite charge (what distinguishes matter and antimatter is the intrinsic parity).
- **Gauge bosons** are the carriers of the interactions. They have integer spin.
  - **e.m.** γ
  - **strong** g
  - **weak** $Z^0, W^\pm$

Types of Particle

- Quarks
  - u,d c,s b,t
  - We do not see free quarks, the particles actually observed are the “traditional” color singlet particles such as protons, neutrons and pions,...
- Leptons
  - e, μ, τ, ν_e, ν_μ, ν_τ
- Gauge bosons
  - γ, W, Z, gluons
  - (only γ is observed directly)
- Higgs Boson H^0



Types of Particle

- Particles divided into
  - Fermions – spin ½ , 3/2 , 5/2 etc.
  - Bosons – spin 0, 1, 2 etc.
- Hadrons – made up of valence quarks
  - Baryons (3 quarks) and mesons (2 quarks) and of a "sea" of gluons
- Leptons appear to be point-like, without an internal structure
- Antiparticles
  - … appear to be a *necessary* consequence of quantum field theory