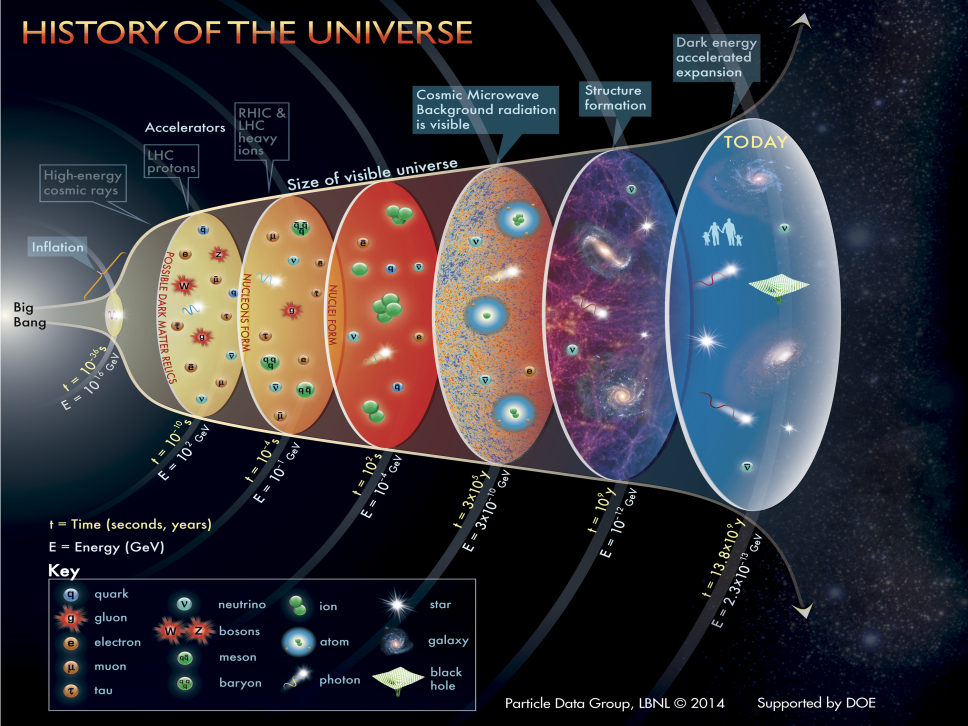
# Particles and Universe

Maria Krawczyk, Aleksander Filip Żarnecki

February 28, 2017


HISTORY OF THE UNIVERSE
Big Bang
Inflation
High-energy cosmic rays
LHC protons
Accelerators
RHIC & LHC heavy ions
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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## Main goal

Present an up-to-date status of theoretical and experimental particle and astroparticle physics, including the most recent achievements of the field.

Follow results coming from experiments at the Large Hadron Collider (LHC), the neutrino oscillation experiments, evidence for the existence of Dark Matter, as well as for the gravitational waves.

## Outline

- Introduction to the Standard Model
- Detection of particles, experiments at large colliders
- Selected aspects of the Theory of Fundamental Interactions
- Tests of the Standard Model
- Search for and study of the properties of the Higgs particle
- Flavour mixing and neutrino oscillations
- Models beyond the Standard Model and search for their signatures
- Origin and evolution of the Universe, Dark matter, Dark energy

**Requirements** for the positive grade

- lecture attendance (2 unjustified absences are allowed)
- 50% of points from test exam (for satisfactory grade)

**Test exam**

- Test will consist of 30 open questions.
  Short answers are expected, one sentence in most cases.
- Expected time to write: 90 minutes.
- Own, hand-written notes are allowed.
- Books, printouts or note copies are NOT allowed.
- No electronic equipement is allowed.

**Web page**

All details and lecture slides available at
http://www.fuw.edu.pl/~zarnecki/PAU/

## Electricity and Magnetism

Electromagnetic field influences the motion of a charged object:

$$\frac{d}{dt} m\vec{v} = q\vec{E} + q\vec{v} \times \vec{B}$$

Charges and their motion are the source of the electromagnetic field
Maxwell equations (1865):

$$\begin{aligned} \varepsilon_\circ \,\mathrm{div}\vec{E} &= \rho \\ \mathrm{rot}\vec{E} &= -\mu_\circ \frac{\partial \vec{B}}{\partial t} \\ \mathrm{div}\vec{B} &= 0 \\ \mathrm{rot}\vec{B} &= \vec{j} + \varepsilon_\circ \frac{\partial \vec{E}}{\partial t} \end{aligned}$$

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Electric and magnetic fields affect each other
$\Rightarrow$ electromagnetic wave: $c = \frac{1}{\sqrt{\varepsilon_\circ \mu_\circ}}$

# End of XIX c.

**Electricity and Magnetism**

Electromagnetic waves were discovered by Heinrich Hertza in 1886
$\Rightarrow$ great success, validation of the Maxwell theory

But the nature of electricity remained unknown!..

Still, the physics seemed to be an almost a “closed” field, everything was described...

## Electricity and Magnetism

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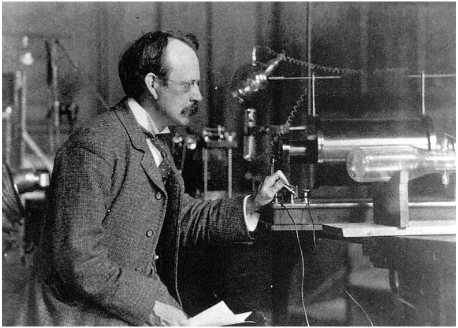
But the nature of electricity remained unknown!..

Still, the physics seemed to be an almost a “closed” field,
everything was described...

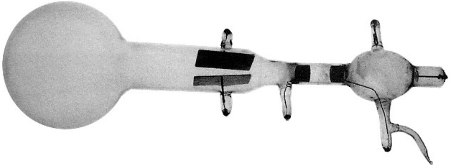
Except for strange phenomena related to current flow in gases:
spectral lines, cathod and anod rays
$\Rightarrow$ one of main fields of experimental activities

Discovery of X-rays by Wilhelm Röntgen in 1895 was unexpected,
but could still fit in that picture...

**Joseph Thomson** 1897



Thomson studied cathod rays

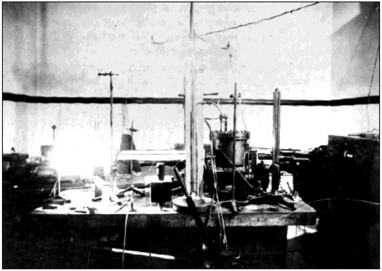


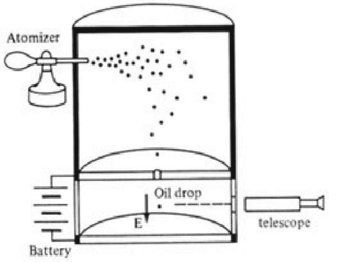
he demonstrated that they bend in the external electric field

He estimated the charge to mass ratio for the electron:

$$\frac{e}{m} \approx 2 \cdot 10^{11} \frac{C}{kg}$$

**Robert Millikan** 1909



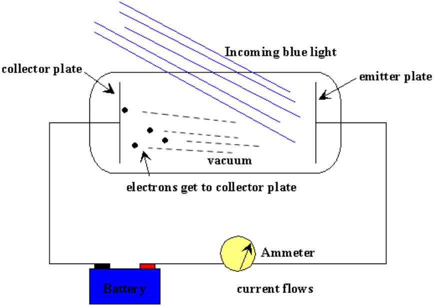



By measuring the free fall of tiny olive droplets in air, Millikan estimated the electron charge and, taking the Thomson result on $e/m$, evaluated electron mass:

$$m_e = \frac{1}{1837} \cdot m_H$$

## Photoelectric effect

Discovered by Hertza in 1887
In 1902, Philipp Lenard demonstrated that the photoelectric effect is observed only for selected wavelengths of light:

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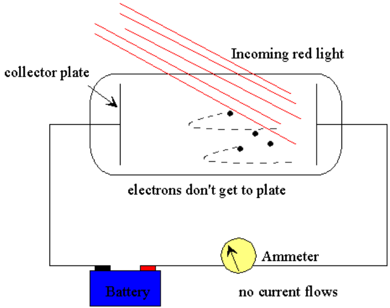


This effect could not be explained if light is described as the electromagnetic wave!

## Photoelectric effect

In 1905, Albert Einstein proposed a hypothesis that light is a flux of electromagnetic energy quanta, which we call photons today.

Photon energy:

$$E_\gamma = h\nu = \frac{hc}{\lambda}$$

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Photon energy:

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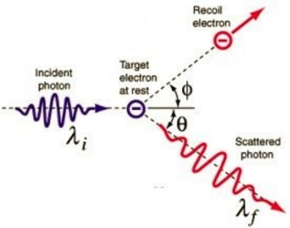
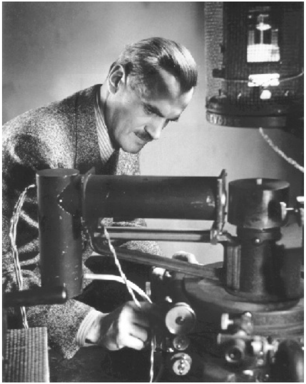
To liberate electron, the photon energy has to be higher than the so called work function of the cathod element

⇒ wavelenght dependence

**Arthur Compton** 1923

Photon scattering off electrons



Compton demonstrated that photons carry not only the energy, but also the momentum $\Rightarrow$ they behave as particles

## Natural radioactivity

Discovered by Henri Becquerel in 1896.

He tried to verify the hypothesis, that X-ray emission is related to fluorescence - emission of light by a substance (eg. uranium) that has absorbed light or other electromagnetic radiation.

# Radioactivity

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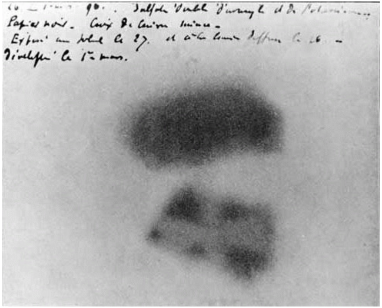
Sun was the brightest light source available at that time.

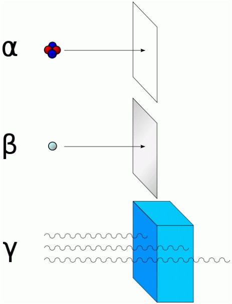
Unfortunately, the weather was poor in Paris, so Becquerel put the uranium sample and unexposed photographic plate into a drawer...



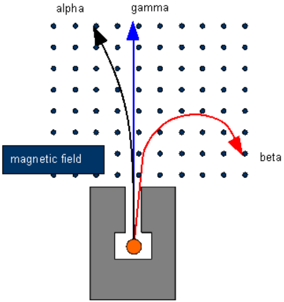
Radioactivity was intensively studied in the following years.

At the beginning of the XX c. three types of radiation were recognized, based on

penetration of matter




bending in the magnetic field



**1903**

Nobel prize for H.Becquerel, M.Sklodowska-Curie and P.Curie

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E.Rutherford and F.Soddy published the article explaining radioactivity as a transformation of elements: one type of atom emits the radiation while transforming into atom of another element.

- $\alpha$ radiation (Helium nucleus)
$$^{238}_{92}U \rightarrow ^{234}_{90}Th + \alpha$$
- $\beta$ radiation (electrons)
$$^{60}_{28}Co \rightarrow ^{60}_{29}Ni^{\star} + e^{-} \ldots$$
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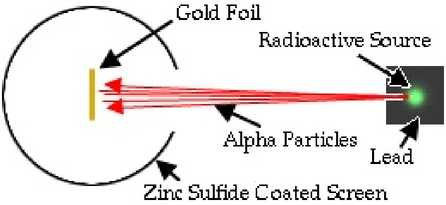
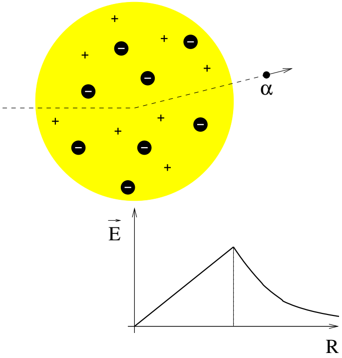
But the atom was still considered as an elementary object...

Strong radioactive sources became one of main tools in research...

## Rutherford experiment

Scattering of $\alpha$ particles of gold foil



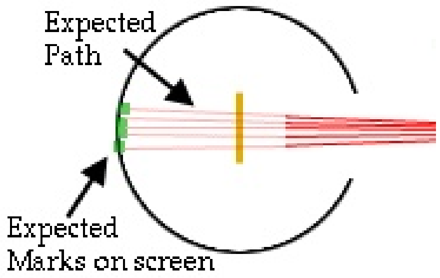

Scyntylation observed when the scattered particle hit the fluorescent screen was used to estimate the scattering angle.

Thomson model:
Uniformly charged atom with point-like electrons moving freely inside ("plum pudding model")

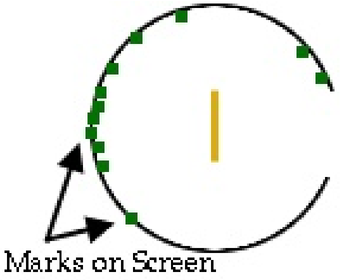
## Rutherford experiment

Results of H.Geigera i E.Marsdena measurements (1909):

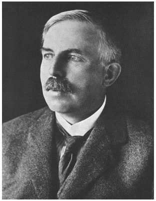
**Expected**

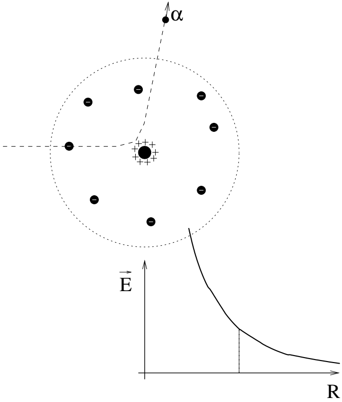



**Measured**



## Rutherford model (1911)





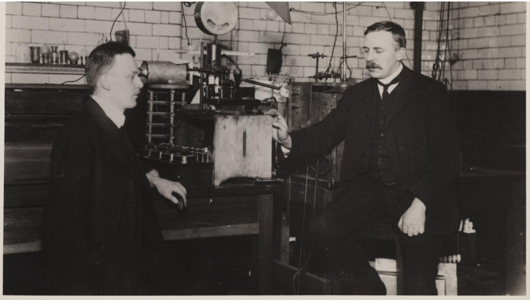

Rutherford proposed the model of atom made up of a central charge, surrounded by a cloud of electrons.

The positive charge of the atom ($10^{-10}$m) is confined to almost point-like ($10^{-14}$m) nucleus

$\alpha$ particles can scatter at much larger angles

After the I World War, Rutherford continued to study nuclei of elements with scattering experiments. He also studied induced nuclear reactions.

In 1919 he reported results proving that the hydrogen nucleus is present in other nuclei $\Rightarrow$ considered as proton discovery.



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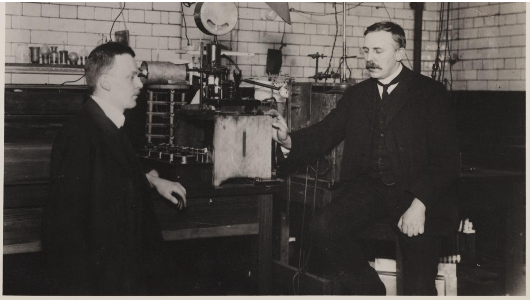
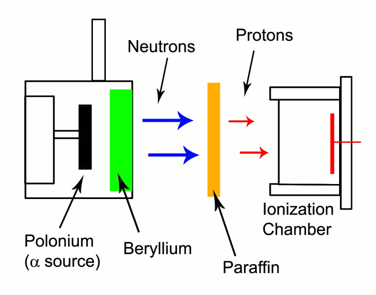


However, Rutherford still believed that heavy nuclei are build of hydrogen ($^1H$) and helium nuclei ($^3He$ and $^4He$), which he considered elementary.

# Discovery of neutron

Existence of neutral constituents in nuclei was already considered by Rutherford in 1920. But there was no experimental evidence.

In 1930, Bothe and Backer discovered that beryllium irradiated with $\alpha$ particles emits radiation which is much more penetrating. This radiation was energetic enough to knock protons out of the paraffin target.



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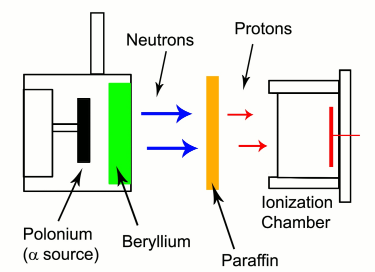
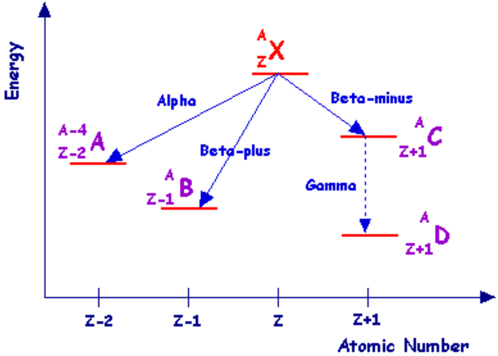



In 1932, James Chadwick proved that this was not the gamma radiation, but a new type of particle - neutron.

With discovery of neutron, structure of atomic nuclei became clear.

All radioactive decays observed, could be explained in terms of the element transmutation (change of mass and atomic numbers).



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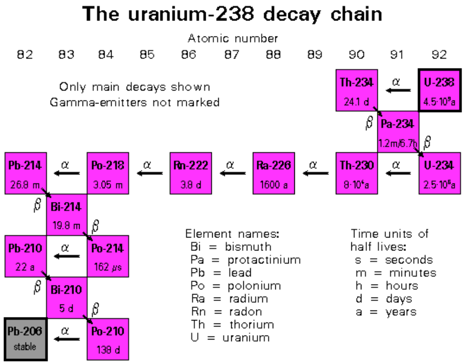
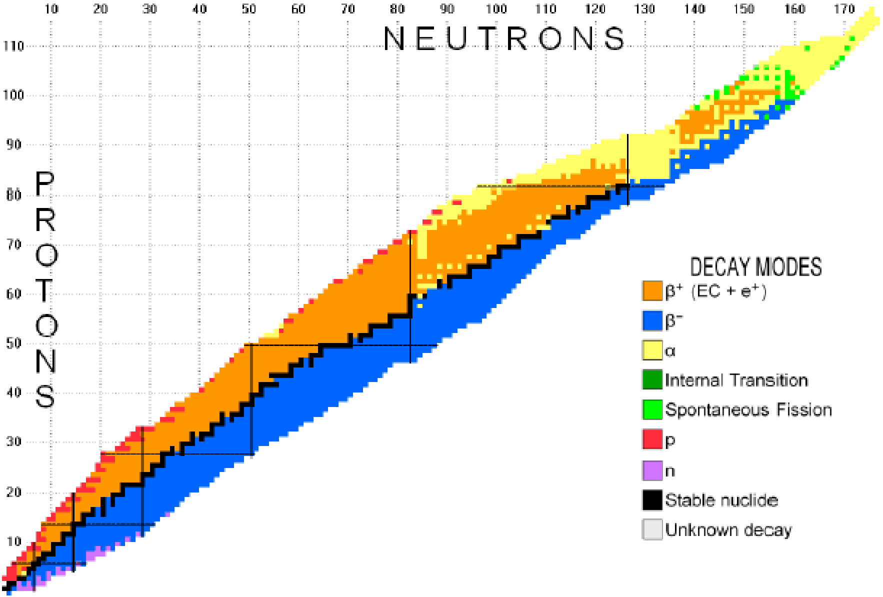


# Radioactivity



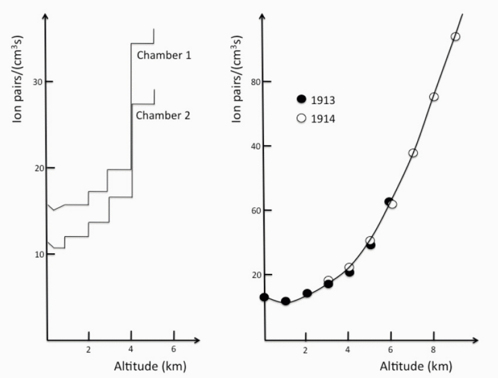
Already Coulomb noticed that charged bodies, even perfectly isolated from the environment, loose their charge with time. He could not explain that...

In 1900, Charles Wilson discovered that air molecules are partly ionized. He attributed it to the natural radioactivity of Earth elements.

First measurements of Theodor Wulf at the Eiffel Tower showed that ionization does not drop with altitude.

In 1912, Victor Hess showed that ionization is, in fact, increasing at high altitudes.

Detailed measurements conducted by Victora Hessa in 1913 showed that the ionization is increasing fast for altitudes above 2 km.
The only plausible explanation was that it comes from the cosmic space...



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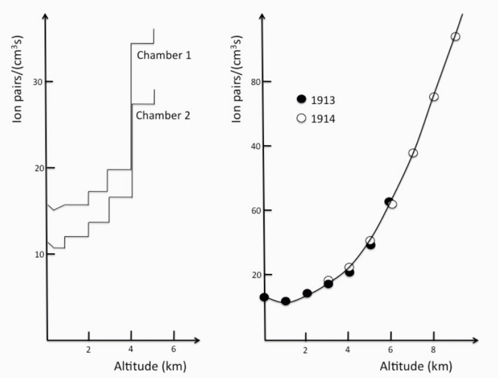



However, it was not clear until 1932, if cosmic rays were charged particles or the energetic gamma radiation...

With radioactive sources energies up to 50 MeV could only be obtained. Cosmic rays were the only source of high energy radiation.

Many experiments were build, using cloud chambers or with photographic emulsion, to search for new phenomena in cosmic ray interactions.

Carl Anderson put his Wilson chamber in a strong magnetic field and put a thin lead plate in the middle.

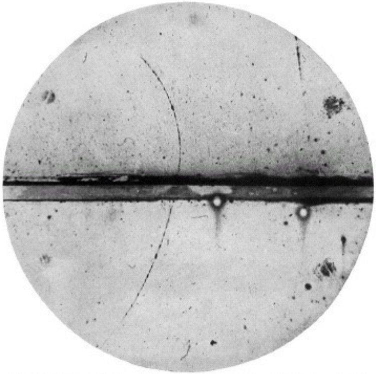
With radioactive sources energies up to 50 MeV could only be obtained. Cosmic rays were the only source of high energy radiation.

Many experiments were build, using cloud chambers or with photographic emulsion, to search for new phenomena in cosmic ray interactions.

Carl Anderson put his Wilson chamber in a strong magnetic field and put a thin lead plate in the middle.

In 1932 he observed the particle which had a positive charge (as a proton) but the mass of the same order of magnitude as that of electron.

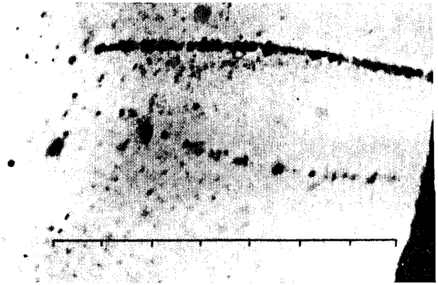
$\Rightarrow$ positron ($e^+$)



# Muon discovery

The muon was first observed in 1932 by Paul Kunze in Rostock. He observed a particle with positive charge, but the mass seemed to be smaller than that of the proton and higher than that of the electron.

The observation was published, but it was not compatible with the "standard model" of that time...



$\Leftarrow$ muon $(\mu^+)$

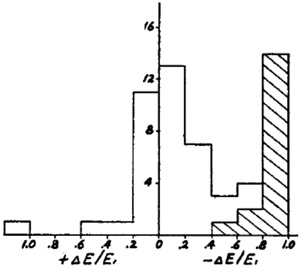
$\Leftarrow$ electron $(e^-)$

# Muon discovery

In 1936 the American physicists Carl D. Anderson and Seth Neddermeyer presented results from the study of a large number of cosmic particles.

They concluded that two components are needed to explain their results:

- non-penetrating, easily stopped by 0.7 to 1.5 cm of lead
  $\Rightarrow$ can be interpreted as "free positive and negative electrons"
- penetrating, loosing very little energy in lead
  mass smaller than that of a proton $\Rightarrow$ new particle ?...



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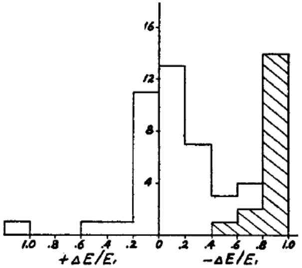



Because of its mass, it was at first thought to be the particle predicted by the Japanese physicist Yukawa Hideki in 1935, to explain the strong force that binds protons and neutrons together in atomic nuclei.

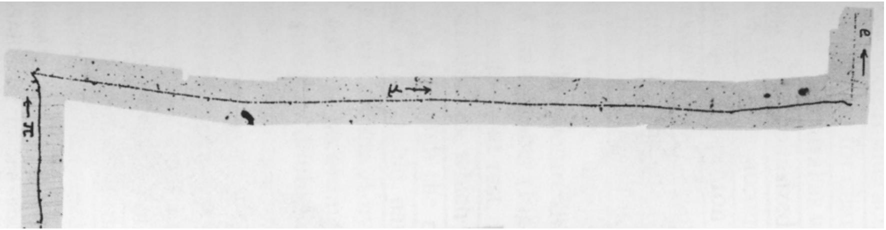
However, it was not interacting strong enough with matter...

# Pion discovery

In 1947, Cecil Powell's group at Bristol University studied cosmic ray interaction in photographic emulsion.

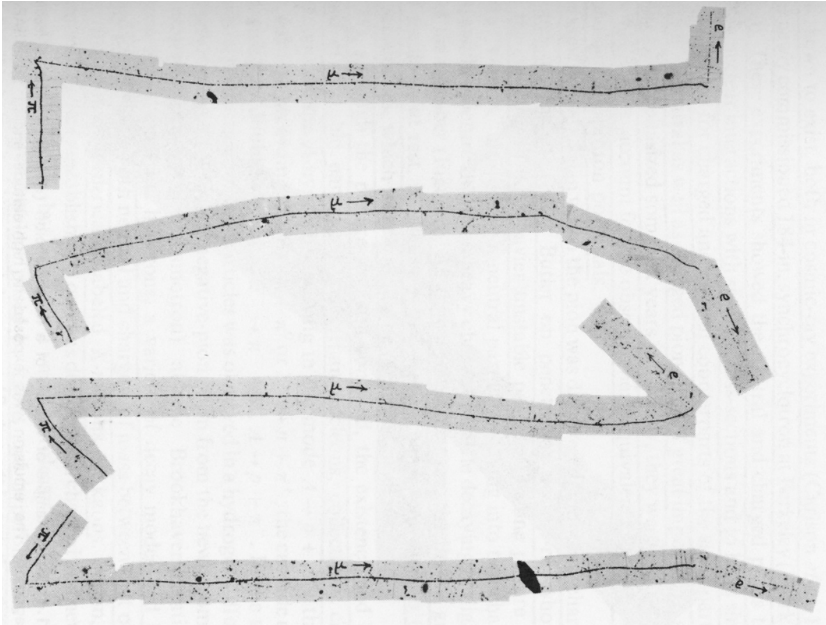
They discovered that the muons $(\mu^{\pm})$ are produced by other particles, pions $(\pi^{\pm})$, which live for only a few hundredths of a microsecond.

One of the reconstructed decay chains:




$$\pi^{+} \longrightarrow \mu^{+} \ \nu_{\mu} \longrightarrow e^{+} \ \nu_{e} \ \bar{\nu}_{\mu} \ \ \nu_{\mu}$$

# Pion discovery



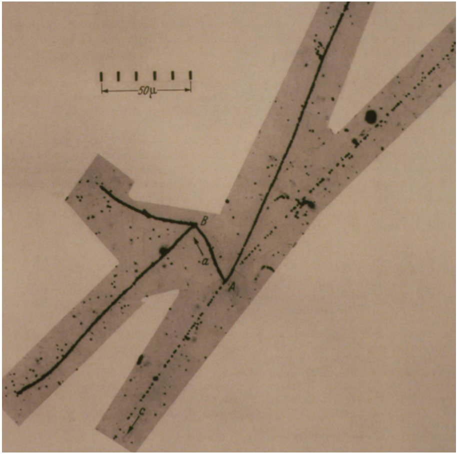
# Strange particles

In 1948, Powell's team at Bristol University studying cosmic ray interactions with photographic emulsion made another spectacular discovery.

They observed the decay of an unknown particle (coming in from top right) into 3 pions.

$$K^+ \rightarrow \pi^+ \pi^+ \pi^-$$

The kaon was the first discovered member of the family of "strange" particles...



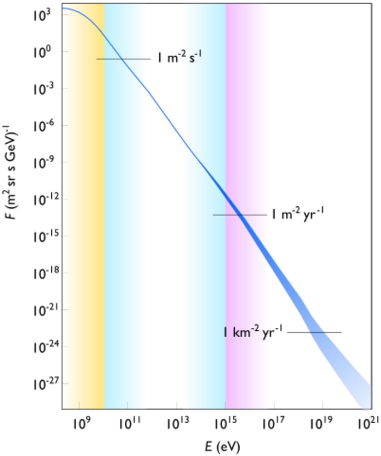
## Primary cosmic rays

Observed in the cosmic space, outside Earth's atmosphere

Composition:

- protons ($^1H$) $\sim$ 86%
- $\alpha$ particles ($^4He$) $\sim$ 13%
- heavier nuclei $\sim$ 1%
- neutrons, electrons $\ll$ 1%

(neglecting neutrinos and gammas)




Same as the "composition of the Universe..."

# Cosmic rays

## Secondary cosmic rays

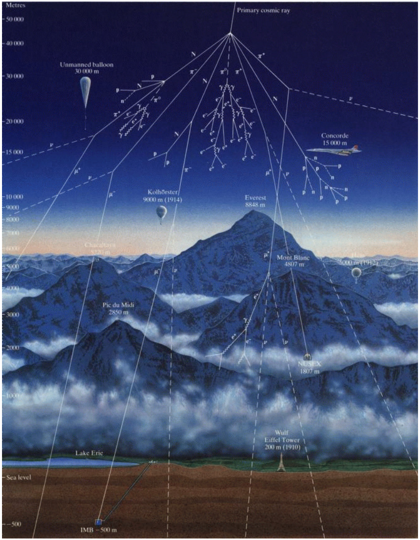
Result of the primary cosmic ray interactions in the Earth's atmosphere. Secondary particles, mainly pions and kaons, are copiously produced in these interactions. Both pions and kaons are unstable, produced in their decay chain are muons and electrons.

At the sea level:

- muons $\mu^{\pm}$ $\sim$70%
- electrons $e^{\pm}$ $\sim$25%
- protons and pions $\pi^{\pm}$ $\sim$3%

Average flux:

180 charged particles per $m^2 \cdot s$



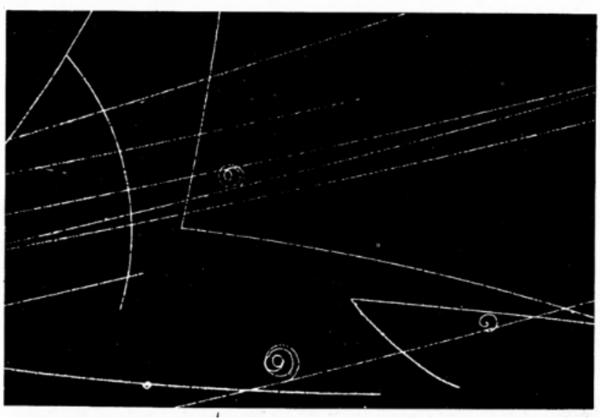
# Strange particles

In October 1950, V. D. Hopper and S. Biswas discovered another strange, long lived particle, decaying to proton and pion:

Lifetime much longer than expected

$$\Lambda \rightarrow p + \pi^{-}$$
$$\tau \approx 3 \cdot 10^{-10} s$$

$$\Delta \rightarrow p + \pi^{-}$$
$$\tau \sim 10^{-23} s$$



# Strange particles

In October 1950, V. D. Hopper and S. Biswas discovered another strange, long lived particle, decaying to proton and pion:

Lifetime much longer than expected

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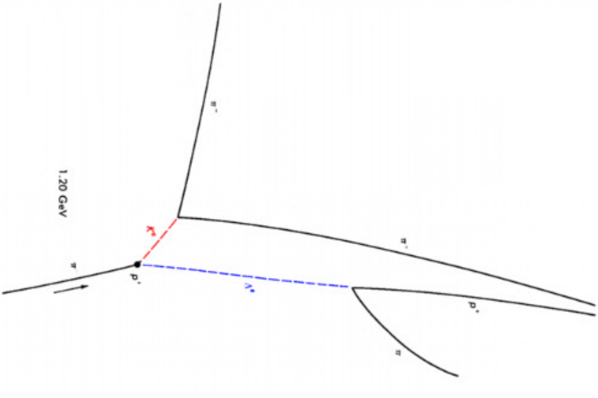


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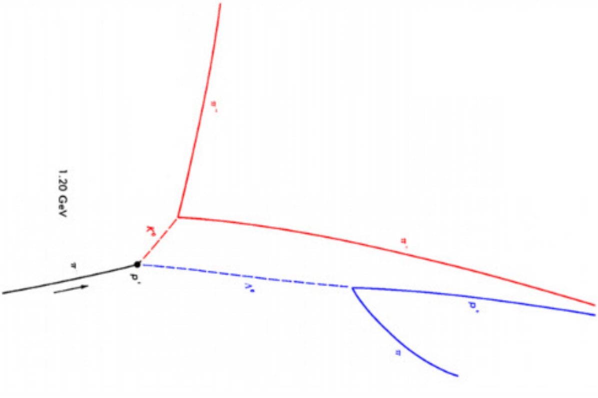
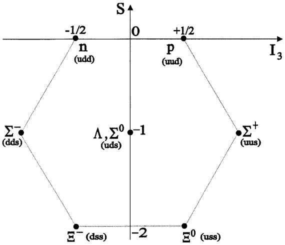


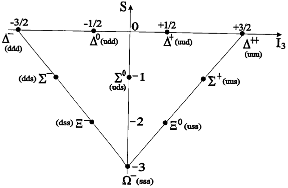

$\pi^- \; p \longrightarrow \Lambda^\circ \; K^\circ \longrightarrow \pi^- \; p \;\; \pi^- \; \pi^+$

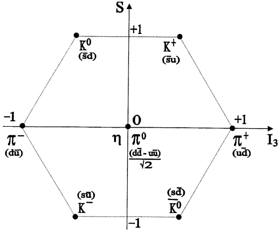
Many new particles discovered after 1950.

They could be grouped into multiplets, based on their properties.

It started to remind the periodic table of ellements.
⇒ indication of a more fundamental description.



Concurrently to the scientific discoveries new research tools were being developed

| | | | |
|---|---|---|---|
| 1897 | – | electron | |
| 1911 | – | atomic nucleus | cloud chamber |
| 1919 | – | proton | |
| 1929 | – | | Van der Graaff accelerator |
| 1931 | – | neutron | Lawrence cyclotron |
| 1932 | – | positron | Cockcroft-Walton generator |
| 1937 | – | muon $\mu^{\pm}$ | |

# Changing landscape

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| 1947 – | pion $\pi^{\pm}$ | |
| 1949 – | kaon $K^{\pm}$ | |
| 1952 – | | bubble chamber |
| 1955 – | | synchrotron |

$\Rightarrow$ dawn of modern particle physics

# Changing landscape