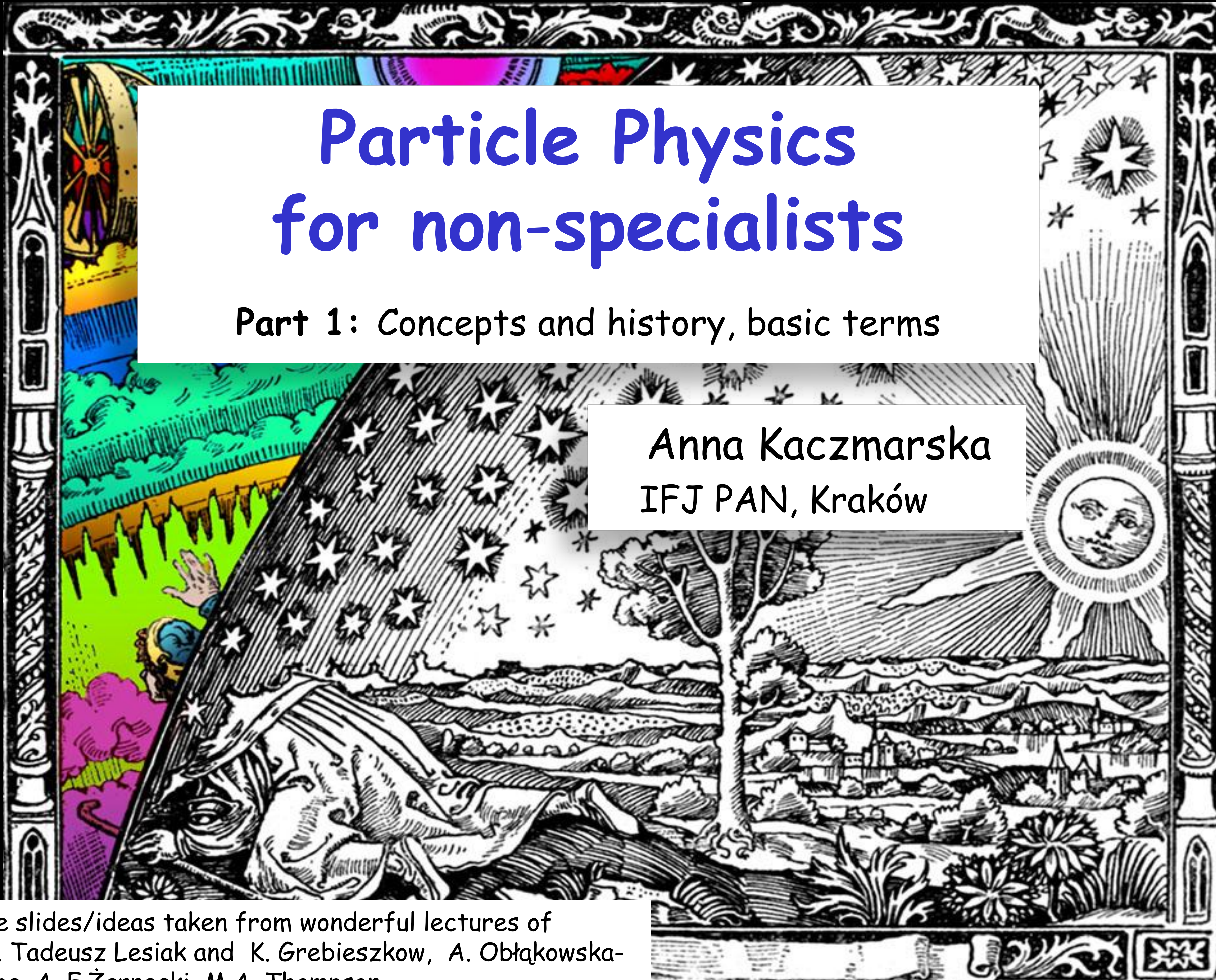


Particle Physics for non-specialists

Part 1: Concepts and history, basic terms

Anna Kaczmarska
IFJ PAN, Kraków

Some slides/ideas taken from wonderful lectures of prof. Tadeusz Lesiak and K. Grebieszkow, A. Obłąkowska-Mucha, A. F.Żarnecki, M.A. Thompson

Content of the course

- **The Particle Physics for non-specialists course** consists of 6 lectures (2x45')
  - **I. Concepts and history, basic terms**
  - II. Symmetries in particle physics, the quark model, Feynman diagrams
  - III. Accelerators and detectors
  - IV. Electromagnetic and Strong Interactions
  - V. Weak Interactions and CP symmetry breaking, Electroweak Interactions and Higgs boson
  - VI. Beyond Standard Model, Neutrino Physics

- Slides will be available on indico
  - [I only have to find where it is ☺]
- **Literature**
  - Perkins *Introduction to High Energy Physics*
  - Griffits *Introduction to Elementary Particles*
  - Martin, Shaw *Particle Physics*
  - Halzen & Martin: *Quarks & Leptons: an Introductory Course in Modern Particle Physics*
  - Particle Data Group: "Review of Particle Physics" [http://pdg.lbl.gov]

- The (mini-)exam
  - written form, short answers to question (from the list - to be provided earlier)

- Please ask questions anytime
- Interrupt if I'm too fast, or…
- … speed me up if I'm telling you something you have already learnt
- Let's have as much interesting discussion as possible!

- If some questions come to your minds after lectures please do not hesitate to contact me:
  - Anna.Kaczmarska@ifj.edu.pl
  - Office 0208

Warning

This course may change your vision of the Universe.
What you will hear may alter your perception of reality.

Stay awake and keep an open mind!

We are entering a Quantum World...

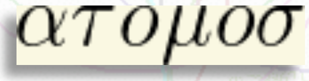
Eternal questions

- People have long asked: "*What is the world made of?*" and "*What holds it together?*"
- In ancient times, people organized the world around them into fundamental elements, such as earth, air, fire, and water

Empedocles (c. 400 BCE)
Aristotle

Democritus (c. 400 BCE)

(gr.) atomon = „with no parts”

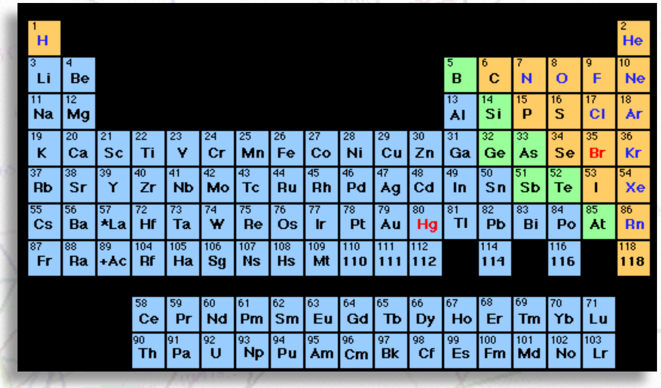


Is the atom fundamental?

People realized that they could categorize atoms into groups that shared similar chemical properties

1869 – Mendeleev creates his periodic table of elements

Conclusion: atoms are made up of simpler building blocks!

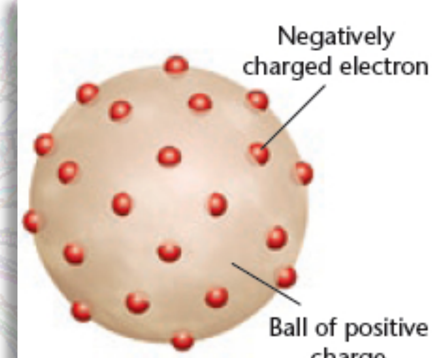


1897- Joseph Thomson showed that cathode rays were composed of previously unknown negatively charged particles, which he calculated must have

- size much smaller than atoms
- very large value for their charge-to-mass ratio

Discovery of electron!

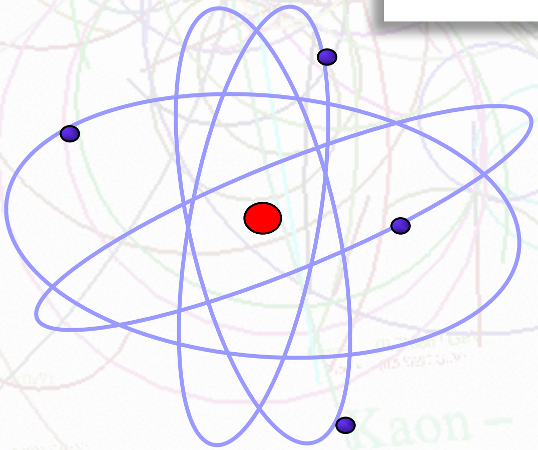
"Plum pudding" cake model of atom



Thomson's atomic model

1912 – Rutherford found nucleus in the atom. Electrons are on orbits around it.

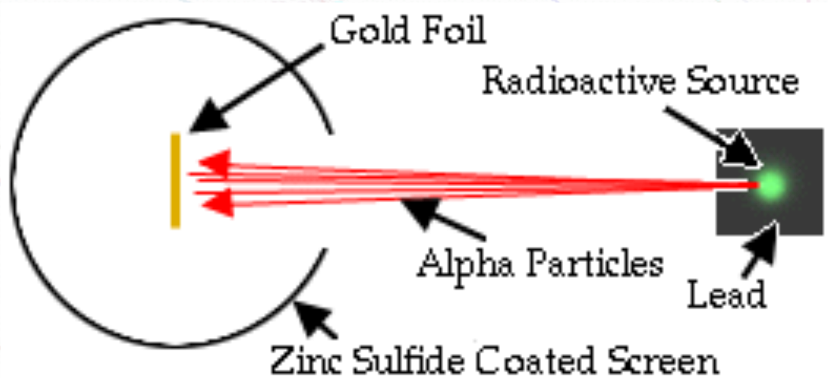
"Planetary" model of atom



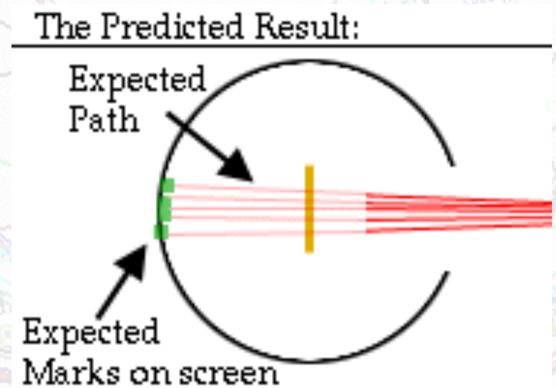
10^{-10} m

Rutherford's experiment

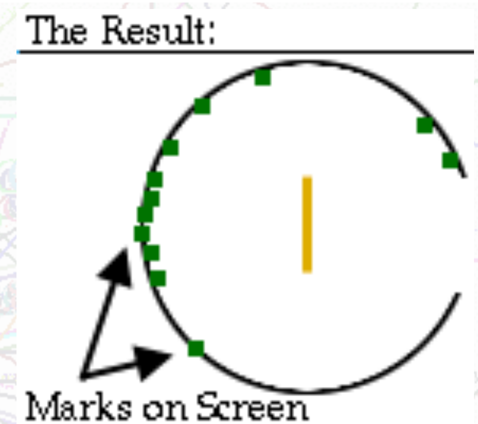
Experiment

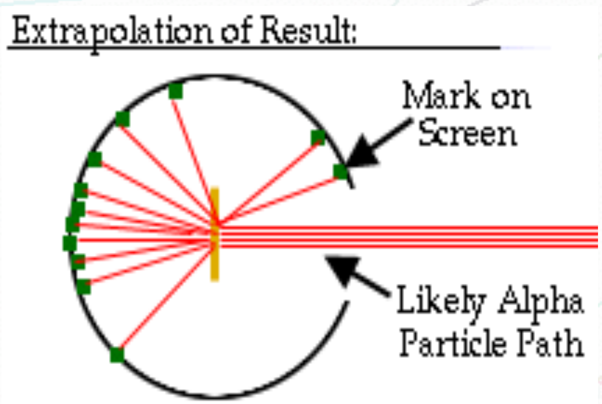


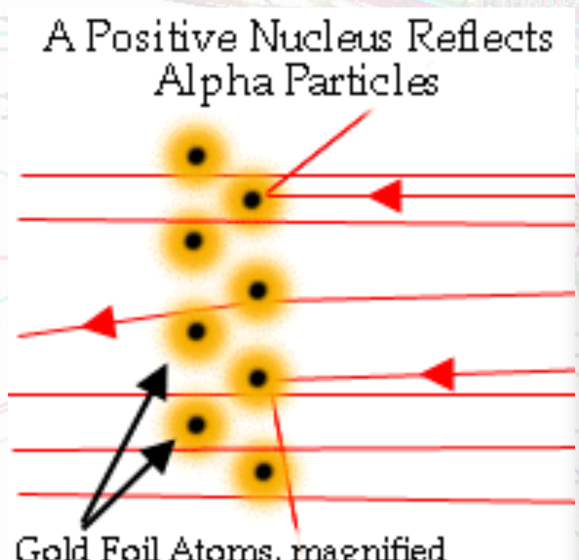
Expectations



Almost all the alpha particles did pass through the foil but some deflected off at different angles. Very few of the alpha particles even bounced backwards after hitting the gold foil.







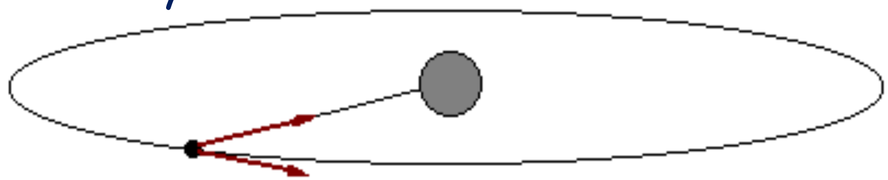
"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

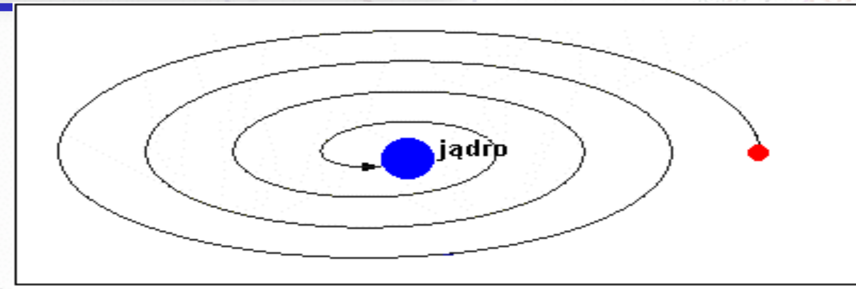
Analysis

Conclusion: Atoms have a dense zone of positive charge, much smaller than the whole atom. **Atomic Nucleus!**

Models of atom

Planetary model





Electrons orbit the nucleus which has a positive charge. The centripetal force for the orbit is caused by Coulomb forces.

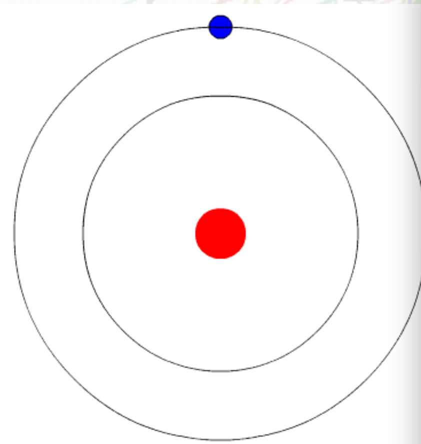
The classical electromagnetic theory: any charged particle being accelerated emits electromagnetic waves, losing energy and, then, electrons should fall over the nuclei.

Atomic spectrum of such radiation should be continuous

But it is not!

Niels Bohr (1885 – 1962)
Nobel Prize 1922

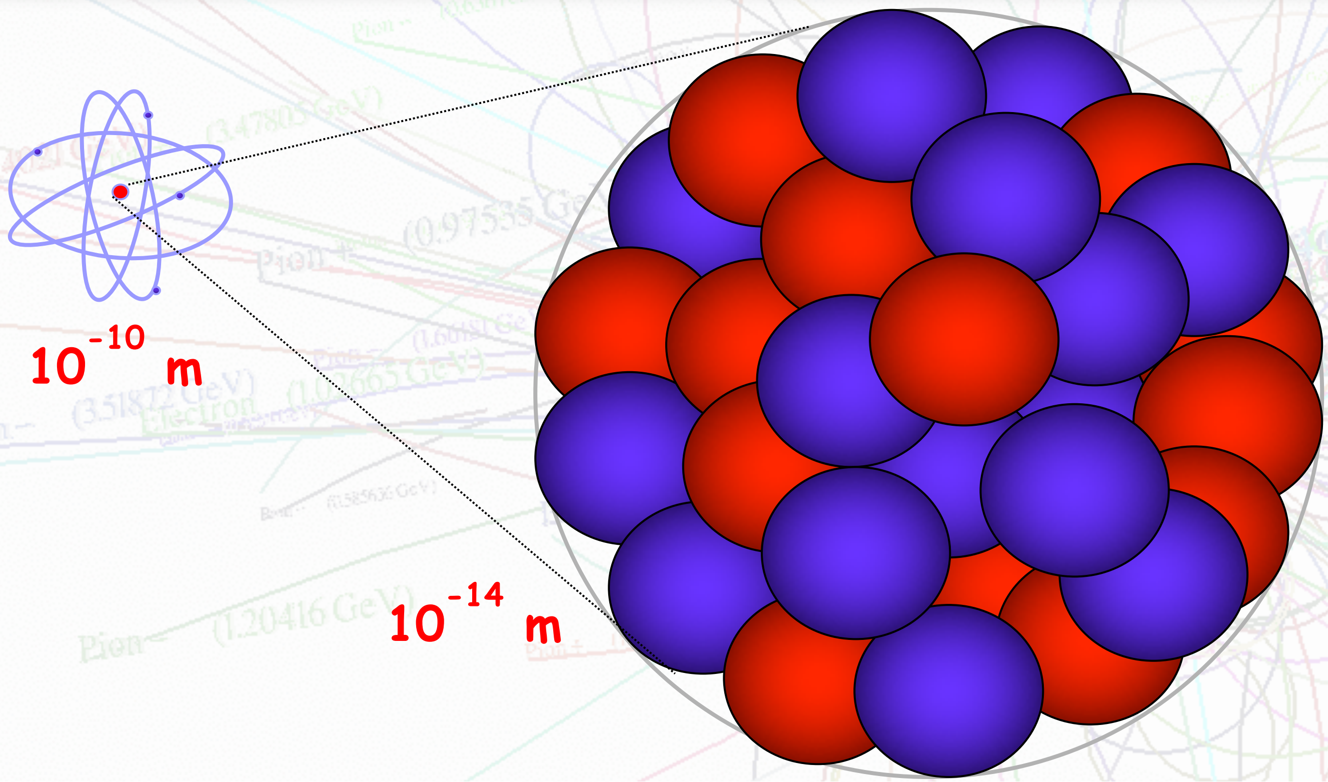
Based on Max Planck ideas: radiation is emitted in portions (quants)



- Only some orbits are "allowed"
- In an allowed orbit, an electron is exempt from the classical laws of electromagnetism and does not radiate energy.
- Electrons may "jump" from orbit to orbit with the energy difference between these two states being given off or absorbed in the form of a single photon of electromagnetic radiation.

Is the Nucleus Fundamental?

Nucleus is made of positively charged protons (Rutherford's experiment) and neutrons which have no charge (discovered later by Chadwick in 1932)



This picture is quite distorted. If we draw the atom to scale and made protons and neutrons a centimeter in diameter, then the electrons and quarks would be less than the diameter of a hair and the entire atom's diameter would be greater than the length of **thirty football fields!**

99.999999999999% of an atom's volume is just empty space!

Digression: cosmic rays

Already Coulomb found that electroscopes can spontaneously discharge - "natural Earth radioactivity"?

T. Wulf (1910) – invented a new/portable electroscope and used it on the top of the Eiffel tower. Assuming that the radiation came from Earth, they expected to find a rapid decrease in the radiation. They did not find the decrease they expected and there seemed to be evidence that the radiation actually increased.

Victor Hess (1912) -took electroscope on a balloon flight (5 km) and measured the amount of **radiation increase as the balloon climbed**.
This radiation was called "*Cosmic Radiation*" later became "***Cosmic Rays***".
Won Nobel Prize in 1936.

1932 – we have: e^-, p, n, but… are those all particles?

An incident cosmic ray particles (mainly p's) interacts with the atoms at the top of the atmosphere. Due to its high energy it disintegrates the atoms producing a cascade -> new particles can be created!

⇒ Cosmic accelerator for poor

Charged particles leave traces in for example: photographic emulsions and cloud chambers.

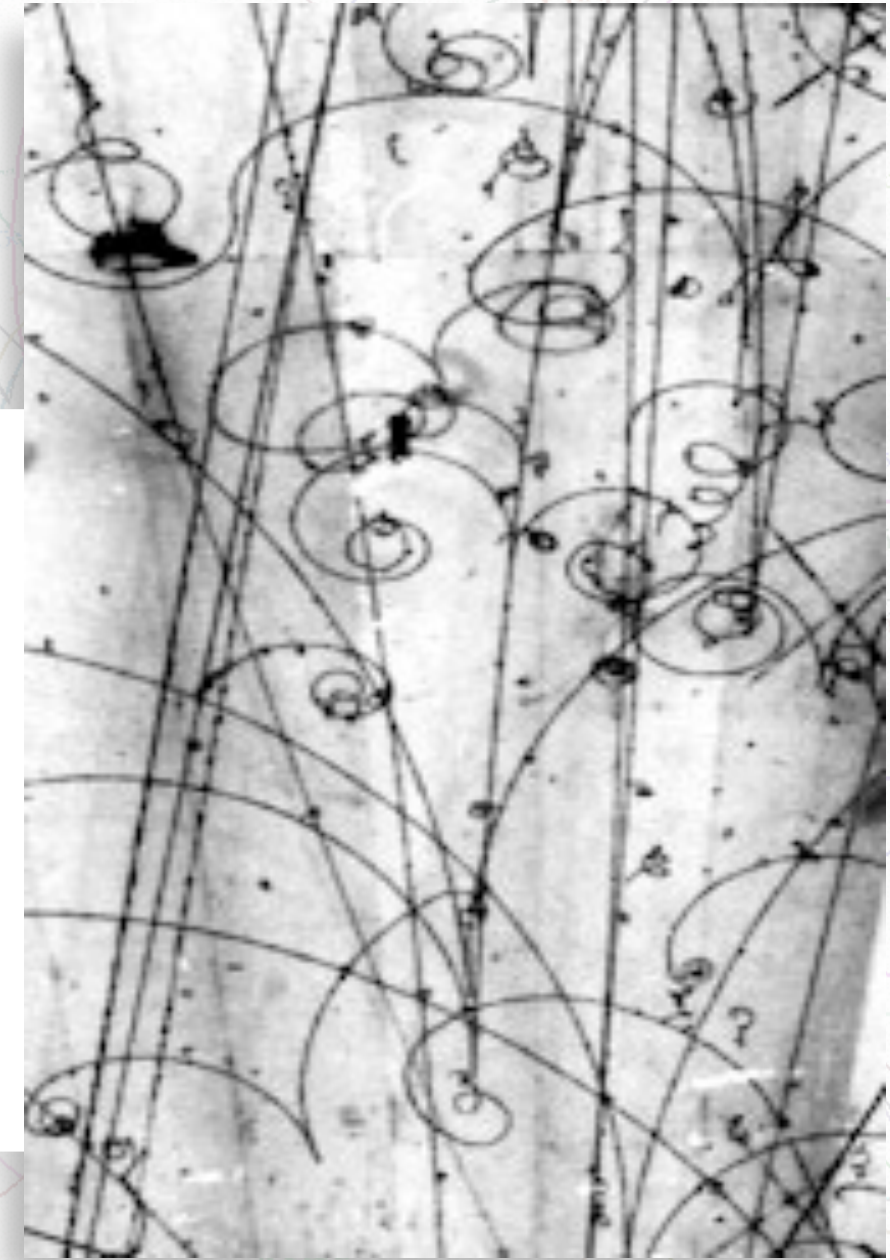
This showed us that electrons and protons are not the only ones charged particles in the nature!

1936 – particle 200 times heavier than electron -> muon. And it decays!

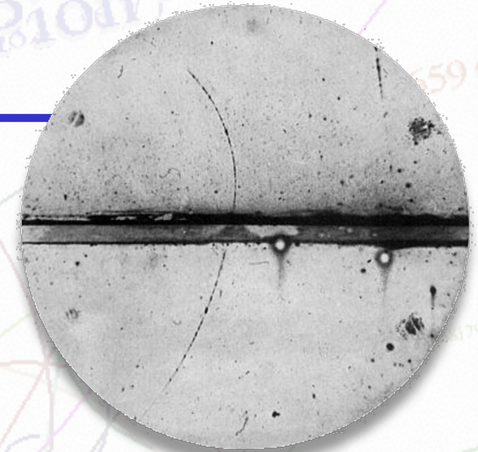
1947 – long sought pion (Yukawa, 1934)

1949 – mesons K – first "strange" particles (they live quite long and are produced only in pairs)

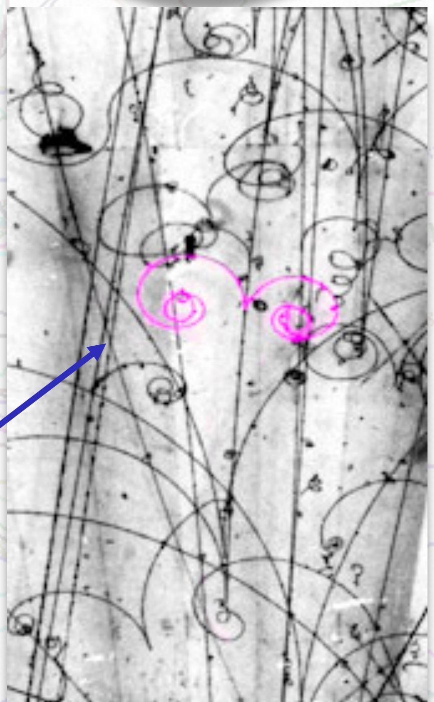
etc..

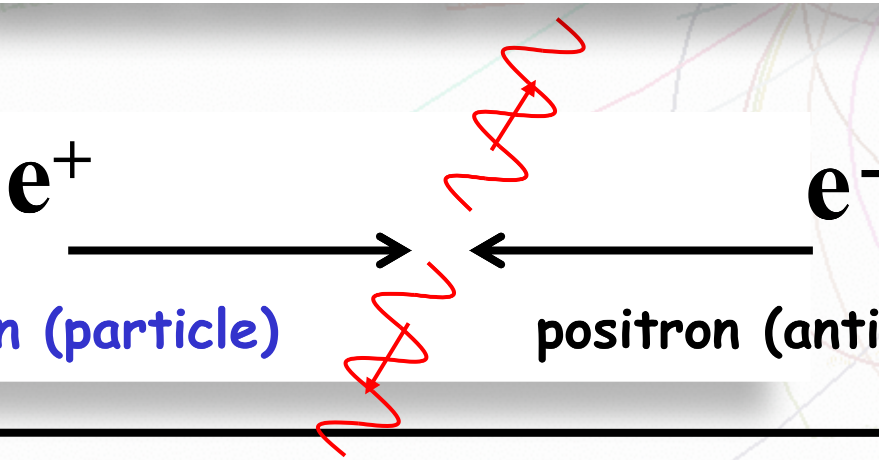


And yet anti-particles…



- Predicted by Dirac (1928) -> two solutions of his equation for e
- Discovered (by chance!) – Anderson 1932
  - allowed cosmic rays to pass through a cloud-chamber
  - magnet surrounded this apparatus, causing particles to bend depending on their electric charge
  - ion trail left by each positron appeared on the photographic plate with a curvature matching the mass-to-charge ratio of an electron, but in a direction that showed its charge was positive
- Particle and its anti-particle have the same mass as one another, but opposite electric charge and other differences in (additive) quantum numbers
- Particle–antiparticle pairs can annihilate each other, producing photons
  - since the charges of the particle and anti-particle are opposite, total charge is conserved.





electron (particle)

positron (anti-particle)

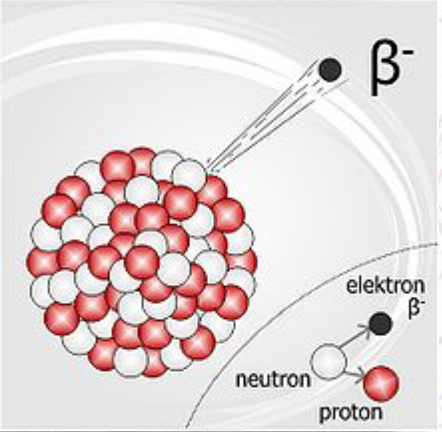
Electron-positron pair created out of photons hitting the bubble-chamber liquid (in magnetic field)

Is this all story? Not exactly ☺

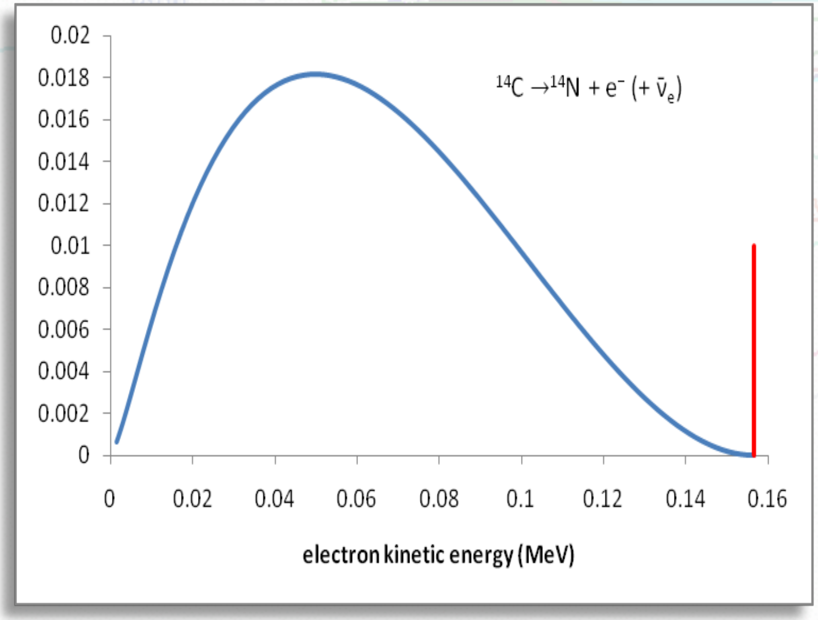
Wolfgang Pauli (1900 – 1958)
Nobel Prize 1945

Mystery of nuclear β decay

If β decay == 2-body decay:

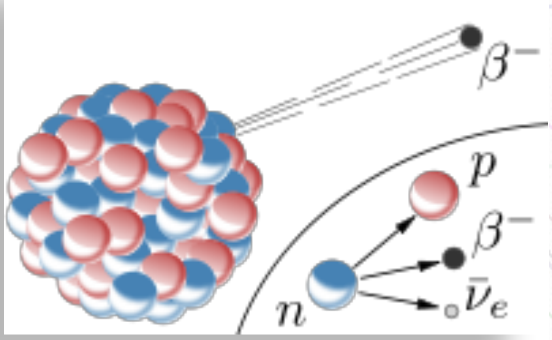


Electron should have a discrete and not continuous spectrum! Energy not conserved???



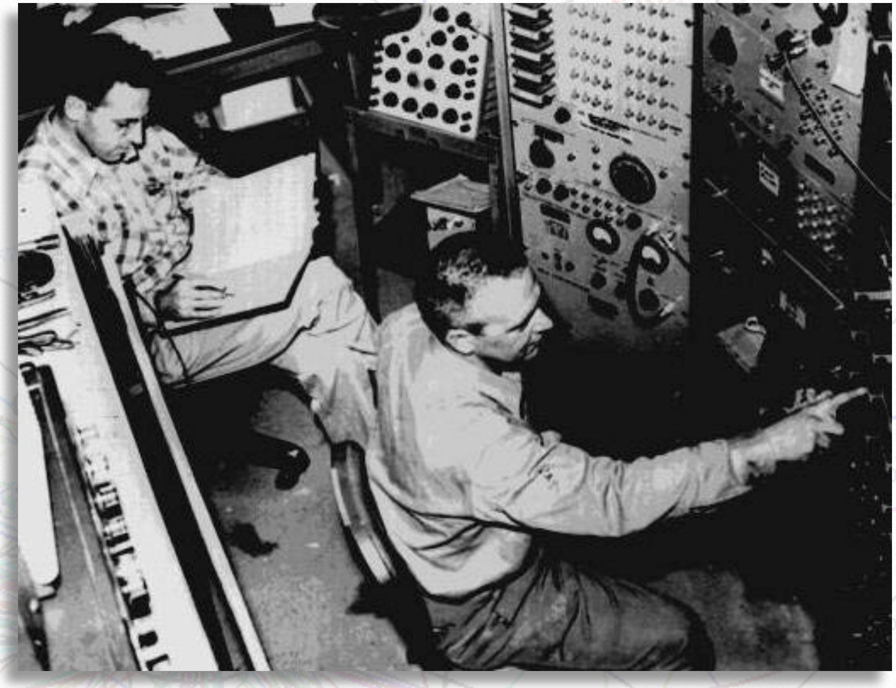
Pauli proposed a "desperate remedy"– he introduced a new neutral particle, weakly interacting with matter.
He called it "neutron" – changed by Fermi to „neutrino" after Chadwick discovered neutron.

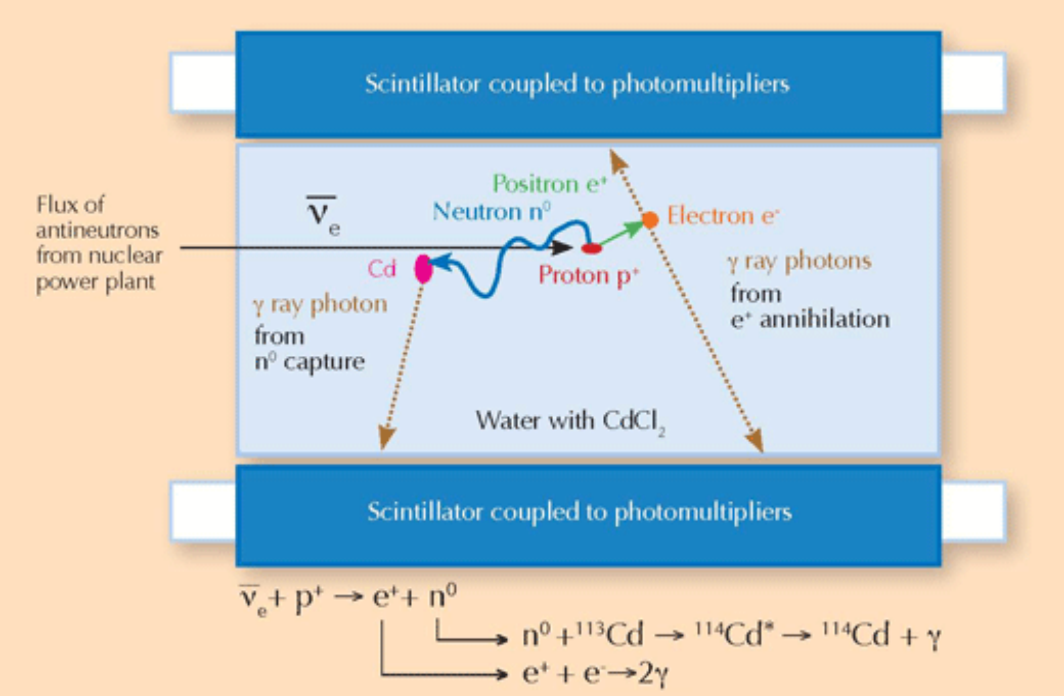
Because neutrinos interact so weakly with matter, Pauli bet a case of champagne that nobody would ever detect one. Indeed this was the case until 1956, when Cowan and Reines detected antineutrinos emitted from a nuclear reactor. When their result was announced, Pauli kept his promise.



Neutrino's detected… (1956)

- Cowan & Reines
  - Reins Nobel Prize 1995 (Cowan died in 1974)
- Probability of neutrino interactions is very low. To register it one needs a very intense flux of neutrinos
  - intense neutrino flux from nuclear reactor





- Antineutrino interacts with p, producing n and e^+
- Positron annihilates with an atomic electron produces photons
- Neutron captured by a Cd nucleus, releasing more photons
  - signal from n appears later than from e = > background rejection

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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

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WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

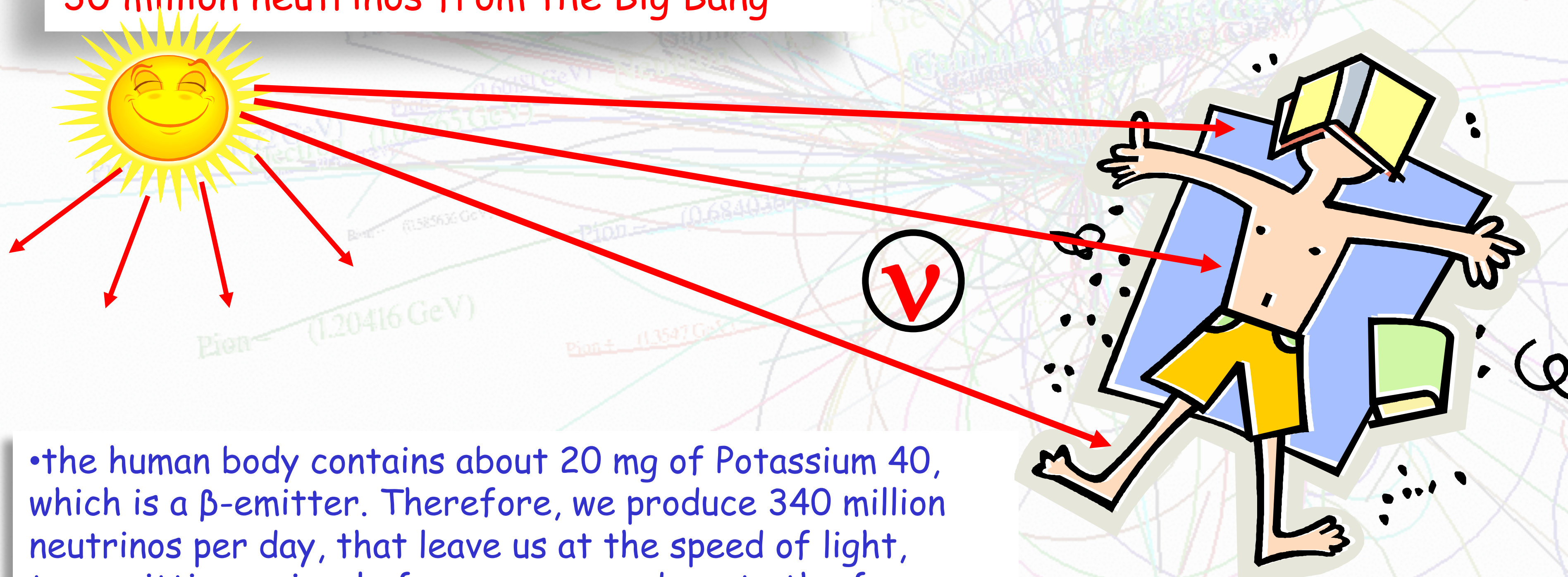
Neutrinos

Electron, proton and neutrons are rarities!
For each of them in the Universe there is 10^9 neutrinos

Every cm^2 of Earth surface is crossed every second by more than 10^{10} neutrinos produced in the Sun

Within your body at any instant: roughly 30 million neutrinos from the Big Bang

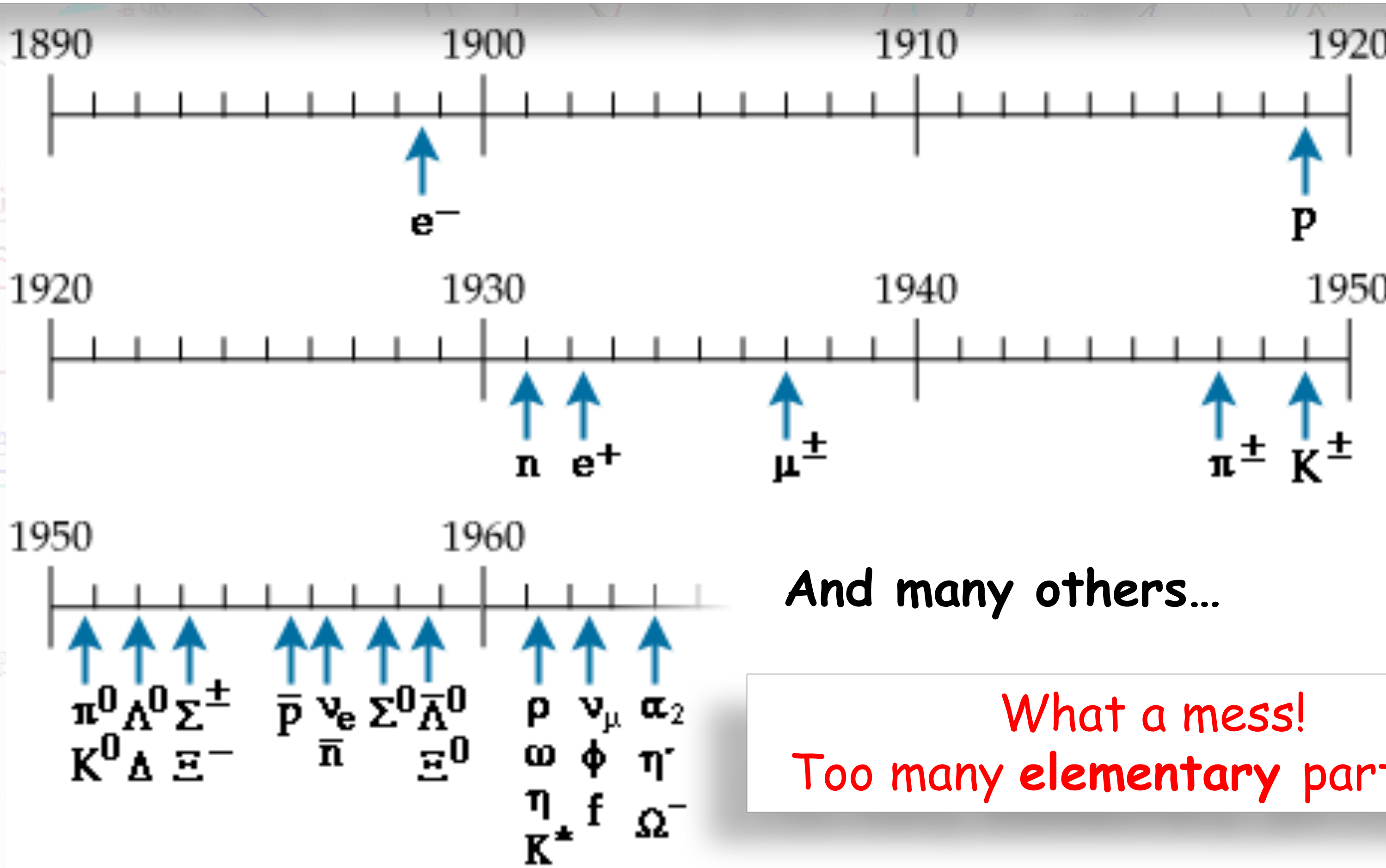
Typical power plant produces neutrinos ~ 10^{20} /s



•the human body contains about 20 mg of Potassium 40, which is a β-emitter. Therefore, we produce 340 million neutrinos per day, that leave us at the speed of light, transmitting a signal of our presence down to the far corners of the Universe ☺

Number of observed particles increases…

Studies of cosmic rays and development of high-energy particle accelerators in the early 1950s, cased the grow of particle "zoo"



And many others…

What a mess!
Too many **elementary** particles!

Some similarities notices: the proton and the neutron have rather the same masses, properties of π^0, π^+, π^- etc.
Similar particles were grouped in so called multiplets.

Crazy idea: quarks (1)

M. Gell-Mann, G. Zweig (1964)

Gell-Mann and Zweig independently proposed that all hadrons (particles interacting strongly) are in fact composed of even more elementary constituents called ***quarks***.
The quarks come in three types:

u (up) – q = 2/3
d (down) – q = -1/3
s (strange) – q = -1/3

The quarks carry fractional charges!

All hadrons known at that time could be composed from those 3 quarks!
Meson = composed of a quark and an antiquark
Barion = composed of three quarks

Crazy idea: quarks (2)

Problems of the quark model:

- psychological: fractional charges of quarks have to be accepted
- experimental: nobody have seen a free quark!
- connected to spin statistics: some baryons break Pauli's Principle

Volume 8, number 3 PHYSICS LETTERS 1 February

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann - Nobel Prize 1969 (but not for quarks!)

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH. 401
17 January 1964

Manuscript was accepted by Physics Letters only because Gell-Mann was the author
(Zweig's article exists only as CERN preprint)

Success of the Quark Model (1)

The discovery of the omega baryon composed of three s quarks -> predicted by the quark model
It was discovered at Brookhaven in 1964

$$K^- + p \rightarrow \Omega^- + K^+ + K^0$$

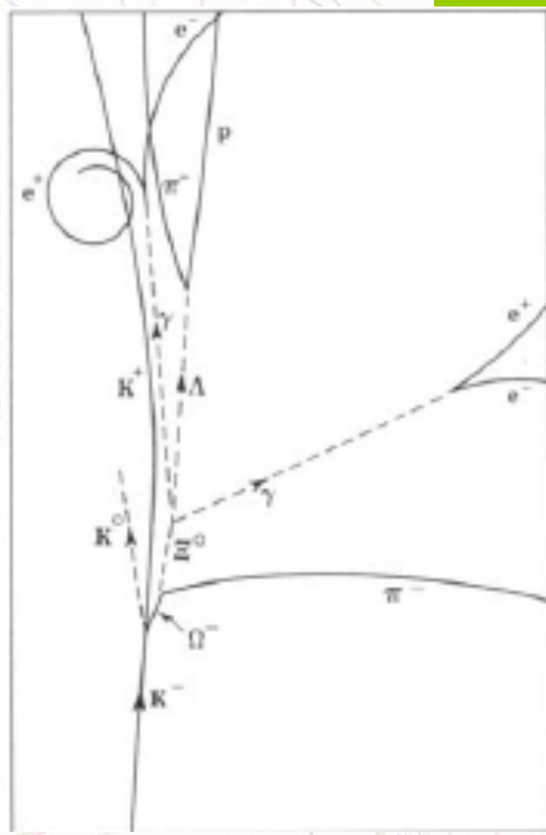
$$\Omega^- \rightarrow \Xi^0 + \pi^-$$

$$\Xi^0 \rightarrow \pi^0 + \Lambda^0$$

$$\Lambda^0 \rightarrow \pi^- + p$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\gamma \rightarrow e^+ + e^- \qquad \gamma \rightarrow e^+ + e^-$$

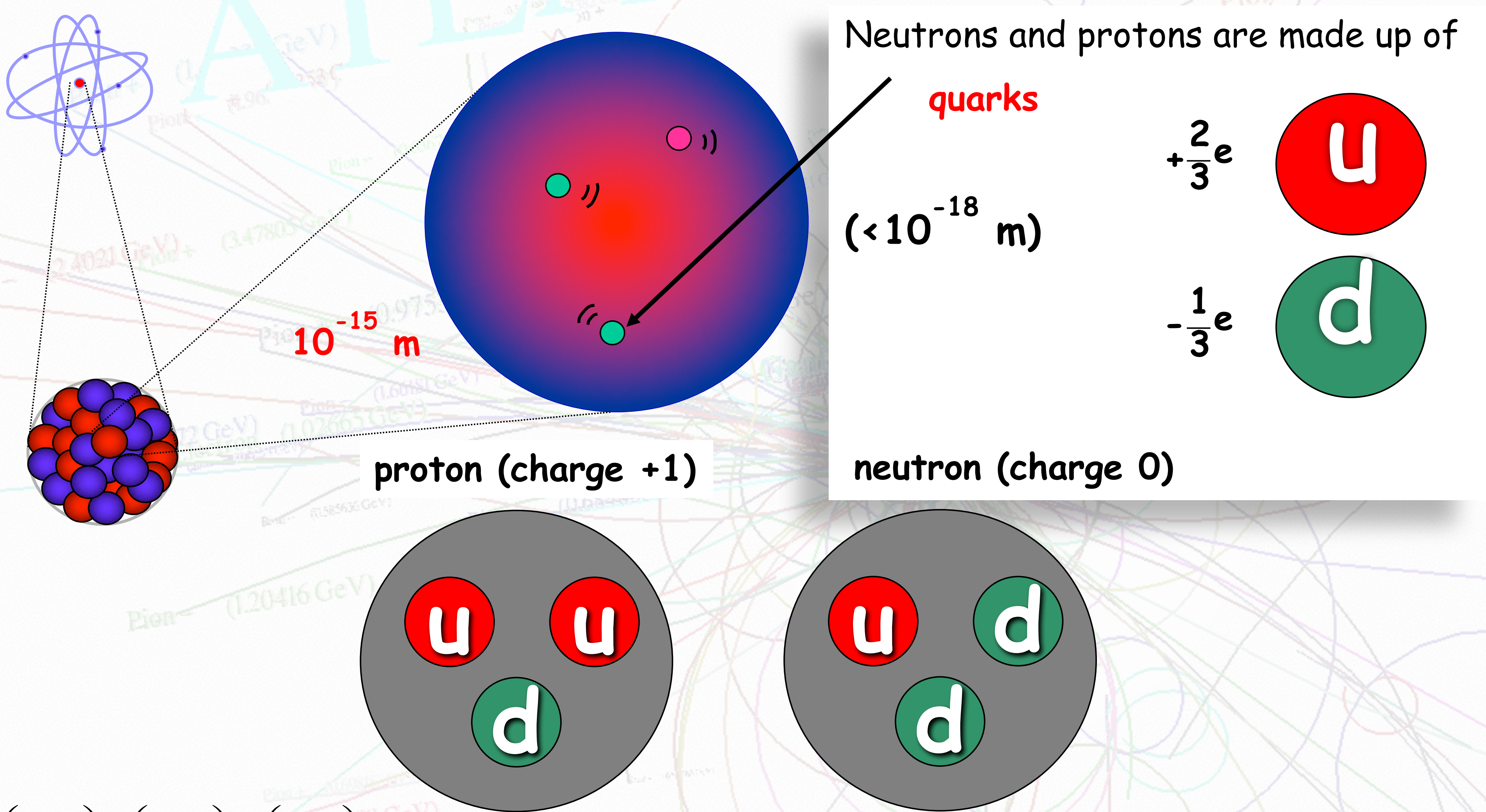


Success of the Quark Model (2)

- In 1968, a series of electron-proton scattering experiments at SLAC (US) revealed the first signs that nucleons have an inner structure
  - using the same method as Rutherford
- The team fired electrons at protons and observed how the electrons bounced off. Most of the incident particles pass right through, whereas a small number bounce back sharply
- This means that the charge of the proton is concentrated in small lumps - point-like particles inside the protons
- Nobel Prize 1990 for Henry Kendall, Jerome I. Friedman and Richard E. Taylor

- Postulated number of quarks = 3 (u, d, s) increased quite fast to 6 quarks as explanation for existence of observed (heavier) hadrons
- The last quark – t (top) with mass equal almost to mass of atom of gold was discovered in 1995 (Tevatron)

So our protons and neutrons are not fundamental !

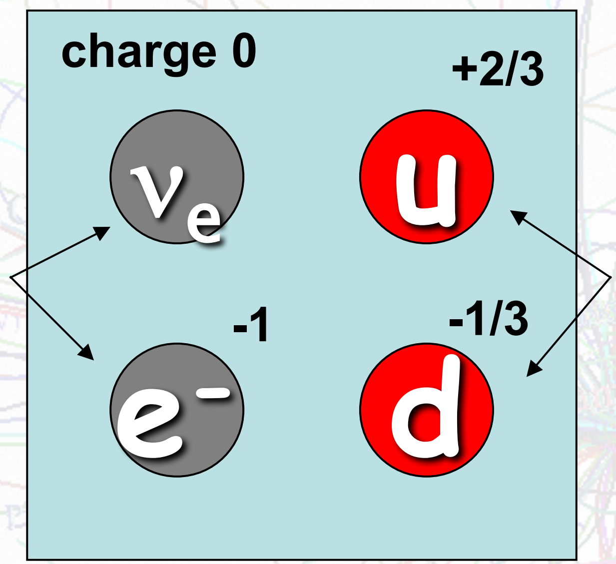


$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

The particles of ordinary matter

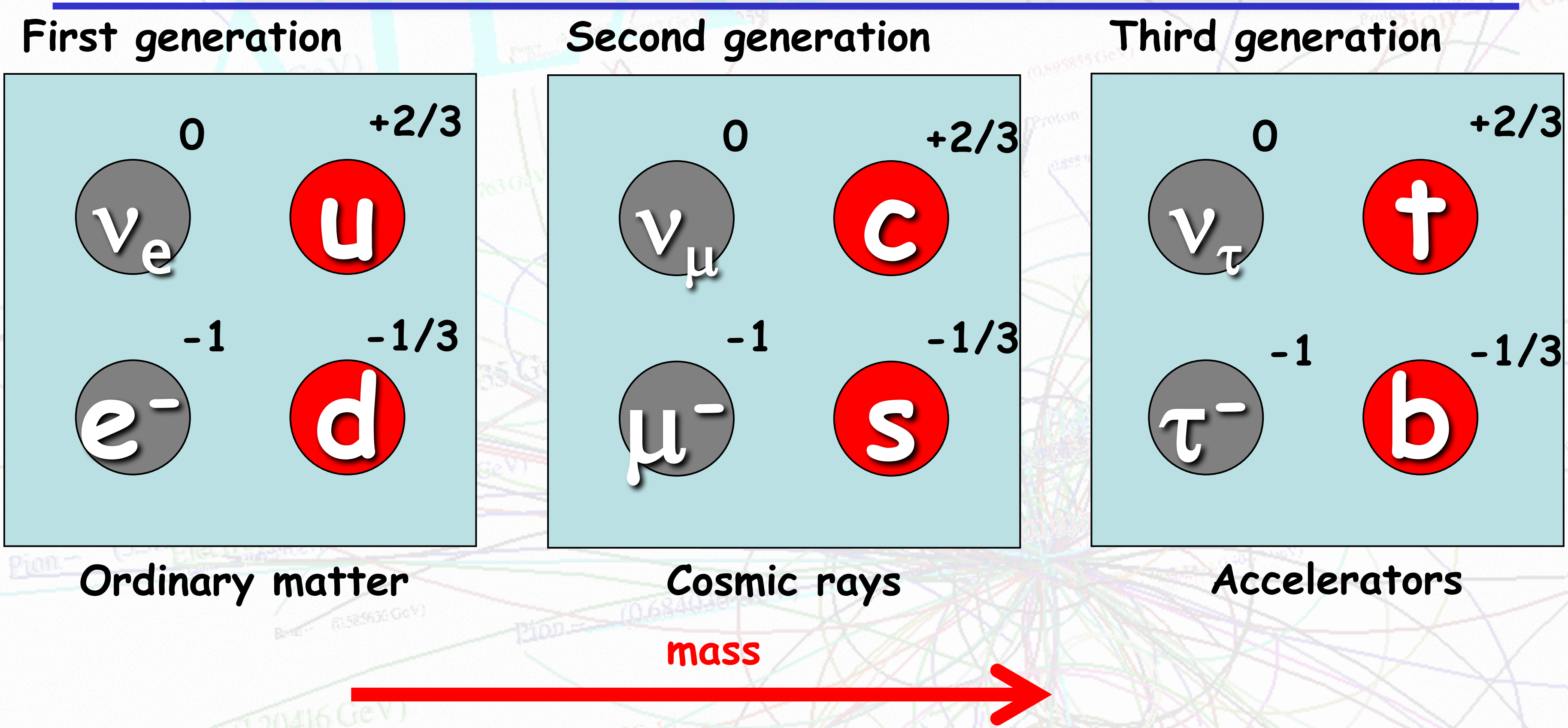
Leptons:
ν = neutrino
e = electron



Quarks:
u = up
d = down

All stable matter around us can be described using electrons, neutrinos, u and d quarks

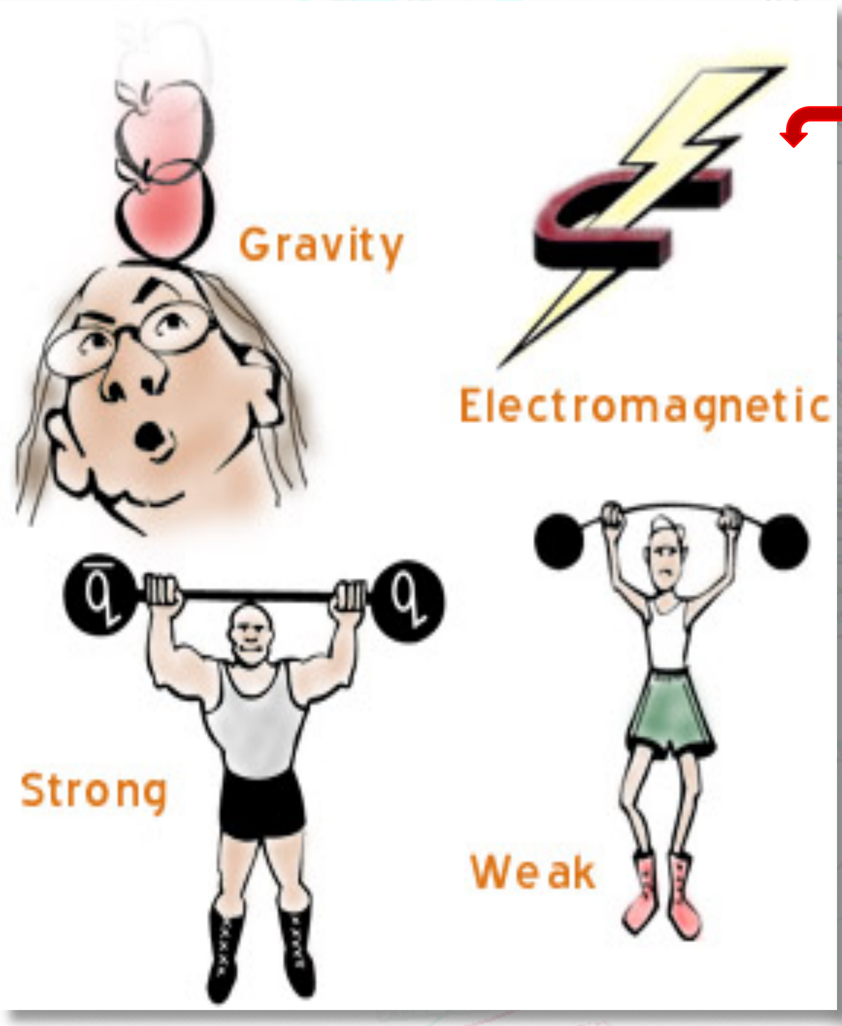
Nature replicates itself: 3 generations



3 generations in everything similar but the mass!

- All visible matter consists of the first generation particles
- Particles from the second and third generations unstable and decay to particles from the first generation
- All observed particles can be described by 6 quarks and 6 leptons
- **Why 3 generations? Symmetry/structure not understood!**

What holds it together?



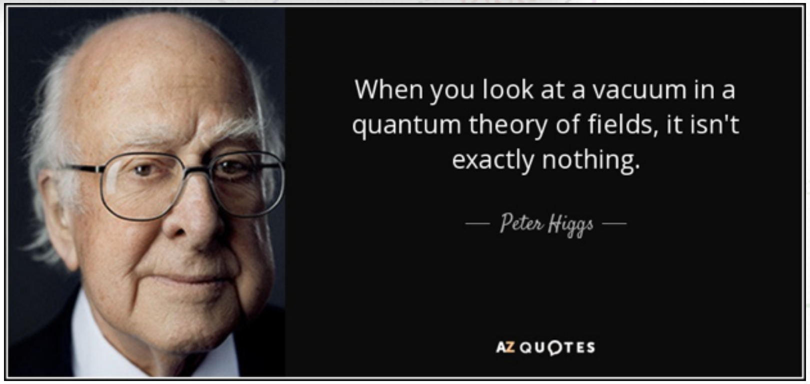
The universe, which we know and love, exists because the fundamental particles interact.

There are four fundamental interactions between particles, and **all forces in the world can be attributed to these four interactions!**

Classically, interaction at a distance is described in terms of a potential or field due to one charged particle acting on another. The field is in entire space around the source charge. In case of change of field it was changed everywhere at the same moment.

In quantum theory, action at a distance is viewed in terms of an exchange interaction, the exchange being a specific quantum (particle) associated with the particular type of interaction.

Digression: vacuum and virtual particles



- **Vacuum:**
  - In classical physics, it means nothing exists
  - In quantum mechanics, vacuum is actually a sea of **virtual particles**
  - In quantum mechanics, there is a concept called **vacuum fluctuations**
  - Although the average energy of space is zero, local fluctuations of energy are allowed by Heisenberg uncertainty principle

$$\Delta E \Delta t \sim \hbar$$

  - Energy fluctuations create pairs of particles and antiparticles. A pair can exist momentarily and is therefore virtual. They annihilate quickly.

- **Particles:**
  - **real** – propagate freely on even macroscopic distances
    - $E^2 = p^2 + m^2$
  - **virtual** – exist for a time-scale allowed by uncertainty principle, so short that you can't observe them by any measurement
    - $E^2 \neq p^2 + m^2$!
  - Real particle is always surrounded by a cloud of virtual particles (one cannot isolate it!)

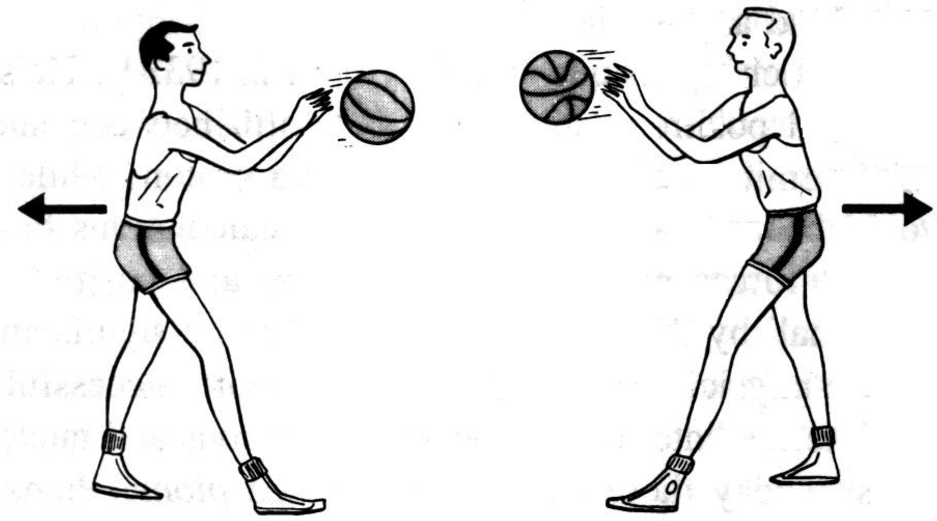
How interactions are carried

- Analogy: basketballs tossed between the basketball players
  - Range of interaction is connected to the mass of the carrier

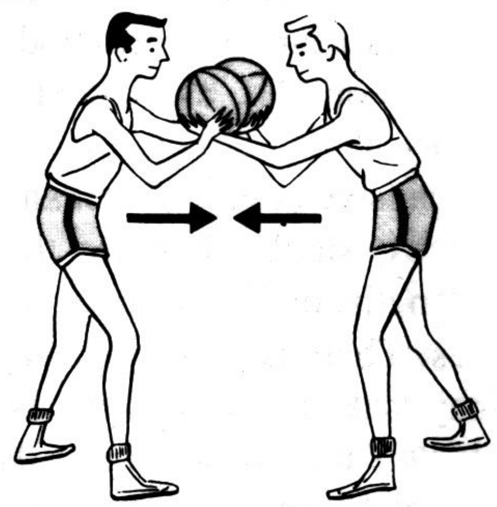
- But this is the end of simple analogy: in classical description a ball exists but our **carrier/quantum is virtual**
  - since the quantum carries momentum and energy the conservation laws can only be satisfied if the process takes place within a timescale limited by Uncertainty Principle

- We do not observe a carrier or a field
  - something we can observe/measure is an effect of interaction – for example change in particle momenta after exchange of a carrier

- Each interaction is mediated by the exchange of different carrier -> **boson**



repulsive force due to particle exchange

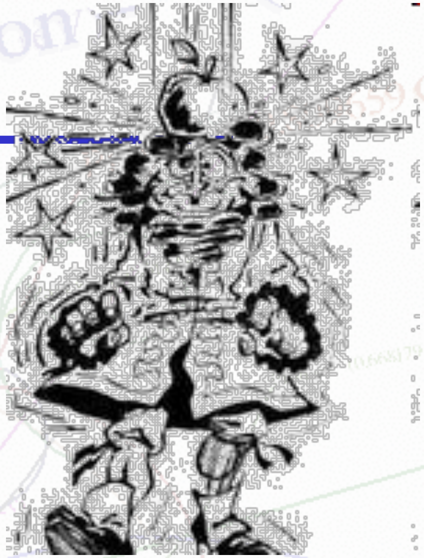


attractive force due to particle exchange

Digression: Fermions and bosons

- Fundamental particles are of two types:
  - **Fermions** with half-integral spin $\Rightarrow$ they obey Fermi-Dirac statistics
  - **Bosons** with integral spin $\Rightarrow$ they obey Bose-Einstein statistics
- The statistics obeyed by a particle says how the wavefunction describing an ensemble of identical particles behaves under interchange of any pair of particles
  - wave function Ψ itself has no physical importance, but the probability density of the particle is given by $|\Psi|^2$
  - particles are identical thus $|\Psi(x_1,x_2)|^2 = |\Psi(x_2,x_1)|^2 \Rightarrow \Psi(x_1,x_2) = \pm\, \Psi(x_2,x_1)$
    - **-1** → antisymmetric wave function $\Rightarrow$ **Fermions**
      - ***building matter: quarks, leptons***
      - his gives rise to Pauli principle: two or more identical fermions cannot exists in the same quantum state (all electrons in atoms do not fall to the ground state)
    - **+1** → symmetric wave function $\Rightarrow$ **Bosons**
      - ***interaction carrier particles***
      - there are no restrictions on the number of bosons in the same quantum state (e.g. laser)

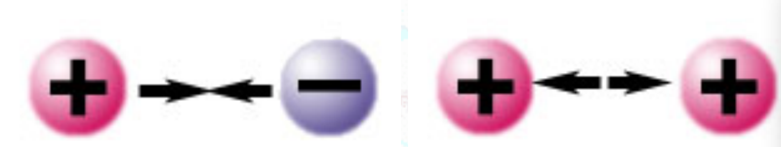
Gravitational Interaction



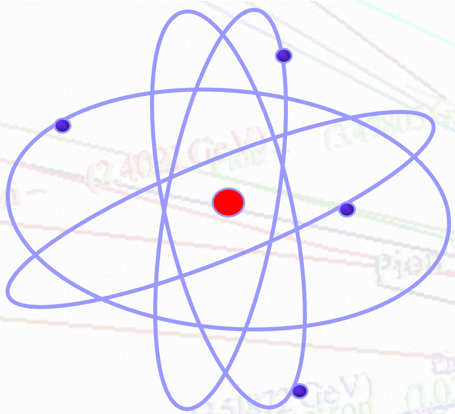
- Gravity is one of the fundamental interactions, but the Standard Model cannot satisfactorily explain it
    - this is one of those major unanswered problems in physics today
- In addition, the gravity force carrier particle has not been found. Such a particle, however, is predicted to exist and may someday be found: the **graviton**

- The effects of gravity are extremely tiny compared to the other three interactions
    - theory and experiment can be compared without including gravity in the calculations
    - **thus, the Standard Model works without explaining gravity**

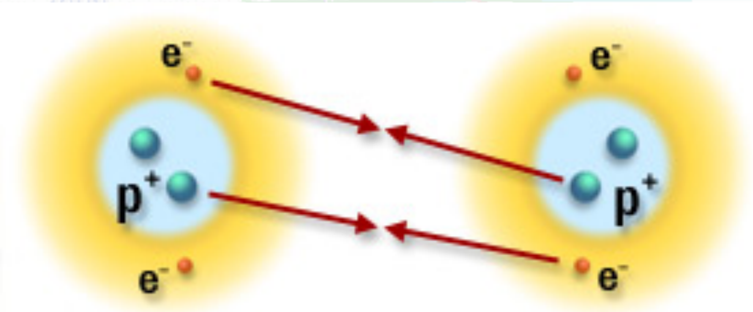
Electromagnetic Interaction



Electromagnetism is the force that acts between electrically charged particles
- like-charged repel and oppositely-charged attract



The EM force holds atoms and molecules together
- It is so dominant over the other fundamental forces that they can be considered to be negligible as determiners of atomic and molecular structure.

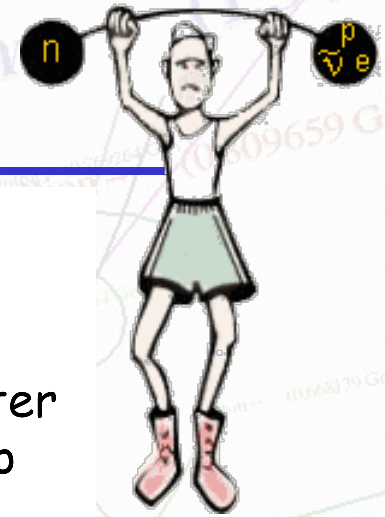


RESIDUAL E-M FORCE IN ACTION: THE ATOMS ARE ELECTRICALLY NEUTRAL, BUT THE ELECTRONS IN ONE ARE ATTRACTED TO THE PROTONS IN ANOTHER, AND VICE VERSA!

The carrier particle of the electromagnetic force is the **photon**.
- Photons of different energies span the electromagnetic spectrum of X rays, visible light, radio waves etc.
- Photons have no electric charge, zero mass and always travel at the "speed of light" in a vacuum.

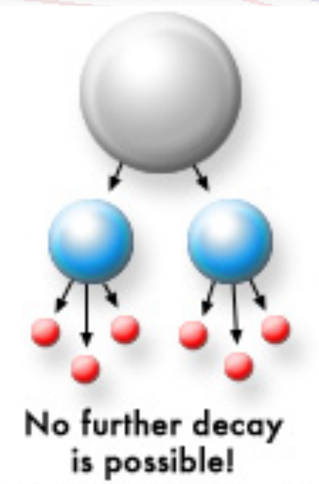
The full quantum field theory describing charged particles and electromagnetic interactions is called quantum electrodynamics - QED.

Weak Interaction



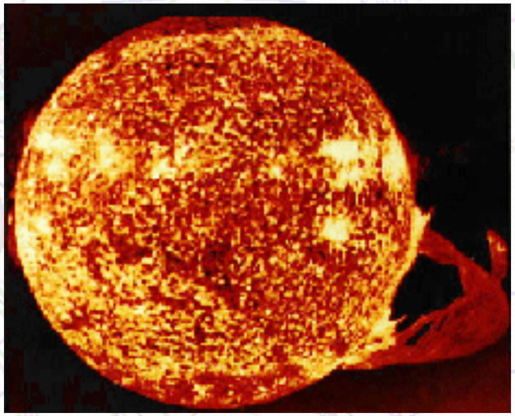
Weak interaction changes one kind (flavor) of fermion into another. It has destructive nature, plays a greater role in things falling apart, or decaying.

- It is responsible for the decay of massive quarks and leptons into lighter quarks and leptons. The only matter around us that is stable is made up of the smallest quarks and leptons, which cannot decay any further.



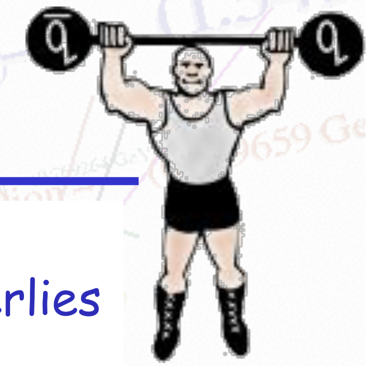
Without the weak force, the sun would not exist. The weak force allows the fusion of p's and n's to form deuterium. The excess energy from this fusion is the source of heat from the sun.

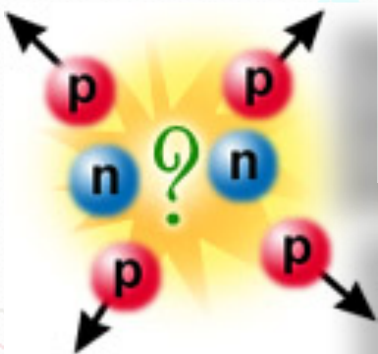
If the weak force is too weak, or absent, long-lived stars fueled by weak reactions could not exist and universe could not produce life.



- The carrier particles of the weak interactions are the W^+, W^-, and the Z
- The W's are electrically charged and the Z is neutral
- They have large mass ~90 GeV/c^2

Strong Interaction (1)

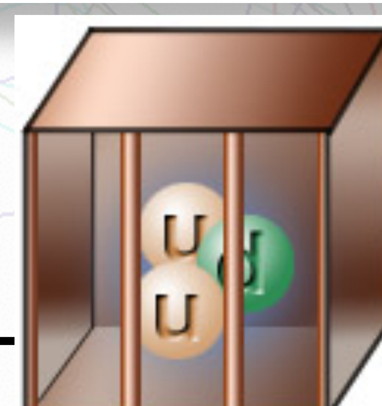




The strong force binds quarks together to make protons and neutrons. It also holds together the nucleus and underlies interactions between all particles containing quarks.

- Quarks have electric charge, and they also have an altogether different kind of charge called **colour charge**
- The strong interaction is mediated by the exchange of massless bosons called **gluons**
- New! Gluons carry colour charge an thus can interact with each other. Thus strong interaction is like a spring between two balls:
  - on small distances interaction is weak (springs not stretched, balls "do not feel" presents of other balls)
    - ***Asymptotic freedom***
  - On larger distances interaction increases fast (if we want to remove one ball, springs are stretching)
    - ***Color confinement***

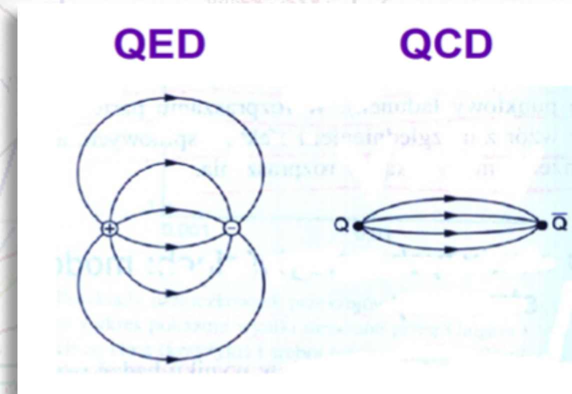
These rules are detailed in the theory of quantum chromodynamics (QCD), which is the theory of quark-gluon interactions.

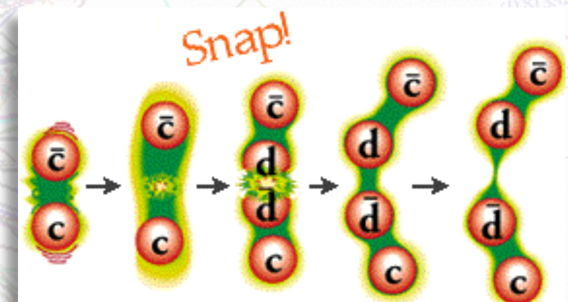


Strong Interaction (2)

If two quarks are close together, the force is weak, however, this force increases drastically if they are separated in space

- If two electrically-charged particles separate, the electric fields between them diminish quickly, allowing electrons to become unbound from nuclei
- If two *quarks* separate, the gluon fields form narrow tubes (or strings) of color charge – quite different from EM!
- Because of this behavior, the color *force* experienced by the quarks in the direction to hold them together, remains constant, regardless of their distance from each other
- ***Since energy is calculated as force times distance, the total energy increases linearly with distance***



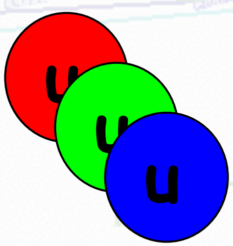


- If one of the quarks in a given hadron is pulled away from its neighbors, the color-force field "stretches" between that quark and its neighbors
- More and more energy is added to the color-force field as the quarks are pulled apart
- At some point, it is energetically cheaper for the color-force field to "snap" into a new quark-antiquark pair
- Energy of the color-force field is converted into the mass of the new quarks, and the color-force field can "relax" back to an unstretched state.

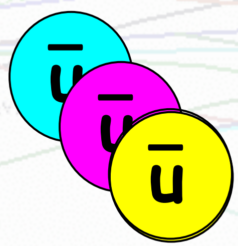
Problems with fermions and color charge

- **Problem:** quarks have spin +-½, they are fermions. But:
  - For example Δ++ = uuu or Ω- = sss has spin 3/2 => 3 quarks in the same state => violation of Pauli's Principle!
- Solution: quarks have additional property, a colour charge

Each quark can be in one out of three charge colours

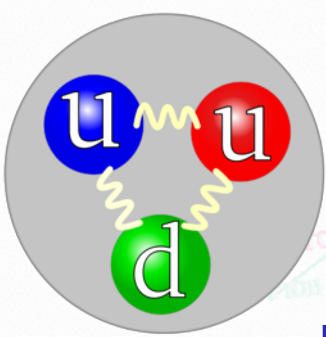


Antiquark has anti-colour



Interaction is carried by gluons. They have anti-colour and colour

Free particles made out of quarks have no net colour charge (they are colour neutral).

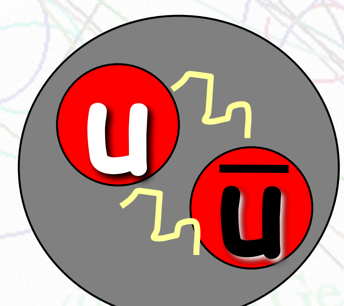


Baryons (3 quarks: red + green + blue = white)

proton

Mesons (pair quark-antiquark)
for example: red + antired

pion
π



Range of forces

- The range of forces is related to the mass of exchange particle M
- An amount of energy $\Delta E = Mc^2$ borrowed for a time Δt is governed by the Uncertainty Principle

$$\Delta E \times \Delta t \sim \hbar$$

- The maximum distance the particle can travel is $\Delta x = c\,\Delta t$, where c is velocity of light

$$\Delta x = \hbar c / \Delta E$$

$$\Delta x = \hbar c / Mc^2$$

- The photon has M=0
  - infinite range of EM force
- W boson has a mass of 80 GeV/c^2
  - range of weak force is 197 MeV fm/ 8×10^5 MeV = 2×10^{-3} fm
- Strong Interactions
  - range is of the order of 1 fm = 10^{-15} m (size of hadron)

Summary: Forces

- The weak force acts between all quarks and leptons
- The electromagnetic force acts between all charged particles
- The strong force acts between all quarks (i.e. objects that have color charge)
- Gravity does not play any role in particle physics

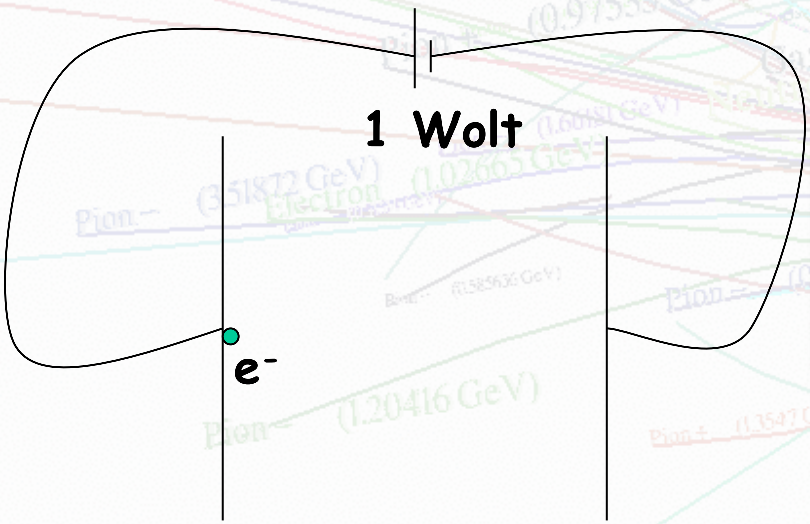
	Weak	EM	Strong
Quarks	+	+	+
Charged leptons	+	+	–
Neutral leptons	+	–	–

Force	Gauge boson	Symbol	Charge e	Mass GeV/c^2	Relative strength
Strong	(8) gluons	g	0	0	1
Electro-magentic	photon	γ	0	0	$\sim 10^{-2}$
Weak	'intermediate vector bosons'	Z^0 $W^\pm$	0 ±1	91.188 80.40	$\sim 10^{-7}$
Gravity	graviton		0	0	$\sim 10^{-40}$

Natural Units (1)

- The standard system of units in general, is the International System of Units (SI)
- Not so good for particle physics: $M_{proton} \sim 10^{-27}$ kg
- In particle physics we use a system of units known as the 'Natural Units' based on the language of particle physics: quantum mechanics and relativity.
  - reduced Planck's constant $\hbar$ [Js]
  - speed of light in vacuum *c [m/s]*

$\hbar$ = c = 1 in Natural Units



Unit of energy [E] = 1 eV (electronvolt) it is the amount of energy gained by the charge of a single electron moving across an electric potential difference of one volt

1 eV ~ 1.602×10^{-19} J

- Energies involved in atomic processes (chemical reactions or light emission) ~ several eV
- Energies in nuclear processes (like radioactive decays) ~ 1 million electronvolts (1 MeV)
- Large Hadron Collider LHC accelerates protons to energy 6.5 trillions electronvolts - 6.5 TeV (1 TeV $=10^{12}$eV)

Natural Units (2)

Energy	GeV	Time	$(\mathrm{GeV}/\hbar)^{-1}$
Momentum	GeV/c	Length	$(\mathrm{GeV}/\hbar c)^{-1}$
Mass	GeV/c^2	Area	$(\mathrm{GeV}/\hbar c)^{-2}$

Energy	GeV	Time	GeV^{-1}
Momentum	GeV	Length	GeV^{-1}
Mass	GeV	Area	GeV^{-2}

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta-	Y	10^{-24}	yocto-	y
10^{21}	zetta-	Z	10^{-21}	zepto-	z
10^{18}	exa-	E	10^{-18}	atto-	a
10^{15}	peta-	P	10^{-15}	femto-	f
10^{12}	tera-	T	10^{-12}	pico-	p
10^{9}	giga-	G	10^{-9}	nano-	n
10^{6}	mega-	M	10^{-6}	micro-	μ
10^{3}	kilo-	k	10^{-3}	milli-	m
10^{2}	hecto-	h	10^{-2}	centi-	c
10^{1}	deka-	da	10^{-1}	deci-	d

Quantity	SI unit	Natural unit	Relation (Conversion factor)
Mass (M)	kg	GeV	$1\ \mathrm{GeV} = 1.78 \times 10^{-27}\ \mathrm{kg}$
			$1\ \mathrm{kg} = 5.61 \times 10^{26}\ \mathrm{GeV}$
Length (L)	m	GeV^{-1}	$1\ \mathrm{GeV}^{-1} = 0.1975 \times 10^{-15}\ \mathrm{m}$
			$1\ \mathrm{m} = 5.07 \times 10^{15}\ \mathrm{GeV}^{-1}$
Time (T)	s	GeV^{-1}	$1\ \mathrm{GeV}^{-1} = 6.59 \times 10^{-25}\ \mathrm{s}$
			$1\ \mathrm{s} = 1.52 \times 10^{24}\ \mathrm{GeV}^{-1}$

Cross section

- The most general definition: given a particle approaching another particle, the **cross-section** for this process is the probability that the two particles interact with each other
- In a simple geometrical interpretation of it can be thought of as the area within which a reaction will take place.
  - thus the units of a cross-section are the units of an area: 1 barn = 10^{-24} cm^2

$$\sigma = \frac{\text{no of interactions per unit time per target}}{\text{incident flux}}$$

Flux = number of incident particles/ unit area/unit time

- Cross sections change with the energy of an incoming particle
- One should think of the cross section as a measure of the range and strength of the force between two particles

Force	Typical Cross Sections
Strong	10 mb
Electromag	10^{-2} mb
Weak	10^{-13} mb

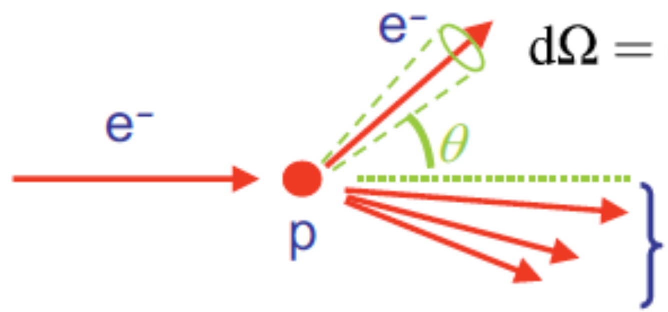
Cross section jargon

Differential Cross section

$$\frac{d\sigma}{d\Omega} = \frac{\text{no of particles per sec/per target into } d\Omega}{\text{incident flux}}$$

or generally

$$\frac{d\sigma}{d\ldots}$$



$$d\Omega = d(\cos\theta)d\phi$$

with $$\boxed{\sigma = \int \frac{d\sigma}{d\Omega} d\Omega}$$

- ***Differential*** - cross section for scattering within a restricted range of some observable, e.g. angle range $d\theta$ around some direction θ
- ***Elastic*** - we count only the cases when neither beam particle or target particle disintegrated
- ***Inelastic*** - just opposite, i.e., when either beam particle or target particle or both disintegrate
- ***Total*** - sum of the elastic and inelastic
- ***Inclusive*** (e.g., $p + p \to \pi^+ + anything$): any process with at least one π^+ in the final state (all π^+ would typically be counted in this case)
- ***Exclusive*** (e.g., $p + p \to p + p + \pi^0$): exclusively for some fully defined final state (no extras)

Particle Lifetime

- Particle lifetime, τ, is the time taken for the sample to reduce to $1/e$ of original sample
- Probablity that after time t particle still not decayed
  - $P(t) = e^{-t/\tau}$
  - Chance to survive time τ: ~37%
- Different forces have different typical lifetimes
- Also define total decay width – from Heisenburg Uncertainty Principle: energy and time are related

$$\Gamma \equiv \hbar/\tau.$$

Force	Typical Lifetime
Strong	10^{-20} - 10^{-23} s
Electromag	10^{-20} - 10^{-16} s
Weak	10^{-13} - 10^{3} s

- In its own rest frame particle travels $v\tau = \beta c\tau$ before decaying
- In the lab, time is dilated by γ
- If τ is large enough, energetic particles travel a measurable distance $L = \gamma\beta c\tau$ in lab

		τ	$c\tau$
mion	μ	$2.2 \cdot 10^{-6}$ s	660 m
kaon	$K^{\pm}$	$1.2 \cdot 10^{-8}$ s	3.7 m
lambda	Λ	$2.6 \cdot 10^{-10}$ s	7.9 cm
mezon	$B^{\pm}$	$1.7 \cdot 10^{-12}$ s	0.5 mm
taon	τ	$2.9 \cdot 10^{-13}$ s	87 μm
pion	π°	$8 \cdot 10^{-17}$ s	25 nm
mezon	ρ°	$5 \cdot 10^{-24}$ s	1.3 fm

Decays of particles

- Decay of particle is transition from one state to another – it is not decay of particle into its constituents!
- E and p have to be conserved: $m_{initial} > \mathrm{sum}(m^{i}_{final})$
- Larger mass means (in general) more possible decay modes

Particles can have more than one possible final state or **decay mode**.
e.g. The K_S meson decays 99.9% of the time in one of two ways:

$$K_S \to \pi^+\pi^-, K_S \to \pi^0\pi^0$$

- Each decay mode has its own matrix element, $\mathcal{M}$. Fermi's Golden Rule gives us the **partial decay width** for each decay mode:

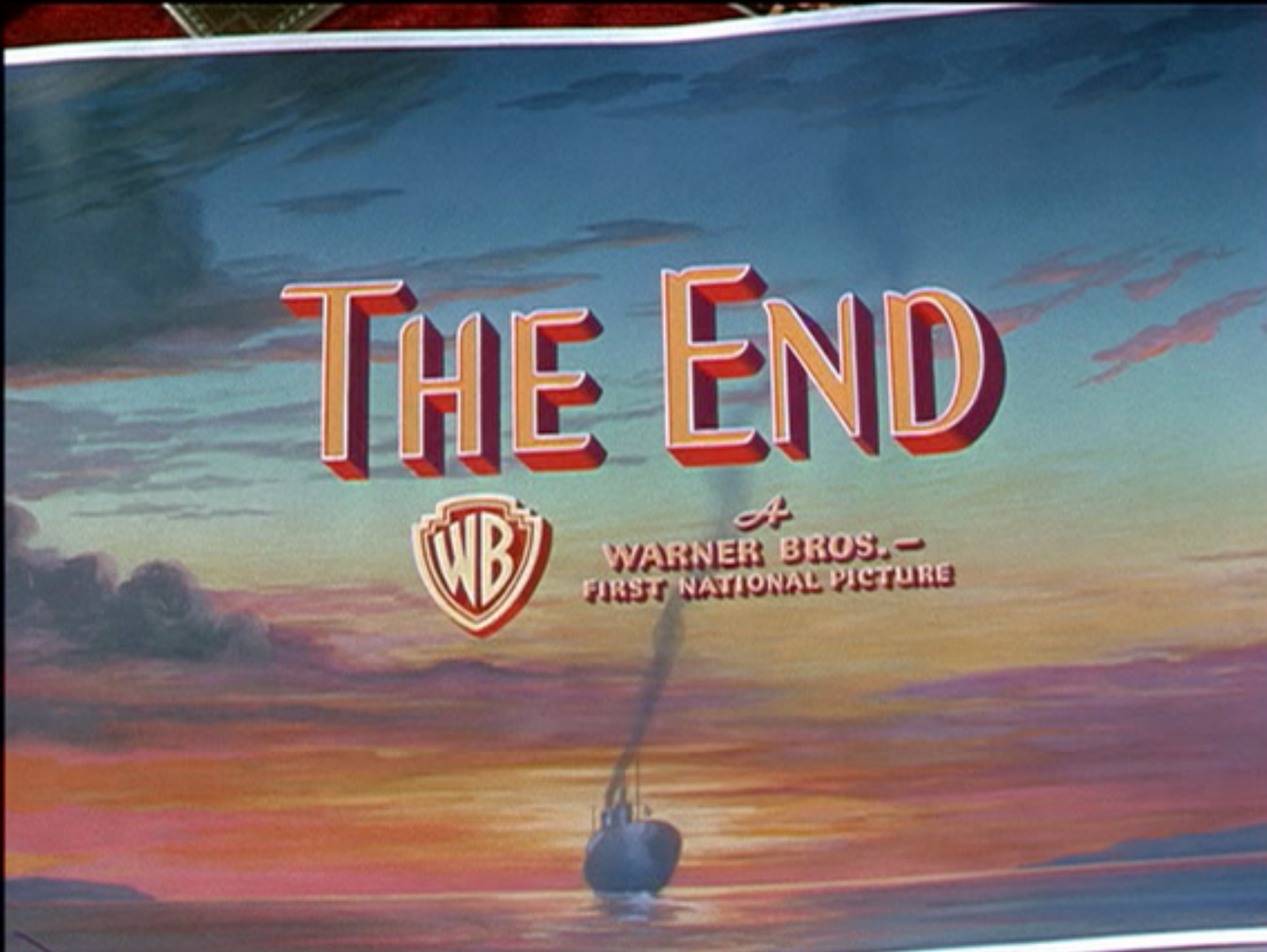
$$\Gamma(K_S \to \pi^+\pi^-) \propto |\mathcal{M}(K_S \to \pi^+\pi^-)|^2 \qquad \Gamma(K_S \to \pi^0\pi^0) \propto |\mathcal{M}(K_S \to \pi^0\pi^0)|^2$$

- The **total decay width** is equal to the sum of the decay widths for all the allowed decays.

$$\Gamma(K_S) = \Gamma(K_S \to \pi^0\pi^0) + \Gamma(K_S \to \pi^+\pi^-)$$

- The **branching ratio**, **BR**, is the fraction of time a particle decays to a particular final state:

$$BR(K_S \to \pi^+\pi^-) = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S)} \qquad BR(K_S \to \pi^0\pi^0) = \frac{\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_S)}$$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