Lecture 4

What do we know so far:

atoms consist of nuclei immersed in a cloud of electrons

particles are small, light, energetic: p, n, e, neutrino

processes are described by ***quantum mechanics*** *and* ***relativity***

electromagnetic interactions *keep atoms together*

strong interactions *keep nuclei together*

Additional comment:

- *Strong force has a short range and must act fast*
- *Free neutron lives for a while before decaying*

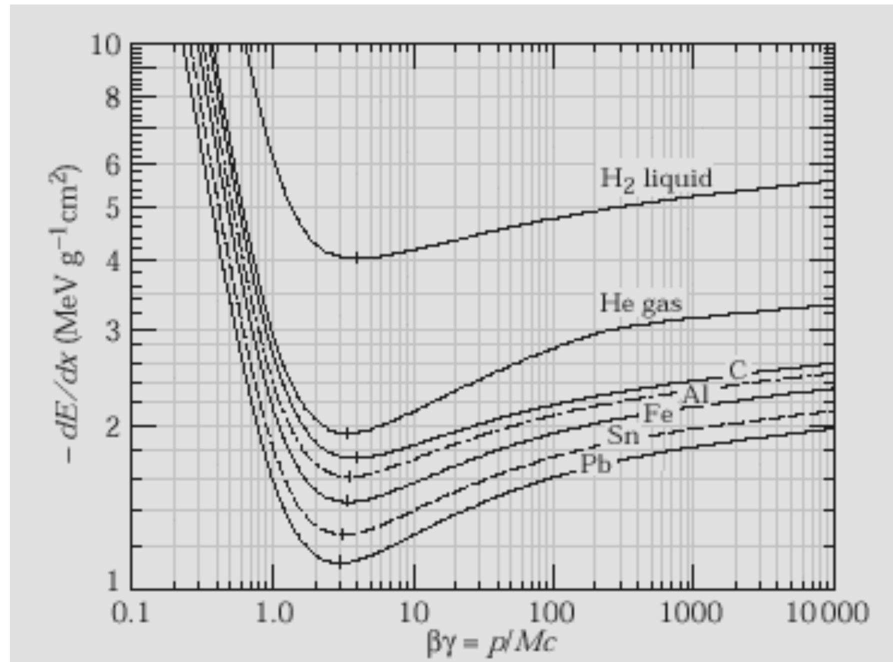
  -> the force responsible for the decay must be weak
- *At quantum level all processes are probabilistic, i.e., we cannot know the outcome of an individual process but only the* ***probability*** *of each specific outcome*

Reminder - 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})**



Bremsstrahlung – energy loss due to emission of photons

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

COSMIC RAYS

- **Discovered by V.F. Hess in the 1910's by the observation of an increase of radioactivity with altitude during a balloon flight**
- **Until the late 1940's, the only existing source of high-energy particles**

Composition of cosmic rays at sea level – two main components

- **Electromagnetic "showers", consisting of many e^- and γ-rays, mainly originating from:**

  γ + nucleus → e^+e^- + nucleus (pair production);

  e^- + nucleus → e^- + γ + nucleus ("bremsstrahlung")

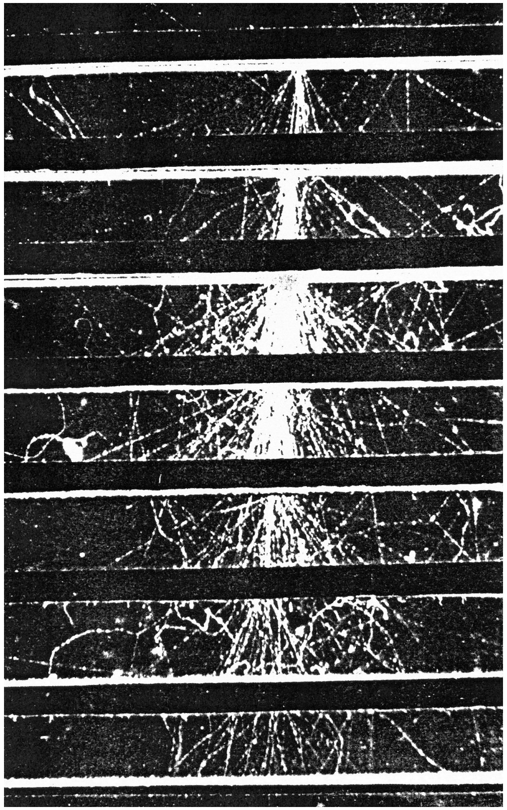
  The typical mean free path for these processes ("radiation length", x_0) depends on Z.

  - For Pb ($Z = 82$) $x_0 = 0.56$ cm
  - Thickness of the atmosphere $\approx 27\ x_0$

- **Muons (μ^-) capable of traversing as much as 1 m of Pb without interacting; tracks observed in cloud chambers in the 1930's.**

  Determination of the mass by simultaneous measurement of momentum $p = m\mathrm{v}(1 - \mathrm{v}^2/c^2)^{-½}$ (track curvature in magnetic field) **and velocity v** (ionization)**:**

$$m_\mu = 105.66\ \mathrm{MeV}/c^2 \approx 207\ m_e$$



**Cloud chamber image of an electromagnetic shower.
Pb plates, each 1. 27 cm thick**

1937: Theory of nuclear forces (H. Yukawa)

Hideki Yukawa

Existence of a new light particle ("meson") as the carrier of nuclear forces

Relation between interaction radius and meson mass m:

$$R_{\text{int}} = \frac{\hbar}{mc} \quad \Rightarrow \quad mc^2 \approx 200\ \text{MeV} \ \text{for}\ R_{\text{int}} \approx 10^{-13}\ \text{cm}$$

Yukawa's meson initially identified with the muon – in this case μ^- stopping in matter should be immediately absorbed by nuclei → nuclear breakup
(not true for stopping μ^+ because of Coulomb repulsion - μ^+ never come close enough to nuclei, while μ^- form "muonic" atoms)

Experiment of Conversi, Pancini, Piccioni (Rome, 1945):

study of μ^- stopping in matter using μ^- magnetic selection in the cosmic rays

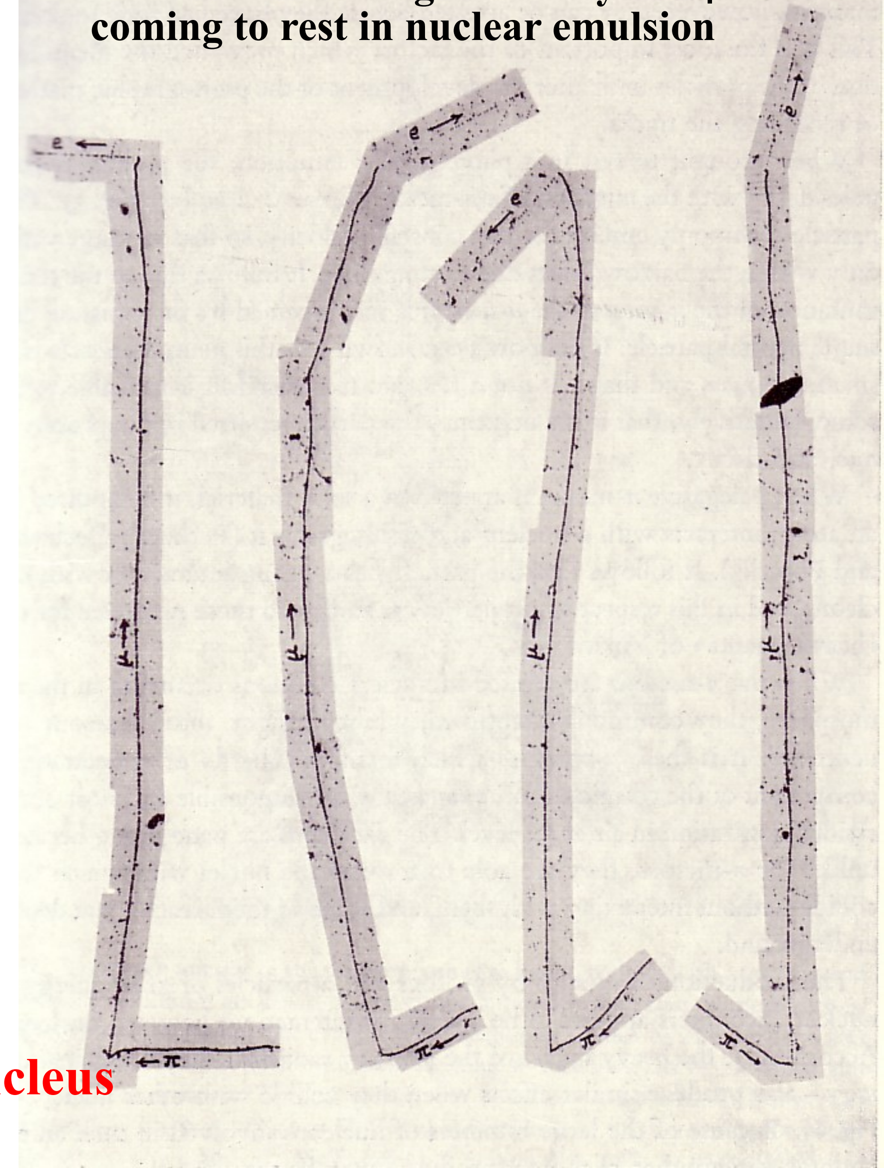
In light material ($Z \sim 10$) the μ^- decays mainly to electron (just as μ^+ to positron)
In heavier material, the μ^- disappears partly by decaying to electron, and partly by nuclear capture (process later understood as $\mu^- + p \rightarrow n + \nu$).
However, the rate of nuclear captures is consistent with the weak interaction.

$\Rightarrow$ **the muon is not Yukawa's meson**

1947: Discovery of the π- meson (the "real" Yukawa particle)

Observation of the π^+ -> μ^+ -> e^+ decay chain in nuclear emulsion exposed to cosmic rays at high altitudes

Four events showing the decay of a p$^+$ coming to rest in nuclear emulsion



Nuclear emulsion: a detector sensitive to ionization with ~1 mm space resolution (size of AgBr microcrystals suspended in gelatin)

In all events the muon has a fixed kinetic energy (range of ~ 600 mm in nuclear emulsion ~i.e. 4.1 MeV) → two-body decay

Today's knowledge:

m_π = 139.57 MeV/c^2 ; spin = 0

Dominant decay mode: π^+ -> μ^+ + ν

(and π^- -> μ^- + ν)

Mean life at rest: t_π = 2.6 x 10^{-8} s = 26 ns

π^- at rest undergoes nuclear capture, as expected for the Yukawa particle

A neutral π – meson ($\pi°$) also exists:

m ($\pi°$) = 134. 98 MeV /c^2

Decay: $\pi°$ → γ + γ, mean life = 8.4 x 10^{-17} s

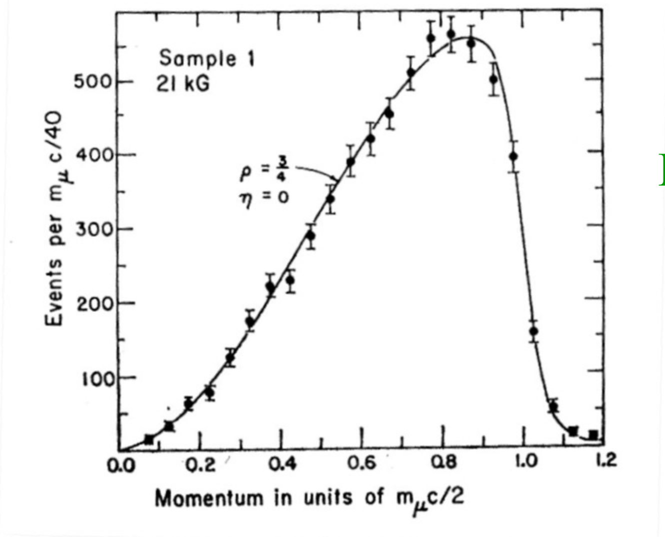
π mesons are the most copiously produced particles in proton – proton and proton – nucleus collisions at high energies

The pion is the most common particle produced in nuclear collisions.
Most of the tracks you have seen in the photographs of cosmic rays interactions with nuclear emulsion were pions.
Pions come with three different charges: π^+, π^-, π^0
They are unstable and decay after $\sim 10^{-8}$ s
As the detection techniques improved, many other short-lived particles were discovered. These we will discuss later

Muon decay

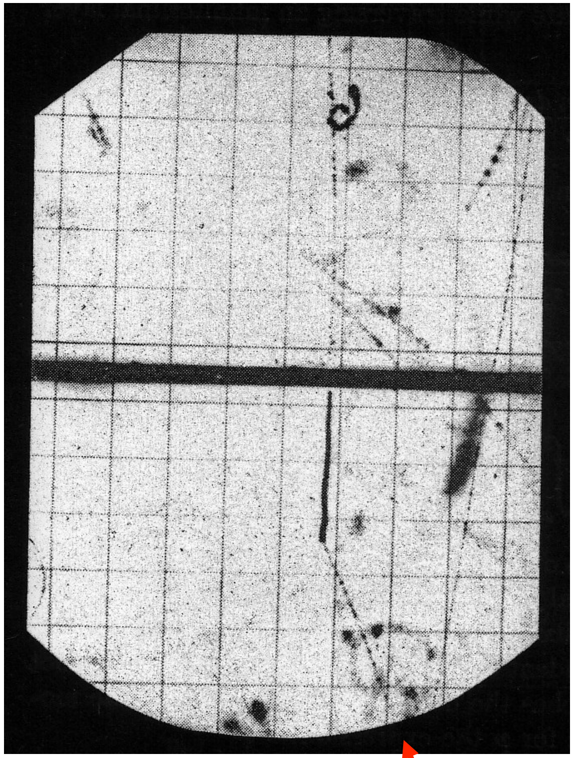
$\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$

Decay electron momentum distribution



Cosmic ray muon stopping in a cloud chamber and decaying to an electron →

m



decay electron track

Muon spin = ½

Muon lifetime at rest: $t_\mu = 2.197 \times 10^{-6}$ s -> 2.197 ms

Muon decay mean free path in flight:

$$\lambda_{decay} = \frac{v\tau_\mu}{\sqrt{1-(v/c)^2}} = \frac{p\tau_\mu}{m_\mu} = \frac{p}{m_\mu c}\tau_\mu c$$

$\boldsymbol{p}$: muon momentum
$t_m c \sim$ **0.66 km**

→ **muons can reach the Earth surface after a path ≈ 10 km because the decay mean free path is stretched by the relativistic time expansion**

Theory of β-decay (E. Fermi, 1932-33)

Enrico Fermi

β^- decay: n → p + e^- + $\bar{\nu}$

β^+ decay: p → n + e^+ + ν (e.g., $^{14}O_8 \rightarrow {}^{14}N_7 + e^+ + \nu$)

n: the particle proposed by Pauli
(named "neutrino" by Fermi)

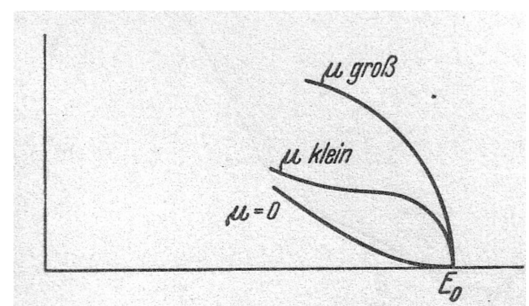
$\bar{\nu}$: its antiparticle (antineutrino)

Fermi's theory: a point interaction among four spin ½ particles, using the mathematical formalism of creation and annihilation operators invented by Jordan
→ particles emitted in β– decay need not exist before emission – they are "created" at the instant of decay

Prediction of β – decay rates and electron energy spectra as a function of only one parameter: Fermi coupling constant G_F (determined from experiments)

Energy spectrum dependence on neutrino mass m
(from Fermi's original article, published in German on Zeitschrift für Physik, following rejection of the English version by Nature)

Measurable distortions for m >0 near the end-point (E_0: max. allowed electron energy)

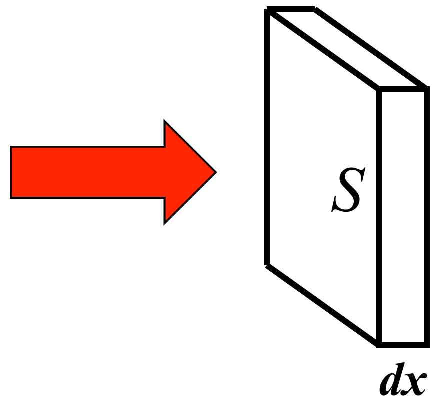


Neutrino detection

Prediction of Fermi's theory: $\bar{\nu} + p \rightarrow e^{+} + n$

$\bar{\nu}$ – p interaction probability in thickness *dx* of hydrogen-rich material (e.g., H_2O)

Incident $\bar{\nu}$:
Flux Φ [$\bar{\nu}$ $cm^{-2}s^{-1}$]
(uniform over surface S)



Target:
surface *S*, thickness *dx*
containing *n* protons cm^{-3}

$\bar{\nu}$ p interaction rate = $\Phi\, S\, n\,$ s dx interactions per second

σ : $\bar{\nu}$ – proton cross-section (effective proton area, as seen by the incident $\bar{\nu}$)

$\bar{\nu}$p interaction probability = $n\, \sigma\, dx = dx/\lambda$

Interaction mean free path: $\lambda = 1 / n\, \sigma$
Interaction probability for finite target thickness $T = 1 - \exp(-T/\lambda)$

$\sigma(\bar{\nu}\, p) \approx 10^{-43}$ cm^2 for 3 MeV $\bar{\nu}$ → $\lambda \approx 150$ light-years of water !

Interaction probability $\sim T/\lambda$ very small ($\sim 10^{-18}$ per meter of H_2O)
→ need very intense sources for antineutrino detection

Nuclear reactors: very intense antineutrino sources

Average fission: n + $^{235}U_{92}$ -> $\underbrace{(A_1, Z) + (A_2, 92 - Z)}_{\text{nuclei with large neutron excess}}$ + 2.5 free neutrons + 200 MeV

a chain of β decays with very short lifetimes:

$$(A, Z) \xrightarrow[e^- \ \bar{\nu}]{} (A, Z+1) \xrightarrow[e^- \ \bar{\nu}]{} (A, Z+2) \xrightarrow[e^- \ \bar{\nu}]{} \ldots.$$ (until a stable or long lifetime nucleus is reached)

On average, 6 $\bar{\nu}$ per fission

$$\bar{\nu}\ \text{production rate} = \frac{6P_t}{200\ \text{MeV} \times \underbrace{1.6\times 10^{-13}}_{\substack{\text{conversion factor}\\ \text{MeV} \times \text{J}}}} = 1.87\times 10^{11} P_t\ \bar{\nu}/\text{s}$$

P_t: reactor thermal power [W]

For a typical reactor: $P_t = 3 \times 10^9$ W ≈ $5.6\times10^{20}\ \nu/\bar{s}$ (isotropic)

Continuous $\bar{\nu}$ energy spectrum – average energy ~3 MeV

Comanche Peak nuclear Power Plant
Somervell County, 60 miles southwest of Dallas

2 reactors 1.25 GW each = 2.5 GW
$\rightarrow$ $1.87\times10^{11}\times2.5\times10^{6} = 4.67\times10^{20}$ *ν/s*

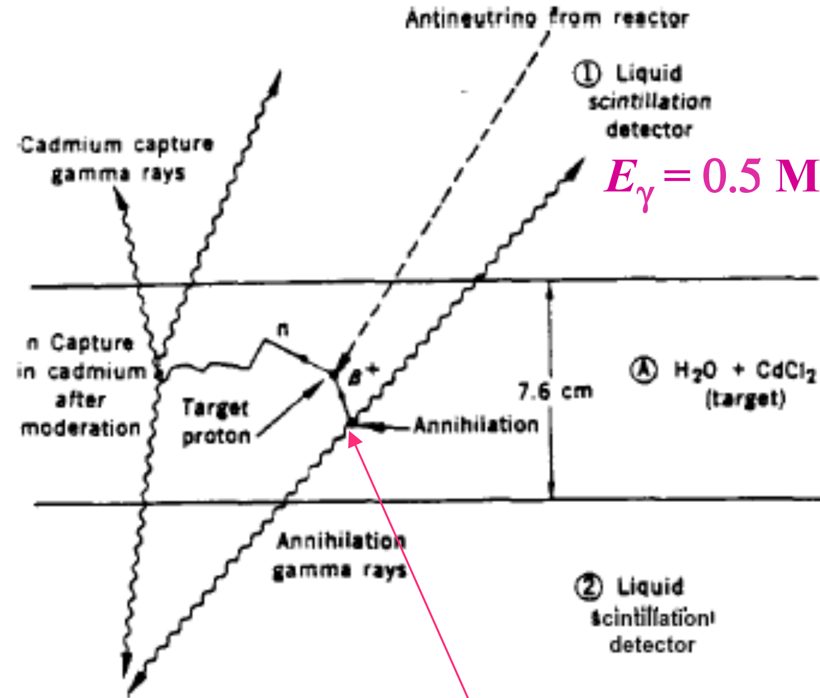
If you assume that the cross section of your body is 1 m^2
and that the flux of reactors neutrinos is distributed uniformly on a surface of the sphere centered at the reactor then there are $\sim 3.7\times10^{9}$ *ν from that reactor crossing your body every second.*

First neutrino detection

(Reines, Cowan 1953)

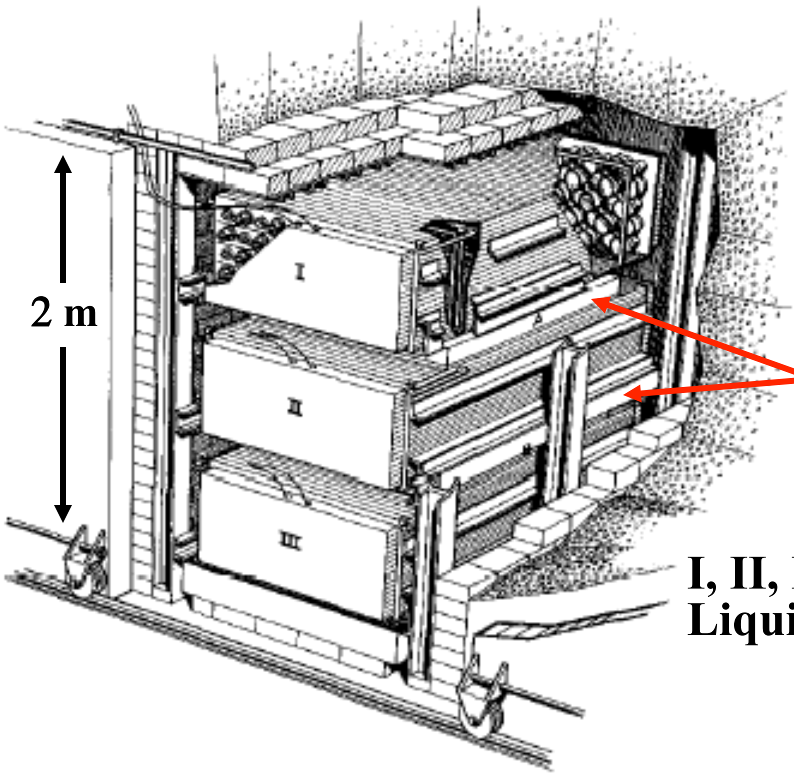
$\bar{\nu} + p \rightarrow e^+ + n$

- detect 0.5 MeV γ-rays from $e^+e^- \rightarrow \gamma\gamma$ ($t = 0$)
- neutron "thermalization" followed by capture in Cd nuclei $\rightarrow$ emission of delayed γ-rays (average delay ~30 ms)



$E_\gamma = 0.5$ MeV

$e^-\beta^+ \rightarrow \gamma\gamma$ ($\beta^+ = e^+$)



H_2O + $CdCl_2$

I, II, III: Liquid scintillator

Event rate at the Savannah River nuclear power plant:

3.0 ± 0.2 events / hour

(after subtracting event rate measured with reactor OFF)

in agreement with expectations

Particle interactions (as known until the mid 1960's)

In order of increasing strength:

- **Gravitational interaction (all particles)**

Totally negligible in particle physics

Example: static force between electron and proton at distance D

Gravitational: $f_G = G_N \frac{m_e m_p}{D^2}$ **Electrostatic:** $f_E = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{D^2}$

Ratio $f_G / f_E \approx 4.4 \times 10^{-40}$

- **Weak interaction (all particles except photons)**

Responsible for β decay and for slow nuclear fusion reactions in the star core

Example: in the core of the Sun ($T = 15.6 \times 10^6$ **°K)** $4p \rightarrow {}^4He + 2e^+ + 2n$

Solar neutrino emission rate $\sim 1.84 \times 10^{38}$ **neutrinos/s**

Flux of solar neutrinos on Earth $\sim 6.4 \times 10^{10}$ **neutrinos** $cm^{-2}\ s^{-1}$

Very small interaction radius R_{int} **(max. distance at which two particles interact)**

($R_{int} = 0$ in the original formulation of Fermi's theory)

- **Electromagnetic interaction (all charged particles)**

Responsible for chemical reactions, light emission from atoms, etc.

Infinite interaction radius

(example: the interaction between electrons in transmitting and receiving antennas)