Введение в квантовую физику. Лекция 2.

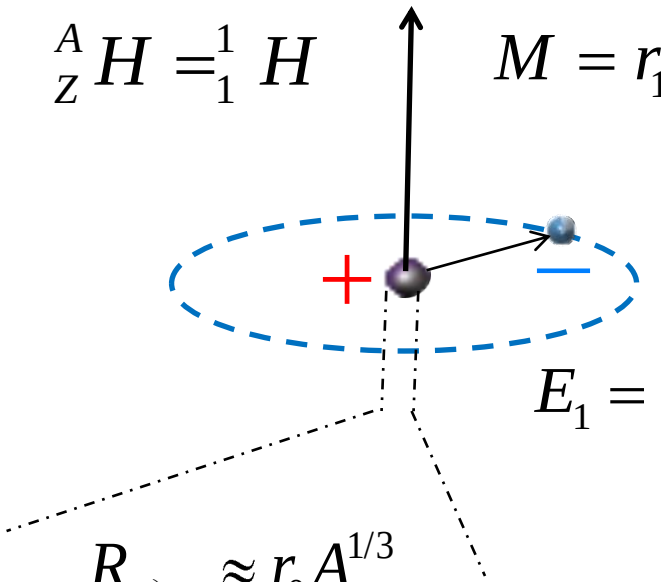
Порядки величин в квантовой физике. Естественная система единиц. Современные представления о фундаментальных взаимодействиях и частицах.

Порядки физических величин в квантовой физике

$$СИ: e^2 = \frac{1}{4\pi\varepsilon_0} e^2$$

Атом водорода

$${}^{A}_{Z}H = {}^{1}_{1}H$$



$$R_{ядра} \approx r_0 A^{1/3}$$

$$r_0 \approx 1.2 \cdot 10^{-15}\, м$$

$$10^{-15}\, м = 1 Ферми$$

Момент импульса

$$M = r_1 p = \hbar = 1.05 \cdot 10^{-34}\, Дж \cdot с$$

$$r_1 = a_B \approx 0.53 \cdot 10^{-10}\, м$$ **Первый Боровский радиус**

$$E_1 = \frac{p^2}{2m} - \frac{e^2}{r_1} = -13.6 эВ$$ **Энергия основного состояния**

$$\Delta x \cdot \Delta p \geq \hbar \quad r \approx \Delta x \quad p \approx \Delta p$$

$$E(r) = \frac{\hbar^2}{r^2 2m} - \frac{e^2}{r} \Rightarrow \frac{dE}{dr} = -\frac{\hbar^2}{r^3 m} + \frac{e^2}{r^2} = 0$$

$$r_1 = a_B = \frac{\hbar^2}{e^2 m} \approx 0.53 \cdot 10^{-10}\, м$$

Порядки физических величин в квантовой физике

Постоянная Планка	**$h=6.63\ 10^{-34}$ Дж с**
	$\hbar=1.05\ 10^{-34}$ Дж с
Элементарный заряд	$e=1.60\ 10^{-19}$ Кл
Масса электрона	$m=0.91\ 10^{-30}$ кг
Масса протона	$M=1{,}67\ 10^{-27}$ кг
Постоянная Больцмана	$k=1.38\cdot10^{-23}$ Дж/К
Скорость света	$c = 3.00\ 10^{8}$ м/с
Гравитационная постоянная	$G = 6.67\ 10^{-11}$ м^3/(кгс^2)
Постоянная Авогадро	$N_A=6{,}02\ 10^{23}$ моль$^{-1}$
Атомная единица массы	1 а.е.м. = $1.66\ 10^{-27}$ кг

$$1эВ = 1.6\cdot10^{-19}\ Дж$$

Тепловая энергия (T=293K) kT=0.025эВ=1/40 эВ

Энергия покоя электрона mc^2=0.51 МэВ

Естественные единицы квантовой электродинамики

Фундаментальные константы: $\hbar$, m, e, c

m — *единица массы*

mc^2 — *единица энергии* Энергия покоя электрона = 0.5 МэВ

$\frac{\hbar}{mc}$ — *единица длины* Комптоновская длина волны электрона $\lambda\!\!\!^{-}_c$ = 3.86 10^{-13}м

$\frac{\hbar}{mc^2}$ — *единица времени*

Характеристики атома водорода в естественных единицах

Скорость электрона $v = \sqrt{e^2 / ma_B} = \alpha c$

Первый боровский радиус $a_B = \frac{\lambda\!\!\!^{-}_c}{\alpha} = \frac{\hbar^2}{me^2}$

Энергия ионизации $R_\infty = \frac{1}{2}\alpha^2 mc^2 = \frac{e^2}{2a_B} = \frac{e^4 m}{2\hbar^2}$

Электростатическая энергия отталкивания двух электронов, находящихся на единичном расстоянии :

$$\alpha = \frac{e^2 / \frac{\hbar}{mc}}{mc^2} = \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

Постоянная тонкой структуры α характеризует величину электромагнитного взаимодействия

Планковские единицы

Фундаментальные константы: $\hbar$, G, c, k

Планковская масса $M_{Pl} = \sqrt{\frac{\hbar c}{G}} \cong 2{,}17651(13) \times 10^{-8}$ кг

Планковская длина $l_{Pl} = \frac{\hbar}{M_{Pl} c} = \sqrt{\frac{\hbar G}{c^3}} \cong 1{,}616199(97) \times 10^{-35}$ м

Планковское время $t_{Pl} = \frac{l_{Pl}}{c} = \sqrt{\frac{\hbar G}{c^5}} \cong 5{,}39106(32) \times 10^{-44}$ с

Планковская температура $T_{Pl} = \frac{M_{Pl} c^2}{k} = \sqrt{\frac{\hbar c^5}{k^2 G}} \cong 1{,}416833(85) \times 10^{32}$ К

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0–0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009–0.13)\times10^{-9}$	0
μ muon	0.106	−1
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τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
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c charm	1.3	2/3
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t top	173	2/3
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*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² = 1.67×10^{-27} kg.

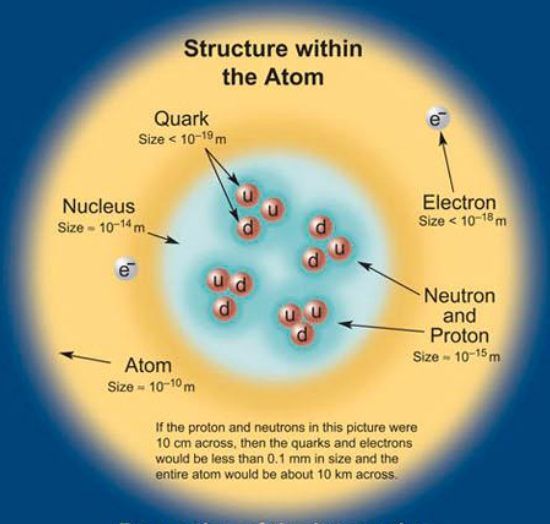
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, −1, 0, 0 respectively.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
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This chart has been made possible by the generous support of:

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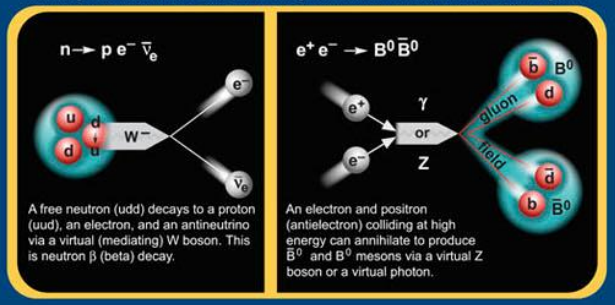
Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



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An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

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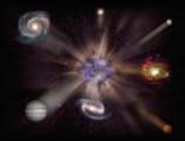
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?



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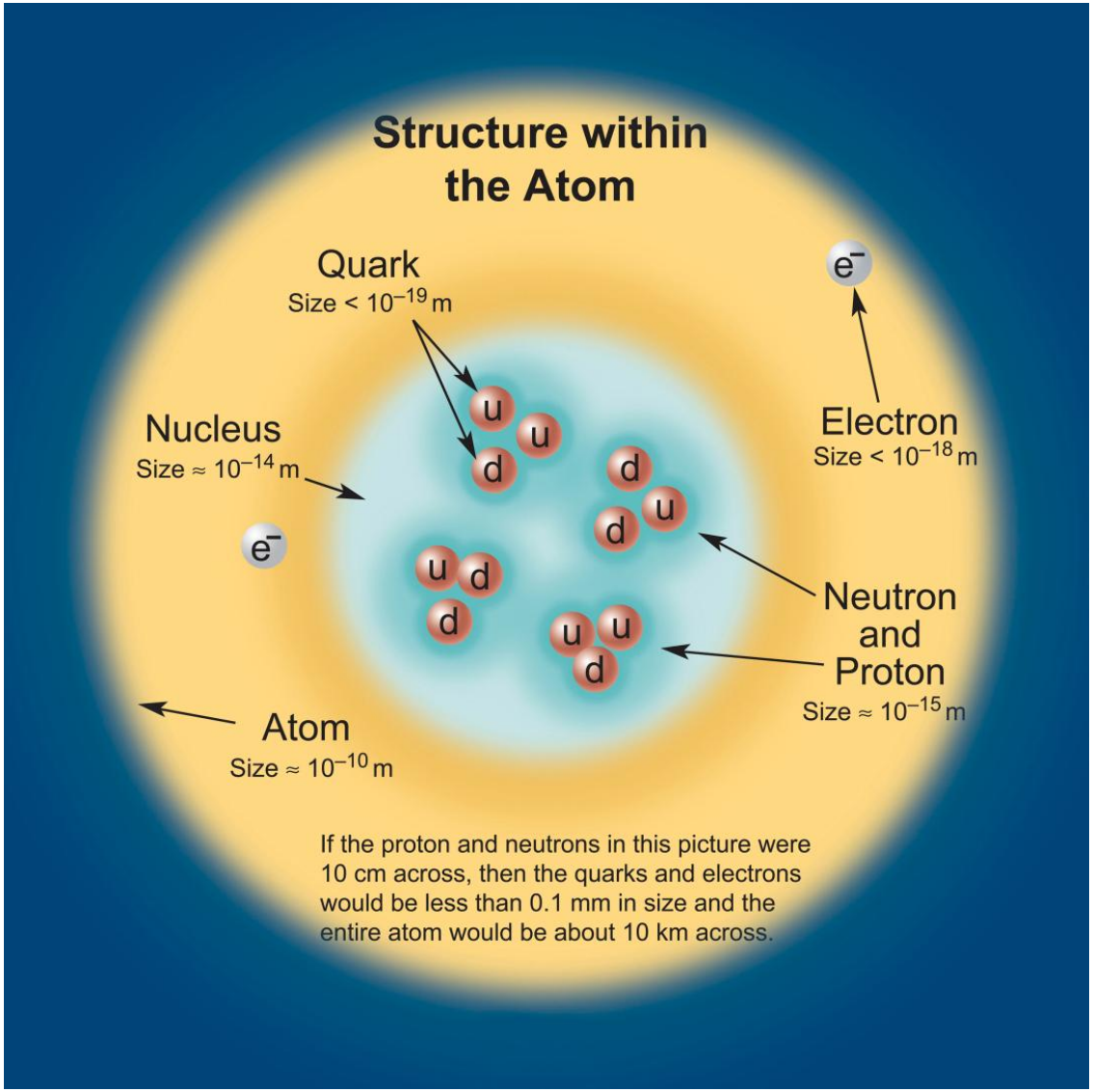
http://www.cpepweb.org/

Строение атома



Фермионы

FERMIONS

matter constituents
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Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
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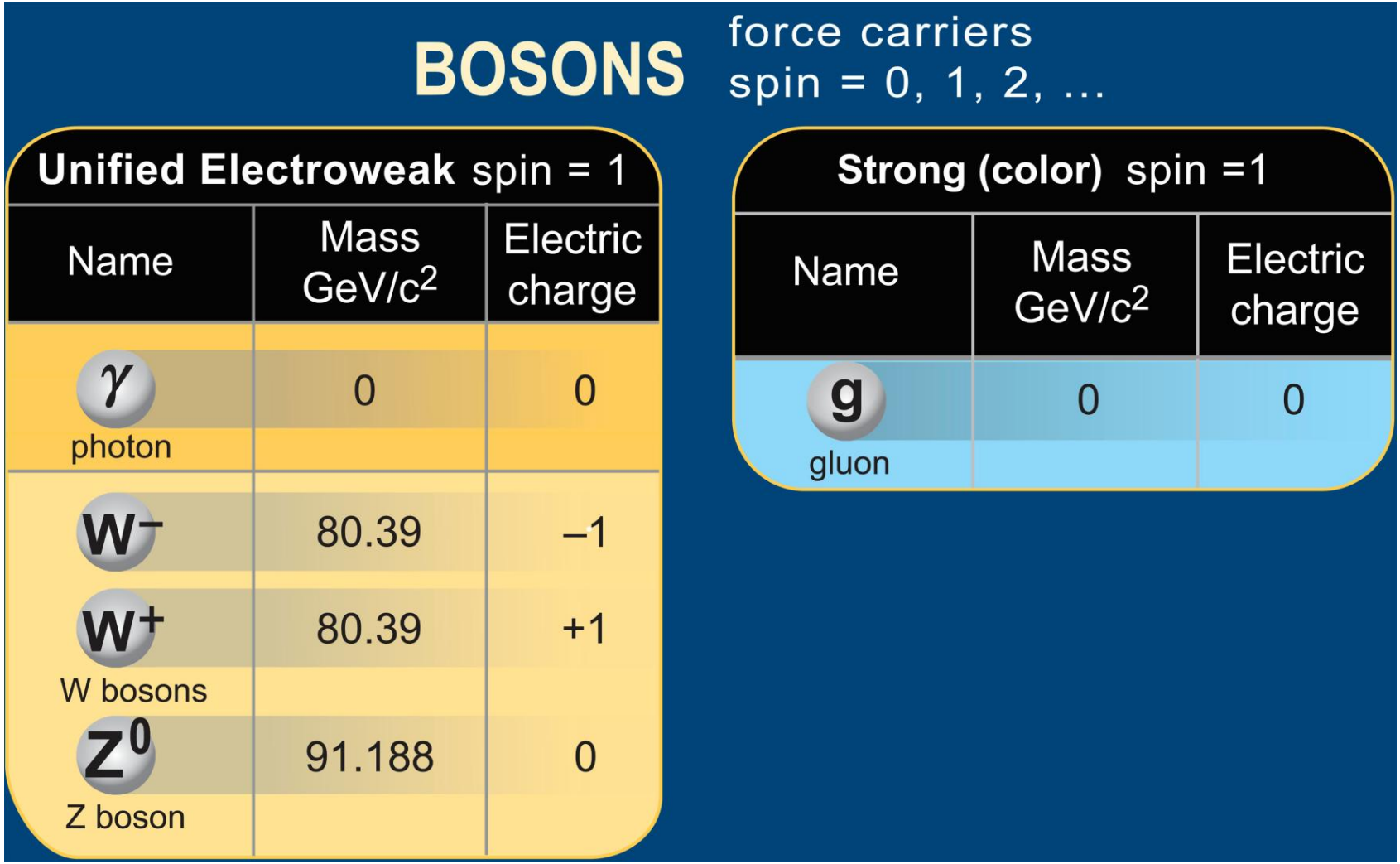
Бозоны


BOSONS
force carriers
spin = 0, 1, 2, …
Unified Electroweak spin = 1
Name
Mass GeV/c²
Electric charge
γ
photon
0
0
W⁻
80.39
–1
W⁺
80.39
+1
W bosons
Z⁰
91.188
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Electric charge
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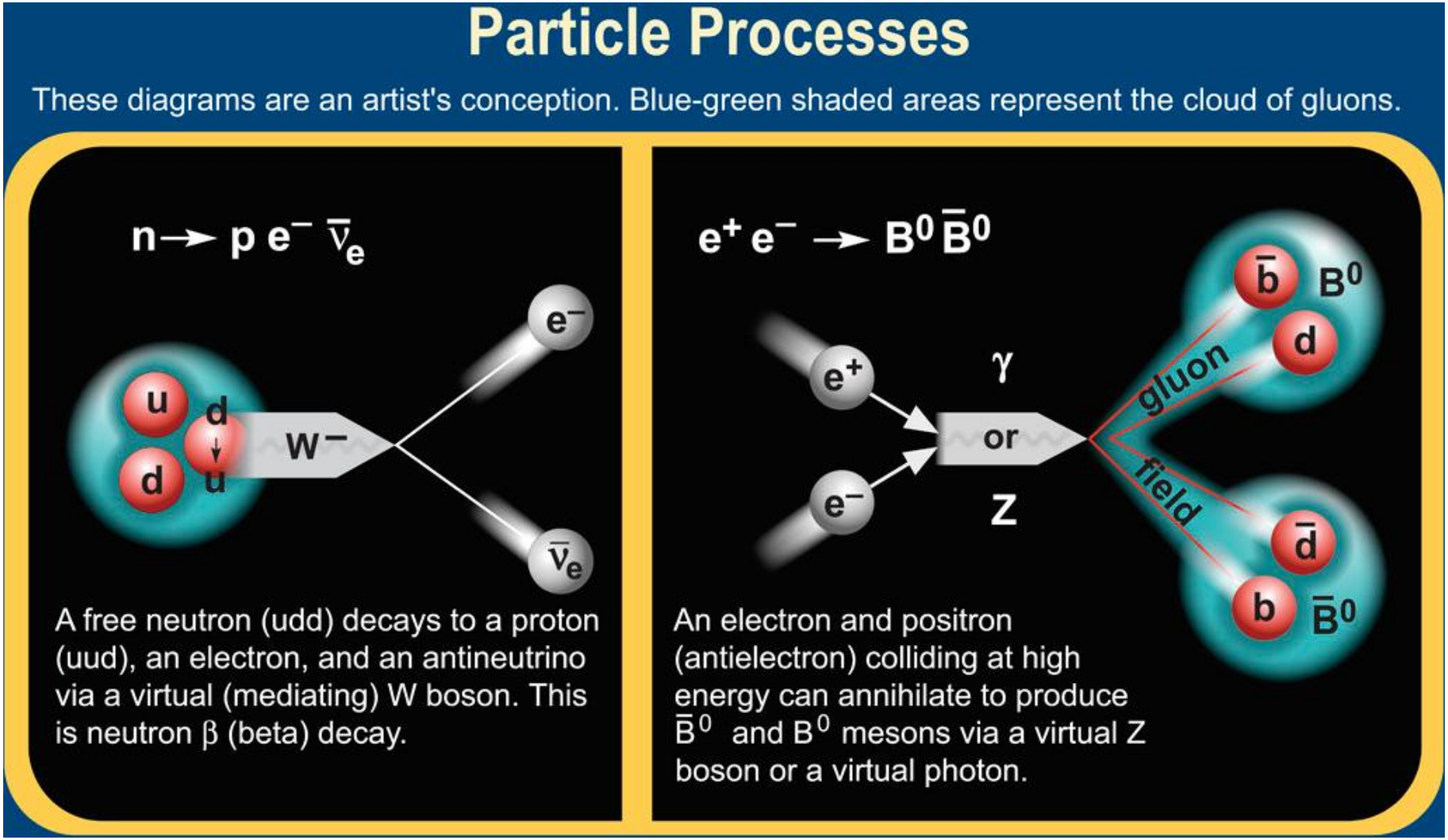
Взаимопревращения частиц



Неразгаданные тайны

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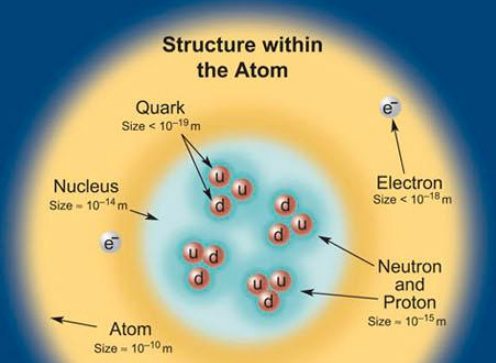

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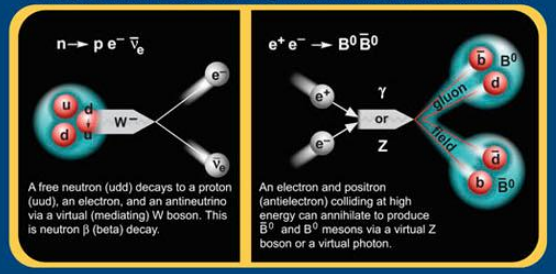

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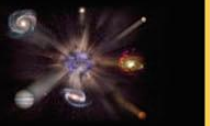

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