Basic Theoretical Ideas

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Particle and Universe

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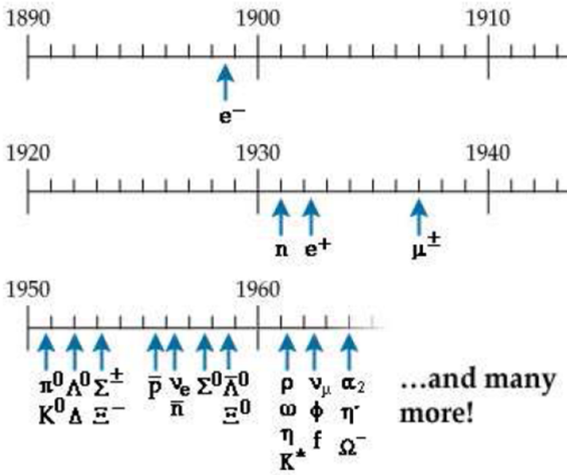


I. 1900-1928 II. 1930-1955

III. 1956 - 1975 IV. 1976 - 2012

Plan

- Quantum Mechanics and Relativity 1900 - 1928
- New particles, new interactions 1930 - 1955
- Particle physics 1956 - 1975
- Standard Model 1976 - 2012 ($\rightarrow$ astrophysics, cosmology)

I. Quantum Mechanics and Special Relativity 1900-1928

Maxwell equations 1864

Quantum:

- Blackbody's radiation $\rightarrow$ energy quantum Planck 1900
- Quantum (particle) of light - Einstein 1905
- Wave property of matter - de Broigle 1924
- Bohr's atom 1913 (stationary orbits, quantum numbers)
- Pauli exclusion 1925, a new two-valued quantum number
- Spin- Goudsmit,Uhlenbeck '25

Relativity:

- Special relativity-Einstein 1905 (velocity of light c, space-time, time dilatation, Lorentz contraction, $E = mc^2$)
- General relativity-Einstein1915

Symmetry:

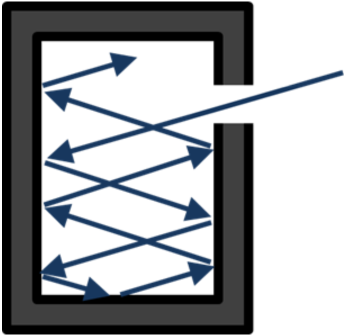
- Noether (symmetry $\rightarrow$ conservations laws) 1918
- Weyl (global and local (gauge) symmetry, unification of EM with GR) 1918

QM - Heisenberg (matrix 1925, uncertainty principle'27), Schrodinger (wave 1925-6); Dirac 1928 -description of photon-electron interaction based on QM and relativity: antiparticles,creation/annihilation particles

Blackbody radiation

Radiation is a process in which energy is transfered by electromagn. waves (no matter needed). Absorption and emission by and from an object, so surface of the object matters. Vibration of molecules (studied 1860-90):

- black object - absorption of visible light. Perfect blackbody absorbs all e-m waves (cavity).
- Energy of radiation depends on time, area, wave length λ (frequency f $\sim 1/\lambda$), temp. (T^4 Stefan law)
- Blackbody radiation intensity Rayleigh-Jeans - wrong at short waves. Wien displacement (maxium) law (wrong at long waves). Planck - correct.



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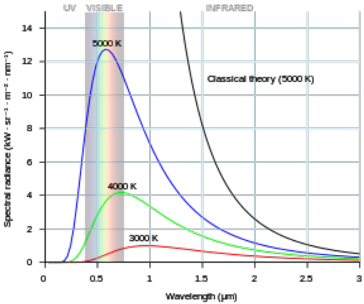

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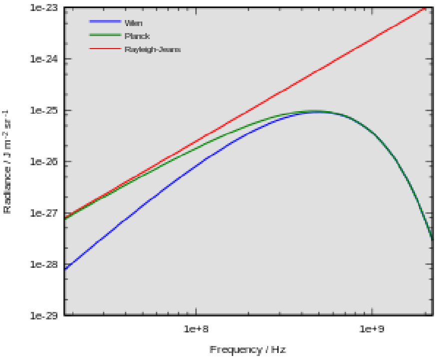


Planck

After many attempts, he concluded in 1900 that only by assuming radiation by walls of cavity in discrete bundles (quanta) one can get a proper description of the whole spectrum of radiation.

- Portion of *energy* (quantum of energy) proportional to its frequency $E = h\nu$, ν - frequency $[c/\lambda]$;
  Planck constant $h = 6,63x10^-34\, J \cdot s$
- First presentation Oct 19, 1900 – at the Berlin Phys. Soc. meeting, next day - results of a new measurement by Rubens, in agreement with Planck's prediction. Quantum - presented on 14 Dec. 1900 at the Prussian Phys. Soc.
- However Planck did not accept himself this finding. He described it as "an act of despair ". But he knew - "Today I have made a discovery as important as that of Newton".

Quantum = "How much?"

Einstein made the next step in 1905 -
he assumed that quanta of energy occur not only in the emission or absorption - but they travel as a whole.

- *"Indeed, it seems to me that the observations of black-body radiation, photoluminescence, production of cathode rays by ultraviolet light, and other related phenomena associated with the emission or transformation of light appear more readily understood if one assumes that the energy of light is discontinuously distributed in space. ... that move without dividing, and can be absorbed or generated only as complete units..."*

- The only physicist that time who supported Einstein was Johannes Stark. In 1909 he wrote the *momentum* of a light quantum explicitly

$$p = E/c.$$

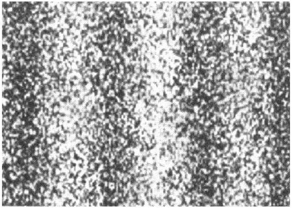
“The bold, not to say, the reckless, hypothesis”

- In 1913 Einstein was considered to became a member in the Prussian Academy of Science - Planck and others wrote: “That he sometimes has missed the target in his speculations, as for example, in his hypothesis of light quanta, cannot really be held too much against him, for it is not possible to introduce really new ideas, even in the most exact sciences, without sometimes taking a risk”.
- Millikan’s words from 1916 (on his own results on photoelectric effect) ”We are confronted, however, by the astonishing situation that these facts were correctly and exactly predicted 9 years ago by a form of quantum theory which has now generally been abandoned.”
- Compton (photon-electron scattering) 1922/3 supported light quanta
- Still in 1925 James Jeans wrote that “The general opinion of physicists seems to be that the theory cannot be regarded as an expression of physical reality”.

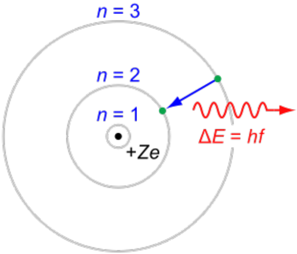
De Broigle 1924 postulated that electron (and all matters i.e. other particles) have wave properties. .

This was his doctorate - Einstein supported this idea, supervisor was not sure..

Below - 70000 electrons passing the two-slit scheme



Two postulates:
I. Orbital angular momentum of electron L is equal to $n\hbar$ ($h/2\pi$). Only on the orbital with such angular momentum electron does not radiate.
II. Difference of energies of electron at two orbitals is equal to a product of h and frequency (f) $\rightarrow$ the atomic spectrum



- Stationary orbits? But how? de Broglie idea (1924 !) helps (standing waves...)
- Quantum numbers - states of the atom is described by the energy n, orbital momentum l, magnetic quantum number m_l

Pauli exclusion and spin

- Pauli (born 1900) postulated exclusion principle in 1925.
  The complicated system of electrons in "closed shells" (Bohr '22) can be reduced to the simple rule of one electron per state, if the electron states are defined by four quantum numbers (n, l, m_l, x).
  For this purpose he introduced

a new two-valued quantum number (x)

- Samuel Goudsmit and George Uhlenbeck (students!) introduced electron spin (two states!) in 1925.
- Pauli was against... after one year he accepted this idea
- Today - we divide all particles to such as electron (one per state) - fermions, and such as the photon (many in a state) - bosons.

The Pauli exclusion principle is responsible for stability of matter - this suggestion was made in 1931 by Paul Ehrenfest, who pointed out that the electrons of each atom cannot all fall into the lowest-energy orbital and must occupy successively larger shells. Atoms therefore occupy a volume and cannot be squeezed ... (his address on the occasion of the award of the Lorentz Medal to Pauli).

Einstein used only two postulates:

- The velocity of light in empty space c is the same in all inertial frames independently of the relative motion of an observer and a source.
- The principle of relativity, that the laws of physics are identical in all inertial frames.

Results:

- space-time (4-vectors),
- time dilatation, Lorentz contraction
- $E = mc^2$...

Lifetime of a particle depends on frame- but the fact that it is stable or not is frame-independent.

Relativistic effects important if velocity v is close to c.

Quantum Mechanics and Quantum Electrodynamics 1925-8

- Spring 1925 Heisenberg - the first form of QM (matrix)
- Fall 1925 Schrodinger - an alternative form (wave), in 1926 - proof that two forms equivalent.
- 1927 - Uncertainty principle by Heisenberg $\Delta x \cdot \Delta p \geq \hbar/2$
- 1928 Dirac relativistic wave equation (for electron) - the first theory to account fully for special relativity in the context of quantum mechanics.
  Existence of an antimatter (the same mass and lifetime, opposite el. charge) (symmetry under transformation of charge C called also matter-antimatter transformation) - where is antielectron?
- Quantum Electrodynamics...(almost)

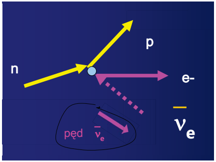
Possible to perform any computation for any physical process involving photons and charged particles !?

II. New era 1930 -1955

- 1930 neutrino - Pauli hypothesis (to save energy-momentum conservation in the beta decay); no mass, no el. charge - not seen directly. (Discovery in 1956.)
- 1932 neutron was discovered and

  A) 1932 Heisenberg postulated a description of nuclear (strong) interaction in terms of dublet of proton and neutron (common name - a nucleon). The isospin SU(2) symmetry was assumed (observed independence of nuclear force $pp \equiv nn \approx pn$)

  B) 1933 Fermi postulated description of process: neutron $\rightarrow$ proton + electron + neutrino (current-current interaction in analogy of QED with electric currents) - theory of weak interaction



Beta decay: point-like interaction, strength $\rightarrow$ Fermi constant $G_F = 1.1 \cdot 10^{-5}/GeV^2$, charged current (CC) interaction which is weaker than el-mag. interaction

4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tübingen personally, because I am indispensable here due to a ball which will take place in Zürich during the night from December 6 to 7....

Your humble servant,

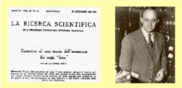
W. Pauli

Pauli also left in his diaries: "Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally."

Chadwick discovers neutron (1932):

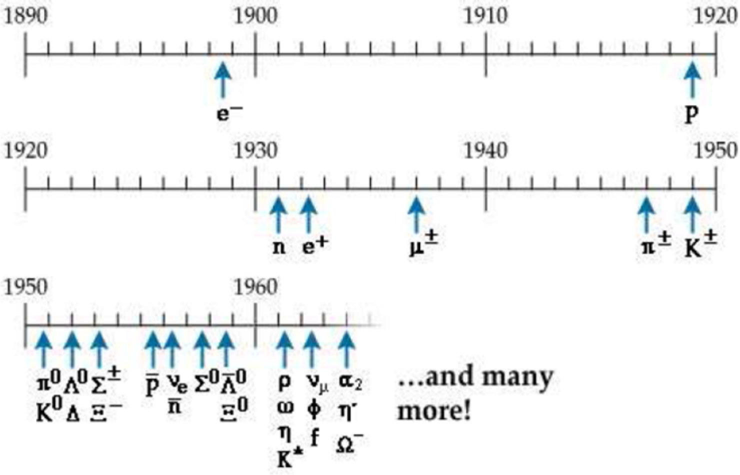
- Mass of neutron similar to mass of proton: not Pauli's particle!
- Fermi introduces name "neutrino" (ν_e), which is different to neutron, and beta decay is decay of neutron:

$$n \to p\, e^- \, \bar{\nu}_e$$



- Discovery: positron (1932), heavy electron (muon 1937) - leptons
- 1941 Pauli (relativistic field theory of elementary particles) - symmetry as a gauge principle to describe interaction "QED=U(1)"
- First order calculations in QED OK!, then infinities! Renormalization (Kramers 1938,;Bethe, Tomonaga, Schwinger, Feynman, Dyson 1947-1950) - infinities hidden in mass and charge parameters.
- Yang-Milles (gauge) theory for isospin SU(2) 1954 - massless (vector) carries of forces ?? (name - gauge bosons)
- 1949 Strange particles discovered (Kaons)
- 1956 Parity (P) non-conservation in weak interaction Yang, Lee, Wu...P transformation leads to a mirror image, so eg. *Pauli: since nature "does not know" whether we observe it directly or through a mirror, mirror reflection invariance must hold and hence parity must be conserved. Landau - "Space cannot be asymmetric".* Over one night Landau found the solution - CP symmetry (C symmetry was broken as well).

Discoveries...



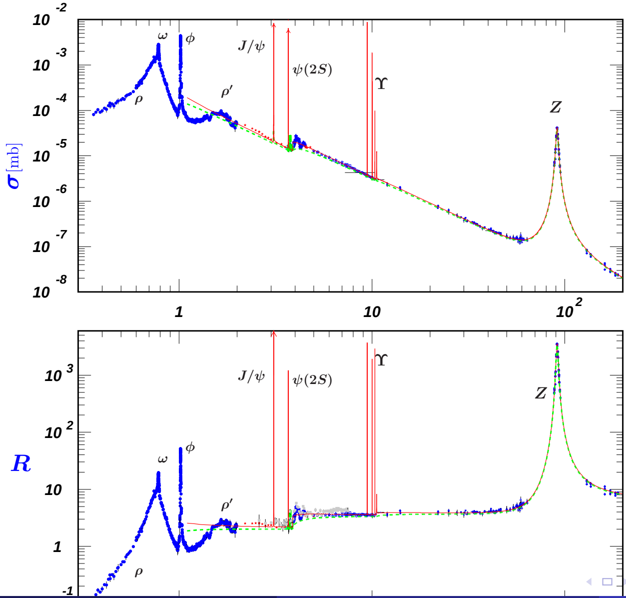
look at 1964!

Particle Physics 1956-1975

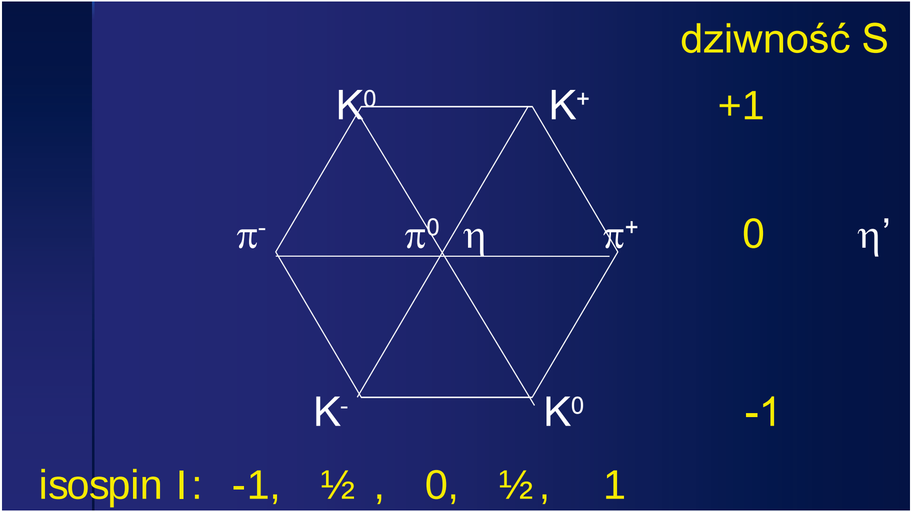
- Many particles discovered, mainly hadrons,with strong interaction
- 1964 Classification led to Quark Model - Gell-Mann, Zweig
- 1961 Glashow - unification of electromagnetic and weak forces SU(2)xU(1) - electroweak interaction EW- gauge bosons $W^{\pm}$, (Z?)
- 1964 Brout-Englert-Higgs (BEH) mechanism for Yang-Mills theories (spontaneous symmetry breaking - generation of gauge bosons masses)
- 1964 small CP violation in weak interaction observed ($\rightarrow$ matter-antimatter asymmetry in the Universe)
- 1967 Salam, Weinberg incorporated BEH mechanism to the EW interaction (only for leptons)
- 1971 d'Hooft, Veltman - EW theory is renormalized
- 1973 Gross, Wilczek, Politzer - QCD theory of strong interaction SU(3) color;colored quarks and gluons, asymptotic freedom
- 1973 Neutral current observed (means Z)
- 1974 Charm quark found

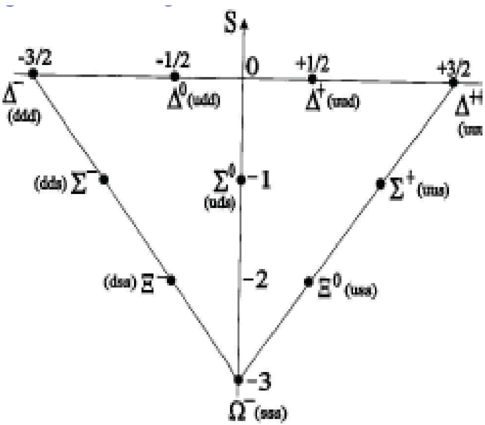
$\rightarrow$ Standard Model SU(2)xU(1)x SU(3)

Resonances

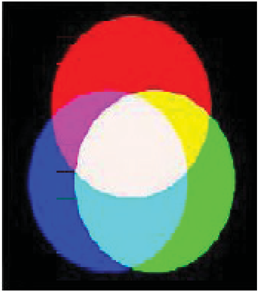


Quark diagram (octet) - Isospin vs Strangeness

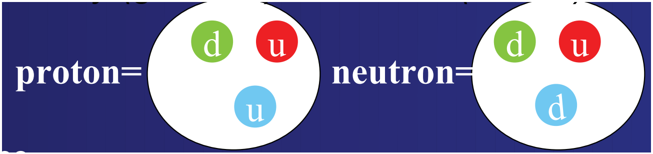



S
-3/2
-1/2
0
+1/2
+3/2
Δ^- (ddd)
Δ^0(udd)
Δ^+(uud)
Δ^{++}
(dds) Σ^-
Σ^0 -1
(uds)
Σ^+ (uus)
(dss) Ξ^-
-2
Ξ^0 (uss)
-3
Ω^- (sss)

Hadrons- bounds states of colored quarks- barions (qqq) and mesons (q $\bar{q}$)- are colorless!



Proton and neutron and light quarks

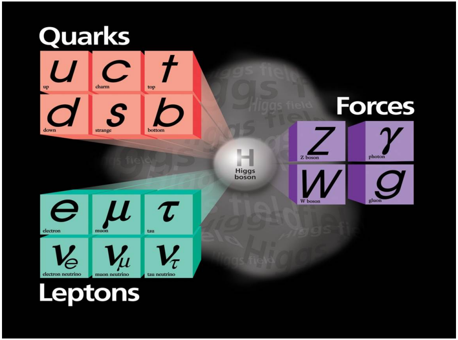


- 1983 W/Z gauge bosons discovered - very heavy (80/90 GeV)!
- Fundamental particles:

  quarks and leptons,

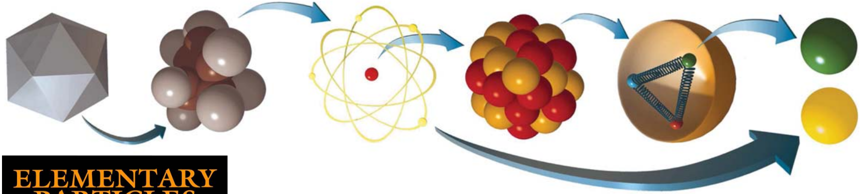
  carriers of interactions (bosons): - photon, W+,W-,Z , gluons

  the Higgs boson (discovered in 2012)

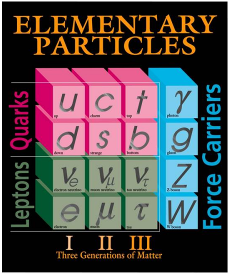


Standard Model

- Fundamental level



$< 10^{-18}$ m

- 

Why 3 generation?

- Masses of fundamental particles - Higgs boson

Higgs boson discovered!

Year 1964

→ LHC 4.07.2012

Higgs-like particle with mass125 -126 GeV

observed by ATLAS+CMS (+Tevatron)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

26.06.1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

27.07.1964

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BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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(Received 12 October 1964)

12.10.1964