A brief review, from basic atomic constants to "Mendeleev Table" of leptons, quarks, fundamental bosons, and then to superunification of all forces and particles.

1 Constants of atomic physics.

The discovery in 1896 of Pieter Zeeman, which we are celebrating today, was a great step in unveiling the structure of atoms. At the same time it was a great step in measuring the fundamental constants of Physics. As was shown by H. Lorentz, the Zeeman splitting was determined by the ratio $e/mc$, where $e$ and $m$, the charge and the mass of electron, and $c$, the velocity of light, are three out of the four fundamental constants of atomic physics. The fourth constant, $\hbar$, was introduced by Max Planck in 1900. (I am using the modern notations and terminology.) The fundamental constants $\hbar, e, m$ are the natural units for atomic physics. They determine the size and the energy levels of the hydrogen atom (but not its mass, which, as for any other atom, is determined by the mass of the nucleus). Three decades later this led to Nonrelativistic Quantum Mechanics. (An additional important ingredient was spin, the Pauli principle that explained the Mendeleev Table.)

Already in the original interpretation of Zeeman effect by Lorentz an important role belonged to the velocity of light, which enters the expression of the Lorentz force. Were $\hbar, e, m$ the same as they are, but the velocity of light were infinite, the atoms would not emit and absorb light, and there would be no Zeeman splitting. In this sense atomic physics cannot be considered to be non-relativistic. Note that fine structure constant involves $c$:

$$\alpha = e^2/4\pi\hbar c$$

During the XX century the constants $\hbar, c$ took deep roots in Physics and have fundamentally changed its very basis. The electric charge $e$ has been joined by the weak and strong charges. As for the mass of the electron, $m$, it turned out to be one of a whole constellation of fundamental masses.

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2 QED, leptons and hadrons.

The Dirac equation combining electron and positron opened a new chapter of Physics – the Relativistic Quantum Mechanics, which dealt with what we now call Feynman tree diagrams. Twenty years later, in the middle of the century, the Feynman loops became manageable and the QED (the Quantum Electrodynamics) arose, beautiful, as the Venus of Botticelli.

But it was clear that this beauty was not alone on the painting. Since early 1920’s protons and since early 1930’s neutrons and neutrinos were known. After the World War II new particles have been discovered. They belonged to two different groups: leptons and hadrons. Leptons are: electron, its neutrino and their relatives. The first leptons, identified after the war were muons. Hadrons are: proton, neutron and their relatives. The first hadrons discovered after the war were pions. Soon they were joined by a crowd of other strange creatures: strange mesons, hyperons, resonances. Botticelli was impetuously transforming into a Bosch.

A great relief and order was brought by three ideas:

1. that all hadrons are particles composed of a few building blocks (sakatons – in the 1950’s, quarks – after 1964);

2. that in addition to the electromagnetic interaction, there are only two other interactions behind all this Boschian chaos: the strong and the weak one;

3. that the source of strong interaction are three basic, so called colour charges, whilst the source of weak interaction are two basic weak charges.

At present the ”Mendeleev table” of basic elements consists of 16 particles, not counting antiparticles and colour degrees of freedom (colour charges).

3 The ”Mendeleev table” of fundamental particles.

The 16 basic elements are subdivided into two groups: 4 basic bosons with spin one, and 12 basic fermions with spin 1/2.

The four bosons are carriers of four forces:

\( \gamma \) – photon – of electromagnetic force, with \( \alpha = e^2/4\pi\hbar c \),

\( W \) – of weak force for charged currents, with \( \alpha_W = f_W^2/4\pi\hbar c \),

\( Z \) – of weak force for neutral currents, with \( \alpha_Z = f_Z^2/4\pi\hbar c \),

\( g \) – gluon – of strong force, with \( \alpha_s = g^2/4\pi\hbar c \).

The main difference between photon and \( Z \) and \( W \) bosons is that photon is massless, while \( m_Z = 91 \text{ GeV} \), \( m_W = 80 \text{ GeV} \).
The main difference between photon and gluon is that photon is single and electrically neutral, while there exist eight gluons carrying eight different combinations of colour charges, and emitting and absorbing themselves. The result of this selfinteraction is the phenomenon of confinement of coloured gluons and quarks inside snow-white hadrons. The forces between hadrons are not the basic ones, they are secondary and resemble the Van der Waals and chemical forces between atoms.

Twelve fermions are subdivided into three generations – two quarks and two leptons in each:

|       | 1st | 2nd | 3rd | Q     |
|-------|-----|-----|-----|-------|
| quarks| \(u\) | \(c\) | \(t\) | \(2/3\) |
|       | \(d\) | \(s\) | \(b\) | \(-1/3\) |
| leptons| \(\nu_e\) | \(\nu_\mu\) | \(\nu_\tau\) | 0 |
|       | \(e\) | \(\mu\) | \(\tau\) | -1 |

Each electrically charged fermion has its antiparticle. It may be, that the same is true for neutrinos, but it is also possible that neutrinos, like photons, have no antiparticles: each neutrino is its own antiparticle. Another unsolved problem, whether neutrinos are massless or have non vanishing masses.

What are the roles of the three fermionic generations? The atomic shells are made of electrons, the atomic nuclei are made of the \(u\) and \(d\) quarks held together by gluons inside protons and neutrons: \(p = uud\), \(n = ddu\). Electronic neutrinos are needed for weak reactions in the sun and stars. As a result

\[
2e^- + 4p \rightarrow ^4He + 2\nu_e + 27 \text{ MeV}.
\]

Without electronic neutrinos there would be no sun and hence we would not exist. Thus, the first generation of basic fermions is absolutely necessary for the existence of our world.

The second and third generations seem, at first sight, to be absolutely useless. But, maybe, they were essential in the first nanoseconds of the Big Bang by preventing full annihilation of protons and electrons into neutrinos and photons. Maybe, they had (and have?) some other functions. They definitely played an important role in the history of physics. The study of strange particles (containing \(s\)-quark) lead to the discovery of quarks and to the discovery of violation of P, C, CP and T symmetries in weak interactions, which lead to unification of electromagnetic and weak interactions into one electroweak interaction. In accordance with this unified theory (in the Born
approximation, i.e. neglecting electroweak radiative corrections):

\[
\frac{m_W^2}{m_Z^2} = \frac{\alpha_W}{\alpha_Z} = 1 - \frac{\alpha}{\alpha_W}.
\]

One of the key elements of the electroweak theory is the Z boson. Let us note that the experimental study of \(2 \cdot 10^7\) Z boson events at LEP I collider (CERN) has proved that there are only three light (or massless?) neutrinos. Thus, new particles help to understand the old ones.

The last free box in the Table of basic fermions has been filled in only two years ago, when the heaviest quark \(t\) was discovered at the Tevatron collider (FNAL). The mass of this quark is \(175 \pm 15\) GeV.

4 The higgs and the origin of mass.

It might sound strange, but the value of the top mass is the most natural one of all leptons and quarks. In order to see this, let us consider the so called Higgs mechanism, that is used in electroweak theory to generate masses of fundamental particles. At the basis of this mechanism lies the (still hypothetical) Higgs field, the quantum excitations of which are neutral scalar (spinless) bosons – higgses. The mass of the higgs is unknown at present. In the most popular scenario higgs is heavier than Z boson but lighter than top quark. The search for the higgs is the major priority of a new \(e^+e^-\) collider LEP II and of the future Large Hadron Collider (LHC) at CERN.

Higgs field is coupled to all massive particles, the value of the coupling constants being proportional to the particles masses. They are called Yukawa coupling constants.

The unique feature of the Higgs field is that it has a non-vanishing vacuum expectation value (VEV) \(\eta = 250\) GeV throughout the world. Mass of a fermion is a product of its Yukawa coupling times \(\eta\). Masses of \(W\) and \(Z\) bosons are \(g_W\eta/2\) and \(g_Z\eta/2\) respectively. The mass of the top quark is the most natural one in the sense that its Yukawa coupling is of the order of unity.

5 Running of \(\alpha_s\) and confinement.

For \(\eta = 0\) all fundamental bosons and fermions would become massless. This however does not refer to hadrons. Most of them would remain massive even if the quarks were massless. For instance, the masses of the proton and neutron would be practically the same, as they are. This conclusion is deeply connected with the phenomenon of confinement and with the running of the coupling constant \(\alpha_s\).
According to quantum field theory the values of all charges, of all coupling constants depend on distance (or momentum, or energy). The constants are changing with these variables because of vacuum polarization. The famous $\alpha = 1/137.0359895(61)$ is in fact the value of $\alpha(q^2)$ at a vanishing momentum transfer: $q^2 = 0$. In the interval from 0 to $m_Z$ $\alpha$ increases from 1/137 to 1/129. The $\alpha_W$ and $\alpha_Z$, in the same interval, change very little, they "crawl":

$$\alpha_W(0) = 1/29.01 \quad \alpha_W(m_Z) = 1/28.74$$
$$\alpha_Z(0) = 1/23.10 \quad \alpha_Z(m_Z) = 1/22.91$$

According to Quantum Chromodynamics (QCD) the behaviour of $\alpha_s$ is totally different; $\alpha_s$ runs in the opposite direction and runs fast:

$$\alpha_s(m_Z) \approx 0.12 \quad \alpha_s(1GeV) \approx 1$$

and it would "blow up" at smaller momentum transfers, or distances larger than the radius of confinement, if it were possible to separate unscreened colour charges by such distances. The non-perturbative strong self-interaction of gluons, and their interactions with quarks produces gluon and quark condensates with characteristic energy scale $\Lambda_{QCD} \approx 300$ MeV. It is $\Lambda_{QCD}$ that sets the scale of masses of hadrons built from light quarks ($u, d$) and gluons.

6 Symmetries and grand unification.

Up to this point I tried to avoid mentioning symmetries and groups, using physical, rather than mathematical, language. But in order to understand the essence of physics one has to appreciate its mathematical beauty, the beauty of symmetries. First of all, special relativity is represented by Poincaré group. Second, QCD is represented by a local SU(3) colour symmetry with gluons as quanta of gauge fields of this symmetry. Third, electroweak theory is described by SU(2)×U(1) gauge symmetry, which is spontaneously broken to U(1)$_{em}$ by the higgs VEV. Unification of all three types of interactions is expected to be based on a higher broken gauge symmetry described by such groups as unitary group SU(5), orthogonal group SO(10) or exceptional group E$_6$, which contain SU(3) and SU(2)×U(1) as their subgroups. This idea of grand unification finds strong support in the fact that the three gauge coupling constants $\alpha_s$, $\alpha_W$ and $\alpha$ (the latter with a proper coefficient 8/3), being so different at low energies, tend to a single meeting point, at $E_{GU} \approx 10^{16}$ GeV, where all of them have the same value of the order of 1/30.

The fermionic multiplets of higher groups contain both leptons and quarks. For instance, in the case of SO(10) each generation of fermions (with account of antiparticles and of three colours of quarks) forms a 16-plet. Among the 45
vector bosons of $\text{SO}(10)$ there are bosons with such couplings, that their exchange leads to the proton decay into a positron (or antineutrino) plus accompanying light hadrons (mesons). Another baryon number violating interaction produces decays of nuclei, in which two neutrons transform into mesons; it also transforms neutron into antineutron in vacuum.

The above decays of nuclei have lifetimes longer than $10^{32}$ years, because the corresponding bosons are very heavy: their masses are of the order of $10^{16}$ GeV. The search for such decays is one of the highest priorities of the new gigantic underground detector Super Kamiokande.

7 SUSY and superstrings.

A symmetry, which might be broken not so badly, as grand unification symmetry, is supersymmetry, or SUSY. According to SUSY, there exist at least one superpartner for each particle we already know. In this minimal case there exist bosonic analogues of leptons and quarks (sleptons and squarks with spin 0), and fermionic analogues of bosons (photino, gluino, zino, wino and higgsino with spin 1/2). The lighter of these superparticles may be discovered at LEP II and LHC. The lightest of them might be stable and constitute a substantial part of the so called dark matter. It is interesting that Feynman loops of superpartners help to focus more accurately the three running gauge couplings at the grand unification point.

The energy of grand unification is only four orders lower than the Planck mass, $m_P$, introduced into physics by Planck, when he discovered the quantum of action:

$$m_P = \left(\frac{\hbar c}{G}\right)^{1/2} = 1.2 \cdot 10^{19} \text{ GeV} \approx 2.2 \cdot 10^{-5} \text{ grams},$$

where $G$ is the gravitational (Newtonian) constant: $G = 6.6720(41) \cdot 10^{-8} \cdot \text{cm}^3 \cdot \text{g}^{-1} \cdot \text{sec}^{-2}$. The Planck length, $l_P$, and Planck time, $t_P$, were introduced in the same paper:

$$l_P = \frac{\hbar}{m_P c} = 10^{-33} \text{ cm},$$

$$t_P = \frac{\hbar}{m_P c^2} = 3 \cdot 10^{-44} \text{ sec}.$$  

At energies of the order of $m_P$, or distances as short as $l_P$, the energy of gravitational interaction becomes of the order of the total energy and quantum effects become important. This is the realm of quantum gravity.

The quantum of excitation of gravitational field is called graviton. It is massless, neutral and has spin 2. Its source is the energy-momentum tensor.
divided by \( m_P \). Therefore at low energies (\( E \ll m_P \)) its coupling to the matter is extremely weak. Therefore it has not been observed experimentally, and will not be observed in the foreseeable future. Even gravitational waves, classical ensembles of zillions of gravitons, have not been yet detected by specially built antennas. But for them prospects are quite realistic.

A consistent theory of quantum gravity has not been created yet. The most promising way to it is marked by the sign "superstrings". Superstrings are tiny one-dimensional objects of the characteristic Planck length \( l_P \), with fermionic and bosonic excitations on them (therefore the prefix "super"). Most of these excitations are very heavy, of the order of \( m_P \). But there are a few of them which remain massless. They look like pointlike particles, from distances much larger than Planckian. Some of the superstring models have patterns of massless degrees of freedom, which closely resemble some of the supersymmetric grand unification groups. Thus, superstrings, are believed not only to provide a selfconsistent theory of quantum gravity, but to provide it in a broader framework of a unified theory of all interactions, a theory of everything (TOE). All values of known (and to be discovered) fundamental gauge and Yukawa coupling constants are expected to arise as dimensionless elements of the solution of the TOE equations. It was shown recently that various superstring models correspond in fact to perturbative expansions in vicinity of different points of the same theory.

If superstring ideas are correct, then the nature is based on three fundamental dimensional constants: maximal velocity of particles \( c \), quantum of action and of angular momentum \( \hbar \), and Planck length \( l_P \) (or, what is equivalent in units of \( \hbar, c, \) Planck mass \( m_P \), or Newton constant \( G \)). The dimensions of other physical quantities can be expressed in terms of dimensions of \( c, \hbar, G \). In particular, the dimensions of length \([L]\), time \([T]\) and mass \([M]\), with which elementary physics text-books usually start, are:

\[
[L] = [l_P], \quad [T] = [t_P], \quad [M] = [m_P].
\]

The \( c, G, \hbar \) units has been considered as the most "natural units of nature" long before the superstrings (Eddington, Gamov, Ivanenko, Landau, Bronshtein, Zelmanov, Wheeler). From this point of view the program of Einstein to build a unified theory of gravity and electromagnetism, without using \( \hbar \), was doomed from the beginning.

8 Anthropic universe.

A remarkable feature of our world is how perfectly it is tuned to favour our existence. The anthropic properties of nature are discussed in many articles
and books. Let me remind a few examples of such fine tuning in particle
and nuclear physics. Start with proton and neutron. The mass difference
\( m_n - m_p \) is 1.3 MeV. Were it the case that this mass difference were 0.5 MeV
or smaller, then the neutron would become stable, whilst the hydrogen atom
would be unstable: \( e^- + p \rightarrow n + \nu_e \). The most abundant element in the
world would be helium, not hydrogen. The stars would explode at a rather
young age. The genesis of life would become impossible for many reasons.
Analogous dramatic changes are produced by making the electron 0.8 MeV
heavier. Note that neutron-proton mass difference is determined essentially by
the mass difference of \( d \) - and \( u \)-quarks \( (m_d \sim 7 \text{ MeV}, m_u \sim 5 \text{ MeV}) \). Note
also that in two other generations the lower quarks \( (s, b) \) are not heavier, but
substantially lighter than their upper partners \( (c, t) \). Compared to the Planck
mass, the tuning of \( u, d \), \( e \)-masses is of the order \( 10^{-22} \)!

Even more striking is the sensitivity of our world to much less fundamen-
tal quantity, such as the binding energy of the deuteron, \( \varepsilon = 2.2 \text{ MeV} \). Decreasing
it by only 0.4 MeV would make impossible the main reaction of hydrogen
burning in the sun, \( pp \rightarrow de^+\nu_e \), so that only the much less effective reaction
\( ppe^- \rightarrow d\nu_e \) would survive.

Another example is given by energy levels of \( ^{12}C \) and \( ^{16}O \). The famous
carbon level at 7.65 MeV lies only 0.3 MeV higher than the sum of masses
of three \( \alpha \)-particles, and therefore resonantly enhances the cross-section of
the reaction \( 3\alpha \rightarrow ^{12}C \). The nucleus \( ^8{Be} \) being unstable, carbon cannot
be produced in two body \( \alpha + ^8{Be} \) collisions. Without 7.65 MeV resonance
the three-body formation would be not effective enough. As a result carbon
would disappear in the reaction \( \alpha + ^{12}C \rightarrow ^{16}O \) much faster than it would
be produced, and the universe would have not enough carbon to create life.

When looking at the diagram of \( ^{12}C \) levels (there are about 30 of them
in the interval of 30 MeV) one cannot help admiring that the level 7.65 MeV
does not lie 0.5 MeV lower. The list of such examples may go on and on. How
thin is the margin of safety of everything which is so dear to our hearts! Most
essential features of our world are determined by absolutely non-essential (from
the point of view of fundamental constants) details of "hadronic chemistry",
not speaking about ordinary chemistry and biochemistry.

The anthropic properties of the universe have led to formulation of a num-
ber of speculative principles.

The weak anthropic principle is based on the notion of an ensemble of
an infinite number of universes with values of dimensionless fundamental con-
stants, which have been fixed during their cosmological evolution. From the
very fact of our existence it follows that we live in one of the best of the worlds.

The cosmological realization of the above statistical ensemble is an infinite
network of universes each of which, at its early inflationary stage, produces innumerable daughter universes. They may have different symmetry breaking patterns, even different numbers of space-time dimensions, and unlimited variety of values of dimensionless fundamental constants. But here we arrive to the gates of Metaphysics.

9 Concluding remarks.

Looking back at those who made great discoveries at the dawn of our century and at those who helped them, let us ask ourselves: Was it possible for any of these pioneers to predict the major steps in evolution of fundamental physics in the XX century, its impact on the life of the mankind, and its present landscape? The negative answer seems to me obvious. It would be even more difficult for us to guess, what summits the fundamental physics would reach in the next hundred years, unless the external factors will terminate its development. Unfortunately, it would be very easy to predict the landscape of physics and of science in general, if the existing antiscientific trends would prevail. It will be devastation: intellectual, scientific, cultural, technological, environmental. The life on our planet, a unique phenomenon, based on a unique tuning of fundamental constants of nature, might be ruined. Our duty, as scientists, to be unanimous and to do our best in defending and promoting fundamental science.

10 Bibliography.

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