The fundamental constants of physics

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A natural system of fundamental physical units c, $\hbar$, and m_P is discussed, where c is the velocity of light, $\hbar$ is Planck's constant, and m_P is the Planck mass, which is related to the Newtonian gravitational constant by the equation $m_P^2 = \hbar c/G$. In a natural system of units, such questions as: "How does the anthropic nature of the physical universe arise? Is it unique, or does an infinite set of universes exist?" and "Are the fundamentals of the physical universe knowable and what is the strategy for knowing them?" become particularly urgent.

1. INTRODUCTION

This paper is devoted to the question concerning the fundamental constants of physics. It is well known that an adequate choice of physical units is one of the most important prerequisites for solving any specific physical problem. This is especially true in relation to the fundamental questions of physics. A discussion of the question of the choice of fundamental physical units makes it possible to judge with greater understanding not only the history of fundamental physics, but also predictions of its development. Such a discussion binds together the physics of elementary particles and cosmology, and inevitably touches upon the most systematically different questions: from ones of the politics of science (Is it necessary to construct gigantic colliders, or can one see the entire plan for the structure of the physical universe by an effort of pure reasoning?) to philosophical ones (Why is the physical universe so well suited for the existence of life, and is it unique?).

2. LET US PLAY WITH THE VELOCITY OF LIGHT

It makes sense to start a discussion of fundamental physical constants from a somewhat unexpected question: what would be changed in the universe around us if the velocity of light were different than what it actually is, let us say, faster by ten orders of magnitude, i.e., $3 \cdot 10^{20}$ cm/sec? In order that this question make sense, one must stipulate what happens at the same time to other physical constants. So then, let Planck's constant $\hbar$, the electron charge e, and the masses of the electron m_e and of the proton m_p remain constant, while the velocity of light become different.

The three quantities $\hbar$, e, and m_e enable one to obtain the dimensionalities of all physical quantities. Thus, it is convenient to choose the Bohr radius, the radius of the hydrogen atom

$$r_B = \hbar^2/m_e e^2,$$

as the unit of length, the Bohr energy

$$E_B = e^2/r_B = e^4 m_e/\hbar^2,$$

as the unit of energy,

$$t_B = \hbar/E_B = \hbar^3/e^4 m_e$$

as the unit of time, and, as the unit of velocity,

$$v_B = r_B/t_B = e^2/\hbar.$$

Thus, an atom is both a clock (t_B) and a ruler (r_B). Therefore, the question of changing the velocity of light is not an empty one, is not a question of redesignating and choosing units.

Since chemical reactions are basically determined by electron exchange, then neither chemistry nor biochemistry would be seriously changed. And nevertheless, the universe would be radically changed. The point is that the properties of a photon would be changed radically. For the same energy E that is determined by the energies of the atomic levels, the photon emitted by the atom would have a momentum k that is ten orders of magnitude smaller:

$$k = E/c,$$

and its wavelength

$$\lambda\!\!\!^{-} = \hbar/k = \hbar c/E$$

would be ten orders of magnitude longer. Let us note that its frequency ω would remain unchanged: $\omega = E/\hbar$.

The probability of the emission of a photon by an excited atom is proportional to its phase space and consequently, to $k^2 dk$. But

$$k^2 dk = E^2 dE/c^3,$$

and the time for an excited atom to radiate it away optically would exceed the age of the universe. (Atoms would go over into the ground state due to collisions with each other.) The Thomson cross section for photon scattering by free electrons would be reduced by 40 orders of magnitude:[1]

$$\sigma_T = (8\pi/3)r_0^2,$$

where $r_0 = e^2/m_e c^2$, and the Rayleigh non-resonant scattering of light by atoms is[2]

$$\sigma_R \sim (e^2 r_B^2/E_b)^2(\omega/c)^4 \sim r_B^2(v_B/c)^4.$$

It is such that photons would be practically uncoupled from matter. There would be neither the Sun nor a light bulb to shine, nor eyes to see.1) All the remaining changes in the universe would possibly be less dramatic. Thus, for example, by Maxwell's equation

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$$\mathrm{curl}\ \mathbf{H} = \mathbf{j}/c$$

the magnetic field **H** and electric current **j** would be uncoupled. So there would be neither dynamos nor electric motors. But chemical sources of current would remain, although the question as to whether one could buy a battery in a store does not have a definite answer.

At first glance, the circumstance that photons with $c \to \infty$ are uncoupled from charges, while the Coulomb interaction between charges remains unchanged is found to contradict the widely known theoretical statement that the interaction between charges is determined by the exchange of virtual photons. However, one must nevertheless take this statement, which is absolutely correct within a four-dimensional formalism, "with a grain of salt." This is most simply seen if one recalls how the effect which characterizes the interaction of a four-dimensional potential A_i with an electric charge will look; $-(e/c)\int A_i \mathrm{d}x^i$, and if one allows for the fact that $A_i = (A, \varphi)$ and $x_i = (x, ct)$ (see Ref. 1).

The example with the velocity of light shows how very relativistic our universe is: in the Galilean limit, it becomes unrecognizably different.

A photon is a relativistic particle. This becomes apparent not only in the kinematics but, as we see, also in its dynamical properties and in its interactions. For some reason, this circumstance is not emphasized in the popular scientific literature. And it's a pity. If only the readers of popular scientific books on the theory of relativity recognized this, then possibly fewer refuters and improvers of this theory would come forth from their ranks.

After considering the case of a very high velocity of light, it is instructive to turn ourselves to the case of a low velocity of light. Effects of the type of slowing of the time measurements of moving clocks during a trip in an automobile were considered by O. A. Vol'berg, who wrote the appendix "An entertaining trip into Einstein's country" to Ya. I. Perel'man's book[3] "*Entertaining Mechanics*" in 1935. In order to make the discussion understandable, Vol'berg assumed that the velocity of light was twice the velocity of the automobile. In 1939, in his book "*Mr. Tompkins in Wonderland*," George Gamow[4] placed the hero on a bicycle and reduced the imagined velocity of light even more. Here all everyday life, except for the slowing of clocks and the contraction of scales, remained unchanged both for Vol'berg and for Gamow. However, it is easy to verify that this cannot be obtained without any accompanying changes of the constants $\hbar$, e, m_e, and m_p. If one holds these constants fixed and reduces c, then the universe will be changed long before the velocity of light will approach the velocity of an automobile.

Indeed, the value of the so-called fine structure constant α,

$$\alpha = e^2\hbar c.$$

is a parameter which characterizes the role of relativistic effects in a hydrogen atom. From experiment, $\alpha \approx 1/137$. It is easy to verify that $\alpha = v_B/c$. Thus, by reducing the velocity of light by at most two orders of magnitude, it would approach the velocity of an electron in a hydrogen atom.

Here one must emphasize that the binding energy of an electron in a hydrogen atom would be, as before, of the order of $E_B = m_e e^4/\hbar^2$, but the rest mass energy of the electron $m_e c^2$ would become comparable with this value. In this sense, the ordinary Coulomb interaction in an atom would become strong.

With a further reduction of c, the quantity $2m_e c^2$ would become less than the binding energy of an electron in a hydrogen atom, and a hydrogen atom H would become so much lighter than a bare proton p that it would become energetically favorable for decay of the proton to a hydrogen atom and a positron e^+:

$$p \to H + e^+.$$

One may say that, in this case, the electron is superbound in hydrogen.

Until now, we have discussed only the lightest atom. But superbound electrons would have shown up considerably sooner in heavy atoms, in their inner shells. The appropriate parameter here is $0.8Ze^2/\hbar c$, where Z is the nuclear charge, and the numerical coefficient 0.8 allows for the fact that one may not neglect the radius of a heavy nucleus in comparison with the radius of an inner electron orbit. As a result, let us say, at $c = 3 \cdot 10^9$ cm/sec, all atoms heavier than silicon would contain superbound electrons, and at $c = 3 \cdot 10^8$ cm/sec, as has been said above, superbound electrons would have shown up also in hydrogen.

A further increase of the value of $\alpha = e^2/\hbar c$ compared to unity would have to lead to a very strong interaction of electrons with positrons. It is not clear as to whether free electrons can exist in general under these conditions, or will confinement ensue for them; life imprisonment in electrically neutral positronium atoms similar to the manner of the confinement of colored quarks and gluons occurs in white hadrons. Perhaps free electric charges would become just as impossible as are free color charges. I write "not clear" since electrodynamics with $\alpha \gg 1$ has not yet been subjected to a systematic theoretical analysis.

3. THREE FUNDAMENTAL CONSTANTS

The example considered in the previous section was based on the assumption that $\hbar$, e, and m_e are the most fundamental dimensional constants, while the velocity of light appears to be less fundamental. But actually we know that, besides the electromagnetic interaction, there are at least two more gauge interactions, the weak and the strong, which are characterized by the charges g_w and g_s that have the same dimensionality as e. Besides the electron, there exist 15 more particles (5 leptons, 6 quarks, 1 photon, 1 gluon, and 2 weak bosons, not counting the anti-particles and the varieties of color). In viewing this diversity of charges and masses, e and m_e already do not appear to be the chosen constants for the role of the most fundamental constants.

Everyone who is even slightly acquainted with elementary particle physics does not doubt that $\hbar$ and c are certainly such constants, for each of them is unique and universal in its role. The velocity c is the limiting velocity for the propagation of physical signals. The constant $\hbar$ is the quantum of angular momentum and, what is no less important, it is the fundamental quantum unit of action. As far as the third fundamental constant is concerned, the opinion has gradually been building up among specialists (a consensus, as it is conventional to say now) that the Newtonian constant G of universal gravitational interaction or some kind of combination of the quantities G, $\hbar$, and c is the best candidate for this missing constant. The most popular of these combinations is called the Planck mass and is denoted by m_P.

As is well known, V_g is the potential energy of the gravitational interaction of two bodies with masses m which are located at a distance r from each other, and it equals

$$V_g = -Gm^2/r.$$

If one recalls that the potential energy of the Coulomb interaction of two charges equals

$$V_e = -e^2/r\,,$$

and allows for the fact that $\alpha = e^2\hbar c$ is a dimensionless quantity, then it is easy to understand that it is natural to represent G in the form

$$G = \hbar c/m_P^2,$$

where m_P is the so-called Planck mass introduced by Planck at the very end of the last century[5] by combining the constants $G, \hbar$, and c. The Planck length $l_P = \hbar/m_P c$ and Planck time $t_P = \hbar/m_P c^2$ were introduced in the same paper. Starting from the known value of G, it is easy to find that

$$m_P \approx 1{,}2\cdot 10^{19}\ \mathrm{GeV}/c^2,$$

$$l_P \approx 10^{-33}\ \mathrm{cm},$$

$$t_P \approx 10^{-43}\ \mathrm{sec}.$$

One often speaks of the Planck energy $E_P = m_P c^2$ and of the Planck momentum $k_P = m_P c$. The physical meaning of the Planck scale started to become clear considerably later.

The first detailed paper devoted to the c, G, and $\hbar$ system, "Universal constants and the ultimate transition" was published at the start of 1928 by G. Gamow, D. Ivanenko, and L. Landau.[6] (The first two authors were then 24 years old, and the last one was 20 years old. According to the testimony of one of the authors, the paper was written in the form of a joking birthday present to a female student acquaintance. Not one of them referred to this paper later on[2], although there are a number of profound ideas in it.)

At the start of the 1930s, M. P. Bronshteĭn gave a detailed classification of physical theories based on c, G, and $\hbar$ units, and used them to quantize gravity. He introduced the term $cG\hbar$-physics (M. P. Bronshteĭn was executed by shooting in 1938 in his 32nd year). Then L. D. Landau[7] and J. A. Wheeler[8,9] in the mid-1950s started to address the role of the Planck mass. This time the discussion was about whether, as one approaches Planck distances l_P or momenta k_P, the gravitational interaction must become comparable in strength with the other interactions, and significant quantum fluctuations must arise for it (G. Gorelik[10,11,12] discussed the history of this question in more detail).

At present, the Planck mass m_P, along with the constants $\hbar$ and c, is considered as a fundamental physical quantity, which characterizes the energy scale for theories of super-unification for all interactions, including gravitation. As is well known, superstring theory is considered to be the most promising direction for creating a super-unification theory (see the books by A. M. Polyakov[13] and M. B. Green, J. Schwartz, and E. Witten[14]). Instead of point particles, extended one-dimensional objects, "strings," which have characteristic Planck dimensions l_P, are the fundamental objects of this theory.

At the same time, the Planck scale with its characteristic time t_P forms the basis of quantum cosmology, of which the wave function of the universe is the fundamental object (see, for example, the books by C. W. Misner, K. S. Thorne, and J. A. Wheeler[15] and S. Hawking,[16] the papers by S. Coleman,[17] S. Weinberg,[18] M. Gell-Mann and J. Hartle,[19,20] the book and review by A. Linde,[21,22] and also the popular review by J. J. Halliwell[23]). One of the objectives of quantum cosmology is to understand how, in the process of the evolution of the early universe, the properties of particles and the vacuum were fixed.

One can express the dimensions of any physical quantity by the dimensions of length L, time T, and mass M. Starting from our worldly experience, one might expect that nature chooses fundamental length, time, and mass as three natural independent units. But nature decided otherwise: the limiting velocity of signal propagation c ($[c] = [L/T]$) *and the quantum of action* $\hbar$ ($[\hbar] = [ET] = [ML^2/T]$) acquired fundamental meaning.

In order to represent M. P. Bronshteĭn's ideas in graphic form, A. L. Zel'manov drew[24,25] in the 1960s a "physical theories cube" constructed on the three $1/c$, G, and $\hbar$ orthogonal axes (see Fig. 1). When one of the units goes to zero, a limiting transition into a plane occurs. For fixed values of $\hbar$ and c, it is already unimportant what the third fundamental unit is; mass, length, or the Newtonian constant G itself.

Today one usually replaces G by $1/m_P$ and speaks of physics on the Planck scales.

The physical theories cube, which is an integral part of modern physics folklore, is depicted in Fig. 2. Newtonian mechanics (NM), or more accurately, that part of it which does not take gravity into account, is located at the origin of coordinates. Above it is located non-relativistic (Newtonian) gravity (NG), to its right is quantum mechanics (QM), and in front of it is the Special Theory of Relativity (STR). A synthesis of the Special Theory of Relativity and quantum mechanics gives quantum field theory (QFT). A synthesis of non-relativistic gravity and the Special Theory of Relativity gives the General Theory of Relativity (GTR). A synthesis of quantum mechanics and non-relativistic gravity gives non-relativistic quantum gravity (NQG), a theory with respect to which it is not clear whether there exist objects which it describes (see below about this). And finally, the synthesis of all theories in the future may lead to a universal Theory of Everything (TOE, the English acronym for this theory).

The main achievements of twentieth century physics, which led to radical changes in the whole way of life of humanity, lie in the $\hbar c$ plane. And although we have traversed a

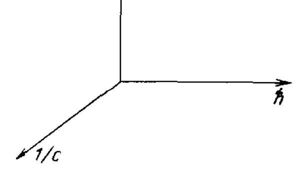

FIG. 1. The $1/c$, G, and $\hbar$ axes.

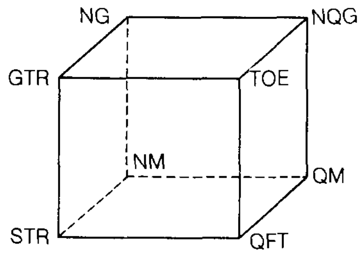

FIG. 2. The physical theories cube.

path from 10^{-8} GeV to 100 GeV along the energy axis, we are still 17 orders of magnitude away from the Planck mass. So that the energy layer investigated appears to be vanishingly thin on the Planck scale.

It is obvious that the well known charges e, g_w, and g_s are dimensionless quantities in $c\hbar$ units. One usually characterizes them by the dimensionless quadratic values:

$$\alpha = e^2/\hbar c, \quad \alpha_w = g_w^2/\hbar c, \quad \alpha_s = g_s^2/\hbar c.$$

According to quantum field theory, the charges of interacting particles change as a function of the distance between the particles (of the transferred momentum or energy). We know that, in the momentum interval from 0 to 100 GeV, α increases slightly, from 1/137 to 1/128, and α_s decreases sharply, from a value of the order of one (at confinement scales of $E \leqslant 1$ GeV) to ~ 0.1 for $E \sim 100$ GeV. As far as α_w is concerned, it is approximately constant in this interval, $\sim 1/30$, but must, in principle, change at higher energies. Extrapolation of the curves for all three "running" constants indicates that they all will "converge" at common values, that are appoximately 1/40 at energies from 10^{13} to 10^{16} GeV. The closeness of the energy for this grand unification to the Planck mass serves as one more argument for the latter being a natural fundamental energy unit in physics.

Let us now turn to masses. The mass scale for hadrons which consist of light u, d, and s quarks is mainly (but not only) determined by the characteristic confinement radius. The masses of hadrons which consist of heavy (c and b) quarks are mainly determined by the masses of these quarks. In turn, according to the hypothesis of Higgs bosons, the masses of quarks, just like the masses of leptons, are determined by the value of η, the vacuum condensate of a Higgs field, which is approximately 250 GeV. In its simplest variant, each of the masses is a product of the η values and of one of the constants which characterizes the interaction of one or another lepton or quark with a Higgs field. Such constants are called Yukawa constants; they have the same dimensions as do the e, g_w, and g_s charges and, consequently, they are dimensionless in units of $\hbar$ and c. (Let us note in passing that the mass of the W-boson is determined by the product of η and $\frac{1}{2}g_w$, and g_w is replaced by $g_w^2/\sqrt{g_w^2 - e^2}$ for the Z-boson).

The scheme outlined here for the origin of the masses is the very simplest one. Other, more refined schemes also exist. In some of them there are no Yukawa interactions at all, and they are replaced by complicated non-Abelian gauge structures (technicolor).

But what is an undoubted fact is that, at present, elementary particle theory contains over twenty dimensionless parameters which appear as arbitrary today. (The three angles and the phase of the Kobayashi–Maskawa matrix, which determines the interaction of weak quark currents and the violation of CP-invariance in weak interactions, are also among the arbitrary parameters. It is possible that an analogous but still more complicated matrix describes charged lepton currents with neutrino participation. The more complicated nature of weak neutrino interactions may be determined by the fact that not only Dirac, but also Majorana masses are possible for them.) At the modern level of science, it appears that we shall solve nothing in the structure of the theory by changing one or another of these parameters, although, of course, here the appearance of the universe that is described by it is radically changed.

Purely kinematic exercises with the velocity of light a la Mr. Tompkins are an extremely frivolous activity from the point of view of fundamental physics. (No wonder, according to the testimony of Z. Kazimir,[26] this activity "seemed to Bohr stupid rather than funny".) Also a discussion of the dynamical properties of a universe in which it is imagined that $c \to \infty$, but $\hbar$, e, and m_e remain unchanged is "rather stupid" from the point of view of the $cG\hbar$ system. But from this same point of view, the efforts of many years to construct a single theory of the gravitational and electromagnetic fields without taking the constant $\hbar$ into account certainly appear to be doomed to failure. In fact, not the dimensional quantity e, but the dimensionless α is the fundamental parameter of electrodynamics. (As is well known, classical electrodynamics becomes internally inconsistent at the distances which characterize the classical electron radius $r_0 = e^2/m_e c^2 \sim 10^{-13}$ cm, which are 20 orders of magnitude longer than the Planck distances $l_P \sim \hbar/m_P c \sim 10^{-33}$ cm.) The problem of constructing a single fundamental theory in one plane taken separately, be that $1/c \to 0$, $\hbar \to 0$, or $G \to 0$, is Utopian.

4. THE ANTHROPIC NATURE OF THE PHYSICAL UNIVERSE

The question as to whether all the dimensionless parameters in the final physical theory will be fixed by a condition of consistency, or if certain of them will remain arbitrary, is today a question of belief. It does not have a scientific answer at present. The word "arbitrary" means in this context that a given dimensionless parameter assumed its value in the process of the cosmological evolution of the universe at an early stage of it. Here, with a greater or lesser probability, it could have also assumed other values.

Even a fleeting glance at the arbitrary, "free" parameters, suffices to astonish one how favorable their values are for our existence. The elementary particle masses appear especially surprising on the Planck scale.

For example, the difference of the masses of the neutron and proton, $m_n - m_p$, is 1.33 MeV $\sim 10^{-22} m_P$. But if this difference were, let us say, 1 MeV less, the neutron would become stable, and the hydrogen atom, as I. L. Rozental' emphasized,[27-30] would be unstable:

$$e^- + p \to n + \nu_e.$$

The set of reactions $\nu_e p \leftrightarrow n e^+$ and $e^- p \leftrightarrow n \nu_e$, which determine the ratio between the numbers of neutrons and protons that are left to us as the legacy of primeval nucleosynthesis, would have, under these conditions, shifted the balance towards an equal abundance of protons and neutrons. As a result, not hydrogen, but helium atoms would have been the most abundant matter in the universe. And the entire evolution of the formation and burning of stars would be changed radically. They would have exploded rapidly. Life would have been impossible for many reasons. A small (~ 1 MeV) increase of the electron mass leads to analogously radical consequences.

Thus, the entire structure of the universe is extremely sensitive to small "disturbance" of the value of the electron mass and/or the difference of the masses of the proton and neutron, and essentially, to the difference of the masses of the u and d quarks. In fact, the neutron is heavier than the proton because of the fact that the *d* quark is heavier than the *u* quark ($m_d \sim 7$ MeV, $m_u \sim 5$ MeV). Let us note that, in the two other generations of quarks, unlike the first generation, the lower quarks (s,b) are significantly lighter than their upper partners (c,t).

Until now, we have discussed the sensitivity of our universe to values of the masses of the fundamental fermions, m_e, m_u, and m_d. The sensitivity to less fundamental quantities, such as the binding energy of the nucleons in a deuteron,[28] is even more remarkable. From experiment, $\varepsilon_d \sim 2.2$ MeV. A reduction of this binding energy by at most 0.4 MeV would lead to the situation that the main reaction for burning hydrogen in the Sun $pp \to de^+ \nu_e$ would turn out to be forbidden, and only the considerably less probable reaction $pe^- p \to d\nu_e$ could go on. Essentially, everything depends on the details of the nuclear forces between the nucleons which, from the point of view of quantum chromodynamics, are something like the "chemistry of strong interactions."

Another, even subtler example; this is the details in the situation of the energy levels of the ^{12}C and ^{16}O nuclei. The famous level of the carbon nucleus with an excitation energy of 7.65 MeV lies at most 0.3 MeV above the sum of the masses of the ^{4}He + ^{8}Be nuclei. The ^{8}Be nucleus is unstable, and therefore, without this level, which by resonance amplifies the cross-section of the $3(^4\mathrm{He}) \to {}^{12}\mathrm{C}$ reaction, carbon would be formed considerably less efficiently than it would be burned up in the reaction $^{12}\mathrm{C} + {}^4\mathrm{He} \to {}^{16}\mathrm{O} + \gamma$, and the universe would be so poor in carbon that life would hardly have arisen. Arguments of just this kind led Fred Hoyle to his prediction at the start of 1953 of the existence of the 7.65 MeV level and to his discovery of it in cooperation with experimenters at the California Institute of Technology about a week later. (The history of this discovery has been very clearly described by Hoyle in the symposium "*Essays in Nuclear Astrophysics: Dedicated to W. Fowler on His Seventieth Birthday,*"[31] and the astrophysical role of the energy levels of ^{12}C and ^{16}O has been described in Hoyle's book "*Galaxies, Nuclei, and Quasars.*"[32]) When you look at the energy level diagram for the ^{12}C nucleus (there are about 30 of them in an interval of the order of 30 MeV; see Ref. 33) and you see the first three levels at 4.43 MeV, 7.65 MeV, and 9.64 MeV, then a feeling of profound gratitude captures the spirit for the 7.65 MeV level, and for the fact that it was not lowered by 0.5 MeV. What a small safety factor for all which is dear to us!

One more example was indicated by F. Dyson,[34] who noted that the presence of even a weakly bound state for two protons, i.e., for the ^{2}He nucleus also would have had a decisive effect on the entire development of the universe. One could multiply examples such as these many times. But what do small changes of the nuclear forces mean from the Planck point of view?

If a Grand Unification Theory is valid, then the characteristic confinement momentum Λ_{QCD} (the inverse confinement radius) is related to the Grand Unification characteristic momentum Λ_{GUT} by the relation

$$\frac{1}{\alpha_s(\Lambda_{\mathrm{GUT}})} - \frac{1}{\alpha_s(\Lambda_{\mathrm{QCD}})} \approx \ln\frac{\Lambda_{\mathrm{GUT}}}{\Lambda_{\mathrm{QCD}}}.$$

(The missing coefficient, which is of the order of one, in front of the logarithm is determined by the contribution of particles with color. If one does not take into account superparticles and other hypothetical particles, but allows for only the ordinary gluons and quarks, then it equals $7/2\pi$). If we now neglect $1/\alpha_s(\Lambda_{\mathrm{QCD}})$, which is of the order of one, in comparison with $1/\alpha_s(\Lambda_{\mathrm{GUT}})$ which, as was already stated above, is of the order of 40, then a simple relation is found

$$\Lambda_{\mathrm{QCD}} \sim \Lambda_{\mathrm{GUT}} e^{-1/\alpha_s(\Lambda_{\mathrm{GUT}})}.$$

We see that a decrease of $\alpha_s(\Lambda_{\mathrm{GUT}})$ by half, from 0.02 to 0.01, decreases Λ_{QCD} by 17 orders of magnitude. It is sufficient to decrease $\alpha_s(\Lambda_{\mathrm{GUT}})$ by at most 10% in order that Λ_{QCD} be decreased by a factor of 10, and that the masses of the nucleons would already be determined not by Λ_{QCD}, but by the current masses of the light quarks. Allowing for the fact that $m_u \sim 5$ MeV and $m_d \sim 7$ MeV, we would have $m_p \sim 17$ MeV and $m_n \sim 19$ MeV.

Here, perhaps, the time has arrived to speak of the comment of J. Sal'vini, who pointed out that, if the masses of nuclei and electrons were comparable, there could be neither crystals nor solid bodies, and consequently, also, no classical instruments of quantum mechanics. The question of its probabilistic interpretation does not even arise here, although all the dynamic consequences of quantum mechanics remain. A small disturbance of the "free" parameters would lead to a situation that not only physicists, not only all live creatures such as we know them, but also individual chapters of physics textbooks would fall through into Tartarus.[3)]

5. THE ANTHROPIC PRINCIPLES

Along with the already mentioned "lucky accidents," there are many others, which are associated with the evolution of the Milky Way and of stars.[36-39] Thus, crude dimensional estimates show that the lifetime of an ordinary star, in whose interior the carbon, nitrogen, oxygen, and heavier elements that are necessary for life are created, must be of the order of $(\hbar/m_p c^2)(\hbar c/G m_p^2)^2$. This time is sensitive to the ratio $G m_p^2/\hbar c = m_p^2/m_P^2$, which one often denotes in the literature as α_G by analogy with α_e, α_w, and α_s. (Let us note that the designation α_G does not seem fortunate, since in this case the discussion is not about the magnitude of a gravitational charge, but about the magnitude of the proton mass. In fact, the magnitude of G is a fundamental dimensional unit in the $cG\hbar$ units. But the use of the designation α_G supposes that the proton mass m_p, and not the Planck mass m_P, is the fundamental unit of the dimensionality of mass.)

An enormous literature is devoted to the anthropic nature of the universe. P. C. W. Davies' book "*The Accidental*

Universe"[40] may serve as a good popular introduction. The most complete book on this theme is the one by J. D. Barrow and F. J. Tipler, "*The Anthropic Cosmological Principles*"[41]; it contains over 700 pages, over 1,500 references, and it covers diverse aspects from physics, astrophysics, cosmology, biochemistry, biology, and computer science to history, philosophy, problems of extraterrestrial civilizations, and religion.

The anthropic properties of the universe led to the formulation of a number of hypothetical (speculative) principles.

The weak anthropic principle starts from the idea of an ensemble containing an infinite number of universes. The *a priori* probability of creating an anthropic universe is vanishingly small. But this small value has no bearing on the subject, since the *a posteriori* probability is significant. It follows from the fact of our existence that we are not able not to live in one of the "very best of universes."

An infinite network of universes, each of which generates innumerable daughter universes in its early inflationary stage, is the theoretical realization of this statistical ensemble. Not only different symmetry breaking schemes, but also different numbers of space-time dimensions can be realized in each of them. However, an infinite variety of values for the dimensionless free parameters turns out to be possible even for a given number of space-time dimensions and for a given symmetry breaking scheme. Ya. B. Zel'dovich[42] made a contribution to the anthropic principle in its weak form. A. D. Sakharov returned to it many times in his publications. Thus, he wrote in Ref. 43: "Some authors consider the anthropological principle to be unfruitful and even not in accord with the scientific method. I do not agree with this. In particular, I note that the requirement that the fundamental laws of nature apply under conditions that are significantly different from those in our universe can have heuristic importance for finding these laws."

A discussion of the anthropic principle within the framework of the inflationary universe is contained in papers by A. Linde.[21,22]

In the context of an infinite abundance of variants, it no longer seems so surprising that at least one turned up in which intelligent life capable of knowing the universe is possible.

It is important to emphasize that, notwithstanding the fundamental impossibility of transmitting information from one universe into another one, they all (on paper) are "children" of one "primeval Lagrangian" with the same dimensional fundamental units: c, G, and $\hbar$.[4)]

In contrast to the weak principle, the strong anthropic principle states that the universe must necessarily be constructed so as to provide for the possibility to know itself. A number of different formulations of the strong principle exists, which are discussed in detail in the book by Barrow and Tipler. It is possible that all its broken symmetries and all values of the free dimensionless parameters are fixed by a self-consistency condition for this unimaginably complicated nonlinear system. (L. Maiani expressed this point of view.)

6. IN WHAT IS THERE HOPE?

The questions which arise in connection with the anthropic principles are immeasurably more complicated than the questions that are solved by modern elementary particle physics. The strength of physics in general, and of fundamental physics in particular, be that high energy physics on colliders or the physics of subterranean, low-background laboratories, lies in the capability to find and solve questions which lend themselves to solutions. As I. Pomeranchuk once said in the studio of the sculptor Vadim Sidur: it is important, both in creating sculptures and in solving a physical problem, to understand and to feel what one can neglect.

Can one, by making finite, local steps, arrive at a comprehension of very profound global (or, more accurately) universal truths, in which nothing may be neglected? A comparison of the part of the energy scale accessible to experimental investigation (with a realistic prospect for $\leqslant 10^5$ GeV) with the Planck energy scale $\sim 10^{19}$ GeV which is the natural one for a Theory of Everything and seemingly symbolizes the tragic gap between the ideal and reality in twentieth century physics, can cause an especially strong attack of pessimism. The confusion is also brought about by the fact, that the number of particles which remains to be discovered in the TeV range is no less than the number of fundamental particles already known. So that it seems that, at least in the immediate future, we shall move towards an ever larger variety of the fundamental building blocks of matter.

However, progress in creating a unified picture in modern fundamental physics is characterized not so much by a decrease in the number of fundamental particles as by a decrease in the number of "free" parameters. The establishment of a theoretical quantitative relation between dimensionless parameters, which previously were independent, raises physics to a new, higher level of unity. The scope of phenomena that are described from a unified point of view is greatly expanded here. The creation of the modern standard model for the electroweak and the strong interactions was the most recent such stage.

It is interesting to compare theoretical physics with mathematics. In mathematics, along with the seeming unbounded process of growth and branching, there also occurs a process of synthesis, when by the effort of pure reason, profound relations are established between fields and concepts that seem distant at first glance.

In theoretical physics there are also processes of differentiation and integration. But here experiment and the observation of nature also play a very important role. They throw the seeds of new theoretical sprouts into the ground, they stimulate the growth of some theoretical phantasies and mercilessly weed out others.

We have great expectations from experiments on future TeV colliders. Of course, much may be discovered on machines that are already operating: the t quark, light Higgs bosons, and the very lightest of the supersymmetry particles. But only TeV colliders can reveal the entire richness of scalar and supersymmetry particles, can give a hint as to how particle masses are constructed, and can sharply reduce the number of free parameters of fundamental physics.

Data on the current constants α_s, α_w, and α_1 (the last one is a combination of α and α_w) are a clear example of how TeV physics could serve as a launching pad for very far-reaching extrapolations in energy. As Ugo Amaldi recently emphasized,[44] data obtained on the LEP accelerator indicate that, with the known set of particles, these current constants do not meet at a single "triple" point, but at three "double" points at 10^{13} GeV, 10^{14} GeV, and 10^{16} GeV. At the same time, as J. Ellis, S. Kelley, and D. V. Nanopoulos noted,[45] allowance for the supersymmetry partners of the ordinary particles focuses all three curves at one point at 10^{16} GeV. Immediately there are two corollaries of this result. The first one refers to the fact that the supersymmetry particles mentioned must be light with masses not greatly exceeding 1 TeV. Otherwise, the curves of the current constants will acquire break points, and the focusing will be disrupted. And the second one is that new detectors for searches for proton decay that are orders of magnitude more massive than previous detectors are needed.

Experiments with neutrinos, especially with solar neutrinos, may turn out to be another invaluable source of fundamental data, since specifically, they are especially sensitive to small differences of mass and to small angles of mixing of the different types of neutrinos.

The solution of the problem of dark matter in the universe may turn out to be an unexpected gift.

Of course no imaginable accelerators will enable either us or our descendants to reach Planck energies. But it is not impossible (and keeping in mind the just considered example of extrapolating the three current constants it is even plausible!) that the exponential inaccessibility for experimenters is one side of a coin, the other side of which is the logarithmic accessibility for theoreticians. In fact, perhaps it will turn out to be sufficient for theoreticians to analyze and understand only the exponents that are expressed by only two-digit numbers.

If in the next few decades we succeed in sorting out the physics of phenomena up to TeV energies, then this may prove to be a sufficiently broad base platform for examining by a mental effort many details of physics at Planck energies. In fact, the astronomical distances to celestial bodies have not hindered studying them in more detail than the interior of our own planet. Yes, and helium was first discovered on the Sun and not on the Earth.

In speaking of theoretical "insight," one must not forget the intensive process of synthesizing theoretical physics and mathematics, as a result of which new fields of mathematics are created. Ideas of beauty or simply beautiful ideas also can perform an important role (see the remarks above on mathematics).

It is appropriate to conclude this section with the following remark. For many years, the early universe was considered by theoretical physicists as a natural Planck laboratory. If, however, the temperature of the universe after inflation never exceeded values of the order of 1 TeV, as many cosmologists are inclined to think,5) then, as a result of inflation, the "Planck laboratory" receded exponentially far beyond the horizon. And the next generation of supercolliders may tell us more about the early universe than do astrophysical observational data. And the detection of proton decay by the next generation of subterranean detectors would give information about energies that are absolutely inaccessible to observational cosmology.

7. MENTAL EXPERIMENTS. IS THE PLANCK SCALE NOT A MIRAGE?

From the definition of the Planck mass, it follows that the gravitational interaction between two particles, each of which has a Planck mass and a unit electric charge e is 137 times stronger than the electromagnetic interaction between them. But just by itself, this still does not mean that the gravitational interaction for such particles actually becomes strong: in fact, they may be located fairly far from each other.

The gravitational attraction will become actually strong when the distance between the particles is decreased so much that the interaction potential will become comparable with their rest mass energy:

$$Gm_P^2/l_P = m_P c^2.$$

Keeping in mind that $G = \hbar c/m_P^2$, we find $l_P = m_P c$ for the Planck length. In this case, the quantum fluctuations of the gravitational field are of the order of magnitude of the field itself. We come into the quantum gravity region. In order that such a situation be realized, it is necessary that the dimensions of the particles themselves be no larger than l_P.

The differential cross-section for elastic gravitational scattering $d\sigma/dq^2$ for two energetic point particles is of the order of

$$d\sigma/dq^2 \sim G^2E^4/q^4,$$

where E is their energy in the center of mass system, and q is the transferred momentum (units of $c = 1$ and $\hbar = 1$ are used). For $E \sim q \sim m_P$, the cross section $d\sigma/dq^2 \sim 1/m_P^4$, and the unitarity of the amplitude is saturated in the s-wave. However, the formation of a black hole becomes important at such energies and transferred momenta. Already John Michell[51] (in 1784) and Pierre S. Laplace[52] (in 1796) spoke of black holes.6) At $r < r_g = 2Gm/c^2$, the potential energy of the gravitational attraction for a photon "attempting" to escape from a body with mass m and a radius smaller than r_g is larger than its kinetic energy.

The smaller is the mass of the body, the smaller is its gravitational radius r_g. For such astronomical objects as ordinary stars, $r_g \ll R$, where R is the star's radius (for example, for our Sun, $r_g \approx 3$ km). If, as a result of evolution, a mass of the order of the solar mass is concentrated in a region with a radius smaller than r_g, then a black hole arises. Such black holes arise during the explosions of supernovae.

If one imagines a system consisting of two identical black holes which are located at a distance from each other of the order of r_g, then the potential energy of their attraction would equal

$$\frac{Gm^2}{r_g} \sim \frac{Gm^2c^2}{Gm} \sim mc^2,$$

and the gravitational field strength (force) is

$$\frac{Gm^2}{r_g^2} \sim \frac{Gm^2c^4}{G^2m^2} \sim \frac{c^4}{G} \sim \frac{c^3m_P^2}{\hbar},$$

i.e., it would be characteristically Planckian. Thus, one can obtain the Planck strength of a gravitational field in a mental experiment with two macroscopic black holes. However this field would be classical; its fluctuations on the Planck scale would still be small.

If there existed particles with $m \sim 0.01m_P$ to $m \sim 0.1m_P$, then the gravitational attraction between them would lead to the formation of atom-like quantum systems, in which their motions would be non-relativistic. These systems would be described by non-relativistic quantum gravity (see Fig. 2). The present concentration of such particles must not significantly exceed $\sim 10^{-16}$ of the concentration of ordinary hydrogen. Otherwise they would already make an unacceptably large contribution to the mass of the dark matter. The detection of such particles is a very difficult task.

In particle physics, the Planck scale could turn into a mirage if the particles (including the graviton?) had intrinsic sizes l such that $l \gg l_P$. In this case the Planck sizes would, even in principle, be unattainable in particle interactions. A large number of papers (see the books of Ref. 53, the popular science paper by A. D. Sakharov,[54] and several recent theoretical papers[55]) are devoted to attempts to construct a non-local field theory. However, no one has succeeded in constructing a consistent fundamental non-local field theory (truly, and not phenomenologically, non-local): casuality is violated. In this sense, the quest for internal consistency of the theory drives us to Planck distances.

A good mental experiment for thinking out how non-locality would affect gravitational interaction is the collision of two particles with a specified impact parameter $l \gg l_P$ and with such high (super-Planck $E \gg m_P c^2$) energies in the center of mass system that $G(E/c^2)^2/l \sim E$. After approaching to the distance l, these particles would form a black hole.

A. D. Sakharov wrote in Ref. 54: "At present, more and more physicists are leaning towards the position that specifically the boundary L_0 will determine the most significant changes in our ideas.

It is nevertheless very important to become convinced that no intermediate characteristic length between $r = 2.8 \cdot 10^{-13}$ cm and $L_0 = 1.61 \cdot 10^{-33}$ cm plays such a fundamental role.

8. CONCLUSION

In the main stair landing of the Physics Department of the University of Padua, the university at which Galileo Galilei lectured in his time, hangs a marble slate with his words which, translated into English, sound approximately so:

"In my opinion, it is better to find the truth if only in a small matter than to argue at length about very great questions without having obtained any truth at all."

These words of Galileo[56] express the credo of every professional physicist. But what, besides purely subjective reasons, impelled me to violate the precept of Galileo? I think that, first of all, it is that the experimentally inaccessible Planck mass occupies a larger and larger place in physics with every year. This forces one to look for in some sense a metaphysical frame for a physical picture of the universe.

In 1918, A. S. Eddington,[57] following Planck in emphasizing that, of all the physical systems of units, the *cGħ* system is absolutely the preferred one, noted that the Planck length "must serve as the key to some very significant structure." Several years later, in his excellent in all remaining respects book "*Dimensional Analysis*," P. W. Bridgman,[58] after ridiculing this statement, declared that these units have no relation to real physics. By the way, the first and last Russian edition of this book appeared almost 60 years ago, and it would be very useful to reprint it. But as far as disputes with Eddington and Planck go, the pan of the balance moves steadily in their direction. Even within ordinary astrophysics the Planck units are accepted in our time as the natural ones (see the book by É. Dibai and S. Kaplan[59]).

Over the time of working on this paper (August 1990 to May 1991), I discovered that a number of ideas, which I had at the start or which occurred to me in the course of the work, had been published earlier by other authors. So that only certain details, accentuations, comments, and comparisons are properly mine.

The idea of the plurality of universes has been discussed in the scientific literature since the times that scientific literature itself appeared.[60] Many striking words have been said about it. I should like to quote the words with which the Nobel Lecture by Andreĭ Dmitrievich Sakharov[61] is concluded:

"I also defend the cosmological hypothesis, according to which the cosmological development of the universe is repeated in its main features an infinite number of times. Here other civilizations, including more "successful" ones, must exist an infinite number of times on the pages of the Book of the Universe "preceding" and "following" our universe. But all this must not belittle our holy quest specifically in this universe, where we, like a flare in the darkness, arose for one instant from the black void of the unconscious existence of matter, to achieve the requirements of Reason and to create a life worthy of ourselves and of The Purpose that is vaguely guessed by us."

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[1] At first glance, the statement that the interaction of photons with matter vanishes seems to contradict the circumstance that the cross section for the resonance scattering of light increases as λ^2. However, with the enormous lifetime and vanishingly small width of a resonance line, it is practically impossible to get into resonance.

[2] If one leaves out of consideration the indirect reference of Mr. Tompkins' initials: C. G. H.

[3] Let us note that the binding energy of an electron in a positronium ion is ~ 0.2 eV, and the binding energy of a molecule consisting of two positronium atoms is ~ 0.1 eV (for example, see Ref. 35). So that a condensed state of them could exist at very low temperatures in the case when $m_e = m_p$.

[4] However, in the case of universes absolutely isolated from each other, the statement about the generality of the dimensional units c, G, and $\hbar$ does not have operational meaning. If one imagines a universe in which the values of c, G, and $\hbar$ expressed in our grams, centimeters, and seconds are different than for us, but all the dimensionless parameters which we discussed above are the same as for us, then all of physics in that and in our universes will be indistinguishable. Of course, their grams, centimeters, and seconds will be different from ours, but the numerical values of c, G, and $\hbar$ expressed in their grams, centimeters, and seconds will be the same as for us.

[5] At a temperature of the order of several TeV a phase transition occurred in which the baryon asymmetry of the universe[46-50] was apparently formed in final form.

[6] In the appendix to the Russian translation of Pierre Simon Laplace's book "*Exposition du Systeme du Monde*,"[52] the translator quotes the following statement by Laplace: "A shining star with a density equal to that of the Earth and with a diameter 250 times larger than the Sun's diameter will not allow a single light beam to reach us because of its gravity; therefore, it is possible that the most luminous celestial bodies in the universe turn out to be invisible for this reason." It is only strange that the quotation is given with a somewhat unusual reference: the newspaper "*Leninskaya Pravda*," the edition of December 21, 1980.

7) Of course, the reference list lays no claim to be either a complete or even a well thought out selection. These are simply those books and papers which I used, read or scanned during my work on this paper. Those pages or paragraphs which have a direct bearing on the questions that I have discussed are marked for some references.

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