ELEMENTARY PARTICLES OF MAXIMALLY LARGE MASSES (QUARKS AND MAXIMONS)

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In a field theory including the theory of gravitation (both classical and quantized), there occur some expressions for characteristic masses: $m_0 = (\hbar c/\kappa)^{1/2}$, $m_1 = e/\kappa^{1/2}$. An attempt is made to consider these mass values as upper limits for possible masses of elementary particles (maximons). These mass values have the remarkable property that only for such extreme values of particle masses does a specific mechanism appear (gravitational collapse of small masses) which allows the formation of systems of arbitrarily small masses from maximons. The peculiarities of these particles and their possible relation to quarks are discussed.

THE well known paper of Fermi and Yang[1] was the first to propose the idea that the pion may be regarded as a system consisting of a nucleon and antinucleon with a mass defect larger by one order of magnitude than the mass of the resulting system (the pion). This idea has attracted the attention of many authors and has been widely used in the development of various model representations,[2] mainly for hadrons (strongly interacting particles). As these model representations were developed, the mass of the fundamental particles increased, first to hyperon masses, and more recently, in connection with the quark concept, masses one order of magnitude higher were considered for the fundamental particles.

The latter mass values of the fundamental-particle masses are usually considered as experimental lower bounds, since there are no theoretical boundaries (like fundamental lengths) in this region of mass values.[1)] If one makes use of the general theory of relativity (gravitation), one can form two expressions with the dimension of a mass out of the universal constants. One of these combinations is characteristic of quantum theories:

$$m_0 = (\hbar c / \varkappa)^{1/2} \sim 10^{-5} \text{ g} \qquad (1)$$

($\hbar$ is the Planck constant, κ is the gravitational constant, c is the velocity of light); the other mass belongs to the classical domain:

$$m_1 = e / \varkappa^{1/2} \sim 10^{-6} \text{ g} \qquad (2)$$

(e denotes the electric charge).

As will be seen in the sequel, a certain interest attaches to consideration of expressions (1) and (2) as candidates for the mass of a fundamental particle of "quark type." In [3] such particles of maximally large mass were called maximons to distinguish them from quarks, from which they may, in general, differ in some of their properties (cf. Secs. 3 and 4).

1. THE MASS $m_0 = (\hbar c(\kappa)^{1/2}$

One can assume that the appearance of the expression (1) and of the associated length

$$\hbar / m_0 c = l_0 = (\hbar \varkappa / c^3)^{1/2} \sim 10^{-33} \text{ cm} \qquad (3)$$

in the theory is not at all accidental and that the l_0 represents actually a fundamental length, such that distances smaller than l_0 are devoid of physical meaning owing to quantum fluctuations of the metric. Thus one might interpret m_0 as the actual upper limit for the possible values of the masses of fundamental particles under consideration ($m_0 > m_1$).

But it may be that it is more essential that at such mass values, localized in the region of the fundamental length l_0, a completely new mechanism starts functioning, namely a mechanism capable of ensuring that the mass of the resulting composite system of maximons is arbitrarily small. We have in view here the phenomenon of gravitational collapse (Sec. 2), which is possible for small masses realized with high densities.

[1)]The nearest length which could be considered is the one associated with weak interactions: $l = (G/\hbar c)^{1/2} \sim 0.7 \times 10^{-16}$ cm. But, as will be shown below, one can indicate considerably smaller lengths. The smallest among them is the most universal.

A particle of mass m_0 localized in the region l_0 exhibits several specific properties.[3] Two maximons of mass m_0 interact gravitationally as follows

$$\varkappa m_0^2 / r = \hbar c / r. \tag{4}$$

In other words, the gravitational interaction of two maximons is $\hbar c/\epsilon$ times larger than their Coulomb interaction, if the electric charge of the maximon is ϵ.

Thus, two maximons of electric charge $\epsilon < (\hbar c)^{1/2}$ will form a bound system. The "Bohr radius" of this system, estimated from the Heisenberg uncertainty relation, turns out to be

$$r_0 \sim \hbar^2 / \varkappa m_0^3 = l_0. \tag{5}$$

The estimate (5) shows that the dimensions of the bound systems under consideration have to be such that the corresponding gravitational defect is of the order of the maximon masses:

$$\Delta mc^2 \sim \varkappa m_0^2 / l_0 = (\hbar c / \varkappa)^{1/2} c^2 = m_0 c^2. \tag{6}$$

The estimate (6) has a qualitative character only, it is only indicative of the enormous mass defect which necessarily appears in such systems. But what is more essential is the fact that the gravitational collapse of such a system is an unavoidable result.

2. GRAVITATIONAL COLLAPSE FOR SMALL MASSES

Under collapse conditions the whole energy is gravitationally enclosed in a region of radius $r_{gr} = 2\kappa m/c^2$ with average mass density

$$\rho \geqslant \frac{m}{{}^4/_3 \pi r_{gr}^3} = \frac{3}{32\pi} \frac{c^6}{\varkappa^3 m^2}. \tag{7}$$

Thus, the smaller the mass, the larger the density which is necessary for the realization of a collapsing state. A collapsing system consisting of two maximons ($m = 2m_0 = 2(\hbar c/\kappa)^{1/2}$) must have an average mass density

$$\rho \geqslant \frac{3}{32\pi} \frac{c^5}{4\varkappa^2 \hbar}.$$

But according to Eqs. (6) and (7), the system under consideration must have linear dimensions $\leq l_0$, i.e. a density

$$\rho \sim 3c^5 / 2\pi \varkappa^2 \hbar, \tag{8}$$

and the system consisting of two maximons must be in a collapsing state. The latter circumstance does not add anything essentially new to the arguments of the preceding section. However, it is important for the sequel that a collapsing system may possess an arbitrarily small mass.

Ya. B. Zel'dovich[4] has considered the example of an ultrarelativistic gas when the particle density n and the density ρ of matter, initially at rest, are related through the equation of state

$$\rho = {}^3/_4 \hbar (3\pi)^{1/3} c^{-1} n^{4/3}. \tag{9}$$

For the mass M of this system and for the total number N of particles the equations become, respectively

$$M = 4\pi \int_0^R \rho(r) r^2 dr, \tag{10}$$

$$N = 4\pi \int_0^R n\, dV = 4\pi \int_0^R n(r) e^{\lambda/2} r^2 dr. \tag{11}$$

The invariant volume element is $dV = 4\pi \times [\exp(\lambda/2)] r^2 dr$. The distribution ρ is chosen such that

$$\rho = a / r^2, \quad r < R; \qquad \rho = 0, \quad r > R, \tag{12}$$

where a is an arbitrary constant. On the basis of Eqs. (9), (10) and (12) there appears an expression for M in the form

$$M = \mathrm{const} \cdot N^{2/3} (\hbar a)^{1/2} (1 - 8\pi \varkappa c^{-2} a); \tag{13}$$

where $a \to c^2/8\pi\kappa$, the mass $M \to 0$ for arbitrary N.

It is essential that it be possible to obtain a configuration of particles, such that their total mass can become arbitrarily close to zero, independently of the number of particles. In order to reduce ordinary matter, e.g., neutrons, to such a state it is necessary to spend an enormous amount of energy to compress matter to the desired densities. This energy barrier that separates the equilibrium state from the collapsing state is estimated by Zel'dovich at

$$M_{max} \sim N^{2/3} (\hbar c / \varkappa)^{1/2}. \tag{14}$$

According to (1), the latter expression can be rewritten as

$$M_{max} \sim N^{2/3} m_0. \tag{15}$$

This means that in order to bring a system consisting of a small number of neutrons into a collapsing state it is necessary to spend an energy per neutron of the order of the self energy of the maximons $(\hbar c/\kappa)^{1/2}$. This means that for particles of mass $m_0 = (\hbar c/\kappa)^{1/2}$ (maximons) there does not exist an energy barrier for the transition into a collapsing state.

We see that for a mass $m_0 = (\hbar c/\kappa)^{1/2}$ there appears indeed in a natural way a specific mechanism for a system of two particles, which in principle can give rise to a resulting system of arbitrarily small mass.

The preceding considerations suffer from one more serious defect: the relations (1) and (3) exist because of the Planck constant, whereas the collapse of the systems, which develops in the region of quantum fluctuations of the metric, has been considered on the basis of classical theory. What is more important, the possible states of the resulting system are also considered on the basis of classical theory. At present there does not exist a quantum theory of the collapse of small masses. One might assume, for instance, that the final states of the systems consisting of maximons will turn out to have discrete mass values. It is natural to assume that the entire process of quantum collapse of masses will have the character of quantum transitions into these discrete states.

As is well known, a realistic quark model of hadrons assumes the existence of an as yet unknown type of forces which lead to the binding of the quarks (i.e., of particles with large, but as yet unknown masses: $m_q > m_N$) into systems that represent the baryons, pions, and other quanta of the nuclear fields. The question arises: to what extent the maximons could pretend to play the role of quarks, and at the same time the proposed mechanism (collapse) could play the role of a mechanism binding the maximons into the particles which we observe?

3. MAXIMONS; QUARKS, AND PARTICLE HIERARCHY

As follows from the preceding discussion, in distinction from the quark idea, the idea of the existence of maximons is in no way related to group-theoretical symmetry concepts. Maximally heavy fundamental particles of the type under consideration must naturally (owing to quantum fluctuations) appear in any matter which is in a superdense state.

Such a superdense state of matter is assumed as an initial stage of the development of the Universe according to the Friedmann model, which seems to be the most acceptable cosmological model in the light of present astrophysical and astronomical data. If one adopts this model of the Universe, assuming that at some initial time a state of maximal matter density (more correctly, with a density close to $\rho \sim c^5/\kappa^2\hbar$) is realized in the Universe, then the formation of maximons seems unavoidable. Situations in which matter localized in a region of space of dimensions l_0 and matter density m_0/l_0^3 gravitationally collapses into maximons should also be unavoidable.

Since the maximons are collapsing blobs of matter and could be formed out of any kind of matter, such maximons could, in principle, exhibit different properties. For instance, they could be strongly interacting or not, weakly interacting or not, electrically neutral or charged, etc.[2)] Consequently, in order to discuss the properties of the maximons and their possible role in the hierarchy of particles it is necessary to introduce a hypothesis about the type of matter which was present at the initial stage of development of the Universe.

One could, of course, assume (as is often done) that in the first stages of development of the Universe, matter does not differ radically in its properties from those forms of matter which we know, i.e., is capable of strong, weak and electromagnetic interactions. But it is also admissible to assume that at the initial stage the matter of the

[2)]Throughout this paper the term maximon is sometimes used in the sense of a "genuinely elementary" particle and sometimes for a collapsing system, consisting for example of neutrons, i.e., in the sense of a composite system. This circumstance reveals the possibility of considering the various interpretations of such a particle as a maximon.

It is also impossible to exclude the possibility that for such large densities the differences in the properties of the initial matter disappear, or are "averaged out" in a peculiar manner within the maximons (including the possibility of the appearance of parastatistics), under conditions of a wide variety of forms of matter (Fermi and Bose matter) which can simultaneously be brought to the superdense state, for example in a periodic manner (oscillating Universe). Conversely, the system of these maximons could also determine in a model approximation (in the quark sense) the properties of these same nucleons. It must be said that in present day quantum theory the past simple concept of a "genuinely elementary particle" has been lost. For example, the conception of the neutron cannot be separated from that of the pion. Moreover all fields (particles) contribute to the image of the neutron and vice versa. These mutual and "feedback" (bootstrap) relations are characteristic for the present conceptions about the nature of "elementary" particles.

The general theory of relativity provides further fantastic possibilities for the discussion of the "feedback" (bootstrap) relations among "composite" and "elementary" particles. It sufficient to remember that a "slightly" non-closed Universe of total mass equal, for instance, to the mass of the neutron (the total mass of a closed Universe is well known to be zero) should manifest itself in experiments carried out by a Schwarzschildian observer as a particle of small mass (of the order of neutron mass) and small radius (cf. the author's talk at the Yalta Spring School of Physics, April, 1965).

Universe possessed more elementary properties.

If one attempts to express more formally the ideas leading to the maximon idea in the language of theoretical physics, one should start from the Einstein equation

$$R_\mu{}^\nu - {}^1\!/_2 g_\mu{}^\nu R = -\varkappa T_\mu{}^\nu, \qquad \text{(I)}$$

which describes the gravitational field created by matter. In this equation matter is represented by the tensor T_μ^ν. This tensor is a function of the fields $\psi, \psi_1, \ldots, \psi_n$, which characterize matter in the Universe. If, following Heisenberg, or simply selecting the most elementary example, one limits oneself to a Universe filled by a single spinor field ψ, the Dirac equation for this field in curved space

$$D\psi = 0, \qquad \text{(II)}$$

together with the Einstein equation, form a complete set of equations describing the physical world under consideration. Eliminating the gravitational field $g_{\mu\nu}$ from the two equations, we should arrive at a highly nonlinear equation for the ψ-field. According to the preceding considerations one could expect this equation to admit of particle-like solutions of maximon character.[3)] The question further arises: to which manifolds of particle-like solutions form systems consisting of maximons, and what relation such objects have to the observed hierarchy of real elementary particles?[4)] Unfortunately, at the present stage of purely qualitative consideration of the possibility of a maximon structure of, say, hadrons, one can point only to isolated considerations in favor of, as well as against such a possibility. In particular one can indicate in which respects the maximons could differ from quarks.

At the present stage of consideration of the properties of maximons we have no arguments in favor of the fact that nucleons, for instance, are necessarily formed out of three electrically charged maximons. If convenient, such a possibility can only be postulated for the time being. At the present stage, no objections can be found against the assumption that maximons possess gravitational and electromagnetic interactions, but certain difficulties appear if one assumes that the maximons are particles capable of interactions via nuclear forces. Here we have in mind an essential distinction between the properties of maximons and those of quarks, which are assumed to be capable of nuclear interactions.

The arguments on which the preceding assertion is based are the following:

In order to construct electrodynamics, one can admit very small fundamental lengths, and the applicability of electrodynamics up to lengths of the order of l_0 does not lead to any internal contradictions (weak logarithmic divergences).

The situation is quite different if the nuclear forces are acting at distances l_0 without any change in their strong functional dependence on the distance. It is well known that such small distances are incompatible with the theory of strongly interacting fields.

If maximons do not exhibit nuclear interactions, this may have the following implications:

a) Hadrons are not formed out of maximons. Maximons exist as elementary particles in addition to the other elementary particles, for instance quarks.

b) Conversely, hadrons (e.g., nucleons) are formed out of a system of maximons, specifically in the process of gravitational collapse, as discussed above.

The latter hypothesis could imply that nuclear forces occur only in complex maximon systems (in the manner of van-der-Waals forces in molecules). This would mean, that in distinction from gravitational forces, and maybe from electromagnetic forces, the nuclear forces are not fundamental forces.

The question arises as to how characteristic nuclear lengths ($\hbar/m_N c$) can, in principle, appear in a system of collapsing particles with dimensions l_0.[5)] Making more concrete the possibility

3)In a rough classical approximation such a solution could pictorially be represented as a limiting state of a wave packet consisting of spherical waves of wavelength $\lambda \sim l_0$ as $t \to \infty$. We think of a packet for which the energy is gravitationally enclosed in a region of radius l_0. But the neglect of the quantum properties of the maximon makes such rather classical concepts untenable. Moreover, the question remains whether the particle-like solution under discussion is stable within the framework of classical physics (cf. Papapetrou's theorem [5]).

4)Such a world may turn out to be too poor, but it still presents a certain interest as a model. Complicating the problem one could introduce, for example, several types of primary fields, endowing them with certain characteristics (quantum numbers) peculiar for the quark symmetry. It should be stressed that we have in mind here the nonlinearity of the equations for the ψ-field; which occurs naturally in strong gravitational fields. At the first stages of analysis it is useful not to introduce a nonlinearity of the field proper (e.g., of the kind envisaged by Heisenberg). In other words, one should first investigate in a pure form the role and possibilities of the natural nonlinearities due to strong gravitation.

5)We should say, of course, that we do not know what the meaning of quantum collapse is: the space-time characteristics of the final states of the quantum systems may differ considerably from those of classical systems.

of a hierarchical generation of fields, in particular, the appearance of nuclear forces, one could illustrate this possibility as follows.

In order for a particle claiming the name of nucleon[6)] to appear in a system of maximons which admittedly does not possess nuclear interactions, such a particle must be accompanied by a pion field surrounding it (the bare nucleon should "dress" itself). Such a field could appear automatically, if the pions, for instance, are systems consisting of bare nucleons and antinucleons. But then the characteristic lengths for the physical (dressed) baryons can be those lengths which naturally follow from the structures of the pions, K mesons, and other quanta of the strong-interaction fields, since for a small (but definite) residual mass of the bare nucleon the properties of the physical nucleon are determined just by these fields.

In a consistent mathematical theory of the generation of particles (for example from a ψ field) this situation could be realized in such a manner that the same nonlinear equation that is capable of producing the wave function of the baryon also yields the nonlinear interaction between the baryons (many-fermion interactions), which generates the pions and other quanta of the strong-interaction field.

The question of how far these considerations can be confirmed by an analysis of the corresponding equations, at least for some models, remains open. If indeed the gravitational collapse of maximons (or quarks) is the mechanism responsible for the production of, say, nucleons, then any attempt to characterize the properties of compound particles in terms of any kind of potential wells may turn out to be very remote from the situation which is actually realized (in the collapse). If the maximons exhibit only gravitational and electromagnetic properties, and the possibility of strong interactions appears only in complex systems, the corresponding properties may turn out to be essential, and are most clearly expressed in the domain of electromagnetic effects.

4. THE MASS $m_1 = e/\kappa^{1/2}$

One can construct a quantity of the dimension of a mass in terms of the universal constants e, the electric charge, and κ, the gravitational constant:

$$m_1 = e / \varkappa^{1/2}.$$

In classical physics a model of a particle of mass m_1 is realized in terms of electrically charged matter in which gravitational attraction is balanced by electrostatic repulsion. Within the framework of general relativity this model has been considered by Papapetrou[6] and in more detail by Bonnor, and in particular by Arnowitt, Deser and Misner.[7]

The metric characterizing this model has the form

$$ds^2 = \left(1 + \frac{m_1}{r}\right)^{-2} dt^2 - \left(1 + \frac{m_1}{r}\right)^2 (dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2).$$

The mass of such a system can be estimated from simple equilibrium conditions:

$$\varkappa m_1^2 / r = e^2 / r,$$

i.e.,

$$m_1 = e / \varkappa^{1/2} \sim 10^{-6} \text{ g} \tag{16}$$

The ratio of the mass of the "classical" maximon to the mass (1) of the quantum maximon is

$$m_1 / m_0 = (e^2 / \hbar c)^{1/2} \sim 1/10. \tag{17}$$

It is remarkable that for a given charge e there exists only one value of the mass in a static model of the particle.

Another curious trait of this model is that no characteristic length is associated with a given extended particle, since the identical dependence on the distance of both the gravitational and electromagnetic interactions enables an equilibrium to be established for a spherically-symmetric system of any size, and for any centrally-symmetric density distribution within such a system.[7)] It is clear that the gravitational and electric equilibrium must be violated if there exist two maximons with such relative kinetic energy that the total mass of the system becomes $M > 2e/\kappa^{1/2}$.

From the point of view of classical theory, a particle of charge $\epsilon < (\hbar c)^{1/2}$ and of mass m_0 equal to the mass of the quantum maximon is not a static system. Such a system becomes static

6)Here we deal with, so-to-say, a "bare" nucleon, i.e., a system of maximons for which the mass is $m \ll m_0$.

7)In the quantum region even for $M = 2e/\kappa^{1/2}$ two classical maximons could form a collapsing system, "tunneling" through the energy barrier, which is not very high in this case.

for an electric charge equal to[8] $\epsilon = (\hbar c)^{1/2}$.

One can indicate further considerations in favor of the idea that quantum maximons cannot possess certain of the properties of quarks.

A quantum maximon consists of matter which is gravitationally confined to a region smaller than its gravitational radius. It is impossible for radiation of any kind to be produced in such a region. In particular, a quantum maximon cannot decay via either strong or weak interactions. In the quark model, the lambda-quark is assumed to be more massive than the other two, and radiative transitions between quarks are possible, in particular with emission of leptons.

In distinction from the quantum maximon, the classical maximon is not a system in a collapsing state, and is necessarily electrically charged. If one does not assume special interdictions, it will decay rapidly, owing to its immense mass (an example of such interdictions are fractional electric charges). In other words, classical maximons could not exist in a free state without special interdictions. But even in this case (i.e., assuming that electric charge, for instance, is integer-valued) such a maximon could play the role of a structural unit in systems with enormous mass-defects representing the known elementary particles.

The fact that a unique mechanism for the formation of a small mass out of a system of maximons appears in a natural way is one of the peculiarities of the maximon. But one qualitative characteristic of these forces differs, at least on first inspection, from the ones necessary for the realization of SU(3) symmetry, for example, in the realm of hadrons: it would seem that gravitational forces do not distinguish between particles and antiparticles.

In other words, if one could construct the baryons, for instance, from maximon-quarks, then in accordance with what was said above, the pions should be constructed directly from baryons and antibaryons, as was usually done in the prequark models for composite particles. That is to say, the dynamics of the model essentially modifies the quark symmetry.[9]

More definite (affirmative or negative) answers to these questions can be expected from an analysis of nonlinear equations of the type which was mentioned above in connection with the various assumptions (under conditions of superhigh energy density) about the fields which make up the tensor T_{μ}^{ν}. A discussion of the possible existence of maximons and of their possible role in the hierarchy of particles is an attempt to guess some qualitative specific features of the nonlinear physics which occurs in strong gravitational fields produced by a superdense (possibly primitive) state of matter.

If allowance for the quantum character of maximon collapse does not change the classical possibility of producing resulting systems of arbitrarily small masses, then it is hard to imagine that such systems exist in addition to those particles which we already know from experiment. If such a possibility is forbidden by a consistent quantum theory,[10] then in principle maximons should exist as particles among the other particles, and possibly in addition to quarks.

By the way, the widely used equation $l_0 = (\hbar\kappa/c^3)^{1/2}$ relates universal constants. This also leaves open the question of which of the constants appearing in this relation are the fundamental ones and which are derived. One could assume, for example, that

$$\hbar = l_0^2 c^3 / \varkappa, \tag{18}$$

i.e., that the length is a fundamental constant and Planck's constant is only a consequence of the existence of a fundamental length. Equation (18) would be of interest if one could construct a theory in which quantum effects would appear as consequences of the existence of a fundamental length l_0. Thus, this could represent a reduction of quantum effects to geometry.

5. THE BEHAVIOR OF MAXIMONS IN MATTER

Since an energy of $\sim 10^{28}$ eV is necessary for the production of maximons, the possibility of pro-

[8]Here we deal with the charge (ϵ) of the bare particle in classical physics. In quantum theory the physical charge (e) may be equal to the electron charge, independently to the charge of the bare particle ($\epsilon > e$). The vacuum polarization effect may lead to this result, since it leads to a strong shielding (at small distances $\sim l_0$) of the electric charge of the "bare" particle. The charge of a bare particle can be considered as universal and be set equal, e.g., to $\epsilon^2 = \hbar c$. From this point of view the constant e is not a fundamental constant of the theory.

[9]Let us assume, for instance, that no system consisting of a free quark and antiquark is formed, or, more exactly, that the lifetimes of such systems vanish literally.

[10]For example two maximons necessarily transform into one maximon with emission, in any form, of the surplus mass of the system.

ducing such particles even in the accelerators of the remote future is excluded. But one may assume that in its initial stage of development the matter of the Universe was composed predominantly of maximons. Assuming that with the passage of time the initially present maximons are partially converted into forms of matter which we know, via the collapse mechanism of small masses, it is still possible to assume that part of the initially present maximons could have been preserved up to the present time.[11)]

By the way, it is easy to see that the amount of matter still existing in the maximon state at the present time might turn out to be so large as to guarantee that our Universe is closed. Indeed, the critical matter density which guarantees closure of the Universe is $\rho_C \sim 10^{-29}$ g/cm^3. This means that for a mass of 10^{-5} g a maximon density of[12)]

$$\sim 10^{-24} \text{ particles/cm}^3 \qquad (19)$$

would be sufficient for the Universe to be closed. The corresponding fluxes could be equal to

$$N \leqslant 10^{-24}c \sim 10^{-14} \text{ particles/cm}^3 \text{ sec.} \qquad (20)$$

An upper bound for the flux N in the Universe can be estimated from data on the temperature of the Earth. The energy transferred by the maximon flux to our planet should not exceed the thermal regime of the Earth known from geophysical data. According to these[8] the heat generated each second in 1 cm^3 of the Earth is of the order $H = 2 \times 10^5$ eV. If the Earth temperature is in equilibrium and the maximons release all their energy to the Earth, the flux (N) of maximons reaching the Earth should not exceed

$$N \leqslant RH / 3m_0 \quad (4\pi R^2 N m_0 = {}^4/_3 \pi R^3 H), \qquad (21)$$

where R represents the radius of the Earth. We obtain for N[13)]

$$N \leqslant 10^{-14} \text{ particles/cm}^2 \text{ sec.} \qquad (22)$$

The numbers (20) and (22) do not disagree, since in fact the mean velocity of maximons is very likely to be much smaller than c and is of the order of the velocities attained by particles in gravitational fields of celestial bodies, i.e., 10^6–10^7 cm/sec. In other words, if (19) is true, the maximon flux at the surface of the Earth could be of the order

$$10^{-14} \leqslant N \geqslant 10^{-18} - 10^{-17} \text{ particles/cm}^2 \text{ sec.} \qquad (23)$$

The behavior of maximons in matter at velocities which these particles acquire in the gravitational fields of celestial bodies (e.g., in their falling on Earth) is peculiar. For such relatively low velocities (10^6–10^7 cm/sec) the maximons should possess a colossal kinetic energy

$$E = m_0 v^2 / 2 \sim 10^{20} \text{ eV}. \qquad (24)$$

But owing to such a large kinetic energy charged maximons cannot produce any ionization tracks. Indeed, the maximal value of the energy transferable to an electron in a collision with a maximon is

$$T_{max} = 2 m_{el} v^2 < 0{,}01 \text{ eV}. \qquad (25)$$

for $v = 10^6$ cm/sec.

In collisions with nucleons the energy transfer can increase up to 10 eV per collision. Assuming that the cross section for such collisions is of the order of atomic cross sections (10^{-16} cm^2) the energy loss over one meter of path of the maximon through matter is of the order of

$$\Delta E \lesssim 10^{10} \text{ eV}. \qquad (26)$$

a quantity negligible in comparison with the kinetic energy acquired by the maximon in its fall toward the Earth ($\sim 10^{20}$ eV). Even for energy loss figures of the order of (26) a maximon is capable of traversing a solid of $> 10^7$ km thickness. In other words, maximons could circulate for long periods of time along orbits situated inside our planet. Slowly losing their energy, the maximons would then accumulate in the center of our planet, undergoing combinations into ordinary matter with enormous energy release and thus raising the temperature of the central regions of the Earth.

If the flux of these particles is not much smaller than 10^{-14} particles/cm^2 sec, then during one year one such particle would cross an area of 1000 m^2. Even if the particles are charged, if they have a velocity of the order of 10^6 cm/sec one is

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11)We do not analyze the mechanism of burning out of maximons in the initial stage of development of the Universe. Matter at superhigh density may exhibit properties which are so far unforeseen. We do not know what kind of statistics is followed by maximons in the ultradense state (Boss, Fermi, or even parastatistics).

12)This means that there are only 10^{-19} maximons for each nucleon in the Universe (the nucleon density is 10^{-5} nucleons/cm^3).

13)In order that the energy equilibrium of the Sun be determined in essence by the maximons falling on the Sun, it is necessary to have $N \sim 10^{-8}$ particles/cm^{2}sec. In general, a denser maximon atmosphere could be expected in the vicinity of massive celestial bodies.

unable to indicate any direct method for their detection.

As already indicated, maximons cannot be detected through their ionization. Apparently it is also impossible to detect them by calorimetric methods—their energy losses are of the same order as the ionization losses of charged penetrating cosmic particles ($<10^7$ eV/cm). Electromagnetic transition radiation, although independent of the mass of the radiating particle, is too small in absolute value.[9]

In principle, such a particle should produce mechanical oscillations in a solid, i.e., sound, but the "whistling" of such a particle would be more than 10^7 times weaker than the whistle of a rifle bullet (on the basis of a rough energetic estimate).[14)]

On the surface of the Earth the gravitational force on a maximon would be

$$mg \sim 10^{-2} \text{ dyn}.$$

This means that at intermolecular distances $\sim 10^{-7}$ cm these forces do work of the order

$$mgh \sim 10^{-9} \text{erg} \sim 10^3 \text{ eV}.$$

This should mean that in no container on the surface of the Earth can these particles be detected. They would tumble to the center of the Earth under the action of gravity. It is true that some indirect indications of the existence of such a particle could be obtained in an underground neutrino experiment.

Indeed, if the maximons release their energy in the form of radiation upon transforming into ordinary matter at the center of the Earth, then in a particle shower with total energy of the order of 10^{28} eV there could appear a relatively large strongly collimated flux of electrons, mesons, and possibly neutrinos with energies of say 10^{25}–10^{15} eV.

At large energies electrons and even muons ($E_\mu > 10^{12}$ eV) lose energy in dense media by photon production in bremsstrahlung in the Coulomb field of nuclei. But at even higher energies the radiative energy losses in dense media decrease again (owing to the so-called Landau-Pomeranchuk effect,[10] cf. also the more detailed analysis by Migdal[11]); the Bethe-Heitler cross section, which varies as dv/v, goes over for dense media into $dv/(E_0 v)^{1/2}$. For example, the bremsstrahlung produced by an electron with energy $E_0 \sim 10^{17}$ eV falls off by a factor of about two compared with the corresponding Bethe-Heitler cross section.[12] [15)] At such energies the electron becomes a penetrating particle. At the energy values under consideration (10^{20}–10^{25} eV) the ranges of electrons and muons in the ground may turn out to be comparable with the radius of the Earth.

Thus, in an underground neutrino experiment one could observe correlated simultaneous "neutrino events," i.e., showers of penetrating particles (electrons, mesons) traveling "upside down." But this would be a lucky coincidence, i.e., a whole series of conditions must be fulfilled.[16)]

Celestial bodies (starting with small meteorites), by gathering maximons by means of their gravitational forces, could serve as sources of cosmic rays and may make an essential contribution to the upper region of the energy spectrum. Consequently, this part of the spectrum could consist not only of protons but also of electrons and photons.

Since the appearance of maximons is possible only in superdense matter, the detection of maximons (which can only be relics of the remote past) would be a decisive experimental verification of the Friedmann universe, and of the fact that in its development the Universe has indeed passed through a state of superdense matter. Those cosmological models which do not involve a stage in which the Universe passes through a state with superdense matter do not imply the existence of free maximons.

The widespread skepticism with respect to the role of gravitational effects in elementary particle physics is based on a "fear" of small lengths, such as those which are characteristic for gravity. This skepticism is supported by arguments that for a consistent theory the necessary lengths are of the order of the nucleon radii (10^{-14} cm). But, first of all, there exists a well developed field theory (electrodynamics) for which such lengths are acceptable.[13] And secondly, together with a hierarchy of particles the hierarchy of interactions discussed above is quite conceivable.

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14)The kinetic energy of a bullet of 5 g is almost of the same order (10^{23}eV); this energy is dissipated over a path of approximately 1 km, whereas a maximon would lose the same amount of energy over a path of $\gtrsim 10^7$ km.

15)G. T. Zatsepin has called to my attention the estimates of Pomanskii [12]. I am grateful to Zatsepin also for a discussion on the subject.

16)The possibility under discussion is meaningful if and only if, as a result of maximon collapse in the center of our planet, a photon is formed with energy not much below the mass of the maximon, thus giving rise to a grandiose cascade shower. This assumption has a certain amount of plausibility if the maximon does not exhibit nuclear interactions.

In particular, the idea which treats nuclear forces as nonfundamental forces which appear in relatively complicated systems, at relatively large distances, does not seem to be absurd so far. This idea may turn out to be a heuristically valuable approach in attempts to find a consistent theory of fields. One should note the paradoxality of the fact that two of the most skeptical thinkers among the physicists of the twentieth century, namely Pauli and Landau, have definitely come out in favor of a possible fundamental role of gravitation in elementary particle physics.[14-15]

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103