Gravitation and Elementary Particle Physics

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PREFACE

It is a quest to unify four, seemingly different, fundamental interactions: strong, electromagnetic, weak, and gravitational, that characterize modern field theory. Yet until recently the prospects for such a unification seemed all too vague. The last few years have however witnessed some solid progress towards the unified description of the weak and electromagnetic interactions based on the gauge approach and these studies were given a new powerful push.

It is a discussion of some of the tasks that need solving before this goal can be approached that is now offered to our readers.

Having characterized the current status of field theory, it is essential to note above all that the theoretical field concepts used to describe gravitational interaction are radically different from those used to describe weak, strong, and electromagnetic interactions.

It is well known that the most popular comprehensive theory of gravitation, i.e. Einstein's general theory of relativity (GTR), actually moves away from the conventional understanding of "field" by identifying the field variable with the metric tensor of Riemannian space-time, thus making the theory completely geometric. As a result; the GTR has proved to be devoid, in principle, of conservation laws for matter and gravitational field when taken in conjunction. Many attempts, even going back to the work of Einstein himself, to introduce into the GTR a substitute for the energy-momentum conservation law of matter and gravitational field taken in conjunction have all, when closely scrutinized, proved unsuccessful. The GTR is in fact constructed at the expense of the conservation laws and so the gravitational field in Einstein's theory is not in the spirit of Faraday-Maxwell. Such a radical difference between the gravitational field and other fields would be justified had there been telling reasons and primarily had there been experimental data indicating non-conservation of energy-momentum in any physical process. However, there are no such data and this signifies that, in the case of gravitational interaction too, we have no reason to reject a fundamental physical law, i.e. that of energy-momentum conservation. Hence the task of constructing a theory that would, on one hand, allow a gravitational field to be treated as an energy-momentum carrier analogous to any other physical field, and that would, on the other hand, also conserve Einstein's grand idea of a space-time geometry closely associated with matter. Solving this problem would permit the abyss that has, until now, separated the theory of gravitation from those of the other interactions to be bridged, and thus undoubtedly help the unification of these theories.

This is one of the possibilities offered by the field approach to the construction of a new theory of gravitation and which is analyzed in the first paper "The theory of space-time and gravitation" by V.I. Denisov and A.A. Logunov. This approach is based on two fundamental propositions. Firstly, it is required that the conservation laws hold for matter and gravitational field taken in conjunction, this being achieved by choosing a pseudo-Euclidean geometry as the inherent one for the gravitational field. Using this approach, a gravitational field is characterized by its own energy-momentum tensor which contributes to the system's complete energy-momentum tensor.

Secondly, there is a geometrization principle (an identity principle) which states that the equations of motion of matter under the action of a gravitational field in the pseudo-Euclidean space-time have a metric tensor γ_{ni} that can be equated with identical equations of motion of matter in an effective Riemannian space-time having a metric tensor g_{ni} which depends on the gravitational field and the metric tensor γ_{ni}. This identity principle reflects the universal nature of the interaction of gravitational field with other physical fields and it follows from the results of gravitational experiments although a definite choice of the Lagrangian density of interactions between all the fields must be made to describe it. According to this principle, the covariant energy-momentum conservation law of matter and gravitational field in the pseudo-Euclidean space-time can be represented as a covariant energy-momentum conservation equation for the matter alone in the effective Riemannian space-time. This proves that an effective Riemannian geometry emerges within the scope of the field approach because, figuratively speaking, the gravitational field possesses energy-momentum.

One of the most natural implementations of the field approach is a theory of gravitation using a symmetric tensor of second rank to describe the gravitational field. Since this field involves four irreducible representations having the spins 2, 1, 0, and 0′, the formalism of projection operators is used to eliminate the surplus spin states, thus ensuring, in turn, the gauge invariance of the theory.

This field theory of gravitation allows all the available gravitational experiments in the solar system to be described and makes it possible to construct a non-stationary model of the homogeneous Universe that can explain the observed consequences of the cosmological expansion of the Universe. In addition, it satisfies the principle of correspondence to the Newtonian gravitation theory, and finally, it predicts a set of fundamental corollaries. It should be noted, however, that the theory suggested is only one of the many theoretical schemes conceivable. The experimental evidences of the various interactions are rather distinctly specified in terms of their own characteristic regularities. Hence, one of the most peculiar features of strong interactions is the multiple production of particles at high energies, which means that multiple production processes play a principal role in the study of the nature of strong interactions.

These processes have been discovered in cosmic rays and for a long time semiphenomenological concepts based on applications of the laws of thermo- and hydrodynamics had to be employed to explain their mechanism. The pioneering theoretical studies of the characteristics of multiple processes such as the number density of particles, the energy, etc., are associated with the names of W. Heisenberg, E. Fermi, L.D. Landau, I.Ya. Pomeranchuk *et al.* and date back to the late forties and early fifties. At that time the study of multiple production processes of particles within the framework of quantum field theory looked very promising since the amplitudes of the corresponding transitions were extremely complicated and the experimental research encountered fundamental difficulties. The problem is that kinematics of events with a large number of particles is extremely complex and there were no particular hopes of studying it in any detail using standard characteristics (chosen reaction channels and their differential cross sections), nor were there any particular ways to study them. At the then comparatively low energies of the colliding particles, the number of reaction products was small; however, new and powerful particle accelerators were commissioned in the sixties. The fraction of multiple processes has unremittingly risen as the energy was increased and there was an urgent need to find a simpler and more convenient method to describe multiple production processes.

Such a method was found in 1967 in the work by A.A. Logunov, M.A. Mestverishvili, and Nguyen Van Hiew. A production cross section of a single secondary particle is introduced as the main object of the theory instead of their transition amplitudes, whilst integrating over the variables related to the remaining secondaries. As a result, we obtain a quantity (now known as the inclusive cross section) which can be investigated both theoretically and experimentally in a much simpler way than the ordinary cross sections and which, at the same time, contains sufficient information about the dynamics of interacting particles and their structure. In a similar fashion production cross sections of two, three, and more chosen particles can be introduced and, following Feynman's proposal in 1969, every process contributing to the production of the given number of the chosen (detectable) particles is called inclusive.

The inclusive approach in high energy physics has proved to be most suitable for the description of the multiple production processes that have no dependence on the type of interacting particles and it has in many ways promoted the development of this branch of physics. In fact, the introduction of inclusive cross sections has immediately allowed the powerful apparatus of axiomatic quantum field theory, which was developed earlier but had only been applied before to the processes of elastic scattering and charge exchange, to be applied to multiple production processes as well. A number of substantial restrictions that are imposed on the high energy behavior of inclusive cross sections have been obtained using these general principles of quantum field theory. Even in the first experiments on measuring inclusive cross sections a previously unknown regularity that is characteristic of inclusive processes as such was discovered, i.e. the scale invariance of inclusive cross sections. In the course of successive experiments an appreciable number of these scaling laws was discovered for the multiple production processes of various origins. The advance of the inclusive approach has also stimulated the development of many phenomenological models which enable experimental results to be both described and predicted.

The need for a theoretical substantiation of the scaling in deep inelastic processes by the field theory has provided a new and powerful impetus for a thorough investigation of the non-Abelian gauge theories that has resulted in the significant advance in this area of research. Some extremely important problems have now also appeared on the agenda, such as the relation between the inclusive cross sections and three-particle scattering amplitudes and hence the limitations on the behavior of these cross sections need to be established. A survey of the results obtained in the last few years by studying inclusive processes, both starting from general principles and also within the scope of various models, is presented in the second paper, "Inclusive processes and the dynamics of strong interactions", by A.A. Logunov, M.A. Mestverishvili, and V.A. Petrov.

The third paper, by N.N. Bogolyubov, M.A. Matveev, and A.N. Tavkhelidze, "Colored quarks", contains a review of a number of the most important advances in elementary particle physics, nuclear physics, and high-energy physics that have been inferred from the concept that colored quarks are fundamental constituents of matter. The notion of color, i.e. a new quantum number, was introduced in 1965 by N.N. Bogolyubov, B.V. Struminskii, and A.N. Tavkhelidze in the USSR and independently, by Y. Nambu and M.Y. Han in the USA, in connection with the problem of quark statistics. It is now basic to hadron spectroscopy and quantum chromodynamics as well as the various versions of the unified gauge theories of strong, weak, and electromagnetic interactions.

At the outset the problem of the dynamic description of hadrons as composite quark systems is discussed as is a construction of the form factors and amplitudes of various processes involving hadrons. The main aim of building dynamic quark models is to explain why quarks have not, despite many attempts, been discovered in a free state.

Explaining the absence of free quarks is called quark confinement or non-emission and remains to date one of the most important tasks of elementary particle physics and quantum field theory. The dynamic model initiated at JINR (Dubna) in 1964 was based on the idea that heavy quarks were bound within hadrons by immense forces, that, on one hand, dictates a large mass defect of quarks in hadrons and, on the other, prevents their emission. These ideas have boosted the development of the modern quark models of elementary particles, the quark bag model and the parton model being the most popular.

As will be shown in the paper, the dynamic composite model enable both the observed static features of elementary particles (magnetic moments, axial-vector constants of weak transitions, etc.) and the hadron form factors to be described systematically. Notice in particular that the enhancement of the magnetic moments of a heavy quark bound in a hadron has for the first time been satisfactorily explained within the framework of this model, and has enabled the absolute values of the proton and neutron magnetic moments (in nuclear magnetons) to be evaluated:

$$\mu_p \simeq 3, \quad \mu_n \simeq -2.$$

In addition, the model can describe the mass splittings that occur within meson and baryon multiplets and permits the renormalized axial constant of the nucleon weak interaction, and its relativistic corrections, to be determined allowing for the internal quark motion in hadrons. A quark model of the electromagnetic and weak meson decays, which was developed from the dynamic approach, was vital for the elaboration of elementary particle theory. Thus the weak lepton decays of the pseudoscalar π- and K-mesons and the electromagnetic decays of the vector ρ^0-, ω^0-, and φ^0-meson resonances into electron-positron pairs can be described as the annihilation of quarks and antiquarks bound in these mesons. Notice that the relevant decay widths are governed by the magnitudes of the functions of bound quark-antiquark pairs for matching coordinates:

$$\Gamma(\pi \to \mu\tilde{\nu}) = \frac{G^2 \cos^2\theta}{2\pi^2} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2 |\psi_\pi(0)|^2,$$

$$\Gamma(V^0 \to e^+e^-) = \frac{16\pi\alpha^2}{3m_V^2} Q_V^2 |\psi_V(0)|^2,$$

where

$$Q_\rho = \frac{1}{\sqrt{2}}, \quad Q_\omega = \frac{1}{3\sqrt{2}}, \quad Q_{\varphi^0} = -\frac{1}{3}.$$

These formulas and the idea of the quark annihilation mechanism itself are at the base of the current theoretical analysis of the various decay modes of the members of a new family of heavy particles, namely, ψ/J- and Υ-mesons. Y. Nambu made an important contribution to dynamic hadron theory when, for the first time in 1965, he introduced vector fields, i.e. the carriers of the color interaction which were prototypes of quantum-chromodynamical gluon fields. It should be stressed that quantum chromodynamics (QCD), whose rapid progress over the last decade has been observed by us, emerged as a result of generalizing the color $SU^c(3)^{(8)}$ symmetry as a local gauge transformation.

It is scarcely possible to enumerate all the advances of QCD whose development was significant for the progress of strong interaction theory. As will be shown in detail in this paper, QCD has meant that a wide range of phenomena having approximate scaling invariance (the automodel behavior) can be treated consistently and a quark counting method for processes with high transferred momenta can be well-grounded. It is hoped that quark confinement can be theoretically explained by the non-Abelian nature of the QCD gauge symmetry. In the last few years colored quarks and fundamental QCD forces have begun to find their way into the theory of nuclear phenomena. Let us emphasize that the asymptotic behavior pattern of the deuteron electromagnetic form factor is a direct indication of a quark structure in the nucleus, as it matches quark counting predictions quite well. It is well known that a quark counting formula, that was established in 1973, governs the energy dependence of the differential cross sections for large angle scattering and the hadron form factors at high energies, $E = \sqrt{S}$, and high momentum transfers, $Q = \sqrt{-t}$:

$$\frac{d\sigma}{dt} = (ab \to cd) \left(\frac{1}{S}\right)^{n_a+n_b+n_c+n_d-2} f(\theta),$$

$$F_a(t) \sim \left(\frac{1}{t}\right)^{n_a-1},$$

where $n_{a,b,c,d}$ are the numbers of elementary constituents (quarks and antiquarks) in the reacting hadrons and θ is the scattering angle in the center-of-inertia frame. The quark counting formula describes the numerous experimental data on elementary particle scattering surprisingly well and makes it possible for explicit information about the number of hadrons' elementary constituents to be deduced from experiments. This information, when applied to an analysis of recent experimental data on electron-deuteron scattering, indicates the presence of a hard six-quark deuteron structure.

The paper discusses the function of quark degrees of freedom when describing nuclear phenomena, especially those occurring at high energies and momentum transfers and indicates, in particular, the possible excitation of "hidden color" in nuclear matter and a number of other corollaries. It seems certain, the notion that colored quarks and gluons are fundamental constituents of matter will radically change our ideas about the world of atomic nuclei and a new light will be shed both on the properties of nuclear matter and the nature of nuclear matter and nuclear forces.

The analysis of Greenberg's hypothesis about a quark's para-fermi statistics performed by the authors of this paper is interesting. Whilst the hypothesis does enable a problem, in which there is a virtual violation of the Pauli principle for a baryon consisting of three quarks, to be solved, para-fermi statistics is too narrow and does not permit the gauge SU^c (3) symmetry that forms the QCD basis to be introduced.

A maximum gauge symmetry compatible with a parastatistics of rank 3 is the SO (3) group. It has three gluons and a particle spectrum containing diquarks and other exotic hadrons.

The paper is concluded by a discussion about whether color symmetry is an exact or approximate law of nature. This principal problem of elementary particle theory, as yet unsolved, is closely related to the question about quark charges.

Even the first works on the three-triplet model indicated that in the case of colored quarks integral values could be chosen for the electric and baryonic charges. Introducing integral quark charges which are dependent on the quark's color state results in an obvious breakdown of color symmetry, at least for electromagnetic interactions of particles.

This paper considers the unified gauge models of the strong and electromagnetic interactions which spontaneously break color symmetries and integral charge quarks, and discusses the corollaries of these models that are being observed experimentally.

These profound and principal problems, dealt with in this paper, obviously cannot be solved theoretically, and experiment must have the last word.

It should be stressed that the hypothesis about the integrity of quark charges resulted, in particular, in the concept of unstable quarks and was the starting point for a number of unified gauge models of elementary particles tolerating nucleon decay and other processes in which the baryon number is not conserved. An experimental verification of the predictions of similar theories should take place soon.

This paper, by N.N. Bogolyubov, V.A. Matveev, and A.N. Tavkhelidze, should help scientists to be aware of the profound influence the idea that colored quarks are fundamental constituents of matter has exerted on the development of the physics of elementary particles and nuclear and high energy physics, and assists the evaluation of the qualitative changes that have been observed in those areas of research in the last two decades.

3 March 1982

A.A. Logunov

1 The Theory of Space-Time and Gravitation

V. I. Denisov and A. A. Logunov

1.1 INTRODUCTION

Einstein's general theory of relativity (GTR) is one of the fundamental physical theories at the present time and has a deep rooted concept of a relation between matter and space embedded in it. The theory explained and predicted a number of gravitational effects, a genuine triumph.

However, there are a number of difficult problems with the GTR that have remained unsolved, one of which is the basic one of energy-momentum of a gravitational field. A general study of this problem [1-9] has led us to conclude that it is impossible, in principle, to solve it within the framework of the GTR since the gravitational field in Einstein's theory is not really a field in the spirit of Faraday-Maxwell, i.e. it is not characterized by an energy-momentum tensor density. This can be verified easily by comparing the physical properties of gravitational and other fields.

All the physical theories that describe the different forms of matter include energy-momentum tensor density as one of the most important features of a field. This tensor density is commonly obtained by varying the density of the field Lagrangian, L, with respect to the components of a metric space-time tensor g_{ni}[1] thus:

$$T^{ni} = -2\frac{\delta L}{\delta g_{ni}} = \sqrt{-g}\,\mathsf{T}^{ni} \tag{1.1}$$

where T^{ni} is the field energy-momentum tensor. This feature shows a field exists since a nonzero value of the density of the energy-momentum tensor is a necessary and sufficient condition for a physical field in this region. The energy-momentum of any physical field contributes to the complete energy-momentum tensor of a system and does not become zero outside the field source. This makes it possible to consider energy transfer by waves in the Faraday-Maxwell spirit, i.e. to study the field intensity pattern in space, to determine the energy fluxes through a surface, to compute the changes in the energy-momentum value during radiation and absorption, and to perform other energy based computations.

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[1] Henceforth the Latin indices run over the values 0, 1, 2, 3, and the Greek ones, 1, 2, 3. The metric signature is chosen in the form (+, −, −, −).

The *gravitational field in the GTR* does not have the features typical of other physical fields, for it does not have the feature discussed above.

Indeed, the density of Lagrangian in Einstein's theory is composed of two parts, the density of the gravitational field Lagrangian, $L_g = L_g(g_{ni})$, which depends only on the metric tensor g_{ni}, and the density of the matter Lagrangian, $L_M = L_M(g_{ni}, \varphi_A)$, which depends on the metric tensor g_{ni} and the remaining fields of the matter φ_A. Thus, the quantities g_{ni} in Einstein's GTR have two meanings, being both the variables of the field and the metric space-time tensor.

As a result of this physical and geometrical duality, an expression for the density of a complete, symmetric energy-momentum tensor (a variation of the Lagrangian density with respect to metric-tensor components) coincides with field equations (a variation of the Lagrangian density with respect to gravitational field components). This implies that the density of the complete, symmetric energy-momentum tensor of a system is strictly equal to zero:

$$T^{ni} + t^{ni} = 0, \tag{A}$$

where $T^{ni} = -2\dfrac{\delta L_M}{\delta g_{ni}}$ is the density of the symmetric energy-momentum tensor of matter (here by matter we assume all other fields, too, except gravitational),

$$t^{ni} = -2\frac{\delta L_g}{\delta g_{ni}} = -\frac{c^4\sqrt{-g}}{8\pi G}\left[R^{ni} - \frac{1}{2}g^{ni}R\right]. \tag{1.2}$$

It also follows from expression (A) that all the components of the density of the symmetric energy-momentum tensor t^{ni} of the gravitational field vanish everywhere outside matter.

These results clearly demonstrate that the gravitational field in Einstein's GTR does not exhibit the properties typical of other physical fields, since it does not have that basic physical feature, an energy-momentum tensor outside the source.

A curvature tensor R^i_{nlm} is a physical characteristic of a gravitational field in Einsten's theory. A clear explanation is given by Synge [10, p. VIII]: "... If we accept the idea that space-time is a Riemannian four-space (and if we are relativists we must), then surely our first task is to get the feel of it just as early navigators had to get the feel of a spherical ocean. And the first thing we have to get the feel of is the Riemann tensor, for it is the gravitational field—if it vanishes, and only then, there is no field. Yet, strangely enough, this most important element has been pushed into the background." And further he wrote: "... In Einstein's theory, either there is a gravitational field or there is none, according as the Riemann tensor does not or does vanish. It is an absolute property; it has nothing to do with any observer's world-line..."

Unfortunately, some of the theorists who specialize in the GTR have still not understood this fundamental point. This lack of understanding might explain, for example, statements by a number of authors [11, 16, 17, 74, 127] who claim that, given a transformation into an appropriate coordinate system, a gravitational field within a small space-time region could be considered as absent in Einstein's theory. Yet a physical feature of gravitational fields is in fact that they can change the energy-momentum of matter, i.e. it demonstrates the force action of a gravitational field on matter described by equation [11] thus:

$$\frac{\delta^2 n^i}{\delta s^2} + R^i_{mkl} u^m u^l n^k = 0, \tag{1.3}$$

where $u^i = \frac{dx^i}{ds}$ is the velocity four-vector, and n^i is the infinitesimal displacement vector of geodesics. Yet a description using curvature waves yields no information concerning a wave transferred energy flux.

Thus, Einstein's GTR combines matter and a gravitational field, the first being characterized, as in all other physical theories, by the energy-momentum tensor (a tensor of rank two), and the second, by the curvature tensor (a tensor of rank four). From the difference in the dimensions of physical parameters of the gravitational field and matter in Einstein's theory it follows immediately that there are, in principle, no GTR conservation laws relating matter and gravitational field. This fundamental fact established first by us [6] suggests that Einstein's theory has been constructed at the expense of the laws of conservation, rejecting them when matter and gravitational field are taken together.

H.A. Lorentz and T. Levi-Civita have proposed the quantities in (1.2) to be considered as the density components of the energy-momentum tensor of gravitational field, and expression (A) as a specific conservation law for the density of complete energy-momentum tensor. The conservation law (A) is peculiar because it is a local conservation law enabling the change in the energy-momentum tensor of gravitational field at some point to be found from the change in the energy-momentum tensor of matter at that point:

$$\frac{\partial}{\partial t} T^{0i} = -\frac{\partial}{\partial t} t^{0i}. \tag{1.4}$$

However, in Einstein's theory, the tensor t^{ni} is only characteristic of geometry inside matter, hence a change in the GTR energy-momentum of the matter is only directly related to a change in the scalar curvature R and the tensor R^{ni} of rank two within the region occupied by the matter. The curvature waves described by the tensor R^i_{nlm} of rank four are not directly related to the change in the energy-momentum of matter, but are related implicitly via the metric