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IN PRAISE OF QUANTUM FIELDS

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IN PRAISE OF QUANTUM FIELDS *

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ABSTRACT

A comprehensive discussion of several topics vital for the structure of a modern Quantum Field Theory are discussed, namely: physical content of the notion of a Quantum Field; meaning of infinite renormalization; renormalizability as quantizability; the influence of several principles of quantum nature (quantizability, gauge dynamics, supersymmetry) on quantum fields dynamics; main trends of QFT evolution; present status of QFT and its frontier role in physics.

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Dedicated to Nicholai N. Bogoliubov on occasion of his 80th birthday.

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1. Quantum Field - the Basement of Particle Theory

The newest chapter of a modern theoretical physics is the theory of quantum fields (QFT), which provides the framework for a theoretical description of microparticles and their interactions.

The key element of this theory is the notion of a *quantum field*. From the present viewpoint it represents the universal (and, probably*/, the sole) form of matter, underlying all its physical manifestations.

Historically the quantum field (QF) emerged from the peculiar synthesis of the classical Faraday-Maxwell field and the probability field of quantum mechanics**/.

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*/ This reservation concerns the gravity (see below Sect. 6).

**/ For a more detailed discussion see Ref.1. Note however that in English translation of this paper [Sov.Phys.Uspekhi 30(9), Sept.87, pp 791-815] unhappily there stands the term quantized field instead of *quantum* field.

The cornerstone of QFT was laid more than 60 years ago by P.A.M.Dirac in the famous paper[2] devoted to quantization of radiation. Here, for the first time, a new object - QF - was introduced. The dynamical variables which satisfy the Maxwell's equations are not numerical functions but quantum-mechanical operators acting on the Schrödinger wave function that describes the state of a physical system.

The second source of the general concept of a quantum field was the quantum-mechanical wave function satisfying the nonrelativistic Schrödinger equation. In quantum mechanics the corresponding wave field being associated with a material particle represents a field of probability amplitudes. The extension of this picture to problems containing N particles made it necessary to introduce the probability field defined in a so called configurational space of $3N$ dimensions. However, the use of the second quantization method proposed in[2], which has been extended by Wigner and Jordan[3] to an ensemble of fermions, made it possible to use instead some new field in ordinary 3-space which is an operator in the quantum-mechanical sense. The application[4,5] of the Wigner-Jordan method to the Dirac equation yielded the 4-component operator-valued spinor field - quantum Dirac field - describing electrons and positrons in a completely symmetric way.

From this and some other constructions the new physical object has gradually emerged. To each species of relativistic microparticle one associates a field, which implements some local representation of the Lorents group and at the same time has a quantum-operator meaning.

The quantum field concept has taken the place of two notions, a classical field and a classical point particle. It is essential that one QF, like the quantum Dirac field, describes all particles (and antiparticles) of a given sort in the Universe. With regard to interaction, we note that the elementary event is always an interaction of several fields of one or several species at a common space-time point or, in corpuscular terms, an instantaneous and local conversion of certain particles into others.

The basic principles and ideas of local theory of interacting quantum fields forming the simple picture just described were discovered and formulated mainly by the early thirties. However, the new paradigm penetrated into theoreticians consciousness very slowly, and took its final form perhaps only in the first series of well known Schwinger studies[6] in the late forties. Only at that time, thanks to the visuality of Feynman diagrams and the spectacular achievements of renormalized perturbative calculations in quantum electrodynamics, a new universal picture of the microcosm structure started to win general recognition.

Looking back, we see that the building of a local renormalized theory of interacting quantum fields, even in the first half of the fifties, stood on the correct basement. Nevertheless, in the second part of that decade QFT went out of fashion, being treated by the majority of physicists, including practicing theoreticians, as a "theoretical theory" lying far away from the current needs of particle physics.

Since that time several important theoretical ingredients were added : non-abelian gauge fields and the principle of gauge dynamics, spontaneous symmetry breaking mechanism, renormalizability as a physical condition. Quite parallel to this new physical realities have appeared: hadronic quark model, V - A structure of weak interactions, parton picture.

As a result, in the mid-seventies, the whole situation changed drastically. The particle interaction theory based on gauge dynamics of local quantum fields was formulated for the electroweak and strong interactions. Due to this, the QFT structure became rather simple. During the adjacent decade these quantum field models were proved to be physically adequate. As a result, the local QF basis of a microparticle theory has been generally recognized, and QFT is now considered to be the only framework for the theoretical description of particle dynamics.

In what follows we shall proceed along the kernel line of QFT evolution and present the analysis of some its main trends.

In the formation of the present structure of QFT several general principles were of utmost importance[7]:

- Principle of Quantizability (generalized renormalizability),
- Principle of Gauge Dynamics,
- Principle of Supersymmetry.

Now we consider the first of them in greater detail.

2. Renormalization and Quantizability

The renormalization procedure is usually performed in the course of the quantum field equations solution and, as a whole, looks like a special prescription that is formulated in addition to the laws of motion. This circumstance, as well as the impossibility of the direct physical interpretation of singular renormalization relations, leads to the feeling of aesthetic, and

sometimes even in principle, dissatisfaction.

However, the claims that the renormalization procedure has no mathematical sense[8] in any case cannot be supported. As is well known, mathematically the ultraviolet (UV) trouble can be formulated as a problem of multiplication of distributions. The theory of distributions (or generalized functions), as a new chapter of modern mathematics, was created[9,10] as a response to a rather wide use of singular objects (like Dirac delta-function), in theoretical and mathematical physics.

From this standpoint, UV divergences are just a reflection of the indefiniteness in the products of Stückelberg-Feynman propagators (which are generalized functions) when the values of their space-time arguments coincide. On this basis, Bogoliubov and his disciples[11,12] developed a powerful and elegant formalism that can be considered as a "perturbative scattering matrix renormalization without regularization and counter-terms". The central point of this construction is the Bogoliubov-Parasiuk[13] theorem which, with a full mathematical rigor, completely solves the problem of obtaining finite matrix elements without any use of counterterms. The recipe part of this construction - the so-called *Bogoliubov's R-operation* - since that time has served as a basis for obtaining finite single-valued results in renormalizable QFT.

The traditional appreciation of the physical content of the term *renormalization* is directly connected with its immediate meaning, and the "obvious" picture of particles dressed by interaction. Such a simple point of view was, for many years, supported by quantum electrodynamics (QED), where the renormalization procedure at the very end is equivalent to a redefinition of two parameters, mass m and charge e of the electron, e.g.

$$e_o \to e_{phys} = Z\, e_o \qquad (*)$$

However, as was later realized, generally, there exists no simple correspondence between the initial Lagrangian parameters and the renormalized quantities, in terms of which the observables are parametrized. As is well known, even in the simplest case of a one-coupling massless model (like QED in UV limit), the results of renormalized calculations depend not only on the renormalized coupling value, but also on a scale parameter μ, which provides the scale where initially there was none.

A rather instructive example is provided by the model of Yukawa pseudoscalar pion-nucleon coupling. Here, in the course of renormalization, there "spontaneously" arises the second coupling constant of quartic pion self-interaction. More complicated situations arise in the models with the Higgs mechanism, and especially in nonperturbative quantum chromodynamics (QCD), where the renormalized parameters, in terms of which the physical results are parametrized, are hadronic masses rather than renormalized quark masses and couplings.

Concerning the physical aspects of infinite renormalization, one should say that the renormalization relations like (*) (with a singular factor Z) must not be discussed physically at all. The point is that it is impossible to take the electron of vacuum fluctuations and measure its bare charge e_o . This means that the problem is on the same logical footing as the question of a trajectory existence for a quantum particle. Hence if we identify the "physical sense" with "measurability", all physical

motivations against infinite renormalization disappear.

The property of renormalizability in the late forties was first considered as a limitation coming from the imperfection of available theoretical methods. This point of view gradually changed, and presently renormalizability formalizes the possibility of constructing a self-consistent quantum version of a given field interaction model. It may be said that renormalizability is equivalent to quantizability.

Let us note that the above terminology, in accordance with the underlying traditional ideology, treats the classical field as primary and the quantum as secondary. However, we know quite well that it is the quantum picture that is adequate to physical reality, the classical one being only an approximation. Hence it is necessary to consider just the quantum field as the primary physical entity, the sole entity which stands for fields and particles of classical physics and transforms into them in the corresponding limits. From this point of view, the renormalizability-quantizability property acquires another meaning. It should *now be considered as an existence condition for the problem of constructing a consistent quantum-field interaction which obeys the classical analog of a given form.* This is the content we shall attribute to the quantizability principle in what follows.

We see also that nonrenormalizability is equivalent to the impossibility of formulating a consistent quantum model of a given field-interaction mechanism. From this standpoint, models turn out to be equivalent to the four-fermion Fermi: pseudovector Yukawa and pseudoscalar Yukawa interactions (with a single coupling constant, i.e., without direct pion-pion interaction), as well as the gauge electroweak model of just the lepton (with noncompensated triangle anomalies). All these interaction mechanisms cannot be obtained from any consistent quantum field models as suitable (semi)classical limits.

What is the physical content of the notion of renormalizability? The pragmatic answer can be formulated as a ban on the power rise of matrix elements and cross-sections with energy. A more sophisticated one tells[14] us that, "The physical meaning of renormalization is that the influence of *small* distances on the physics at *large* distances may be effectively allowed for with the aid of a restricted number of finite parameters". The result of the above discussion provides us with another further answer. The renormalizability ≡ quantizability means the realizability on the quantum level.

3. Dynamical Principles of Quantum Nature

We can now give a simple formula for *the principle of quantizability*, generalizing the property of renormalizability:

> In a relativistic field theory one should consider only those interaction mechanisms which allow a nonconradictory quantum treatment, and represent the classical counterparts of self-consistent quantum-field models.

The gauge dynamics principle is based upon the concept of local gauge symmetry, beginning with the papers of Yang-Mills and Utiyama, in the mid-fifties. It starts from the idea of the nonobservability of the phase of a field function. The physical content of this idea is connected with the quantum nature of this object, which can be considered as the operator generalization of

the relativistic Schrödinger-Dirac ψ function. In other words, a simple physical interpretation of the local gauge symmetry can only be given for quantum fields.

The third principle is *the principle of supersymmetry*, which is very popular in modern speculative constructions. This symmetry connects QFs obeying different quantum statistics. The supersymmetry transformations involving Bose and Fermi field operators cannot be simply formulated for classical fields.

As far as the formulation of all three principles just mentioned is concerned, essentially they involve specific quantum ideas and notions; they can be considered as *Principles of Quantum Nature*.

We turn now to the role[2] of these principles in forming the basic features of modern QFT. Recall first that, even in the early fifties, it became clear that in QFT the arbitrariness in the Lagrangian of a given system of fields is described by a small number of interaction constants. This is in sharp contrast to quantum mechanics where the problem of the interaction of a given set of particles can be formulated with arbitrary functions (potentials) for every pair of particles. The QFT does not admit arbitrary functions, this follows from the requirement of renormalizability or quantizability.

Relations between different coupling constants can be established with the help of local gauge symmetry. Besides, this symmetry also prescribes the form of the interaction dynamics. It is of a very specific form and involves a gauge vector field responsible for the interaction. The minimal form of this interaction with different matter fields is characterized by a single coupling constant.

Towards the end of the seventies it became clear that not only electromagnetic, but weak and strong interactions as well, are mediated by the gauge dynamics mechanism. Due to this the theory of interacting quantum fields describing the microcosm is essentially ruled only by three coupling constants. Beyond this nice and simple picture there still stands gravity. As is well known, since Utiyama's paper, classical gravity can also be described in the language of local symmetry dynamics. However, the problem of quantum gravity is not solved yet. Here the most popular hopes are connected with supergravity and superstrings.

Supersymmetry establishes simple connections between coupling constants within a definite set of Bose and Fermi fields forming a superfield. Hence the implementation of the third quantum principle again reduces the amount of freedom in the dynamics of QFs.

If a superfield contains a vector gauge field we obtain a "supergauge" field. In the corresponding supergauge models mutual cancellation of divergences from contributions of different constituents of the superfield is possible. Formally, the situation is close to the Pauli-Villars regularization. A crucial point is the presence of a non-Abelian gauge field which plays the role of the Pauli-Villars demon in a compensation procedure. The demand for a such cancellation reduces further the possible choice of quantum field models.

We see that the subsequent use of these "quantum nature" principles introduces a powerful deterministic element into the realm of quantum phenomena which is reigned by statistical laws.

4. The Present Status of QFT

The QFT development, in the course of the last 15 years, seems to be proceeding along two lines. One of them, which can be considered more pragmatic, is devoted to the solution of problems connected with current theoretical and experimental puzzles. The second, which is more speculative, looks for further generalizations and simplifications of the whole theoretical picture, based mainly on the ideas of supersymmetry and superstrings.

To illustrate existing trends and problems in particle interaction theory, let us turn to the running coupling plot presented in the Figure. The zigzag line "I" marks the *frontier* region correlated with the upper energy and momentum transfer values accessible at particle accelerators. The cloudy object "II" located at 10^{15} - 10^{19} Gev symbolizes the region of *super-theoretical* speculations.

The frontier agenda is tightly connected with real physics, i. e. with needs of a theory explaining observed data. Here we meet such deep problems as confinement, the origin of the Higgs mechanism, the structure of a gauge vacuum state and methods of nonperturbative analysis.

Quite contrary to this, the goals of supertheory are more pretentious and sophisticated. They include the search for Grand Unification, supergravity and the "Theory of Everything" ; implying the solution of such problems as the origin of electric charge quantization, mass hierarchy, quantization of gravity and elimination of UV divergences.

It must be noticed that the initiation of such superphysical strategy in modern QFT had used mainly internal logical and aesthetical reasoning. No direct experimental evidence of any sort indicating a need for supersymmetry has so far been found.

From our general point of view, as formulated in Section 1, the most important issue in the superphysics agenda is the quantization of gravity. The solution of this problem will give us a simple and closed picture for the all matter in the Universe.

The spirit of superphysical strategy can be related to the methodological ideas put forward a half a century ago by Dirac[15], which can be summarized by the maxima formulated in 1959, during his visit to the Chair of Theoretical Physics at the Moscow Lomonosov University: "Physical laws should have mathematical beauty". As we learn from the history of QFT this was often the case. However, we also know that not every mathematical beauty can be found in Nature.

Let us now take a glance at QFT evolution from the outside. After about six decades of its development, local QFT is firmly recognized as the only basis of microparticle theory. Its ideas and results play more and more increasing roles in other parts of physics, like astrophysics, cosmology and nuclear physics.

At the same time, many theoretical methods that had been created for particle physics theory (e.g. Feynman diagrams, Schwinger-Dyson equations, renormalization group), were successively applied to the other diverse parts of theoretical physics. In this context, QFT should be considered as a frontier part, both physically and methodologically, of the whole of theoretical physics.

From the inside point of view, during the second half of its existence, the theory of quantum fields has undergone an essential simplification of its inner logical structure. Conceptually, the primary result is the discovery of a simple and universal algorithm for constructing a dynamics of relativistic quantum fields based on the gauge principle: "the symmetry determines the dynamics". The realization of this thesis substantially simplified the logical structure of the field interaction, giving it features of universality.

However this progress arose on a rather complicated foundation. The price paid consists of two parts:

- complication of the mathematical formalism and
- rise of the physical abstraction level.

Here we mean that chapters of mathematics, such as generalized functions (distributions), Lie groups, functional integrals and geometrical methods, became ordinary tools of theoretical physics research. At the same time, during the last quarter of this century, there appeared, in particle theory, a new stratum of basic physical objects and notions that cannot be observed directly. To the nonexistence of the electron trajectory there have been added the nonobservability of a new quantum number "color", underlying the strong interaction dynamics and the nonobservability of quarks and gluons. The idea of a vacuum as a complicated state having little in common with a physical void became accepted. It can be said that in the modern theory of the microworld we are dealing with a higher level of abstraction of the fundamental physical concepts than in quantum mechanics. This tendency might be emphasized even more strongly in the near future, if super- theoretical constructions obtain some physical support.

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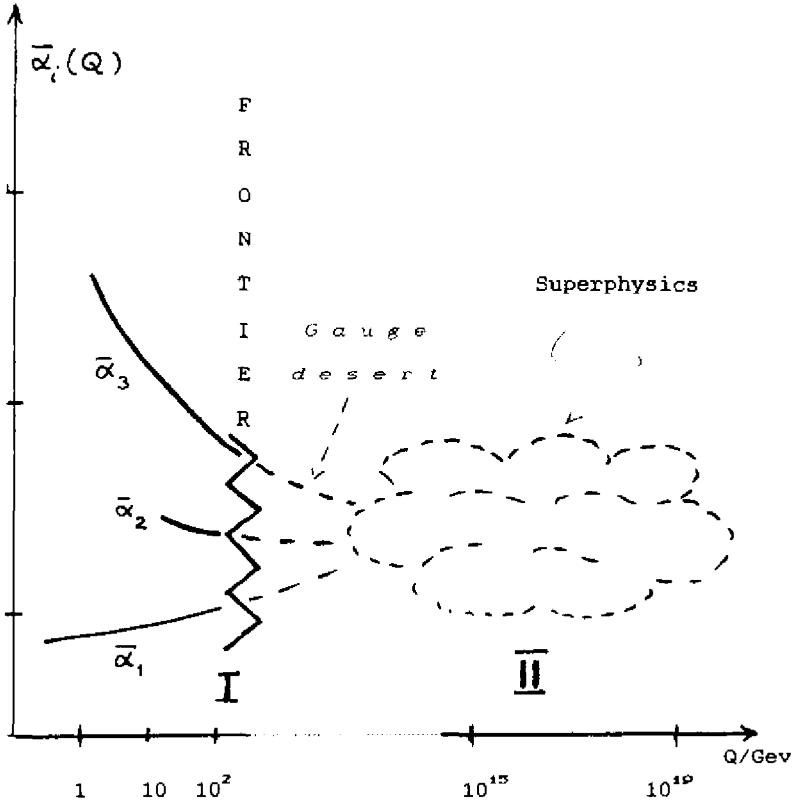

Confinement	GUT,
Higgs mech.	Proton decay,
Gauge vacuum	Quantum gravity,
T-quark	Superstrings

Figure

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