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Quantum Theory of Fields and Origin of Gravity

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The unification of the quantum theory of fields and general relativity is supposed possible on the basis of Sakharov's hypothesis that gravity results from variations in vacuum fluctuations. It is shown that under very general conditions this hypothesis leads to Riemannian geometry of the world-lines of free particle motion. The origin of causal spacetime relations is discussed as the problem complementary to that of the source of geometry. This involves an interpretation of the EPR experiment and supports the idea that spacetime relations in microphysics result from adjusting quantum processes to the causality of macroscopic participators.

INTRODUCTION

Since the first article by Einstein (1918) on the energy description in general relativity (GR), the attempts to incorporate gravity into the mainstream of field theories count-up a number of fundamental and seminal works, such as Arnovitt, Deser, and Misner (1960), DeWitt (1961, 1967), Utiyama (1597), Kibble (1961), Isham (1975), and Marlow (1980). In the recent development the theories of gravity prevail that either consider gravity as a local gauge group of the global Poincare group (Utiyama (1957), Kibble (1961), Sciama (1962); also see Hehl et al. (1976) for a review) or, in the next promising step, as supergravity, i.e., the local gauge group of global supersymmetry (see Deser (1980), van Nieuwenhuisen (1981), Wess and Bagger (1983), and Duff, Nilsson, and Pope (1986) for a review). No generally acknowledged views however exist so far on the subject.

Sakharov (1968) has introduced an unorthodox idea into quantum treatment of gravity. He assumes that gravity is not a fundamental quantum field but an induced quantum effect caused by an interaction of quantum vacuum fluctuations with spacetime curvature. According to Sakharov

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(1982), Sakharov's commentary, p. 159). "The zero-point Lagrangian of the gravitational field is a vacuum correction" brought about by "the change in the action quantum vacuum fluctuations accompanying the curving of space." The Hilbert action for gravity

$$S = -\frac{1}{16\pi G}\int R\sqrt{-g}\, dx$$

is interpreted as a correction of the first power relative to the invariants of the Riemann tensor, with gravitational constant, G, defined by

$$16\pi G^{-1} \approx \int_0^{k_0} k\, dk$$

This integral is constructed from dimensional considerations, k_0 being a cutoff impulse. In the single-loop approximation Sakharov has found

$$G^{-1} = \frac{1}{2\pi}\sum c_i m_i^2 \ln\frac{\Lambda}{m_i^2}$$

where c_i are constants ~ 1, and Λ cutoff parameter.

The proclaimed secondary status of gravity implies the calculability of gravitational constant in the framework of a "right" quantum theory with calculable particle mass spectrum. According to the recent development (see Adler (1980, 1982) and Misner, Thorne, and Wheeler (1973) for a review), the calculability is expected to be realizable within a class of quantum field theories.

The approach based on an action principle however scarcely removes all the issues submitted by gravity. (a) The Hilbert action gives itself no clue to a mystery of gravitational energy. (b) Though being of a secondary origin, gravitational field has to be quantized, so that an expanded quantum formalism should be developed to adopt all the gravity anomalies. (c) Though not being fundamental from the quantum point of view, the theory of gravity will probably alive as a theory of spacetime because the observable curved spacetime includes all gravitational phenomena and therefore inseparable from them.

Sakharov's concept can however be also formulated in terms of a microscopic model dealing with quantum fluctuation unambiguously. This is the way chosen in the present paper. The paper aims to explore Sakharov's concept making no use of quantities that still remain ill defined in reference to gravity, such as corrections for gravitational energy which itself waits for its clear definition.

Calculations in Section 1 are supposed to be a starting point of the program. They show that under fairly general conditions the inhomogeneity in vacuum fluctuations induces the Riemannian spacetime geometry. Exposing the roots of gravity to be in vacuum fluctuations, this approach gives a fundamental meaning to the process of geodesic deviation rather than to metric. The structure of the Einstein equations is examined from this point of view. This leads (Section 2) to the definition of invariant gravitational energy. These results are expected to provide a background for the attempts of deriving the Einstein equations on a microscopic basis.

In short, a way to the invariant energy description is the following. Taking into consideration the Einstein equations, one arrives at the idea that the source of gravity, i.e., the energy-impulse distribution in spacetime, has its immediate counterpart in vacuum inhomogeneity which duplicates this distribution. Then, the vacuum inhomogeneity in empty space should be a counterpart of gravitational energy located there. This leads to the energy-momentum tensor for gravity to be a tensor with ten independent components, like for ordinary matter, but with the algebraical structure of the Weyl tensor. This is in accordance with the recently given (Gliner and Dymnikova (1983)) covariant energy description of gravity. The Einstein equations are generalized to fourth rank equations in order to include gravitational energy.

The duplication of energy-momentum distribution by the pattern of the vacuum inhomogeneity implies that the Einstein equations should be regarded as *equivalence relations* (of the "$E = mc^2$ kind") rather than differential equations (cf. Gliner and Dymnikova (1983)). This seems to be important for understanding the origin of spacetime relations.

Another expectation, based also on Sakharov's vision ((1982), papers 15 and 16), is that the gravity in empty space represents a kind of vacuum polarization caused by matter. The slow decrease of the polarization is due to the absence of negative masses, so that there arises no double charge-layers that localize the polarization strongly. In this vision the origin of the Einstein equations is a problem of quantum polarization that should be now reconsidered with due account of the Weyl pattern of gravitational energy. Therefore a promise exists that the Einstein equations, at least in the first approximation, can be obtained independently of so far questionable quantum theories of advanced levels.

Sections 3 and 4 discuss extremely hypothetical issues of the origin of $(3+1)$ spacetime dimensionality and causality in their possible connection with quantum fluctuations.

The involvement of vacuum fluctuations in the curving of spacetime implies that spacetime on the whole can also be closely connected with the fluctuations (cf. Misner, Thorne, and Wheeler (1973). In Section 3 a pregeometry is constructed as a set of the fluctuations with ordering operators identified with particles. A possibility is discussed that $(3+1)$

dimensionality and causality are not inherent in or generated by this set. Their institution is assumed due to the *macroscopic censorship*—the same ties that exist between macroscopic participators and quantum reality. In Section 4 the idea of an indefinite dimensionality on the pregeometrical level is linked with a kind of proximity revealed in such phenomena as distant quantum correlations or the identity of physical constants throughout the universe.

Sakharov's idea about a fundamental role of vacuum fluctuations in physical world is apparently a way to the unification of still separated branches of physics.

1. The macroscopic averaging eliminates the influence of uniformly distributed quantum vacuum fluctuations on macroscopic particle's world-lines. But an inhomogeneity in the spacetime distribution of the fluctuations would cause a systematic drift of a particle along the gradient of the inhomogeneity. Such a process cannot be eliminated by averaging and therefore affects the particle motion. One can suspect that just this inhomogeneity causes a geodesic deviation that transforms Minkowskian spacetime into a curved spacetime.

There is a philosophic reason for this hypothesis (it is really a reminiscence of a known Einstein's remark concerning spacetime). The unvarying density of vacuum fluctuations would turn the fluctuations into an unphysical phenomenon which influences other phenomena but is influenced by nothing. So, the distribution of vacuum fluctuations is expected to be a dynamic variable. Another reason. Because of the evidence that free particle motion is independent of particle properties, the run of the world-lines of free motion provides the only arena where an inhomogeneity in vacuum fluctuations can be clearly displayed.

The complete quantum consideration is not necessary to estimate the general effect of a vacuum inhomogeneity on macroscopic particle motion. The Markov theory is applicable to fluctuations under very general conditions. The formal mathematical postulates that give the meaning to the macroscopic averaging can be the following. (a) Microscopic particle motion is a strong Markovian process, i.e., the subsequent random displacement of a particle only depends on a *random* current state of particle motion but not on any preceding conditions ("future is independent of past for known random present"). (b) Spacetime has an intrinsic probabilistic topology, i.e., open spacetime domains can be specified so that a particle inside an open domain will stay there for a nonzero time. Under these conditions averaged particle paths exist and each of them can be defined as a continuous function of a parameter affiliated with a path. In terms of spacetime geometry it can be affine parameter. These general results lead us to avoid the averaging itself but nevertheless find the class of geometries to which the averaged paths belong.

The "weak equivalence principle" says that the particular properties of elementary particles do not contribute to their averaged paths. In the context of the present paper or Sakharov's action principle it is a quantum postulate which should be justified in a future quantum consideration. In terms of microscopic particle motion the postulate can be formulated as follows. The frequency of the displacements of a particle influenced by vacuum fluctuations is equal to particle's characteristic frequency, mc^2/h, whereas each displacement is equal to the Compton length of the particle. Then a particle roams with the velocity of light, independently of the particle properties. The microscopic paths of unidentical particles are composed from the displacements of specific characteristic length for each kind of particles. Since however the frequency of the displacements is in inverse ratio to their length, the difference between microscopic paths of unidentical particles does not influence the macroscopic particle paths.

The world-lines of freely moving particles represent the *only basis* for all geometrical physical measurements. In the sense of this *principle of relativity*, the spacetime geometry is the geometry of the world-lines. A metric is introduced by the condition that the world-lines are extremum lines of this geometry. In the sense of this identification, the world-lines of free motion are below called *geodesics.*

An inhomogeneity in vacuum fluctuations will be called *weak* if the corresponding spacetime geometry has, as its tangent geometry, the geometry belonging to a homogeneous fluctuation pattern. This implies that the weak approximation can be defined by the condition that the effect of fluctuations should be completely expressed in terms of one scalar potential function because a tensorial potential would be incompatible with the suggested local homogeneity. The pattern of relative accelerations of geodesics is therefore established by means of the derivatives of a scalar function. This particularly means that in the limit of vanishing gap between geodesics the influence of the inhomogeneity on their relative run vanishes also (no effects on the particle itself in the weak approximation). Therefore, the vacuum inhomogeneity affects no characteristic of a single path, all effects are relative, involves two or more paths, and distance conditioned. Nonsingular gravitational situation can be apparently thought of as related to a weak vacuum inhomogeneity.

In physical measurements each relation between given geodesics can be only defined by means of other, measuring, geodesics crossing the measured ones. The formal technique for such measurements is well-known as the measurements of *geodesic deviation.* To reveal explicitly the symmetry between measured and measuring world-lines, let us consider a symmetric scheme of the infinitesimal measurement of geodesic deviation. Let $\{U\}$ and $\{V\}$ be two-dimensional congruences of geodesics, each of them covering the same open two-dimensional infinitesimal neighborhood $\{P\}$ of a point P. (This geometrical construction is always possible, at least locally, because it is globally possible in the homogeneous spacetime.) Each of these congruences can be used for measuring geodesic deviation in another congruence. One can, e.g., consider a geodesic $U \in \{U\}$, neighboring upon geodesic $U_0 \in \{U\}$ passing through the point P, and use the segments between U and U_0 on geodesics from $\{V\}$ as a basis for measuring a deviation U from U_0. In the same manner, the congruence $\{U\}$ can be used to depict deviation in $\{V\}$.

Along with a spacetime point P, the required scalar function must evidently also depend on variables connected with the both measured and measuring congruences. Let us choose these variables to be displacements along geodesics $U \in \{U\}$ and $V \in \{V\}$. In an infinitesimal neighborhood $\{P\}$ these displacements can be presented as vectors

$$l^i = uu^i \quad \text{and} \quad n = vv^i \tag{1}$$

where u^i and v^i are vectors tangent to geodesics U and V, and u and v increments of affine parameters along these displacements. Then the required function can be supposed to be a function of three arguments:

$$I = I(P;\, l^i, n^i) \tag{2}$$

Since the measurement process is symmetric relative to both congruences, l^i and n^i enter the function symmetrically, i.e.,

$$I(P;\, l^i, n^i) = I(P;\, n^i, l^i) \tag{3}$$

If a congruence $\{V\}$ is taking to be measuring, then n^i has the sense of the *separation vector* between a geodesic U_0 passing through P and a nearby geodesic $U \in \{U\}$.

With the accuracy up to infinitesimal quantities of higher order, the second differences $\delta^2 n^i$ of the separation vector along U are proportional to the acceleration of a geodesic U relative to U_0. Therefore one must suppose that, within this accuracy, the vector field $\delta^2 n^i$ in $\{P\}$ is defined by the derivative $\partial I/\partial n^i$.

The form of the function $I(P;\, l^i, n^i)$ can be now found from the condition that the relative acceleration vanishes in the limit of zero separation. This means that

$$\partial I/\partial n^i = 0 \qquad \text{if} \quad \epsilon_{iab}\, l^a n^b = 0 \tag{4}$$

because there is no separation if vectors l^i and n^i are parallel. Let us consider the formal expansion in the power series relative to l^i, n^i:

$$
\begin{aligned}
I(P; l^i, n^i) = a_0 &+ a_a(l^a + n^a) + a_{ab} l^a n^b + b_{ab}(l^a l^b + n^a n^b) \\
&+ a_{abc}(l^a l^b n^c + n^a n^b l^c) + b_{abc}(l^a l^b l^c + n^a n^b n^c) \\
&+ a_{abcd} l^a l^b n^c n^d + b_{abcd}(l^a l^b l^c n^d + n^a n^b n^c l^d) \\
&+ c_{abcd}(l^a l^b l^c l^d + n^a n^b n^c n^d) + \cdots
\end{aligned}
\tag{5}
$$

where coefficients $a_0, a_i, \ldots, b_{ik}, \ldots, c_{iklm}$ depend on P only. Then, formally,

$$
\begin{aligned}
\partial I / \partial n^i = a_i &+ a_{ai} l^a + 2 b_{ai} n^a + a_{abi} l^a l^b + 2 a_{iab} n^a l^b \\
&+ 3 b_{iab} n^a n^b + 2 a_{abci} l^a l^b n^c + b_{abci} l^a l^b l^c \\
&+ 3 b_{iabc} n^a n^b l^c + 4 c_{iabc} n^a n^b n^c + \cdots
\end{aligned}
$$

Taking $n^i = k l^i$, $k = \text{const}$, one obtains, by virtue of (4),

$$
\begin{aligned}
a_i &+ (a_{ai} + 2k b_{ai}) l^a + (a_{abi} + 2k a_{iab} + 3k^2 b_{iab}) l^a l^b \\
&+ (2k a_{abci} + b_{abci} + 3k^2 b_{iabc} + 4k^3 c_{iabc}) l^a l^b l^c + \cdots = 0
\end{aligned}
$$

Equating to zero terms that are linearly independent relative to k and l^i, one finds

$$
\begin{aligned}
a_i = a_{ik} &= b_{ik} = 0 \\
a_{(ik)l} = a_{i(kl)} &= b_{i(kl)} = 0 \\
a_{(ikl)m} = b_{(ikl)m} &= b_{i(klm)} = c_{i(klm)} = 0
\end{aligned}
\tag{6}
$$

Due to these symmetry properties, the lowest order term contributing to the right-hand side of (5) is the fourth-order term $a_{abcd} l^a l^b n^c n^d$. Allowing for the terms of higher orders in (5), it is easy to show that the fifth-order terms are of orders $l^2 n^3$, $l^3 n^2$, so that

$$
I(P; l^i, n^i) = -\tfrac{1}{2} J_{abcd} l^a l^b n^c n^d + O(l^2 n^3, l^3 n^2) \tag{7}
$$

where $J_{iklm} = -2 a_{iklm}$.

The symmetry properties of the tensor J_{iklm} which immediately follow from this equation are

$$
J_{iklm} = J_{kilm} = J_{ikml}. \tag{8}
$$

Because of (3)

$$
J_{iklm} = J_{lmik} \tag{9}
$$

Finally, it follows from (6) that

$$
J_{i(klm)} = 0 \tag{10}
$$

From the properties of symmetry given by (8)-(10), it is evident that the tensor $J_{iklm}(P)$ must be identified with the *Jacoby curvature tensor.* Therefore one comes to the standard treatment of geodesic deviation in Riemannian geometry. The Riemannian metric can be introduced by the condition for geodesics to be the extremal curves in this metric.

Equating the second difference $\delta^2 n^i$ with $\partial I/\partial n^i$, dividing the equation obtained by u, and passing to the limit $u \to 0$, one obtains the equation of geodesic deviation

$$\delta^2 n^i / \delta u^2 = -J^i_{abc} n^a u^b u^c + o(n^i) \tag{11}$$

which determines the relative acceleration of geodesics in congruence $\{U\}$ in terms of separations given by increments of the affine parameter on geodesics in congruence $\{V\}$.

To make the interpretation of this equation free from the choice of congruences of geodesics, one can perceive that above this choice has been made quite arbitrary. Therefore one can consider (11) as a relation between two arbitrary neighboring geodesics, say U and U', one passing in the direction u^i through a point P and another in an arbitrary direction through some nearby point P'. The segment n^i on the third geodesic connects points P and P'. One can further notice that the choice of U' is also quite arbitrary, and only the variables P, P', and u^i influence the acceleration. So, in terms of particle motion (if applicable), one concludes that all particles passing a point P' are "seen" by an observer passing a point P in a direction u^i as moving with the *same* acceleration given by (9). Hence the property of free moving particles to be mutually accelerated is reduced to the property of spacetime.

This consideration also reveals that the affine parameter v, the "distance" between points P and P', is independent of affine parameter u. Therefore parameter v can be eliminated from equation (11). The Riemann curvature tensor can be introduced by

$$J_{iklm} = \tfrac{1}{2}(R_{ilkm} + R_{imkl}), \qquad R_{iklm} = \tfrac{4}{3} J_{m[ki]l}$$

In the result, the equation of geodesic deviation takes its standard form

$$\frac{\delta^2 v^i}{\delta u^2} = -R^i_{abc} u^a v^b u^c \tag{12}$$

where, however, the Riemann tensor gets the new interpretation as a manifestation of a vacuum inhomogeneity. Passing to the limit $u \to 0$, $v \to 0$ in (5), one can also find the finite form of the scalar function (3),

$$\hat{I} = \lim_{u,v \to 0} u^{-2} v^{-2} I(P; l^i, n^i) = -\tfrac{1}{2} R_{abcd} u^a v^b u^c v^d$$

2. The touchstone of each attempt to bridge the gap between quantum theory and general relativity is probably the gravitational energy. The energy-momentum operator is inseparable from a quantum formalism. Merging gravity into this formalism is therefore inevitably ambiguous until the covariant energy description of gravity is found and introduced into the quantum consideration. The present paper discusses only the classical aspect of this problem. The recently given (Gliner and Dymnikova (1983)) covariant energy description of gravity is confirmed here from the point of view delivered by Sakharov's concept. The description seems appropriate for incorporating it into a quantum formalism.

Sakharov's concept alters the starting point of GR. With the idea that the roots of gravity are in vacuum fluctuations, the process of geodesic deviation acquires a fundamental sense, analogous to that of metric in the standard approach. Hence, it is the equation of geodesic deviation that should appear now as the geometric basis of the theory. The reference to the metric tensor as the main concern of the Einstein equations

$$G^i_k = -\kappa T^i_k \tag{13}$$

now seems to be out of place, so that these equations must be reinterpreted with due regard of this fact. Let us consider the decomposition of the Riemann tensor given by

$$R^{ik}_{lm} = I^{ik}_{lm} + C^{ik}_{lm} \tag{14}$$

where C^{ik}_{lm} is the Weyl tensor and

$$I^{ik}_{lm} = -\tfrac{1}{2}(\delta^i_l G^k_m - \delta^k_l G^i_m - \delta^i_m G^k_l + \delta^k_m G^i_l) + \tfrac{1}{3}(\delta^i_l \delta^k_m - \delta^k_l \delta^i_m)G \tag{15}$$

which is a tensor equivalent to the Einstein tensor due to

$$G^i_k = I^{ia}_{ak} - \tfrac{1}{2}\delta^i_k I^{ab}_{ba}$$

Equations (13)-(15) include only algebraic operations. In that way Einstein's equations appear, in the concept of the vacuum inhomogeneity, to be algebraic rather than differential. This means that they constitute an *equivalence relation*, in the same sense in which this term is commonly applied to the equation $E = mc^2$. This equivalence relation is between energy (understood in the sense of the full energy-momentum ternsor T^i_k) and the vacuum inhomogeneity described by the tensor G^i_k or, which is the same, I^{ik}_{lm}. In this sense, "energy is vacuum inhomogeneity" (cf. also Zel'dovich, 1967).

To complete this interpretation, the second term in equation (14), the Weyl tensor, should also find its energetic equivalent by means of some equivalence relation analogous to the Einstein equations (13). The simplest consideration is the following: Since vacuum inhomogeneity duplicates "energy," the vacuum inhomogeneity in a spacetime region, where energy-momentum tensor vanishes, is the equivalent of the energy of gravity. Therefore, the energy description of gravity is produced by a tensor with the symmetry of the Weyl tensor, both these tensors are joined by an equivalence relation.

The analogues conclusion has been already made by Gliner and Dymnikova (1983) and explained as follows. The conversion of Newtonian space and time into the Minkowskian spacetime caused the correlated modification of the energy description of matter. One may expect a further modification concurrent to the institution of Riemannian spacetime geometry. This modification has to be done with due regard of the anisotropy of Riemannian spacetime: a corresponding anisotropy of the components of the energy-momentum tensor might be expected. The formal mathematical realization of this idea (Gliner and Dymnikova (1983)) converts the energy-momentum tensor into a forth rank tensor, say T^{ik}_{lm}, with the same symmetry as the Riemann tensor. The contraction of this fourth-rank *energy tensor* gives the standard energy-momentum tensor. The traceless part, $\tilde{T}^{ik}_{lm}$, of the energy tensor, which was called the *energy deviator*, has the same algebraic structure as the Weyl tensor. Therefore these tensors can be combined in an equivalence relation

$$C^{ik}_{lm} = -\kappa \tilde{T}^{ik}_{lm} \tag{16}$$

complementary to the Einstein equations. In particular, this equivalence relation provides the full energy description of gravity. The energy deviator describes the spacetime anisotropies of the components of the energy-momentum tensor, i.e., anisotropies of mass, impulse, and their fluxes.

Equation (16) can be regarded as an equivalence relation covering the part of the energy associated with the Weyl tensor, in particular with the gravitational field in empty space. The equivalence relations (13) and (16) can be joined in the combined equivalence relation

$$G^{ik}_{lm} = -\kappa T^{ik}_{lm} \tag{17}$$

where G^{ik}_{lm} is the Riemann curvature tensor in the form providing $G^{ia}_{ak} = G^{i}_{k}$, with G^{i}_{k} the Einstein tensor, and T^{ik}_{lm} is the energy tensor in the form providing $T^{ia}_{ak} = T^{i}_{k}$. The agreement of relation (17) with GR follows from the fact that (Gliner and Dymnikova, 1983), being considered as differential equations relative to the metric tensor, this relation can be reduced to the standard second-rank Einstein equations whenever the equations of state for matter are independent of the gravitational field.

The concept outlines above argues in favor of an inhomogeneity in vacuum fluctuations being the origin of gravity understood in terms of Einstein's general relativity. The properties of gravity in this approach, however, naturally acquire their description also in terms of the quantum theory of fields, where previously they appeared peculiar. This raises hope for the unification of quantum and gravity theories on the basis of deducing the Einstein equations from quantum arguments.

3. The $(3+1)$ spacetime relations between vacuum fluctuations were suggested above. This is the view of quantum field theory, but evidently presents only a substitute for the process of the formation of $(3+1)$ spacetime dimensions. The applicability of this substitute in different branches of microphysics seems to be rather trivial. It anticipates the already known macroscopic spacetime relations. Such a trick removes the spacetime formation from the procedure of macroscopic averaging. Therefore some inconsistency exists in the previous section. The experience in microphysics speculations does validate the treatment of vacuum fluctuations in terms of $(3+1)$ spacetime relations (at least in its final results). At the same time, the $(3+1)$ spacetime dimensions remain to be granted as a primary reality, contrary to the expectation that the whole of spacetime geometry, including its dimensional properties, must find its explanation in something more fundamental.

This and the next section are devoted to a preliminary discussion of this point. An effort is made to guess what kind of hypothesis on the origin of the causal $(3+1)$ spacetime relations would be made by an unprejudiced mind influenced by known physical facts rather than *a priori* opinion on the interrelation between micro- and macrophenomena of nature.

One finds just vacuum fluctuations to be the most deep-rooted entities of reality. Therefore an inviting idea is to treat vacuum fluctuations as primary or *primitive* physical events. One can propose, on the basis of the "no *ad hoc* assumption rule," that these primitive events form an uncountable, unordered point set, a *primitive set*, possessing by itself no dimensions and structure (to be, so to speak, the material base of the world). From the common point of view each elementary particle is disturbed by a sequence of vacuum fluctuations. In terms of the primitive set as the primary reality, this picture should be reversed to consider particles in their relation to the primitive set. Then a particle can be pictured as a sequence of these disturbances, i.e., a *primitive path* on the primitive set. In this sense a particle is defined by an ordering operator on the primitive set which arranges some primitive events in an enumerable sequence. The no *ad hoc* assumptions rule assumes further that each primitive path constitutes *its own* particular dimension. A primitive event that is in common for a number of paths can be regarded as a preinteraction between particles. The preinteractions turn the set of one-dimensional paths into a multidimensional primitive net or *pregeometry*.

There exists an internal integer measure given by the number of primitive events along a path. This measure introduces the smallest feasible unit of predistance with no physical constant being involved and no room for an event between two successive primitive events. In terms of this measure one can introduce a predistance between primitive events p_0 and p_1 along a given sequence of path segments as

$$S(p_0, p_1) = \sum_{(\nu)} q_\nu[dx^\nu] \tag{18}$$

where $[dx^\nu]$ is the number of primitive events on the νth segment and q_ν is a matrix, all of these segments together are assumed to constitute a given path between p_0 and p_1. The measure quadratic in S can be introduced as

$$S^2(p_0, p_1) = e_1[dx^1]^2 + \cdots + e_\nu[dx^\nu]^2 + \cdots \tag{19}$$

where $e^2 = 1$, and the number of dimensions is not restricted.

Thus, some structure arises to a considerable extent naturally on the primitive set. But somewhere near this point the potentialities contained in the starting notions are exhausted, and one faces two options: either (1) admit that a spacetime ordering comes into the primitive set from an upper physical level (e.g., as a result of a selection rule posed by some already existing laws governing the particle behavior, so that only such virtual paths or geometries *survive* that are in accordance with the laws); or (2) without any intrinsic causes, introduce between elements of the primitive set such peculiar interrelations that are already equivalent to certain advanced physical laws that provide spacetime ordering suitable for sensible physics.

That the physical laws are founded on the deepest level of reality is probably the traditional train of thought. But no evidence really exists in favor of this point of view, whereas the relation between classical and quantum mechanics testifies to quite the opposite.

According to Landau and Lifshitz (1977), "A more general theory can usually be formulated in a logically complete manner independently of a less general theory which forms a limiting case of it.... It is in principle impossible, however, to formulate the basic concepts of quantum mechanics without using classical mechanics." Distant correlations in quantum systems demonstrate the nontrivial character of this peculiar relation, as was first revealed by Einstein, Podolsky, and Rosen (EPR) (Einstein *et al.*, 1935). Let us summarize the relevant facts in terms of paths in the phase space of a quantum system:

Let D be the set of possible macroscopic participators (experimental arrangements) d in the spacetime development of a quantum system Q. For a given $d \in D$ there exists such a set P of the virtual phase paths p of the system Q that the quantum mechanical probabilities of the values of observables can be defined by the Feynman integration along the paths $p \in P$. The

EPR phenomenon is the fact that $P = P(d)$, i.e., P depends on $d \in D$. To describe the total situation, one can say that although the union $\bigcup_{d \in D} P(d)$ of all sets $P(d)$ represents the quantum system proper, only such virtual paths *survive*, i.e., contribute to the quantum mechanical probability, that are compatible with a given macroscopic participator $d \in D$ obeying the laws of classical physics.

Applying this rule to the primitive net, one evidently has to conclude that only such primitive paths survive (in their interrelation with upper physical levels) and contribute to the macroscopically observable particle motion that are compatible with the $(3+1)$ geometry of macroscopic participators. Thus, the quantum concept of macroscopic participator justifies the consideration of microphysical reality in terms of the $(3+1)$ geometry that is granted from above. By analogy with quantum mechanics, no consideration of the process of surviving itself is expected to be necessary and, probably, possible.

4. In searching for the origin of the $(3+1)$ causality, the idea of surviving redirects us to macroscopic physics. This is in line with causal relations in quantum mechanics. Based on the correspondence principle, quantum mechanics introduces no causal requirements that would be stronger than the macroscopic causality in the macroscopic limit. This implies that all causal relations in quantum physics can be formulated in terms of its limiting case, macroscopic physics. Therefore, within the scope of the no *ad hoc assumption rule*, one might expect that any process at a microlevel is causally admissible if no violation of causality at the macroscopic level is involved. Probably no theoretical evidence exists against a much stronger statement: microphysics is the expansion of macrophysics subjected only to the condition that macrophysics is provided as a limiting case. This, so to speak, *principle of macroscopic censorship* adopts the minimum of *a priori* assumptions, can serve as a working principle, and allows of verification.

In the spirit of the idea of surviving or macroscopic censorship (in its strong or weak form), one concludes that causality "enters" physics at the macroscopic level with causal relations relaxing downward. The complete lack of predictability at the lowest level would be logically satisfactory because the lack of even stochastic causality eliminates the irrational speculation of the existence *ad infinitum* of deeper and deeper levels inside physical substance.

The causality relaxation could clear the way to a number of unclassical interactions. Not restricted in their spreading by the speed of light in the $(3+1)$ macroscopic manifold, they could be a tool for linking a large physical system into a single whole in spite of the impossibility of classical interaction between remote parts of the system. The existence of distant correlations in quantum systems apparently confirms that the set of unclassical interactions is not empty. These correlations represent (at least in the scope of a not extremely sophisticated interpretation) quantum effects including either the instant change of the state of a system or the influence on a system of an arrangement involving no classically defined forces. Along with the EPR phenomenon, distant correlations are inherent in such effects as the influence of spin on the symmetry of a wave function, the unlocalizability of a particle in relativistic quantum theory (Hegerfeldt, 1984; Hegerfeldt and Puijsenaars, 1980), the Aharonov–Bohm effect (Aharonov and Bohm, 1959; Wodkiewicz, 1984; Babiker and Loudon, 1984), and the influence of a distant magnetic field on the angular momentum of a system (Lipkin and Peskin, 1982). All these formally nonlocal effects cannot, however, provide macroscopic superluminal signals and therefore involve no violation of macroscopic causality.

Considering all these effects as a relaxation of causality that results in some kind of instant communication, one comes to the idea of *non-Einsteinian proximity.* The idea of an unusual proximity also arises in fields not connected with quantum mechanics immediately, e.g., in the problem of the identity of physical laws and constants throughout the universe. In the search for a clue to the origin of the fundamental constants, for example, it is natural enough to seek their roots in the most universal logical constructions, such as natural numbers or arithmetic axioms. Such an approach must deal, however, with the problem of the *anthropic peculiarities* of the universe. Even a small alteration of the values of the fundamental constants would cause such deep changes in the universe that neither human beings nor organic life would be possible (Dicke, 1961; Carter, 1974, 1983; Carr and Rees, 1979; Press and Lightman, 1983). So, either the anthropic collection of the fundamental constants is already contained implicitly in the "primordial things and ideas" such as natural numbers or arithmetic rules, or the constants drop into newly arising universes stochastically, so that life has a chance to appear in a convenient universe. The first alternative implies an unbelievable predetermination of just the anthropic universe in the utmost abstract notions (though why not?). So, one probably prefers to choose the second and try to explain how stochastically arising entities can be identical over the whole universe.

There is an analogy between this problem and distant quantum correlations. The argument of the impossibility of a causal communication between the remote parts of a physical system is present in both cases, as well as the affiliation of all involved physical quantities to the same integral physical system (the universe in the first case, an isolated quantum system in the second). Therefore, one can believe that just the relaxation of macroscopic causality leads to effects that provide remarkable properties of the universe, such as the uniqueness of the physical laws and constants, the universal symmetries defining fundamental properties of matter, and the ability of a physical system to act as a whole. The non-Einsteinian proximity acquires in this interpretation the simple physical meaning of affiliation to a single physical system.

Some kind of restoration of the prestige of macroscopic physics laws follows from the above discussion. This does not seem surprising. After macroscopic averaging, the congruence of virtual paths of a quantum system turns into a single admissible path. This gives no reasonable choice but deterministic causality at the macroscopic level. The observed arranging role of macroscopic participators—i.e., the significance of the limiting case of a more general theory—simply makes clear that just the unflexible macroscopic causality logically restricts the variations of physical reality and, in particular, fixes $(3+1)$-dimensional spacetime geometry as one of the geometries (or the unique geometry) that provides *the consistency of physics as a whole.* The idea, put in an especially sharp form by Wheeler (1980; Misner *et al.*, 1973), of a *logical ground* of physics is therefore extended to the thought that deterministic macroscopic physics is a logical ground (roof?) of physics. Being a deterministic scheme, macroscopic physics could be considered as an isomorphism of a "calculus of propositions" in accordance with Wheeler's idea.

In this connection, it is a fact of great importance that the system of macroscopic laws is unique, at least in some restricted sense. For instance, a world with another number of spacetime dimensions than ours would possess some anomalies making impossible the existence of stable atoms (Gurevich and Mostepanenko, 1971). The principle of macroscopic censorship leads us to expect that the problem of the uniqueness of the system of physical laws can be reduced to the corresponding problem for macroscopic laws only.

From the considered hypothetical point of view, the problem of the unification of quantum theory and general relativity cannot be dealt with apart from the context of the causal structure of the physical world.

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REFERENCES

Adler, S. L. (1968). *Physical Review Letters*, **44**, 1567.

Adler, S. L. (1982). *Review of Modern Physics*, **54**, 729.

Aharonov, Y., and Bohm, D. (1959). *Physical Review*, **115**, 485.

Arnovitt, R., Deser, S., and Misner, C. (1960). *Journal of Mathematical Physics*, **1**, 434.

Arnovitt, R., Deser, S., and Misner, C. (1961). *Il Nuovo Chimento*, **19**, 668.

Babiker, M., and Loudon, R. (1984). *Journal of Physics A*, **17**, 2973.

Carr, B. J., and Rees, M. J. (1979). *Nature (London)*, **278**, 605.

Carter, B. (1974). In *IAU Symposium 63: Confrontation of Cosmological Theories with Observational Data*, M. S. Longair, ed., Reidel, Dordrecht.

Carter, B. (1983). *Philosophical Transactions of the Royal Society of London, Series A*, **310**, 347.

Deser, S. (1980). In *General Relativity and Gravitation*, ed. A. Held, Plenum Press, New York.

DeWitt, B. S. (1961). *Journal of Mathematical Physics*, **2**, 151.

DeWitt, B. S. (1967a). *Physical Review*, **160**, 1113.

DeWitt, B. S. (1967b). *Physical Review*, **162**, 1195.

Dicke, R. (1961). *Nature (London)*, **192**, 440.

Duff, M. J., Nilsson, B. E. W., and Pope, C. N. (1986). *Physics Report*, **130**,, 1.

Einstein, A., Podolsky, B., and Rosen, N. (1935). *Physical Review*, **47**, 777 (1935).

Gliner, E., and Dymnikova, I. (1983). *Physical Review*, **28**, 1278.

Gurevich, L., and Mostepanenko, V. (1971). *Physical Letters*, **35A**, 201.

Hegerfeldt, G. C. (1984). *Physical Review D*, **10**, 3320.

Hegerfeldt, G. C., and Puijsenaars, S. N. M. (1980), *Physical Review D*, **22**, 377.

Hehl, F. W., von der Heude, P., Kerlick, C. D., and Nester, J. M. (1976). *Review of Modern Physics*, **48**, 393.

Isham, C. J. (1975). In *Quantum Gravity*. Clarendon Press, Oxford.

Kibble, T. W. B. (1961). *Physical Review*, **2**, 212.

Landau, L. D., and Lifshitz, E. M. (1977). *Quantum Mechanics*, Chapter I, Pergamon, New York.

Lipkin, H. J., and Peshkin, M. (1982). *Physics Letters*, **118B**, 385.

Marlow, A. R. (1980). In *Quantum Theory and Gravitation*, ed. A. R. Marlow. Academic Press, New York.

Misner, C. W., Thorne, K. S., Wheeler, J. A. (1973). *Gravitation*, Freeman, San Francisco.

van Nieuwenhuisen, P. (1981). *Physics Report*, **68**, 191.

Press, W. H., and Lightman, A. P. (1983). *Philosophical Transactions of the Royal Society of London, Series A*, **310**, 323.

Sakharov, A. D. (1968). *Soviet Physics—Doklady*, **12**, 1040 [*Doklady Akademii Nauk SSSR*, **177**, 70 (1967)].

Sakharov, A. D. (1982). *Collected Scientific Works*. Marcel Dekker, New York.

Sciama, D. W. (1962). In *Recent Development in General Relativity. Festschrift für Infeld.* Pergamon, Oxford.

Utiyama, R. (1957). *Physical Review*, **101**, 1597.

Wess, J., and Bagger, J. (1983). *Supersymmetry and Supergravity*. Princeton University Press, Princeton, N.J.

Wheeler, J. A. (1980). In *Quantum Theory of Gravitation*, A. R. Marlow, ed., Academic Press, New York.

Wodkiewicz, K. (1984). *Physical Review A*, **29**, 1527.

Zel'dovich, Ya. B. (1967). *JETP Letters*, **6**, 345 [*Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, Pis'ma v Redaktsiyu*, **6**, 922].