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Time-symmetric quantization of relativistic fields.
2. Electroweak theory. Observable effects of TSQ

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Abstract

In the method of time-symmetric quantization (TSQ) of relativistic systems, based on the Stückelberg-Feynman interpretation, the creation-annihilation operators of quanta of complex fields and massless gauge fields, are automatically normally ordered, and there is no vacuum energy and charge (Z. Zakir 2023, article 1). In this second article the application of TSQ to massive bosonic fields of electroweak theory and the observational consequences of TSQ are considered. It is shown that the vacuum of these fields is free of zero-point energy and zero-point charge, and thus a contribution of these fields to the cosmological constant is absent. A direct observational consequence of TSQ is crossing symmetry in particle physics. The observable effects, which were attributed to the zero-point energy of the vacuum, are actually generated by the fields of real charges, and there is no evidence of the existence of zero-point energy of fundamental fields. This fact contradicts the prediction of the standard formulation of quantum field theory, but indirectly confirms TSQ.

Keywords: electroweak theory, scalar bosons, massive gauge bosons, zero-point energy, Lamb shift, Casimir effect, cosmological constant

Content

1. Introduction

In the first paper [1], the method of time-symmetric quantization (TSQ) was formulated and then it was applied to quantum field theory (QFT) and string theory. TSQ consists in consecutively following the Stückelberg-Feynman interpretation [2,3] at quantizing relativistic systems, the covariant formulation of which includes the negative energy states. It was shown that the vacuum of complex fields in TSQ does not contain zero-point energy and zero-point charge. The photon field and other massless gauge fields are also described in terms of complex fields, since helicity plays the role of a chiral charge.

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In the present second article, firstly, it will be shown that this is also true for fields of electroweak theory. Charged massive bosons $W^{\pm}$ are a particle-antiparticle pair and in TSQ their vacuum has no zero-point energy. The two transverse components of the neutral boson Z_L, Z_R are also charge conjugate, since helicity plays the role of a chiral charge. Therefore, in TSQ, the vacuum of these field degrees of freedom also does not have zero-point energy.

The longitudinal component of the neutral boson $Z_{||}$ appears at gauge transformation instead of one of the components of the neutral scalar field. Prior to this, the two components of this complex scalar field were charge conjugate and their quantization would not lead to zero-point energy. After spontaneous symmetry breaking and gauge transformation, they acquire different masses. However, the masses are given to these scalar fields by means interaction terms, i.e. by mass renormalization. In the free Hamiltonian without the contribution of interactions, they still remain charge conjugate, although one of the scalar fields now appears in the longitudinal component of the gauge boson in the form $Z_{||} \sim \partial_{||}\phi$. Therefore, in TSQ, these field degrees of freedom also do not contribute to the zero-point energy of the vacuum.

At considering the observational consequences of TSQ, it is noted that a direct consequence of TSQ is crossing symmetry, which is well-known and widely used in particle physics. The observable effects, which were previously attributed to the zero-point energy of the vacuum, as has long been known, are fully explained by the fields of real sources. In particular, the Lamb shift is a consequence of loop corrections and has nothing to do with fluctuations of a hypothetical vacuum external field associated with the zero-point energy in the free Hamiltonian. Similarly, the Casimir effect is a consequence of the van der Waals forces that arise from the long-wavelength part of the fluctuating field of atoms in solids. Therefore, in fact, there is no evidence of the existence of the zero-point energy of fundamental fields. This contradicts the standard formulation of QFT, which predicted their presence, and is in agreement only with TSQ. The fact that there is no vacuum energy of free fields in TSQ solves the problem of the cosmological constant with respect to such contributions.

In Section 2, TSQ is applied to the fields of the electroweak theory, and in Section 3, the consequences of TSQ for the observable effects are considered. A more detailed discussion of these issues is given in the book [4].

2. Time-symmetric quantization in electroweak theory

2.1. Quantization of bosonic fields of electroweak theory

Let us consider in TSQ the fields of electroweak theory with local symmetry $SU(2)\times U(1)$. If there is a particle-antiparticle pair, then in TSQ the antiparticle is described as a particle of negative energy going backwards in time, and in such a theory there is no the zero-point energy of the vacuum [1]. The problem arises only for truly neutral particles, which have no antiparticle.

The field operators of two transverse components of a charged gauge field W_L^-, W_R^+ are mutually charge-conjugate and their quanta behave like a particle-antiparticle. The two longitudinal components of these two charged fields $W_{||}^-, W_{||}^+$, appearing instead of the two charge-conjugate components of the scalar doublet $\phi^{\pm}$, also remain mutually charge-conjugated. Therefore, in TSQ, the vacuum of charged gauge fields $W^{\pm}$ does not contain zero-point energy and zero-point charge.

Two transverse components of the neutral gauge field Z_L, Z_R, being analogues of the photon, before giving them mass were mutually charge-conjugate, since the role of the chiral charge was played by helicity. Since mass is given to them by the inclusion of interaction terms, i.e. mass renormalization, then in their free Hamiltonian, which does not contain interaction terms, these two field degrees of freedom still remain charge conjugate. Therefore, their vacuum in TSQ also does not contain zero-point energy.

Within the framework of TSQ, special consideration is required for the longitudinal component of the neutral massive vector field $Z_{\|}$, which appears instead of one of the two components of the complex scalar field ϕ^0, as well as the second component of this scalar field, the Higgs field χ. If these two field degrees of freedom were independent and quantized separately, then in TSQ, each such field without a charge-conjugate component would lead to zero-point energy.

Before the gauge transformation, which eliminated one of the scalar fields and gave rise instead to the longitudinal component of the massive vector field $Z_{\|}$, these two neutral bosonic degrees of freedom were charge conjugate components of the complex scalar field ϕ^0. After the gauge transformation, they acquire different masses and, at first glance, cease to be mutually charge-conjugated states.

In fact, the presence or absence of the zero-point energy of the vacuum refers fully to the properties of the free Hamiltonian, without contribution to this Hamiltonian of the interaction terms leading to the renormalization of masses, charges and field operators. Accounting for this circumstance eliminates the question about the possibility of zero-point energy of these components of the fields. The free Hamiltonian of the electroweak theory contains only massless fields, which are pairwise charge conjugate and do not lead to zero-point energy in the free Hamiltonian. Masses appear effectively after taking into account the interactions with gauge fields and the self-action of the scalar field, i.e. the mass terms are by definition the contributions of the interaction terms. These masses are proportional to the interaction constants and their inclusion in the free Hamiltonian does not introduce zero-point energy, which is independent of any interaction constants.

Thus, at quantization of the electroweak theory fields in the framework of TSQ, zero-point energy and zero-point charge are absent for massless free fields with “bare” masses and charges, and further renormalization of charges and the appearance of effective masses do not generate zero-point energy and zero-point charge of the vacuum (details in

Below, some features of this approach to field quantization and renormalization in electroweak theory will be considered (a more detailed discussion is presented in [4]).

2.2. Free Hamiltonian: absence of zero-point energy and massless propagator

In the electroweak theory, the doublet of complex scalar fields is shifted by adding a real constant η. This shift, through interaction terms, gives effective masses $\delta m_{(i)}$ to the transverse physical components of the gauge fields $W^{\pm}, Z^0$ and the four scalar fields.

These effective masses are proportional to the interaction constants and in diagrams for free propagators of massless quanta appear as two-point interaction vertices dividing the world lines into two parts.

Then in the electroweak theory a gauge transformation is performed that eliminates three degrees of freedom of scalar fields, and instead of them three longitudinal components of gauge fields $W^{\pm}, Z^0$ appear.

However, as soon as the gauge bosons become massive, their propagators no longer satisfy the renormalizability conditions, since they grow faster with increasing momentum than is admissible. This difficulty is circumvented by introducing into the Lagrangian special gauge fixing terms. Then ghost fields, including fermion ones, appear in the Lagrangian, and the theory becomes sufficiently complicated.

As shown in the previous section, within the framework of TSQ, there appears another, simpler and clearer from the physical point of view, possibility of satisfying the renormalizability conditions, while at the same time ensuring the absence of zero-point energy. To do this, it suffices for us, as is usually done in QFT, initially operate with the free Hamiltonian only, without any interaction terms.

The point is that if the two-point interaction terms are included in the bare Lagrangian only because they behave like a mass term, then the question arises: why are the three-point and four-point interaction terms, which have analogues in this Lagrangian, also not included?

Therefore, if the issues of vacuum energy and the construction of free propagators are considered on the basis of the free Hamiltonian, then due to the pairwise charge conjugacy of the fields, zero-point energy will not appear. In addition, because the free propagators of gauge bosons remain the same as for massless fields, the renormalizability conditions are satisfied as usual. The fact that gauge bosons acquire an effective mass upon mass renormalization does not affect their behavior at very small distances, where they behave as massless.

Problems with renormalizability occur only for vector bosons with a bare or "bare" mass m_0 in the free Hamiltonian, which changes the behavior of propagators at high energies. But for gauge bosons with an effective mass δm, the free propagator does not depend on this addition, which arises only when interactions are taken into account. The full propagator, on the other hand, enters only tree diagrams with renormalized charges and grows at large external momenta, which is no longer related to renormalizability.

3. On the observable consequences of TSQ

3.1. Crossing symmetry in particle physics

In the previous standard interpretation of QFT, based on the introduction of states of only positive energy, the operators of negative energy particles a_{-k} and a^*_{-k} were eliminated by replacing "manually" with operators of positive energy antiparticles. At the same time, such a replacement was made directly in the field operators: $a^*_{-k} \to b_k$, $a_{-k} \to b^*_k$, which then led to problems in products of field operators. Then these problems were also overcome “manually”, arranging the operators in the order needed to fit the theory to the experiments.

In TSQ, as well as in one of its forms practically used in particle physics – crossing symmetry, such a replacement of operators also includes the replacement of initial and final states, which leads to non-trivial consequences for the products of operators. Therefore, carefulness and more precise definitions are required here. In particular, all replacements of operators a_{-k}, a^*_{-k} and their products by antiparticle operators b^*_k, b_k and their products must be consistent with the crossing symmetry conditions.

Crossing symmetry allows one to immediately obtain the amplitudes of several “related” processes from the expression for the amplitude of one process. Thanks to this symmetry, a particle in the initial (final) state with a 4-momentum $+p_\mu$ can be transferred to the final (initial) state with a 4-momentum $-p_\mu$ and, changing the direction of evolution in time to the reverse, can be considered a description of an antiparticle:

$$A + B \to C + D, \quad A + \bar{C} \to \bar{B} + D, \quad A + \bar{D} \to C + \bar{B}. \tag{1}$$

Thus, the crossing transformation, consisting of a rotation of the world line around the vertex in the diagram with translation to opposite light cone, changes the sign of 4-

momentum and the time evolution direction, turns a particle into an antiparticle (and vice versa).

During the crossing transformation, the change in the sign of particle's energy and the change in the sign of the time interval cancel each other, which leaves the sign of the antiparticle's energy positive. In this case, the particle moves in the direction of the arrow in the diagram, and the antiparticle moves in the opposite direction. Thus, the line of the particle directed to the past corresponds to the antiparticle going to the future.

At the same time, TSQ, and hence the crossing transformation, refer to separate lines in the Feynman diagram, regardless of other lines, which distinguishes them from the *CPT* transformation, which refers to the entire diagram as a whole.

As an example, consider the relationship between the scattering amplitudes of electrons and positrons in a Coulomb field. The matrix element of the positron transition:

$$S_{fi} = ie\int d^4x \left\langle -p_i, s_i \left| \bar{\psi}(x)\gamma^0\psi(x) \right| -p_f, s_f \right\rangle A_0(x). \tag{2}$$

after substituting the field operators, takes the form:

$$S_{fi} = -\sum_{p,s} \left\langle -p_i, s_i \left| b^+_{-p,s} b_{-p,s} \right| -p_f, s_f \right\rangle \tilde{S}_{fi}, \tag{3}$$

where $\tilde{S}_{fi}$ are all other factors. At the same time, at crossing-transformation of the amplitude for electron scattering, transforming it into the amplitude for a positron, we get:

$$S_{fi} = \sum_{p,s} \left\langle p_f, s_f \left| d^+_{p,s} d_{p,s} \right| p_i, s_i \right\rangle \tilde{S}_{fi}. \tag{4}$$

From comparing the two expressions, (3) and (4), we obtain:

$$-\left\langle -p_i, s_i \left| b^+_{-p,s} b_{-p,s} \right| -p_f, s_f \right\rangle = \left\langle p_f, s_f \left| d^+_{p,s} d_{p,s} \right| p_i, s_i \right\rangle, \tag{5}$$

which is the matrix form of the operator relations for fermions following from the two forms of their Hamiltonian.

Bringing together of the quantization rules in TSQ with the crossing symmetry, which is the fundamental symmetry of particle physics, leads to a number of changes, which, together with those discussed above, lead to the fact that TSQ takes the form of *crossing-symmetric quantization*. Consequences for interacting fields, including refinements in the definitions of causal propagators of particles, rules for ordering of operator products, and rules for diagram technique, are considered in [4].

3.2. Experimental confirmation of the absence of zero-point energy of fields

Quantum fluctuations in the fields of real sources, such as electrons and protons, lead to many observable effects. The predictions of QFT with such real sources agree with experiments, and often the accuracy of such agreement is unprecedented.

A. *Lamb shift.* In particular, the Lamb shift is determined by the interaction energy $H_I^{(r)} = \mathbf{j}\cdot\mathbf{A}_{(r)}$, where $\mathbf{A}_{(r)}$ describes virtual photons, and $\mathbf{j}$ is the current of electrons and protons. Virtual photons are an excited state of the electromagnetic field generated by real sources and they are not related to the hypothetical vacuum external fields $\mathbf{A}_{(0)}$ associated with zero-point vacuum energy $H_0^{(0)}$. Experiments have shown that the observable value of the Lamb shift $\Delta E_I^{\exp}$ is completely explained by the contribution $\Delta E_I^{(r)}$ of virtual photons from real sources:

$$\Delta E_I^{\exp} = \Delta E_I^{(r)}, \qquad (6)$$

In the standard formulation of QFT, however, zero-point fluctuations in the field vacuum should have made an additional contribution to the Lamb shift. In this case, the zero-point energy of the electromagnetic field $H_0^{(0)}$, which was inevitable there, should have been generated by fluctuating vacuum fields $\mathbf{E}_{(0)}, \mathbf{B}_{(0)}$:

$$H_0^{(0)} = 2\int d^3k \frac{1}{2}\omega_k = \int d^3x \frac{1}{2}(\mathbf{E}_{(0)}^2 + \mathbf{H}_{(0)}^2) \qquad (7)$$

and in the total energy there would be a contribution from the energy of interaction of charges with these vacuum fields $H_I^{(0)} = \mathbf{j}\cdot\mathbf{A}_{(0)}$, where $\mathbf{E}_{(0)}, \mathbf{B}_{(0)}$ are field strengths of $\mathbf{A}_{(0)}$. Since this additional interaction energy $H_I^{(0)}$ enters into the interaction Hamiltonian *additively* with the interaction energy $H_I^{(r)}$ of the same particles with the fields of real sources $\mathbf{A}_{(r)}$, the contribution of zero-point fluctuations $\Delta E_I^{(0)}$ had to be summed with the contribution of real sources $\Delta E_I^{(r)}$.

Since both contributions are of the same order (which is why they are usually confused), the predicted energy shifts become actually doubled:

$$\Delta E_I = \Delta E_I^{(0)} + \Delta E_I^{(r)} \approx 2\Delta E_I^{r}. \qquad (8)$$

Observations testify the existence of only a single contribution, which should be attributed to the contribution of real sources ΔE_I^r, since this contribution cannot be ignored.

B. *Casimir effect.* In the case of the Casimir effect, the observable effect is also fully explained by the contribution of the fields of real sources, which are fluctuating atoms of a solid state that generate fluctuating radiation fields. As is well known, the theory of van der Waals forces successfully describes the Casimir effect, including temperature dependences, explaining this effect as a consequence of the radiation field of atoms during their vibrations in a crystal, including vibrations at the “zero-point *temperature*” of the crystal. Since the contributions from purely vacuum fields of $H_I^{(0)}$ are the same order and must be added to the radiation of atoms ($H_I^{(r)}$), then the previous interpretation with zero-point energy in this case also gives twice the value of the Casimir effect than is observable.

Thus, the contributions of real sources, which cannot be ignored, completely explain the results of observations of both effects - the Lamb shift and the Casimir effect. Therefore, the experiments exclude the zero-point fluctuations of the vacuum, and only TSQ is in agreement with these experiments.

However, a myth was created about these experiments, as if they confirmed the opposite statement that the zero-point energy of the vacuum was apparently manifested in them. This myth then took root in the scientific literature and was included in textbooks on QFT. In reality, this myth is based on a logical trick, where the phenomenon is first explained by a desired (but unreal) cause, ignoring the real cause. Then, when the same phenomenon still has to be explained by its real cause, the “proven” contribution of the desired cause is silent, since this addition would violate the agreement between theory and experiment.

In traditional scientific methodology, if a phenomenon is assumed to have two simultaneously influencing causes, then the consequences of their influence must also be taken into account simultaneously. If, however, the phenomenon is fully explained by only one of the causes, the existence of which is beyond doubt, then the second cause must be considered absent and therefore refuted. In our case, the real cause, which cannot be ignored and which is sufficient to explain the observations, is the fields of real sources. The influence of the zero-point fluctuations of the vacuum fields, without which everything is explained anyway, is a myth.

3.3. Solution of the cosmological constant problem for free fields

As observations show, the cosmological constant is very small and TSQ naturally explains this observational fact in terms of the absence of a contribution from the vacuum of free fundamental fields.

But this fact was mysterious in the previous formulation of QFT with a large contribution from the zero-point energy of the SM fields. All attempts to reduce this energy within the framework of the standard formulation of QFT only aggravated the situation, requiring the introduction of an ever-increasing number of unrealistic hypotheses.

At the same time, the existence of gravity from the very beginning made it unacceptable to attempt to eliminate the divergent zero-point energy by artificial methods, such as “normal ordering” or shifting the energy reference point. In this regard, SM, which relied on the standard formulation of QFT, also turned out to be fundamentally untenable, which was strange because of its highest efficiency.

Therefore, the disappearance of the zero-point energy of the vacuum of the fields in TSQ indicates the internal self-consistency and correctness of the physical ideas and principles underlying the entire relativistic quantum theory.

At the same time, this excludes only the contribution of the vacuum of free fields and therefore does not mean a complete solution of the cosmological constant problem. Other possible contributions, such as those of field condensates and other nonperturbative contributions, require further investigation.

Notice, that in the theory of interacting fields, TSQ leads to automatic normal ordering of many products of operators, which excludes divergent loop contributions to the vacuum energy. This fact, therefore, solves the cosmological constant problem also in terms of the contribution of the vacuum of interacting fields, at least within the framework of perturbation theory.

3.4. The absence of zero-point energy in the case of broken supersymmetry

The possible existence of supersymmetry, a symmetry between bosons and fermions, which solves the problems with divergences in field theory and unification problems in particle physics, has been one of the most encouraging and widely developed hypotheses of the last half century.

There were three expectations from this new symmetry: mutual cancellation of the zero-point energies of bosons and fermions, partial cancellation of divergences in loop diagrams, and the possibility of creating simpler models for unifying fields and particles. Here we dwell only on the first of these hopes - on the possible elimination of zero-point energies.

The idea of the possibility of canceling the zero-point energies of bosons and fermions follows from the fact that in the standard quantization of fermion fields, not the usual zero-point energy, but zero-point energy of a negative sign arose!

However, the consecutive quantization of fermions in TSQ showed that, in fact, fermions in the relativistic theory do not have zero-point energy at all. In the previous treatments, the (negative) zero-point energy appeared due to the fact that the antiparticle operators were introduced into the fermionic field functions manually. In TSQ, the transition to antiparticles is made either by crossing-transformation of separate world lines of particles, or by CPT -transformation of the entire diagram, and these operations do not lead to zero-point energy. In the diagrams of specific processes, the transition to antiparticles is done exactly in this way, but such a transition does not change the Hamiltonian precisely because of the indicated symmetries of the Hamiltonian.

Thus, of the three main arguments in favor of supersymmetry, one related to zero-point energies turned out to be really irrelevant.

4. Conclusion

In the first article [1], in which the foundations of TSQ were formulated and its applications to relativistic fields and strings were considered, it was shown that the vacuum of complex fields does not contain zero-point energy. At the same time, the negative sign of the probability flow for particles of negative energy was associated with the fact that their world lines, according to the Stückelberg-Feynman interpretation, are directed backward in time.

In this second article, when considering the application of TSQ to the electroweak theory, it is shown that the main results of TSQ, in particular, the absence of zero-point vacuum energy, also remain valid.

Firstly, all components of the vector field describing charged bosons $W^{\pm}$, as well as the two transverse components of the neutral gauge boson $Z_{\perp}^{0}$, remain pairwise charge-conjugate even after acquiring mass. In TSQ this is sufficient for the absence of zero-point energy in the vacuum of their fields. Special attention is required only for the longitudinal component $Z_{\parallel}^{0}$, which appears instead of one of the two components of the complex neutral scalar field, as well as the remaining second component of this field.

On the one hand, before the acquisition of masses, both neutral field degrees of freedom were mutually charge-conjugate components of a complex massless scalar field. Therefore, within the framework of TSQ, the “bare” Hamiltonian of such fields, where there are no contributions from the interaction terms, does not contain zero-point energy.

Secondly, the particle masses of these field degrees of freedom arise as a result of interactions. Therefore, they are effective masses, being similar additions due to interactions as are the additions to the "bare" masses from loop diagrams, making the latter renormalized masses. But these additions, which are proportional to the interaction constants, have nothing to do with the zero-point energy of the vacuum and, of course, do not generate such an energy.

Thus, since the Hamiltonians and propagators of massive particles used in the theory are “renormalized” in the above sense, then in TSQ the standard form of the electroweak theory practically does not change. The appearance of effective masses due to interactions and the gauge transformation of fields, which rearranges their degrees of freedom, do not lead to the zero-point energy in the free Hamiltonian.

In the article it was also considered the fact that TSQ, excluding the zero-point vacuum energy of the SM fields, is in agreement with known experiments. The fact is that the results of all experiments on effects previously attributed to zero-point energy are completely explained by the contributions of the fields of real charges. This fact confirms TSQ, where there are no such contributions, and contradicts the standard form of QFT, where such contributions were predicted.

The absence of the zero-point energy of the vacuum of free fields in TSQ and in experiments also solves the cosmological constant problem in the part concerning such contributions.

A more detailed discussion of TSQ and its consequences is given in the book [4].

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