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On the invariant properties of quantum uncertainty relations with respect to parameters of virtual photons responsible for interaction processes in quantum particle systems

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A R T I C L E   I N F O

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A B S T R A C T

Uncertainty relations (UR) are considered based on analysis of the peculiarities of virtual photons involved in electromagnetic inter-particle interaction processes in the frame of quantum field theory. Based on the virtual photon approach, particular properties of UR are discussed with respect to both species of the uncertainty relations dependent or independent on the velocity of particle moving in the coordinate–time space. In the frame of this approach, the underlying physical reason for a universal property of Heisenberg's UR is established, which consists in their invariance on the frequency of virtual photons. In line with the virtual photon approach, UR properties are discussed for the case of bound electron states, as well as peculiarities of Heisenberg's relations at inter-particle distances smaller than Compton length resulting from the decrease of virtual photon's contribution into the interaction processes at short distances.

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1. The occurrence of quantum mechanics manifested a new stage in physics that gave birth to the acceptance of indeterminism, uncertainty principles and probabilistic nature of physical phenomena, which were confirmed experimentally in the most profound way as applied to the whole of three types of the fundamental interactions, including the unified theory of electromagnetic and weak interactions. Heisenberg's uncertainty relations are one of the most fundamental propositions of quantum mechanics asserting the precision limit for the simultaneous determination of quantum observables as a result of the wave-corpuscle nature of quantum objects [1,2]. Although the quantum uncertainty relations date back to about a century, extensive discussions are still being continued concerning the interpretation and understanding of their physical meaning. First and foremost this refers to the following uncertainty relation [3–6]:

$$\Delta\varepsilon\Delta t \geq \hbar, \tag{1}$$

where $\Delta\varepsilon$, Δt are the energy and the time variations. Most of the discussions show not only different but even contradicting understanding of the physical meaning of uncertainties described in framework of non-relativistic quantum theory by this inequality [3,4]. Reviews [3,4] present an extended list of papers, which allows to take a closer look at the relevant problems and state-of-the-art in this research field. The main reason why the uncertainty relation (1) was interpreted quite differently is that there are quite different physical problems where relation like (1) can arise and in each concrete case the meaning of the quantities in (1) proves to be different [3]. This was most clearly demonstrated by Mandel'shtam and Tamm [5] and, later on, by other authors in subsequent works referred in [3]. The term "uncertainty in energy" in (1) was defined either as an accuracy of energy measurements, or the difference between the energies of the object measured at two points in time, or the uncertainty of this difference, or the energy variation taking place during the measurement time interval [3]. Moreover, sometimes it was even not clear what is understood by the term "energy": whether this is the kinetic or the total energy [3]. The uncertainty relation

$$\Delta p\Delta x \geq \hbar, \tag{2}$$

states that the values of the momentum p and coordinate x cannot be precisely known simultaneously. Here Δp, Δx are the uncertainties of the momentum and coordinate, respectively. The main difficulties centre around the term "simultaneous", in particular when it concerns the possibility of making the experiment measurement both of these values taking into account the limitation of the signal velocity by the light speed. The relativistic theories pay less attention to the physical meaning of the uncertainty equations. Still the uncertainty relationships are naturally integrated

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into relativistic quantum electrodynamics (QED) and allow describing quantum properties of the particles, as well as particle interactions, with high precision taking into account many factors to be important under considerations [7–14].

In this paper we discuss the problem of uncertainty relations with an emphasis on the interpretation of the underlying physical phenomena responsible for the physical nature and the peculiarities of the quantum uncertainty relationships. The uncertainty relations are considered on the base of analysis of peculiar features on virtual photons. The latter are involved in electromagnetic inter-particle interaction processes in frame of QED and relativistic quantum field theory. Based on the suggested concept of virtual photons, peculiarities of quantum uncertainty relations are traced, and the main reason for the universal character of uncertainty relationships from the wavelike point of view is established. As shown it lies in the fact that the quantum uncertainty relations appear to be invariant with respect to the frequency and other parameters of virtual photons. The invariance of Heisenberg's uncertainty relations is directly associated with the universal ability of photons of arbitrary frequency to transfer always the same fixed value of the photon action that is equal to the Planck constant. In the virtual photon model, two groups of the uncertainty relations are formed that are invariant with respect to the parameters of virtual photons involved in interaction processes. The first group represents Heisenberg's uncertainty relations, whereas another one is complementary to them and includes the particle velocity. The virtual photon approach is employed as well to the analysis of the uncertainty relations in the case of bound electron states and the peculiarities of Heisenberg's relations when passing from systems with large distances between interacting particles to the systems with shorter inter-particle distances of order and less than Compton length of electron. The effect of "softening" of the Heisenberg's uncertainty relations (UR) is discussed as a result of a decrease of the virtual photon contribution into inter-particles interaction processes under short distances.

Several points of crucial importance that justify the application of virtual photon approach suggested here for the analysis of quantum UR should be noted. The first one is that the interpretation of UR's in the frame of relativistic quantum electrodynamics differs from its interpretation in the frame of non-relativistic quantum mechanics [7]. As is known, QED theory excludes completely the possibility of accurate determination of quantum variables separately contrary to non-relativistic quantum mechanics [7]. Hence, when considering the uncertainty relations, one has to take necessarily into account the basic results of relativistic quantum electrodynamics. Another point is that the information regarding the quantum wave-like properties of particles is always reached as a result of an interaction processes (i.e. interaction between particles or between particles and the measuring device). Data on the properties of free particles are in principle beyond the possibility of any experiment. Since according to QED theory, the electromagnetic interaction processes are realized in the form of discrete acts by means of sequential emission and absorption by particles of quanta of electromagnetic field, e.g. virtual photons, it follows that the suggested virtual photon approach model can be profitably employed when analyzing the regularities of the quantum uncertainty relations. There is another point to be worthy of notice. As it has been shown by Kennard [15], Robertson [16], Schrödinger [17] and the others, the uncertainty relations in fact may be changed, for example, as applied to pure and entangled quantum states when taking into consideration such factors as the coherency. As a result, the UR (2) includes an additional factor that causes an increase of the quantum uncertainty values [3,4,15–17]. This gives more assurance to expect some changes in the Heisenberg's URs when going to stronger interaction particles' systems with smaller inter-particle distances.

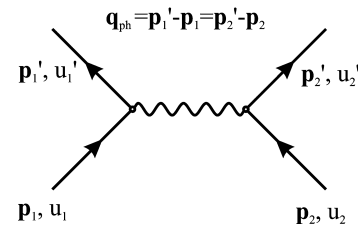

Fig. 1. Feynman diagram for the interaction of two charged particles (1 and 2) including emission and absorption of virtual photons. Transitions of particle 1 from the initial state $\{p_1, u_1\}$ to the final state $\{p_1', u_1'\}$ and of particle 2 from the initial state $\{p_2, u_2\}$ to the final one $\{p_2', u_2'\}$ (in the simple spin approximation $\boldsymbol{q}_{\text{ph}} = \boldsymbol{p}_1' - \boldsymbol{p}_1 = \boldsymbol{p}_2' - \boldsymbol{p}_2$) are shown.

2. The processes of electromagnetic interaction in quantum electrodynamics, as distinct from classical electrodynamics, are realized in the form of discrete acts of sequential emission and absorption by particles of quanta of electromagnetic field that are virtual photons. They form electric potential like Coulomb type in the surrounding particle space and may interact with other particles or collapse in the absence of such particles [7–14]. In the most general case of arbitrary distances between the charged particles, such as electrons, the electromagnetic interaction theory based on the Feynman diagram technique requires consideration of the terms of many orders in the perturbation theory expansion with the small parameter $\alpha = e^2/\hbar c \approx 1/137$. It is necessary to consider a number of internal lines in the Feynman diagrams taking into account the spin characteristics, peculiarities associated with the quantum fluctuations of vacuum, photon conversion into electron–positron pairs and some other effects, which makes the description of the interaction processes between the particles at short distances more complicated [7–14]. Relativistic theory operates with four-dimensional vectors that are invariant with respect to the Lorenz transformation. In this case, energy and momentum conservation laws are applicable to all vertices of the diagrams. The characteristics of each virtual photon are defined by the relationship $p^2 = \varepsilon^2/c^2 - \boldsymbol{p}^2$, where $\boldsymbol{p}^2 = p_x^2 + p_y^2 + p_z^2$ and $\varepsilon^2 = m_{\text{ph}}^2 c^4$, where m_{ph} is the mass of a virtual photon [7–14]. Quantum field theory considers the interaction processes in the matrix representation form. In the case when the virtual photons are involved, the common creation and annihilation operators are involved similarly to the case of usual particles [7–14]. When describing the inter-particle interaction with the transition of one particle from the initial state with momentum p_1 and spin function u_1 to the final state with p_1' and u_1' and the transition of another particle from the initial state with p_2 and u_2 to the final state with p_2' and u_2' by emission and absorbing of virtual photons, the matrix transition term in the first approximation takes the form [8]:

$$M = \sum_{\lambda} \frac{-ie^2}{\hbar c}(2\pi)^4 \delta^4\big(p_1 + p_2 - p_1' - p_2'\big) \times \left[\frac{(\tilde{u}_1\lambda_\lambda u_1)(\tilde{u}_2\lambda_\lambda u_2)}{(p_1 - p_1')^2 - i\varepsilon} - \frac{(\tilde{u}_2\lambda_\lambda u_1)(\tilde{u}_1\lambda_\lambda u_2)}{(p_2 - p_2')^2 - i\varepsilon}\right]. \quad (3)$$

Here $(\tilde{u}_1\gamma_\lambda u_1)$ are the spin Dirac matrices and ε is a small positive number. Formula (3) describes the interaction of two identical particles, say, two electrons, with allowance for possibility of exchange identity. If different particles interact, such as an electron and a proton, the second term in (3) describing the exchange identity is excluded [8]. The simplest diagram shown in Fig. 1 shows the interaction of charged particles with the virtual photons involved.

In the framework of QED, the electrical potential produced by a particle with the charge e at distance r from it, with the participation of the electromagnetic field quanta, i.e. of virtual photons, in

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