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DOUBLE-SLIT EXPERIMENT AND BOGOLIUBOV'S CAUSALITY PRINCIPLE

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In the Bogoliubov approach the causality principle is the basic constructive element of quantum field theory. At the same time, this principle has obvious classical interpretation. On the other hand, it is well-known Feynman statement that the double-slit experiment is «impossible, absolutely impossible to explain in classical way, and has in it the heart of quantum mechanics». We describe how taking into account of infrared singularities allows one to give quite evident interpretation to double-slit experiment. And this interpretation agrees with the Bogoliubov's causality principle.

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In the Bogoliubov [1] approach the causality principle is the basic constructive element of quantum field theory. This principle is closely related to locality and states that any excitation in one domain of the Minkowski space does not affect physical processes in another space-like separated domain. At the same time, this principle has obvious classical interpretation.

On the other hand, it is well-known Feynman [2] statement that the double-slit experiment is «impossible, absolutely impossible to explain in classical way, and has in it the heart of quantum mechanics». We describe how taking into account of infrared singularities allows one to give quite evident interpretation to double-slit experiment. And this interpretation agrees with the Bogoliubov's causality principle.

Further we consider how we can describe particle scattering by two slits a and b. We note that in contrast to considering the same experiment in the standard quantum mechanics, we consider that the scattered particle hits either the domain of slit a or the domain of slit b in each separate case, not passing in a mysterious way through both slits simultaneously. This means that we consider a particle well localized in each separate act. An interference pattern is vividly observed in this experiment. Physically, this means that the scattering on one slit depends on the presence or absence of the other slit, i.e., a nonlocality is present here.

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We see how this nonlocality can be explained in the framework of a local field theory. For clarity, we here discuss the example of the process of scattering of an electron on a nucleus, well studied both theoretically and experimentally. Because the electron is much lighter than the nucleus, this process is well approximated by the electron scattering on a classical source. In what follows, we discuss exactly this process in the framework of the perturbation theory in the standard quantum electrodynamics.

In the first order of the perturbation theory in the electron charge, this process is described by the Feynman diagram *a* shown in Fig. 1. In this figure, straight lines correspond to the electron, wavy lines correspond to the photon, and the crossed circle corresponds to the source of the classical electromagnetic field. Calculating the differential scattering cross section when taking diagram *a* into account causes no troubles and results in the celebrated Rutherford formula corrected by taking the electron spin into account. The obtained formula describes the experimental situation well. But both theory and experiment have now gone far beyond the accuracy level ensured by the first correction to the perturbation theory.

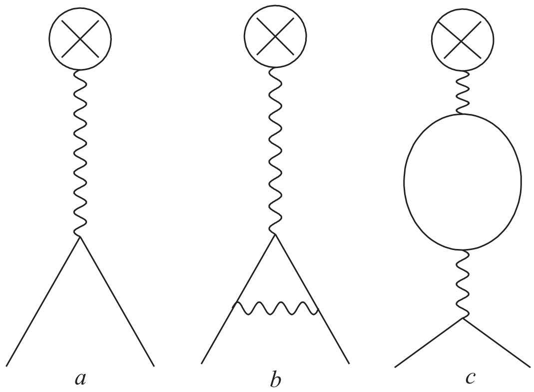

Fig. 1. Diagrams describing the elastic scattering

The next order of the perturbation expansion that contributes to the process under study is the third order. There, we must take contributions coming from diagrams *b* and *c* in Fig. 1 into account. Taking these diagrams into account results in substantial theoretical difficulties. First, the so-called ultraviolet divergences appear because the intermediate (virtual) particles can carry arbitrarily large energies and momenta. In quantum field theory, a well-defined algorithm (the renormalization theory) was developed to overcome this difficulty. We do not discuss this problem in what follows. Second, diagram *b* results in the so-called infrared divergences caused by the presence of massless particles in the complete particle set. In the example under consideration, such particles are the photons. Quantum field theory also provides an algorithm for overcoming this difficulty. We discuss it in more detail.

The algorithm is based on the following experimental fact. The elastic scattering process described by diagrams *a–c* cannot be experimentally separated from the process of bremsstrahlung depicted in diagrams *d–f* in Fig. 2. In this process, electron scattering is accompanied by emitting one (diagrams *d* and *e*) or more (diagram *f*) photons. The contribution of diagrams of such a type to the scattering cross section cannot be experimentally separated from the contributions of diagrams *a–c* if the total energy of photons emitted in the bremsstrahlung is below the sensitivity threshold of the measuring device.

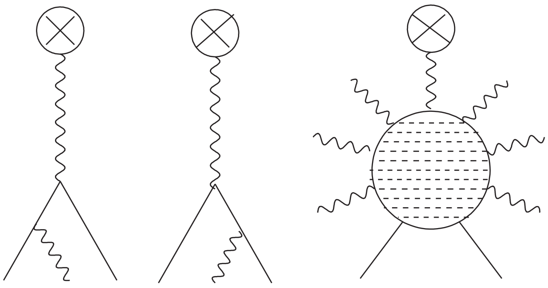

Fig. 2. Diagrams describing the bremsstrahlung

Calculations show that if we take diagrams *d* and *e* into account together with diagrams *a–c*, then infrared singularities are compensated. But the scattering cross section then becomes dependent on a parameter characterizing the sensitivity of the measuring device. We can take the total energy $E_{\max}$ of additionally emitted photons as such a parameter. This is an absolutely physical parameter, and the dependence of the measured scattering cross section on this parameter should therefore not cause any principal objection. But taking diagrams *a–e* alone into account results in one more difficulty. The dependence of the scattering cross section on the parameter $E_{\max}$ is singular, and the cross section can become negative at sufficiently small $E_{\max}$.

In modern theory, this difficulty is attributed to an artifact related to using the perturbation theory. Indeed, if higher orders of the perturbation theory are considered taking contributions from diagrams of type (*f*) with an infinitely increasing number of emitted photons into account and summing all these contributions, then the cross-section dependence on the parameter $E_{\max}$ becomes regular. Moreover, this cross section tends to zero as $E_{\max} \to 0$. This does not cause objections from the physical standpoint. The purely elastic scattering in which no bremsstrahlung photons are emitted is just one among infinitely many channels along which this process may proceed. It is therefore not amazing that each of these channels contributes infinitesimally to the total cross section.

Here we need a new insight into the process called elastic scattering. In reality, this process is never purely elastic. Electron scattering is always accompanied by the bremsstrahlung, which cannot be registered even by a measuring device with very high sensitivity. Moreover, the result of the experiment becomes strongly dependent on the device sensitivity if the latter is too high. When the sensitivity becomes infinitely high, the registered scattering cross section must tend to zero because we study the measuring device in this case and not the physical object (electron) under investigation.

The above example teaches us several useful lessons.

Lesson 1. Separating characteristics of a physical object under study are somewhat conditional. These characteristics cannot be separated completely from the characteristics of the measuring device with which this object interacts.

Lesson 2. A physical object (electron in the above example) with which we associate definite physical characteristics (differential cross section of elastic scattering) is accompanied by a field (bremsstrahlung photons) that is not registered by the measuring device but affects the result of the measurement of the characteristics under study.

Lesson 3. The presence of the accompanying field does not contradict locality axioms of quantum field theory. In the above example, both the electron and the bremsstrahlung photons propagate in the future light cone with the vertex at the scattering point.

Lesson 4. The result of measuring the characteristics (scattering cross section) ascribed to a well-localized object under study (electron) may depend on the characteristics of physical objects (bremsstrahlung photons) that are located in the domain that is space-like with respect to the localization domain of the object under study. This may be interpreted as a nonlocality of the object under study.

The above lessons result in the following conclusion. We can split the physical problem under study into two parts as regards the measurement process. The first part, called the *kernel* in what follows, is registered by a measuring device. The second part, called the *dark field* in what follows, is not directly registered by the measuring device, but the instrument reading can depend on characteristics of the dark field. The separation into these two parts is not absolute and depends on the measurement procedure. This mobility of the boundary finds its partial realization in the renormalization group formalism in the mathematical apparatus of quantum field theory.

Each quantum particle reveals itself through the corresponding observable quantities or, more precisely, through local observables whose values can be found by performing measurements in a bounded domain $\mathcal{O}$ of the Minkowski space.

The domain $\mathcal{O}$ can be naturally considered to be a localization domain for the quantum particle under consideration. In any case, the domain $\mathcal{O}$ must contain the particle localization domain. More precisely, the localization domain of a particle must be associated with its kernel. However, as explained above, the registered values of observables may depend on the characteristics of the dark field. This field is not necessarily localized in the domain $\mathcal{O}$. On the other hand, observable values are determined by the state of physical system. The matter carrier of the state is therefore not only the kernel of the quantum object under study but also the associated dark field. The state therefore cannot be regarded as being localized in the domain $\mathcal{O}$. But it is the dark field localization.

We note that not every dark field affects the result of measuring observables (the scattering cross section in the above example); only the one that is created together with the kernel does, i.e., only the dark field coherent to the kernel is essential.

We now return to discussing the experiment on the scattering from two slits. We regard the electron as the scattered particle.

We consider the screen with two slits as a classical device which forms quantum ensemble of electrons. This ensemble has certain structure. Firstly, when the ensemble is formed, each electron localized either in the domain of slit a or in the domain of slit b (it is better to speak about the electron kernel, not the electron itself). Second, during interaction with the screen each electron somehow feels both slits.

The first condition for electron localization is self-evident and does not need additional comments. We only note that it will certainly provoke frantic objections from orthodox followers of the standard quantum mechanics, who will insist on that we cannot speak about electron localization before performing a measurement. Why not? Only because they cannot say anything meaningful on this subject?

To explain the second condition qualitatively, we can propose the following model of how the electron interacts with the slits or, more precisely, with the screen in which these silts are cut. In the scattering process, not only the electron kernel but also the companion dark field that is coherent with the kernel approach the screen. Because this field is massless, it reaches the screen even before the kernel. This field generates collective oscillations of the screen that are also coherent with the kernel. The arising oscillations are very weak, but because of the coherence, they may interact resonantly with the kernel. At least, they may play the role of a random force participating in creating the probability distribution of the scattered electron momentum. In contrast to the electron kernel, the dark field reaches both slits, and the character of the random force depends essentially on whether only one slit is open or both slits are open simultaneously. This can be a physical reason for the appearance of the interference pattern.

Summarizing, we can draw the following conclusions.

Quantum theory, both relativistic and nonrelativistic, can be formulated such that it does not contradict the locality condition accepted in quantum field theory. The measurement process also does not contradict this condition.

From the measurement standpoint, a physical system under study can be separated into two parts: the so-called kernel and the accompanying dark field. The kernel is the material carrier of corpuscular properties of the physical system. The kernel is localized in the Minkowski space. The algebra of local observables is the mathematical representation of the kernel. The structure of the dark field does not contradict the relativistic condition of locality, but the dark field has a localization worse than that of the kernel. The state of a physical system is determined by both the kernel and the dark field structure. The dark field is the material carrier of the wave properties of the physical system.

In the report, I have told only about physical essence of the problem. Discussion of a mathematical side of the problem can be found in paper [4].

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