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Quantum entanglement, Wheeler's delayed choice experiment and its explanation on the basis of quantization of fields

Alexey V Melkikh

Ural Federal University, Yekaterinburg, Russia

Email: melkikh2008@rambler.ru

Abstract. The result of Wheeler's delayed choice experiment is a natural consequence of the entanglement of moving photons and particles (atoms, molecules) of the slit through which they move. The inclusion of quantum fields (taking into account that speed of virtual particles is not limited) self-consistently explains why interaction's propagation velocity after closing one slit is larger than the speed of light.

1. Introduction

One manifestation of entanglement is Wheeler's delayed-choice experiment. Wheeler's thought experiment [1] is a variant of an experiment using two static slits, in which one of the slits may be closed after a photon passes through both slits, but before the photon has reached the screen. Practically, this applies a delayed choice to the structure of the system with which a photon interacts. How does a particle "know" that one of the slits was closed? How fast is the "knowing" communication? To answer these and other questions, a more detailed discussion of entanglement that explicitly takes into account the quantization of fields is required.

2. Wheeler's thought experiment and concepts of entanglement in quantum mechanics

Currently Wheeler's delayed-choice experiment has been experimentally implemented, although in a somewhat different form (see, for example, [2-5]). A schematic of Wheeler's delayed choice experiment is shown in Figure 1.

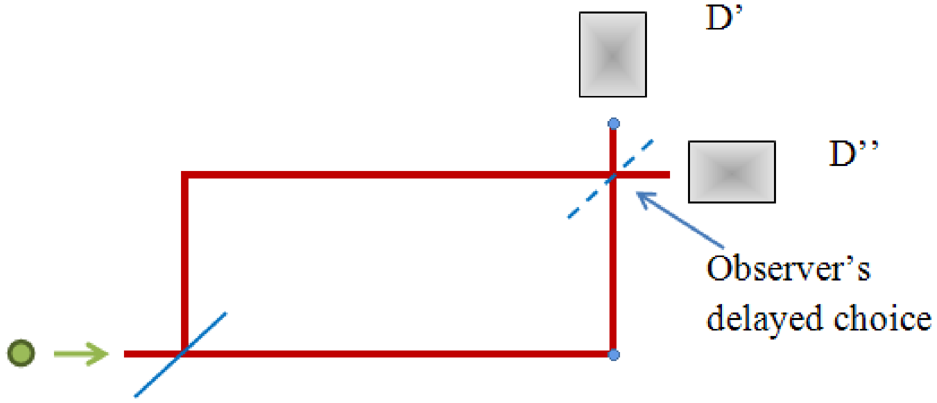

Figure 1. A schematic of Wheeler's delayed choice experiment in Mach-Zehnder interferometer.

A photon is sent to the Mach-Zehnder interferometer and is split into the superposition of two states, which move along two arms of the interferometer. By inserting the second splitter, either particle or wave behavior may be detected by the detector D' or D''. This is much like the photon passing through slits. If there is one slit, the screen image has a maximum corresponding to the photon's position (i.e., the photon shows particle properties). If there are two slits, an interference pattern is observed on the screen (i.e., the photon demonstrates wave properties).

Experiments have shown that the act of measurement fully determines how particles behave in the past, including moments, when the position of the particle is unachievable even with the speed of light. A variant of this experiment would be when the particle passes (for example, in outer space) very long distances before being recorded with the apparatus (such as a telescope).

Another variant of Wheeler's experiment is the quantum eraser [6, 7]. If the experimenter wishes to delete the information of slit through which the particle passed, then, anywhere it is situated, the interference pattern appears on the screen.

However, in the framework of quantum mechanics, including relativistic cases, it is difficult to explain this experiment. What is entangled with the photon? What conditions are needed for this entanglement? What is the mechanism of propagation for action at a distance? In Wheeler's experiment, why is this interaction's propagation velocity larger than the speed of light? To answer these and other questions, let us consider a more detailed picture, in which the quantization of fields is taken into account.

3. Explanation of entanglement on the basis of explicitly accounting for the quantization of fields

An explanation of entanglement may be given by explicitly accounting for quantum fields. Let's call the version of quantum mechanics, in which the fields are considered classically, "quantum mechanics of particles", distinct from one considering particles and fields. Quantum mechanics of particles and fields can explain entanglement as an interaction through virtual particles. Virtual particles are not subject to the limit imposed by the speed of light, so interaction at an arbitrary distance is natural for them. As mentioned earlier in connection with the solution of the problem of measurement [8], the quantum mechanics of particles is not a closed science - only the quantum mechanics of particles and fields together can be considered closed. Only such a comprehensive consideration avoids the measurement paradox while simultaneously solving the problem of the collapse of the wave function.

The system of equations for particles and fields (see, for example, [9, 10]) is as follows:

$$\left\{\gamma_\mu\left(\frac{\partial}{\partial x_\mu}-ieA_\mu(x)\right)+m\right\}\psi(x)=0 , \quad (1)$$

$$\left\{\gamma_\mu^T\left(\frac{\partial}{\partial x_\mu}+ieA_\mu(x)\right)-m\right\}\bar{\psi}(x)=0 , \quad (2)$$

$$\Box A_\mu(x)=-j_\mu(x) , \quad (3)$$

where $\psi(x)$ is the wave function (operator) and $j_\mu(x)$ is the 4-density of electron current, which is equal to

$$j_\mu(x)=\frac{ie}{2}\left(\bar{\psi}(x)\gamma_\mu\psi(x)-\bar{\psi}^c(x)\gamma_\mu\psi^c(x)\right) .$$

The subscript "c" indicates the change of the charge sign. A_μ is the potential of the electromagnetic field, γ_μ are the Dirac matrices, e is electron charge, and $\Box$ is

$$\Box\equiv\frac{\partial^2}{\partial t^2}-\frac{\partial^2}{\partial x^2}-\frac{\partial^2}{\partial y^2}-\frac{\partial^2}{\partial z^2} .$$

For a virtual particle, the well-known relation between the momentum and energy does not hold:

$$E^2\neq p^2c^2+m_0^2c^4 .$$

As a consequence, virtual particles cannot be observed by classical devices. Is it possible to measure the virtual particles at all?

We may be able to speak about the measurement of the totality of the virtual particles. When an electron in a hydrogen atom jumps from one level to another, a photon emission of a certain length occurs. By measuring the properties of the photon, the energy levels of the atom can be obtained. In particular, we can determine the Lamb's shift of the levels. That is, obtained in the measurement (which is inevitably connected with the emission or annihilation of particles) are not only the properties of the electron at a certain level, but the properties of the "electron + virtual particles". Other experiments that demonstrate the indirect presence of virtual particles are the Casimir effect and dynamic Casimir effect [11].

Thus, measurements show agreement with a theory in which the virtual particles exist, but not with the theory in which fields are classical.

The same process involving virtual particles may look different. The larger virtuality of the particle, the shorter time and distance, in which the virtual process takes place. The speed of the virtual particles, determined by the momentum and energy, can be arbitrarily large.

There are various interpretations of quantum field theory. In particular, the "partial" interpretation was discussed in [12, 13].

The movement of quantum particles is associated with the group velocity, which is defined as

$$v_g=\frac{d\omega}{dk} .$$

This velocity cannot be larger than speed of light. For the phase velocity

$$v_p=\frac{\omega}{k}$$

such a restriction is absent.

It is believed that the phase velocity is not physically observable for elementary particles, so its use does not make practical sense. This, however, does not apply to virtual particles. Although they are not directly observable, as noted above, the effect of the totality of the virtual particles can be experimentally observed. Because in these experiments on particle entanglement, phase plays an

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important role, the phase velocity, which can be attributed to the virtual particle, is fundamentally important.

4. Wheeler's experiments explanation on the basis of accounting for field quantization

The result of Wheeler's delayed choice experiment is also a natural consequence of the entanglement of moving photons and molecules (atoms, particles) of the slit through which they move. That is, a photon (particle A), flying through the two slits, was entangled with the atoms of the diaphragm through the exchange of virtual particles with the atoms. The most powerful entanglement is between the photon and the particles that actually form the slit because they alter the trajectory of the photon most significantly. With the more distant particles, the interaction is much weaker, so their condition will affect the state of the photon weakly.

How far would the photon flew, it continued to exchange virtual particles with atoms of the diaphragm. The rate of this exchange via virtual particles is not limited.

Suppose now that one slit is closed for a negligible time compared to the total time of flight of the photon. However, because the entanglement speed is not limited, the photon is now entangled with a modified diaphragm with one slit. As a result, its phase will change over the characteristic time of closing the slit; it will behave as if there were originally only one slit and the interference pattern on the screen disappears. This is the same, if as a result of the measurement we would receive information on which slit the photon has passed.

Thus, the slit closing may be considered a measurement-like process in a quantum sense; both processes create the same state event, wave emission by one slit. Indeed, the measurement determining a photon's (particle A) passage through a certain slit destroys its coherent state and a new wave is re-emitted (Figure 2).

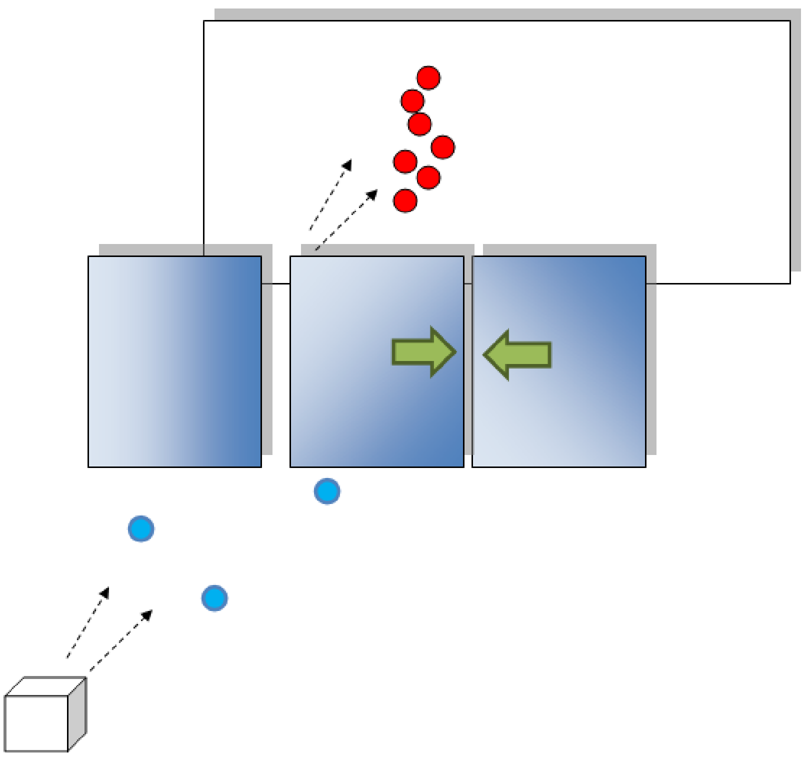

Figure 2. Photon is entangled with a modified diaphragm with one slit

In the erasing experiment the emitted photon can be absorbed (deleted). At the same time, the uncertainty generated by the measurement also disappears. If this is done arbitrarily late, particle A will be affected because it remains to be connected with emitted particles by means of virtual particles.

Thus, Wheeler's delayed choice experiment can be explained in terms of the quantum mechanics of particles of fields.

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