https://doi.org/10.18524/1810-4215.2024.37.311727

THE EINSTEIN-PODOLSKY-ROSEN PARADOX: FALSE SUPERLUMINAL INFORMATION TRANSFER

S.L. Parnovsky

Taras Shevchenko National University of Kyiv,
Kyiv, Ukraine, *parnovsky@knu.ua*

ABSTRACT. The paradox about the supposedly instantaneous transfer of information associated with the determination of the parameters of one of the particles included in a quantum entangled pair is considered. It is shown that this conclusion is drawn on the basis of not quite correctly formulated conditions of the thought experiment underlying the imaginary paradox.

Keywords: quantum entanglement, special relativity, superluminal transmission of information.

АНОТАЦІЯ. Розглянуто парадокс Айнштайна-Подольського-Розена про нібито миттєву передачу інформації, пов'язану з визначенням параметрів однієї з частинок, що входять до квантової заплутаної пари. Ці дві частинки поєднуються певним чином, незалежно від відстані між ними, якщо їхній стан залишається незмінним. Явище квантової заплутаності підтверджено експериментами.

У найпростішої версії парадоксу пара заплутаних фотонів народжується десь у космосі. Один із них прилітає на Землю, де фізики вимірюють його спіральність. Це дає змогу дізнатися спіральність другого фотона, який у цей момент знаходиться десь у туманності Андромеди. Виникає питання про можливість отримати інформацію зі швидкістю вище світлової.

Запропоновано неквантову аналогію парадокса, що виникає через можливу зміну проекції спіну або спіральності при взаємодію з частинками або полями. Продемонстровано, що спроби уникнути такої зміни призводять до впливу на величину, що вимірюється. Перша з можливостей є ілюстрація відомого твердження квантової механіки про вплив процесу вимірювання, в даному випадку спостереження, на стан спостережуваної системи. Друга, пов'язана зі оточенням частинки непрозорою оболонкою призводить до зміни стану частинки через ефект Казимира та зміну поляризації вакууму.

Висновок про можливість миттєвої передачі інформації зроблено на основі не зовсім коректно сформульованих умов уявного експерименту, що лежить в основі нібито парадоксу. Запропоновано поняття часткової квантової заплутаності та параметр, пов'язаний із зменшенням кореляції станів частинок, які спочатку були заплутані.

Ключові слова: квантова заплутаність, спеціальна теорія відносності, надсвітлове передавання інформації.

1. Introduction

The discussion between Einstein and Bohr played a important role in the process of understanding the concepts of quantum mechanics, which was being created at that time. Einstein proposed a number of thought (gedanken) experiments that were supposed to disprove the foundations of quantum mechanics, for example, the Heisenberg uncertainty principle. However, Bohr was able to show the falsity of these attempts in all cases. A kind of continuation of this series of thought experiments was the article (Einstein et al, 1935). Its ideas subsequently led to the emergence of the concept of quantum entanglement, when two particles link together in a certain way no matter how far apart they are in space. Their state remains the same.

The existence of quantum entanglement has been confirmed in numerous experiments and is not questioned. The experiments described in (Storz et al, 2023) are an important stage in the study of this quantum mechanical phenomenon in which the quantum states of two or more objects are interdependent. For example, one can get a pair of photons in an entangled state, and measure the spin of the one of the photons. If its helicity turns out to be positive, then the helicity of the second should be negative, and vice versa.

In this paper I want to discuss some aspects related to the paradox usually associated with this concept. I do not go into details related to Bell's inequality (Bell, 1964), etc., limiting myself to a discussion and analysis of simple thought experiments.

The paradox associated with the existence of a pair of quantum entangled objects is connected with the fact that a measurement of a parameter of one particle is related to an instantaneous termination of the entangled state of the other. In the simplest example, a pair of entangled photons is born somewhere in space. One of them arrives on Earth, where physicists measure its helicity. This makes it possible to know the helicity of the second photon, which is somewhere in the Andromeda Nebula at that moment. Is this a transmission of information at faster than the speed of light in a vacuum? This is forbidden by the special theory of relativity. I am going to show that the paradoxicality of this situation has much to do with its formulation.

2. Analysis of the paradox

2.1. Preliminary analysis of the paradox

The presence of non-trivial and somewhat mysterious quantum entanglement may hinder understanding of the paradox. Therefore, we start by considering the EPR paradox counterpart for the non-quantum classical world. This is possible for many paradoxes related to quantum mechanics, including the famous Schrödinger's cat (Parnovsky, 2023).

In the case of a pair of entangled photons we can also present a thought experiment that is close in essence and not related to the world of quanta. We take out two playing cards from the deck, for example, the king of spades and the seven of clubs. We put them in two envelopes and randomly write two recipients on them. One of the recipients receives a letter with the king of spades in Glasgow and realizes that the second recipient in Sydney received a letter with a seven of clubs. The situation resembles a paradox with quantum entangled photons, but without the halo of mystery.

Let's not discuss how long it takes the addressee to draw a conclusion and compare it with the time it takes light to travel from Sydney to Glasgow through the globe. This is not important when analyzing a situation that has become plain and simple. The key question is how accurate is the conclusion about the card inside the envelope in Sydney.

In reality, all that the addressee from Glasgow sees is an envelope with the king of spades inside. The final conclusion is also based on additional information, which is the result of assumptions and descriptions of the organization of our thought experiment. It is implicitly assumed that two envelopes were sent with the specified playing cards inside, with the second addressee being a participant in the experiment from Sydney. The letters are not lost and not be replaced along the way. For the EPL paradox, the entangled particles must not interact with anything and retain spin or helicity.

I want to add a more general remark. There is a difference between obtaining real information and using the results of the estimates and calculations that underlie the paradox under discussion. A predicting the helicity of a distant photon or the projection of the spin of a massive distant particle is like the situation with a rocket sent to Alpha Centauri carrying a time bomb. Observers on Earth may believe that the bomb has exploded at a calculated point in time, but they will not receive direct information about the explosion until more than 4 years later. Up to this point, it is not information, but just a guess. You never know what could happen to the rocket, the bomb and the clockwork.

The production of a pair of quantum entangled particles is provided by the laws of physics, including quantum mechanics and the law of conservation of angular momentum of particles. But the requirement that the state of the particle must not change during its journey is very important. This is implicitly assumed in the conditions of the gedanken experiment, but how much is it admissible in reality? If an elementary particle moves in space, it can change the projection of its spin on a given axis while interacting with another particle or in an external field. For example, during interaction with photons of CMB radiation (see the Greisen–Zatsepin–Kuzmin cutoff (Greisen, 1966; Zatsepin, Kuz'min, 1966)).

2.2. The need for observation and its impact on particles

In order to be sure that the emitted particle has not changed helicity or projection of spin, one must know that it has not interacted with anything during the motion. Here it is worth remembering that in quantum mechanics the measurement process and the observation process as a special case affects the state of the system. This has been repeatedly illustrated by various examples.

Say an observer wants to know if there is a black cat in a dark room. He can use a flashlight, but this would cause the pressure of the torch's light to affect the cat, naturally if it is in the room, and would change its momentum as a result. From this it is not difficult to obtain a constraint related to the Heisenberg uncertainty principle. Corresponding estimates are given, for example, in the book (Parnovsky, 2023).

If we place observers in space along its trajectory, armed with torches or other means of gaining information about the world around it, to make sure that a receding entangled particle does not interact with other particles, the particle may change its helicity or spin projection due to interaction with the light from these torches.

Let's try to break the deadlock in another way, making our thought experiment much more complicated. We surround the massive particle with a sphere of strong opaque material, which do not let photons or other particles near it. It flies at the same speed, escorting the particle and protecting it from unwanted interactions. However, this would not solve the problem. The mere existence of the shell changes the oscillations of the physical fields within it, including the electromagnetic one. This leads to a change of polarization of the vacuum, i.e. to the manifestation of the Casimir effect (Casimir, 1948; DeWitt, 2022).Its influence can change the projection of a particle's spin on a chosen axis.

So, it is quite possible that the spin or helicity of a particle moving in this medium may change. Some mechanisms of such a change are related to the very fundamentals of quantum mechanics, such as the effect of a measurement process on the object being measured. Therefore, they always work. I note that the particle, whose state is supposedly determined remotely, may simply not be present at the point in space-time, where it should be according to calculations.

3. Partial quantum entanglement

The above is sufficient to show that when using a pair of quantum entangled particles and having received information about the spin or helicity of one of them, we can determine the position or the very fact of the existence and spin or helicity of the second one only with a certain probability different from unity. This is sufficient to consider the obtained estimate not information, but merely an assumption.

To obtain quantitative characteristics, an approach somewhat similar to the concept of partially coherent light (Born and Wolf, 1999) can be used. Let us indicate the basic approach. Consider the motion of one of the particles produced as an entangled pair at distance $x = 0$. Let it be a fermion with spin 1/2, having two projections on the selected axis: 'spin up' and 'spin down', or a photon with positive or negative helicity. The pair was born from the initial configuration with zero angular momentum, so that the projections or helicities of the two produced particles are initially opposite.

The quantities $p_+(x)$ and $p_-(x)$ show the probabilities that the particle will show positive and negative spin projection or helicity when measuring at distance $x < 0$ from the point of birth of the pair. These quantities can change due to interaction with particles and fields during the particle's motion, but their sum is equal to 1.

$$p_+(x) + p_-(x) = 1. \tag{1}$$

Let us assume that the effect of external factors is random and isotropic. Let the particle, having traveled the path dx, change the direction of its spin with equal probability from 'spin down' to 'spin up' or vice versa:

$$\frac{dp_+(x)}{dx} = -\frac{dp_-(x)}{dx} = \alpha(p_-(x) - p_+(x)). \tag{2}$$

The quantity $\alpha \geq 0$ characterizes the rate of change of the spin component during the motion of the particle. It does not take into account the possibility of annihilation or transformation of the particle by interaction or by scattering. For simplicity, we assume that this quantity is constant. The solution to the system of equations has the form

$$p_+(x) = p_+(0)\exp(-2\alpha x) + \frac{1 - exp(-2\alpha x)}{2}. \tag{3}$$

If $\alpha = 0$, as is implicitly implied in the standard formulation of the paradox, then $p_+(x) = p_+(0)$. But for any small non-zero value of $\alpha > 0$, this value changes. For $x \ll \alpha^{-1}$, we get $p_+(x) \approx p_+(0)$, and for $x \gg \alpha^{-1}$, we get $p_+(x) \to 1/2$.

The latter is related to the used assumption of isotropy of interaction. In reality, it can be anisotropic with distinguished directions determined by the direction of the fields, say, the galactic or intergalactic magnetic field and the speed of the used frame of reference relative to the one in which the dipole component of the relic radiation is zeroed. Note that in the process of interaction with the CMB, the energy and speed of fermions can decrease [5,6].

Any value of $\alpha > 0$ makes the connection between $p_+(x)$ and $p_+(0)$, and hence between the spin projections of two partially entangled particles, not uniquely defined but probabilistic with a correlation that decreases as the particles move away. The actual experiments [2] were conducted at $x \ll \alpha^{-1}$, and the formulation of the paradox not only assumes $x \gg \alpha^{-1}$, but also requires obtaining information rather than an estimate, albeit a very probable one.

So, if the particles have to travel huge interstellar or even intergalactic distances, then the probability that they remain entangled is greatly reduced. As a result, for this reason alone, registration of the state parameters of one of the particles does not guarantee knowledge of the state parameters of the second particle. Accordingly, it is impossible to speak about the transfer of information about it with superluminal speed.

4. Conclusions

The phenomenon of quantum entanglement has been confirmed by experiments. However, a paradox about the supposedly instantaneous transmission of information is associated with it. The analysis carried out showed that in reality this paradox does not exist. The conclusion about the possibility of instantaneous transmission of information was made on the basis of not quite correctly formulated conditions of the gedanken experiment that underlay the imaginary paradox. An essential detail of the analysis is the well-known statement of quantum mechanics about the influence of the process of measurement, in this case, observation, on the state of the observed system.

Acknowledgements. The work was supported by the Ministry of Education and Science of Ukraine under Project No. 0122U001865.

References

Bell J.S.: 1964, *Physics Physique Fizika*, **1**, 195.

Born M., Wolf E.: 1999, Principles of optics: electromagnetic theory of propagation, interference and diffraction of light (7th expanded ed.) (Cambridge: Cambridge University Press).

Casimir H.B.G.: 1948, Proc. of the Koninklijke Nederlandse Akademie van Wetenschappen, **B51**, 793.

DeWitt B.S.: 1975, *PhR*, **19**, 295.

Einstein A., Podolsky B., Rosen N.: 1935, *PhR*, **47**, 777.

Greisen K.: 1966, *PhRvL*, **16**, 748.

Parnovsky S.: 2023, About the Biggest, the Smallest, and Everything Else: Travelling Through the Universe with a Physicist Guide. (Singapore: World Scientific)

Storz S., Schär J., Kulikov A., et al.: 2023, *Nature*, **617**, 265.

Zatsepin G.T., Kuz'min V.A.: 1966, *JETPL*, **4**, 78.