On the physical nature of entanglement

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Abstract

The problem of explaining the physical nature of the entanglement concept is only part of the more fundamental problem of symmetry in quantum physics. We have a number of direct and indirect experimental proofs of time asymmetry in quantum physics. This asymmetry requires the existence of a memory of a quantum system about its initial state, which is the physical essence of the concept of entanglement. The possibility of experimental study of nonlocal properties of quantum memory is also discussed.

Keywords: entanglement, time reversal noninvariance, quantum memory, entropy, nonlocality.

Introduction

“Entanglement, according to Erwin Schrodinger *the essence* of quantum mechanics, is at the heart of the Einstein-Podolsky-Rosen paradox and of the so called quantum-nonlocality – the fact that a local realistic explanation of quantum mechanics is not possible as quantitatively expressed by violation of Bell’s inequalities” [1]. However, despite the numerous theoretical and experimental researches the entanglement remains to be a subtle and evasive concept.

The term entanglement is extremely widely used in the literature on quantum physics, but physical definition of the term 'entanglement' is absent till now [2]. It looks like a synonym for the mathematical concept of "superposition of states". The concept of entanglement is often associated with information [3], contextuality [4]. From this, the physical meaning of the term 'entanglement' does not become clearer.

In our opinion, the problem of explaining the physical nature of the entanglement concept is only part of the more fundamental problem of symmetry in quantum physics. In turn, the problem of symmetry is an important part of the problem of interpretation of quantum mechanics. There are a lot of variants of interpretation of quantum mechanics: Copenhagen, many word interpretation (MWI), De Broglie-Bohm, informational interpretation, QBism, objective collapse, relational interpretation, transactional interpretation and many other [5]. “New interpretations appear every year. None ever disappear” [6].

In such cases, philosophers say that a paradigm shift is needed. The paradigm in quantum mechanics is the concept of symmetry or unitary transformations. Translated from mathematical to physical language, this means that "all the laws of physics are symmetric in time". Physicists often repeat this statement as a mantra.

Time reversal noninvariance

We have now a strange situation: violation of T-invariance has long been recognized in the field of high-energy physics in the case of weak interactions [7]. But, in the field of low-energy physics (nonlinear optics, conventional quantum physics), it has not been possible to achieve a similar recognition for many years, despite the presence of quite obvious experimental evidence.

It is surprising, that in optics (in the field of electromagnetic interactions) a lot of direct and indirect experimental proofs of strong time reversal invariance violation exist for many years. All this results were received in the works, which were not aimed to find any invariance violations. Even more surprising fact is that the scientific community does not ready to accept these results.

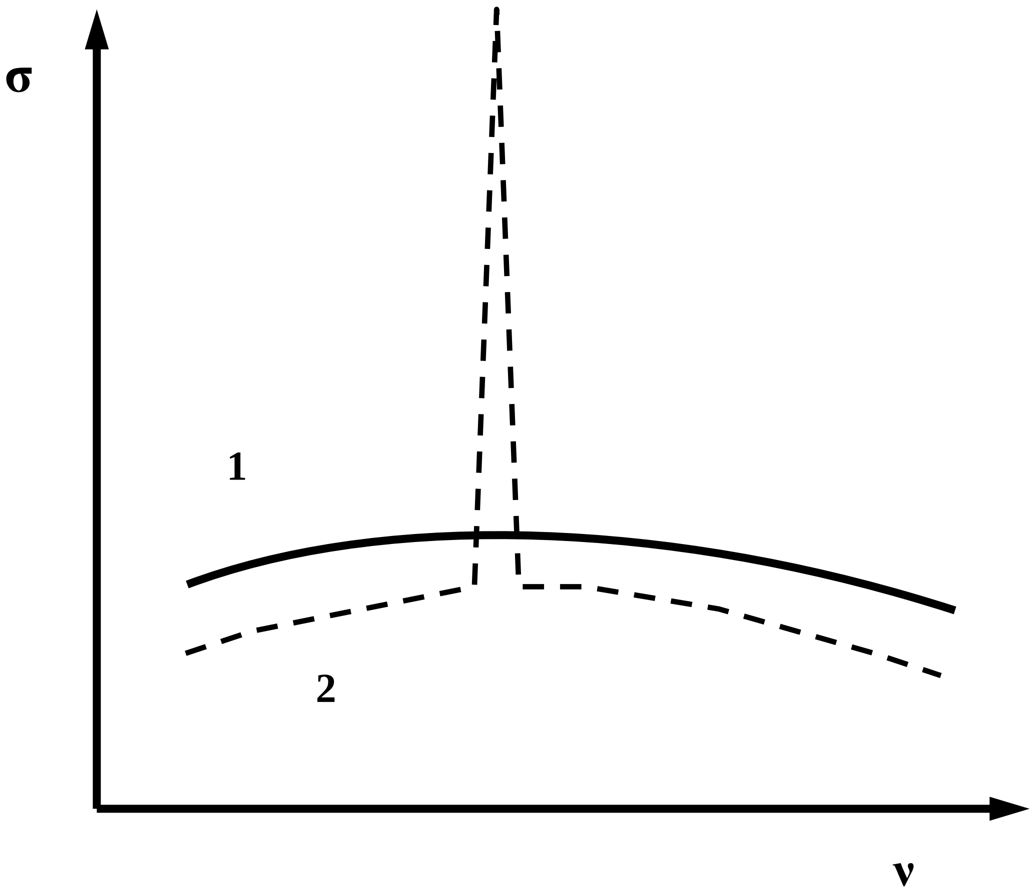

Figure 1. Schematic representation of the spectral dependence of cross-section for absorption (1) and stimulated emission (2) in polyatomic molecules during their interaction with laser radiation.

We especially love the first such direct proof, since it is directly related to us :). There is infrared multiple photon excitation of polyatomic molecules phenomenon. Here the excitation of molecules by laser radiation occurs through the unexpectedly intense far wings of the absorption lines [8, 9]. It is important that this is a real continuum of absorption. With this in mind, the other pump-probe experiments in molecular beams show that the forward and reversed processes are very different from each other [10]. According to the spectral width, they differ by five orders of magnitude (Fig. 1). And, the evaluation of the difference of differential cross sections gives value more than three orders of magnitude.

Other clear and direct experimental proof of nonequivalence of forward and reversed processes is published in [11]. Although, the authors do not discuss this problem. Here, the forward (splitting) and reversed (mixing) processes with a photons were studied (Fig. 2). On the first stage the narrowband (0.04 nm) radiation of nanosecond laser was transformed through down-conversion in the nonlinear crystal into two broadband signal and idler beams (each spectral width ~ 100 nm). On the second stage this two broadband beams were mixed in the sum frequency generator (SFG). It is expected that by mixing the two beams with a broad spectral distribution the beam with even broader spectral distribution will appear. However, the experiments show that in this case the mixing of entangled photons leads to regeneration of initial narrowband radiation and this is the example of reversed process into the initial state. In contrast, the mixing of non-entangled photons should give broadband radiation and this is the example of only forward process. The experiment shows that the efficiency of reversed process is much greater, than the efficiency of forward process.

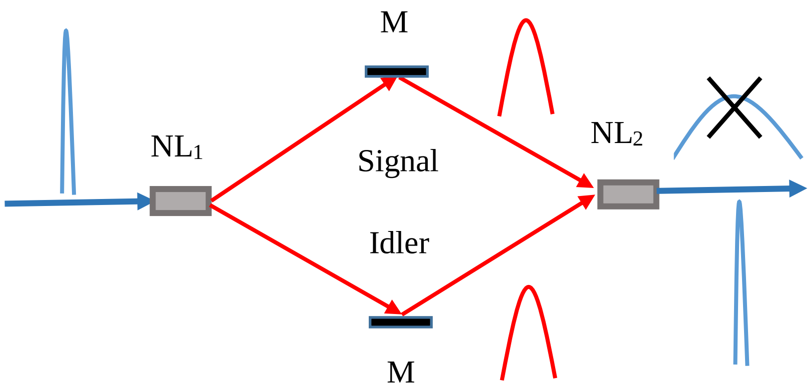

Figure 2. Scheme of the experiments for splitting and mixing of photons in nonlinear crystals. NL_1 and NL_2 – nonlinear crystals, M – mirrors.

Other quite direct proof is well-known Bloch oscillations of cold atoms in a vertical optical lattice [12]. Here cold atoms fall freely in a vacuum under gravity. The vertical optical lattice is formed by two oppositely directed laser beams. The commonly used explanation assumes that antinode of a standing wave are potential barriers which can reflect atoms. The main problem of this explanation is that the amplitude of oscillation of the atoms does not coincide with the period of the optical lattice. This amplitude is usually much greater than the lattice period.

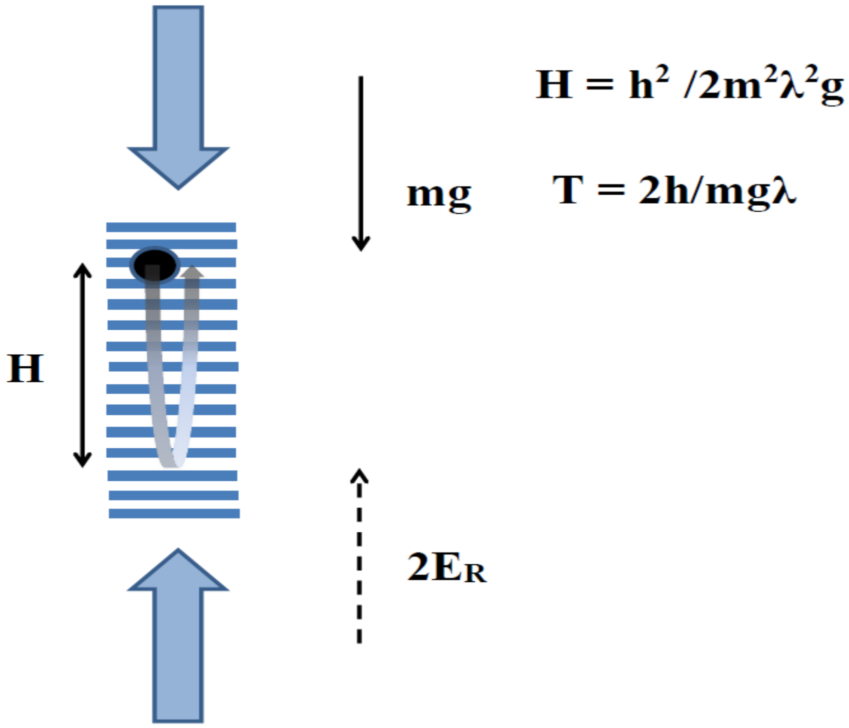

Figure 3. Scheme of the Bloch oscillations of cold atoms in a vertical optical lattice.

Of course, there is a beautiful mathematical description of the phenomenon based on the Gross-Pitaevskii equation. But, this description in direct or indirect way assumes that the motion of atoms in an optical lattice is due to the spatially asymmetric scattering of photons. At the certain moment of time the Raman optical transition takes place. The atom absorbs a photon from the upward beam and emits a photon in the direction of downward beam. As a result, the atom receives double recoil momentum and returns to the starting point of the space (Fig. 3).

In reality, we have the experimental fact of high spatial asymmetric scattering of photons, which is a direct consequence of the enormous inequality of differential cross sections of forward and reversed processes.

Direct experimental evidence of the non-invariance of time reversal, apparently, should include else the results of [13], where the authors studied the reflection of polarized light from metal planar chiral structures. Although, the physical mechanism of the processes here is not clear and this subject is quite difficult for understanding by physicists from other fields of research (the so-called “specialization barbarism” [14]).

In addition to direct proofs, there is a huge amount of indirect evidence of the non-invariance of time reversal. There are great number of phenomena in optics, which practically do not have any clear physical explanation: population transfer during sweeping of resonance conditions, photons mixing, photon echo, coherent population trapping-electromagnetically induced transparency, amplification without inversion, so-called field-free alignment of molecules, optical precursor, entangled two-photon absorption, Hong-Ou-Mandel effects and so on [15]. All this experimental phenomena usually have some mathematical descriptions (sometimes very good) and very poor or unconvincing physical explanations. However, these phenomena are easily physically explained by the nonequivalence of forward and reversed processes.

All this discussed direct and indirect experimental evidences clearly show inequality of forward and reversed processes in quantum physics. An extremely large and sharp differential cross-section of reversed transitions is the real physical base of nonlinear optics. Recognition of this fact immediately leads to a very interesting conclusion: quantum system must have a memory about its initial state. Without such a memory, the quantum system will not be able to distinguish a forward process from a reversed one.

This memory looks like a physical equivalent of the concepts of information, contextuality, entropy. We don't know where this memory is stored. However, there is a strong suspicion that this quantum memory is non-local.

Non-locality

The problem of nonlocality has long been widely discussed in quantum physics [16 – 18]. However, there is no reliable evidence of nonlocality. This is some kind of elusive thing. Nonlocality is usually associated with the violation of Bell's inequalities. However, this does not say anything about the nature of nonlocality. Moreover, the correctness of the application of these inequalities is challenged by a number of theorists [19, 20]. Today, nonlocality is a kind of elusive entity: it seems to be there, but what exactly it consists of is not clear.

At the same time, experiments have been known for many years in which nonlocality manifests itself in a quite direct way [21, 22]. We are talking about one of the variants of the Hong-Ou and Mandel (HOM) effect [23]. Figure 4 shows a little simplified scheme of such an experiment performed in [21]. Here, the HOM effect was studied using collinear entangled photons obtained by down conversion in a nonlinear type II crystal (1). The delay between photons was regulated by quartz plates, in which photons with different polarizations propagate at different speeds. Two entangled photons arrive at the beam splitter (2) and then enter at two detectors D1 and D2. Between the beam splitter and one of the detectors there are quartz plates (3), with the help of which the experimenters change the delay between the entangled photons. A typical HOM effect is observed.

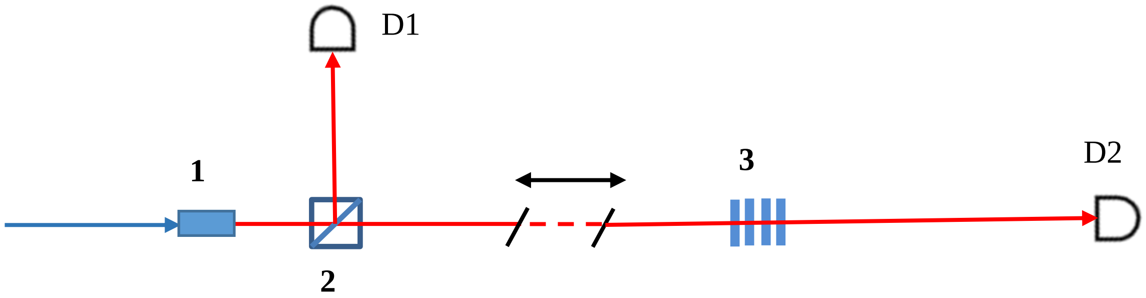

Figure 4 Simplified experimental scheme for cases when the photon delay control device is located after the beam splitter. 1 - nonlinear crystal, 2 - beam splitter, 3 - quartz plates.

The most interesting thing here is that the manipulations with quartz plates are carried out after the beam splitter, but not before it (as in the vast majority of works). It looks like a violation of causality. The splitting of photons by a beam splitter (consequence) precedes the cause (plates manipulation). However, it is not about the violation of causality, of course. We are dealing with an obvious manifestation of nonlocality. The photons, coming to the beam splitter, in some mysterious way “know” what will happen next and behave accordingly.

This situation is completely analogous to that which exists in the classical two-slit interference. When a photon or electron passes through a slit, it somehow mysteriously "knows" about the existence of the second slit [24]. In the case of slits, for various reasons, we cannot spread them far apart. However, in the case of the HOM effect, we can separate the beam splitter and quartz plates at least several kilometers away [25]. We can experimentally study in this way nonlocality of quantum memory. The study of non-locality here consists in separating the beam splitter and the device for manipulating photons as far as possible in space. In this case, we will get an idea of the degree of nonlocality of the memory of this quantum system. If the effect persists, then we can try to determine how fast this “knowledge” spreads. These are various variants of experiments with the so-called delayed choice [26 - 28].

Surprisingly, but for more than 20 years there has not been an experimenter who would dare to continue these experiments. These very simple and important experiments are needed to understand the physical nature and study the properties of the nonlocal memory of quantum systems.

Conclusion

We can now give a physical definition of the term: *entanglement is a memory of quantum system about its initial state, which manifests itself through inequality of differential cross-sections of forward and reversed processes*. We don't know where this memory is stored. But, we have a good opportunity to experimentally study the nonlocal properties of this memory.

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