QUANTUM-CLASSICAL PHASE TRANSITION WITH SPONTANEOUS SUPERPOSITION BREAKING AND SINGLE PHOTON INTERFERENCE

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In this work we theoretically suggest and consider a realistic experiment of single photon interference at beam splitter where micro-detector of the photon trajectories is presented by single atom. It admits studying of the quantum entanglement between photon and detector (Schrödinger cat effect) which clearly demonstrates that detection procedure (collapse) has no any absolute character. Also it admits modeling of the collapse by spontaneous (non-dynamical) unitary symmetry (superposition) breaking (effective hiding) by quantum-classical continuous phase transition. (Practically, collapse can be considered as an especial case of the general formalism of spontaneous symmetry breaking.) Finally it admits a simple solution of the quantum mechanics foundation problem.

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1. Introduction

As it is well-known remarkable experiments of the interference of single quantum system (photon, electron, atom, molecule, etc.) at a diaphragm with two slits or, analogously, at beam splitter, etc. [1]-[6] (in excellent agreement with real experimental facts [7], [8]) represents corner stone for demonstration of the basic principles of standard quantum mechanical formalism [2], [3], [9]-[12]. In this work we shall theoretically suggest and consider a new realistic experiment of single photon interference at beam splitter where micro-detector of the photon trajectories is presented by single atom. It admits studying of the quantum entanglement between photon and detector (Schrödinger cat effect) which clearly demonstrates that detection procedure (collapse) has no any absolute character. (It has been observed more or less explicitly that concept of the absolute collapse within quantum mechanics is analogous to concept of the absolute space and time in classical mechanics [1], [12].) Also it admits modeling of the collapse by spontaneous (non-dynamical) unitary symmetry (superposition) breaking (effective hiding) by quantum-classical continuous phase transition [13], [14]. (Practically, collapse can be considered as an especial case of the general formalism of spontaneous symmetry breaking that can be successfully applied in many different domains of the physics, e.g. in elasticity of rigid bodies,
quantum theory of ferromagnetism, quantum theory of electro-weak interactions as well as in chaotic inflation cosmology [15]-[18].) Finally it admits a simple solution of the quantum mechanics foundation problem.

2. An experiment of single photon interference at two beam splitters

Consider well-known experimental arrangement of single photon interference at beam splitter presented at figure 1. Here source S emits single photon with well-defined momentum and corresponding wave length that propagates toward beam splitter BS. Concretely, it will be supposed that single photon is spontaneously emitted by single atom of some concrete chemical element by quantum jump from some excited, e.g. first excited quantum state $|E>$ in the ground quantum state $|G>$. (In this sense, for reason of simplicity, mentioned single atom will be denoted as simple two-level quantum system TLS.) As it is well-known, immediately after strictly deterministic, unitary symmetric quantum dynamical interaction between photon and BS photon is exactly described by the following quantum superposition of “reflected” quantum state (trajectory) $|R>$ (which can be presented as a plane wave that propagates toward total mirror M1) and “transmitted” quantum state (trajectory) $|T>$ (which can be presented as a plane wave that propagates toward total mirror M2)

$$|ph> = i \frac{2^{-1/2}}{2^{1/2}} |R> + 2^{1/2} |T>$$

Later, after redirection of “reflected” state by M1 and “transmitted” state by M2, this quantum superposition (1) propagates toward detection photographic plate DPP at which interference patterns appear.(For reason of simple notification it will be considered that “reflected” quantum trajectory $|R>$ is roughly speaking determined by centers of BS, M1 and DPP, while “transmitted” quantum trajectory $|T>$ is roughly speaking determined by centers of BS, M2 and DPP.) Strictly speaking, by any individual detection DPP detects single photon in some “point”, i.e. small domain at DPP surface, while at statistical ensemble of detections intensity or number of the detections in different small domains of DPP surface holds many local minimums and maximums corresponding to interference patterns.

Consider now next less or more realistic concrete experimental arrangement presented at figure 2. Here single previously mentioned quantum two-level system (practically single atom) TLS is introduced. It will be supposed that TLS is, roughly speaking, placed at “reflected” photon trajectory in some “point” between M1 and DPP, as well as that motion of TLS can be effectively neglected during photon propagation between S and DPP. It implies that external (center of mass) quantum state of TLS can be considered effectively approximately as wave packet with practically zero average momentum value and coordinate average value in mentioned “point” at “reflected” photon trajectory (during photon propagation). Also, it will be supposed that TLS is sufficiently massive so that TLS external quantum state practically cannot be changed by quantum dynamical interaction with photon. For all this reasons we shall not further consider explicitly external quantum state of TLS.
Of course, TLS holds two eigen states of internal (relative particle) energy observable, ground $|G>$ and excited $|E>$. (It will be supposed that life time of excited state is much larger than time of photon propagation between S and DPP.)

Further, it will be supposed that initially, i.e. before quantum dynamical interactions between photon and TLS, TLS is in excited state $|E>$. It implies that initially, i.e. before quantum dynamical interaction between photon and two-level system, quantum super-system ph+TLS that includes photon and TLS is described by non-entangled quantum state $|ph>|E>$. As it is not hard to see, “transmitted” photo does not immediately quantum dynamically interact with two-level system.

Since photon energy is identical to difference between excited state energy and ground state energy quantum dynamical interaction between “reflected” photon and TLS can be considered as stimulated emission of a new, copy photon (coherent with practically non-perturbed “reflected” photon) by TLS when TLS turns out from excited state in ground state.

So, as it is not hard to see, immediately after mentioned quantum dynamical interactions between photon and two-level system, quantum super-system ph+TLS is described by the following entangled quantum state

$$\text{(2)} \quad |\text{ph+TLS}> = i \ 2^{-1/2} \left( |R> |R> |G> + 2^{-1/2} |T> |E> \right).$$

If later, by individual detection, DPP simultaneously detects two photons, it, according to (2), implies that both photons are “reflected”. But if later, by individual detection, DPP detects only single photon, it, according to (2), implies that mentioned photon is “transmitted”. Of course in the statistical ensemble of the individual detection two “reflected” photons will be detected by statistical weight $i \ 2^{-1/2} \sqrt{1/2}$, while single “transmitted” photon will be detected with statistical weight $2^{-1/2} \sqrt{1/2}$. Simply speaking DPP (with TLS as micro-detector) detects statistical mixture of “reflected” and “transmitted” photon(s) but not quantum superposition of “reflected” and “transmitted” photon (1). Precisely, here by any individual detection that represents photon trajectory detection, quantum superposition breaking, i.e. collapse appears and quantum superposition of the photon trajectories turns out in corresponding statistical mixture of the photon trajectories.
Even if collapse effectively appears only after quantum dynamical interaction between photon and TLS this collapse is not result of mentioned quantum dynamical interaction only. Result of mentioned quantum dynamical interaction is entangled quantum state (2) principally different from corresponding statistical mixture after collapse. Moreover by experimental arrangement presented at figure 3, it can be simply demonstrated that collapse does not represents result of some hypothetical non-unitary extension of quantum mechanical dynamics only, or, that collapse has not dynamical origin and absolute character. Here new two-level system TLS1 initially in ground state $|G\rangle$ behind TLS and new total mirror M3 are placed roughly speaking at “reflected” trajectory. Also, M2 is rotated in such way that it now redirects “transmitted” photon toward BS, while DPP is placed down in respect to BS. Finally, roughly speaking, distance between BS and M3 (via M1) is identical to distance between BS and M2.

Suppose firstly that in mentioned experimental arrangement quantum dynamics and standard quantum mechanical formalism are satisfied. Then, as it is not hard to see, here after the first quantum dynamical interaction between photon and TLS entangled quantum state (2) (metaphorically called Schrödinger cat effect) is realized. Later TLS1 absorbs one “reflected” photon (practically without any influence at other “reflected” photon) and turns out in excited state. Non-absorbed “reflected” photon, after redirection by M3, again quantum dynamically interacts with TLS1. This interaction can be considered as stimulated emission of a new, copy photon (coherent with practically non-perturbed previous photon) by TLS1 when TLS1 turns out from excited state in initial ground state. Later one of two photons will be quantum dynamically absorbed by TLS which turns out from ground in excited state without any perturbation of other photon that propagates toward M1. This photon later, after redirection by M1, propagates toward BS in quantum state that can be denoted by $|\downarrow\rangle$. On the other hand, “transmitted” photon, after redirection by M2, propagates again toward BS in quantum state that can be denoted by $i|←\rangle$. All this simply implies that when entangled quantum state (2) exists photon is, immediately before new, second quantum dynamical interaction with BS, described by the following quantum superposition

$$2^{-1/2} |\downarrow\rangle + i2^{-1/2} |←\rangle$$

As it is not hard to see, immediately after new, second quantum dynamical interaction between photon and BS photon certainly propagates toward S in quantum state that can be denoted by $i|BS,S\rangle$ and never toward DPP (quantum state that describes propagation of the photon from BS
toward DPP can be denoted by $|\text{BS},\text{DPP} \rangle$). It can be added that such result can be expected in full agreement with well-known existing experimental facts.

It can be supposed hypothetically that in mentioned experimental arrangement quantum dynamics and standard quantum mechanical formalism are not satisfied so that instead of entangled quantum state (2) there is exactly corresponding statistical mixture of quantum states $|\text{R} \rangle |\text{R} \rangle |\text{G} \rangle$ and $|\text{T} \rangle |\text{E} \rangle$ with corresponding statistical weights $|\text{i}^{1/2}|^2=1/2$ and $|\text{2}^{1/2}|^2=1/2$. It of course corresponds to hypothetical supposition on the absolute character of the quantum superposition breaking, i.e. collapse irreversibly realized by some non-unitary extension of the quantum dynamics. In this case, as it is not hard to see, after second dynamical interaction between photon and BS in mentioned experimental arrangement photon will be described by statistical mixture of quantum states $|\text{BS},\text{S} \rangle$ and $|\text{BS},\text{DPP} \rangle$ with identical statistical weights. It can be expected that it contradicts to well-known experimental facts.

Now we shall suggest generally and consider in experimental arrangement at figure 2. modeling of the collapse by spontaneous (non-dynamical) unitary symmetry (superposition) breaking (effective hiding) by quantum-classical continuous phase transition.

### 3. Wave packet approximation and (self)collapse as spontaneous superposition breaking

According to standard quantum mechanical formalism quantum system is exactly and completely described by quantum dynamical state of the unit norm from Hilbert space as the basic physical space. This quantum dynamical state strictly deterministically evolves during time according to to unitary symmetric (that conserves quantum superposition) quantum dynamical evolution (without any super-luminal characteristics).

(According to theoretical [19] and experimental [20], [21] facts super-luminality characterizes only such extensions of the standard quantum mechanical formalism where superposition breaking, i.e. collapse is absolute and which has dynamical character.)

Unitary symmetry implies that descriptions of quantum dynamical state in all referential frames (eigen basis of all Hermitean operators) in Hilbert space have the same right, or, that there is no absolute referential frame in Hilbert space. (In this sense, as it has been observed more or less explicitly [1], [12] quantum mechanics is deeply conceptually analogous to theory of relativity.)

If exact quantum dynamical state of quantum system satisfies well-known characteristic wave packet approximation conditions [2], [9], [22] it can be approximately considered as the wave packet. Concretely, in Ehrenfest picture, average value of the quantum dynamical equation can be Taylor expanded [22] so that first term in expansion represents classical dynamical term for average coordinate value while other terms are proportional to increasing degrees of the coordinate uncertainty exponents. If coordinate average value is much larger than coordinate uncertainty, i.e. wave packet width, first term turns out in classical dynamical term for wave packet while other terms can be effectively neglected. Down limit of such wave packet approximation is characterized by Heisenberg uncertainty relations. In this way (only until all approximation conditions are satisfied) classical mechanics can be considered as globally dynamically stable approximation of the quantum mechanics as exact theory. Simultaneously (under same approximation conditions) mentioned wave packet can be globally approximately treated as the classical mechanical particle that satisfies approximate classical mechanical dynamical equation.
Further, exactly quantum mechanically superposition of any two wave packet is well-defined. But, it can be simply proved [13], [14] that superposition of two weakly interfering wave packets does not represent any wave packet. Namely, then mentioned Taylor expansion of Ehrenfest average value of the quantum dynamical equation becomes divergent. For this reason exactly existing quantum superposition of two weakly interfering wave packets, approximately classically is globally non-stable and it cannot be globally presented as any wave packet. However, mentioned superposition can be locally presented by one or other wave packet in corresponding small domains in which mentioned wave packets are well defined. This situation is conceptually completely analogous to situations in general formalism of the spontaneous symmetry breaking [16], [17]. It implies (see [13], [1]) that superposition of weakly interfering wave packets, within (quasi) classical approximation, (self)collapses or turns out spontaneously (non-dynamically) in statistical mixture of mentioned wave packets. On the other hand, at exact quantum level of analysis accuracy, there is no any breaking of the superposition of corresponding wave packets. (It can be added that situation in which overlap intensity of two wave packets in superposition continuously decreases during time can be considered as a continuous phase transition from superposition to statistical mixture.)

All this can be simply generalized for super-systemic superposition, especially for entanglement (see [13], [14]). If, after realization of exact quantum entanglement between measured quantum system and detector (Schrödinger cat effect), eigen states of detector pointer observable represent weakly interfering wave packets, self-collapse at detector appears on the classical level of analysis accuracy. Simultaneously, in respect to self-collapsed detector, at measured quantum system corresponding relative collapse, i.e. statistical mixture of quantum system measured observable eigen states, e.g. trajectories, appears. According to correlations between quantum system measured observable eigen states and detector pointer observable eigen states, relative collapse at quantum system seems effectively as pure quantum phenomena.

So, measurement or detection represents such effective phenomena in which at measuring apparatus or detector effectively (approximately “classically”) self-collapse as spontaneous (non-dynamical) unitary symmetry (superposition) breaking (effective hiding) appears (with irreducible statistical characteristics) within effectively “absolute” referential frame as basis of weakly interfering wave packets as eigen states of detector “pointer” observable. Simultaneously, in respect to self-collapsed detector, at detected quantum system relative collapse as effectively quantum phenomena appears (with irreducible statistical characteristics) within effectively “absolute” referential frame as basis of eigen states of detected observable correlated (via entanglement) with. basis of eigen states of detector “pointer” observable. Simply speaking, (self and relative) collapsed state represents approximately dynamically locally stable projection of exactly existing entangled quantum state in situation when approximately dynamically globally stable projection of exactly existing entangled quantum state does not exists at all. As it is well-known [11], in distinction to reversible unitary quantum dynamical evolution collapse is principally irreversible. Here it can be very simply explained. Collapsed state, at approximate level of analysis accuracy, evolves further dynamically deterministically and it cannot return in initial approximately dynamically globally non-stable state. On the other hand at exact level of analysis accuracy where entangled quantum state exists collapse has been never realized and exact quantum phenomena are reversible.

In this way quantum mechanics can be simply consistently founded and it represents quite natural bridge between classical mechanics and quantum field theory.

Consider now exactly existing entangled quantum state (2). As it has been previously discussed external quantum state of two-level system represents corresponding wave-packet,
while internal quantum state of two-level system can be either excited or ground. Generally speaking ground state is stable (it cannot decay during time). On the other hand excited state in non-stable and it (roughly speaking), after its life time interval, decays in ground state of two-level system and free propagating photon. Formally but correctly it can be considered that before life time moment quantized amount of electromagnetic field, i.e. photon has been captured, localized or “frozen” within two-level system which within usual simplification corresponds to excited state of two-level system only. In further wave-packet approximation it can be considered that before life time moment quantized amount of electromagnetic field, i.e. (roughly speaking) photon has been captured, localized or “frozen” within two-level system wave-packet. In this sense we can speak about effective wave packet of “frozen” photon.

According to previous discussion we can change exact entangled quantum state (2) with the following effective quantum state of entangled two photons

\[ |\text{ph+ph} > = i 2^{-1/2} |R > |R > + 2^{-1/2} |T > |\text{fph,TLS} > \]

Here \(|R > |R > \) describes two “reflected” photons, while \(|T > |\text{fph,TLS} > \) describes two photons - first one in “transmitted” state and second one (described by wave packet \(|\text{fph,TLS} > \) ) “frozen” in TLS.

During time interval within which “reflected” photon leaves TLS wave-packet domain and arrives at DPP quantum state \(|R > \) and wave-packet \(|\text{fph,TLS} > \) become extremely weakly interfering. It implies that after mentioned time interval phase transition (in which any quantum superposition of \(|R > \) and \(|\text{fph,TLS} > \) spontaneously (non-dynamically) self-collapses in corresponding statistical mixture) occurs effectively approximately. Strictly speaking here only \(|\text{fph,TLS} > \) represents wave-packet and only it can be spontaneously classically localized within corresponding TLS domain with corresponding statistical weight, e.g. \(|2^{-1/2}|^2=1/2\). But opposite event, i.e. absence of the classical localization of the photon within TLS can occur with the complementary statistical weight, e.g. \(|i2^{-1/2}|^2=1/2\). It corresponds to effective appearance of quantum state \(|R > \) in some additional detection of the photon even if \(|R > \) does not represent wave packet.

Thus, according to model of the collapse as spontaneous superposition breaking, self-collapse effectively appears at second photon, while at first photon relative collapse as effective quantum phenomena appears. Simultaneously entangled quantum state (4) (whose existence represents Schrödinger cat effect) spontaneously turns out in statistical mixture of \(|R > \) and \(|T > |\text{fph,TLS} > \) states with the statistical weight \(|i 2^{-1/2}|^2=1/2\) and \(|2^{-1/2}|^2=1/2\). It implies corresponding statistical mixture of relatively collapsed first photon finally detected by DPP.

4. Conclusion

In conclusion the following can be repeated and pointed out. In this work we theoretically suggest and consider a realistic experiment of single photon interference at beam splitter where micro-detector of the photon trajectories is presented by single atom. It admits studying of the quantum entanglement between photon and detector (Schrödinger cat effect) which clearly demonstrates that detection procedure (collapse) has no any absolute character. Also it admits modeling of the collapse by spontaneous (non-dynamical) unitary symmetry (superposition) breaking (effective hiding) by quantum-classical continuous phase transition. (Practically,
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References

[1] N. Bohr, Atomic Physics and Human Knowledge (John Wiley, New York, 1958)
[2] P. A. M. Dirac, Principles of Quantum Mechanics (Clarendon Press, Oxford, 1958)
[3] R. P. Feynman, R. B. Leighton, M. Sands, The Feynman Lectures on Physics, Vol. 3 (Addison-Wesley Inc., Reading, Mass. 1963)
[4] R. P. Feynman, The Character of Physical Law; (MIT Press: Cambridge, 1967)
[5] Mathematical Foundations of Quantum Theory, ed. A. R. Marlow, (Academic Press, New York, 1978)
[6] V. Scarani, A. Suarez, Am. J. Phys. 66 (1998) 718
[7] M. Arndt, K. Hornberger, A. Zeilinger, Physics World (March 2005) 35 and references therein
[8] V. Jacques, E. Wu, T. Toury, F. Treussart, A. Aspect, P. Grangier, J.-F. Roch, Single photon wavefront-splitting interference: an illustration of the light quantum in action arxiv (quant-ph): 2011.12644 v1 (2020) and references therein
[9] A. Messiah, Quantum Mechanics (North-Holland Publ. Co., Amsterdam, 1970)
[10] B. d’Espagnat, Conceptual Foundations of the Quantum Mechanics (Benjamin, London-Amsterdam-New York, 1976)
[11] J. von Neumann, Mathematische Grundlagen der Quanten Mechanik (Springer Verlag, Berlin, 1932).
[12] N. Bohr, Phys.Rev., 48 (1935), 696
[13] V. Panković, T. Hübsch, M. Predojević, M. Krmar, From Quantum to Classical Dynamics: A Landau Phase Transition with Spontaneous Superposition Breaking, arxiv (quant-ph): 0409010 v1 (2004) and references therein
[14] V. Panković, Journal of Advanced Physics 5 (2016) 1
[15] J. Bernstein, Rev. Mod. Phys. 46 (1974) 7
[16] S. Coleman, An Introduction to Spontaneous Symmetry Breaking and Gauge Fields in Laws of Hadronic Matter, ed. A. Zichichi (Academic Press, New York, 1975)
[17] F. Halzen, A. Martin, Quarks and Leptons: An Introductory Course in Modern Particle Physics (John Wiley, New York, 1978)
[18] A.D. Linde, Rep. Prog. Phys., 47 (1984) 925
[19] J. S. Bell, Physics, 1 (1964) 195
[20] A. Aspect, P. Grangier, G. Roger, Phys. Rev. Lett. 47 (1981) 460
[21] A. Aspect, J. Dalibard, G. Roger, Phys. Rev. Lett. 49 (1982) 1804
[22] A.A. Sokolov, I.M. Ternov, V-Ch.Zhukovskii, Quantum Mechanics (Nauka, Moscow, 1979) (in Russian)