AHARONOV-BOHM EFFECT AND QUANTUM – CLASSICAL PHASE TRANSITION (BY SPONTANEOUS SUPERPOSITION BREAKING)

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Abstract

In this work we theoretically considered Aharonov-Bohm effect in some new variations of remarkable experiments of single electron interference at diaphragm with two slits. It will be correlated with possibility (shortly noted by Feynman) of a practically “continuous” phase transition from detection of the quantum system trajectories superposition (interference) in detection of the quantum system trajectories statistical mixture (and vice versa) in real experiments. All this can be very important for the quantum mechanics foundation (including question on the photon-detector interaction, i.e. Schrödinger cat effect) since it clearly demonstrates that quantum superposition breaking, i.e. (self-)collapse has not necessarily absolute character as well as that it can be realized even at quantum micro-systems (photon, electron, atom, etc.). We discuss a consistent model of the collapse as spontaneous (non-dynamical) breaking (effective hiding) of the unitary symmetry (that conserves superposition) of the quantum dynamics. It can be considered as an especial case of the general formalism of the 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.

Key words: Aharonov-Bohm effect, spontaneous superposition breaking, electron-detector entanglement
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1. Introduction

As it is well-known theoretically considered remarkable experiment of the interference of single quantum system (photon, electron, atom, 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 cornerstone for demonstration of the basic principles of standard quantum mechanical formalism [2], [3], [9]-[11].

In this work we shall theoretically considered Aharonov-Bohm effect [12], [13] in some new variations of remarkable experiments of single electron interference at diaphragm with two slits. It will be correlated with possibility (shortly noted by Feynman [4]) of a practically “continuous” phase transition from detection of the quantum system trajectories superposition (interference) in detection of the quantum system trajectories statistical mixture (and vice versa) in real experiments. All this can be very important for the quantum mechanics foundation (including question on the photon-detector interaction, i.e. Schrödinger cat effect) since it clearly demonstrates that quantum superposition breaking, i.e. (self-)collapse has not necessarily absolute character as well as that it can be realized even at quantum micro-systems (photon, electron, atom, etc.). We shall discuss a consistent model of the collapse as spontaneous (non-dynamical) breaking (effective hiding) of the unitary symmetry (that conserves superposition) of the quantum dynamics [14],[15]. It can be considered as an especial case of the general formalism of the 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 [16]-[19].

2. Interference of the single electron at diaphragm with two slits and basic problem of the quantum mechanics foundation

Consider shortly, within standard quantum mechanical formalism, usual experiment of the single quantum micro-system, e.g. electron interference at (horizontal) diaphragm DP with two slits S1 and S2 (without electron trajectories detection TD) roughly presented at Figure 1. Single electron e with well-defined momentum, i.e. de Broglie wave-length, immediately after propagation through both slits at DP and before interaction with DPP, is described by the following quantum superposition

\[ |e > = a |S1 > + b |S2 > \]

(but not statistical mixture) of two quantum states |S1 > corresponding to electron that arrives from S1 and |S2 > corresponding to electron that arrives from S2 where a and b represent corresponding superposition coefficients. or trajectories corresponding to propagation through two slits respectively. It is unambiguous experimental fact that detection photo plate, after interaction with electron, effectively detects quantum superposition (1), i.e. corresponding characteristic interference patterns (existence of
many intensity local minimums and maximums. But here, as well as by detection or measurement of any quantum observable, basic, primary problem of the quantum mechanics foundation stands open. Namely, if we, for reason of simplicity, suppose that DPP represents one dimensional physical system along x-axis, then DPP effectively detects electron in some point x with statistical weight, i.e. distribution $|<x|e>|^2$. This statistical distribution has different values in different points and it corresponds to interference patterns. However, any quantum dynamical interaction between two quantum systems, including electron and DPP, must be, within standard quantum mechanical formalism, described by unitary (that conserves superposition), strictly deterministic, quantum dynamical evolution. Concretely, here such quantum dynamical interaction must realize electron-DPP entanglement over x coordinates. More precisely this entangled quantum state in any coordinate x holds (in idealized form) the following term $<x|e>|e,x>|DPP,x>$ where $|e,x>$ and $|DPP,x>$ represent electron and DPP x-coordinate state. Mentioned electron-DPP entangled quantum state (or quantum superposition quantum dynamically extended from electron at electron+DPP) is exactly strictly different from previously statistical mixture obtained effectively by DPP detection and it represents basic, primary problem of the quantum mechanics foundation.

Relevant solution of mentioned problem needs unambiguous experimental test of the existence of mentioned entanglement between electron and DPP (Schrödinger cat effect). (Of course, existence of the electron-DPP entanglement implies non-existence of the absolute breaking or collapse of the same entanglement (absolute non-existence of
effective statistical mixture as an exact phenomena), and vice versa.) But realization of such experiments is technically extremely hard and any such experiment is not realized to this day.

In absence of the definite experimental answer what is more fundamental, mentioned quantum superposition or statistical mixture, there are two different options.

First option is that mentioned statistical mixture is more fundamental than corresponding quantum superposition. For example von Neumann [11] supposed ad hoc additional part of interaction between e and DPP that absolutely irreversibly reduces or collapses quantum superposition state in corresponding statistical mixture. Ad hoc character of the postulate on the absolute collapse can be eliminated within hypothetical non-trivial extensions (by so-called hidden variables) of the standard quantum mechanical formalism (e.g. [20]- [22]) that predicts some form of the absolute collapse (mostly as dynamical breaking of the unitary symmetry of the quantum dynamics). But as it is well-known [23]- [25], in distinction to quantum mechanics any such hidden variables theory must be necessarily super-luminal or non-local what is extremely non-plausible. Especially non-locally extended quantum mechanics strictly contradicts to local quantum field theory.) In this way, as it has been suggested by Bohr [1], [26], concept of the absolute collapse within quantum mechanics is very similar to concept of the absolute space and time within classical mechanics.

Second option is that mentioned quantum superposition is more fundamental than corresponding statistical mixture. In this case standard unitary (that conserves superposition) quantum dynamics does not need any extension. But in the same case a consistent model of the collapse as effective quantum superposition breaking or as effective “phase transition” from quantum superposition in statistical mixture must be consistently developed. First step in this direction are ideas [27], [28] that collapse in some sense represents an approximate phenomena connected with weak interference (of wave packets) conditions. (However, as it is well-known, at the exact quantum mechanical level of analysis accuracy, superposition of weakly interfering quantum states stands superposition, without any approximate transition in statistical mixture.) Second, very important step in mentioned direction was observation (without detailed physical explanation) [29] that mathematical structure of the standard quantum mechanical formalism admits that collapse be considered as a continuous Landau phase transition. It can be correlated with third step in the same direction, i.e. with old Bohr ideas [1], [26] on approximate “classical” description of the measurement, i.e. detection apparatus in detection procedure, when an approximate level of analysis accuracy must be introduced. All this admits, as it has been definitely proved [14], [15], that collapse can be considered as the spontaneous (non-dynamical) breaking (effective hiding) of the unitary symmetry (superposition or entanglement) by phase transition from exact quantum in approximate level of the analysis accuracy. It can be considered as an especial case of the general formalism of the 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 [16]-[19].

But firstly we can consider experiment of the single electron interference at diaphragm with two slits when electron trajectory detector TD is added (as it is formally
roughly presented at Figure 2.). Here TD effectively detects electron trajectory or, precisely speaking, TD effectively changes or collapses quantum superposition (1) in statistical mixture of quantum states $|S_1>$ and $|S_2>$ with corresponding statistical weights $|a|^2$ and $|b|^2$. But exact, unitary symmetric, quantum dynamical interaction between e and TD only extends quantum superposition (1) in the following entangled quantum state of quantum super-system e+TD

$$a \, |S_1> \, |TD_1> + b \, |S_2> \, |TD_2>$$

where $|TD_1>$ and $|TD_2>$ represent eigen states of TD characteristic “pointer” observable. Entangled quantum state (2) is strictly exactly different from previously mentioned statistical mixture so that we have again basic, primary problem of the quantum mechanics foundation.

When later electron effectively described by mentioned statistical mixture of trajectories interact with GPP, DPP, in analogy with previous discussions, will effectively detect statistical distribution along x-axis (without interference patterns) that represents statistical mixture of statistical distributions corresponding to first and second electron trajectory.

So it can be very simply and clearly explained why by effective electron trajectories detection quantum superposition (1), precisely effectively corresponding interference patterns become broken. It simply speaking implies additional interaction between electron and TD that within standard quantum mechanical formalism must be strictly considered. But of course, basic, primary problem of quantum mechanics foundation, that here appears in many steps, needs additional explanation.

3. A simple real experiments of a “continuous” phase transition between quantum superposition in the of statistical mixture detection

Consider such real experimental arrangements in which TD is directly connected with DPP.

Consider firstly real experimental arrangements roughly presented at Figure 3. (where S1 is open and S2 is closed) and Figure 4. (where S1 is closed and S2 is open). Then, at a statistical ensemble of single electron detection where experiment at Figure 3. and experiment at Figure 4. are realized with corresponding statistical weights $|a|^2$ and $|b|^2$

Is formally mathematically but not strictly physically analogous to experiment presented at Figure 2.

Consider further a simple real variation (roughly presented at Figure 5.) of previously discussed experiment of single electron interference at diaphragm with two slits. Here an additional vertical diaphragm VDP with single slit S3 placed between centers of DPP and DP. Length d of VDP (without S3) and linear dimension s of S3 can be considered as some parameters whose values can be changed practically “continuously” (in a series of small “discrete” steps) so that s+d corresponding to distance between DPP and DP stands constant.

For d=0, as it is not hard to see, experiment at Figure 5. is identical to
experiment at Figure 1. In this situation, DPP, which cannot be considered as electron trajectory detector, finally detects electron trajectories superposition.

But for \( d \) identical to whole distance between GP and DPP experimental arrangement represents practically remarkable de Broglie box. In this situation, after quantum dynamical interaction with DP and before detection by DPP, electron is in quantum superposition of two trajectories even if mentioned two trajectories do not interfere at all. In this situation DPP can be considered as electron trajectories detector since left part or domain (in respect to center) of DPP detects only electron that propagates through S1 while right part or domain (in respect to center) of DPP detects only electron that propagates through S2. In same situation, by any individual detection, DPP detects effectively one or other electron trajectory with corresponding statistical weights.

For some intermediate \( d \) between 0 and total distance between DPP and DP, DPP roughly approximately can be divided in four practically disjunctive domains. In left interference domain LID and right interference domain RID electron from both splits can arrive so that in mentioned domains interference patterns can be detected. In left no-interference domain LNID (for sufficiently large \( s \)) only electron from S1 can effectively arrive, while in right no-interference domain RNID (for sufficiently large \( s \)) only electron from S2 can effectively arrive. In this way DPP here represents a statistical mixture of electron trajectory detector (corresponding to LNID and RNID) and electron trajectories interference detector (corresponding to LID and RID) with corresponding statistical weights.
weights (dependent of d) as “continuously” changeable parameters.

In this way a real “continuous” phase transition between electron trajectories interference detection and electron trajectories detection is unambiguously demonstrated.

At next real experiment roughly presented at Figure 6. Aharonov-Bohm coil ABC is introduced in previous experimental arrangement. It means that here Aharonov-Bohm effect (interference patterns shift) can be realized in LID and RID, while in LNID and RNID (where interference patterns do not exist) any statistical distribution shift does not appear.

All this simply points out that here basic, primary problem of the quantum mechanics foundation can be reduced at studying of the quantum dynamical interaction between single electron in quantum superposition of at least two quantum states and DPP.

4. How single electron and photo plate really quantum dynamically interact

DPP (simplified presented as one-dimensional physical system) can be divided in segments or intervals DPP(n)=((n-1/2)Δ , (n+1/2) Δ ) with center in nΔ for sufficiently small interval width Δ and for whole number n between -k and k where k represents some sufficiently large natural number. In any segment DPP(n) quantum system q of same type that consists of few or many atoms is placed. It means that for given DPP(n) q center of mass quantum state Ψ(q,n,CM) is defined only within a relatively deep potential hole within DPP(n). It admits that Ψ(q,n,CM) can be “classically” approximated
by a wave packet with zero average momentum and average x-coordinate $n\Delta$. But, for
given DPP(n), q relative particle quantum state, initially, i.e. before interaction with
electron, is some “ground” quantum state $\Psi(q,n,G)$. It means that for given DPP(n) total
quantum state of q is $\Psi(q,n,CM) \Psi(q,n,G)$.

On the other hand electron is initially, i.e. before interaction with DPP(n) described
by quantum state $\Psi(e,n)$ that can be approximately presented as plane wave with well-
defined momentum that propagates toward DPP(n).

In this way, quantum super-system e+DPP(n=, initially, i.e. before interaction
between e and DPP(n), is described by non-entangled quantum state

\[ (3) \quad \Psi(e,n) \Psi(q,n,CM) \Psi(q,n,G) \]

Immediately after quantum dynamical interaction between e and e and DPP(n)
quantum state (3) turns out deterministically in the following non-entangled quantum state

\[ (4) \quad \Phi(e,n) \Psi(q,n,CM) \Psi(q,n,E) \]

Here $\Phi(e,n)$ represents quantum state of the electron captured or “absorbed” within
(potential hole characteristic for) DPP(n), while $\Psi(q,n,E)$ represents “excited” quantum state of q relative particle. In additional “classical” approximation $\Phi(e,n)$ (as well as $\Psi(q,n,CM)$) can be treated as wave packet with zero average momentum and average x-coordinate $n\Delta$.

Suppose now that electron is initially described by the following quantum superposition

\[ (5) \quad c(n)\Psi(e,n) + c(m)\Psi(e,m) \quad \text{for } n \neq m \]

where $c(n)$ and $c(m)$ represent superposition coefficients. Such superposition exactly
exists even if quantum states $\Psi(e,n)$ and $\Psi(e,m)$ extremely weakly interfere, i.e. overlap.

Then, initially, quantum super-system e+DPP(n)+DPP(m) is described by the
following non-entangled quantum state

\[ (6) \quad (c(n)\Psi(e,n) + c(m)\Psi(e,m)) \Psi(q,n,CM) \Psi(q,n,G) \Psi(q,m,CM) \Psi(q,m,G) \]

This state (6), immediately after quantum dynamical interactions between e, DPP(n) and
DPP(m), turns out deterministically in the following entangled quantum state

\[ (7) \quad c(n) \Phi(e,n) \Psi(q,n,CM) \Psi(q,n,E) \Psi(q,m,CM) \Psi(q,m,G) + c(m) \Phi(e,m) \Psi(q,n,CM) \Psi(q,n,G) \Psi(q,m,CM) \Psi(q,m,E) \]

It is very important to be observed and pointed out that mutually extremely weakly
interfering electron quantum states $\Phi(e,n)$ and $\Phi(e,m)$ represent in additional “classical”
approximation two mutually extremely weakly interfering wave-packets of the electron.

Finally, it is not hard to see, that suggested simple model of the quantum dynamical
interaction between single electron and detection photo plate can be used (with simple
corrections) as model of the quantum dynamical interaction between single photon and
detection photo plate.

5. Basic concepts of the general formalism of the spontaneous (non-
dynamical) symmetry breaking (effective hiding)

Now we shall prove that all previously discussed experimental facts can be consistently
explained within standard quantum mechanical formalism by model of the collapse as
spontaneous (non-dynamical) breaking (effective hiding) of unitary symmetry (that conserves
quantum superposition or entanglement) of quantum dynamics. But firstly we must present
basic concepts of the general formalism of the spontaneous (non-dynamical) breaking
(effective hiding) of some dynamical symmetry.

As it is well-known [16]-[18] there are two principally different ways for breaking of
the dynamical symmetry, dynamical and spontaneous (non-dynamical), which will be shortly
considered. Basic characteristic of a physical theory that can be applied for description of a
physical system is corresponding dynamics. This dynamics or precisely dynamical equations
hold corresponding dynamical symmetries. Unique solution of mentioned dynamical
equations, if it exists, represents dynamically stable and observable dynamical state that
deterministically evolves during time. (Words stable and observable here refer to
corresponding dynamics.) Consider situation in which the physical system can be described
by two discretely different physical theories, one, more accurate or simply speaking exact,
and other, less accurate or simply speaking approximate. (In this sense we can speak about
two different levels of analysis accuracy, one exact corresponding to exact theory and other
approximate corresponding to approximate theory.) Exact theory can be considered as a non-
trivial extension of the approximate theory, while approximate theory can be considered as a
non-trivial reduction of the exact theory. There is such situation in which some approximate
dynamical symmetry does not represent any exact dynamical symmetry. It means that
mentioned approximate dynamical symmetry is not conserved at exact level of analysis
accuracy or that mentioned approximate dynamical symmetry becomes broken by transition
from approximate at exact level of analysis accuracy, i.e. by means of such exact dynamical
terms that do not appear at approximate level of analysis accuracy. It represents dynamical
breaking of the approximate dynamical symmetry.

Dynamical symmetry breaking holds many very important applications within
physics, classical and quantum. For example, experimentally verified parity breaking in weak
interactions is a typical dynamical symmetry breaking. But there are such very important
physical situations where concept of the dynamical symmetry breaking cannot be applied at
all. For example in attempt of unification of the electromagnetic and weak interaction
additional mass term cannot be immediately introduced in the dynamics. Namely such term
dynamically breaks gauge symmetry of the electro-weak dynamics without which theory
does not admit renormalization and diverges. Also, as it has been previously discussed,
absolute collapse or dynamical breaking of unitary symmetric (that conserves quantum
superposition or entanglement) quantum dynamics cannot be realized at all by additional (at
quantum level of accuracy hidden) dynamical variables from some more accurate level of
analysis. Namely, in distinction to relativistic local quantum dynamics, any non-trivial
extension of quantum dynamics that satisfies existing experimental facts must be necessarily
relativistic non-local or super-luminal

There is such situation in which exact dynamics should be approximately reduced or
projected in approximate dynamics. For reason of the discrete difference between exact
dynamics and approximate dynamics there are different possibilities for realization of mentioned projection. Some exact dynamical state can be globally (i.e. in whole space of the arguments) consistently (convergent) approximated by corresponding approximate dynamical state and then some exact dynamical symmetries become effectively hidden but not broken. Here, roughly speaking, exact dynamical state becomes globally dynamically stable and observable even at the approximate level of analysis accuracy. Some other exact dynamical state that cannot be globally (i.e. in whole space of the arguments) approximated by any corresponding approximate dynamical state. For this reason, exactly existing, exactly dynamically stable and observable dynamical state is globally approximately dynamically non-stable and non-observable. Here, roughly speaking, exact dynamical state becomes globally non-stable and non-observable at the approximate level of analysis accuracy. Finally, there is such exact dynamical state that cannot be globally (i.e. in whole space of the arguments) but can be locally (in some disjunctive domains of the arguments) consistently (convergent) approximated by corresponding local approximate dynamical states. In this sense such exact dynamical state is locally approximately dynamically stable and observable. It means that within any mentioned local domain of arguments approximate dynamics holds one consistent solution, i.e. approximate dynamical state which within this domain can locally represent exact dynamical state. Formally we can speak about spontaneous (non-dynamical) transition from the globally approximately dynamically non-stable exact dynamical state in the locally approximately dynamically stable exact dynamical state. But this transition or this event is inherently probabilistic or statistical. Namely it cannot be described deterministically neither by exact dynamics (within which such transition does not exists at all), nor by approximate dynamics (since its validity is limited in restricted domain of the exact dynamical state arguments). According to usual geometric definition of probability, probability of mentioned transition or event can be defined as the relative measure of corresponding arguments domain. It can be added that here exact dynamical state cannot be simultaneously separated in all local domains in case when its norm must be conserved as it is case within quantum field theory. Finally, after mentioned probabilistic local transition or projection, further deterministic approximate dynamical evolution appears which does not admit reverse transition. Discussed transition by which many, symmetric, local approximate dynamical solutions are probabilistically and irreversible changed by one actual local approximate dynamical solution represents in fact spontaneous symmetry breaking. More accurately speaking we have here effective hiding of the symmetry at approximate level of analysis accuracy (at exact level of analysis accuracy symmetry is not broken but it is conserved).

Spontaneous symmetry breaking holds many very important applications within physics, classical and quantum. Within electro-weak theory exact quantum dynamical solution of the exact dynamical equation exists, but it cannot be obtained analytically. For this reason approximate dynamics, i.e. perturbation theory must be used. Perturbation theory diverges for zero field value (false vacuum), but locally converges for “circularly” distributed field values (real vacuums). Translation, i.e. transition from zero field value (false vacuum) to some field value at “circle” (real vacuum) realizes spontaneous breaking of the “circular symmetry” (in fact gauge symmetry). As it has been detailed discussed in [18], word “translation” here is not conclusive, as well as word “choice” or question “how Nature chose one of equally probable real vacuums”. All mentioned phrases refer on the dynamical breaking of the symmetry concept. Within spontaneous symmetry breaking there is no “choice” but only irreducibly probabilistic event at approximate, perturbation theory level of accuracy, and exactly conserved gauge symmetry. In domains of not so high energies theory
of perturbation can be used as technically simple theoretical method, but it cannot be considered as any principal “choice”.

6. Collapse as spontaneous (non-dynamical) superposition breaking (effective hiding)

As it is well-known within standard quantum mechanical formalism, basic quantum space is Hilbert space of the quantum states with unit norm. Quantum system is completely described by quantum state of the unit norm from Hilbert space and this state strictly deterministically evolves during time according to unitary symmetric quantum (mechanical) dynamics. Physical characteristics of the quantum system are presented by Hermitian operators with real eigen values and referential frames in Hilbert space represent bases of all observables. Quantum dynamical state is presented in some referential frame by quantum superposition over all basic states that define this referential frame. For this reason unitary symmetry of the quantum dynamics (that conserves superposition) simply implies that all referential frames in Hilbert space have the same right and that within Hilbert space there is no absolute referential frame or absolute observer.

It can be observed that only previous few statements express practically all basic concepts of the quantum mechanics as an exact physical theory. (Of course here we do not speak on the necessity of the relativistic generalization of the quantum mechanics toward quantum field theory etc.) Within such exact theory quantum superposition or quantum entanglement as an especial quantum superposition in the Hilbert space of quantum super-system have clear physical sense. It is in an excellent agreement with experimental facts that point out that quantum entanglement is not only distance independent\[24], \[25], but also number of quantum sub-systems and temperature independent \[30]. (Within hidden variables and similar physical theories, where it is supposed that usual or phase space represents basic physical space quantum superposition and entanglement cannot obtain clear physical sense without non-plausible super-luminal interactions.) Further we shall shortly consider how exact quantum mechanics can be reduced globally and locally in the approximate classical mechanic that is detailed discussed in \[14], \[15].

Suppose that quantum dynamical state represents a wave packet. Under additional, well-known \[2],\[9],\[31] approximation conditions mentioned wave packet can be globally approximately treated as the classical mechanical particle that satisfy approximate classical mechanical dynamical equation. (Namely, in Ehrenfest picture, average value of the quantum dynamical equation can be Taylor expanded \[31] 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 (until all approximation conditions are satisfied) classical mechanics can be considered as approximate physical theory.

Consider exactly quantum mechanically two wave packets with practically the same (coordinate intervals) widths. It can be considered that mentioned two wave packets weakly interfere if distance between their centers is larger than one width.

Consider quantum dynamical state that represents (non-trivial) superposition of two weakly interfering wave packets. As it has been proved in \[14],\[15], such quantum superposition cannot be globally classical presented as the classical particle. (Namely, then
mentioned Taylor expansion of Ehrenfest average value of the quantum dynamical equation becomes divergent.) Simply speaking, exactly existing superposition of two weakly interfering wave packets, approximately classically is globally non-stable and non-observable. But, of course, mentioned superposition is approximately classically locally stable and observable within any of two wave packets. Then, according to general formalism of the spontaneous symmetry breaking, here inherently probabilistically (with typical quantum mechanical probabilities) and spontaneously event of appearance of one or other wave packet becomes realized at classical level of analysis accuracy. However, at the quantum level of analysis accuracy superposition of weakly interfering wave packets stands conserved. For this reason, as it has been previously discussed, mentioned event appearance does not correspond to any real “choice” if this word “choice” should imply deterministic description of the event within dynamical superposition breaking. However, if by new detection only such quantum observables for which mentioned wave packets represent eigen states will be analyzed, classical level can be used as technically simple theoretical method, but it cannot be considered as any principal “choice”. Then, according to determinism of the classical dynamics, new detector will detect the same wave packet which appears by the previous spontaneous superposition breaking. But if by new detection other (complementary) observables will be detected quantum superposition of weakly interfering wave packets must be used. Obviously all this represents an excellent model of the self-collapse at classical level of analysis accuracy.

Further, consider quantum dynamical state that represents (non-trivial) superposition of two wave packets. Suppose that initially mentioned wave packets are strongly interfering but that, according to deterministic quantum dynamical evolution, distance between centers of wave packets increases during time. Then in moment when wave packets centers become sufficiently distant, i.e. when wave packets become weakly interfering, conditions for self-collapse as spontaneous superposition breaking become satisfied and in this sense we can speak about collapse as a continuous phase transition.

Consider now measurement or detection procedure. Before quantum dynamical interaction between quantum system and detector, quantum system is described by superposition of the eigen states of measured observable, while detector is described by "zero" eigen state of the pointer observable. During deterministic quantum dynamical interaction between quantum system and detector entangled quantum state (bi-orthogonally expanded over quantum system measured observable eigen states and detector pointer observable eigen states) of the quantum super-system (that includes quantum system and detector) becomes realized. This entangled state (in absence of new interactions with additional physical systems) stands conserved during time. Suppose that within mentioned entangled state of super-system detector pointer observable eigen states represent wave packets. Suppose that mentioned wave packets are initially strongly interfering and that mentioned wave packets become during time weakly interfering. In moment when all mentioned wave packets become mutually weakly interfering at the classically described detector self-collapse as spontaneous (non-dynamical) entanglement breaking (effective hiding) appears. In other word, here spontaneous superposition breaking at super-system appears in full analogy with spontaneous superposition breaking at simple system. Simultaneously, for reason of correlations between detector pointer observable eigen states and quantum system measured observable eigen states, in respect to self-collapsed detector quantum system becomes effectively uniquely described by corresponding statistical mixture of the eigen states of measured observable. It this sense at quantum system relative collapse effectively appears as seemingly “absolute”. But within exact entangled state of super-system statistical mixture by relative collapse of the quantum system is one of many possible second
kind mixtures of this quantum system. Relative collapse at quantum system is effective but not absolute quantum phenomena and it occurs only in respect to classically self-collapsed detector. Super-system that includes quantum system and detector is exactly described by entangled state. If by a new sub-systemic detection at quantum system only, only such quantum observables compatible with previously detected observable will be analyzed, quantum system can be effectively exactly described by statistical mixture characteristic for previous relative collapse. In this sense detections of the first and new detector are identical. But if by new detection other (complementary) observables will be detected entangled state of super-system, i.e. a different second kind mixture of the quantum system must be used. Obviously all this represents an excellent model of the measurement or detection in full agreement with all known experimental data.

Additionally, consider shortly, such inverted experimental situation where quantum dynamical state represents (non-trivial) superposition of two wave packets. Suppose that initially mentioned wave packets are weakly interfering but that, according to deterministic quantum dynamical evolution, distance between centers of wave packets decreases during time. Then in moment when distance between wave packets centers become equal or smaller than one wave packet width, i.e. when wave packets become non-weakly interfering, conditions for self-collapse as spontaneous superposition breaking become non-satisfied and in this sense we can speak about disappearance of the collapse (at approximate level of analysis accuracy) and “restored” superposition of two wave packets (at exact level of analysis accuracy) as a (inverse) continuous phase transition.

7. Collapse as spontaneous superposition breaking and interference of the single electron at diaphragm with two slits

Finally we shall consider model of the collapse as spontaneous superposition breaking in previously discussed experiments of the single electron interference at diaphragm with two slits, i.e. by quantum dynamical interaction between electron and detection photo plate.

Simply speaking, before quantum dynamical interaction with detection photo plate, electron is described by quantum superposition of two extremely weakly interfering plane waves, without consistent classical mechanical approximation. But, after quantum dynamical interaction between electron and detection photo plate, i.e. DPP(n) and DPP(m), quantum super-system e+DPP(n)+DPP(m) is exactly quantum dynamically described by entangled quantum state (7). This quantum state includes two electron quantum states Φ (e,n) and Φ (e,m) that within additional “classical” approximation can be considered as extremely weakly interfering wave-packets. In this way all conditions for appearance of self-collapse at e as spontaneous superposition or entanglement breaking (effective hiding) are satisfied at approximate, classical level of analysis accuracy. Simultaneously, relative collapse appears at DPP(n) and DPP(m), i.e. at detection photo plate. Roughly speaking, quantum dynamical interaction with detection photo plate “localized” electron in separate domains when at such electron (self-)collapse occurs at approximate, classical level of analysis accuracy.

That is all and nothing more is necessary for a complete explanation of the single electron interference at diaphragm with two slits experiments within standard quantum mechanical formalism.
8. Conclusion

In conclusion we can briefly repeat and point out the following. In this work we theoretically considered Aharonov-Bohm effect in some new variations of remarkable experiments of single electron interference at diaphragm with two slits. It will be correlated with possibility (shortly noted by Feynman) of a practically “continuous” phase transition from detection of the quantum system trajectories superposition (interference) in detection of the quantum system trajectories statistical mixture (and vice versa) in real experiments. All this can be very important for the quantum mechanics foundation (including question on the photon-detector interaction, i.e. Schrödinger cat effect) since it clearly demonstrates that quantum superposition breaking, i.e. (self-)collapse has not necessarily absolute character as well as that it can be realized even at quantum micro-systems (photon, electron, atom, etc.). We discuss a consistent model of the collapse as spontaneous (non-dynamical) breaking (effective hiding) of the unitary symmetry (that conserves superposition) of the quantum dynamics. It can be considered as an especial case of the general formalism of the 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.

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