Nonlinear Quantum Nonlocality and its Cosmophysical Tests

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Abstract

Analysis of Bell-EPR nonlocal correlations in microscopic measurement theory framework indicates that novel quantum nonlocality effects can exist. In particular, it can result in distant correlations between the systems of elementary quantum objects or particles. Doebner-Goldin nonlinear quantum formalism applied for nonlocal correlation description, comparison with some cosmophysical experiment results discussed.

1 Introduction

In 1964 J.S. Bell published the result now known as Bell theorem, which defines the basic properties of quantum-mechanical nonlocal correlations [1]. Nowadays it was confirmed experimentally and initiated extensive development of quantum information theory and its applications [2, 3]. However, despite that tremendous progress, J.S Bell himself and other researchers argued that quantum nonlocality phenomena are far from complete understanding and can possess some unknown features [1, 4]. In the same vein, many alternative nonlocality theories, prompted by similar thinking, were proposed [5, 6, 7, 8, 9, 10, 11, 12]. Additional arguments in favor of these doubts provide the analysis of Bell-EPR correlations from the point of microscopic measurement theories [5, 6]. The problem of quantum measurement or wave function collapse discussed extensively for long and reviewed in many books and papers [13, 14, 15]. Dynamics of quantum mechanics (QM) described by the Schroedinger equation, which is linear and local [16, 17]. In its framework, the measurement of quantum observable can be treated also as the interaction of measured state and measuring device (detector) [14, 15]. However, in QM axiomatic its final state postulated to follow the independent projection postulate, which corresponds to nonlinear and stochastic measurement outcome. In early QM days the projection postulate necessity was advocated by macroscopic nature of measuring apparatus, which supposedly should make its evolution classical (Heisenberg cut)[14]. Meanwhile, multiple experiments in microscopic and mesoscopic domains contradict directly to this assumption, no deviations from linearity were found even for relatively large objects [18, 19]. Plainly, detectors consist of elementary objects — particles, atoms, etc., hence its seems reasonable to consider the measurement as the sequence of multiple interactions of measured object with these detector elements. Different variants of such
microscopic interaction models were proposed, yet it follows that in standard QM framework, even for very large number of detector constituents or its environment elements, with which they can interact (decoherence), the resulting system evolution still will be linear, and thus no stochastic measurement outcomes can appear [13, 14]. Therefore, it was proposed that at fundamental level quantum evolution equation should include also small nonlinear or stochastic terms, which would dispatch in sum the resulting stochastic outcomes [6, 15].

Such measurement formalism becomes even more complicated if to consider also the measurement of Bell-EPR correlated state pairs or more complicated correlated systems. Suppose that parameters of two Bell-EPR correlated particles $\nu_{1,2}$ are measured by corresponding detectors $D_{1,2}$, being divided by space-like interval. Then, as follows from Bell theorem, measurement outcomes of some $\nu_{1,2}$ observables will be statistically correlated [6, 14]. In this framework, it demands that the elementary interactions of $\nu_{1,2}$ with $D_{1,2}$ elements should be distantly correlated, i.e. entangled. Detailed analysis of such NC dynamical mechanism was performed by E.J. Gillis, here we mainly follow its context [6]. It supposes that individual pairs of elementary interactions in $D_1, D_2$ are entangled and being accounted over whole detector volumes constitute complicated and indeterministic event sequence. In this framework, such fundamental interactions of $\nu_{1,2}, D_{1,2}$ element pairs are nonlinear and nonlocal. Despite that this model still isn’t finalized due to its formalism complexity and some open questions exist, obtained results indicate that consistent microscopic measurement theory can be constructed. Hence it gives hope that collapse problem can be resolved within standard physics realm without addressing to such radical resorts as many world interpretations or subjective collapse by human brain [21, 20]. Information-theoretical analysis of quantum measurements supports its feasibility [22].

One of this approach problems concerns with hypothetical correlations between distant individual pairs of interacting elementary objects. Really, if such correlated evolution is universal for quantum dynamics, then such nonlocal correlations (NC) between distant elementary object interactions can exist, in principle, not only in the measurement processes, which incorporate many such elementary object pairs, but also in arbitrary quantum processes like particle scattering or system decay. Possible existence of such microscopic NC effects was hypothesized earlier, basing on astrophysical arguments [9, 8]. In this paper we consider nonlinear model of such distant microscopic correlations, which accounts some microscopic measurement model features. Experimental results which supposedly indicate such NC effect existence reviewed and compared with model predictions. First results for simplified variant of this model published in [23].

In our approach this microscopic NC mechanism supposedly can retain some essential features of standard Bell-EPR correlations. First of all, it’s notable that in Bell-EPR setup the correlations appear between internal states of distant localized systems, in our our example, these are $D_{1,2}$ internal states. Their eigenstates for measured observable correspond to certain measurement outcomes. Such state correlation appear during particle-detector interactions, which change the measurement system state dramatically, assuming that it’s in pure state it follows that $|<\psi_i|\psi_f>|<1$ for its initial and final states [14]. It indicates that in Bell-EPR effect the evolution of one measurement system supposedly influences nonlocally evolution parameters of other distant one and vice versa, as the result, their measurement outcomes will be correlated even if they are separated by space-like interval [4]. There is no energy, momentum or orbital momentum transfer between distant systems during this correlation formation.

Basing on that Bell-EPR correlation features let’s discuss the conditions to which hypo-
Theoretical microscopic NC mechanism should obey. Plainly, beside causality demands, such microscopic NC effects should agree with all standard invariance principles, i.e. time, space shift and rotation symmetries. In accordance with considered Bell-EPR properties, it assumed that NC by itself can’t transfer the energy, momentum or orbital momentum between distant objects, such transfer can be performed by conventional fields only. It will be shown that exploit of nonlinear NC Hamiltonians permits to change system states even for such constraints. Let’s discuss which quantum systems can be most sensitive to such NC influence. Consider two distant systems $S_1, S_2$ evolving during time interval $\{t_0, t_f\}$. From these assumptions it follows that according to QM rules the initial $S_1, S_2$ states can’t be stationary and non-degenerate, because such states are ground ones and possess the minimal possible energy, and only some essential energy transfer can make them to evolve to another ones which are excited states. Hence the only reasonable possibility is that $S_1, S_2$ are degenerate systems, i.e. they have several states with the same energy and evolve from its initial state to another degenerate one. Example of such system is the particle at energy level $E$ confined in symmetric double well potential divided by potential wall of the maximal height $U_m$ such that $E < U_m$. Suppose that system $S_1$ has two degenerate orthogonal states $g_1, g_2$ in these wells and at $t_0$ it is in the state $g_1$ confined in one well. Thereon, due to under-barrier tunneling it would spread gradually into other well [17, 24], so that it will evolve with the time to some $g_1, g_2$ superposition. In this case, hypothetical $S_2$ NC influence on $S_1$, in principle, can change the final state parameters, in particular, resulting $g_1, g_2$ probabilities at $t_f$. Due to reciprocal $S_1$ influence, analogous $S_2$ evolution perturbation would occur, if $S_2$ possesses similar structure. If this is the case, $S_1, S_2$ measurements would indicate deviations from QM predictions. Such state degeneration is typical for many molecular and nuclear systems, in this paper nonlinear model of analogous NC processes will be considered, underlying mathematical formalism was formulated in [25].

2 Experimental Indications

Here we review experimental results which supposedly evidence for microscopic NC existence and can prompt possible model features. Up to now it was acknowledged that due to strong nuclear forces no environment influence can change decay parameters of unstable nuclei significantly [26]. However, recent results indicate that some cosmophysical factors related to Earth motion along its orbit and solar activity can influence them, in particular, their life-time and decay rate [27, 28, 30, 31, 29]. First results, indicating deviations from standard exponential $\beta$-decay rate dependence, were obtained during the precise measurement of $^{32}$Si isotope decay rate [29]. In addition to standard decay exponent, sinusoidal annual oscillations with the amplitude about $6 \times 10^{-4}$ relative to total decay rate and maximum in the end of February, were found. Since then, the annual oscillations of $\beta$-decay rate for different heavy nuclei from Ba to Ra were reported, for most of them the oscillation amplitudes are of the order $5 \times 10^{-4}$ with their maximum on the average at mid-February [28]. Life-time of $\alpha$-decay isotopes $^{212}$Po, $^{213}$Po, $^{214}$Po was measured directly, the annual and daily oscillations with amplitude of the order $7 \times 10^{-4}$, with annual minimum at March and daily minimum around 6 p.m. were found during 6 years of measurements [30, 31]. It was shown also that decay rates of $^{53}$Mn, $^{55}$Fe $e$-capture and $^{60}$Co $\beta$-decay correlate with solar activity, in particular, with intense solar flare moments, preceding them for several days; in this case, observed decay variations are of the order $10^{-3}$ [27, 28].
Parameters of some chemical reactions also demonstrate the similar dependence on solar activity and periodic cosmophysical effects [32, 33, 34]. First results were obtained for bismuth chloride hydrolysis, its reaction rate was shown to correlate with solar Wolf number and intense solar flare moments [32]. It was demonstrated that for biochemical unithiol oxidation reaction its rate correlates with solar activity, in particular, with intense solar flares and it also grows proportionally to Wolf number. Besides, it was found that its rate correlates with periodic Moon motion and Earth axis nutation [34]. Takata biochemical blood tests also indicate strong influence of solar activity and Sun position on its results [35]. It performed via human blood reaction with sodium carbonate Na$_2$CO$_3$ resulting in blood flocculation. Its efficiency parameter demonstrates fast gain for the blood samples taken 6-8 minutes before astronomical sunrise moment, this gain continues during next hour. Its value demonstrates approximate invariance during the solar day and gradual decline after sunset, such daily dependence conserved even in complete isolation from electromagnetic fields and solar radiation. Such parameter behavior is independent of mountain or cloud presence, which can screen the Sun during solar day. This parameter also rises with solar Wolf number growth and for test location shift in the direction of Earth equator. Significant parameter correlations with Sun eclipse moments also were observed; some of these results were confirmed by other researchers [36, 37, 38, 39, 40].

Testing blood samples taken at different altitudes up to several km, authors concluded that influence source isn’t the Sun itself, but Earth atmosphere at altitudes higher than 6 km [35, 41]. It’s established now that during solar day intense photochemical reactions occur at such altitudes, in particular, O$_2$, SO$_2$, NO$_2$ molecule destruction by ultraviolet solar radiation, which results in ozone and other compound synthesis [42]. Hence it can be supposed that those photochemical reactions induce NC influence which changes the results of blood reaction with Na$_2$CO$_3$. It can explain, probably, why reaction rate gain starts 6-8 min. before astronomical sunrise and is independent of cloud or mountain presence. Really, at that time solar radiation already reaches Earth atmosphere at such altitudes, and so photochemical reactions occur there, clouds or mountains cannot absorb this radiation, being located at lower altitudes. Similar daily variations of deuterium diffusion rate into palladium crystal also were reported [43].

Experiments of other kind also exploit biochemical and organic-chemical reactions, example is reaction of ascorbic acid with dichlorphenolindophenol [33, 44]. Authors noticed first that dispersion of their reaction rates can change dramatically from day to day, sometimes by one order of value, whereas average reaction rate practically doesn’t change [33, 45]. Further studies have shown connection of this effect with some cosmophysical factors, like solar activity, Wolf numbers, solar wind and orbital magnetic field. In particular, average rate dispersion becomes maximal during solar activity minima of 11 year solar cycle [33, 46]. Shielding of chemical reactors from external electromagnetic field in iron and permalloy boxes practically doesn’t change the reaction dispersions, hence such cosmophysical influence cannot be transferred by electromagnetic fields.

Individual nuclear decay or chemical reaction acts normally are independent of each other [26]; such stochastic processes are described by Poisson probability distribution [47]. For this distribution, at any time interval $dT$ the dispersion of decay count number $\sigma_p = N^{1/2}$, where $N$ is average count number per $dT$. If resulting dispersion $\sigma < \sigma_p$, it means that this process becomes more regular and self-ordered and described by sub-Poisson statistics with corresponding distribution [48]. For $\sigma \to 0$ time intervals between events tend to be constant. If on the opposite $\sigma_p < \sigma$, it corresponds to super-Poisson statistics, which is
typical for collective chaotic processes; in both cases it can be supposed that solar activity acts on reaction volume as the whole, similarly to crystal lattice excitations. For quantum systems such dispersion variations are typical for squeezed states [48], such approach will be exploited here. These results evidence that high solar activity makes molecular systems to perform chemical reactions in more self-ordered and regular way. In general, similar considerations are applicable to arbitrary statistical distributions of studied systems not only Poisson-like ones. It is notable that similar temporary Bell-EPR correlations appear in unstable system decays, example is electromagnetic $\pi^0$-meson decay: $\pi^0 \rightarrow 2\gamma$ [26, 16]. In that case, if both $\gamma$-quanta detected at equal distances from decay point, then detection moments $t_1, t_2$ in two detectors are correlated according to probability distribution

$$p^d(t_1, t_2) = \frac{1}{\sqrt{\pi} \sigma_t} \exp \left[ -\frac{(t_1 - t_2)^2}{\sigma_t^2} \right]$$

where $\sigma_t$ is quantum uncertainty of event time measurement [16]. It means that for such decay event ensemble the photon statistics will be sub-Poissonian, corresponding to considered event distribution for $\sigma < \sigma_p$. Similar effect was observed also for optical photon down-conversion [48]. Summing up described results, they assume possible existence of distant interactions of nonelectromagnetic origin, which supposedly can be attributed to hypothetical NC effects. Up to now no alternative consistent explanations of such distant influences were proposed.

### 3 Microscopic nonlocality model

Experimental results considered here evidence that these distant correlations occur for evolving quantum systems when such system by itself suffers significant transformation even without hypothetical NC influence, in particular, it occurs for chemical reactions and decays of unstable nuclei. In standard QM framework, system evolution operator defined mainly by quantum-to-classical correspondence, for assumed NC effects such guidelines are absent, here it will be constructed basing only on general QM principles and cited experimental results.

We shall consider NC effects for nucleus $\alpha$-decay, which supposedly were observed in experiments described in [30, 31]. Gamow theory of $\alpha$-decay assumes that in initial nucleus state, free $\alpha$-particle already exists inside the nucleus, however, its energy $E$ is smaller than maximal height of potential barrier $U_m$ constituted by nuclear forces and Coulomb potential [49]. Hence $\alpha$-particle can leave nucleus volume only via quantum tunneling through this barrier. Therefore, alike for considered double well example, $\alpha$-particle energy is the same inside and outside nucleus, and corresponding inside-outside states are degenerate. Hence such degeneration permits, in principle, for hypothetical NC mechanism to change nucleus decay rate without any energy transfer to $\alpha$-particle, but just changing the barrier transmission rate. Below NC effects will be considered for system $S$ of $N$ independent, identical nucleus $\{A_i\}$, its initial state is $\{A_i\}$ product state. In Gamow model $\alpha$-particle Hamiltonian for metastable nucleus

$$H = \frac{\vec{P}^2}{2m} + U_N(\vec{r})$$

where $m$ is $\alpha$-particle mass, $\vec{P}$ is its momentum operator, $U_N$ is nucleus barrier potential, $\vec{r}$ is $\alpha$-particle coordinate relative to nucleus center [50]. If at $t_0$ for arbitrary $A_i$, $\alpha$-particle was in
initial state $\psi^i(t_0) = \psi^i_0$, then Shroedinger equation solution for $\psi^i(t)$ in WKB approximation [16, 49] gives the decay probability rate at given $t$

$$p_i(t) = \lambda \exp[-\lambda(t - t_0)]$$  \hspace{1cm} (2)

here $p_i$ is the time derivative of $A_i$ total decay probability from $t_0$ to $t$; resulting nucleus life-time is proportional to $\lambda^{-1}$. Hence at $t \to \infty$ $A_i$ state evolves to final state $\psi^f_1$, such that $< \psi^f_1|\psi^f_1> = 0$. In fact, similar considerations are applicable to the evolution of arbitrary metastable system, like atoms or molecules, yet for $\alpha$-decay its description is most simple [49, 50]. In particular, analogous metastability properties are characteristic also for considered chemical reactions [32, 34, 33, 44].

It was argued above that for Bell-EPR correlations the evolution of one measurement system influences the evolution parameters of other distant one and vice versa [4, 6], illustrative example is Bell-EPR temporary correlations considered in previous section. One can suppose that similar mechanism defines the properties of discussed microscopic NC effects. In this framework, our assumption is that intensity of NC effect induced by some system $S_1$ will be proportional to some function of $S_1$ transition rate from its initial internal state $\psi_{in}$ to final one $\psi_f$, such that $< \psi_{in}|\psi_f> = 0$. Analogously to Bell-EPR correlations, since NC influence should be reciprocal, it reasonable to suppose that such $S_1$ influence on some $S_2$ system would change $S_2$ transition rate, and vice versa for $S_2$ NC influence on $S_1$. In particular, it can be supposed arbitrarily that NC influence intensity of nucleus $A_i$ decay on the evolution of another nucleus is proportional to $p_i(t)$ of eq. (2). This assumption will be reconsidered below in QM formalism framework, it will be shown that its applicable only for some approximation and in general NC influence described by corresponding QM operator.

Experimental results discussed in previous section indicate that NC influence can make collective system evolution less chaotic and more regular, in particular, can result in squeezed states with sub-Poisson statistics. Its notable that self-ordering is quite general feature of quantum dynamics, examples are crystal lattices or atomic spins in ferromagnetic. Besides the collective system self-ordering, other forms of symmetrization, induced by standard QM dynamics, concerned with individual object state. Example is elastic particle scattering, in that case, the final state possesses larger angular symmetry than incoming plane wave state [17]. These analogies together with cited experimental data permit to suppose that such NC influence transforms system evolution so that it results in more time-symmetric and self-ordered states, in comparison with its nonperturbed evolution, our choice of NC Hamiltonians will be prompted by this assumption. For example, enlargement of metastable system life-time can be treated as the growth of evolution symmetry, because the decay probability rate $p_e(t)$ becomes more homogeneous in time, its asymptotic limit is $p_e(t) \to const$ for $t > t_0$. It is notable that experimental results reviewed above demonstrate enlargement of nucleus life-time induced by enhanced solar activity [28, 27], the same is true for its influence on some chemical reaction rates [32, 34].

Typical experimental accuracy of nuclear decay time moment measurement $\Delta t$ is several nanoseconds [26]. Formally, such measurement described as the sequence of multiple consequent state measurements divided at least by $\Delta t$ interval. If first one shows that nucleus is in $\psi_0$ state, and next one that its in the state $\psi_1$, it means that nucleus decay occurred during this time interval [16, 17]. In QM formalism, a general state of quantum system $S$ described by density matrix $\rho$, if $A_1, A_2$ nuclei are $S$ components, the partial $A_{1,2}$ density matrices $\rho_{1,2}$ can be defined. For each $A_i$ it turns out that if some other $S$ components are
also measured, then its decay probability rate would differ from eq. (2) and becomes

$$\gamma_i(t) = \frac{\partial}{\partial t} Tr \rho_i(t) P^i_1$$

(3)

where $P^i_1$ is projector on $A_i$ final state [16].

4 Nonlinear decay formalism

It was supposed that NC effects should not change the system average energy, however, if corresponding NC Hamiltonian is linear operator then for $\alpha$-decay in Gamow model this condition is violated [25]. It will be shown here that nonlinear Hamiltonians can satisfy much better to this condition. It’s acknowledged now that nonlinear corrections to standard QM can exist at fundamental level [51, 52, 53]. In nonlinear QM formalism, particle evolution described by nonlinear Schroedinger equation of the form

$$i\hbar \partial_t \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + U(\vec{r}, t)\psi + F(\psi, \bar{\psi})\psi$$

(4)

where $m$ is particle mass, $U$ is system potential, $F$ is arbitrary functional of system state. Currently, the most popular and elaborated nonlinear QM model is by Doebner and Goldin (DG) [52, 53]. In its formalism, simple variant of nonlinear term is $F = \frac{\hbar^2}{m} \Gamma \Phi$ where

$$\Phi = \nabla^2 + \frac{|\nabla \psi|^2}{|\psi|^2}$$

(5)

is nonlinear operator, $\Gamma$ is real or imaginary parameter which, in principle, can depend on time or other external factors, here only real $\Gamma$ will be exploited. With the notation

$$H^L = -\frac{\hbar^2}{2m} \nabla^2 + U(\vec{r}, t)$$

(6)

we abbreviate eq. (4) to $i\hbar \partial_t \psi = H^L \psi + F \psi$ where in our case, $H^L$ is Gamow Hamiltonian.

Main properties of eq. (4) were studied in [52, 25], for constant $\Gamma$ they can be summarized as follows: (a) The probability is conserved. (b) The equation is homogeneous. (c) The equation is Euclidean - and time-translation invariant for $U = 0$. (d) Noninteracting particle subsystem remain uncorrelated (separation property). Distinct values of $\Gamma$ can occur for different particle species. (e) For $U = 0$, plane waves $\psi = \exp[i(\vec{k}_0 \vec{r} - \omega t)]$ with $\omega = E/\hbar$, $|\vec{k}_0|^2 = 2mE/\hbar^2$ are solutions both for real and imaginary $\Gamma$. (f) Writing $< Q > = \int \bar{\psi} \hat{Q} \psi d^3x$ for operator expectation value, since $\int \bar{\psi} F \psi d^3x = 0$ for arbitrary $\psi$, the energy functional for solution of eq. (4) is $< i\hbar \partial_t > = < H^L >$. Hence the average system energy would change insignificantly if not at all if $F$ added to initial Hamiltonian, therefore, it advocates DG ansatz application in NC models. In particular, it will be shown that in WKB approximation, which is the main ansatz for decay calculus, the energy expectation value doesn’t change in the presence of such nonlinear term.

As was noticed, Bell-EPR correlations appear between internal states of distant systems, by the analogy, we suppose that in our model nonlinear term $F$ acts on $\{A_i\}$ nuclei internal states $\psi^i(t)$. It’s notable that nonlinear term $F$ in $\alpha$-particle Hamiltonian can modify the particle tunneling rate through the potential barrier. In particular, analytic solution of this
problem was obtained for rectangular potential barrier, in that case, the barrier transmission rate depends exponentially on \( \Gamma \) [25]. To calculate corrections to Gamow model for arbitrary potential \( U \), WKB approximation for nonlinear Hamiltonian of (4) can be used [17]. In this ansatz, for rotation-invariant \( U \) \( \alpha \)-particle wave function reduced to \( \psi = \frac{1}{r} \exp(i\sigma(r)/\hbar) \); function \( \sigma(r) \) can be decomposed in \( \hbar \) order \( \sigma = \sigma_0 + \sigma_1 + \ldots \), here \( r = |\vec{r}| \) is the distance from nucleus center [16, 17]. Given \( \alpha \)-particle with energy \( E \), one can find the distances \( R_0, R_1 \) from nucleus center at which \( U(R_{0,1}) = E \). Then, for our nonlinear Hamiltonian the resulting equation for \( \sigma_0 \)

\[
\left( \frac{1}{2m} - \Lambda \right) \left( \frac{\partial \sigma_0}{\partial r} \right)^2 = E - U(r)
\]

where \( \Lambda = \frac{2m}{\hbar^2} \) for \( R_0 \leq r \leq R_1 \), \( \Lambda = 0 \) for \( r < R_0, r > R_1 \) [25]. Its solution for \( R_0 \leq r \leq R_1 \) can be written as

\[
\psi(r) = \frac{1}{r} \exp(i\sigma_0/\hbar) = \frac{C_r}{r} \exp\left[-\frac{1}{\hbar} \int_{R_0}^r q(\epsilon) d\epsilon \right]
\]

where \( C_r \) is normalization constant,

\[
q(\epsilon) = \left\{ \frac{2m[U(\epsilon) - E]}{1 - 4\Gamma} \right\}^{\frac{1}{2}}
\]

Account of higher order \( \sigma \) terms practically doesn’t change transmission coefficient which is equal to

\[
D = \exp\left[-\frac{2}{\hbar} \int_{R_0}^{R_1} q(\epsilon) d\epsilon \right] = \exp\left[-\frac{\phi}{(1 - 4\Gamma)^{\frac{1}{2}}} \right] \approx \exp[-\phi(1 + 2\Gamma)]
\]

here \( \phi \) is constant for given nucleus, whereas \( \Gamma \), in principle, can change in time, assuming that its time change scale is much larger than the barrier transition time. Note that \( \Lambda \) term induced by nonlinearity doesn’t change the average particle energy in comparison with corresponding linear ansatz \( H^L \). To calculate nucleus life-time, \( D \) multiplied by the number of \( \alpha \)-particle kicks into nucleus potential wall per second \( n_d \), so it gives \( \lambda = n_d D \) [49], for DG model \( n_d \) doesn’t depend on \( F \) term [25].

It is natural to assume that NC effect for any system of restricted size grows with the number of system constituents \( N \) involved into reactions. For the case of two systems of which one of them \( S_1 \) is large and other one \( S_2 \) is small, for them NC effects supposedly realized in master regime, i.e. \( S_1 \) can significantly influence \( S_2 \) state and make it evolution more ordered and symmetric as well as its own evolution, whereas \( S_2 \) practically doesn’t influence \( S_1 \) state evolution. It can be assumed also that in this case, \( S_2 \) self-influence NC effect is insignificant in comparison with \( S_1 \) NC influence. Then, resulting NC effect in \( S_2 \) supposedly depends on \( S_1 \) evolution properties and \( S_1, S_2 \) distance \( R_{12} \). It was argued that enlargement of nucleus life-time, i.e. \( p_i(t) \to \text{const.} \), can be interpreted as system evolution symmetrization. Let’s study how such NC influence can be described in master regime approximation. Consider two nucleus systems \( S_1, S_2 \) with the average distance \( R_{12} \) between \( S_1, S_2 \) elements, supposedly it’s much larger than \( S_{1,2} \) size; for the simplicity we’ll consider only static situation when object positions are fixed. \( S_1 \) is the set of \( N_1 \) unstable nuclei \( \{A_i\} \) prepared at \( t_0 \) with decay probability rate described by eq. (2). \( S_2 \) includes just one unstable nucleus \( B \) prepared also at \( t_0 \), its evolution normally described by Gamow Hamiltonian \( H^L \) ansatz of (6). Its decay constant \( \lambda_b \), in principle, can differ from \( \lambda \) of eq. (2) if for \( B U \neq U_N \) of eq. (1). In such set-up, presumably NC effects induced by \( S_1 \) would
influence $B$ evolution and perturb also its own evolution as well. Hence for $S_1$ nuclei their initial decay probability rate can change to some $p_i^B(t)$. Suppose that all geometric factors of such NC influence on $B$ for given $S_1$ described by real function $\chi(N_1, R_{12})$ which absolute value grows with $N_1$ and diminishes with $R_{12}$, i.e. $\chi$ is phenomenological NC propagation function. Resulting corrections to $H^L$ are supposed to be small and so can be accounted only to the first order of $\Gamma$. Basing on assumptions discussed above, in particular, that resulting NC effect proportional to $S_1$ total transition rate, it follows that parameter $\Gamma$ in $F$ nonlinear term becomes the function $\Gamma(R_{12}, t) = \chi(N_1, R_{12})p_i^B(t)$, so that phenomenological $B$ Hamiltonian

$$H^d(t) = H^L + \frac{\hbar^2}{m}\chi(R_{12})p_i^B(t)\Phi$$  (11)

where $\Phi$ is nonlinear operator of eq. (5) for $B$ $\alpha$-particle. Solving evolution equation in WKB approximation it follows from eq. (10) that if no measurements of $S_1$ states were performed, then $B$ decay probability rate

$$p_b^B(t) = C_b\exp\{-[(t - t_0)\xi(t)]\}$$  (12)

here $C_b$ is normalization constant

$$\xi(t) = \frac{\lambda_b}{n_d}\chi(12)^{2\Gamma(R_{12}, t)}$$  (13)

Hence for such ansatz, $B$ decay probability rate $p_b^B(t)$ depends on total $S_1$ nuclei decay probability rate and would differ from $B$ probability rate $p_b(t)$ in Gamow model; for $\chi > 0$ $B$ life-time would enlarge. It can be assumed that $p_i^B(t) \approx p_i(t)$ of eq. (2), because in our model typical $S_1$ NC self-influence expected to be small. Note that $B$ kinematic parameter $n_d$ practically doesn’t change in this case [25].

Now NC effects between elementary systems will be considered beyond master regime approximation. Suppose that for system $S_1$ $N_1 = 1$ and nuclei $A_1, B$ states described by wave functions $\psi^1(t), \psi^B(t)$ correspondingly. Then for the same initial conditions as above, the system initial wave function $\psi_s = \psi_0^1\psi_0^B$. In QM framework, probability of given state $\varphi$ presence at particular time defined by its projector $P_\varphi$, in accordance with it, $A_1$ transition rate described by the operator $Q_1^A = \frac{d\Gamma_1}{dt}$, where $P_1^A$ is projector on $A_1$ final state of eq. (3), $Q_1^B$ is corresponding derivative for projector on $B$ final state; they can be calculated from Erenfest theorem [17]. Therefore $\Gamma$ for $A_1, B$ terms replaced by the operators $\Gamma_A = \chi(N_1, R_{12})Q_1^A$ and $\Gamma_B = \chi(N_1, R_{12})Q_1^B$, corresponding $A_1, B$ Hamiltonian

$$H_s(t) = H^L + \frac{\hbar^2}{m}\chi(N_1, R_{12})Q_1^A\Phi + H_1 + \frac{\hbar^2}{m}\chi(N_1, R_{12})Q_1^B\Phi_1$$  (14)

where $\Phi_1$ is nonlinear operator of eq. (5) for $A_1, R_{12}$ is $A_1, B$ distance. It follows that in first perturbation order $<Q_1^{1B}> = p_{1B}(t)$ with $p_{1B}(t) = p_i(t)$ of eq. (2). Since $A_1, B$ operators commute, transition rate operators can be replaced by their expectation values

$$H_s(t) = H^L + \frac{\hbar^2}{m}\chi(N_1, R_{12})p_{1B}(t)\Phi + H_1 + \frac{\hbar^2}{m}\chi(N_1, R_{12})p_b(t)\Phi_1$$  (15)

Solution of evolution equation for Hamiltonian of eq. (14) gives transition rate for $B$ decay described by eq. (12) with $p_i^B(t) = p_i(t)$, for $A_1$ resulting rate $p_{1B}(t)$ can be calculated analogously. Hence obtained ansatz supports the use of eq. (11) for NC influence calculations in
master regime. Any alternative NC effect ansatz would demand the use of more complicated operators, hence the hypothesis of its proportionality to transition rate operator seems reasonable. Obtained $A_1, B$ states are correlated but not entangled, so that the system state $\psi_s = \psi^1(t)\psi^\alpha(t)$ at arbitrary time, however, in the next order their entanglement can appear.

Under NC influence for $\chi > 0$ resulting $A_1, B$ nucleus life-times becomes larger than initial one. Such $S_1, S_2$ evolution modification can be interpreted as the growth of $S_1, S_2$ evolution symmetries such that resulting decay probability rates $p_1(t), p_2(t)$ becomes more homogeneous in time in comparison with initial $A_1, B$ probability rates. It can be supposed also that inverse process, i.e. $A_1$ nucleus synthesis via reaction of $\alpha$-particle with remnant nucleus would induce the opposite NC effect on $B$, reducing $B$ nucleus life-time and so reducing its evolution symmetry. Hence proposed NC mechanism can change, in principle, the evolution symmetry in both directions enlarging or reducing it. Thermonuclear reactions in the Sun result in production of unstable isotopes [26], hence according to that model, variations of such reaction intensity can result in variation of solar NC influence rate on nuclear decay parameters on the Earth [28, 27]. Such reaction rate variations supposedly can occur during solar flare formation, because it results in intense ejection of charged particles and $\gamma$-quanta from solar surface [54]. It supposedly can be the reason for observed correlations between solar flare moments and isotope decay rate decline on Earth [28, 27]. It was assumed above that NC should not change any subsystem average energy, in our model this condition fulfilled in WKB approximation. System momentum and orbital momentum conserved due to Hamiltonian rotational symmetry.

5 Squeezed State Production

Now let’s consider NC model, which describes decay self-ordering symmetry gain, resulting in sub-Poisson event statistics. For that purpose multiple time formalism for evolution operator calculation will be used, which is standard approach for time-dependent Hamiltonians [17]. Consider the system $S$ of $N$ nuclei, as was supposed, due to conjugal NC influence between $S$ elements, its evolution would become more regular and self-ordered without significant life-time change. Hence $S$ evolution can differ from the case of independent nuclei and would result in the temporary correlation between decays of $S$ nuclei. Consider the simplest case $N = 2$ with $A_1, A_2$ nuclei prepared at $t_0$ at the distance $R_{12}$. $S$ evolution operator can be chosen analogously to the one for squeezed photon production in atomic resonance fluorescence [48]. In its simple variant, photon production is suppressed if the time interval between two consequently produced photons is less than some fixed $\Delta T$. Due to it, resulting photon production becomes more regular, and their statistics would become sub-Poissonian. Suppose that $A_1$ NC influence rate on $A_2$ characterized by real function $k(R_{12})$, its absolute value supposedly diminishes as $R_{12}$ grows, the same function describes $A_2$ NC influence on $A_1$; $k$ can be regarded as NC coordinate Green function. Analogously to our previous considerations, suppose that $A_1$ NC influence intensity on $A_2$ evolution is proportional to $A_1$ transition rate operator and vice versa, but integrated over some time interval. In this case, analogously to eq. (14) $\Gamma$ of eq. (5) becomes the operator. For the simplicity, we assume that $A_1, A_2$ decay evolution ansatz can be factorized into $A_1, A_2$ terms. For example,
phenomenological $A_2$ Hamiltonian

$$H^c_2(T) = H_2 + \frac{\hbar^2}{m} \int_{t_0}^{T} k(R_{12}) \varphi(T - t) Q^1_1 \Phi_2 dt$$  \hspace{1cm} (16)$$

$Q^1_1$ operator defined above, $\Phi_{1,2}$ are $A_{1,2}$ nonlinear operators of eq. (5) with corresponding notations; $\varphi$ is causal Green function

$$\varphi(\tau) = \eta(\tau - \nu) - \eta(\tau)$$

Thus, corresponding NC time dependence described as the difference of two step functions $\eta(\tau) = \{0, \tau < 0; 1, \tau \geq 0\}$ which is simple variant of such ansatz [47]. Here $\nu$ is the time range in which $A_1$, $A_2$ decay acts are correlated. Hence $A_2$ Hamiltonian $H^c_2$ is time-dependent, at given time moment $T$ it depends on $A_1$ decay rate during time interval $\nu$ previous to $T$. Analogous modification occurs for $A_1$ Hamiltonian with corresponding index change. As the result, such NC influence for $A_{1,2}$ described by evolution operator with multiple time ansatz

$$W(T) = C_t \exp\left\{ -\frac{i}{\hbar(T - t_0)} \int_{t_0}^{T} \left[ H_1(t_1) + H_2(t_2) + (T - t_0) G(t_1, t_2) \right] dt_1 dt_2 \right\}$$  \hspace{1cm} (17)$$

where $C_t$ is time-ordering (chronological) operator [17]. Third term in this equality is NC dynamics term, it suppresses nucleus decays at small time intervals between them, so that

$$G(t_1, t_2) = \frac{\hbar^2}{m} k(R_{12}) \left[ \varphi(t_1 - t_2) Q^2_1 \Phi_1 + \varphi(t_2 - t_1) Q^1_1 \Phi_2 \right]$$  \hspace{1cm} (18)$$

where $\Phi_{1,2}$ are of eq. (5), $Q^2_1$ is $Q^1_1$ equivalent for $A_2$. Note that the second right-side term corresponds to $H^c_2$ Hamiltonian of eq. (16). Due to $A_1, A_2$ operator commutativity, the operators $Q^1_{1,2}$ for $A_{1,2}$ in first perturbation order can be replaced by their expectation values $\gamma_{1,2}(t)$ of eq. (3). If no measurement of $A_{1,2}$ state was performed for $t_f < T$, then $\gamma_{1,2}(t) = p_i(t)$ of eq. (2). Otherwise, if such measurement was done at some $t_f$ and $A_i$ was found to be in the final state, then for $t_o > t_f$ it follows that $\gamma_i(t_o) = 0$. If no $A_{1,2}$ measurement was done, then in WKB approximation the joint $A_{1,2}$ decay probability rate $p_s$ for $k > 0$ will differ from independent decay case when $p_s(t_1, t_2) = p_1(t_1)p_2(t_2)$ and is equal to

$$p_s(t_1, t_2) = C \lambda^{2+4\theta} \exp[-g(t_1, t_2)(t_1 + t_2 - 2t_0)]$$  \hspace{1cm} (19)$$

where $C$ is normalization constant, analogously to eq. (13)

$$g(t_1, t_2) = \exp[(1 + 2\theta) \ln \lambda]$$  \hspace{1cm} (20)$$

where $\lambda$ is from eq. (2)

$$\theta = \frac{\hbar^2}{m} k(R_{12}) [\eta(t_1 - t_2) \varphi(t_1 - t_2) \gamma_2(t_2) + \eta(t_2 - t_1) \varphi(t_2 - t_1) \gamma_1(t_1)]$$  \hspace{1cm} (21)$$

Due to it, if the time interval between two decay moments is less than $\nu$, the nucleus decay rate will be suppressed, and resulting decay event distribution will become more regular, i.e. sub-Poissonian. Note that in the considered approximation $A_1, A_2$ states are correlated, but not entangled. For $N > 2$ the considered NC dynamics term in $W(T)$ would change to
$G(t_1, ..., t_N)dt_1...dt_N$ with corresponding integration over $N$ independent time parameters. As the result, for analogous $G$ ansatz the joint decay probability of two arbitrary consequent decays will be suppressed for small time intervals between them, and $N$ decay event distribution will be sub-Poissonian. Two considered symmetrization mechanisms, i.e. lifetime enlargement and event sub-Poisson symmetrization, in principle, can coexist and act simultaneously in some systems. Here the system self-ordering NC effect was considered, however, some distant system $S_m$ also can induce, in principle, analogous NC evolution symmetrization in system $S$, as experimental results evidence \[33, 44\]. It can be supposed that analogous NC effect description is applicable also to chemical reactions and other atomic and molecular systems. Nonlinear Hamiltonians were used here for NC effect description, however, its possible also that in collective systems NC effects at fundamental level can be described by linear Hamiltonians, so that nonlinear QM appears as the corresponding effective theory \[53\].

6 Conclusion

Considered experimental results and theoretical analysis evidence that novel communication mechanism between distant quantum systems can exist. Its based on specific form of QM nonlocality, different from well-known Bell-EPR mechanism, in particular, its effects supposedly can be observed even between microscopic quantum systems. In this paper, microscopic NC effects studied for metastable quantum systems, namely, $\alpha$-decay with nonlinear NC Hamiltonian. Such microscopic NC influence supposedly has universal character, in particular, such nonlocal influences can exist between the systems of scattering particles. However, for metastable systems NC effects are expected to be more easily accessible for experimental observation due to their relatively long duration. Beside nuclear decays and chemical reactions, such microscopic NC effects can be observed, in principle, for other systems in which metastability and tunneling plays important role. This is true, in fact, for biological systems, it was proposed earlier that long-distance correlations observed inside living organisms and plants can be induced by QM nonlocality \[55, 56\]. However, standard Bell-EPR mechanism can not induce such NC effects in dense and warm media, which is characteristic for biological systems. Possible description of such biological effects via microscopic NC influence mechanism discussed in \[57\]. It’s worth to stress that in this nonrelativistic model nonlinear Hamiltonian terms describe nonlocal effects only, whereas local interactions are linear. EPR-Bohm paradox and Bell inequalities demonstrate that quantum measurement dynamics is essentially nonlocal \[1, 4\]. However, as was argued above, it seems doubtful that dynamics of quantum measurements differs principally from the rest of QM dynamics, more reasonable is to expect that both of them can be described by some universal formalism, hence the presence of nonlocal terms in it would be plausible \[6, 5\]. It isn’t clear whether NC Hamiltonians, exploited here, are suitable for the description of measurement processes also. However, it’s notable that particle detectors are usually the metastable systems, so it is reasonable to consider such models as possible candidates \[26\].

Concerning with causality for NC communications, at the moment it is still possible to assume that such NC can spread between systems with velocity of light. But even if this spread is instant, it is notable that usually superluminal signalling in QM discussed for one bit yes/no communications \[1, 4\]. In our case, to define the resulting change of some parameter expectation value, one should collect significant event statistics which can demand
significant time, so it makes causality violation quite doubtful possibility. In addition, NC dependence on the distance between two systems expressed by $\chi$ propagation function can be so steep that it also would suppress effective superluminal signalling. Situation can be similar to QFT formalism where some particle propagators spread beyond light cone, but due to analogous factors, it doesn’t lead to superluminal signalling [58]. Note that some nonlinear QM models by themselves permit superluminal signalling, but it doesn’t contradict to our nonlocal formalism [25, 53].

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