On possibility to observe new fundamental forces in open quantum systems

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A possibility and peculiarities of registration of new fundamental forces in open quantum systems are discussed. As a possible example, variations of decay rates of radioactive elements reported in scientific literature are considered in detail.

1. INTRODUCTION

During last three decades the theory of open quantum systems was developed in several directions. Among new approaches arising in this period are the Lindblad equation for density matrix, operator generalization of the Ito integral, different methods for descriptions of quantum systems interacting with the measuring device, and others. A range of physical applications of the mathematical formalism was also extended appreciably. It includes new attempts to describe the quantum measurements, theory of tunneling processes under dissipation conditions, solution of different problems concerning models of quantum computers and quantum lines of communications.

It is necessary, however, to note a fact (practically escaped researchers’ attention) that open quantum systems can also serve as peculiar detectors of new fundamental forces that can be feasible at present only by means of the systems of this genus. As an example, we refer to the quantum gravitational interference destruction mechanism leading to an equation of the Lindblad type¹. In the general case, the forces in question can be any rather weak ones which act on the quantum system from the part of a macro- or megasystem. Corresponding tests have features discriminating them from the usual accelerator experiments and, therefore, there is a risk to interpret the appearance of new interactions as drawbacks of an experiment itself and, consequently, to reject it.

This paper is devoted to consideration of some general properties of open quantum systems in context of the possibility to search the new fundamental interactions,

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as well as to discussion of some experiments in which such interactions could be already seen.

2. JOINT CONSIDERATION OF QUANTUM SYSTEM AND MEASURING INSTRUMENT

As is well known\(^{(2)}\), the Schrödinger and von Neumann equations for closed quantum systems are intimately connected with continuous projective representations of the Galilean group\(^{3}\). The action of the one-parametric sub-group of temporal shifts on the set of states of a quantum system is described by the formula

$$\rho_t = e^{-\frac{i}{\hbar}Ht} \rho_0 e^{i\frac{H}{\hbar}t},$$

(1)

where \(H\) is Hamiltonian of the system. From this, after the formal differentiation over \(t\), we obtain the von Neumann equation which gives rise to the Schrödinger one for the pure states, \(\rho_t = |\psi_t\rangle\langle \psi_t|\). Interactions of the quantum system with its environment results in breakdown of the symmetry with regard to some transformation of the Galilean group, and this circumstance turns the theory of representations of groups into an important instrument for the open quantum system investigations too. The mathematical apparatus elaborated by now (in particular, the method of dynamic semigroup (see Refs. 4 and 5)) takes into account, in an explicit form, only the breakdown of symmetry for the sub-group of the temporal shifts. In what follows, we shall formulate a model for which the spatial rotation symmetry breakdown will play an essential role.

Any interactions of quantum system, \(S\), with its environment come to light due to their influence on the probability distribution of measurement results. Let us denote by \(\mu_\rho(\chi)d\chi\) a probability of some observable registration by means of a measuring instrument, \(M\), in the interval \((\chi, \chi + d\chi)\), if the quantum system is in a state \(\rho = \sum_i p_i |\psi_i\rangle\langle \psi_i|\). In the general case the probability distribution \(\mu_\rho(\chi)d\chi\) may be singular and the variable \(\chi\) several-dimensional, as is the case with correlative spin experiments of Einstein-Podolsky-Rosen type. According to the existing theory,

$$\mu_\rho(\chi)d\chi = Tr[\rho M(d\chi)],$$

where \(M(d\chi)\) is the positive operator valued measure describing the action of \(M\) on \(S\). In the Dirac notations \(M(d\chi) = |\chi\rangle\langle \chi|d\chi\), where the orthogonality condition,

$$\langle \chi | \chi' \rangle = \delta(\chi - \chi'),$$

\(^{3}\)Generalization of this device onto the Lorentz group is well-known too\(^{(3)}\), but here we restrict ourselves to consideration of a more simple nonrelativistic case.
is considered neither necessary nor realistic one, but the resolution of identity,

$$\int |\chi\rangle\langle\chi|d\chi = 1,$$

is supposed to take place$^{(6)}$.

As a result of some Galilean group transformation, \( g \), the density matrix and the measuring instrument are changed:

$$\rho_g = U_g \rho U_g^\dagger, \quad M_g(d\chi) = V_g M(d\chi) V_g^\dagger.$$  \hspace{1cm} (2)

Here, in accordance with the Wigner theorem, \( U_g \) and \( V_g \) are unitary or antiunitary operators acting in the Hilbert space of states of system \( S \). Equations (2) generalize formula (1) for the case of a simultaneous consideration of \( S \) and \( M \) systems. Therefore, for the sub-group of temporal shifts, they replace the Schrödinger equation. Probability distribution \( \mu_\rho(\chi)d\chi \) will be invariant under \( g \) transformation if and only if

$$U_g = V_g.$$  

Actually, measuring instrument \( M \) is a compound system consisting of closed and open subsystems, \( M = M_c + M_o \). In the beginning of the measurement process the closed part \( M_c \) interacts only with \( S \) and, after receiving a sufficient energy, it starts interacting with \( M_o \). That makes sense to speak about the unitary transformation, \( V_g \), only for \( M_c \), which is the most sensitive part of \( M \).

Breakdown of the invariance with respect to the Galilean group can be caused by interactions both \( S \) and \( M_c \) with environment. In this case, operators \( U_g \) and \( V_g \) may be nonunitary, or, in the general way, equations (2) cannot be applicable at all, since the Wigner theorem conditions are violated. Theoretically, new fundamental forces may reveal themselves not only by means of the true Galilean evolution of \( M_c \) and a distorted one of \( S \) (the traditional conception of the measurement), but also in the inverted form, when \( M_c \) is distorted and \( S \) is not, or due to \( S \) and \( M_c \) simultaneous distortion. Observable breakdown of the invariance properties of \( M_o \) with respect to the Galilean group are usually accepted as incorrect performance of the experiment.

Joint consideration of the quantum system and the measuring instrument, though it seems to be trivial, in fact is more general than a traditional approach based on a separate description of the quantum system alone. In particular, it permits to generalize in a reasonable way the very concept of interaction. For example, quantum cryptography is based on the fact that \( \mu_\rho(\chi)d\chi \) is altered because of the illegal
access results in replacement of \( \rho_t = U_t \rho U_t^\dagger \) by some other transformation, although a change of energy of the quantum system not necessarily takes place after the manipulations of a disturber are completed (7–10). It is reasonable to designate these interactions by a special name, e.g. informational, to distinguish them from the standard potential ones. Such interactions manifest themselves as an extra factor (which cannot be calculated using the Schrödinger equation) acting on the probability distribution \( \mu_\rho(\chi)d\chi \).

Special examples of the informational interactions are the noted quantum Zeno and anti-Zeno effects (see Refs. 11 and 12). In these cases controllable changes of a measuring instrument which "observes" the state of an unstable system can lead to changing the decay probability, \( \mu_\rho(t)dt \), of the system.

3. CONCRETE EXPERIMENTAL EXAMPLES

Now let us consider some papers in which variations of decay rates of radioactive elements have been reported and, presumably, unknown interactions have been registered. These unusual experiments can serve only as a possible illustration to our previous reasoning since the announced results are a challenging diversion from the standard lore in the subject and still demand further careful examination.

In paper(13), in spite of the efforts undertaken for elimination of temperature, man-caused and other effects on the recording equipment, changes of \( \beta \)-decay rate, with periods 24 hours and 27 days, were observed at two laboratories 140 km apart (INR RAS, Troitsk, \(^{60}\text{Co} \), and JINR, Dubna, \(^{137}\text{Cs} \)). Extremum deviations of count rate (0.7% for \(^{60}\text{Co} \) and 0.2% for \(^{137}\text{Cs} \)) from the statistical average took place for the both laboratories when they were oriented properly along the three definite directions established in the outer space. Bursts of count rate of beta-radioactive sources during long-term measurements, similar to data of Ref. 13, were also reported in an independent paper(14).

Series of papers devoted to dependence of \( \alpha \)-activity, as well as different macroscopic fluctuations, on the cosmological factors was published by Prof. S.E. Shnol et al. in Russian scientific journals (see Ref. 15 for details and the bibliography). Here we give only a brief review of the data from Refs. 16 and 17. In these studies a phenomenon of a deviation of probability distributions from the expected Poisson one was established. The measurements were carried out in fixed with respect to the Earth’s surface laboratories during 5 minute time intervals. Non-randomness of repetitions of the shape of the observed distributions was also established at the regular time intervals. In short, the main results are the following:
1. Re-appearance of the same form of a probability distribution took place most likely in the nearest interval of observation.

2. There was a reliable growth of probability of the same form to re-appear after 24 hours, 27 days, and one year.

3. Synchronous measurements of the form carried out in different laboratories showed that for distances less than 100 km about 60% pairs of the distributions had the same form. Probability to observe similar distributions turned out to be high also for measurements on a research ship in the Indian Ocean and in a remote laboratory near Moscow, which were in the same time zone.

These data, in the case of their conformation, will almost undoubtedly testify against the invariance of the radioactive atom (and/or detector) properties with respect to spatial rotations. Seemingly, just this conclusion follows at once from the both principal papers Refs. 13 and 16. A discrepancy demanding further consideration is only elucidation of a possible source of the influence on $S + M_c$. Indeed, according to the experiments of Shnoll at al., it is natural to connect the observed effect with the influence of the nearest cosmic environment, such as the Sun and the Moon. Authors of Ref. 13 explain a dependence of $\beta$-decay rate by the mutual orientation of $S$ system and unknown cosmic field directed toward the Constellation Hercules.

4. NEW QUANTUM NUMBERS

From the preceding considerations it is possible to give the following explanation of the observed phenomena. Generators of the spinor representation of the rotation sub-group,

$$\sigma^z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \sigma^+ = \sigma^x + i\sigma^y = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad \sigma^- = \sigma^x - i\sigma^y = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix},$$

can be factorized by means of the relations:

$$\sigma^+ = a^\dagger b, \quad \sigma^- = b^\dagger a,$$

where

$$a = |0\rangle\langle +|, \quad b = |0\rangle\langle -|,$$

and $|0\rangle$ is the vacuum state. Sign $^\dagger$ denotes the hermitian conjugation. Actually, we introduce in such a way the birth and annihilation operators for atoms ready and
unready to decay (atoms of the type \( a \) and \( b \), correspondingly). They satisfy the fermion anticommutative relations,

\[
aa + a^\dagger a = 1, \quad bb + b^\dagger b = 1,
\]

which can be also interpreted as resolutions of identity in the Fock spaces for particles of types \( a \) and \( b \).

From the physical point of view, the undertaken factorization implies the definition of new quantum numbers,

\[
n_a = a^\dagger a, \quad n_b = b^\dagger b,
\]

which correspond to probabilities of atom to decay and to survive, correspondingly. Since \( \sigma^z = n_a - n_b \) and eigenvectors of operators \( n_a \) and \( n_b \) coincide with eigenvectors of \( \sigma^z \), we shall call the property of the radioactive atom to decay by quasi-spin.

Under spatial rotations, the ability of the system of the atom plus the measuring instrument to demonstrate the decay, in the general case, are changed:

\[
Tr[\rho n_a] \rightarrow Tr[U\rho U^\dagger V_n a V^\dagger].
\]

If, e.g., we take an atom completely ready to decay, \( \rho_+ = |+\rangle\langle+| \), and rotate it relatively to the fixed instrument, than corresponding transformations appear as follows:

\[
V = 1; \quad U |+\rangle = \alpha |+\rangle + \beta |-\rangle,
\]

where \( |\alpha|^2 + |\beta|^2 = 1 \). Thus the spatial rotations lead, in our model, to changing the probability to observe the decay by the factor \( |\alpha|^2 \). We suggest that there are fixed directions in the cosmic space such that atoms are the most unstable if their quasi-spins are oriented along them.

Positive hints at the existence of the quasi-spin polarization follow from the experiment. Indeed, although the experiment did not reveal noticeable correlations between changes of \( \beta \)-decay rate for two different radioactive sources, \(^{60}\)Co and \(^{137}\)Cs, the sources demonstrated a systematic increase of nuclear decay rate at their quite certain, different for different sources, spatial orientations\(^{(18)}\). But if even a state of the polyatomic system is not polarized, the existence of the “readiness-to-decay” quantum number can be observed because of its influence, especially significant for completely unpolarized atomic ensembles, on the quantum statistics. Besides, models which will be considered in the next section show that the energy of an unstable atom should depend on its orientation regarding to a pseudo-vector of current interacting with the atom by means of a new, “the fifth” force.
5. MODELS OF INTERACTIONS

The “readiness to decay” of atoms can be changed by an external field, \( \varphi \), carrying this quantum number. Our non-relativistic consideration does not forbid us to introduce the following interaction in the spirit of the Lee model\(^{(19)}\):

\[
H_{\text{int}} = \frac{\lambda}{\sqrt{N}} \sum_{i=1}^{N} (\varphi a_i^\dagger b_i + b_i^\dagger a_i \varphi^\dagger),
\]

where \( N \) is a number of radioactive atoms and \( \lambda \) is a coupling constant. Evidently, this interaction preserves the total number of atoms and the total “readiness to decay”. In this model, experimentally observed variations of nuclear decay rates could be a consequence of exchange between radioactive atoms on the Earth and the Sun by quanta of the \( \varphi \) field (the corresponding Feynman graph is quite obvious).

Interactions between radioactive atoms can be also written in the form of the Fermi 4-particle interaction, i.e. as “current \( \times \) current”\(^4\). As far as the current components here are the Pauli matrices, \( \sigma_x, \sigma_y, \sigma_z \), the interaction invariant with regard to the spatial rotations can be written in the form:

\[
v = v(r) \left( \vec{\sigma}_1 \cdot \vec{\sigma}_2 \right).
\]

It does not modify the total quasi-spin, \( \vec{S} = \vec{\sigma}_1 + \vec{\sigma}_2 \), of two interacting atoms. The obtained potential resembles the spin dependent nucleon potential, and the theory of nuclear forces prompts one more possible potential,

\[
u = u(r) \left[ 3(\vec{\sigma}_1 \cdot \vec{n})(\vec{\sigma}_2 \cdot \vec{n}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \right],
\]

which preserves \( \vec{S}^2 \). Apparently, assumptions of this model could be tested and, if needed, \( v(r), u(r) \), could be established in space ship experiments.

It is clear, a current acting upon the radioactive atom may be not only the quasi-spin of other atoms, but a pseudovector of a different nature too. In this connection, an assumption\(^{(21)}\) that the pseudovector of current of the so-called light monopole\(^{(22)}\) can be an effective catalyst of the weak decays is of interest. Another possible source is enigmatic dark matter and dark energy which prevail in the universe according to the modern astrophysical data. It is also possible to identify the field \( \varphi \) with Goldstone excitations corresponding to breaking the rotational symmetry of the space.

\(^{4}\)Actually, this means that we consider an effective field theory which can be obtained after fixing a proper energy cut-off and taking the path integral over the high-frequency fields (see, e.g., Ref. 20).
6. “PREGEOMETRY”

As it was pointed out above, the operators describing the “readiness to decay” can be found with the help of the factorization of spatial rotation sub-group generators. In their turn, these generators appear naturally if we use the Dirac (non-commutative) factorization of the spatial metrics:

\[ ds^2 = \eta_{\alpha\beta}dx^\alpha dx^\beta = \frac{1}{2}\sigma_\alpha\sigma_\beta dx^\alpha dx^\beta, \]

where we take into account the anti-commutative properties of the Pauli matrices:

\[ \sigma_\alpha\sigma_\beta + \sigma_\beta\sigma_\alpha = 2\delta_{\alpha\beta}. \]

This prompts us to an idea that the described mechanism of the decay control can be related to general properties of the space itself and, therefore, be universal. Such a strong assumption is also supported by a resemblance of the nuclear decay rate probability distributions to fluctuations of biochemical reaction rates, which are observed concurrently at the same spatial location\(^{(16)}\). It is also close enough to an idea of Misner, Thorn and Wheeler, who speculated about existence of a connection between geometry and classical two-valued logic\(^{(22)}\). The connection between geometry and logics is caused in our model by dual properties of the Pauli matrices \(\sigma_x, \sigma_y, \sigma_z\). Indeed, they are transformed as components of the axial vector, on the one hand, and they operate in the space of the quasi-spin components, on the other hand. But, according to our interpretation, the quasi-spin controls the truth values of statements about realization of a fixed result of two possible outcomes. Besides, the measurement process plays an important role. It turns a closed quantum system into an open one (in the sense of the informational interactions defined above).

Of course, the exciting theoretical possibilities considered in the present paper will be urgent only in the case of the final confirmation of the data presented in Refs. \((13-17)\). Therefore, the most topical task now is checking the results of the above-mentioned papers and carrying-out analogous experiments under altered conditions like setting the device with radioactive sources on a rotating platform, in underground or cosmic laboratories, etc. To stimulate interest to this poorly understood problem was one of the aims of our paper.
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