Scientific Session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (May 30, 1990)

Usp. Fiz. Nauk **160**, 185–188 (October 1990)

A scientific session of the Division of General Physics and Astronomy of the USSR Academy of Sciences was held on May 30, 1990 at the S. I. Vavilov Institute of Physics Problems of the USSR Academy of Sciences. The following reports were presented:

1. R. A. Syunyaev. Studies of the Galactic center zone, pulsars and quasiperiodical sources in the x-ray range. "Kvant" module and "Granat" observatory results.
2. L. A. Khalfin. Zeno's Quantum Effect.

A summary of one report is given below.

L. A. Khalfin. Zeno's Quantum Effect.

1. Will the decay probability of an unstable state decrease if measurements are made frequently — does this state undergo decay? Will the probability of a transition from an initial state, under a fixed interaction, decrease if one measures frequently whether the transition took place? The quantum theory asserts that, yes, it will happen—which seems impossible and paradoxical from the classical point of view. The effects of changing a decay law, a transition probability (not only decreasing it, but possibly increasing it, generally speaking), depending on the frequency of measurements, are referred to as Zeno's Quantum Effects (ZQE). From quantum theory it follows that in the extreme form, under continuous changes, the initial (unstable) state "freezes" and no quantum dynamics whatever develops in time (!). This amazing prediction of the modern quantum theory is naturally referred to as Zeno's Quantum Paradox.

2. For the decay of unstable states (of atoms, nuclei, elementary particles) the ZQE has not yet been experimentally found. However, at the end of 1989 the ZQE for the probability of a transition between atomic levels was experimentally observed by a group of physicists in the USA. The journal "Science" sensationally informed the scientific community about this event.[1] We describe only the idea and the results of the experiment without going into details. Consider a three-level atomic system. The lifetime of energy level 3 is very short, hence an atom excited from the ground state (level 1) to level 3 returns very rapidly to level 1. During this process, photons are emitted with frequency ν_{13}. If we measure the number of photons with frequency ν_{13} from the reverse transition $3 \to 1$, we will thereby measure the number of atoms present in the ground level 1. The experiment we describe consists of the following. A laser of photon frequency ν_{12} during a time interval T irradiates atoms that were in the initial state 1 and excites them to level 2. Simultaneously, the same atoms are irradiated, using a laser having a photon frequency ν_{13} at instants spaced by short intervals of time $\Delta t \ll T$. By measuring the number of photons with frequency ν_{13} from the reverse transition $3 \to 1$ the numbers of atoms in the initial state 1 at instants of time $t_n = n\Delta t$, $n = 0,1,2,...$ are found. The experimentally observed effect (ZQE) consists of the result that the shorter is the time interval Δt between measurements of the number of atoms in the initial state 1, the lower is the probability of raising them to the excited state 2 during the time interval T (!).

3. The physical essence of ZQE is associated with the simultaneous influence of two fundamental aspects of quantum theory: 1) reduction of the state vector resulting from measurements; 2) nonexponential nature of the law of decay, i.e. nonuniformity in time of the transition probability per unit of time. The study of ZQE is of great interest because both the state vector reduction under measurements, connected with the problem of quantum-classical correspondence (see modern results in Refs. 2,3 and the review of Ref. 4), and the nonexponential nature of the decay law (nonuniformity in time) are parts of the fundamental features of quantum theory.

4. Zeno's Quantum Effect (and Paradox) was first predicted[5,6] by the author's research at the end of the 1950's and the beginning of the 1960's. In 1968 ZQE was proven[7] under a minimum requirement assumption of the finiteness of the first moment (average value) of the energy density distribution for the unstable state. Ten years later similar results were repeated in studies by Sudarshan and Misra[8], who named this phenomenon Zeno's Quantum Paradox. After that, until the most recent publication,[9] similar results have been studied in many investigations from which we point out only Refs. 10,11 containing other references, wherein can be found additional suggestions for different names for the ZQE ("Watchdog effect,"[12] "A watched pot never boils"[13])—depending on some details of the method used in studying this effect.

5. Reproduced below is the main theoretical result. Consider the Cauchy problem of quantum theory:

$$H|\psi(t)\rangle = i\frac{\partial|\psi(t)\rangle}{\partial t},\quad |\psi_0\rangle = |\psi(t=0)\rangle,\quad \langle\psi_0|\psi_0\rangle = 1,$$

$$H = \text{const}(t). \tag{1}$$

In agreement with the Fok–Krylov theorem,[14] the amplitude of the decay probability $p(t) = \langle\psi_0|\psi(t)\rangle$ can be written as

$$p(t) = \int_{\text{Spec}H} \omega(E)\exp(-iEt)\,dE, \tag{2}$$

where $\omega(E)$ – is the energy density distribution (an invariant of the motion) for an unstable physical system. The decay probability per unit of time is

 0038-5670/90/100868-02$01.00

$$\Gamma(t) = -\frac{dL(t)}{dt} L^{-1}(t),$$

where $L(t) = |p(t)|^2$. For a pure exponential decay law $L(t) = \exp(-\Gamma t)$, we have $\Gamma(t) = \Gamma = \mathrm{const}(t)$, i.e., uniformity in time and Γ can be calculated from the time dependent perturbation theory — Fermi's golden rule. In 1957 for the first time, in the author's publications[5] and later in many subsequent articles (see, e.g., the review of Ref. 15) it was proven that the decay law $L(t)$ cannot be precisely exponential, because Spec $H \geqslant 0$, and in addition the nonexponential element in the decay law is an analytical function in Re$t > 0$ and for this reason cannot be equal to zero during any time interval. This fundamental nonuniformity in time already leads to the ZQE. However, the essential Zeno's Quantum Effect follows from the theorem (LA Khalfin, 1968 Ref. 7):

$$\int_{\mathrm{Spec}\,H} E\omega(E)\,dE < \infty \Rightarrow \left.\frac{dL(t)}{dt}\right|_{t=0} = 0. \qquad (3)$$

The ZQE and Zeno's Paradox follow directly from Eq. (3): at $t = 0$ all unstable states freeze (and become stable) $\Gamma(t = 0) = 0$. See Ref. 16 for a possible application of this result to the problem of proton decay. From (3) it follows that in the vicinity of $t \approx 0$ it can be assumed that $L(t) \approx 1 - \sigma^2 t^2$, where σ^2 is the dispersion of the energy density distribution.

6. The most important task is the evaluation of the region having significant nonexponentiality $[0, t_{\mathrm{n.e.}}]$. This region is defined by the energy density distribution $\omega(E)$, i.e. by the "preparation" (history) of the initial state $|\psi_0\rangle$ and is connected with the inverse problem $L(t) \to p(t) \to \omega(E)$ of the quantum theory of decay, which was studied in Refs. 6, 17. In Refs. 18,19 general estimates of $t_{\mathrm{n.e.}}$ were obtained which are generally determined by the region of high values of the energy E, in particular by the dispersion σ^2, and not by pole characteristics of the energy distribution responsible for the exponential term in the decay law. From the estimates in Refs. 18,19 it follows that if the σ^2 term is smaller, then generally speaking, the $t_{\mathrm{n.e.}}$ term is larger. For the usual energy distributions of unstable particles $t_{\mathrm{n.e.}}$ are sufficiently small. However, the ZQE for the two-level states such as $K^\circ - \bar{K}^\circ$ mesons cannot be small.[20] Multilevel systems can be prepared such that the ZQE region becomes observable. At the same time, a decrease in the decay rate later goes over into a sharp increase — this effect being referred to[9] as the "ticking effect."

7. For observing the ZQE it is necessary to have as high a time resolution for measurements as possible. At the same time it is possible to make the observation of the ZQE easier by special preparation of unstable states, e.g., by decreasing σ^2 which depends on the reaction producing unstable states. From the forgoing it is clear that observation of the ZQE, within the framework of the inverse problem, would allow obtaining unique information about the history (preparation) of the unstable states that cannot be, in principle, obtained from a study of the exponential decay law (cf. Ref. 21 concerning the possibility of applying the baryonochronological method to cosmological problems).

8. Methods for the "freezing" of physical processes, in particular the decay processes, by means of the ZQE, which open up tremendous possible applications, appear as fantasies today. However, in principle there are no restrictions on this and the first observation of the ZQE made recently[1] underlines that this exciting possibility connected with the ZQE can be realized in the future.

[1]Science **246**, 888 (1989).

[2]L. A. Khalfin, and B. S. Tsirelson, *Proc. Symposium on the Foundations of Modern Physics*, (Eds.) P. Lahti and P. Mittetstaedt, World Scientific, Singapore, 1987, p. 369.

[3]L. A. Khalfin, *Complexity, Entropy and the Physics of Information*, (Ed.) W. Zurek, Addison-Wesley, 1990. (SFI Studies in the Science of Complexity. V.IX).

[4]L. A. Khalfin and B. S. Tsirelson, Quantum-classical correspondence in the light of Bell inequalities.-Preprint, MIT, 1990

[5]L. A. Khalfin, Dokl. Akad. Nauk SSSR **115**, 277 (1957) [Sov. Phys. Dokl. **2**, 232 (1958)]; Zh. Eksp. Teor. Fiz. **33**, 1371 (1958) [Sov. Phys. JETP **6**, 1053 (1958)]. Quantum theory of decay of physical systems (in Russian), for candidate of phys. math. sciences degree, Author's abstract of thesis FIAN SSSR, M., 1960.

[6]L. A. Khalfin, Dokl. Akad. Nauk SSSR **141**, 599 (1961) [Sov. Phys. Dokl. **6**, 1010 (1962)].

[7]L. A. Khalfin, Pis'ma Zh. Eksp. Teor. Fiz. **8**, 106 (1968) [JETP Letters **8**, 65 (1968)].

[8]B. Misra and E. C. G. Sudarshan, J. Math. Phys. **18**, 756 (1977).

[9]L. S. Schulman, C. R. Doering, and B. Gaveu, *Quantum decay in multilevel systems*, Clarkson University preprint, 1990.

[10]A. Sudbery, Ann. Phys. (N.Y.) **157**, 512 (1984).

[11]A. Peres, Am. J. Phys. **48**, 931 (1980).

[12]K. Kraus, Found. Phys. **11**, 547 (1981).

[13]M. T. Parkinson, Nucl. Phys. B. **69**, 399 (1974).

[14]N. S. Krylov and V. A. Fok, Zh. Eksp. Teor. Fiz. **17**, 93 (1947).

[15]L. Fonda, G. C. Ghirardi, and A. Rimini, Rep. Prog. Phys. **41**, 587 (1978).

[16]L. A. Khalfin, Phys. Lett. B. **112**, 283 (1982).

[17]L. A. Khalfin, Investigations in the quantum theory of unstable particles (in Russian), Author's abstract of thesis for the doctorate in phys. math. sciences, Theor. Phys. Lab., JINR, Dubna, 1972.

[18]L. A. Khalfin, *Intern. Symposium on Weak and Electromagnetic Interactions in Nuclei: Abstracts.*—Heidelberg, 1986.

[19]L. A. Khalfin, Preprint LOMI E-2-83.—Leningrad, 1983.

[20]L. A. Khalfin, *Intern. Symposium on Weak and Electromagnetic Interactions in Nuclei: Abstracts.*—Montreal, 1989.

[21]L. A. Khalfin, Preprint LOMI E-11-83.—Leningrad, 1983.

Translated by I. Pribluda and R. N. Dubinsky