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Quantum Zeno Effect, Nuclear Conversion and Photoionization in Solids

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The quantum Zeno effect in continuous passive observation of radioactive decay is described starting from the "first principles". It is argued, that in this case the quantum Zeno effect reduces to the influence of inelastic scattering of decay products in surrounded media to decay constant. A new class of quantum Zeno effects is introduced, which are named as "threshold quantum Zeno effects" (TQZE). It is shown, that TQZE could explain recently discovered deep suppression of the conversion decay of $1/2^+$-isomer of uranium-235 in the lattice of silver. TQZE predicts also some new phenomena, which may be observed in the near-threshold behavior of atomic photoionization cross-sections. Possible experimental manifestations of this new phenomena are discussed.

I. INTRODUCTION

The main reason to carry out this investigation was a very unusual situation with decay of an isomeric state of ^{235}U nucleus. The nucleus of ^{235}U has the first exited level with spin and parity $1/2^+$ [1, 2] and with energy of excitation only 76.8 ± 0.5 eV [3]. The decay of this isomeric level to the ground state $7/2^-$ is realized by internal conversion of nuclear $E3$-gamma-transition with the half-life time usually about 26 minutes [1, 2]. As the transfer energy of this transition is rather low, so only few outer subshells of uranium with sufficiently low binding energy may participate in the conversion process ($6s$, $6p$, $6d$, $7s$ and $5f$). Practically, the $6p$-subshell of uranium gives the main contribution to the process of conversion (more than 90%) [4]. The $6p$-subshell is represented by two $6p_{1/2}$-electrons with binding energy 26–30 eV and by four $6p_{3/2}$-electrons with binding energy 15–20 eV depending from the chemical state of uranium [5–8]. The $6p$-subshell and other valence-band electrons could be disturbed notably under the influence of chemical bonding of surrounded atoms. This disturbance naturally must influence to the decay rate of the isomer. This influence was the main point of interest from the very beginning of investigation of decay of this isomer [2]. These "chemical" variations of conversion decay rate was experimentally investigated in a great

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number of works [9–17]. It was found that the magnitude of these effects was around 2–3% from the full lifetime of isomer. These values are in reasonable agreement with the theoretical estimates for the effects of this type [4, 18]. The classical method of decay rate measurement was used in the cited higher papers [9–17]. The isomer nuclei, which were produced in ^{239}Pu α-decay, were collected on surfaces of conductive materials, and then the conversion electrons counting rate was measured. Decay of the isomeric atoms only in the near surface layers could be detected with making use of this classic method due to a very low energy, and consequently a very low mean free path of conversion electrons in substance. Decay constant of uranium isomer in the bulk of matter, where atomic states and surrounding conditions may be strongly different from the ones near the surface, rests unknown in such experiments.

A new method of ^{235m}U lifetime measurements was used in the investigations of Kol'tsov *et al.* [19, 20] recently. I couldn't discuss this method in detail in this paper, but I want to mention the main points of it. The essence of this method consists in the following. At the beginning some known amount of excited isomer's atoms are implanted in some material, then they are kept in it during some definite time, and at last these atoms are extracted from this material. The extracted atoms turned out to be deposited on some metallic surface. The amount of survived exited isomer's atoms could be determent by counting the conversion electrons by usual way. This amount allows to determine the lifetime of the isomer atoms when they were implanted in substance and was not visible. This new method permits to determine the decay constant of ^{235m}U when the isomer atoms are placed rather deep in the metallic matrices in distinction from early works. The results of this measurements turned out rather wonderful and interesting. Some indications was obtained, that decay of isomer atoms which were implanted to the matrix of silver may be highly suppressed by factor achieved to 8–10 in comparison with decay on the surface of metals. This suppression is far beyond the chemical variations of the decay constant of ^{235m}U observed early [9–17]. It is possible to say about "freezing" of radioactive decay in this case.

In this paper I argue the point of view, that this suppression of decay may be connected with the phenomena related to the quantum Zeno paradox (QZP), which arises in the quantum theory of measurements, and discuss some new features of this phenomenon. The term "quantum Zeno paradox" was introduced in papers [21, 22], although this phenomenon was investigated also in some early works (for example, [23–25]). Then QZP was discussed many times (see for review [26, 27], some later works will be cited in subsequent parts of paper). The main point of the QZP consists in that evolution of a quantum object should be stopped when it is subjected to continuous observation with macroscopic apparatus. The fact, that quantum Zeno effect (QZE), connected with QZP, really can lead to suppression of quantum transitions, is already known from experiment proposed by Cook [28] and carried out by Itano *et al.* [29]. But these results are connected with some kind of forced periodic quantum oscillations between discrete states, not with the radioactive decay from initial discrete state to continuum as was proposed

in the seminal works [21, 22]. The opinion, that QZE could not notably disturb radioactive decay, is rather popular up to now [28, 30, 31]. Below I try to prove, that it is not so in general, but instead QZE has got some features, that may lead, in principle, to almost complete suppression of radioactive decay, and suppression of decay of ^{235m}U in silver may be the special case of this. I want to show also, that this features of QZE predicts some new interesting phenomena. This phenomena one may expect to find in the structure of absorption edges in X-ray spectra.

In the Section II the wave function collapse and QZP are considered in connection with the problem of a passive observation of radioactive decay. In the same section of paper possible connections of QZP with suppression of decay of the uranium isomer is qualitatively discussed. It is shown there, that the problem reduces to accounting for the influence of inelastic scattering of conversion electrons in the material of detector or in any surrounded matter to probability of conversion decay.

The Section III is the key for all present investigation. In this section the problem is considered in the frame of "first principles", i. e. by solution of complete time-dependent Schrödinger equation for united system "nucleus + decay particles + scatterer (detector)". The general expression for decay constant, disturbed by inelastic scattering of decay particles (conversion electrons etc.) or by continuous observation, has received.

A physical meaning and possible orders of magnitude for quantities, introduced in the Section III, are discussed in the Section IV.

It is shown in the Section V, that the usual QZP follows from the general formalism of the Section III in the limit of very strong inelastic scattering of decay particles. Some conclusions for the quantum theory of measurements from this fact and the physical meaning of QZP are discussed.

Two new phenomena, related with QZP, are introduced in the Section VI. They are connected with the special case of radioactive decay near threshold of reaction and are named as threshold quantum Zeno effects (TQZE) of the first and second type.

It was shown in the Section VII, that TQZE of the first and second type could influence to the near-threshold behavior of photoionization cross-sections of atomic shells. The analysis of some published experimental data shows, that such influence is actually observed perhaps. These data permit to obtain independent experimental estimates for quantities, which are typical for TQZE, in addition to the consideration in Section IV.

A possible influence of TQZE to ^{235m}U decay in metals is discussed in the Section VIII. It was shown, that this influence may be very strong, but the uncertainty of estimates remains rather high.

The theory of present article is briefly compared with some other theories of QZE in the Section IX. Some contradictions between them are resolved.

The final conclusions are formulated in the Section X.

The Appendix contains an expression for inelastic scattering operator, introduced in Section III.

II. Quantum Zeno Paradox and the Isomer of ^{235}U.

The strong suppression of ^{235m}U decay in silver has not been explained theoretically up to now. It is clear only, that this phenomenon could not be understood as realization of such rather good known mechanisms as rebuilding of atomic shells in chemical bonding [41] or interference of conversion electrons connected with elastic scattering on the neighboring atoms [42] (the last is the effect which is quite analogous to the well known EXAFS in photoionization of atoms [43]). On the other hand, the *qualitative* consideration, connected with the quantum Zeno paradox, points out to the one of the possible ways of the explanation. Let's briefly discuss this paradox for completeness of consideration and then return to the uranium isomer. The quantum Zeno paradox is widely treated in literature, but I shall consider it in the more narrow sense, only in connection with the continuous passive observation of radioactive decay.

One of the basic statement of quantum theory is the projection postulate, which describes the measurement, carrying out on a quantum system by a macroscopic apparatus. For the first time it was established by P. A. M. Dirac [44] and then was investigated thoroughly by Johann von Neumann [45]. One could find a very interesting and contemporary discussion of the projection postulate and related topics in the book [46]. In the particular case, which is interesting for us, the contents of the projection postulate may be reduced to the following.

Let it be that some quantum system X evolves under the influence of its Hamiltonian H starting from the state $|\Psi_0\rangle$, which is defined at the moment of time $t=0$. Let it be also, that at some moment $t>0$ the measurement is carried out with this system. The purpose of this measurement is to detect whether the system still stay in the initial state $|\Psi_0\rangle$ or already leaves it. It is possible to say that this is a measurement of the value of dichotomic observable, which is equal to 1, if the system turns out to be in the state $|\Psi_0\rangle$ and equal to 0 in opposite case. The operator of such observable is, obviously, simply the projector $|\Psi_0\rangle\langle\Psi_0|$. Then the projection postulate says, that

(i) at the moment of time t the system will be discovered in the state $|\Psi_0\rangle$ with the probability $p(t)=|\langle\Psi_0|\Psi(t)\rangle|^2$;

(ii) if the system was discovered in the state $|\Psi_0\rangle$, then just after the measurement the state of the system is $|\Psi_0\rangle$.

The jump of the system's state from $|\Psi(t)\rangle$ to $|\Psi_0\rangle$ at the moment of measurement is referred to, as it known, as a reduction or collapse of wave function.

The projection postulate (i, ii) (especially item (i)) explicitly connects the measurement with just one moment of time t, consequently such measurement *must* be treated as instantaneous. But such interpretation of a measurement is not always sufficient. Let's examine the case of passive continuous observation of a radioactive decay. Let's suppose that the system X is a radioactive nucleus (or an atom with radioactive nucleus), and $|\Psi_0\rangle$ signifies its exited state. The excited state of the

nucleus decays with emitting some decay particles, for example conversion electrons as in the case of ^{235m}U. Let's assume that the nucleus is surrounded by detectors from all sides so that the probability of registration of decay products is 100%, and there is no another external intervention to the evolution of nucleus. We shall treat all detectors as one unit detector for simplicity, or we can consider, that nucleus is placed inside the detector type of ionization chamber or scintilloscope. During the time while the detector gives no signal about the registration of decay particles *we continuously receive information that the nucleus rests in the exited state.* Thus with no doubts we carry out a continuous measurement of the nuclear state in this case. This kind of measurement can't be regarded in the frame of projection postulate by a simple way. What should we do now? There is no answer on this question in the frame of standard phenomenological theory of measurement, which is the inalienable part of the quantum mechanics basis.

Let's try to reduce the notion of a continuous measurement to the discrete one in order to close this gap. Let's suppose that we register the information from the detector only in the successive moments of time $t_0 = 0$, $t_1 = \Delta t$, ..., $t_n = n\,\Delta t$, ..., where Δt is some finite interval of time. (It could be done for example, in a manner of work [32], where QZP in negative results experiments was considered). Obviously, we shall see the next picture: at the moments of time t_0, t_1, ... up to some moment t_N we shall find, that the detector still not discharged, but at moments $t_{N+1}, t_{N+2}, \ldots$ the detector is already discharged and thus has detected the decay. This must be interpreted as the decay has occurred in interval $[t_N, t_{N+1}]$.

We get some information about the state of the system in each moment of time t_i. So let's suppose, that we can use the projection postulate in each moment t_i now. The projection postulate says, that we have got wave function collapses at each moment of measurement $t_0, \ldots, t_i, \ldots$. Moreover, at moments $t_0, \ldots, t_N$ the state function was reduced to $|\Psi_0\rangle$ and at moments $t_{N+1}, \ldots$—to some decay states. To make transition to the truly continuous observation let's image to ourself now, that we infinitely diminish the interval Δt between successive measurements. So we come to necessity to describe the succession of endless often measurements, each of which causes collapse of wave function of the nucleus. Let's show now, that this is just the origin of QZP.

The system X evolves freely under control by its own Hamiltonian H between the moments of measurements. If the initial state of the system at the moment $t = 0$ was $|\Psi_0\rangle$, then the measurement at the moment $t = 0$ will give the state of the system equal to $|\Psi_0\rangle$ with probability $p(0) = 1$. At the moment of measurement number 1 at moment $t_1 = \Delta t$ the state of the system is

$$|\Psi(\Delta t)\rangle = e^{-iH\Delta t}\,|\Psi_0\rangle.$$

(We take $h = 1$ here and in the following.) It follows from the statement (i) that the probability to obtain the system in the state $|\Psi_0\rangle$ at the moment Δt is

$$p(\Delta t) = |\langle \Psi_0|\, e^{-iH\Delta t}\,|\Psi_0\rangle|^2.$$

If the system was discovered in the state $|\Psi_0\rangle$, then it follows from the statement (ii) that the wave function has collapsed to $|\Psi_0\rangle$, and at the beginning of the next interval $[\Delta t, 2\,\Delta t]$ the initial state was regenerated. Therefore at the moment of the next measurement $t_2 = 2\,\Delta t$ the probability to discover the system in the state $|\Psi_0\rangle$ changes to $p(\Delta t)$ times once more as the duration of free evolution equals Δt again. Thus the probability to discover the system X in the state $|\Psi_0\rangle$ at the moment of measurement $2\,\Delta t$ is

$$p(2\,\Delta t) = p(\Delta t) \cdot p(\Delta t) = p(\Delta t)^2.$$

(We neglect the possibility of reverse transition from decay states to $|\Psi_0\rangle$) After the same reasoning we find that at any moment of time t the system will be discovered in the state $|\Psi_0\rangle$ with probability

$$p(t) = [\,p(\Delta t)\,]^{t/\Delta t} = e^{-\Gamma(\Delta t)\,t} \tag{1}$$

where

$$\Gamma(\Delta t) = -\frac{\ln p(\Delta t)}{\Delta t}$$

Now let's take the limit $\Delta t \to 0$. Preserving the first non-vanishing order in expansion of $p(\Delta t)$ and then in $\ln p(\Delta t)$ we find easy

$$\Gamma(\Delta t) = D^2\,\Delta t, \tag{2}$$

where the quantity

$$D^2 = \langle \Psi_0 |\, H^2 \,| \Psi_0 \rangle - \langle \Psi_0 |\, H \,| \Psi_0 \rangle^2$$

is the dispersion of the system's energy in the initial state. If we suppose that D^2 is only the finite number, then the Eq. (2) gives $\Gamma = 0$ and Eq. (1) gives $p(t) \equiv 1$ in the limit of $\Delta t \to 0$. So the system is "frozen" in the initial state. This is the contents of QZP.

Let's try to understand the physical meaning of this strange result. It is well known that in the grate majority of cases the continuous observations does not effect visibly to radioactive decay. So the discussion which led to QZP are vicious in some points. It is rather obvious that one of the essential defect of this discussion was the supposition about instantaneous reaction of detector to decay. Actually, just this point permits us to suppose the wave function collapse at the moment of reading data from detector. The supposition about instantaneous reaction of detector to decay is wrong. When we have discovered in some moment t, that the detector is not still discharge, this fact not signifies that nucleus is not still decayed at the same particular moment; we can be sure only, that it was so only some time before this moment, and our confidence in it should smoothly vanish when we approach to the moment t. This delay originates from only finite reaction time of

detector to decay. Any attempt to account for the finite reaction time of detector supposes introduction of some duration to the process of wave function collapse, but the way to do this is unclear. Thus we see, that correct consideration of continuous passive observation with making use of the projection postulate is impossible. Another reason for this conclusion is the collection of arguments connected with the uncertainty relation time-energy. The limit $\Delta t \to 0$ is physically meaningless in accordance with these arguments [30, 28, 33], thus the used higher method of consideration is not acceptable. Nevertheless we may suppose, that QZP correctly points out the tendency, which manifests itself when the detector reaction time become shorter and shorter, and this tendency consists in slowing down the radioactive decay. So we come from the quantum Zeno paradox to the hypothesis about quantum Zeno effect in continuous passive observation of radioactive decay. One could try to find experimentally the QZE manifestation in principle.

Let's justify now the notion of the apparatus or the detector which is used for observation of radioactive decay. The registration of decay is the irreversible changing of the internal state of the detector as a result of its interaction with the decay particles. By another way it is possible to say, that registration is an inelastic scattering of decay particles on the detector, as the state of the last changes. But from the point of view of the physical meaning of the process it is not important on which matter the inelastic scattering of the decay particles occurs. Any scatterer could play the role of detector, if it actually changes its inner state in irreversible way in the process of interaction. For example, the role of apparatus can play any media in which the radioactive nuclei are immersed. It is required only that the layer of the matter would be thick enough and the probability of inelastic scattering of the decay particles would be close to 1. Thus we reduce QZE to the influence of inelastic scattering of the decay products in surrounded media to the probability of radioactive transition.

Let's return to the suppression of decay of ^{235m}U in silver. Kinetic energy of the main part of conversion electrons created in the process of decay of isomer lays in the interval 45–60 eV, which corresponds to the length of the de'Brogl wave in interval 2–1.5 Å respectively. In metals (but not in isolators) the mean free path of such electrons up to inelastic scattering is very short and lays in interval 3–5 Å (theoretical estimates based on the statistical model of electron gas and random phase approximation [47]) or even less, down to ~ 1 Å (experiment [48, 49]). Thus the wave length of the conversion electrons turns out to be of the order of length of its inelastic mean free path. So the final states of the conversion electrons are badly defined in this sense and intensity of inelastic scattering may be considered as very high. As in this case we have got real observation of "frozen" decay [19, 20] so the idea to consider the possibility of connection of this phenomenon with QZE seems to be quite natural.

III. Radioactive Decay with Strong Inelastic Scattering of Decay Products

As the consideration of continuous passive observation of radioactive decay based on simple form of projection postulate fails, so we should search another

possibilities to describe it. The most radical way to solve this problem is to refuse any phenomenology, to return to the "first principles" and to carry out the exact examination of evolution of united quantum system "nucleus + decay particles + scatterer" as a solution of complete time-dependent Schrödinger equation. This way may be characterized also as the successive quantum description of the measurement without the usage of the projection postulate. This idea is not new of course and was used many times, in particular also in fundamental monographs [45, 50].

In the context of QZP a dynamical description of quantum measurements was widely discussed in the number of papers [34–37, 33, 38] in connection with Cook–Itano experiment [28, 29]. But an oscillation-type transition between two discrete levels, not the radioactive decay, was investigated in this works. The models of detector also were far from continuously operating counter. The model of discrete external intervention to evolution of quantum system was investigated in these works (except [38], where continuous measurement was treated as well). So these results could not be directly applied to the problem of continuous passive observation of radioactive decay. A dynamical approach to purely continuous observation was used in papers [39, 40, 38], but only the case of oscillation-type transitions between discrete levels was investigated in this works as well. A dynamical approach to continuous observations of radioactive decay in the context of QZP was used in papers [31] and [26]. Although these two works contain many interesting results, in particularly the dynamical derivation of QZP in the case of radioactive decay, the models of detector were rather idealized and far from real scattering matter or switched on counter. In work [51] the realistic model of detector for registration of decay products was considered, but only the case of weak inelastic scattering was treated, while very strong scattering take place in the case of ^{235m}U decay in metals (particularly in silver). Thus, the description of radioactive decay with strong inelastic scattering of decay products or, in other words, the case of continuous passive observation of radioactive decay with very fast detector, evidently is unknown up to now.

Let's try to fill this gap. This problem is unusual in some degree for the theory of radioactive decay, because *we can't use the perturbation theory* in description of interaction between decay particles and scatterer (detector) due to strength of this interaction. So I shall reproduce this theory in some details. We shall consider the model oriented to the description of completely converted nuclear γ-transition such as in the nucleus of ^{235}U, but it would be easy to generalize or modify this description to the cases of any kind of radioactive decay or any another transition from discrete initial state to continuum: radiation or radiationless transitions in atoms and so on.

Let's consider three relatively independent quantum systems X, Y and Z with nondisturbed Hamiltonians H^0_X, H^0_Y and H^0_Z respectively (fig. 1). The double-level system X represents the nucleus with conversion electric transition from exited state $|x_0\rangle$ to the ground state $|x_1\rangle$ under influence of Coulomb interaction V with atomic electrons. The system Y is an atomic electron, which is being in the bounded state with wave function $|y_0\rangle$ at the initial moment of time, and then transits into

continuous spectrum with orthonormalized basis $|y_\xi\rangle$. Vectors $|y_\xi\rangle$ may signify any convenient basis of wave functions. We meanwhile neglect of the processes of relaxation of atomic shell after ionization of electron (see Section IV A for more details). The conversion electron, that is the system Y, in its turn interacts with the system Z, which is the scattering substance or detector, by means of the operator W, which represents the Coulomb interaction of conversion electron with all electrons and atomic nuclei of substance. At the initial moment of time the substance is being in the initial ground state $|z_0\rangle$ (the absolute zero of temperature), but under the influence of disturbance W could transit to some excited state in continuum $|z_\mu\rangle$. This excitation represents the act of inelastic scattering of conversion electron. As the main interest for us is concentrated on metals in the role of the external scattering matter, so the main process of inelastic scattering is the excitation of nearly free electron gas, and the state $|z_0\rangle$ may be identified with Fermi-vacuum of this electron gas. It is very important for the following consideration, that the energy spectrum of states $|z_\mu\rangle$ all lies above the energy of the state $|z_0\rangle$.

So we consider the decay from the state

$$|\Psi_0\rangle = |x_0 y_0 z_0\rangle, \tag{3}$$

which is considered to be defined at the zero moment of time. The notation as $|x_0 y_0 z_0\rangle$ will be understood as the shortening for the direct product

$$|x_0 y_0 z_0\rangle \equiv |x_0\rangle \otimes |y_0\rangle \otimes |z_0\rangle,$$

which will be used in the following in this paper. The direct product of operators will be written in explicit way.

It is easy to see that state (3) has not the right symmetry relative to the transpositions of conversion electron Y and matter electrons. We shall ignore this fact, i. e. we neglect of an exchange interaction in the process of scattering of conversion electron in media. Our formalism would be explicit if we described the process of conversion in μ-mesoatom, not in the ordinary atom, but this point can't qualitatively change our conclusions.

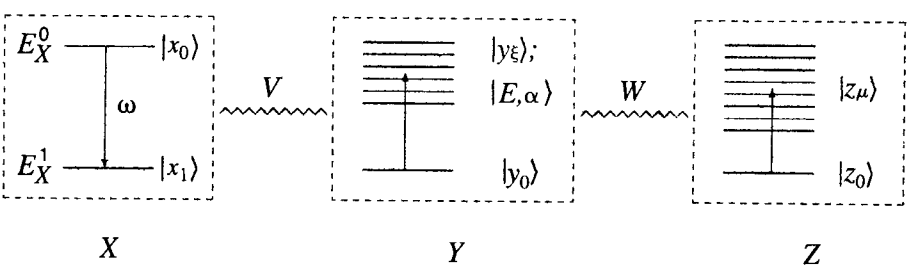

FIG. 1. The model of radioactive decay with inelastic scattering of decay products: $X \otimes Y \otimes Z$, where X is the nucleus, Y is the atomic eletron which excites in process of nuclear conversion, and Z is the surrounded media (scatterer). V and W are the interactions, which lead to the nuclear transition and to the scattering of the conversion electron, respectively.

The complete Hamiltonian of the united system $X \otimes Y \otimes Z$ has the form

$$H = H^0 + V + W, \tag{4a}$$

$$H^0 = H^0_X \otimes I_Y \otimes I_Z + I_X \otimes H^0_Y \otimes I_Z + I_X \otimes I_Y \otimes H^0_Z, \tag{4b}$$

$$V = V_{XY} \otimes I_Z, \tag{4c}$$

$$W = I_X \otimes W_{YZ}, \tag{4d}$$

where I_X, I_Y, I_Z are the unit operators in the spaces of states for systems X, Y and Z, V_{XY} acts only in $X \otimes Y$, W_{YZ}—in $Y \otimes Z$. For eigenenergies of the nondisturbed Hamiltonians we shall use the denotations of the type E^i_S, where the symbol S is the index of system (X, Y, Z) and i is the index of state. Let's introduce also the nondisturbed total initial energy of the united system:

$$\mathscr{E}_0 = E^0_X + E^0_Y + E^0_Z$$

so that $H_0 |\Psi_0\rangle = \mathscr{E}_0 |\Psi_0\rangle$. Without the limitation of generality we shall suppose that

$$\langle \Psi_0 | V | \Psi_0 \rangle = 0, \qquad \langle \Psi_0 | W | \Psi_0 \rangle = 0. \tag{5}$$

Let's suppose that the state $|y_0 z_0\rangle$ is the eigenstate of the system $Y \otimes Z$. In our particular case this means, that the well localized $6p$-electrons of uranium are poorly mixed with the electrons of conductivity of matter by means of interaction W. On this reason $|y_0 z_0\rangle$ must be the eigenvector of the operator W_{YZ} with some eigenvalue w. But with Eq. (5) we get $w = 0$. Thus

$$(H_0 + W) |\Psi_0\rangle = \mathscr{E}_0 |\Psi_0\rangle. \tag{6}$$

The interaction V will be considered as usual as a small perturbation which causes the exponential decay of state $|x_0\rangle$. So it is possible to limit yourself by the first order of the perturbation theory with respect to V. On the contrary, it is impossible to consider the interaction W as a small perturbation, as it is obvious from Section II. Moreover, it will be necessary to use the formal limit of infinitely strong interaction W for regarding the QZP. By this reasons we couldn't use the low orders of perturbation theory with respect to operator W but must include it to our consideration by nonperturbative way. In agreement with this idea let's introduce the interact representation only with respect to V in which W is inserted to the nondisturbed Hamiltonian:

$$|\Psi_I(t)\rangle = e^{i(H^0 + W)t} |\Psi(t)\rangle,$$

$$V_I(t) = e^{i(H^0 + W)t} V e^{-i(H^0 + W)t}.$$

If we take into account the initial condition (3), then the time-dependent Schrödinger equation, which describes the evolution of united system $X \otimes Y \otimes Z$, may be represented in the form of integral equation

$$|\Psi_I(t)\rangle = |\Psi_0\rangle - i\int_0^t dt_1\, V_I(t_1)\, |\Psi_I(t_1)\rangle. \tag{7}$$

Let's find the amplitude of the transition $\langle \Psi_0 | \Psi(t)\rangle$. It is necessary to solve Eq. (7) in the second order of perturbation theory with respect to V to obtain this amplitude in the first nontrivial approximation. We easy obtain:

$$\langle \Psi_0 | \Psi(t)\rangle = e^{-i\mathscr{E}_0 t} F(t),$$

where

$$F(t) = 1 - \int_0^t dt_1 \int_0^{t_1} dt_2 \langle \Psi_0 |\, V_I(t_1)\, V_I(t_2)\, |\Psi_0\rangle. \tag{8}$$

The $F(t)$ function will be referred to as nondecay amplitude. In the derivation of Eq. (8) we have used the properties (5) and (6).

Eq. (8) describes the beginning area of decay curve in all details. Particularly, at the great enough times t it must give initial almost linear part of the exponential curve when

$$F(t) \simeq e^{-\gamma t} \simeq 1 - \gamma t. \tag{9}$$

Then, when we take the formal limit $t \to \infty$ and compare Eq. (8) and (9) we find the decay constant γ:

$$\gamma = \lim_{t \to \infty} \int_0^t dt_1 \langle \Psi_0 |\, V_{\mathrm{I}}(t)\, V_{\mathrm{I}}(t_1)\, |\Psi_0\rangle \tag{10}$$

and the probability of transition in the unit of time

$$\Gamma = 2\mathrm{Re}\, \gamma. \tag{11}$$

Eq. (10) may be easy transformed to the form

$$\gamma = \int_0^\infty Q(\tau)\, d\tau \tag{12}$$

where

$$Q(\tau) = e^{i\mathscr{E}_0 \tau} \langle \tilde{\Psi} |\, e^{-i(H_0 + W)\tau}\, |\tilde{\Psi}\rangle \tag{13}$$

and

$$|\tilde{\Psi}\rangle = V\,|\Psi_0\rangle.$$

Vector $|\tilde{\Psi}\rangle$ as the special object which plays the important role in the theory of radioactive decay was introduced in the work [26]. In this work was also noted, that it has the physical meaning as the system's state, that arises virtually just in the first moment of time after the system actually has accomplished the transition. Let's note, that this state is not normalized to unit although it has the finite norm. It is not difficult to see, that $|\tilde{\Psi}\rangle$ may be represented in the form

$$|\tilde{\Psi}\rangle = |x_1 \tilde{y} z_0\rangle, \tag{14}$$

where $|\tilde{y}\rangle$ is some wave packet in the continuous spectrum of the system Y. After the substitution of the expressions (4b), (4d) and (14) to the Eq. (13) we find

$$Q(\tau) = e^{i(\mathscr{E}_0 - E_X^1)\tau} \langle \tilde{y} z_0 |\, e^{-i(H_{YZ}^0 + W_{YZ})\tau}\, |\tilde{y} z_0\rangle. \tag{15}$$

It is convenient to divide interaction W_{YZ} in two parts which are responsible for the elastic and for the inelastic scattering of conversion electron separately. One could do this purely formally by making the classification with respect to the sort of matrix elements of the operator W_{YZ}. Making the substitution

$$I_{YZ} = |y_0 z_0\rangle\langle y_0 z_0| + \int d\xi\, |y_\xi z_0\rangle\langle y_\xi z_0| + \int d\mu\, |y_0 z_\mu\rangle\langle y_0 z_\mu|$$

$$+ \int d\xi'\, d\mu'\, |y_{\xi'} z_{\mu'}\rangle\langle y_{\xi'} z_{\mu'}|$$

to the identity

$$W_{YZ} = I_{YZ} W_{YZ} I_{YZ}$$

we obtain the expansion

$$W_{YZ} = K_Y \otimes P_{z_0} + W^i_{YZ},$$

where

$$K_Y = \int d\xi'\, d\xi''\, |y_{\xi'}\rangle\langle y_{\xi'} z_0|\, W\, |y_{\xi''} z_0\rangle\langle y_{\xi''}|,$$

and the expression for the operator W^i_{YZ} is written out in the Appendix as it is too cumbersome. The term $K_Y \otimes P_{z_0}$ gives the usual elastic scattering of conversion electron on the ground state of the system Z, and the terms that describe miscellaneous inelastic processes are collected in the operator W^i_{YZ}.

Let's introduce the complete elastic Hamiltonian of the system $Y \otimes Z$ as following:

$$H^e_{YZ} = H^0_{YZ} + K_Y \otimes P_{z_0}.$$

Then, after the simple identical transformation, Eq. (15) may be written as

$$Q(\tau) = q(\tau)\, D_e(\tau) \tag{16}$$

where

$$q(\tau) = e^{iE^0_f \tau} \langle \tilde{y} |\, e^{-i(H^0_Y + K_Y)\tau}\, | \tilde{y} \rangle, \tag{17}$$

and

$$D_e(\tau) = \frac{\langle \tilde{y} z_0 |\, e^{-i(H^e_{YZ} + W^i_{YZ})\tau}\, | \tilde{y} z_0 \rangle}{\langle \tilde{y} z_0 |\, e^{-iH^e_{YZ}\tau}\, | \tilde{y} z_0 \rangle}. \tag{18}$$

The energy

$$E^0_f = E^0_Y + \omega$$

is the expected energy of conversion electron in agreement with the energy conservation law. The expression (12) for the decay constant γ now reads:

$$\gamma = \int_{\infty}^{\infty} q(\tau)\, D_e(\tau)\, d\tau. \tag{19}$$

New expression (19) is more convenient because all dependence of the decay constant of nucleus from inelastic processes (i.e. from detecting or measurement) are included into the term $D_e(\tau)$, and the term $q(\tau)$ describes the whole elastic (usual) part of the problem. Really, $D_e(t) \equiv 1$ if the inelastic scattering is absent, i.e. $W^i_{YZ} = 0$.

Let's suppose now, that the complete orthonormal system of eigenfunctions of the continues spectrum of operator $H^0_Y + K_Y$ has been found (this problem really was solved for the isomer of uranium implanted into the silver lattice in work [42]). Let's denote these functions as $|E, \alpha\rangle$ so that

$$(H^0_Y + K_Y)\, |E, \alpha\rangle = E\, |E, \alpha\rangle, \tag{20}$$

and α means all other quantum numbers of the state except the energy. The vector $|\tilde{y}\rangle$ (see Eq. (14)) may be represented in the form

$$|\tilde{y}\rangle = \int dE\, d\alpha\, |E, \alpha\rangle\, v(E, \alpha). \tag{21}$$

As it is easy to show, the coefficients of expansion $v(E, \alpha)$ are the matrix elements of the transition operator:

$$v(E, \alpha) = \langle x_1; E, \alpha | \; V_{XY} \, | x_0 y_0 \rangle. \tag{22}$$

After the substitution of Eq. (21) to (17) and taking into account (20) we find

$$q(\tau) = e^{-iE_f^0 \tau} \int M(E) \, e^{-iE\tau} \, dE, \tag{23}$$

where

$$M(E) = \int |v(E, \alpha)|^2 \, d\alpha. \tag{24}$$

The function $M(E)$ has the meaning of the square of module of the matrix element of transition with account of corresponding phase volume $\int d\alpha$. Substituting now Eq. (23) to (19) and changing the order of the integration we obtain

$$\gamma = \int M(E) \, \Phi(E \leftarrow E_f^0) \, dE, \tag{25}$$

where

$$\Phi(\varepsilon) = \int_0^\infty D_e(t) \, e^{-i\varepsilon t} \, dt.$$

Then, from Eq. (25) and (11) we get

$$\Gamma = 2\pi \int M(E) \, \Delta(E - E_f^0) \, dE \tag{26}$$

where

$$\Delta(\varepsilon) = \frac{1}{\pi} \operatorname{Re} \int_0^\infty D_e(t) \, e^{-i\varepsilon t} \, dt. \tag{27}$$

Eq. (26) gives the desired expression for the probability of radioactive decay per unit of time with subsequent either strong or weak inelastic scattering (or detecting) of the decay particles. Really, the inelastic interaction W_{YZ}^i participates in Eq. (18) and consequently in Eq. (26) for Γ by nonperturbative way.

IV. The Physical Meaning of the Functions $\Delta(\varepsilon)$ and $D_e(t)$

Equation (26) gives in principle all of the necessary information for investigation of influence of inelastic scattering of electrons to the probability of conversion

transition in nucleus. On this stage, however, a technical difficulty appears, which is connected with evaluations of the matrix element in the numerator in the r.h. of Eq. (18). The difficulty is that the interaction W^i_{YZ} is not small and it is necessary to summarize all orders of perturbation theory or use some direct nonperturbative methods to evaluate this matrix element. This work should be done in principle, however I don't follow this extreme program in present paper. Instead I shall try to show, that the problem permits the *qualitative* analysis based on *precise* expression (26) with some simple and natural *suppositions and experimental facts.* Let's begin the discussion with the clarification of the shape of functions $\Delta(\varepsilon)$ and $D_e(t)$ and its physical meaning. There are several independent ways to understand their nature.

A. *The Analogy of Inelastic Scattering with Relaxation of Atomic Shell*

In the Section III we have neglected of the relaxation of atomic shell, which rests in the excited state after emitting the conversion electron. It is not difficult to take into account this fact. With the same method as consideration of Section III one could show, that in the expressions (19) and (27) instead of the factor $D_e(t)$, which connected with decay of the final state of conversion electrons, the new factor appears

$$D(t) = D_e(t)\, D_h(t).$$

The factor $D_h(t)$ is connected with the decay of final exited state of atomic core, and it turns out the usual exponential amplitude of nondecay of this excitation:

$$D_h(t) = e^{-\nu t},$$

where ν is the decay constant of atomic excitation. We see, that the relaxation of exited state of the atom influences on the decay constant of nucleus just in the same way as the relaxation of the final state of conversion electron. As the $D_h(t)$ is the nondecay amplitude of the final state of atom, then, by analogy, $D_e(t)$ is some effective nondecay amplitude of the final state of conversion electron in continuum with respect to the inelastic scattering. If the inelastic scattering occurs sooner or later with probability of 100%, then it is reasonable to suppose, that the function $D_e(t)$ decreases from the initial value $D_e(0) = 1$ to $D_e(+\infty) = 0$ by analogy with behavior of the function $D_h(t)$. The function $\Delta(\varepsilon)$, as the real part of the Fourier image of $D_e(t)$ (27), has some bell-like shape with width about the invert decay time of the function $D_e(t)$. Yet it is not difficult to show, that the square under the contour of function $\Delta(\varepsilon)$ is always equal to one independently from the exact shape of the function $D_e(t)$:

$$\int_{-\infty}^{+\infty} \Delta(\varepsilon)\, d\varepsilon = 1. \tag{28}$$

Thus the $\Delta(\varepsilon)$ function has properties, which are inherent to a distribution of probability.

B. *Golden Rule, Uncertainty Relation, and the Shape of Function* $\Delta(\varepsilon)$

It's not difficult to see, that Eq. (26) is the generalization of the Fermi's Golden Rule for the case of unstable final state of decay. Really, if inelastic scattering of decay particles is absent, i.e. $W^i_{YZ}=0$, then, as it follows from Eq. (18), we get $D_c(t)\equiv 1$ and Eq. (27) gives $\Delta(\varepsilon)=\delta(\varepsilon)$, where $\delta(\varepsilon)$ is the Dirac's delta-function. In this case Eq. (26) transfers to

$$\Gamma|_{W^i_{YZ}=0}=2\pi\int M(E)\,\delta(E-E_f^0)\,dE=2\pi M(E_f^0) \tag{29}$$

which is the usual Golden Rule. In the expression (29) the delta-function expresses the law of energy conservation. For fulfillment of this law it is necessary to have an infinitely long existence of nondisturbed final state of decay. In the case of finite lifetime of the final state, the energy conservation law fulfills only with precision which not exceeds the one given by the uncertainty relation of time-energy. As the result of this the delta-function must spread to some bell-like distribution of finite width

$$S\sim 1/\tau_{eff} \tag{30}$$

where τ_{eff} is the averaged effective life time of the final states of decay. Just this the expression (26) gives. The function $\Delta(E-E_f^0)$ which appears under the integral, must describe the precise way of the delta-function spreading due to the uncertainty relation. Thus, the function $\Delta(\varepsilon)$ should be the distribution with the finite width S (30) and the unit square (28). From the other hand, as $D_c(t)$ connected with distribution $\Delta(\varepsilon)$ trough expression (27), so we could expect that $D_c(t)$ decreases during the characteristic time which is connected with S by Eq. (30) and may be interpreted as effective law of damping of the final states of decay.

C. *Suppression of EXAFS-Oscillations and the Shape of Distribution* $\Delta(\varepsilon)$

The third source of information about the shape of the distribution $\Delta(\varepsilon)$ is the experimentally observable phenomenon of damping of EXAFS-oscillations in X-ray photoabsorption spectra due to inelastic scattering of photoelectrons [52].

First of all let's note, that Eq. (26) obtained for the probability of conversion transition with subsequent inelastic scattering of conversion electrons describes also the cross-section of photoionization of atoms by X-ray quantum with subsequent inelastic scattering of photoelectrons. It is not difficult to convince in this having repeated for this case the considerations of Section III. So the character of influence of inelastic scattering of electrons to the cross-sections (that is the probabilities) of photoionization is quite the same, as the influence to probabilities of conversion. Thus all conclusions which could be obtained by any way for cross-sections of photoionization could be nearly exactly translated to the probabilities of conversion.

The phenomenon of EXAFS (Extended X-ray Absorption Fine Structure) [43] consists in that the dependence of the photoionization cross-section of some definite

atomic level from the energy of X-ray quantum is not monotonous above the threshold of ionization, but has the oscillatory behavior which usually appears from the threshold of photoionization up to energy of about some hundreds electron-Volts above it. The origin of this phenomenon (somewhat simplified) consists in the following. De'Brogl wave of the photoelectron approaches the adjacent atoms, reflexes elastically from them, returns to the central atom which participates in the process of photoionization and interferes there with itself, changing its amplitude. This leads to changing of the matrix elements $M(E)$ and through the Fermi's Golden Rule (29) leads to a changing of the cross-section of photoionization. As the phase of returning electron wave depends from the length of this wave and consequently from the energy of electron, so the value and the sign of interferentional effect for electrons with different energies will be different. The function $M(E)$ acquires an oscillatory behavior, and this is the cause of oscillations of cross-section. It is also well known, that the atoms of the first coordination sphere give the main contribution to the picture of oscillations.

It's not difficult to understand by what manner the inelastic scattering of electrons should influence to the picture of oscillations. If the electron on its way to neighboring atoms or on return way inelastically scatters, then the amplitude of the coherent returned wave diminishes, and interference pattern as the result will be dumped. As in metals the length of inelastic scattering of electrons are of order of distance between atoms, so it ought to expect that the degree of damping of oscillations is rather pronounced, of the order e^{-1}–e^{-2}. Really, the damping of the EXAFS is observed experimentally and has the expected order of magnitude [52].

On the other hand, the conclusion about damping of the EXAFS-oscillations must be a consequence of the exact general formula (26) when it applies to the description of photoionization cross-sections. In essence this formula must provide the smoothing of the oscillations in the behavior of matrix element $M(E)$. It is easy to see that this formula would can do that, if the distribution $\Delta(\varepsilon)$ had a bell-like form of type of Lorenz or Gauss contour with width comparable with the half of period of oscillations of function $M(E)$. Thus the result, which we have got higher by another way in items IV A and IV B is obtained now as the consequence of experimental facts.

D. *Estimation of Width of the Distribution $\Delta(\varepsilon)$ in the Case of Decay ^{235m}U in Metals*

Let's represent a simple semiclassical estimation for the width of the distribution $\Delta(\varepsilon)$ in the case of decay of uranium isomer in metals. Characteristic mean free inelastic pass of electrons with kinetic energy about 50 eV (that is energy of ^{235m}U conversion electrons) in metals is about $d \sim 3$ Å [47–49]. Let's adopt this value for conversion electrons mean free path and estimate the time of electron life before scattering as $\tau_{eff} = d/v$, where v is the classical speed of electron. Finally, if we suppose $S = h/\tau_{eff}$, where S is the width of distribution $\Delta(\varepsilon)$, then we get

$$S \sim 10 \text{ eV}. \tag{31}$$

This value of S is in a good agreement with the following experimental data.

The phenomenon quite analogous to EXAFS in the case of decay of ^{235m}U in silver was investigated theoretically in work [42] by Dobretsov. He had shown, that the function $M(E)$ have got an oscillatory behavior with respect to E and the amplitude of oscillations may be rather high—about 50% from the average value of M. The characteristic period of oscillations is around 20 eV near the energy of conversion electrons (~ 50 eV). These oscillations must strongly influence to the half-life time of isomer and especially to the spectrum of conversion electrons. At the same time the totality of experimental data of ^{235m}U decay tells that this effect by no means manifests itself. So for example, the intensities of peaks in the conversion spectra of uranium isomer oxides are in reasonable agreement with calculations, which did not take into account the EXAFS-like effects [53]. The magnitude of variations of decay constant [9–17] also has purely chemical scale. This tells that the interferentional effects in the decay of ^{235m}U seems to be damped very strong by some mechanisms in great majority of cases. Although it may be several mechanisms of damping EXAFS-like effect (let's mention for example, the thermal disordering) but the only inelastic scattering of conversion electrons is sufficient for explanation of observed picture. Really, the width of the distribution $\Delta(\varepsilon)$ given by Eq. (31) is enough for smoothing of the oscillations of $M(E)$ in accordance with Eq. (26) nearly to e times if oscillations have period ~ 20 eV. (Sine curve of period T smoothed by the Lorenz distribution with the width S at the half of height gives sine curve with the same period again but with amplitude suppressed by factor $\exp(-2S/T)$).

The values of S greater than 10 eV not contradicts to the experimental data and we shall see later (see Section VII) that there are some indications that S may be much greater. Here we note only, that the value $S \sim 10$ eV already is comparable with kinetic energy of conversion electrons $E_k \sim 50$ eV, that is another quantitative expression of high intensity of inelastic scattering of conversion electrons of ^{235m}U in metals in addition to the mentioned in the Section II.

E. *Dependence of Inelastic Scattering of Delay Products from the Degree of Space Locality of Decay Process*

Finally, let's note a wonderful fact connected with functions $D_e(t)$ and $\Delta(\varepsilon)$. As the length of free inelastic path and thus the time of life of electrons up to inelastic scattering depends from the energy of electrons [47–49, 54] so it would be expected that functions D_e and Δ, which describe the inelastic scattering of electrons in precise way, appear in the form $D_e(E_f^0, t)$ and $\Delta(E_f^0, \varepsilon)$ respectively. The direct dependence from the final energy of electrons E_f^0 would occur in these functions! But it is quite definite, that actually it is not so. It is easy to see, that these functions depend from the vector $|\tilde{y}\rangle$ (21), but the energy E_f^0 does not appear in Eq. (18) and (27).

The vector $|\tilde{y}\rangle$ is a wave packet in the basis of vectors $|E, \alpha\rangle$ with weights $v(E, \alpha)$. Usually the distribution $M(E)$, connected with coefficients $v(E, \alpha)$ by relation (24), has more or less sharp jump near the threshold energy, which corresponds, for example, to zero kinetic energy of conversion electrons, and then

rather slow falls down to zero when $E \to \infty$. The rate of the falling down is defined by space region in which the reaction (conversion, photoionization etc.) take place—the smaller the reaction region the slowly falling down. It is not difficult to understand why it is so in general. In the coordinate representation the matrix elements (22) is given by integral of overlapping of the function $|E, \alpha\rangle(\mathbf{r})$ with some other function, let's name it as $L(\mathbf{r})$, which is expressed through $|x_1\rangle$, $|x_0\rangle$, $|y_0\rangle$ and V_{XY}. The functions of continuous spectra $|E, \alpha\rangle(\mathbf{r})$ has some kind of oscillatory behavior with spatial frequency dependent from the energy E: the higher E, the higher frequency. At the same time the function $L(\mathbf{r})$ has a more or less regular behavior and tends to zero when $|\mathbf{r}| \to \infty$. This function determines the spatial region of the transition. The integral of overlapping of the functions $|E, \alpha\rangle(\mathbf{r})$ and $L(\mathbf{r})$ begin vanish when the effective wave length of $|E, \alpha\rangle(\mathbf{r})$ become notably less than spatial region of existence of the function $L(\mathbf{r})$. The less the spatial region of $L(\mathbf{r})$, the higher E when $M(E)$ begin vanish, and consequently the slowly the falling down of function $M(E)$.

In many interesting cases, as the decay of ^{235m}U, the characteristic width of the distribution $M(E)$ is many times grater, than energy of decay particles. As $M(E)$ is the energy form factor of the state $|\tilde{y}\rangle$, so this wave packet, which build in the continuous spectrum, is very wide in the sense of energy distribution. There are contributions of the states as with very low as with very high energy in it, and it contains no information about the energy of transition ω or about the expected final energy of electron E_f^0. As the form of the packet $|\tilde{y}\rangle$ essentially depends from the spatial characteristics of the initial decay process, so this dependence penetrates to functions D_e and Δ through equations (18) and (26). Thus we come to the non-expected (and in some sense paradoxical) conclusion that in such processes as internal conversion or photoionization those characteristics of the inelastic scattering of electrons, that expressed through functions D_e and Δ, depends not from the final energy of electrons, but from the degree of space locality of the transition. Thus, the nondecay amplitude $D_e(t)$ has not so simple meaning as, for example, the nondecay amplitude $D_h(t)$ for decay of an excitation in atomic shell or usual nondecay amplitude of a radioactive decay. The function $D_e(t)$ is not connected with any real lifetime of electron with any definite energy up to inelastic scattering, but this function collects deposits from electrons with all possible kinetic energies from zero to infinity with some definite weights.

V. Quantum Zeno Paradox as the Consequence of the General Formalism

Let's turn now to the analysis of possible observable effects in probability of radioactive decay connected with the inelastic scattering of decay products or in another words—with continuous measurement. One of this phenomena we have already investigated—this is the damping of interferentional deposit due to elastic scattering of electrons to the probability of conversion decay and to the cross-sections of photoionization. Let's show now, that in the limit of very strong scattering

(instantaneous reaction of detector on decay) *the same mechanism* leads to QZP. This result could be obtained on the basis of time representation with Eq. (19) or on the basis of energy representation with Eq. (26). Let's show both.

Let's consider at first the time integral (19). Let's denote the width of the distribution $M(E)$ as S_{Zeno}. As we have seen above (Section IV E), this quantity is determined by the space locality of the decay. This width is very large, but is finite. The $q(\tau)$ function in accordance with Eq. (23) is the Fourier image of $M(E)$ with the precision to an oscillatory factor with absolute value equal to one. Due to this reason $q(t)$ is the falling down (by absolute value) function with characteristic time of vanishing of order $\tau_{Zeno} \sim 1/S_{Zeno}$. If function $D_e(t)$ falls off withing time $\tau_{eff} \ll \tau_{Zeno}$, that signifies the limit of very-very fast reaction of media or detector to decay, then the integral (23) obviously tends to zero and we obtain $\gamma = 0$. This signifies that the decay is "frozen", i.e. QZP.

Let's get the same result by another way. Let's consider the energy integral (26). Let's go to the limit of instantaneous reaction of detector (scatterer) to decay. To get this we (purely formally) tend the effective time of scattering τ_{eff} to zero. Then the width S of distribution $\Delta(\varepsilon)$ in accordance with Eq. (30) tends to infinity. As the square under the contour of distribution Δ always is equal to one (28), then the integral of overlapping of function $M(E)$ with $\Delta(E - E_f^0)$ tends to zero, that gives $\Gamma = 0$ with Eq. (26). This is QZP again. It is obvious, that for essential damping of Γ it is necessary *in general* that $S \gg S_{Zeno}$, from which $\tau_{eff} \ll \tau_{Zeno}$ follows again.

Let's note, that the last mechanism is actually smoothing of function $M(E)$ in point E_f^0 by very wide distribution $\Delta(\varepsilon)$, so the origin of QZP is just the same, as damping of interferentional deposit to probability of conversion decay or photoionization cross-section (see Section IV C). Thus one can say, that damping of EXAFS oscillations due to inelastic scattering of photoelectrons is a special sort of QZE, which could appear, when the function $M(E)$ has an oscillatory behavior. This kind of QZE is not small in many cases and is known experimentally long ago.

So we come to QZP now not on the basis of phenomenological consideration connected with the collapse of wave function, but after solution of complete quantum problem for the system of "decaying nucleus + scatterer" or that is the same "decaying nucleus + detector". It is possible to extract some useful conclusions for the quantum theory of measurement from this. Firstly, we must confess that a surrounding conditions, in particular the fact of a passive continuous observation or even a presence of surrounding scattering media, gives some irreducible influence to the process of decay. Secondly, obviously there is a rational grain in qualitative consideration connected with vawe function collapse (Section II) which led to QZP, as soon as it led to right result in the limiting case. This directs one to idea, that there exist *anything* resembling the continuous type of wave function collapse. But the formalism which we obtained above does not give any simple way of generalization the idea of collapse with the purpose to introduce its spreading in the time or to take into account the finite time of reaction of detector to decay. So it's not quite clear, what connection exists between our exact formalism and wave function collapse. Moreover, the impression is formed that any simple phenomenological

approach to description of a continuous measurement is not possible. In the connection with this, let's note, that the possibility to describe the usual discrete instantaneous measurement only with the simple projection postulate, demanding no references on the internal structure of experimental device, seems to be quite nontrivial and requiring further comprehension.

In many works, where QZP is considered in connection with a radioactive decay, it is noted, that QZP is a consequence of the initial nonexponentiality of a radioactive decay curve, especially with the fact, that

$$\left.\frac{dF(t)}{dt}\right|_{t=0} = 0.$$

One could easy get this relation from Eq. (9). Let's briefly discuss this connection.

From Eq. (9) with making use of Eq. (16) we get

$$\frac{d}{dt}F(t) = -\int_0^t q(\tau)\, D_e(\tau)\, d\tau. \tag{32}$$

It is easy to see from (32), that the initial nonexponentiality is the consequence of the fact, that $q(t)$ falls down to zero only during a finite time interval. The initial nonexponentiality would not exist, if $q(t)$ had the shape, resembling the right half of the Dirac's δ-function. At the other hand, the same circumstance is the cause of appearance of QZP: it is seen from Eq. (12), that even infinitely fast falling down of the function $D_e(t)$ would not cause a freezing of decay, if $q(t)$ had a δ-like shape. As the function $|\tilde{y}\rangle$ describes the state of decay products which arises virtually just after the decay [26], so it follows from Eq. (17), that $q(t)$ describes the process of outgoing of decay products from the reaction region in the time aspect. As this process takes a finite time interval, so the function $q(t)$ falls down to zero during a finite time. The characteristic time interval, in which the function $q(t)$ falls down to zero, may be named as a duration of a quantum transition type of radioactive decay. The fact that this duration is finite, not infinitesimal, is a consequence of a finite size of a spatial region, in which the reaction occurs. Thus, on my opinion, it is more convenient to say, that both initial nonexponentiality of decay curve and QZP is a consequence of finite quantum transition duration or finite quantum transition spatial region, but not the QZP is a consequence of initial nonexponentiality. To say that QZP is a consequence of initial nonexponentiality of decay is excessive simplification. The physical meaning of QZP is consequently that quantum transition become impossible when the final states of decay are destroyed at the time, smaller than the duration of quantum transition or in the spatial region, smaller than spatial region of this transition. The duration of transition and connected with it spatial region of transition determines the characteristic time τ_{Zeno}, which leads to QZP appearance. Let's note, that this approach to determination of Zeno time scale is quite new, and notably different from the one, used in other works in this field, particularly in the seminal works [21, 22, 55]. The last, as it

known, was connected with the Crylov-Fock theorem and used deviations of energy form-factor of the initial state of decay from the purely pole form. This deviations usually are badly known and the determination of Zeno time scale by this way was difficult.

VI. Threshold Quantum Zeno Effects

The Zeno scale of time τ_{Zeno}, introduced in the preceding section, is very small as a consequence of large width of function $M(E)$. The effective time of scattering of the order of τ_{Zeno} probably is not achievable in any real decay system. But $\tau_{eff} \sim \tau_{Zeno}$ is only sufficient, not necessary condition to QZE appearance. Actually it is not required so hard regime of scattering of decay particles to obtain strong Zeno effect in many cases because of very often the expected final energy of decay product E_f^0 arranged in a special manner relative the function $M(E)$: namely, very close to its left margin in comparison with complete width S_{Zeno} of this function. Such case is realized in the conversion of ^{235}U, in the near-threshold region of photoeffect and in other reactions near the threshold. Let's denote the distance from the left margin of $M(E)$ to E_f^0 by E_k. In the case of conversion and photoionization this is simply the expected kinetic energy of electron. It follows from Eq. (26) that the noticeable perturbation of probability of transition takes place already in the case when the distribution $\Delta(E - E_f^0)$ comes behind the left margin of the distribution $M(E)$ by its left wing. It is sufficient for this, that the width S of the distribution $\Delta(\varepsilon)$ satisfies the condition $S \sim E_k \ll S_{Zeno}$. It is sufficient to have got the effective time of scattering only

$$\tau_{eff} \sim \tau_{thr} = 1/E_k \gg \tau_{Zeno}$$

for this. It is much more soft condition of scattering, than it is required for classical QZE. Thus two Zeno scales of time appears: hard Zeno scale, connected with the time τ_{Zeno} and soft or threshold Zeno scale, connected with the time τ_{thr}. The considered effect we shall name as threshold quantum Zeno effect (TQZE) of the first kind (TQZE1). As was shown before (Section IV) in the case of conversion of the ^{235m}U we have $S \gtrsim 10$ eV for width of distribution $\Delta(\varepsilon)$ and $E_k \sim 50$ eV. Thus $S \sim E_k$ and this decay is in the region of possible influence of TQZE1.

For the following analysis we suppose, that the function $M(E)$ has the shape of a simple finite jump from zero to some value M_0 at the threshold energy E_{thr} (which is zero of kinetic energy of conversion electron):

$$M(E) = \begin{cases} 0 & \text{if } E < E_{thr} \\ M_0 & \text{if } E \geqslant E_{thr} \end{cases} \tag{33}$$

The character of its behavior at energies $E \sim E_{thr} + S_{Zeno}$ will not be interesting for us as these energies are very high. The function $M(E)$ has nearly such shape in the

case of conversion of isolated free atom of ^{235m}U [4] and in many other cases. The exact shape of the left margin of function $M(E)$ is not important for the following considerations. Let's suppose now, that the distribution $\Delta(\varepsilon)$ is symmetric with respect to the point $\varepsilon = 0$ (actually this means that $D_e(t)$ is real). Then it is obvious from Eq. (26), that at no reasonable times of scattering τ_{eff} the probability of conversion could be damped by TQZE1 more than two times, and even this situation is realized only at $\tau_{eff} \ll \tau_{thr}$, that is a very hard condition of scattering. So the TQZE1 could not explain almost complete suppression of decay of uranium isomer in silver [19,20] although could lead to a visible perturbation of the decay rate (see Section VIII for more details).

There exists however a circumstance which could increase many times the influence of TQZE1. This circumstance is connected with the point, that the used higher supposition about the symmetry of distribution $\Delta(\varepsilon)$ could not be right: namely, the distribution $\Delta(\varepsilon)$ is shifted to the left side relative the point $\varepsilon = 0$ so that all non-zero part of this distribution disposes in the region of negative semi-axis of ε. Let's prove this.

Let's suppose that the value of E_f^0 is such that $E_f^0 < E_{thr}$. We may consider the nuclear conversion process for the atomic level with binding energy of electrons greater than energy of nuclear transition and so on. Obviously, this transition is strictly forbidden by the law of energy conservation. The kinetic energy of electron turns out negative or such transition would signify the exceeding of the final energy of the system over the initial energy. This situation will be kept up to $t \to \infty$, thus the uncertainty relation type of time-energy could not change this conclusion. At the other hand, if $\Delta(\varepsilon)$ does not equal to zero identically at all $\varepsilon > 0$, then the integral of overlapping (26) of $M(E)$ with $\Delta(E - E_f^0)$ may be positive for some E_f^0 which lower than E_{thr}, consequently the transition is not forbidden for this E_f^0. But this is impossible, and this contradiction proves that $\Delta(\varepsilon) \equiv 0$ at all $\varepsilon > 0$. Let's note, that it is very important for this reasoning, firstly, that the distribution $\Delta(\varepsilon)$ has no dependence from the final energy E_f^0 of electrons, that has been established in Section IV E, and secondly, that $|z_0\rangle$ is the lowest state of the system Z. The last condition is fulfilled as was mentioned in Section III. In the opposite case the lack of initial energy of nuclear transition or X-ray quantum may be compensated in future by the transition of system Z to lower states if this transition is realized rapidly enough, and higher arguments become wrong.

It is not difficult to image yourself the function $D_e(t)$ which would lead to distribution $\Delta(\varepsilon)$ with necessary properties. It is necessary for function $D_e(t)$ to have the shape essentially different from the exponential one and to have the multiplier, which effectively behaves itself as oscillatory term led to positive energy shift. For example, the function

$$D_e(t) = \frac{\sin \lambda t}{\lambda t} e^{-i\rho t}, \qquad \rho > \lambda > 0 \tag{34}$$

satisfies these requirements. This function $D_e(t)$ produces the distribution $\Delta(\varepsilon)$ with Π-like shape of width 2λ and shifted from the position $\varepsilon = 0$ to the leftside by the

quantity $\rho > \lambda$ and thus disposed completely in the region $\varepsilon < 0$. The example (34) is slightly artificial of course, it serves only as an illustration that the requirements to distribution Δ may be fulfilled. Actually the distribution $\Delta(\varepsilon)$ should be smooth. Yet one could expect that it has not only the left side shift, but it has asymmetry relative its maximum of such a form that its left wing may be stretched out and the right one may fall down sharply to fulfill the condition $\Delta(\varepsilon) = 0$ when $\varepsilon > 0$.

It is not difficult to understand now that the probability of transition may be highly suppressed or even may be just zero due to the left side shift of $\Delta(\varepsilon)$ even for the above-threshold energies $E_f^0 > E_{thr}$. The probability of decay is strongly suppressed when the main part of the distribution $\Delta(E - E_f^0)$ disposes at the left side from the threshold E_{thr}, where $M(E) \equiv 0$. This phenomenon we name as "threshold quantum Zeno effect of the second kind" (TQZE2). So, TQZE1 we connect with the finite width of the distribution $\Delta(\varepsilon)$ and TQZE2—with the shift of the same distribution to the left side. Certainly, the both effects always exist simultaneously and making difference between them has mainly the euristical meaning. In some cases the TQZE1 may predominate and in the other—TQZE2. But generally speaking the deposits of these effects impossible to distinguish well. Let's note finally, that both TQZE1 and TQZE2 are the special cases of smoothing of function $M(E)$ by distribution $\Delta(\varepsilon)$ in point E_f^0, thus they have just the same nature as usual QZP and damping of EXAFS-oscillation considered higher.

VII. The Near-Threshold Behavior of the Photoionization Cross-Sections

As it was mentioned above the Eq. (26) describes correctly not only the probability of inner nuclear conversion or other radioactive processes, but also the cross-sections of photoionization. Thus all of the effects which were discussed above will be inherent to photoionization as well. It follows from our discussion, that the TQZE are in essence some sort of the threshold effects, so the manifestation of these effects ought to find first of all in the near-threshold structure of photoabsorption spectra. Probably this would to be the best test of TQZE.

It is not difficult to understand what kind of the phenomena should be expected. Firstly, the edge of photoabsorption spectra must be spreaded out by the width of distribution $\Delta(\varepsilon)$ due to a convolution of function $M(E)$ with distribution $\Delta(\varepsilon)$ by Eq. (26); secondly, the whole spectrum should be shifted to the right side as the result of the left side shift of $\Delta(\varepsilon)$. In practice the shift and the width of Δ may be different for the different parts of species due to a non uniformity of their structure (the boundaries of grains and so on). This may cause the additional broadening of the edge. So it ought to find the broadening of the edges of absorption spectra that is not connected with the natural width of ionized atomic state and solid state effects connected with the band structure, EXAFS and so on. In agreement with the discussion of Section IV E a dependence of the shape of edge of absorption spectrum from the degree of locality of corresponding atomic shell (which coincides with the locality of photoionization transition) may be one of the most striking sign

of the searched phenomenon. It is most convenient to compare the thresholds of absorption spectra for K- and L_I-shells for the same element in the same media. The reasons of this consist in the next points. Firstly the near-threshold structures in such spectra are rather simple, secondly, they must be practically identical without taking into account the inelastic scattering of electrons, and thirdly, the locality of K- and L_I-shells are sharply different.

There are a few of needed experimental data in literature to one's regret. I know only one work [56] which gives the exhaustive information of required type and another two [57, 58], that contents also interesting data, but not so complete.

In the paper [56] the K- and L_I-edges of photoabsorption spectra of metallic silver were compared. This case naturally has also special interest with respect to the suppression of decay of ^{235m}U in silver [19, 20]. The shape of the K- and L_I-edges of absorption was found to be sharply different: although the positions of the main particularities of the EXAFS structure coincides as it was expected, but the contrast of this structure in the K-spectrum is considerable lower than in L_I one and the width of the K-edge is much greater than the width of L_I-edge. The width of the K-edge (from the foot to the top of the slope) is approximately equal to 120 eV as one could derive from data of [56], but the same value for the L_I-edge is only near 20 eV. The known additional factors of spreading of K-edge in comparison with L_I-edge are firstly, slightly greater natural width of the K-shell of silver (9 eV, [59]) than the width of the L_I-shell (7 eV, [59]) and secondly, lower apparatus resolution at the measurement of the K-edge (5 eV) in comparison with the measurement of L_I-edge (0.5 eV) [56]. Thus summarized additional factor of the spreading of the K-edge in comparison with L_I-edge is about 7 eV (in the sense of full width on the half of height of Lorenz contour), that evidently could not explain observed differences of width of K- and L_I-edges of absorption spectrum of silver. So we see, that there is some additional spreading of the K-edge of absorption spectra, which could not be connected with any known factors. At the same time K- and L_I-shells localities is sharply different. Let's suppose for simplified estimation that there is the same connection between the ionization energy E_i and radius r of orbit of electron for the hydrogen atom and for the K- and L_I-shells of silver. Then using the ionization energies $E_i(\mathrm{Ag}, K) = 25514$ eV and $E_i(\mathrm{Ag}, L_I) = 3806$ eV [60] we shall find $r(\mathrm{Ag}, K) = 0.025a_0$ and $r(\mathrm{Ag}, L_I) = 0.17a_0$, where a_0 is the Bohr's radius ($a_0 \approx 0.529$ Å). So we see, that the great differences in widths of K and L_I edges is correlated with the great differences of locality of respective atomic shells, that may be a TQZE manifestation as was mentioned higher. Also we have got an indication, that the increasing of degree of locality of transition has as a consequence the increasing of width of the distribution $A(\varepsilon)$.

In the work [57] the K-edges of absorption of silver and zinc in silver-zinc alloys are compared. The width of K-edge of zinc was not greater than 30 eV in all cases, but the width of K-edge of silver was between 70 and 120 eV. The difference of the widths between K-edges of silver and zinc may be connected with the different locality of corresponding K-orbits again: $r(\mathrm{Zn}, K) = 0.042a_0$ as compared with $0.025a_0$ for silver. Thus we have the same type of correlation as in work [56].

Especially wonderful result one could find in work [58], where the K-edge of absorption of metallic cadmium was measured. Here the full width of K-edge of absorption is grater than 200 eV. The value 200 eV is so great, that it is possible to attempt to extract the shape of distribution $\Delta(\varepsilon)$ from this spectrum without notable mistake supposing that initial spectrum of absorption without spreading due to convolution with distribution $\Delta(\varepsilon)$ is simply the rectangular step. It is sufficient to differentiate the spectrum of K edge and then invert it relative to the ordinate axis. The result is a very asymmetric peak with the width about 110 eV with stretched left wing and sharply falling down right one. So, we have an indication, that actually $\Delta(\varepsilon)$ function may be very wide in some cases.

The interpretation of mentioned higher experimental data is not unique perhaps, but an alternative explanation of them is not known for me now. So we shall suppose that this phenomena indicates the possible order of magnitude of the values, which may be inherent to TQZE in metals, particularly the width of the $\Delta(\varepsilon)$-distribution may achieve the values of 50–100 eV.

VIII. Threshold Quantum Zeno Effect in the Decay of ^{235m}U

Let's make now the estimations of the value of TQZE for the decay of the uranium isomer in metals. We shall proceed from two extreme possibilities due to a great uncertainty of the possible estimations. The first possibility will be referred to as the minimal scenario, the second—as optimistic scenario.

For the minimal scenario we shall use the estimates of width of distribution $\Delta(\varepsilon)$ which was 10 eV (Section IV D). Let's suppose, that at least left wing of the distribution Δ has the shape which is near to the Lorenz one and that it is shifted to the left side from the central point $\varepsilon = 0$ to one width on the half of height of $\Delta(\varepsilon)$, that is to 10 eV. Shift to one width is the minimal demand, which is compatible with more or less reasonable character of the falling down of the right wing of Δ and with the condition $\Delta(\varepsilon) = 0$ at all $\varepsilon > 0$. Actually this shift may be grater. Supposing that the function $M(E)$ has the shape of rectangular step (33) with Eq. (26) we find

$$\Gamma = \left(\frac{1}{2} + \frac{1}{\pi} \arctan \frac{E_k - \rho}{S/2}\right) \Gamma_0. \tag{35}$$

where ρ is the shift of $\Delta(\varepsilon)$ to the left side, E_k is the characteristic kinetic energy of the conversion electrons, S is the width at the half of height of distribution $\Delta(\varepsilon)$ and $\Gamma_0 = 2\pi M_0$ is the probability of conversion without the inelastic scattering. With the values $\rho = 10$ eV, $E_k = 50$ eV and $S = 10$ eV we find from (35)

$$\Gamma = 0.96\, \Gamma_0.$$

We see, that within the minimal scenario the suppression of the decay constant of the ^{235m}U is about 4%, that is not great, but is not negligible. Let's note, that here we have nearly pure TQZE1-effect.

In the optimistic scenario let's use the analogy of the process of conversion and photoionization, and let's suppose, that the estimates of scale of values for TQZE, which were obtained from the analysis of photoabsorption spectra in Section VII, are applicable to the conversion as well. But it is necessary to be careful and use such photoionization data, which connected with photoionization processes with space locality comparable with the locality of the $E3$-transition in the atom of uranium isomer. The locality of the conversion of ^{235m}U was investigated in the works [4, 61]. The most complete data are in the work [61]. It follows from this work, that 70% of probability of conversion for U$6p_{1/2}$-electrons is collected inside the sphere with radius $r = 0.019a_0$ with the center at the uranium nucleus. Thus the value $r \approx 0.02a_0$ may be used as the scale of space locality for the conversion of $E3$-transition in uranium-235. The radius of the K-orbit of cadmium is about $0.024a_0$, that is turned out close to the locality of transition in ^{235m}U. So let's suppose, that it is possible to use the distribution $\Delta(\varepsilon)$ conforming to spreading of K-edge of photoabsorption spectra of cadmium (Section VII) to get a rough estimate of the order of magnitude for TQZE in conversion of uranium. Let's choose the simple step as the shape of $M(E)$ margin, Lorenz function as the shape of the distribution $\Delta(\varepsilon)$ and one width left shift for it. With the kinetic energy of the conversion electrons of ^{235m}U about 50 eV and with width of distribution Δ of 100 eV which is in agreement with the spreading of K-edge of absorption spectrum in cadmium (see Section VII) from Eq. (35) we get

$$\Gamma \approx 0.25\, \Gamma_0. \tag{36}$$

This estimate is already in reasonable agreement with the scale of value of the effect of suppression of decay in silver [19, 20]. Let's note, that in the case of optimistic scenario the estimate type of (36) has got a strong dependence from the shape of the right wing of $\Delta(\varepsilon)$ distribution. For example, if we suppose, that the right wing has not the Lorenz but the Gauss-like shape, then we get the estimate $\Gamma \approx 0.12\, \Gamma_0$ for the same $S = 100$ eV, and we may get in principle just zero value for Γ, if the right wing of Δ falls down sufficiently sharply. The estimate (36) demonstrates only, that the suppression of Γ with TQZE may be very strong if S is about 100 eV as it has been derived from the photoabsorption data. Let's note, that in the optimistic scenario we have nearly pure TQZE2-effect.

Thus we have found, that the expected degree of suppression of decay constant of uranium isomer by mechanism of TQZE may be in interval from few percents to several (or even many) times. These estimates certainly show that we have an interesting object for further more careful investigations.

Now let's discuss two technical but difficult questions. Why in the observations of the uranium isomer decay from the surfaces [9–17] the decay constant demonstrates rather high stability, but at the same time the implantation to the

high deep in the silver leads to strong suppression of decay and no intermediate cases are observed? Why the nearly pure exponential decay curves is observed for uranium isomer disposed on surfaces? It would be expected, that such decay curves should demonstrate non exponential behavior, connected with a smooth decreasing of the decay constant from high values on the surface to low values in the bulk.

The general reason for the difference of the decay constant on the surface and in the bulk of the samples connects with the point, that the surrounding condition of isomer near the surface may distinguish strongly from the one in the bulk. This may lead to strong difference of characteristics of scattering of the conversion electrons and, consequently, to difference in the degree of TQZE effects. The dependence of the degree of suppression of decay from the intensity of inelastic scattering of electrons may have a nearly threshold character. If the width S of the distribution $\Delta(\varepsilon)$ and the left side shift of this distribution is small in comparison with kinetic energy of electrons, then the maximum of distribution $\Delta(E-E_f^0)$ is placed at the right side from E_{thr}. Even relative great changes of S leads only to small changes of Γ in this case. If S and the left side shift reaches such values, that maximum of $\Delta(E-E_f^0)$ is placed in the region near the E_{thr}, then even small changes of S (or left side shift) leads to great changes of Γ. And at the last, if S and the left side shift are such, that the maximum of $\Delta(E-E_f^0)$ is placed noticeable at the left side from E_{thr}, then the decay already is almost completely suppressed and further changing of S does not lead to strong absolute changing of Γ. Let's name this three regions of changing of S as over threshold (S is small), threshold (maximum of $\Delta(E-E_f^0)$ near E_{thr}) and subthreshold (S is great). If the state of the isomer near the surface is in the over threshold region, then even noticeable changes of the state of the surface will not lead to noticeable changes of Γ although may lead to relatively strong changes of S. If the isomer is placed deeper and deeper in the sample then the condition of scattering changes, but due to the threshold-like dependence of Γ from S the isomer atoms may very rapidly transit from the over threshold to subthreshold state with very strong suppression of decay and it will be only a few of atoms in intermediate states with intermediate values of Γ. Thus we may have in practice only two components in decay curve: rather fast with half-life time about 26 min and very slow with half-life time about hours and more.

It will be difficult to detect the conversion electrons from atoms of isomer with highly suppressed decay constant: firstly, such electrons are related with atoms, placed deeply in species and they must penetrate a thick layer of substance to reach the detector, so the probability of their outgoing is small; secondly, their counting rate, being proportional to the decay constant, is small as the decay constant is small; and thirdly, the corresponding component of decay curve is very sloping and its amplitude very slowly varies during the time of measurement (1–2 hours). So the deposit from the highly suppressed decay may be perceived as small addition to the constant detector's background. Thus the decay curve from surface of species will be looked as a single-component and the results of measurements [9–17] possibly depends only from surface states of isomers with probability of decay only weakly perturbed by inelastic scattering of electrons. The high stability of these results may be connected with this fact.

So we see, that model of threshold quantum Zeno effect, introduced in Section VI, may in principle explain the high suppression of the decay of uranium-235 isomer in silver and does not contradict another experimental data.

IX. Differences from Other Theories

In the previous sections I argued, that QZE may be some times very strong in the case of usual radioactive decay. This conclusion is in contradiction with some papers, where authors more or less categorically proclaim, that QZE in radioactive decay could be either very small, or even nondetectable in principle. Let's briefly consider the origin of this contradiction.

Let's mention at first two papers [30, 28] which represent this point of view. This papers were based on ideas, proposed in seminal works [21, 22, 55]. Situation as travelling an unstable particle in bubble chamber with successive collisions of particle with atoms of media, not the passive continuous observation with making use of switched on counter, was treated in all these works. The model of stochastically distributed or periodic wave function collapse was used to describe interactions of unstable particle with media. In this model the duration of the beginning "Gaussian" region of decay curve plays the crucial role. The duration of this time region coincides with τ_{Zeno}, introduced in present paper in Section V. The middle time between successive collapses should be comparable with τ_{Zeno} to get a notable QZE. In the cited papers [30, 28] some arguments, connected mainly with uncertainty relations, was proposed, that such collapses could not be sufficiently frequent, thus QZE could not occur in radioactive decay. But we have seen in Section II and V, that the model of successive collapses of wave function is not proper for the case of continuous passive observations of decay. Thus all arguments of papers [21, 22, 55, 30, 28] are misleading in this situation. And reverse, the consideration of present paper is not applicable in the context of works [21, 22, 55, 30, 28]. So, there is no a contradiction between these works and present one.

Another situation takes place with paper of Kraus [31]. The point of view, that QZE could not occur in the case of radioactive decay also was argued in this work, and the model which is very close to the continuous passive observation of radioactive decay was treated in it. This conclusion was originated, on my opinion, partly due to a very schematic model of detection, while in the present work rather realistic model was developed.

And finally, the great difference between the near-threshold radioactive decay and the far from threshold one, that plays the crucial role in the present paper, was completely ignored in all works [30, 28, 31, 21, 22]. The conclusion, that QZE may be rather strong in the case of near-threshold decays and the special role of near-thresholds decays in QZE may be derived in principle from the consideration of paper [55], but the authors don't pay attention to this special case. But the only taking into consideration of the special role of near-threshold decays permits us to make conclusion, that QZE could be very strong in radioactive decay. This is the main difference of the present investigation from the previous ones.

X. Conclusions

In the present work the model that gives a successive dynamical quantum description of the radioactive decay process with the inelastic scattering of the decay particles or, in alternative formulation—the model of continuous passive observation of decay was created. It was demonstrated with this model, that there is some irreducible influence of continuous observation or simply presence of a surrounded matter to decay process. In particularly, in the case of very fast detector or very strong scatterer the classical quantum Zeno paradox is reproduced, and two new Zeno-like effects are predicted—the threshold quantum Zeno effects of kind one and two. The most noticeable and very nontrivial result of this model is on my opinion the independence of the distribution $\Delta(\varepsilon)$ and the effective amplitude of decay of the final states $D_e(t)$ from the final (or expected) energy of decay products. This is the key point for possibility of high suppression of the decay probability by the quantum Zeno effect mechanisms with rather soft external conditions. In connection with the crucial role of the functions $D_e(t)$ and $\Delta(\varepsilon)$ it is very important to try to evaluate their exact form starting from the "first principles" in some cases.

The threshold quantum Zeno effects not only could be responsible for the observed deep suppression of uranium-235 isomer decay when it is implanted into the matrix of silver [19, 20], but also predicts some new phenomena which could be observed in the structure of the edges of photoabsorption spectra. Some known experimental data [56–58] perhaps actually indicates this phenomena. Let's note, that the experimental evidence of TQZE is far from completeness now, and only the possibility of TQZE manifestation in some definite cases is established in this paper. The suppression of uranium-235 isomer decay in silver lattice may be the first experimental manifestation of quantum Zeno effect in radioactive decay. For the further clarification of the situation a theoretical and experimental investigations in a set of directions are needed.

Appendix: The Inelastic Scattering Operator

The inelastic scattering operator, introduced in Section III, reads:

$$W^i_{YZ} = (A + A^+) + (B + B^+) + (C + C^+) + D \tag{A1}$$

where

$$A = \int d\xi \, d\mu \, |y_0 z_\mu\rangle\langle y_0 z_\mu| \, W_{YZ} \, |y_\xi z_0\rangle\langle y_\xi z_0|,$$

$$B = \int d\xi' \, d\xi'' \, d\mu \, |y_{\xi'} z_\mu\rangle\langle y_{\xi'} z_\mu| \, W_{YZ} \, |y_{\xi''} z_0\rangle\langle y_{\xi''} z_0|,$$

$$C = \int d\xi\, d\mu'\, d\mu''\, |y_0 z_{\mu'}\rangle\langle y_0 z_{\mu'}|\, W_{YZ}\, |y_\xi z_{\mu''}\rangle\langle y_\xi z_{\mu''}|,$$

$$D = \int d\xi'\, d\xi''\, d\mu'\, d\mu''\, |y_{\xi'} z_{\mu'}\rangle\langle y_{\xi'} z_{\mu'}|\, W_{YZ}\, |y_{\xi''} z_{\mu''}\rangle\langle y_{\xi''} z_{\mu''}|.$$

The different terms in the expression (A1) describe the different sorts of inelastic scattering processes. So, the term $(A + A^+)$ describes the process type of "simple electron bridge" when exited electron Y transfers its energy to ground state of system Z and excites it, but returns to ground state $|y_0\rangle$, and reverse process; the term $(B + B^+)$ describes the usual inelastic scattering of the exited electron $|y_{\xi''}\rangle$ on the ground state of system Z when the system Z excites to state $|z_\mu\rangle$ and the electron transits to the state $|y_{\xi'}\rangle$, and reverse process; the term $(C + C^+)$ describes the process type of "electron bridge", but scattering takes place on exited state $|z_{\mu''}\rangle$ of system Z, and reverse process; the term D describes the general case of inelastic scattering in continuous spectra, in this case the direct process coincides with the reverse one.

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