THE MECHANISM OF SUPPRESSION OF QUANTUM TRANSITIONS (QUANTUM WHIRLIGIG)

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The mechanism allowing to stabilize of a state of quantum systems is considered. And, the initial condition can correspond both for excited state and for not excited, stationary state. The considered mechanism for the first time was offered for the excited states, and has received the name as quantum whirligig (QWE). In this work the close connection of the considered mechanism with Zeno effect is shown. The considerations are stated, that many experimental results, which are interpreted as observation of Zeno effect, apparently, correspond to QWE.

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1. INTRODUCTION

The name of effect "Quantum Zeno effect" (QZE) for the first time has appeared in the work of George Sudarshan and Baidyanat Missra [1] in 1977. In this work they have shown, that if to spend often, better continuously observation at excited (unstable) quantum systems, such unstable systems can be saved indefinitely long time. This name has appeared so successful, that despite of that fact, that as it has appeared later, the similar physical phenomena in the quantum mechanics were considered earlier by many other authors (see, for example, such works: Alan Turing [2], John von Neumann [3], Degasperis at all [4] and others) the QZE now is strongly connected to names Sudarshan and Missra.

The mechanism of suppression of quantum transitions considered in the present work is similar to QZE. Therefore, to see clearly the difference between of the offered mechanism and QZE, we shall briefly describe this mechanism. Let we have a two-level quantum system. The zero level is corresponds to the stationary, not excited state. The first level is corresponds to the excited state. Let now under action of resonant perturbation the considered quantum system passes from a zero level to first and back. As it is known, such process is described by the following simple system of the differential equations:

$$i\cdot\hbar\cdot\dot{A}_0 = V_{01}A_1;\quad i\cdot\hbar\cdot\dot{A}_1 = V_{10}A_0, \qquad (1)$$

where A_i – complex amplitudes of wave functions.

We shall consider that matrix elements of interaction are equal, constant and real. Let at the initial moment of time the quantum system finds in the excited condition. Then the solutions of the equations (1) will be functions:

$$A_1 = \cos(\Omega\cdot t),\quad A_0 = \sin(\Omega\cdot t), \qquad (2)$$

where $\Omega = V/\hbar$ – Rabi frequency.

It is convenient for further all interval of time $T = 2\pi/\Omega$ to break on small time intervals $\Delta t = T/n$. Now we shall enter a new element – measurement of a state of investigated system. Let at the moment of time Δt we somehow can estimate a situation of our system. The probability of that fact that she during the time Δt will not pass from the excited state to the basic state will be equal:

$$w(\Delta t) = 1-(\Omega\cdot\Delta t)^2. \qquad (3)$$

This result in the theory of QZE is named as nonexponential law of disintegration (see, for example, [8]). After expiration of the following interval of time we again include process of measurement. The probability of detection of the originally excited system in the initial state will determined by formula:

$$w(2\cdot\Delta t) = \left(1-(\Omega\cdot\Delta t)^2\right)^2. \qquad (4)$$

Such formula reflects the fact of independence of quantum transitions in each interval of time. At the end, after the large number of measurements the probability of a presence of system in the excited state will be expressed by the formula:

$$w(n\cdot\Delta t) = \left(1-(\Omega\cdot\Delta t)^2\right)^n. \qquad (5)$$

Within the limits of a large number of the measurements during the period of time T, the probability of detection of system in its initial excited state approach to unit:

$$w(T) = \exp\left(-\Omega^2T^2/n\right)\xrightarrow[n\to\infty]{} 1. \qquad (6)$$

This fact makes the contents of QZE.

Now it is easy to explain the basic contents of the work. It consists in the following:

1 - we refuse procedure of measurement;

2 - we take into consideration some third level;

3 - we enter stabilizing external perturbation which frequency is resonant for transitions between one of the basic levels and additional level (see Fig.1). Will be shown, that the Rabi frequency of transitions, called by stabilizing perturbation, will be higher, the probability of transition of system from the initial state will be smaller.

2. STATEMENT OF A TASK AND BASIC EQUATIONS

Let's consider quantum system, which is described by Hamiltonian:

$$\hat{H} = \hat{H}_0 + \hat{H}_1(t). \qquad (7)$$

Second summand in the right part describes perturbation. The wave function of system (7) satisfies Schrödinger equation which solution we shall search as a row of own functions of the not perturbed system:

$$\psi(t) = \sum_n A_n(t)\cdot\varphi_n\cdot\exp(i\omega_n t), \qquad (8)$$

where $\omega_n = E_n/\hbar$; $\quad i\hbar\frac{\partial\varphi_n}{\partial t} = \hat{H}_0\varphi_n = E_n\cdot\varphi_n$.

Let's substitute (8) in the equation Shrodinger and by usual way we shall get system of the connected equations for a finding of complex amplitudes:

$$i\hbar \cdot \dot{A}_n = \sum_m U_{nm}(t) \cdot A_m \,, \qquad (9)$$

where $U_{nm} = \int \varphi_m^* \cdot \hat{H}_1(t) \cdot \varphi_n \cdot \exp[i \cdot t \cdot (E_n - E_m)/\hbar] \cdot dq$.

Let's consider the most simple case – the case of garmonic perturbation

$$\hat{H}_1(t) = \hat{U}_0 \exp(i\omega_0 t) + \hat{U}_1 \exp(i\omega_1 t).$$

Then the matrix elements of interaction get the following expression:

$$U_{nm} = V_{nm} \exp\{i \cdot t \cdot [(E_n - E_m)/\hbar + \Omega]\},$$

$$V^{(k)}{}_{nm} = \int \varphi_n^* \cdot \hat{U}_k \cdot \varphi_m dq \,, \quad \Omega = \{\omega_0, \omega_1\} \qquad (10)$$

Let's consider dynamics of three-level system ($|0\rangle, |1\rangle, |2\rangle$). Let's take into consideration that frequency of external perturbation and the own meanings of energy of these levels satisfy to such relations:

$$m = 1,\ n = 0\,,\ \hbar\omega_0 = E_1 - E_0\,;\ m = 2,\ n = 0\,;$$

$$\hbar(\omega_0 + \delta) = E_2 - E_0\,,\quad |\delta| << \omega_0\,;$$

$$\hbar\omega_1 = E_2 - E_1\,,\quad |\delta| \sim \omega_1\,. \qquad (11)$$

These relations point out that fact, that the frequency ω_0 of external perturbation is resonant for transitions between zero and first levels, and the frequency ω_1 is resonant for transitions between the first and second levels. Using these relations in system (9), it is possible to be limited by three equations:

$$i \cdot \hbar \cdot \dot{A}_0 = V_{01} A_1 + V_{02} A_2 \cdot \exp(i \cdot \delta \cdot t)\,;$$

$$i \cdot \hbar \cdot \dot{A}_1 = V_{10} A_0 + V_{12} A_2\,;$$

$$i \cdot \hbar \cdot \dot{A}_2 = V_{21} A_1 + V_{20} A_0 \cdot \exp(-i \cdot \delta \cdot t)\,. \qquad (12)$$

The system of the equations (12) is that system, which we shall analyze. The scheme of energy levels for system (12) is represented in Fig.1.

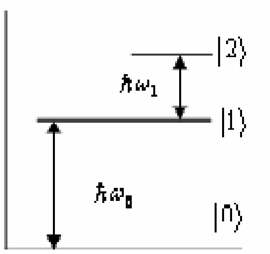

Fig.1. Energy levels.
ω_1 – the frequency of stabilizing perturbation

3. SOLUTIONS OF SYSTEM (12)

Let's consider, first of all, the case, when detuning is large enough. In this case it is possible to neglect those members in system (12), which contain this detuning. Besides we shall consider that the matrix elements of direct and return transitions are equal ($V_{12} = V_{21}$, $V_{10} = V_{01}$). Let's consider also, that the matrix elements of transitions between the first and second levels are much more, than matrix elements of transitions between zero and first levels ($V_{12}/V_{10} \equiv \mu >> 1$). It is convenient to enter dimensionless time $\tau = V_{10} \cdot t/\hbar$. In view of these reasons the system of the equations (12) becomes elementary simple:

$$i\dot{A}_0 = A_1\,,\ i\dot{A}_1 = A_0 + \mu A_2\,,\ i\dot{A}_2 = \mu A_1\,. \qquad (13)$$

Let at the initial moment of time ($t = 0$) the considered quantum system is on first, excited level. Then, as it is easy to see, the solution of system (13) will be functions:

$$A_0 = \frac{1}{i \cdot \mu} \sin(\mu \cdot t)\,, A_1 = \cos(\mu \cdot t)\,, A_2 = -i \sin(\mu \cdot t)\,. (14)$$

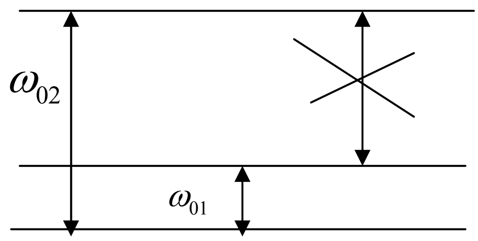

Fig.2. Energy levels of Be ions

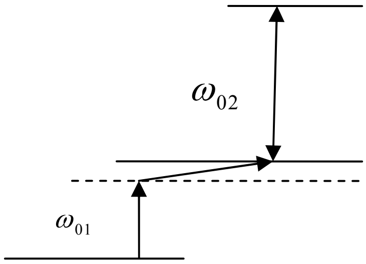

Fig.3. Energy levels of atoms rubidium

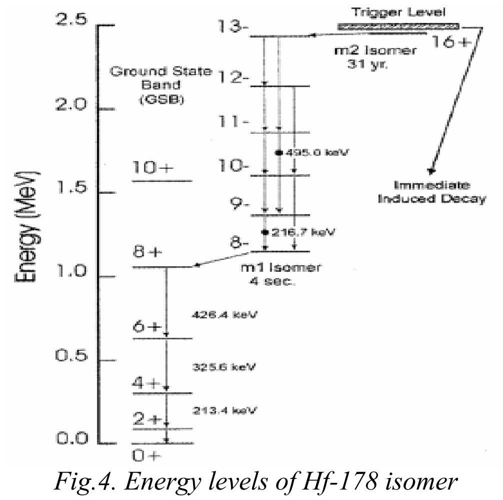

Fig.4. Energy levels of Hf-178 isomer

From the solution (14) follows, that than the large parameter μ, the less will be probability that the system from the excited state will pass in nonexcited, stationary state. It is necessary to say some words about parameter μ. Physically this parameter defines the ratio of number of quanta of low-frequency perturbation which is responsible for transitions between the first and second levels to number of quanta of high-frequency perturbation, which determines transitions between the first and zero levels.

The accounting of influence of the members containing detuning can be made by numerical methods. Such analysis was carried out. He has shown that presence even enough large detuning only slightly influences on result. And, the more value of parameter μ, the smaller appears this influence.

Above we have considered quantum system, which is in the excited state and on which the external stabilizing perturbation acts. It is interesting to consider other physical situation, when considered quantum system at the initial moment of time is at a zero stationary level. Under influence of external perturbation on resonant frequency ω_0 the examined quantum system can pass to the first excited level. There is a question: whether can the external additional perturbation on resonant frequency for transitions from the first level on second suppress transitions from the zero level on the first level? Let's show, that really such opportunity is realized. Let's note, that in this case we act on quantum system by perturbation, which is not resonant for an initial state of quantum system. Moreover, on the first sight the considered quantum system should not feel this perturbation. The paradox consists that such seems neutral perturbation can considerably change property of considered quantum system. This change consists that she becomes practically tolerant to external resonant perturbation. She doesn't feel it. The system of the equations, which describes the given physical situation, coincides with system of the equations (13). The difference consists only that in this case we should change initial conditions. At the initial moment of time the considered system is at a zero stationary level. For the solution of system (13) it is convenient to pass to new variables:

$$A_0 = x_0 + ix_2 ;\ A_1 = x_1 + ix_3 ;\ \ A_2 = x_4 + ix_5 .$$

Let's note, that the system (13) has following integral:

$$\sum_{k=0}^{2} |A_k|^2 = \sum_{k=0}^{5} x_k^2 = 1 . \qquad (15)$$

Integral (15) corresponds to usual normalization of wave functions. Now we should solve system (13) with the following initial conditions: $x_0(0) = 1$; $x_i(0) = 0,\ i > 0$. It is easy enough to show, that the examined system at these initial conditions has the following solution:

$$x_0 = 1 + \frac{1}{\Omega^2}\left(1 - \cos(\Omega \cdot t)\right);\ x_1 = x_2 = x_5 = 0 ;$$

$$x_3 = -\frac{1}{\Omega}\sin(\Omega \cdot t);\ x_4 = \frac{\mu}{\Omega^2}\left(1 - \cos(\Omega \cdot t)\right), \qquad (16)$$

where $\Omega = \sqrt{1 + \mu^2}$.

From the solution (16) follows, that if parameter μ is great enough, the probability to pass into excited state will be small. Thus, by selection of frequency and intensity of external perturbation it is possible to forbid quantum transitions. This inhibition is true as for the excited states, and for basic stationary states.

4. SOME GENERALIZATIONS

Above we have considered general enough quantum systems. However they were limited by induced transitions. In many cases the determining role are played the spontaneous transitions. To generalize the received results on this case it is possible by make using the Fok-Krilov theorem [9]. This theorem can be formulated as follows: the probability to save to quantum system in her initial state ($L(t)$) is equal to a square of the module of characteristic function:

$$L(t) = |p(t)|^2 , \qquad (17)$$

where $p(t) = \int w(E) \cdot \exp(-i \cdot E \cdot t / \hbar) \cdot dE$; $w(E)$ – differential function of distribution of an initial state. At this, the value $w(E) \cdot dE$ defines a spectrum of energy of an initial state. The formula (17) allows to get the important enough information about quantum system, taking into account only some properties of function $w(E)$. So, for example, let the all her special features in a complex plane E represents only by poles (meromoephic function) and let these poles are situated in points $E = E_n \pm i\Gamma_n$. In this case characteristic function will represent the sum of residuals on these poles. At the large enough time the basic role will be played only the pole, which will have minimal imaginary part. In this case expression for characteristic function gets a kind:

$$p(t) \approx \exp\left[-(i \cdot E \cdot t)/\hbar - (\Gamma_{\min} \cdot t)/\hbar\right], \qquad (18)$$

and the probability for system at the moment of time t (($\Gamma_{\min} \cdot t$)>>1) remain in an initial state to be defined by the well known law of exponential disintegration: $L \sim \exp(-\Gamma_{\min} \cdot t / \hbar) \cdot$

The law of disintegration essentially varies on small intervals of time (t<<1). To show it it is convenient to enter centered characteristic function:

$$p_1(t) = p(t) \cdot \exp(i \cdot E_0 \cdot t / \hbar) = \int \exp[i \cdot \Delta E \cdot t / \hbar] w(E) \cdot dE , \qquad (19)$$

where $\Delta E = E_0 - E$; E_0 – average meaning of energy of system at the initial moment of time.

At small intervals of time the expression (19) can be decomposed into a Taylor line. At this, take into account meaning of functions and its derivative at the initial moment of time:

$$p_1(0) = 1,\ p_1'(0) = 0, p_1''(0) = \left\langle \left((\Delta E \cdot t)/\hbar \right)^2 \right\rangle ,$$

we turn out the following expression for probability of a finding system in an initial state:

$$L \approx \left[1 - \left\langle \left((\Delta E \cdot t)/\hbar \right)^2 \right\rangle \right]^2 . \qquad (20)$$

The formula (20) coincides with the formula (3), if as Rabi frequency we shall take value $\Delta E / \hbar$. Thus, the nonexponential law of disintegration on small interval of times is a general characteristic of disintegration process.

If at the initial moment of time in quantum system for some any reasons two energy levels were selected, the differential function of distribution can be presented as: $w(E) \approx \sum_{n=1}^{2} \delta(E - E_n)$. Then the probability to find system in an initial state is equal:

$$L(t) \to (1 + \cos(\Delta E \cdot t))/2 , \qquad (21)$$

where $\Delta E = E_2 - E_1$.

From this formula follows, that two initial states will disappear periodically and periodically to appear. This result reminds the result which was got above. And, as the selected states it is possible to consider the induced processes of transition between two levels on a background of spontaneous transitions. Thus, it is possible to say, that the principle of QWE can be used both for induced, and for spontaneous transitions. As an example of possible stabilization of the excited states it is possible to bring an example of synchrotron radiation suppression, which was considered in works [10-11]. Let's note that the arguments concerning suppression of synchrotron radiation in these works were others. The results, received in this section, give additional arguments for an opportunity of suppression of such radiation.

5. DISCUSSION OF SOME EXPERIMENTAL RESULTS

Now there are many works devoted to an experimental research of QZE. Their quantity quickly grows. Below we briefly shall describe most important, in our opinion, results. The first experimental work, directly devoted to research of QZE, was the work [5]. The importance of this work, first of all, consists in such fact: before this work QZE was considered as some kind of speculative paradox revealed incompleteness of our understanding of quantum processes. After this work the attitude to QZE qualitatively has changed. After this work a plenty others (theoretical and experimental (for example [6])) works devoted to this effect at once has appeared. In experiments of work [5] the ions beryllium were used. Three energy states of this ion (see Fig.2) were used. Distance between a zero level and first level corresponds to energy of microwave quantum. The transitions between zero and second levels could be carried out by influencing on system by optical radiation. The transitions between the first and second levels were forbidden. In experiment the transitions between zero and first levels were studied firstly. For this purpose the ions of beryllium were exposed by high-frequency radiation. The traditional picture of quantum transitions was observed. Then, the ions of beryllium were exposed to influence of short pulses of laser radiation. The laser radiation could transfer the ions from a zero level on the second level. It is necessary to note, that the time of life of the second level was significant smaller, than period of Rabi frequency for transitions between zero and first energy levels occurring under influence of microwave radiation. It was the shortest characteristic interval of time in this task. If the number of pulses of laser radiation falling in an interval of time, which is equal to the Rabi period, was great enough, the authors observed appreciable increase of life-time of the basic, not excited states of ions.

In described above experiment the fact of suppression of quantum transitions was only authentically established. The real suppression was insignificant. In this relation other experiment [7] deserves the attention. This experiment was fulfilled with participation of the Nobel winner Wolfgang Katterle. These experiments succeeded in suppressing the quantum transitions (more than 98% atoms left in their initial states). In the unique experiments of these group researchers the Bose-Einstein condensate of rubidium was used. As well as in experiments described above, the authors used three working energy levels (see Fig.3). And, the transitions between zero and first levels lay, as well as in the previous experiments, in a microwave range and occurred with participation fourth, virtual level. The choice of such transitions (with participation of a virtual level), apparently, was caused by that the Rabi period of these microwave transitions (between zero and first levels) was great enough (16 mc). During this time it was possible to organize a large number of laser pulses, the energy of which corresponds to transitions from the first energy level on second. When the number of laser pulses during the Rabi period of microwave transitions exceeded 300, the practically complete suppression of quantum transitions was observed. Let's note the following essential difference of these experiments from previous. First of all, it, certainly, high degree of stabilization of a quantum states (more than 98%). Further, the most impressing and essential is fact that "observation" was made at the first (excited) energy level. These levels are not populated and as a result of "observation" its remained not populated. It is most typical feature of QZE. Besides in these experiments the process of "observation" was most full appear. Really, the exited atoms of rubidium (the atoms which are taking place at the first, excited level) under action of laser radiation were moved away from a magnetic trap. Thus, the "extreme" variant of process of observation was carried out.

In all cases at discussion about opportunities of QZE for using there was done statement, that such processes can not be realized at a nuclear level, for example, for suppression or acceleration of radioactive disintegration. Below we briefly shall describe some results of experiments, which were spent in the Kharkov Physic-Technical institute under manage of the professor Yu.N. Ranyuk and in the Kiev institute of Nuclear Researches under manage of V.I. Kirischuk, in which, probably, the process of braking of disintegration Hf-178 isomer was observed. The essence of experiment was in the following. The sample of a material, which contained Hf-178, was acted by electron flows with energy from 10 кeV up to 50 кeV. On a sample, as on a target, the energy of electrons was converted in energy of x-ray radiation. The authors supposed that a little bit above basic metastable level of Hf-178 should be short-living trigger level (see Fig.4). The purpose of experiments was in transferring the metastable state of Hf-178 on unstable short-living trigger level. In many experiments the quite distinct acceleration of process disintegration was observed. The authors however are even more often observed opposite effect, when the process of radioactive disintegration was broken at influence of a beam on a target. These last experiments can be easily explained by the mechanism QWE. Really, in considered nuclear system except for a trigger level there are large number others long-living of energy levels. At influence of an electron beam on a target the wide spectrum of x-ray radiation is appeared. Such radiation will transfer nuclear system not only on certain energy level (desirable on the trigger level) but also on many others long-living levels. The system of the equations, which will describe such transitions, is possible to present as:

$$i\dot{A}_0 = A_1\,,\quad i\dot{A}_1 = A_0 + \sum_{k=2}^{N}\mu_k A_k\,;\quad i\dot{A}_2 = \mu_2 A_1\,,\ i\dot{A}_3 = \mu_3 A_1\,;$$
$$\ldots\ i\dot{A}_N = \mu_N A_1\,. \qquad (22)$$

This system describe the connection and transitions of considered system from first (A_1) metastable level on the basic level (A_0) due of spontaneous transferring and on other levels, which are close – located to metastable level. The last transitions are induced transitions. The system (22) is easily solved in a general analytical kind:

$$A_1 = \cos(\Omega\cdot t)\,;\ A_0 = \frac{1}{i\cdot\Omega}\sin(\Omega\cdot t)\,;$$
$$A_k = \frac{\mu_k}{i\cdot\Omega}\sin(\Omega\cdot t)\,;\ k = 2,3,\ldots N\,, \qquad (23)$$

where $\Omega = \sqrt{1+\sum_{k=2}^{N}\mu_k^2}$.

From these solutions follows, that the large number of energy levels will be, the less will be probability for spontaneous transferring and the probability for transition on trigger short-living level. From the formulated picture of transitions it is possible to formulate the basic recommendation for updating experiments. She consists that the conversion of energy of electron beams in x-ray radiation is necessary to spent on independent target with following separation of necessary spectral component. Only with this narrow spectral component should act on a sample with Hf-178. Such scheme of experiment will allow to remove from dynamics of transitions all useless (harmful) energy levels. It is necessary to say, that these results are, apparently, first experimental results, in which the opportunity to affect on nuclear disintegration by external influences was shown.

CONCLUSIONS

Thus, it is possible to formulate the following recommendations for stabilization of the excited quantum systems. First of all, it is necessary to know time of life of these excited states. Further it is necessary to pick up the appropriate energy levels located not too far from an excited state. Further, it is necessary to pick up perturbation which frequency will correspond to transitions between the excited state and this additional level. The intensity of this perturbation should be such, that the appropriate Rabi frequency was as it is possible greater in comparison with return lifetime of the excited system.

The special interest represents an opportunity to stabilize such states, with which the stabilizing perturbation, on the first sight, does not interact. The simplest example can be served the opportunity to suppress a photocurrent at realization of a photoeffect. At this the states of internal electrons in a solid can be stabilized by external microwave radiation. For observation of suppression effect it is necessary, that the Rabi frequency for transitions under action of an external microwave field was as it is possible greater in comparison with return lifetime of photoelectrons. If we shall not be interested in change in a condition of a field (resulting in a photoeffect), the formulas, received in section 2, are completely applied for this case. It is necessary to note, that the analysis of the experimental results, which had been gotten to the present time, shows, that they more naturally and easier can be explained by the QWE. Moreover, this mechanism can be used for considerably wider schemes of physical systems. The explanation of this mechanism does not leave of framework of the traditional quantum mechanics.

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МЕХАНИЗМ ПОДАВЛЕНИЯ КВАНТОВЫХ ПЕРЕХОДОВ (КВАНТОВАЯ ЮЛА)

В.А. Буц

Рассматривается механизм, позволяющий стабилизировать состояния квантовых систем. Причем, начальные состояния могут соответствовать как возбужденному, так и невозбужденному стационарным состояниям. Рассматриваемый механизм впервые был предложен для возбужденных состояний и получил название квантовая юла. В работе показана тесная связь рассматриваемого механизма с эффектом Зенона. Высказаны соображения, что многие экспериментальные результаты, которые интерпретируются как наблюдение эффекта Зенона, по-видимому, соответствуют эффекту квантовой юлы.

МЕХАНІЗМ ПОДАВЛЕННЯ КВАНТОВИХ ПЕРЕХОДІВ (КВАНТОВА ЮЛА)

В.О.Буц

Розглядається механізм, який дозволяє стабілізувати стан квантових систем. Причому, початковий стан може відповідати як збудженому, так і незбудженому стаціонарному стану. Механізм, який розглядався вперше, був запропонований для збуджених станів і одержав назву квантової юли. В роботі показано тісний зв'язок механізму, який розглядається, з ефектом Зенона. Виказані розуміння, що багато-які експериментальні результати, які інтерпретуються як спостереження ефекту Зенона, можливо, відповідають ефекту квантової юли.