On Quantum-mechanical Measurements and Processes of Development of Intelligence

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Abstract

In this paper, we discuss a problem of the influence of quantum-mechanical measurements of a process on the implementation of this process. We consider the quantum-mechanical problem of observing the process of particle transition through a potential barrier accompanied by quantum emission of a quantum two-level system. We show that the processes occurring during quantum-mechanical measurements of the particle have some analogies with processes of development of intelligence.

Key Words: Quantum-mechanical Measurement, Barrier Anti-Zeno Effect, Development of Intelligence.

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Introduction

It is quite difficult to determine what intelligence is. Psychologists have been grappling with issues of the correct definition of intelligence ever since humans started studying the nature of the mind. Many definitions of intelligence have been given over the years. Although the definitions differ, there are reoccurring features. As one of the most important features, the authors point to the ability to adapt to the environment. As early as 1905, A. Binet and T. Simon write in (Binet and Simon, 1905) that intelligence has "*a fundamental faculty of adapting oneself to circumstances*". The definitions of modern psychologists also have an emphasis on adaptation, for example, in (Sternberg, 2000) intelligence is defined as "*ability to adapt oneself adequately to relatively new situations in life*".

Intelligence is most often studied in humans, but is also observed as in non-human animals, and their intelligence, through adaptation mechanisms, affects the evolution of animals. Note that adaptation to the environment does not mean survival or the total number of offspring (if survival would be a measure of successful adaptation, then bacteria might be the most intelligent life on earth). The concept of adaptation implies the achievement of some kind of goal through active interaction with the environment. However, the goals of different creatures may be varied, and therefore, what is the goal, is not specified. It is important that the individual is able to choose their actions in a way that leads to them accomplishing their goals. The greater this ability to succeed in achieving some kind of goal, the greater the individual's intelligence. Human intelligence is understood as general mental capability that involves the ability to reason, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience. In brief, this is "*the ability to deal with cognitive complexity*" (Gottfredson, 1998) when interacting with a changing environment.

In (Legg and Hutter, 2007), based on key features of intelligence that are common to human

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intelligence and intelligence of non-human individuals, the authors proposed a definition of agent's intelligence in its most general form: intelligence is measured by the agent's ability to achieve goals in a wide range of environments.
"Intelligence measures an agent's ability to achieve goals in a wide range of environments".
In order to mathematically formalize the measure of intelligence, the authors of (Legg and Hutter, 2007) proposed to consider a model system that includes an agent with intelligence and an environment. In this model, the environment observes the agent's intelligence, and changes (adaptation) occur in the observed system, which is agent's intelligence.
The question arises: How can the observation of a process affect its outcome?
In the framework of classical physics, observation can in no way influence a process. Nevertheless, long before classical physics, in the fifth century BC, Zeno of Elea has devised aporias that observing a process could affect its outcome (among them, the paradoxes "a watched arrow never flies" and "a watched pot never boils").
However, in quantum mechanics, observation of a process can affect the probability of its implementation (see, for example, Menskii, 2007; Mensky, 2013). Usually the effect of observation is manifested in the fact that the wave function which describes the system changes, namely, the collapse of the wave function arises. Although a very large number of works devoted to the wave function collapse (see, for example, (Zurek, 2009), and references therein), this problem is still not clear (Zurek, Mensky, 2011). In this work, we will also briefly consider this problem.
In quantum mechanics, the Zeno effect is possible when observation of a process slows this process, preventing its realization (Mishra and Sudarshan, 1977; Itano et al., 1990). However, in some cases, the opposite effect can occur, that is, the observation of a process increases the probability of a process. That is called the anti-Zeno effect (Kaulakys and Gontis, 1997; Kofman and Kurizki, 2000; Koshino and Shimizu, 2005). In our resent papers (Namiot and Shchurova, 2017; 2018), we analyzed a barrier anti-Zeno effect, which in a number of cases makes it possible to substantially increase the particle current through a potential barrier. In (Namiot and Shchurova, 2017), we examined the problem of the influence of quantum-mechanical measurements on the process of quantum radiation by a two-level system, as well as on the process of particles passing through a potential barrier. We have presented the calculations and found that observing a particle can significantly increase the probability of a particle passing through a barrier, sometimes even by many orders of magnitude. This is referred to as the barrier anti-Zeno effect. However, the calculations presented in (Namiot, Shchurova, 2017) are quite complicated, and the formalism is cumbersome, and we did not discuss the role of the observing environment in the process of changing the state of the observed system. But the influence of the observing environment is fundamental in this problem.
In this work, in the framework of a simple model, we describe the influence of observations on the process of a particle passing through a potential barrier, which is accompanied by quantum emission of a two-level system. We discuss a situation in which quantum-mechanical observations of a particle can significantly increase the transmission probability of a particle through a barrier. We pay special attention to the important role of the observation environment in the process of changing the state of the observed particle.
Regarding the subject of agent's intelligence, we found that the processes occurring during quantum-mechanical measurements of the particle have some analogies with processes of development of intelligence. We assume that a particle with a two-level system imitates an agent (of course, this is a very simplified simulation). Let the agent's goal be to overcome a high potential barrier (adaptation). In pursuit of its goal, the agent actively interacts with the environment. Then, within the framework of the presented model, the process of quantum-mechanical observations of agent's intelligence affects the changes in the observed system (in agent's intelligence).
Some aspects of the influence of quantum-mechanical observations on changes in the state of biological objects have been described in our recent work (Namiot, Shchurova, 2018).

A Model of Intelligence. Quantum-Mechanical Description of the Effect of Observations on the Particle Passage through a Potential Barrier

In order to mathematically formalize the measure of intelligence, let's consider a system that includes an agent and an environment. The agent and the environment must be able to interact with each other: the agent needs to be able to send signals to the environment, as well as receive signals from the environment. Also, the environment must be able to receive and send signals to the agent.

The definition of an agent's intelligence requires there to be some kind of goal for the agent to try to achieve. In fact, intelligence comes into effect when the agent has an objective that it actively pursues by interacting with its environment. Let the goal be to adapt the agent to a changing environment. In pursuit of its goal, the agent sends a signal to the environment. This signal is perceived by the external environment: the environment observes the agent's intelligence. In order for the agent's goal to have practical consequences (for adaptation to take place), the results of this observation are perceived by the agent, and in accordance with these results, the agent changes, thereby realizing the adaptation goal.

The environment observes the measure of agent's intelligence, and changes (adaptation) take place in the observed system, which is the agent's intelligence.

As an effective measure of intelligence, there may be a time during which an agent can achieve its goal. Indeed, being able to deal with a difficult problem immediately is a matter of experience, rather than intelligence. While being able to deal with it in the very long time might not require much intelligence at all, since simply trying a vast number of possible solutions might produce the desired results. Here we will assume that the measure of intelligence is the ability to achieve the goal as quickly as possible in a difficult situation for the agent.

In the framework of the quantum-mechanical approach to the problem of describing intelligence, we model the agent as a particle with a two-level system. The agent's goal (adaptation) is to overcome a high potential barrier, and to achieve his goal, the agent actively interacts with the environment. The intelligence of an agent is manifested in his ability to pass a potential barrier. Then, the measure of intelligence features how quickly he is able to overcome the barrier. In the quantum-mechanical context, this measure is expressed by the transmission probability through the potential barrier. The greater the transmission probability, the greater the agent's intelligence.

The problem is considered on the example of a process of particle transmission through a barrier, accompanied by a transition from an excited state to the ground state of a two-level system, when the state of the two-level system, interacting with the particle, is detected by the environment. In more detail, two-level system tests a particle and sends out radiation quanta that are perceived by the environment. The environment carries out measurements the state of the two-level system (and the particle state). The results of these measurements are perceived by the particle and act on the particle in such a way that they change its ability to overcome the potential barrier.

We will start the simplest example to demonstrate the influence of observation on the process of passage of a particle through a potential barrier. Suppose that a particle A is in a rectangular potential well Z of width L and the particle is in the ith state with the energy $E_i = \pi^2\hbar^2 i^2/(2mL^2)$ (m is the mass of the particle). Let there be a device B to test this particle. It can be, for example, a two-level system in an excited state, the lower level of which is split into two sublevels $E^{(1)}$ and $E^{(2)}$ ($E^{(1)} > E^{(2)}$).

Sequentially through time Δt, the two-level system is irradiated by quanta whose energy coincides with the energy difference between the two sublevels. The parameters of the interaction of these quanta with a two-level system should be chosen so that, when it is at the second level, the probability of scattering of a quantum on it would be close to unity. (When the system is at the first level, there is no scattering of quanta on it at all). The act of sending a quantum with subsequent determination of whether it has dissipated on a two-level system or has flown without being scattered, we will call the test.

The two-level system interacts with the particle A, and as a result of this interaction, a system can undergo a transition from the first (upper) level (on which it was originally) to the second (lower) level. The characteristic scale S of this interaction is chosen sufficiently small ($S << L$). When we register (using a scattered quantum) a transition in a two-level system, we thereby obtain information that the particle A has been near the device B.

Suppose there is a following situation. Let $(n-1)$ tests have been carried out, and tests have shown that there were no scattered quanta. Consequently, during the testing period $t_{n-1} = (n-1)\Delta t$, the two-level system was at the first level, and, accordingly, the particle A was in the ith state with the energy E_i. But in the nth test (last test), a scattered quantum was recorded. Consequently, a collapse of the wave function has occurred in the system (which includes the particle A and the device B)

at the time $t_n = n\Delta t$.

After the collapse, the two-level system will be at the second level while the wave function of the particle A will already be described not by ith state, but a superposition of states. Suppose that jth state in the superposition satisfies the condition $E_j >> E_i$.We will assume that the state E_j was absent in the penultimate test at the time t_{n-1}. But in the future, even after a very short time interval δt which satisfies the condition

$$\delta t = \hbar / E_j < \Delta t,$$

the energy uncertainty will be large enough so that a state with energy E_j can appear in it (as follows directly from the time-energy uncertainty principle). However, starting from δt, the probability p_j of the appearance of a state E_j will not increase with time. It will somehow oscillate near a sufficiently small average value. Later, at $t \approx t_n = n\Delta t$, when the wave function collapse has already occurred during the last test, the probability p_j will determine that we have fixed the transition of the two-level system B to the second level, and the transition of the particle A to the state E_j.

Let us estimate the probability p_j. We assume that at the initial time instant, the particle A was in the ith state with the energy E_i, and the two-level system was in the upper level with the energy $E^{(1)}$. Suppose that after a time interval exceeding the time τ_h we register the states of the two-level system. (The estimate of τ_h is given below.) Let p_j be the probability that a two-level system will be detected at the lower level, while the particle will be in the jth state with energy E_j. In the first-order perturbation theory, the probability p_j can be represented in the form

$$p_j = \frac{\left|v_{ji}\right|^2}{\left|E_j - E^{(2)} - E_i - E^{(1)}\right|^2} \qquad (1)$$

where $\left|v_{ij}\right|^2$ is the transition matrix element for transition of the particle from the ith state to the jth state the energy E_j, and the two-level system from the upper to the lower level. Let S be the characteristic length of the interaction. It is important that if the condition

$$\sqrt{2mE_j}\, S / \hbar << 1 \qquad (2)$$

is satisfed, then $\left|v_{ij}\right|$does not depend on the energy of the particle. In this situation, it is convenient to use a effective frequency Ω, which is analogous to the Rabi frequency.

Then we express the matrix element as $\left|v_{ij}\right| = \hbar\Omega$.

In the case of large deviations of energy from the mean energy ($E_j >> E_i$, $E_j >> E^{(1)} - E^{(2)}$) that are of interest to us, we can rewrite the expression (1) for p_j in the form $p_j = (\hbar\Omega)^2 / (E_j)^2$. If we consider sufficiently large $E_j$for which the opposite inequality is satisfied, then we have $\Omega \to 0$.

Below we consider only those E_j for which (2) is satisfied.

For us, the dependence of probability p_j on energy is of interest. As follows from (1) and (2), for states with energies $E_j >> E_i$, we have

$$p_j \sim E_j^{-2}, \qquad (3)$$

Where E_j is close to the barrier height V_b. An estimate of the characteristic time τ_h, starting from which it is already possible to register such states, has the form $\tau_h \geq \hbar / E_j$.

The probability p_j decreases rapidly enough with increasing E_j. Therefore, it would seem that these states would not give any significant contribution to the averaged quantities, such as, the average energy of a particle A after interaction with the system B.

However, there is a very important exception to this statement. Consider the case when there is a rectangular potential barrier of a height V_b and a width b ($L >> b$) at the bottom of the quantum well Z (Figure 1).

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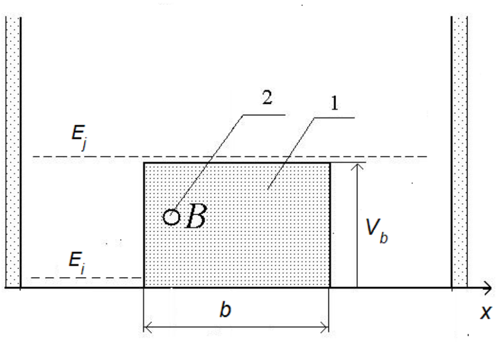

Figure 1. A one-dimensional potential well for the particle *A*; 1 is a symmetric rectangular potential barrier with the width b and height V_b; and 2 is the two-level system *B*.

Suppose that at the initial moment, both the particle A with the energy E_i and the system B are to the left of the barrier ($V_b >> E_i$). The probability p_t of tunneling of the particle A through the barrier to the right side of the well Z is

$$p_t \sim \exp\left(-2\sqrt{2mV_b}\,b/\hbar\right). \qquad (4)$$

It follows from (4) that that the probability p_t of particle tunneling through the barrier decreases exponentially with increasing b.

At a qualitative level, the effect of increasing the probability of passing through a barrier is as follows. As a result of the wave-function collapse recorded by system *B*, particle *A* has energy E_j that exceeds V_b. Particle detection within the barrier leads to the fact that the particle cannot be in a sub-barrier state (in the classically forbidden region). Consequently, the particle proceeds from sub-barrier states to above-barrier state. Once in the above-barrier state, the particle has a chance to fly freely over the barrier and get into the region beyond the barrier. Therefore, the transmission probability through the barrier determined by the collapses associated with observations of such particles will be determined only by the probability that particle A will be recorded in any state with energy $E_j \geq V_b$. The probability to attain such states, according to Eq. (3), is proportional to E_j^{-2}, and do not depend on b. Therefore, the value of p_j is substantially higher than p_j for sufficiently large b. This is the main property of the barrier anti-Zeno effect: when the probability of tunneling is very small, observation of particles passing through the barrier or reflected from it can (under certain conditions) greatly increase the probability of particles entering in the region behind the barrier.

Above, we considered a simple rectangular barrier model to illustrate the basic ideas of the effect of increasing the probability of particle passing through the barrier when states of the particle are observed (the barrier anti-Zeno effect). In our recent work (Namiot and Shchurova, 2017), we considered this effect in a model of a barrier of a special shape, which is similar to the form of barriers to nuclear fusion in a solid, and moreover, has an analytic solution.

Within the framework of this model, the effect of increasing the probability of particle passing through the barrier due to observations is of particular interest in connection with the question of the paradoxical results of experiments on cold nuclear fusion. There are quite a few experimental works performed by different authors and in different laboratories, and the experimental data presented by the researchers indicate the existence of new elements synthesis (cold synthesis) in some biological and inorganic systems (see, for example, (Lipinski S and Lipinski H, 2014). The results of these experiments cannot be explained by chemical or other non-nuclear processes, as well as ordinary tunneling processes. In (Namiot and Shchurova, 2017), we calculated the probability of a particle passing through a potential barrier of a special form, which is similar to the barrier preventing the fusion of nuclei in a solid. We have found that, due to observation, the transmission probability of a particle through a barrier can significantly exceed the probability of "ordinary" tunneling. Numerical estimates for multicharge nuclei demonstrate that the increase in probability due to observations can potentially explain the results of "cold fusion" experiments.

Thus, we have shown above that a testing system (in this case, a two-level system) is necessary to increase the probability of a particle passing through a potential barrier. We note that, in addition, it is required to transfer the energy to the particle, the value of which considerably exceeds the energy of the emitted quantum by a two-level system. In this regard, the question arises: what processes and phenomena provide such a high energy?In fact, an increase in the transmission probability occurs because when the states of a two-level system (and particles) are observed by the environment, simultaneously with the inevitability, the environment acts on the two-level system (and particle). This influence changes not only the state of a two-level system, but also the state of the particle that interacts with a two-level system. In the next section, we will consider the role of the environment in the observation process and try to answer the question posed above.

What is the Reason that Observation of a Process Can Change the Probability of Its Implementation?

In order for a particle to be able to overcome a potential barrier with high probability, it requires energy E_j that is significantly higher than its original energy E_i. However, the two-level system (which interacts with a particle and tests its state) emits energy $\hbar\omega << E_j - E_i$, therefore, even if a two-level system gives up all its energy to the particle, its energy is still not enough to overcome the barrier. The two-level system cannot directly transfer sufficient energy to the particle. However, the emitted quanta of a two-level system are perceived by the environment as scattered quanta that can be recorded. Thus, the environment observes the particle interacting with a two-level system. (In fact, observations are carried out by external devices that are part of the environment, but here we will consider that observations are carried out by the environment.) So, the two-level system and the particle continuously interact with the environment, and although the energy of the scattered quantum can be very small, this interaction can not be considered as small. A registration of the quantum there is already a change in the surrounding environment. And at registration, even a weak signal, being appropriately amplified, can be registered and therefore quite a large change in the environment can take place. In this case, significant changes in the observing environment could lead to significant changes in the energy state of a particle that interacts with the environment.

Here we assume that that observation results depend not only on the state of the observable system itself, but also on the state of the observing system. This assumption, at first glance, seems strange. Bellow, we give reasoning in order to prove that this assumption is incorrect, and then we will show why such reasoning is self-contradictory.

Denote by $\{x\}$ the set of variables related to the observable system, and by $\{X\}$ a set of variables related to the surrounding environment. Using these notations, we can write the total wave function (the wave function of the observable system and the surrounding environment) as $\psi(\{x\},\{X\},t)$. Suppose that during the experiment the observed system does not interact with the surrounding environment. In this case, it would seem, we can represent the wave function $\psi(\{x\},\{X\},t)$ in the form

$$\psi(\{x\},\{X\},t) = \psi_1(\{x\},t)\psi_2(\{X\},t). \quad (5)$$

However, it follows directly from (5) that any events related to the observable system and its environment are independent and are not able to affect one another. In other words, the surrounding environment cannot change the measured result in any way.

However, both before the experiment and after the end of the experiment, the observed system interacts with the surrounding environment (otherwise we can not get any information about the experiment). Therefore, both before and after the experiment, the total wave function cannot be represented in the form (5). But if during the experiment the wave function is described by the expression (5), then it implicitly assumes that the information (obtained during the interaction before and after the experiment) disappears in some way in the surrounding environment. The environment effectively “forgets” this information.

If we were dealing with classical environment, it would be simple to explain such a “forgetting”. In a classical system, it is sufficient to assume that there is dynamic chaos, and the obtained information is lost in the resulting noise.

In a quantum system, this “forgetting” could be explained if the quantum system behaved like a system with local hidden parameters. But as Bell showed, the behavior of a quantum system is not fundamentally reduced to the behavior of a system with local hidden variables, that is, there is no effective “forgetting” in the quantum system. And if there is no “forgetting”, then we cannot assume that ψ_2 depends only on $\{X\}$ and $\{x\}$. So in the general case, we should write

$$\psi(\{x\},\{X\},t) = \psi_1(\{x\},t)\psi_2(\{x\},\{X\},t). \quad (6)$$

From (6), it already follows that the surrounding environment correlates with the observed system. That, in substance, is the reason why the environment can change the result of observations.

Let us return to the discussion of states with particle energy $E_j >> E_i$. An emitted quantum changes not only the observable system from which it was emitted, it also changes the environment in which it was emitted. And in this changed environment, such events can already be observed (albeit very rarely), which would not have been observed if there had not been such a change.

It is not surprising that any, even the most insignificant event (in particular, a quantum emitted by the observable system) can greatly change the surrounding environment. The environment is always, by some parameters, in an unstable or metastable state. (If the environment were completely stable, then it would be impossible to make any measurements in it.) And in unstable systems, even a small impact can cause significant changes. The changed environment, in turn, perceives the observed system as well as changed. From the point of view of the changed environment, the wave function of the observable system itself undergoes changes: a wave function collapse occurs. So when we created such conditions that no secondary quanta can be radiated, we excluded the possibility for the observable system to "report" what is happening in it to the surrounding environment. Thus, we excluded the possibility of a wave function collapse and all that is associated with this collapse, in particular the (rare) possibility to observe states with large values of energy E_j.

Being registered and at the same time receiving energy E_j, the particle cannot return to the sub-barrier state (to the classically forbidden region). As a result of the collapse of the wave function, a particle acquires the properties of a classical particle, and can only be in the over-barrier state. Such a particle can freely fly over the barrier and with a high probability get into the region behind the barrier.

Let's return to the subject of intelligence. An agent achieves its goal (for example, adaptation) by interacting with the environment that observes the measure of the agent's intelligence. If the agent is to succeed in his goal, he must learn about the results of observations from the environment, as he must know what to do in order to get the result. So, the agent has information about the results of this observation of his intelligence, and he has the ability to coordinate his actions so as to be successful in achieving his goal. The environment has already changed by registering a measure of intelligence of the agent, since any registration by the environment is a change in the environment. In case of success in achieving the goal, the measure of intelligence of the agent has also changed, namely, the development of intelligence has occurred. And the agent's intelligence of can no longer return to its previous state.

As noted above, a similar situation where changes in the observing system cause changes in the observable system takes place in the context of quantum mechanics, and is completely impossible within the framework of classical physics.

Conclusion

In this paper, we discussed the question of how observation of a process can affect the implementation of this process. In the framework of classical mechanics, the answer is obvious: observation in no way can influence the process, but in quantum mechanics there may indeed be situations where an observation may affect the process that is being observed. Within the quantum-mechanical approach, we have examined the problem of particle transmission through a high potential barrier, and showed that observing a particle can significantly increase the probability of a particle passing through a barrier. We have shown that processes and phenomena occurring during quantum-mechanical measurements of the particle have analogies with purposeful processes that occur during the development of intelligence.

The contribution of each author to the writing of the article is the same.

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