ON THE PHYSICAL MECHANISM OF QUANTUM JUMPS IN ATOMS

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The possible mechanism of quantum jumps in hydrogen-like atoms as a consequence of the processes of inelastic scattering of an atomic electron on a nucleus inside an atom is discussed. Such processes can occur due to the specific internal structure of the proton. The direct connection has been established between spontaneous transitions in atoms and the quantum jumps under consideration.

Keywords: quantum jumps, inelastic scattering, proton, atomic spontaneous transitions.
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1. INTRODUCTION

Quantum jumps in various atomic systems have been the objects of active fundamental research since the beginning of quantum mechanics [1, 2]. Recently, in connection with the development of attosecond technology and spectroscopy [3], significant progress has been made in studying the dynamics of such short-time processes [4, 5]. However, the physical mechanism of these quantum jumps in atoms is not yet clear. This work discusses such a possible mechanism, which is associated with the processes of inelastic scattering of atomic electrons by the nucleus inside the atom. The consideration was carried out for hydrogen-like atoms, which consist of a single electron and a positively charged nucleus. These, in addition to the hydrogen atom, also include ions of elements such as He^{+}, Li^{2+}, Be^{3+}, etc.

The next section presents the qualitative rationale for this mechanism based on the brief historical overview of development of atomic models. Next (in Section 3) a number of simple relationships are obtained for the spontaneous decay of excited atomic states by means of the quantum jumps under consideration. The final Section 4 presents the main conclusions of this work.

2. QUALITATIVE RATIONALE

It is well known that the classical Rutherford model of the atom turned out to be untenable due to the inevitable and very rapid (within nanoseconds) fall of an atomic electron onto the nucleus due to the radiation of this electron during its accelerated motion. In subsequent Bohr's model of the atom, it was assumed that atomic electrons could move only in certain orbits spatially distant from the atomic nucleus [1,2,6]. Thus, the possibility of atomic electrons falling onto the nucleus was denied, because then the “collapse” of the atomic system was assumed. Indeed, such a “collapse” occurs, for example, in the case of such a hydrogen-like system as positronium, which consists of two structureless antiparticles (electron and positron). Due to the approach of these oppositely charged antiparticles, their annihilation occurs within nanoseconds [7].

According to the modern quantum model of the atom, based on the Schrödinger equation, quantum states of the atomic electrons are described by wave functions that can have non-zero values throughout the entire volume of the atom, including its nucleus [6]. However, during the development of this quantum model, in particular for the simplest hydrogen atom, it was assumed that the electron, during its movement inside the atom, does not directly collide with the nucleus (proton). This assumption was associated primarily with the negligibly small region of the atomic nucleus compared to the characteristic dimensions of the atom. In addition, for example, in the case of the hydrogen atom, it was assumed that its nucleus (proton) is a structureless particle. Therefore, the corresponding Schrödinger equation for the hydrogen atom was solved with respect to the wave function of the electron moving in the Coulomb field of the point nucleus [6]. Thus, stationary quantum states of an atomic electron with certain values of the total energy and angular momentum of this electron were determined [6]. Formally, such excited states of an atomic electron can exist unlimited time, although in reality they spontaneously decay to lower quantum levels down to the ground atomic term. Subsequently, this spontaneous decay of excited states of the atom was described within the framework of quantum electrodynamics based on possible fluctuations of the electromagnetic vacuum [8].

Meanwhile, by the mid-seventies of the last century, fundamental experiments were carried out on the bombardment of protons with fast electrons [9]. Based on the analysis of the observed processes of elastic and inelastic electron scattering in these experiments, a rather complex internal structure of the proton, consisting of quarks and gluons, was established [9, 10]. State of such a proton structure can change significantly under the influence of various elementary particles, including electrons. It is obvious that in the hydrogen atom, due to the Coulomb attraction, the electron will inevitably approach the nucleus until it reaches nuclear gluon-quark structure, where, in addition to the electromagnetic interaction, the strong interaction between elementary particles also becomes significant. However, in contrast to the mentioned case of positronium [7], instead of

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annihilation, processes of elastic and inelastic scattering of the electron on the proton inside the atom will occur. Such a scattering should lead to a redistribution of energy and angular momentum between the atomic electron and the nucleus. These processes were not taken into account in the corresponding Schrödinger equations, compiled only for the electron wave functions, without a possible associated change in the internal state of the atomic nucleus [6]. It is obvious that the considered processes of electron scattering on a nucleus will be very short-time compared to a duration of the atomic electron’s stay in an excited state, since the characteristic dimensions of an atom are many times greater than the effective dimensions of its nucleus. However, it is precisely such abrupt processes of inelastic scattering of an atomic electron on a nucleus that can lead to observed spontaneous transitions in the atom between electronic quantum states with different energies, accompanied by the emission of photons of corresponding frequencies.

Of course, correct consideration of such inelastic scattering of the atomic electron on the nucleus will greatly complicate the solution of the corresponding problem even for the hydrogen atom. Then it will be necessary to solve interrelated equations for the quantum states of the electron and nucleus, taking into account possible changes in the internal structure of the nucleus, which are not yet fully known. Apparently, this will require additional experimental and theoretical studies.

At the same time, in the next section some simple relations will be obtained for the process of spontaneous decay of excited states of an atomic electron as a result of the quantum jumps under consideration.

3. SPONTANEOUS DECAY OF EXCITED ELECTRONIC STATES

Let us consider the excited electronic state $|e\rangle$ of an individual hydrogen-like atom, created at time $t = 0$. It is believed that after some time $\tau \geq 0$, an abrupt decay of this state into lower energy levels of the electron occurs. Assuming such a quantum jump to be instantaneous, we can write the following expression for the population p of the state $|e\rangle$:

$$p(t) = \eta(\tau - t), \qquad (1)$$

where $\eta(\tau - t)$ is the step function (see figure).

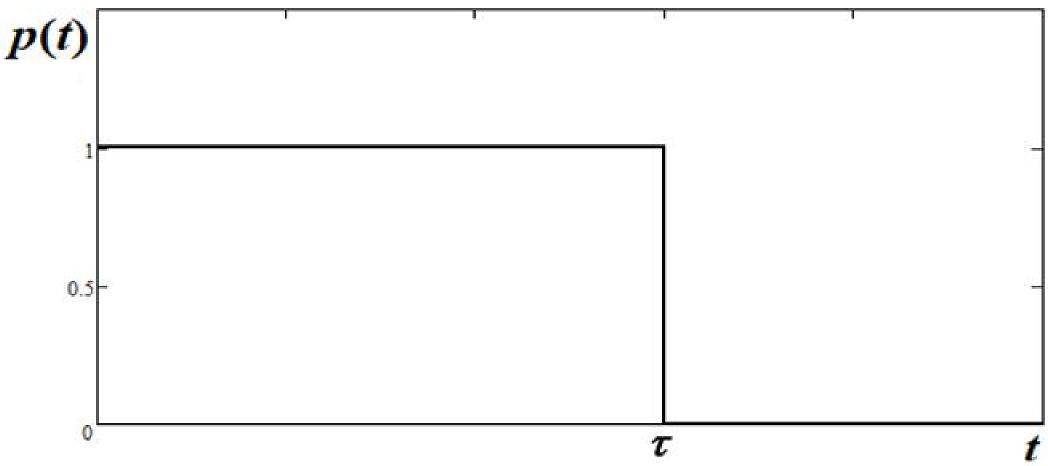

Fig. Time dependence of the population $p(t)$ of the excited state $|e\rangle$ of the atomic electron, starting from its appearance at the moment $t = 0$ until its spontaneous decay as a result of a quantum jump at the moment t=τ

An ensemble of a sufficiently large number of atoms N excited to the state $|e\rangle$ at the moment $t = 0$ decays spontaneously according to the well-known law [6]:

$$N(t) = N_0 exp(-\gamma t), \qquad (2)$$

where N_0 is the number of such atoms at the initial moment $t = 0$, and γ is the radiative damping constant.

At the same time, the dynamics of changes in the population of such an ensemble of excited atoms as a result of the quantum jumps under consideration (1) is also described by the following relation:

$$N(t) = N_0 \int_0^\infty \eta(\tau - t) f(\tau)\, d\tau = N_0 \int_t^\infty f(\tau)\, d\tau. \qquad (3)$$

Here $f(\tau)$ is the distribution function over time moments τ of quantum jumps in individual atoms, which is easily determined from the equality of expressions (2) and (3):

$$f(\tau) = \gamma exp(-\gamma\tau), \quad (\tau \geq 0\ ). \qquad (4)$$

According to the distribution (4), the characteristic lifetime γ^{-1} of the excited state $|e\rangle$ can also be interpreted as the interval of time during which the spontaneous decay of this state $|e\rangle$, by means of considered quantum jumps, is most probable. It is obvious that this time γ^{-1}, associated with the dynamics of the motion of the electron in the state $|e\rangle$ throughout atomic volume, is many times greater than the duration of the quantum jump under consideration, due to the very short-time process of inelastic scattering of this electron directly in the region of the atomic nucleus. This circumstance, in particular, can qualitatively explain the increase in the lifetime of excited Rydberg atoms with increasing their sizes [11]. Indeed, then a relative volume of the nucleus in the atom, where the quantum jumps in question can occur, decreases.

Note that after the aforementioned radiative decay of the excited electronic state $|e\rangle$ into some lower energy quantum levels, these levels will further decay in a similar way by means of considered quantum jumps until the atom reaches the ground stable quantum state.

It was noted above that the radiative decay constant γ (4) of the excited electronic state of an individual atom was previously calculated by methods of quantum electrodynamics within the framework of the concept of the electromagnetic vacuum [8]. At the same time, according to my analysis, this constant γ may be determined directly by probabilities of inelastic scattering of an excited atomic electron on the nucleus inside the atom.

4. CONCLUSION

According to the above arguments, very short-time quantum jumps, that occur during the spontaneous decay of an atom, can be caused by inelastic collisions of an excited electron of this atom with its nucleus. As a result, spontaneous transitions take place in the atom between electronic quantum states of different energies with the emission of recorded photons of the corresponding frequencies.

It is important to note that during such jumps not only sharp changes in the energy of an atomic electron can occur, but also an exchange of its angular momentum with the atomic nucleus. This phenomenon, in particular, can change the established concept of the total angular momentum of an atomic electron as the sum of its orbital momentum and its spin.

In my opinion, further more detailed study of the considered jump-like processes of scattering of bound electrons in an atom on its nucleus will make it possible to present a more correct physical interpretation of observed phenomena in atomic spectroscopy.

[1] *J.E. Baggott.* The Quantum Story: A History in 40 Moments. Oxford University Press (2011).

[2] *Carl S. Helrich.* The Quantum Theory—Origins and Ideas: A Historical Primer for Physics Students. Springer (2021).

[3] *Thomas Schultz, Marc Vrakking.* Attosecond and XUV Physics: Ultrafast Dynamics and Spectroscopy. John Wiley & Sons (2013).

[4] *W.M. Itano, J.C. Bergquist, D.J. Wineland.* Early observations of macroscopic quantum jumps in single atoms. International Journal of Mass Spectrometry, Volume 377, pp. 403-409 (2015).

[5] *Z.K. Minev, et al.* To catch and reverse a quantum jump mid-flight. Nature 570, pp. 200–204 (2019).

[6] C.J. Foot. Atomic Physics. Oxford University Press (2005).

[7] *O.E. Mogensen*. Positron Annihilation in Chemistry. Springer Berlin Heidelberg (2012).

[8] *Ulrich D Jentschura, Gregory S Adkins.* Quantum Electrodynamics: Atoms, Lasers and Gravity. World Scientific Publishing (2022).

[9] *R.J. Roberts.* The structure of the proton: Deep Inelastic Scattering. Cambridge University Press (1990).

[10] *M. Y. Han.* Quarks and Gluons: A Century of Particle Charges. World Scientific Publishing (1999).

[11] *Thomas F. Gallagher. Rydberg Atoms.* Cambridge University Press (2005).

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