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AN ALTERNATIVE INTERPRETATION OF THE FRANCK-HERTZ EXPERIMENT

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Abstract

An alternative interpretation of the general mechanism of generation of the cur-rent-voltage characteristic of the electronic conductivity of mercury vapor, formed from the standpoint of technical cybernetics, is considered. An original substantiation of the physical essence of the phenomenon under consideration is proposed, based on the relativistic model of spectral orbits of hydrogen-like systems.

Key words

Stationary orbit, quantum leap, spectral orbit, electronic resonance, control action.

1 Introduction

Investigating the electronic conductivity of discharged gases, J. Franck and G. Hertz used an installation based on the principle of operation of a four-electrode gas-filled lamp, the glass tube of which contained a cathode (*C*), two internal grids (G_1 and G_2) and an anode (*A*). In this case, the electrons emitted by the cathode were accelerated by the potential difference applied between *C* and G_1. In turn, a small delay potential was created between G_2 and *A*.

Thus, free electrons accelerated by the grid G_1 freely penetrated into the zone L, in which they collided with the molecules of the test gas and, in case of overcoming the restraining voltage created by the grid G_2, reached the anode, initiating a weak electric current, the strength I of which was recorded by a milliammeter. In addition, the electrical voltage U_2 occurring at the corresponding section of the circuit was simultaneously measured. When filling the tube tank with discharged mercury vapor, scientists recorded a very remarkable voltage characteristic (Figure 1).

The peculiarity of the studied dependence is a sudden drop in the current strength *I* when the voltage U_2 reaches a multiple of 4.9 V. At the same time, the preliminary analysis of the basic series of measurements was based on the consideration of the mechanism of ionization of particles in their collisions with accelerated electrons [Franck and Hertz, 1914]. In turn, the comparison of the results of experiments con-ducted with a lamp equipped with a quartz case with the postulates of Bohr's theory [Bohr, 1913] required an adjustment of the physical justification of the phenomenon under study, which led to the formation of a generally recognized proof of the existence of stationary atomic orbits [Franck, 1926].

However, modern research shows that the distances between maximums and minimums of the considered voltage characteristic, which are considered to be the same, are not actually equal, but turn out to grow as the number of its minimums increases [Rapior, Sengstock and Baev, 2006].

2 The Bohr model of stationary electronic orbits

As is known, the key prerequisite for the appearance of the quantum model of the atom was Bohr's attempt to link the famous Planck formula *E=hf* with the equation of the Newtonian balance of forces in the Rutherford atom:

$$\frac{Ze^2}{4\pi\varepsilon_0 r^2} = \frac{m_e \nu^2}{r}, \tag{1}$$

where Z is the atomic ordinal number, e and m_e – are the electron's charge and rest mass, ϵ_0 – is the electric constant, v and r – are the electron's velocity and the radius of its orbit.

At the same time, in order to harmonize the traditional formulations of classical mechanics with Maxwell's electromagnetic theory, Bohr postulated the concept of a stationary electron orbit, being in which an electron

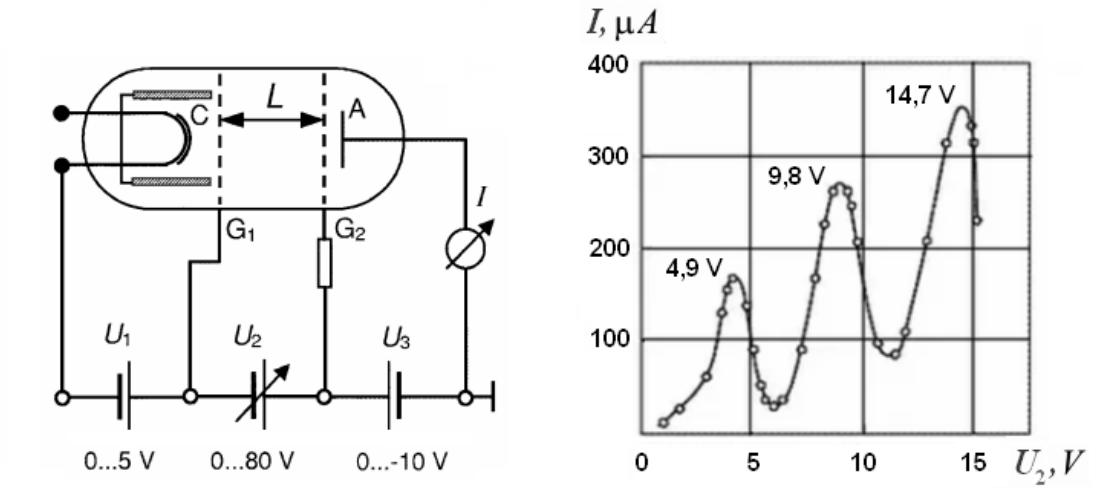

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Figure 1. Electrotechnical scheme of the initial Franck–Hertz installation and current-voltage characteristics of the electronic conductivity of mercury vapor.

somehow does not emit energy. In addition, since relation (1) contained a priori indeterminate parameters v and r, Bohr was forced to use the expression proposed by D. Nicholson to describe the Planck quantization of the angular momentum of an electron rotating around a stationary atomic nucleus in a circular orbit defined by its ordinal number:

$$m_e \nu_n r_n = n\frac{h}{2\pi}, \tag{2}$$

where *n* is the number of the electron orbit, *h* is the quantum Planck constant.

Combining equations (1) and (2) allowed Bohr to obtain a formula for calculating the radii of numbered stationary orbits regulating discrete (quantized) electron energy values:

$$r_n = n^2 \frac{4\pi\varepsilon_0}{Ze^2 m_e}\left(\frac{h}{2\pi}\right)^2. \tag{3}$$

Further, he suggested that the total energy of an electron located in the nth station-ary orbit, given the ratio (1), can be described as:

$$E_n = -\frac{1}{n_2}\cdot\left(\frac{h}{2\pi}\right)^2. \tag{4}$$

In turn, during the transition (quantum leap) of an electron from one stationary orbit to another, a photon with an energy equal to the energy difference of the corresponding electronic levels should be emitted or absorbed:

$$hf = E_m - E_n, \tag{5}$$

where E_m and E_n are the energy values corresponding to the initial and final stationary orbits, respectively. Based on a similar interpretation, for the case of $E_m > E_n$ the emis-sion of a light photon takes place, but if $E_m < E_n$, then the opposite situation is observed, associated with the atomic absorption of a quantum of light (Figure 2).

Thus, the physically observed frequency of the corresponding light radiation, tak-ing into account the relations (4) and (5), can be represented as:

$$f = \left(\frac{1}{n^2} - \frac{1}{m^2}\right)\frac{Z^2 e^4 m_e}{8h^3 e_0^2}. \tag{6}$$

The fundamental adequacy of the quantum leap hypothesis is confirmed by the possibility shown by Bohr to express the Rydberg frequency constant *R* in terms of fundamental physical constants:

$$f = Z^2 R\left(\frac{1}{n^2} - \frac{1}{m^2}\right), R \quad = \frac{e^4 m_e}{8h^3\varepsilon_0^2}. \tag{7}$$

It should be noted that at the initial stage of the development of quantum physics, the Bohr stationary orbitals were subjected to well-deserved criticism. For example, E. Rutherford wrote to him: "It seems to me that your hypothesis has another very weak point. I have no doubt that you yourself are fully aware of this. How does an electron decide with what frequency it will oscillate, moving from one stationary state to another?" [Kumar, 2008]. However, it was the stationary orbits that made it possible to most correctly explain the volt-ampere characteristic of mercury vapor revealed in the of Franck-Hertz experiments.

Indeed, following Bohr's quantum theory, when accelerated electrons collide with mercury particles, the electron shells of its atoms can go into an excited state only after receiving a certain energy pulse. Consequently, if stationary electron orbits physically exist in an atom, then the electrons emitted by the cathode, colliding with the particles of the test gas, must lose energy in clearly

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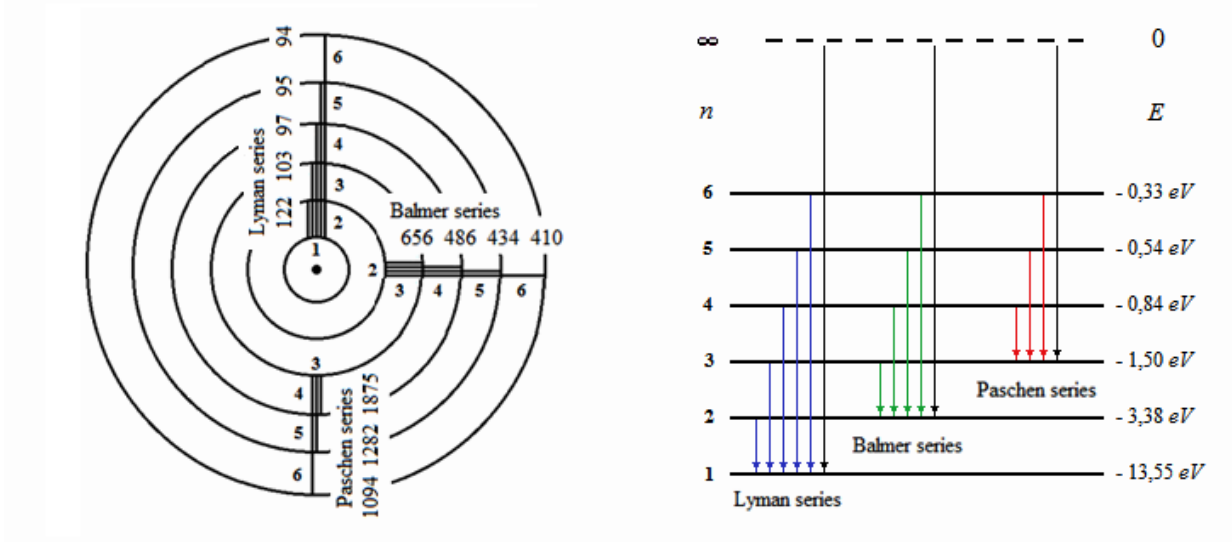

Figure 2. The classical model of Bohr stationary electron orbits and the resulting scheme of hypothetical quantum jumps regulating the induction of the first three series of the linear spectrum of hydrogen.

defined portions equal to the energy difference of the corresponding stationary states of mercury atoms.

The closest to the ground state of the mercury atom is the excited state, which is 4.86 eV away from normal. Thus, while the potential difference between C and G_1 turns out to be less than 4.86 V, free electrons experience only elastic collisions with atoms. When the accelerating voltage reaches the value eU_2 = 4.86 eV, the electron velocity becomes sufficient to realize inelastic collision, in which almost all of their kinetic energy is transferred to the electron shells of atoms (Figure 3).

Consequently, the electrons emitted by the cathode, having lost their initial velocity, cannot overcome the retarding potential applied between G_2 and A. This circumstance reasonably explains the reason for the first drop in the voltage characteristic of mercury at a voltage U_2 = 4.86 V. In turn, all its subsequent peaks turn out to be caused by the primary acceleration of free electrons to the value of their kinetic energy, which makes it possible to realize two, three, etc. inelastic collisions, taking into account the resulting cycle of energy losses.

In addition, mercury atoms, which have received some energy E during inelastic collision with electrons, pass into the corresponding excited state and must return to their normal form by emitting a light quantum with a frequency $f_r = \Delta E / h$. Thus, based on the physically measured value of ΔE = 4.86 eV, it is possible to calculate the corresponding wavelength equal to $\lambda = hc \approx 255$ nm. In turn, the repeated Franck-Hertz experiment, conducted with a four-electrode vacuum lamp enclosed in a quartz shell, directly confirmed the actual presence of an ultraviolet line of the atomic spectrum of mercury with λ = 254 nm.

In other words, the Franck-Hertz experiments confirmed the Bohr postulates, thereby playing a crucial role in choosing the main direction of development of modern quantum physics, which has gone into a fundamental break with the premises of classical Newtonian mechanics. It should be noted that Bohr and his supporters insisted on the completeness of the Copenhagen interpretation developed by them, the completeness of which was doubted by A. Einstein, confident in the existence of hidden parameters describing quantum phenomena at a deeper physical level [Einstein, Podolsky and Rosen, 1935].

3 Relativistic model of spectral electron orbits

Taking into account this circumstance, the authors tried to synthesize an alternative description of the mechanism of generation of the considered voltage characteristic, which does not go beyond the framework of traditional physics. At the same time, the main goal of the study was to find the possibility of excluding stationary orbits postulated by Bohr from the general consideration of the planetary model of the Rutherford atom. In addition, a number of previously obtained author's results were used to achieve this goal [Eremin et al, 2010], [Eremin and Eremina, 2016], [Eremin et al, 2020].

Consider the Planck equation against the background of its direct application to the planetary model of the Rutherford atom. It is quite obvious that the rotation frequency f of an electron moving with linear velocity v along a circular orbit of radius r can be correctly expressed by the classical formula $f=\nu/(2\pi r)$. Consequently, the orbital radii and velocities of atomic electrons are related to their quantum energy characteristics by the relation:

$$E(\nu, r) = \frac{h\nu}{2\pi r}. \tag{8}$$

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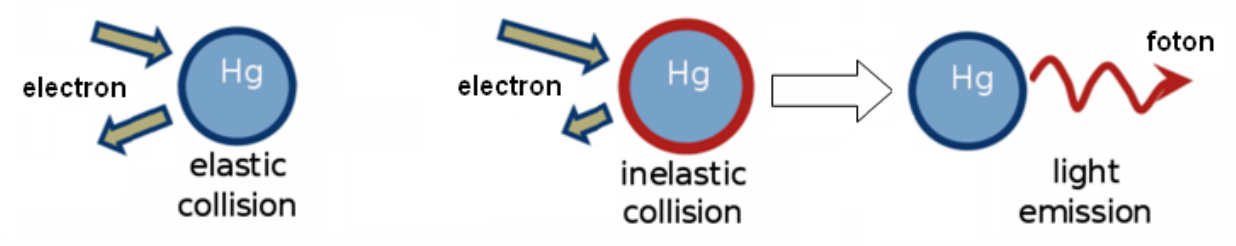

Figure 3. The traditional interpretation of the mechanisms of elastic and inelastic collisions of electrons with mercury atoms based on the use of Bohr stationary orbits.

At first glance, the description of the Rutherford atom of the form (1) uses a force balance model, which excludes the possibility of its unconditional connection with equation (8). However, the values of Coulomb and centrifugal forces are uniquely de-termined by their energy parameters. Therefore, there is an equivalent formulation linking the potential *P* and kinetic *T* of the electron energy within the framework of the condition for the realization of its first orbital velocity:

$$\frac{Ze^2}{4\pi\varepsilon_0 r} = m_e\nu^2 \implies P(r) = 2T(\nu). \qquad (9)$$

If we assume that the Planck energy is a strict physical analogue of the potential energy of an electron, then the minimum value of its linear velocity, resulting from the combination of expressions (8) and (9) under the hypothetical condition E_0=*E*(ν_0, r_0)=*P*(r_0), turns out to be equal:

$$\nu_0 = \frac{Ze^2}{2\varepsilon_0 h}. \qquad (10)$$

In this case, the numerical value of the corresponding orbital radius, resulting from expressions (9) and (10), will be:

$$r_0 = \frac{4\pi\varepsilon_0}{Ze^2 m_e}\left(\frac{h}{2\pi}\right)^2. \qquad (11)$$

Thus, we have obtained an analogue of the first Bohr radius, synthesized by means of classical premises. It should be noted that the considered electron orbit, taking into account the objective presence of radiation friction [Lorentz, 1909], is unstable, i.e. practically unrealizable and represents only a reference element of the desired physical model.

In turn, following the general provisions of the special theory of relativity [Einstein, 1916], the measurement by an external stationary observer of the frequency characteristics of high-speed systems makes it necessary to take into account objective relativistic corrections. Therefore, it is advisable to consider the Planck equation of the form (8) in a rather original form of writing:

$$E(\nu, r) = \frac{h\nu}{2\pi r}\left(1 - \frac{\nu^2}{c^2}\right)^{-\frac{1}{2}}. \qquad (12)$$

Suppose that the linear orbital velocity of an electron is a multiple of a certain part of the speed of light, for example, $^1/_2\, c$, $^6/_7\, c$ and so on:

$$\nu_{n,m} = \frac{n}{m}c, \qquad (13)$$

here *m* is the fraction of the speed of light, *n* is the number of fractions of the speed of light in the orbital velocity. In this case, the expression (13) can be represented as:

$$\nu_{n,m} = n\nu_m, \nu_m = \frac{c}{m}, \qquad (14)$$

where v_m is the basic component of the orbital velocity of the electron.

The direct union of the relations (12)-(14) gives the equation:

$$E(\nu, r) = \frac{h\nu_m}{2\pi r}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)^{-\frac{1}{2}}. \qquad (15)$$

Leaving unchanged the hypothesis that *E*(ν, *r*)=*P*(*r*), and considering (12), we have:

$$\nu_m = \frac{Ze^2}{2\varepsilon_0 h}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)^{\frac{1}{2}}. \qquad (16)$$

Thus, taking into account the physical condition for the realization of the second orbital velocity *P*(*r*)=*T*(ν_m), the original formula of the radii of spectral electron orbits follows directly on the basis of relation (9):

$$r_{n,m} = \frac{2r_0}{Z}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)^{-1}. \qquad (17)$$

Substituting into expression (17) the values of *n* and *m* corresponding to the spectral series of Lyman, Balmer, Paschen, and so on, gives an alternative visualization of the energy electronic levels of hydrogen (Figure 4).

Analyzing the configuration of the electron orbits of an atom obtained by the au-thors, it is easy to notice that

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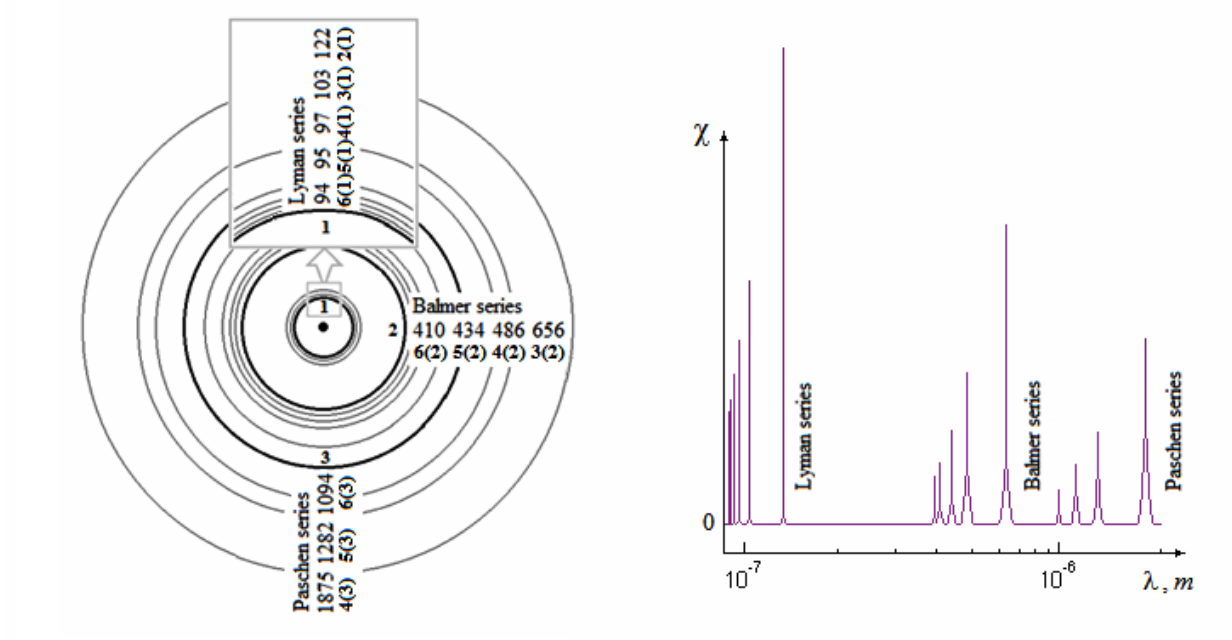

Figure 4. An alternative model of spectral electron orbits and the corresponding long-wave dependence of the optical absorption index, which determines the generation of the first three series of the linear spectrum of hydrogen.

it is radically different from its generally accepted analogue. Indeed, equation (17) describes an extended set of "spectral" orbits, the classical resonances of which fully correspond to the entire set of observed spectral lines. Bohr's formula of the form (3) implies the presence of only a minimum number of "stationary" orbits that determine quantum jumps in pairs corresponding to individual lines.

In addition, based on the traditional Planck formula E=hf, taking into account the assumption $E(\nu, r)$=P(r), and also using expression (14), it is possible to obtain a rela-tion similar to the Balmer-Rydberg formula of the form (7):

$$f = \frac{1}{h} \cdot \frac{Z^2 e^2}{4\pi\varepsilon_0 (2r_0)} \left(\frac{1}{n^2} - \frac{1}{m^2} \right). \qquad (18)$$

Thus, directly within the framework of the described study, a somewhat modified interpretation of the physical essence of the Rydberg frequency constant follows, which is fundamentally equivalent to its Bohr formulation:

$$R = \frac{1}{h} \cdot \frac{e^2}{4\pi\varepsilon_0 (2r_0)} = \frac{m_e e^4}{8h^3 \varepsilon_0^2}. \qquad (19)$$

A comparison of the quantum interpretation of the Bohr atom and its relativistic formulation shows that they are practically equivalent, since any of them allows us to substantiate the generalized Balmer-Rydberg formula. However, the Bohr model is en-tirely based on very specific stationary orbits, the physical properties of which clearly contradict the classical electromagnetic theory of Maxwell. The author's interpretation of the quantum nature of the atom uses a completely different definition of its electronic orbits, the peculiarity of which is the objective presence of a certain reserve of kinetic energy that allows the electron to stay in the spectral orbit for some time, even losing energy to overcome radiation friction.

In addition, estimating the calculated values of the orbital radii, it can be noted that the outer boundary of the atom considered on the basis of the Bohr interpretation (n=7; r_n=49r_0/Z), turns out to be about 5.5 times smaller than that of the same atom described by its relativistic analogue (n=6, m=7; r_0,m≈271r_0/Z). Consequently, the proposed quantum model agrees much better with the need for a strong discharge of gases, which provides the physical possibility of practical generation of their linear spectra [Pfund, 1924].

4 Behavioral strata of radial-velocity dependence

Currently, it is believed that the experience of Franck and Hertz is an indisputable proof of the physical existence of stationary atomic orbits. However, applied research conducted at the University of Hamburg shows that the distance between neighboring maxima and minima of characteristic $I(U_2)$, which is commonly assumed to be a con-stant parameter of the quantum transition of an atom to a lower excited state, increases with the increase in the total number of emissions generated by it [Rapior, Sengstock and Baev, 2006].

In turn, the relativistic interpretation of the mechanism of formation of linear spectra makes it possible to abandon the concept of stationary orbits of an atom described

by ordinal numbers by replacing them with spectral orbits characterized by fractional values of the speed of light. Consequently, a pair of the main quantum numbers of stationary orbits necessary to describe the corresponding spectral line becomes the eigenvalues of a single orbit resonating at a given frequency.

At the same time, the presence of formulations (13) and (17) makes it possible to form a radial-velocity dependence $\nu(r)$, similar to current-voltage characteristics and describing the energy characteristics of electronic orbits, using only their own quantum parameters – n and m. In this case, the velocity and radius of the orbit of a spectral electron can be related to the values measured by Franck and Hertz by means of the following relations [Feynman, Leighton and Sands, 1963]:

$$\begin{aligned} I(\nu) &= \frac{\partial Q}{\partial t} = eNS\nu; \\ U_2(r) &= E\partial x = \frac{eNr}{2\varepsilon_0 S}, \end{aligned} \tag{20}$$

where Q is the total charge of free carriers; N is their concentration on a limited flat ar-ea; S is the area of the selected area; ν is the velocity of movement of charge carriers; E is the intensity of the electric field generated by a uniformly charged infinite plane; x is the distance between the plane and the charge carrier; r is the radius of the excited elec-tron shell.

Let us consider the features of the proposed solution in the case of the objective absence of any control actions, then when the braking potential is turned off for the minimum possible temperature of the test gas. It is quite obvious that a gradual increase in the accelerating voltage initiates electronic transitions characterized by the minimum values of sequentially occupied spectral orbits, and the corresponding values of the electron velocity will increase by a multiple of the smallest fraction of the speed of light. The mechanism of such electronic transitions can be described as follows.

Initially, the free electrons emitted by the heated cathode are accelerated to a certain minimum speed, allowing them to knock out the atomic electrons of the test gas in the event of their inelastic collisions. Suppose that the released electrons leave their orbits, having their own linear velocity, determined by the formula (17). At the same time, previously free cathode electrons, having lost part of their initial energy, pass into a bound state characterized by the quantum parameters of the nearest excited orbit of the form: n_{i+1}=n_i+1, m_{i+1}=m_i. Thus, the relativistic interpretation of the quantum nature of linear spectra provides a sufficiently substantiated possibility of a theoretical description of the radial-velocity dependence (Figure 5), similar to the current-voltage characteristic of the electronic conductivity of gases, physically observed under the conditions under consideration.

On the other hand, an increase in the internal temperature of a gas-filled lamp cre-ates objective conditions that physically restrict the free expansion of the atoms of the gas under test, directly caused by electronic transitions to the previously considered ex-cited states. At the same time, it is quite reasonable to assume that this circumstance causes the need for compaction of the basic sequence of excited spectral orbits. Indeed, evaluating the behavioral stratum of maximally compacted dependence Figure 6), one can notice its good qualitative compliance with modern experimental data [Rapior, Sengstock and Baev, 2006]. Thus, it can be concluded that the forced control of the temperature of the discharged gas located inside the four-electrode lamp of the experimental setup under consideration actually regulates the physical conditions of direct activation of spectral orbits excited by cathode electrons. In other words, this circumstance provides a practical possibility of a steady repetition of the results of the Franck-Hertz experiment with a small amount of deterrent potential.

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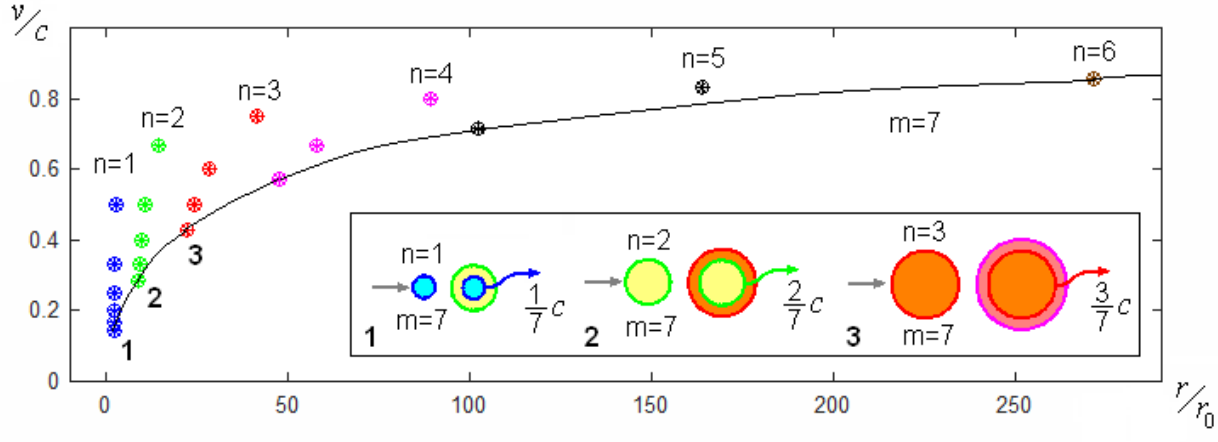

Figure 5. Relativistic radial-velocity dependence of linear hydrogen spectra: blue dots – Lyman series; green dots – Balmer series; red dots – Paschen series; purple dots – Bracket series; black dots – Pfund series; brown dots - Humphrey series.

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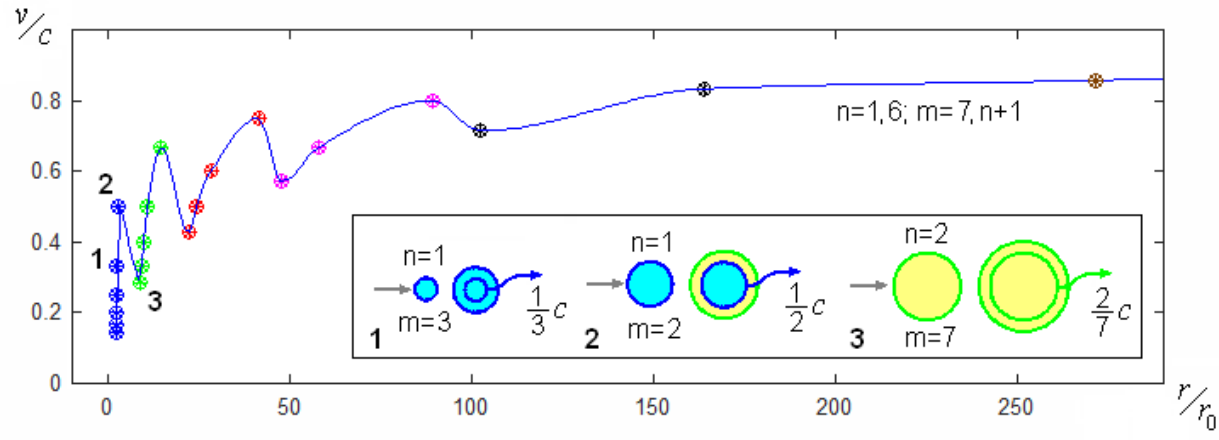

Figure 6. Theoretical graph of the relativistic dependence of v(r) of hydrogen under the existence of a restraining control action.

5 Conclusions

The generally accepted recognition of the possibility of the existence of specific stationary orbits in an atom, laid down by Bohr as the basis of his initial quantum model, is based, one way or another, on the corresponding justification of the experimental results of Franck and Hertz, which regulated the constancy of the energy parameters of the quantum transition of an atom to a minimally excited state. In turn, modern studies of the physical features of this experiment, repeated at different temperatures, significantly undermine its historically established picture, which ten years ago was considered truly fundamental.

To get out of this situation, Rapiar, Seng stock and Bear propose to supplement the description of the mechanisms of inelastic collisions of electrons with atoms with some variable value of their free path, without changing their traditional interpretation. On the other hand, an alternative interpretation of the quantum nature of the linear spectra of hydrogen-like systems based on a relativistic interpretation of the phenomena under study turns out to be no less effective, having a number of undoubted advantages. Namely, the replacement of the general concept of Bohr stationary orbits with their classical spectral analogues proposed in its framework actually returns quantum physics to its classical channel, the existence of which Einstein insisted on.

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