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Could ordinary quantum mechanics be just fine for all practical purposes?

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Abstract The inconsistency and the fundamental obscurity in quantum mechanics have provoked the controversy of many years together with numerous interpretations and attempt to create a more consistent theory of quantum phenomena. To create such a theory the orthodox description of quantum phenomena ought be considered impartially. It is important to draw the reader's attention to the incompleteness of the orthodox description of some quantum phenomena and to the contradiction between theoretical predictions and experimental results. The uncovered impossibility to describe quantum phenomena observed at measurements of atoms and superconducting rings with the help of the same Hamiltonian casts doubt on the successfulness of quantum mechanics for all practical purposes.

Keywords Foundations of quantum mechanics · Bohr quantization · Schrodinger's wave function · Schrodinger's interpretation · Born's interpretation · Macroscopic quantum phenomena · Superconductivity · Quantum periodicity · Zeeman effect · Two kinds of momentum · Canonical Hamiltonian · Non-canonical Hamiltonian

1 Introduction

The progress of physics in the last century is undeniably connected with quantum mechanics. But John Bell said that "This progress is made in spite of the fundamental obscurity in quantum mechanics. Our theorists stride through that obscurity unimpeded... " (see p. 170 in [1]) because "they are likely to insist that ordinary quantum mechanics is just fine 'for all practical purposes'" [2,3]. Bell [2,3] and other critics of quantum mechanics agreed with that ordinary quantum mechanics describes successfully all or almost all quantum phenomena. I would like to draw the reader's attention to experimental results and contradictions of quantum description testifying against this belief of almost all physicists.

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2 What is the 'force' propelling the mobile charge carriers to move in the direction opposite to the electromagnetic force?

As far back as 1913 Bohr postulated that the angular momentum $m_p = rp$ of an electron in an atom should have discrete values $m_p = n\hbar$. Following to Schrodinger [4], Bohr's stationary energy levels of the hydrogen atom [5] can be obtained from the Hamiltonian

$$\hat{H} = \frac{1}{2m}(-i\hbar\nabla - qA)^2 + U \tag{1}$$

in which the potential energy $U = -\mathrm{e}^2/r$ and the magnetic vector potential $A = 0$. This Hamiltonian can be used in other cases, for example the case of electron (or other particles) moving free along one-dimensional ring with a radius r_r, a width w and a thickness d. The potential energy in this case is equal $U = -U_0$ inside the ring, $r_r - w/2 < r = (x^2 + y^2)^{1/2} < r_r - w/2$, $-d/2 < z < d/2$ and $U = 0$ outside the ring. The solutions of Schrodinger's equation $\hat{H}\Psi = E\Psi$ are described with the wave function $\Psi = |\Psi|\mathrm{e}^{i\varphi}$, in which $|\Psi|^2 = 1/wh2\pi r_r = 1/s2\pi r_r$ inside the homogeneous ring and $|\Psi|^2 = 0$ outside the ring. The ring is one-dimensional because we consider the permitted states with the minimal energy corresponding to zero momentum along r and z, $p_r = \Psi^*(-i\hbar\partial/\partial r)\Psi = |\Psi|^2\partial\varphi/\partial r = 0$, $p_z = \Psi^*(-i\hbar\partial/\partial z)\Psi = |\Psi|^2\partial\varphi/\partial z = 0$. The quantization of angular momentum

$$m_p = \oint_l \mathrm{d}l s r \Psi^* \hat{P}_l \Psi = \oint_l \mathrm{d}l s r \Psi^*(-i\hbar\partial/\partial l)\Psi = sr|\Psi|^2\hbar \oint_l \mathrm{d}l\partial\varphi/\partial l = \hbar n \tag{2}$$

may be deduced from the requirement $\oint_l \mathrm{d}l\partial\varphi/\partial l = n2\pi$ that the complex wave function must be single-valued in any point of the circumference $l = 2\pi r_r$ of the ring $\Psi = |\Psi|\mathrm{e}^{i\varphi} = |\Psi|\mathrm{e}^{i(\varphi+n2\pi)}$. According to the canonical definition the gradient operator $\hat{P} = -i\hbar\nabla$ corresponds to the canonical momentum $p = mv+qA$ of a particle with a mass m and a charge q both with $A \neq 0$ and without $A = 0$ magnetic field [6]. Correspondingly the operator of the velocity of a particle with a charge q is $\hat{v} = (\hat{P} - qA)/m$ [7] and of the kinetic energy $m\hat{v}^2/2 = (\hat{P} - qA)^2/2m$. Therefore, the angular momentum (2) and the wave function do not change with the appearance of the magnetic flux $\Phi = \oint_l \mathrm{d}lA$ inside the ring. Whereas the velocity of a charge particle $v = (\hbar/mr_r)(n - \Phi/\Phi_0)$, its current $I = sq|\Psi|^2 v$

$$I_p = \frac{sq}{l}\oint_l \mathrm{d}l\Psi^* \frac{-i\hbar\nabla - qA}{m}\Psi = \frac{n\Phi_0 - \Phi}{L_\mathrm{k}} \tag{3}$$

and its kinetic energy

$$E_\mathrm{k} = \int_V \mathrm{d}V\Psi^* \frac{1}{2m}(-i\hbar\nabla - qA)^2\Psi = \frac{(n\Phi_0 - \Phi)^2}{2L_\mathrm{k}} \tag{4}$$

depend on the magnetic flux $\Phi = \oint_l \mathrm{d}lA$. $L_\mathrm{k} = ml/sq^2|\Psi|^2$ is the kinetic inductance of the ring with the length $l = 2\pi r$, the section $s = wh$ and the density $|\Psi|^2$ of particles with a charge q. The velocity, the current (3) and the kinetic energy (4) cannot be equal to zero when the magnetic flux inside the ring Φ is not divisible $\Phi \neq n\Phi_0$ by the flux quantum $\Phi_0 = 2\pi\hbar/q$. The charge q of electron equals e and of superconducting pair $2e$.

2.1 Observations of quantum periodicity

The canonical definition of the momentum operator and the Hamiltonian (1) are used for the description of quantization effects observed in superconductors [8]. The relations (3) and (4) are used for the description of quantum periodicity observed at measurements of superconducting rings (or loop) with small section $s \ll \lambda_\mathrm{L}^2$ [11–23]. $\lambda_\mathrm{L} = (m/\mu_0 q^2 n_s)^{0.5} = \lambda_\mathrm{L}(0)(1 - T/T_c)^{-1/2}$ is the London penetration depth, $\lambda_\mathrm{L}(0) \approx 50$ nm $= 5\ 10^{-8}$ m for most superconductors [24]. The kinetic inductance $L_\mathrm{k} \approx (\lambda_\mathrm{L}^2/s)\mu_0 l$ exceeds the magnetic inductance $L_\mathrm{f} \approx \mu_0 l$ in this case of weak screening. The magnetic flux $\Delta\Phi_I = L_\mathrm{f} I_p$ induced with the current I_p for a sufficiently thin superconductor with $s \ll \lambda_\mathrm{L}^2$ can always be neglected [24]. Therefore, the approximation $\Phi = \Phi_{\mathrm{ext}} + L_\mathrm{f} I_p \approx \Phi_{\mathrm{ext}}$

is valid. Here $\Phi_{ext} = BS$; B is externally produced magnetic field and $S = \pi r^2$ is the area of the ring. The quantization (2) may also be used for the description of magnetic flux quantization [25,26] and the Meissner effect [27] observed in the case of strong screening, when the superconductor size w is large $w \gg \lambda_L$ [9,10].

According to the universally recognized explanation [24] the quantum periodicity in the transition temperature [28,29], the ring resistance [11–13], its magnetic susceptibility [14] and the critical current [15,16] are observed due to the change of the quantum number n with the magnetic flux at $\Phi = (n' + 0.5)\Phi_0$. The quantum number n changes because the energy (4) is minimal and the superconducting state has maximal probability P_n at $n = n'$ when $\Phi < (n' + 0.5)\Phi_0$ and at $n = n' + 1$ when $\Phi > (n' + 0.5)\Phi_0$ [24]. The two states $n = n'$ and $n = n' + 1$ have the same value of kinetic energy in (4) $E_k = (n\Phi_0 - \Phi)^2/2L_k = \Phi_0^2/8L_k$ at $\Phi = (n' + 0.5)\Phi_0$.

The fractional depression of the transition temperature depends on the kinetic energy (4) $\Delta T_c/T_c \propto -E_k \propto -(n\Phi_0 - \Phi)^2$ [24]. Therefore, the maximums of the $T_c(\Phi)$ oscillations are observed at $\Phi = n'\Phi_0$ and the minimums at $\Phi = (n'+0.5)\Phi_0$ [29]. The oscillations $\Delta R(\Phi) \propto (n\Phi_0 - \Phi)^2$ [11–13] measured in the fluctuation region near the transition temperature, where the resistance changes from $R = 0$ at $T < T_c$ to $R = R_n$ at $T > T_c$, are considered as a consequence of the $T_c(\Phi)$ oscillations [28]. The magnetic susceptibility measured in the fluctuation region equals zero at $\Phi = n'\Phi_0$ and $\Phi = (n' + 0.5)\Phi_0$ [14] because it is proportional to the persistent current average in time $\Delta\Phi_{Ip} = L_f\overline{I_p}$: $\overline{I_p} \approx (n'\Phi_0 - \Phi)/L_k = 0$ at $\Phi = n'\Phi_0$ and $\overline{I_p} \approx P_{n'}(n'\Phi_0 - \Phi)/L_k + P_{n'+1}[(n'+1)\Phi_0 - \Phi]/L_k = 0$ because $P_{n'} = P_{n'+1}$ at $\Phi = (n' + 0.5)\Phi_0$. The persistent current (3) corresponding to the minimal energy (4) is diamagnetic at $n'\Phi_0 < \Phi < (n' + 0.5)\Phi_0$ and paramagnetic at $(n' + 0.5)\Phi_0 < \Phi < (n' + 1)\Phi_0$. Magnetic field dependence of the critical current $I_c(\Phi)$ of a symmetrical ring has the maximums at $\Phi = n'\Phi_0$ and the minimums at $\Phi = (n' + 0.5)\Phi_0$, see Fig. 2 in [15,16], because the persistent current increases the total current in one of the ring halves, see below, and, therefore, $I_c = I_{c0} - 2|I_p| = I_{c0} - 2|n\Phi_0 - \Phi|/L_k$. Thus, Bohr's quantization (2) and the influence of the magnetic vector potential A on the phase $\nabla\varphi$ of the wave function (sometimes called the Aharonov–Bohm effect [30]) seem to describe successfully numerous quantum phenomena observed in superconducting rings and also in normal metal mesoscopic rings [31,32].

2.2 Direct electric current can flow against the direct electric field

A number of authors [33–35] consider a superconducting loop as an artificial atom because its spectrum of permitted states is discrete due to of Bohr's quantization. This artificial atom provides additional experimental opportunities for studies of quantization phenomena. We can, for example, make an asymmetric ring with different sections $s_w > s_n$ of the ring halves, Fig. 1. It is well known that the potential difference

$$V = 0.5(R_n - R_w)I \tag{5}$$

is observed due to different resistance $R_n = \rho 0.5l/s_n > R_w = \rho 0.5l/s_w$ of the ring halves when a conventional electric current I circulates in the ring clockwise or anticlockwise, Fig. 1. According to experimental results the persistent current is observed at non-zero resistance, in the fluctuation region near T_c of superconducting ring [11–14,28,29] and in normal metal mesoscopic rings [31,32]. Therefore, we can answer experimentally on the fundamental question: "Could the persistent current induce the potential difference on the asymmetric ring, like the conventional electric current?" This dc voltage should change periodically in magnetic field like the average value of the persistent current $\overline{I_p}$. Such quantum oscillations of the dc voltage $V_{dc}(\Phi) \propto \overline{I_p}(\Phi)$ were observed at measurements of asymmetric superconducting rings [11–13,19,20,23] and of an asymmetric superconducting quantum interference device [36]. The dc voltage changes its sign at $\Phi = n'\Phi_0$ and $\Phi = (n' + 0.5)\Phi_0$, Fig. 1, as well as the average value of the persistent current $\overline{I_p}$.

This phenomenon reveals a puzzle. It is well known that the electric current I cannot decay at $R_n + R_w > 0$ due to the non-potential Faraday's voltage $(R_n + R_w)I = -\mathrm{d}\Phi/\mathrm{d}t$. Therefore, Ohm's law $j\rho = E = -\nabla V - \mathrm{d}A/\mathrm{d}t$ is valid both in the narrow $R_nI = V - 0.5\mathrm{d}\Phi/\mathrm{d}t$ and wide $R_wI = -V - 0.5\mathrm{d}\Phi/\mathrm{d}t$ halves, as well as the force balance $qE + f_{dis} = 0$. Here qE and f_{dis} are the forces of the electric field and the dissipation force acting on each mobile charge carrier. But the dc voltage $V_{dc}(\Phi) \propto \overline{I_p}(\Phi)$ is observed at magnetic flux $\Phi \neq n'\Phi_0$ and

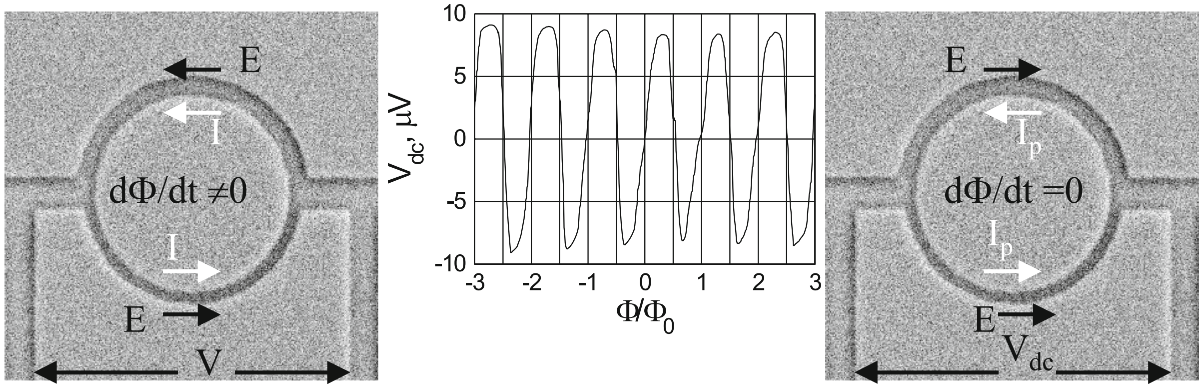

Fig. 1 The *left picture* A conventional electric current I maintained by the non-potential Faraday's voltage $(R_n + R_w)I = -\mathrm{d}\Phi/\mathrm{d}t$ induces the potential difference V on the ring halves with different resistance $R_n > R_w$. The current direction agrees with the direction of the electric field $E = -\nabla V - \mathrm{d}A/\mathrm{d}t$ in the both halves due to the Faraday's voltage $-\mathrm{d}\Phi/\mathrm{d}t = -l\mathrm{d}A/\mathrm{d}t$. The *middle picture* The quantum periodicity in the dc voltage is measured on the halves of asymmetric superconducting ring [11–13,19–23]. The dc voltage $V_{\mathrm{dc}}(\Phi)$ is observed when the magnetic flux $\Phi \neq n'\Phi_0$ and $\Phi \neq (n' + 0.5)\Phi_0$ is constant in time $\mathrm{d}\Phi/\mathrm{d}t = 0$. The *right picture* The observation of the potential difference without the Faraday's voltage $-\mathrm{d}\Phi/\mathrm{d}t = 0$ gives direct evidence of the paradox which cannot be described completely: the persistent current I_{p} circulating clockwise or anticlockwise flows in one of the ring halves against the dc electric field $E = -\nabla V_{\mathrm{dc}}$ directed from left to right or from right to left. The photo of a real aluminium ring with the radius $r = 2\ \mu m$ is shown. Such ring was used for the observation of the $V_{\mathrm{dc}}(\Phi)$ oscillations shown at the *middle*

$\Phi \neq (n' + 0.5)\Phi_0$ constant in time $\mathrm{d}\Phi/\mathrm{d}t = 0$, Fig. 1. Consequently the persistent current $\overline{I_p}(\Phi)$ flows against the electric field $E = -\nabla V_{\mathrm{dc}}$ in one of the ring halves, Fig. 1. This puzzle may be obviously connected with other puzzle. The authors [31] note fairly that "An electrical current induced in a resistive circuit will rapidly decay in the absence of an applied voltage". But the persistent current does not decay in resistive rings [11–13,28,31,32]. The authors [31,37] claim that this equilibrium current flowing through a resistive circuit is dissipationless. The author [37] confesses that "The idea that a normal, nonsuperconducting metal ring can sustain a persistent current—one that flows forever without dissipating energy—seems preposterous". This idea is not only preposterous but also useless because it cannot explain how the persistent current can flow against electric field, Fig. 1.

The dc voltage $V_{\mathrm{dc}}(\Phi) \propto \overline{I_p}(\Phi)$ is observed when a noise [11–13,19,20,23] or an ac current [17,18,21,22] switches the ring or ring segments between superconducting and normal states. A ring segment l_A may be also switched with the help of laser beam heating, Fig. 2. All segments of the ring are in superconducting state at $T < T_c$ when the laser beam is turned off, see the left picture of Fig. 2. The persistent current (3), circulating clockwise at $\Phi \neq \Phi_0/4$ due to the quantization (2), Fig. 2, should decay $I(t) = I_p \exp -t/\tau_{RL}$ during the relaxation time $\tau_{RL} = L_{\mathrm{t}}/R_{A,n}$ when the laser beam will heat the segment l_A above the critical temperature $T > T_c$ at $t = 0$. Here $L_{\mathrm{t}} = L_{\mathrm{f}} + L_{\mathrm{k}}$ is the total inductance of the ring; $R_{A,n} = \rho l_A/s_w$ is the resistance of the segment l_A in the normal state. The potential voltage $V_A = I(t)R_{A,n}$ will maintain the current $I(t)$ of electrons in the segment l_A and will brake superconducting pairs in other segments of the ring. The potential difference observed between points 1 and 2 should be equal $V_{12} = L_{k,12}\mathrm{d}I(t)/\mathrm{d}t = -(L_{k,12}/\tau_{RL})I_p \exp -t/\tau_{RL} = -R_{ef} I_p \exp -t/\tau_{RL}$, according to the Newton's second law $m\mathrm{d}v/\mathrm{d}t = qE = -q\nabla V$, when the approximation of weak screening $L_{\mathrm{f}} \ll L_{\mathrm{k}}$ is valid. Here $R_{ef} = L_{k,12}/\tau_{RL} \approx R_{A,n}L_{k,12}/L_{\mathrm{k}} \approx R_{A,n}/2$ if the section switched in the normal state is small $l_A \ll l$.

We can turn on the laser beam with a frequency $f_{sw} = N_{sw}/\Theta$. The voltage $V_{12} = L_{k,12}\mathrm{d}I(t)/\mathrm{d}t = -(L_{k,12}/\tau_{RL})I_p \exp -t/\tau_{RL} = -R_{ef} I_p \exp -t/\tau_{RL}$ will appear each time after the transition of the segment l_A in the normal state, if the frequency is not very high $f_{sw} < 1/(\tau_l + \tau_s)$. Here τ_l is the time of the cooling of the segment l_A from $T > T_c$ to $T < T_c$; $\tau_s \approx \pi\hbar/8k_B(T_c - T)$ is the time of the relaxation in superconducting state. The potential voltage average in time

$$V_{\mathrm{dc}} = \int_0^{\Theta} \mathrm{d}t \frac{V_{12}(t)}{\Theta} = \sum_{i=1}^{i=N_{sw}} \frac{R_{ef} I_{p,i}}{N_{sw}} f_{sw} \int_{t_i}^{t_i+t_n} \mathrm{d}t \exp -\frac{t - t_i}{\tau_{RL}} \qquad (6)$$

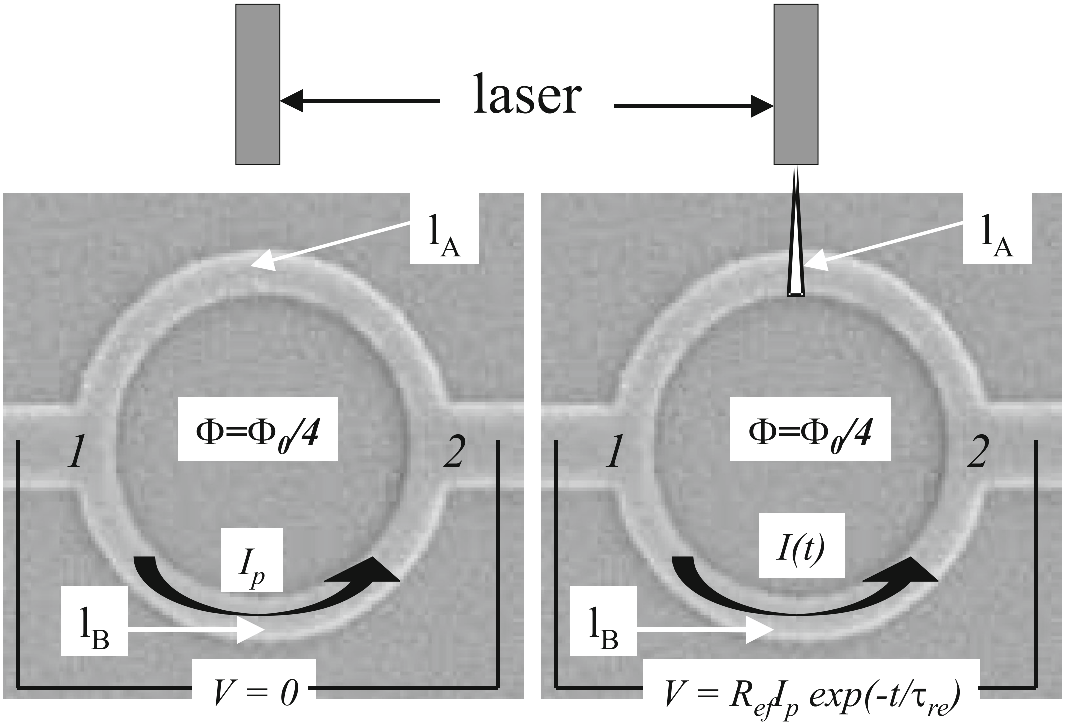

Fig. 2 Superconducting ring can be switched between the states with different connectivity of the wave function with a real physical influence, for example turning on (the *right picture*) and turning off (the *left picture*) of the laser beam heating the segment l_A above T_c. The persistent current, equal $I_p = -\Phi_0/4L_k$ should circulate when the magnetic flux inside the ring $\Phi = \Phi_0/4$ and all its segments are superconducting (the *left picture*). The current should decay during the relaxation time $\tau_{RL} = L/R_{A,n}$ after the transition of the segment l_A in the normal state with a resistance $R_{A,n}$ (the *right picture*). The potential difference will appear after this transition between points *1* and 2. No theory can say how quickly the current I_p will appear in the distant segment l_B after the transition of the segment l_A in superconducting state

is not zero when the average value $\overline{I_p} = \sum_{i=1}^{i=N_{sw}} I_{p,i}/N_{sw}$ of the persistent current $\overline{I_p} = (\overline{n}\Phi_0 - \Phi)/L_k$ is not zero [38,39]. Here $\overline{n} = \sum_n nP_n(\Phi)$ and $P_n(\Phi)$ is the probability of the switching in superconducting state with the quantum number n at magnetic flux inside the ring Φ; t_i is the time of the i turning on of the laser beam; t_n is the time during which the segment l_A is in the normal state. According to (6) the dc voltage $V_{dc} \approx \overline{I_p}L_{k,12}f_{sw}$ could be observed at $t_n \gg \tau_{RL}$ and $V_{dc} \approx \overline{I_p}R_{ef}f_{sw}t_n$ at $t_n \ll \tau_{RL}$.

The ring resistance average in time is not equal zero $\int_0^\Theta dt R_A(t)/\Theta \approx R_{A,n}f_{sw}t_n > 0$ when the segment l_A is switched between superconducting and normal states. Nevertheless the electric current average in time $\int_0^\Theta dt I(t)/\Theta \approx \overline{I_p}(1 - f_{sw}t_n)$ circulates in the ring clockwise or anticlockwise. It is possible because the current decaying at $R_A(t) = R_{A,n} > 0$ down to $I = 0$ at $t_n \gg \tau_{RL}$ must increase up to I_p (3) due to the quantization demand (2) when the segment l_A reverts to superconducting state. The angular momentum of each pair changes from $m_p = \hbar n$ to $m_p = q\Phi/2\pi = \hbar\Phi/\Phi_0$ when $R_A(t) = R_{A,n} > 0$ under influence of the dissipation force $f_{dis} = -\eta v$: $dm_p/dt = (2\pi)^{-1}\oint_l dl dp/dt = (2\pi)^{-1}\oint_l dl(qE + f_{dis}) = (2\pi)^{-1}\oint_l dl f_{dis}$. The potential electric field cannot change the angular momentum because $\oint_l dl qE = -q\oint_l dl\nabla V \equiv 0$. The contrary change from $m_p = \hbar\Phi/\Phi_0$ to $m_p = \hbar n$ should occur due to the quantization (2) when the segment l_A reverts to superconducting state. Consequently the angular momentum average in time does not change $\Theta^{-1}\int_0^\Theta dt dm_p/dt = \hbar(\Phi/\Phi_0 - \overline{n})f_{sw} + \hbar(\overline{n} - \Phi/\Phi_0)f_{sw} = 0$ and we can write the force balance $\Theta^{-1}\int_0^\Theta dt(2\pi)^{-1}\oint_l dl f_{dis} + \hbar(\overline{n} - \Phi/\Phi_0)f_{sw} = (2\pi)^{-1}\oint_l dl\overline{f_{dis}} + rf_q = 0$. The change $f_q = \hbar(\overline{n} - \Phi/\Phi_0)f_{sw}/r$ of the momentum p in a time unit due to the quantization (2) was called in [40] "quantum force".

2.3 Transition between the continuous and discrete spectrum of permitted states

Thus, both the experimental puzzles are deduced from the quantization (2), the principal law of quantum mechanics, without the preposterous claim of the authors [31,37] about a possibility of a dissipationless current flowing through a resistive circuit. According to quantum mechanics, the spectrum of permitted states can be continuous and discrete. The transition between these spectrum impossible in the case of atom is possible in the case of superconducting loop. The difference of the kinetic energy (4) $E_{\mathrm{k}} = I_p\Phi_0(n - \Phi/\Phi_0)/2 = I_{p,A}\Phi_0(n - \Phi/\Phi_0)^2$ between the permitted states $\Delta E_{\mathrm{k}} = E_{\mathrm{k}}(n+1) - E_{\mathrm{k}}(n) = I_{p,A}\Phi_0[1 + 2(n - \Phi/\Phi_0)]$ of real superconducting rings exceeds strongly the energy of thermal fluctuation $k_B T$ when $\Phi \neq (n + 0.5)\Phi_0$. The value $I_{p,A}\Phi_0/k_B$ corresponds to the temperature 1500 K at a typical amplitude $I_{p,A} = 10\ \mu A$ [17,18] of the persistent current $I_p = I_{p,A}2(n - \Phi/\Phi_0)$. The quantum periodicity [11–23] could not be observed without the predominate probability $P_n \propto \exp -E_n/k_B T$ of the permitted state with minimum energy (4). The energy difference $\Delta E_{\mathrm{k}} \approx I_{p,A}\Phi_0$ can be reduced down to zero with the help of the depression of the pair density n_s in the ring segment l_A from $n_{s,0}$ to $n_{s,A}$ because $I_{p,A} = q\hbar/2mr\overline{(sn_s)^{-1}} \approx (q\hbar/2mr)sln_{s,A}n_{s,0}/(ln_{s,A} + l_A n_{s,0} - l_A n_{s,A})$ [39,40]. The latter relation is deduced from the quantization of velocity $\oint_l \mathrm{d}lv = \oint_l \mathrm{d}lI_p/qsn_s = (lI_p/q)\overline{(sn_s)^{-1}} = (2\pi\hbar/m)(n - \Phi/\Phi_0)$, where $\overline{(sn_s)^{-1}} = l^{-1}\oint_l \mathrm{d}l1/sn_s$

The consideration of the transition between continuous and discrete spectrum of permitted states [39] reduces the two experimental puzzles to one question: "What is the 'force' propelling the mobile charge carriers in the superconductor to move in direction opposite to the electromagnetic force?" The mobile charge carriers (superconducting pairs) accelerate in accordance with the Newton's second law $m\mathrm{d}v/\mathrm{d}t = qE$ when the externally produced magnetic field increases in time $\mathrm{d}\Phi_{\mathrm{ext}}/\mathrm{d}t = S\mathrm{d}B/\mathrm{d}t = (L + L_{\mathrm{k}})\mathrm{d}I_p/\mathrm{d}t$: $d(\Phi_{\mathrm{ext}} - LI_p)/\mathrm{d}t = El = L_{\mathrm{k}}\mathrm{d}I_p/\mathrm{d}t = (lm/q)\mathrm{d}v/\mathrm{d}t$. The electric current decays down to zero after switching of the ring segment l_A, Fig. 2, in the normal state also in accordance with the Newton's second law [39]. But the persistent current (3) appears contrary to the Newton's second law when the segment l_A, Fig. 2, returns to superconducting state. This puzzle is consequence of the well-known difference between superconductivity (as macroscopic quantum phenomenon) and perfect conductivity. The Meissner effect discovered as far back as 1933 [27] is the first experimental evidence of this difference and this puzzle. Therefore, the astonishment expressed by Jorge Hirsch is valid: "Strangely, the question of what is the 'force' propelling the mobile charge carriers and the ions in the superconductor to move in direction opposite to the electromagnetic force in the Meissner effect was essentially never raised nor answered" [41,42].

One may suggest some experiments for investigation of this puzzle. An additional mechanical force should act between the boundaries of the Josephson junction interrupting a superconducting loop at $\Phi \neq n/\Phi_0$ because of the increase of the kinetic energy (4) at the mechanical closing of the loop [40]. This mechanical force can be singled out at measurement due to its periodical dependence on the magnetic flux inside the loop. No theory can answer on the question of what is the force propelling the mobile charge carriers in the ring segment l_B at the transition of the segment l_A in superconducting state, Fig. 2. Therefore, we cannot say how quickly the persistent current will appear in the segment l_B after the transition of the segment l_A. This question can be investigated experimentally. It may be a very difficult experiment. It is more easy experiment to verify that the switching of the ring segment l_A between superconducting and normal states, Fig. 2, can induce the dc voltage (6).

The dc voltage can be observed at the measurement of a symmetric ring with the same section of the halves, Fig. 2, when the same segment l_A is switched, Fig. 2. But this phenomenon cannot be observed if all segments of the symmetric ring is switched with equal probability or the whole ring is switched. Therefore, the oscillations $V_{\mathrm{dc}}(\Phi)$ were observed only at the measurement of asymmetric ring, Fig. 1, when the switching was induced by a noise [11–13,19,20,23] or an ac current [17,18,21,22]. The circulating current violates clockwise–anticlockwise symmetry, whereas the observation of the dc voltage violates right–left symmetry. Therefore, the dc voltage cannot be observed both in the conventional case, $V = 0$ at $R_n = R_w$ according to (5) and in the case of the persistent current when the ring halves are identical. The persistent current is observed because of the discreteness of the permitted state spectrum both in superconducting (3) and normal metal rings [43]. The transition between discrete and continuous spectrum takes place in normal metal ring due to electron scattering [39]. We may expect an observation of the oscillations $V_{dc}(\Phi)$ at measurement of a system of asymmetric normal metal rings connected in series as in the work [23]. Such experiment would have fundamental importance.

3 Experimental results contradicting the theoretical predictions

The dc voltage $V_{dc}(\Phi)$ induced by the ac current [21,22] may be described as a consequence of the rectification effect [17,18]. The external current I_{ext}, flowing between points 1 and 2, Fig. 2, switches the ring in the normal state when the current density j reaches the critical value $j_c = qn_s v_{sc}$ in one of the ring halves [44]. Here $v_{sc} = \hbar/m\sqrt{3}\xi(T)$ is the depairing velocity [24]; $\xi(T) = \xi(0)(1 - T/T_c)^{-1/2}$ is the correlation length. The critical current of the symmetric ring, Fig. 2, equals $I_{c0} = 2sj_c$ when the persistent current (3) equals zero $I_p = 0$. The persistent current decreases the critical current

$$I_c = I_{c0} - 2|I_p| = I_{c0} - 2I_{p,A}2\left|n - \frac{\Phi}{\Phi_0}\right| \tag{7a}$$

increasing the current density $j = I_{ext}/2s + I_p/s$ in one of the ring halves [17,18]. Measurements of symmetric ring [15,16] corroborate the theoretical prediction (7a). The value (7a) does not depend on the direction of I_{ext} and I_p because of the identity of the ring halves. The rectification effect can be observed at measurement of an asymmetric ring, for example the ring with the different section of the ring halves $s_w > s_n$, Fig. 1. According to the theory, the critical current of this ring should equal

$$I_{c,n} = I_{c0} - \left(1 + \frac{s_w}{s_n}\right)|I_p| \tag{7b}$$

when the currents I_{ext} and I_p have the same direction in the narrow half s_n and

$$I_{c,w} = I_{c0} - \left(1 + \frac{s_n}{s_w}\right)|I_p| \tag{7c}$$

when in the wide half s_w. The theory predicts the anisotropy of the critical current

$$I_{c,an} = I_{c+} - I_{c-} = \left(\frac{s_w}{s_n} - \frac{s_n}{s_w}\right)I_p \tag{7d}$$

which could explain the quantum oscillations, Fig.1, of the rectified voltage. Here I_{c+} and I_{c-} are the critical current measured when the current I_{ext} flows from left to right and from right to left, Fig. 1. The positive direction of the current I_p is anticlockwise. The magnetic dependence $I_{c+}(\Phi)$ and $I_{c-}(\Phi)$ are described with the relation (7b) when the currents I_{ext} and I_p have the same direction in the narrow half s_n and (7c) when in the wide half s_w. Therefore, no modulus of I_p is written in (7d) in contrast to (7a), (7b) and (7c). The relation (7d) could explain the observed similarity of the quantum oscillations $V_{dc}(\Phi)$ and $\overline{I_p}(\Phi)$. The rectification voltage $V_{dc} \approx R_n\overline{I_{c+} - I_{c-}}/4 = (s_w/s_n - s_n/s_w)R_n\overline{I_p}/4$ may be expected to observe when the ac current $I_{ac}(t) = I_A \sin(\omega t)$ with the amplitude $I_A > I_{c+}, I_{c-}$ switches the whole ring in the normal state with the resistance R_n at $I_{ac}(t) = I_{c+}$ and $I_{ac}(t) = -I_{c-}$ [17,18].

Measurement [17,18] has corroborated that the oscillations $V_{dc}(\Phi)$ are observed due to the anisotropy of the critical current $I_{c,an}(\Phi)$. But the cause of the anisotropy differs fundamentally from the expected one. The observed oscillations $I_{c+}(\Phi)$, $I_{c-}(\Phi)$ [15–18] are described by the relation

$$I_{c+}(\Phi) = I_c\left(\Phi + \frac{\Phi_0}{4}\right);\ I_{c-}(\Phi) = I_c\left(\Phi - \frac{\Phi_0}{4}\right) \tag{7e}$$

rather than (7b) and (7c). The function $I_c(\Phi)$ is described by the relation (7a). The anisotropy

$$I_{an,ex} = I_{c+}(\Phi) - I_{c-}(\Phi) = 2I_{p,A}2\left(\left|n - \frac{\Phi}{\Phi_0} + \frac{1}{4}\right| - \left|n - \frac{\Phi}{\Phi_0} - \frac{1}{4}\right|\right) \tag{7f}$$

of the measured critical current (7e) explains the observation of the rectified voltage $V_{dc}(\Phi)$ oscillating in the magnetic field [17,18]. But the observed shift of the magnetic dependence of the critical current on $\pm\Phi_0/4$ [15–18] seems mysterious. According to the quantization condition (3), (4) the extreme values of the quantum oscillations must be observed at $\Phi = n\Phi_0$ and $\Phi = (n+0.5)\Phi_0$. The relations (7a), (7b), (7c) and the result of measurement of the symmetric ring [15,16] satisfy this principle. The maximum of (7a) is observed at $\Phi = n\Phi_0$ and the minimum at $\Phi = (n+0.5)\Phi_0$. But the magnetic dependence $I_{c+}(\Phi)$, $I_{c-}(\Phi)$ (7e) obtained at measurement of asymmetric ring have the maximum and the minimum at $\Phi = (n+0.25)\Phi_0$ and $\Phi = (n+0.75)\Phi_0$ [15–18].

According to the universally recognized opinion [24] the quantum periodicity is observed due to the change in (3) of the quantum number corresponding to the minimum energy (4) from $n = n'$ to $n = n'+1$ at $\Phi = (n'+0.5)\Phi_0$. The persistent current (3) changes by jump from $I_p = -0.5\Phi_0/L_k$ to $I_p = +0.5\Phi_0/L_k$ with the n change. This jump cannot be observed at the measurement of the critical current of the symmetric ring in accordance with (7a). But the change of the half in which the currents I_{ext} and I_p have the same direction should result to the jump of the critical current of the asymmetric ring from (7b) to (7c). Therefore, the jump $\Delta I_{c+} = (s_w/s_n - s_n/s_w)I_{p,A} = (s_w/s_n - s_n/s_w)\Phi_0/L_k$, $\Delta I_{c-} = -(s_w/s_n - s_n/s_w)\Phi_0/L_k$ should be observed at $\Phi = (n'+0.5)\Phi_0$. The absence of this jump at measurement is a most fundamental contradiction between theory and experiment. According to the Bohr quantization (2) the quantum number n describing angular momentum must be integer. Therefore, the change of this number must result in the jump of the persistent current (3). But this jump is not observed at measurements of both the asymmetric ring [17,18,45] and the ring with asymmetric link-up of current leads [46]. The quantum periodicity in the critical current observed in [17,18,45,46] testifies to the change of the quantum number n. But we cannot say, because of the continuity of the magnetic dependence of the critical current, at which value of the magnetic flux the quantum number n could change by unity.

The jump of the critical current connected with the n change was observed at measurements of more complicated structure [47]. The contradiction between the theory and experimental results was revealed also at measurements of the flux qubit (quantum bit), i.e. superconducting loop with three Josephson junctions. The flux qubit as well as superconducting ring should have the two permitted states n and $n+1$ with the non-zero persistent current $I_p(n) \approx -I_{p,A}$ and $I_p(n+1) \approx +I_{p,A}$ at $\Phi \approx (n+0.5)\Phi_0$. These two states were observed, for example, at measurements of the magnetization, see Fig. 4 in [48]. But the observations of a χ-shaped crossing of the magnetic dependence $I_p(n)$ and $I_p(n+1)$, see Fig. 4 in [49], reveal the contradiction with the theoretical prediction. According to the Bohr quantization, states with the persistent current $-I_{p,A} < I_p < +I_{p,A}$ must be forbidden at $\Phi = (n+0.5)\Phi_0$. The authors [49] interpret the χ-shaped crossing as the single-shot readout of macroscopic quantum superposition of flux qubit states and its absence as classical behavior. But this claim as well as the experimental observation of the states with $I_p(n) = I_p(n+1) = 0$ at $\Phi = (n+0.5)\Phi_0$ contradicts the orthodox quantum mechanics.

4 No theory can describe two opposite cases using the same Hamiltonian

The explanation of the quantum periodicity, considered above, is based on the assumption that the kinetic energy is a total energy of the persistent current which depends on magnetic field. But it is well known that an electric current I_p circulating in the ring with the area S induces a magnetic dipole moment equal to $M_m = I_pS$ which has an energy equal to $E_M = -M_mB = I_p\Phi$ in an externally produced magnetic field $B = \Phi/S$. The total energy $E_t = E_k + E_M$ of the persistent current must be equal to

$$E_t = E_k + E_M = \frac{n\Phi_0^2 - \Phi^2}{2L_k} \tag{8}$$

According to (5), in contrast to (4), the diamagnetic state has a minimum energy at any magnetic flux $\Phi = BS$, the quantum number n should not change with Φ and the quantum periodicity should not be observed.

4.1 We must challenge the conventional description of the quantum periodicity

The energy of the magnetic dipole moment was not taken into account in the theory of quantization [8] because only the kinetic energy of the current can be deduced from the canonical Hamiltonian (1).[1] The energy $E_M = -M_m B = I_p \Phi$ cannot be deduced from the Hamiltonian neither in the quantum nor in the classical case [50]. But it is well known that this energy exists. It is easy enough to show in the classical case that the total energy of the I_p state in an externally produced magnetic field B, defined as the energy expended for the creation of this state, should be equal to the sum $E_t = E_k + E_M + E_f$ of the kinetic energy $E_k = L_k I_p^2/2$, the energy $E_M = I_p \Phi$ of the magnetic dipole moment $M_m = I_p S$ in magnetic field B and the energy $E_f = L_f I_p^2/2$ of magnetic field induced by the current I_p [50]. Since the energy due to the field term $E_f = L_f I_p^2/2$ is less than the kinetic energy of a current by a factor of the order of the ratio of the cross-sectional area of a conductor s to λ_L^2, we can always neglect it for a sufficiently thin conductor [24]. This approximation of weak screening $L_f \approx \mu_0 l \ll L_k \approx (\lambda_L^2/s)\mu_0 l$ is valid for the description of the quantum periodicity [11–23] observed at measurements of a sufficiently thin conductor with the cross-sectional area $s \ll \lambda_L^2$. The energy $E_f = L_f I_p^2/2$ is less than $E_k = L_k I_p^2/2$ but the energy of the magnetic dipole moment $E_M = I_p \Phi$ is not less at $L_f \ll L_k$. Our naive tendency to identify the Hamiltonian with the energy is misleading (see footnote 1).

The energy of the magnetic dipole moment $E_M = I_p \Phi$ is deduced from the history, "involving time-dependent forces" (see footnote 1), of the state rather than from the Hamiltonian [50]. The momentum and the velocity of mobile charge carriers change under the influence of the known forces in the case of perfect conductivity [50]. Therefore, the energy $E_M = I_p \Phi$ is easily deduced in the classical case [50]. Such deduction is not possible in the quantum case because of the incompleteness of quantum mechanics considered above. Quantum mechanics cannot describe the history of the current state (3) involving time-dependent forces [50]. Nevertheless we can also deduce the existence of the energy $E_M = I_p \Phi$ in the quantum case using experimental data [50]. The persistent current I_p of a flux qubit [48,49], a superconducting ring [14] and a normal metal ring [32] was measured with the help of measuring of the additional magnetic flux $\Delta \Phi_{Ip} = L_f I_p$. Consequently a change of the persistent current I_p in a ring with the magnetic inductance L_f, should induce the Faraday voltage $-\mathrm{d}\Phi_{Ip}/\mathrm{d}t = -L_f \mathrm{d}I_p/\mathrm{d}t$ in the first loop creating a magnetic flux, for example, $\Phi_0/2$, see Fig. 2 Qu in [50]. We cannot say during which time the current I_p can change its direction. But the power source inducing the magnetic flux $\Phi_0/2$ should expend the additional energy $2I_p\Phi$ in any case [50]. Thus, we must conclude that the energy of the two permitted states of a superconducting ring n and $n+1$ should differ at $\Phi = (n+0.5)\Phi_0$ and the total energy should be described by the relation (8) rather than (4), if we do not doubt the law of energy conservation. The requirement of this law challenges the conventional description of the quantum periodicity observed in numerous works [11–23].

4.2 We must challenge the description of the Zeeman effect

The energy of the magnetic dipole moment in magnetic field must not be present so that quantum mechanics could describe the quantum periodicity considered above. But this energy must exist to describe atomic phenomena. According to the predominate belief, quantum mechanics describes successfully the both phenomena. But how could this description be possible if the magnetic dipole moment in magnetic field cannot be deduced from the canonical Hamiltonian? How could Dirac explain the Zeeman effect in his book [5] published first as far back as 1930? Dirac used another definition of the operator of the canonical momentum and the Hamiltonian different from the one [6] prevalent now.

Richard Feynman in the Section "The Schrodinger Equation in a Classical Context: A Seminar on Superconductivity" of his Lectures on Physics [7] writes about "Two kinds of momentum": "It looks as though we have two

[1] I could understand that the energy of the magnetic dipole moment cannot be deduced from the canonical Hamiltonian, thanks to my private correspondence with Prof. Anthony Leggett who has surmised soundly that "Perhaps our naive tendency to identify the Hamiltonian with the 'energy' is (as in some cases involving time-dependent forces) misleading?"

suggestions for relations of velocity to momentum, because we would also think that momentum divided by mass, $\hat{p}/m$, should be a velocity. The two possibilities differ by the vector potential. It happens that these two possibilities were also discovered in classical physics, when it was found that momentum could be defined in two ways. One of them is called "kinematic momentum," but for absolute clarity I will in this lecture call it the "mv-momentum." This is the momentum obtained by multiplying mass by velocity. The other is a more mathematical, more abstract momentum, sometimes called the "dynamical momentum," which I'll call "p-momentum"$\cdots$ It turns out that in quantum mechanics with magnetic fields it is the p-momentum which is connected to the gradient operator $\hat{p}$, so it follows that (21.13) is the operator of a velocity". The operator of a velocity according to the relation (21.13) of the Feynman Lectures [7] is $(\hat{p} - qA)/m$, where $\hat{p} = -i\hbar\nabla = -i\hbar(i_x\partial/\partial x + i_y\partial/\partial y + i_z\partial/\partial z)$ corresponds to the prevalent definition.

But Dirac defined the gradient operator $-i\hbar\nabla$ as the operator of the 'mv-momentum' rather than 'p-momentum'. He writes in the beginning of section 41. "The Zeeman effect for the hydrogen atom" of [5]: "We shall now consider the system of a hydrogen atom in a uniform magnetic field. The Hamiltonian (57) with $V = -\mathrm{e}^2/r$, which describes the hydrogen atom in no external field, gets modified by the magnetic field, the modification, according to classical mechanics, consisting in the replacement of the components of momentum, p_x, p_y, p_z, by $p_x + qA_x$, $p_y + qA_y$, $p_z + qA_z$, where A_x, A_y, A_z are the components of the vector potential describing the field". The operator of the "p-momentum" is $\hat{P} = \hat{p} + qA = -i\hbar\nabla + qA$ according to Dirac's definition. According to the classical definition (see the relation (16.10) in [51]) and (1) the term $(\hat{P} - qA)^2/2m = \hat{p}^2/2m = (-i\hbar\nabla)^2/2m$ should be in the Hamiltonian. The energy of the magnetic dipole moment in magnetic field cannot be deduced from such a Hamiltonian. Dirac used another definition of the Hamiltonian: "For a uniform field of magnitude B in the direction of the z-axis we may take $A_x = -By/2$, $A_y = Bx/2$, $A_z = 0$. The classical Hamiltonian will then be" [5]

$$H = \frac{1}{2m}\left[\left(p_x - \frac{1}{2}qBy\right)^2 + \left(p_y + \frac{1}{2}qBx\right)^2 + p_z^2\right] - \frac{q^2}{r} \tag{9}$$

Dirac could deduced the energy of the magnetic dipole moment of an atom in magnetic field only due to this non-canonical definition of the momentum and the Hamiltonian (88): "If the magnetic field is not too large, we can neglect terms involving B^2, so that the Hamiltonian (88) reduces to [5]

$$\hat{H} = \frac{1}{2m}(\hat{p}_x{}^2 + \hat{p}_y{}^2 + \hat{p}_z{}^2) - \frac{q^2}{r} + \frac{qB}{2m}\hat{m}_z \tag{10}$$

The relation (10) corresponds to the relation (89) in [5] without the spin term $\hbar\sigma_z$. $\hat{m}_z = x\hat{p}_y - y\hat{p}_x$ is the operator of the z-component of the orbital angular momentum of an atom. The extra terms due to the magnetic field $(qB/2m)\hat{m}_z$ describes the energy of the magnetic moment $(q/2m)\Psi^*\hat{m}_z\Psi$ in the magnetic field B according to Dirac [5]. "The external magnetic field splits the atomic levels and removes the degeneracy with respect to the directions of the total angular momentum (the Zeeman effect)" [6].

4.3 Quantum mechanics cannot describe both opposite cases

Strangely, the direct opposite of the phenomena observed at measurements of atoms and superconducting rings in magnetic field has never been noticed before. The effect of splitting a spectral line of atoms into several components in the presence of a static magnetic field discovered by Pieter Zeeman as far back as 1896 testifies to the existence of the energy of the magnetic moment in magnetic field. It is well known that this energy must also be present in the case of an electric current circulating in a ring clockwise or anticlockwise. But the quantum periodicity [11–23] cannot be described if this energy is taken into account. Most physicists believed during a long time that quantum mechanics describes successfully both opposite cases. But we must admit that both phenomena cannot be described consistently. To describe the quantum periodicity in the persistent current (3) we must explain why the energy $E_M = -M_{\mathrm{m}}B = I_p\Phi$ could not be taken into account and how the two permitted states n and $n+1$ could have the same energy at $\Phi = (n+0.5)\Phi_0$ if the change of the persistent current (3) from $I_p = -0.5\Phi_0/L_{\mathrm{k}}$ to $I_p = 0.5\Phi_0/L_{\mathrm{k}}$ should induce Faraday's voltage $-\mathrm{d}\Phi_{Ip}/\mathrm{d}t = -L_{\mathrm{f}}\mathrm{d}I_p/\mathrm{d}t$.

The description of the Zeeman effect is doubtful because of the non-canonical definition used by Dirac [5]. According to Dirac's definition $\hat{p} = m\hat{v} = -i\hbar\nabla$ the persistent current $I_p = (sq/m2\pi r)\oint_l dl\Psi^*(-i\hbar\nabla)\Psi = n\Phi_0/L_k$ should not depend on the magnetic flux Φ inside the ring. The Aharonov–Bohm effect [52] and other known phenomena also should not be observed. Quantum mechanics seems to describe successfully different quantum phenomena due to the different definitions of the canonical momentum and the Hamiltonian. A consequence of these different definitions may be observed in section XV. "Motion in a Magnetic Field" of the book [6]. The Hamiltonian (113.1) was written as in Dirac's book $(\hat{p} + eA)^2/2m$ in the paragraph 113 "An atom in a magnetic field", whereas the canonical definition $(\hat{p} - eA)^2/2m$ was used in the relations (111.3), (111.4), (115.2) of all other paragraphs of this section. This inconsistency was in the Russian edition 1963 and was eliminated in the posterior editions of [6]. The editors have written $(\hat{p} + |e|A)^2/2m$ instead of $(\hat{p} + eA)^2/2m$, where $-|e| = e$ is the electron charge. It is obvious that $(\hat{p} + |e|A)^2/2m \equiv (\hat{p} - eA)^2/2m$. But the editors "correcting typo" did not notice that $(\hat{p} - eA)^2/2m$ is only the kinetic energy and the energy of the orbital angular momentum of an atom cannot be deduced from this Hamiltonian without a mathematical mistake.

According to the elementary mathematics the equality $(\hat{P} - eA)^2/2m = m\hat{v}^2/2$ must be deduced from the equality $\hat{P} - eA = m\hat{v}$. The additional summand $\mu_B \hat{L} B$ could appear in the relation (113.2) of the book [6] due to the illegal substitution of $\hat{P}^2/2m$ by $m\hat{v}^2/2$ in $\hat{H}_0$. Here μ_B is the Bohr magneton; $\hbar\hat{L}$ is the operator of the total orbital angular momentum of the atom. Dirac did not use this illegal substitution because he employed the non-canonical definition of the momentum and the Hamiltonian in [5]. He defines the Hamiltonian and the kinetic energy in a different way: $\hat{P}^2/2m = (\hat{p} + qA)^2/2m = (m\hat{v} + qA)^2/2m$ is written in the Hamiltonian (88) whereas the kinetic energy is written as $\hat{p}^2/2m = m\hat{v}^2/2$ in expression (89) of the book [5]. Neither Dirac nor anybody could deduce the energy of the orbital angular momentum $\mu_B \hat{L} B$ using the canonical definition of the Hamiltonian and the kinetic energy. Only the kinetic energy can be deduced from the Hamiltonian according to the canonical definition [50]. We must admit that the explanation of the Zeeman effect by Dirac [5] is doubtful because of groundlessness and inconsistence of his non-canonical definition of the momentum and the Hamiltonian. Quantum electrodynamics should also be challenged because Dirac used the same non-canonical definition in his relativistic theory of the electron [5].

5 Can quantum-mechanical description of physical reality be considered complete?

Einstein insisted that quantum-mechanical description of physical reality cannot be considered complete. Einstein was right [53]. It is delusion to think that the orthodox quantum mechanics describes physical reality. Einstein's dictum "I like to think that the moon is there even if I don't look at it" conveys to the greatest degree the motive of the disapproval of quantum mechanics by Einstein, Schrodinger and other critics.

5.1 Born's interpretation and Dirac's jump

The history of the orthodox quantum mechanics began with a problem. The wave theory proposed by Schrodinger has allowed to describe successfully atomic phenomena. Schrodinger tried to replace particles by wavepackets. But wavepackets diffuse. Schrodinger interpreted his wave function as a real wave [4] and defended this realistic interpretation [54]. But we cannot think that a real density $|\Psi(r)|^2$ can change because of our observation. On the other hand we know from our everyday experience that the uncertainty of the next observation decreases after the first observation. Our experience convinces us that we will see a thing approximately in the same place r at the second observation where we saw it at the first observation. Therefore, we are fully confident that the probability of observation changes from $|\Psi(r)|^2 < 1$ to $|\Psi(r)|^2 = 1$ after the first observation. Therefore, most physicists rejected Schrodinger's interpretation and have accepted Born's interpretation.

However, they did not take into account that the probability of observation $|\Psi(r)|^2$ changes in our mind according to our experience. The knowledge of the observer about the object changes at the observation. But the problem of wavepackets cannot be solved if only the knowledge changes. Therefore, the Dirac jump [5], wave function collapse [55], or "'quantum jump' from the 'possible' to the 'actual"' [56] was postulated. The Dirac jump represents "an unavoidable and uncontrollable impression from the side of the subject onto the object" [57]. The non-locality of the EPR correlation [58], violation of Bell's inequality [59], the problem of free will [60–62] and other fundamental obscurities in quantum mechanics may be deduced logically from this postulation of the subjectivity according to which the change of our knowledge can instantly change the state of a distant quantum system.

But most physicists refused to admit that the question of observation "cannot be ruled out as lying in the domain of psychology" [63]. They, as well as the author [64], "dismissed out of hand the notion of von Neumann, Pauli, Wigner—that 'measurement' might be complete only in the mind of the observer" [2,3]. This mass delusion could be a result of logical inconsistency of some statements postulated by the creators of quantum mechanics. According to the quantum postulate proposed by Bohr *any observation of atomic phenomena should include an interaction they with equipment used for the observation which cannot be neglected* [65]. Bohr [65] and Heisenberg (the uncertainty microscope [66]) stated that we cannot measure some variables with sufficiently great accuracy simultaneously (the uncertainty principle) because of the indeterminacy introduced by this interaction with equipment.

Dirac, on the one hand, following Bohr and Heisenberg, stated that "it is not in general permissible to consider that two observations can be made exactly simultaneously, and if they are made in quick succession the first will usually disturb the state of the system and introduce an indeterminacy that will affect the second" [5]. But on the other hand he had to postulate that the indeterminacy in quick succession of two observations of the same dynamical variable must disappear: "When we measure a real dynamical variable ξ the disturbance involved in the act of measurement causes a jump in the state of the dynamical system. From physical continuity, if we make a second measurement of the same dynamical variable ξ immediately after the first, the result of the second measurement must be the same as that of the first. Thus, after the first measurement has been made, there is no indeterminacy in the result of the second. Hence, after the first measurement has been made, the system is in an eigenstate of the dynamical variable ξ, the eigenvalue it belongs to being equal to the result of the first measurement. In this way we see that a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured, the eigenvalue this eigenstate belongs to being equal to the result of the measurement" [5].

Dirac's statement that "after the first measurement has been made, there is no indeterminacy in the result of the second" contradicts the belief predominant up to now and voiced, in particular, by the author [64] that "the quantum mechanical measurement is terminated when the outcome has been macroscopically recorded" and that "the mind of the observer is irrelevant", see [2,3]. We can think that an interaction with equipment will introduce an indeterminacy. Bohr and Heisenberg proposed just this postulate. But we cannot think that a physical interaction will eliminate the indeterminacy. The idea of the Dirac jump originates in our everyday experience which has convinced us that there is no indeterminacy in the result of the second observation. Heisenberg's statement "Since through the observation our knowledge of the system has changed discontinuously, its mathematical representation also has undergone the discontinuous change and we speak of a 'quantum jump"' [56] is also based on our experience. But according to our experience such a 'quantum jump' describes a process of psychology rather than physics. Dirac entangled psychology and physics postulating that a jump in our knowledge of the system excites a jump in the state of the system.

5.2 Most quantum phenomena are described with the help of Schrodinger's interpretation

Einstein, Schrodinger and other critics of quantum mechanics remonstrated against just this entanglement of physics with psychology. Therefore, it is important to emphasize that most quantum phenomena are described without Born's interpretation and Dirac's jump [67]. Richard Feynman stated in [7] that Schrodinger "imagined incorrectly that $|\Psi|^2$ was the electric charge density of the electron. It was Born who correctly (as far as we know) interpreted the Ψ of the Schrodinger equation in terms of a probability amplitude". But further Feynman wrote that "in a situation in which Ψ is the wave function for each of an enormous number of particles which are all in the same state, $|\Psi|^2$ can be interpreted as the density of particles" [7]. Superconductivity is just such situation. All superconducting pairs are all in the same state in a superconductor. Just, therefore, this macroscopic quantum phenomenon can be observed [9,10]. Schrodinger's interpretation rather than Born's interpretation of the wave function is used for the description of quantization effects considered above: $|\Psi|^2$ is the real density of superconducting pairs n_s. The mind of the observer is indeed irrelevant in this description. Our mind cannot influence on the real density, in contrast to the probability of observation. The real density n_s can be change with the help of a real physical influence, for example the laser beam, Fig. 2.

Einstein et al. [58] have shown eighty years ago that quantum-mechanical description of physical reality is not complete assuming the impossibility of 'spooky action at a distance'. Funnily enough this 'spooky action at a distance' is known as the ERP (Einstein–Podolsky–Rosen) correlation. The non-locality of the EPR correlation ("entanglement of our knowledge" according to Schrodinger [68]) is deduced logically from Born's interpretation and the Dirac jump. The quantum state of a particle spatially separated from an observer A (Alice) should change at her observation of her particle of the EPR pair (from (4) to (6) in [67]) because of the non-locality of our mind and the Dirac jump. Alice get to know instantly about the state of the distant particle observing her particle. This change of her knowledge changes discontinuously the state of both her and distant particle in accordance with the Dirac jump. Therefore, the observation by Alice and an other observer B, Bob of the same dynamical variable of two distant particles should be correlated according to quantum mechanics. This EPR correlation is spooky because "it suggests some sort of psychokinetic effect of the conscious 'observer' on basic physical phenomena" [69] and "The question cannot be ruled out as lying in the domain of psychology" [63].

In contrast to the EPR correlation neither observer nor psychology is needed for the description of the quantization effects observed in superconductors. The segment l_A, Fig. 2, is switched in superconducting state because of the cooling rather than of psychokinetic effect of the conscious observer. The Dirac jump is absent in this description. But we should postulate other jump until we cannot say what is the force accelerating the mobile charge carriers against the electromagnetic force. Quantum description of macroscopic quantum phenomena is at least incomplete without such force. A 'spooky action at a distance' may be assumed because of this incompleteness: the persistent current (3) should appear in a ring segment l_B when a spatially separated segment l_A is switched in superconducting state, Fig. 2. This action at a distance is spooky because of the impossibility to deduce from quantum mechanics a force which could accelerate pairs in the segment l_B. In contrast to the EPR correlation this action at a distance must not be instantaneous. On the other hand this action is real in contrast to the EPR correlation.

6 Conclusion

Bell stated that "that vagueness, subjectivity, and indeterminism, are not forced on us by experimental facts, but by deliberate theoretical choice" [70]. I do not think that this statement is quite correct. It seems some experimental facts, the two-slit interference experiment, violation of Bell's inequalities and some others cannot be described realistically, although most quantum phenomena can be described realistically even without hidden variables. But even these most quantum phenomena cannot be described completely and consistently. The aim of this paper is to draw the reader's attention on this sorrowful fact. It is important because of the efforts of some contemporary authors to solve the problems of quantum mechanics deduced from Born's interpretation, such as EPR correlation, violation of Bell's inequality, the problem of free will in quantum mechanics and others. These efforts could be useless without clear and full realization that the problems of quantum mechanics considered above are fundamentally different. The fact that the quantum periodicity and the Zeeman effect cannot be described with the help of the same Hamiltonian has no relation to the Born interpretation. The self-contradictions of the orthodox quantum mechanics are various. They must be uncovered and estimated to have a chance to create a consistent and complete theory of quantum phenomena.

References

1. Bell, J.S.: Speakable and Unspeakable in Quantum Mechanics. Collected Papers on Quantum Philosophy. Cambridge University Press, Cambridge (2004)
2. Bell, J.S.: Against Measurement. In: The Proceedings of 62 Years of Uncertainty. PlenumPublishing, New York (1989)
3. Bell, J.S.: Phys. World **3**, 33 (1990)
4. Schrodinger, E.: An undulatory theory of the mechanics of atoms and molecules. Phys. Rev. **28**, 1049 (1926)
5. Dirac, A.M.: The Principles of Quantum Mechanics. Oxford University Press, New York (1958)
6. Landau, L.D., Lifshitz, E.M.: Quantum Mechanics: Non-Relativistic Theory, 3rd edn, vol. 3. Elsevier Science, Oxford (1977)
7. Feynman, R.P., Leighton, R.B., Sands, M.: The Feynman Lectures on Physics. Addison-Wesley Publishing Company, Reading (1963)
8. Byers, N., Yang, C.N.: Theoretical considerations concerning quantized magnetic flux in superconducting cylinders. Phys. Rev. Lett. **7**, 46 (1961)
9. Nikulov, A.V.: Bohm's quantum potential and quantum force in superconductor. In: AIP Conference Proceedings, vol. 1101. Foundations of Probability and Physics-5, pp. 134 (2009)
10. Nikulov, A.V.: (2008). arXiv:0812.4118
11. Burlakov, A.A., Gurtovoi, V.L., Dubonos, S.V., Nikulov, A.V., Tulin, V.A.: Little–Parks effect in a system of asymmetric superconducting rings. JETP Lett. **86**, 517 (2007)
12. Burlakov, A.A., Gurtovoi, V.L., Dubonos, S.V., Nikulov, A.V., Tulin, V.A.: (2008). arXiv:0805.1223
13. Gurtovoi, V.L., Ilin, A.I., Nikulov, A.V., Tulin, V.A.: Weak dissipation does not result in disappearance of persistent current. Fiz. Nizk. Temp. **36**, 1209 (2010). arXiv:1004.3914
14. Koshnick, N.C., Bluhm, H., Huber, M.E., Moler, K.A.: Fluctuation superconductivity in mesoscopic aluminum rings. Science **318**, 1440 (2007)
15. Gurtovoi, V.L., Dubonos, S.V., Karpi, S.V., Nikulov, A.V., Tulin, V.A.: Contradiction between the results of observations of resistance and critical current quantum oscillations in asymmetric superconducting rings. Zh. Eksp. Teor. Fiz. **105**, 257 (2007)
16. Gurtovoi V.L., Dubonos S.V., Karpi S.V., Nikulov A.V., Tulin V.A.: (2010) arXiv:1011.6149
17. Gurtovoi, V.L., Dubonos, S.V., Nikulov, A.V., Osipov, N.N., Tulin, V.A.: Dependence of the magnitude and direction of the persistent current on the magnetic flux in superconducting rings. J. Exp. Theor. Phys. **105**, 1157 (2007)
18. Gurtovoi, V.L., Dubonos, S.V., Nikulov, A.V., Osipov, N.N., Tulin, V.A.: (2009). arXiv:0903.3539
19. Dubonos S.V., Kuznetsov V.I., Nikulov A.V.: Segment of an inhomogeneous mesoscopic loop as a DC power source. In: Proceedings of 10th International Symposium on "NANOSTRUCTURES: Physics and Technology". Ioffe Institute, St Petersburg, p. 350 (2002)
20. Dubonos S.V., Kuznetsov V.I., Nikulov A.V.: (2001). arXiv:physics/0105059
21. Dubonos, S.V., Kuznetsov, V.I., Zhilyaev, I.N., Nikulov, A.V., Firsov, A.A.: Observation of the external-AC-current-induced DC voltage proportional to the steady current in superconducting loops. JETP Lett. **77**, 371 (2003)
22. Dubonos S.V., Kuznetsov V.I., Zhilyaev I.N., Nikulov A.V., Firsov A.A.: (2003). arXiv:cond-mat/0303538
23. Burlakov, A.A., Gurtovoi, V.L., Ilin, A.I., Nikulov, A.V., Tulin, V.A.: A possibility of persistent voltage observation in a system of asymmetric superconducting rings. Phys. Lett. A **376**, 2325 (2012). arXiv:1207.0791
24. Tinkham, M.: Introduction to Superconductivity, 2nd edn. McGraw-Hill Book Company, New York (1996)
25. Deaver Jr, B.S., Fairbank, W.M.: Experimental evidence for quantized flux in superconducting cylinders. Phys. Rev. Lett. **7**, 43 (1961)
26. Doll, R., Nobauer, M.: Experimental proof of magnetic flux quantization in a superconducting ring. Phys. Rev. Lett. **7** 52 (1961)
27. Meissner, W., Ochsenfeld, R.: Ein neuer effekt bei eintritt der supraleitfahigkeit. Naturwissenschaften **21**, 787 (1933)
28. Little, W.A., Parks, R.D.: Observation of quantum periodicity in the transition temperature of a superconducting cylinder. Phys. Rev. Lett. **9**, 9 (1962)
29. Morelle, M., Bruyndoncx, V., Jonckheere, R., Moshchalkov, V.V.: Critical temperature oscillations in magnetically coupled superconducting mesoscopic loops. Phys. Rev. B **64**, 064516 (2001)
30. Gurtovoi, V.L., Nikulov, A.V., Tulin, V.A.: Aharonov–Bohm effects in nanostructures. In: Proceedings of 17th International Symposium on "NANOSTRUCTURES: Physics and Technology". Institute of Physics NAS, Belarus, Minsk, p. 87 (2009). arXiv:0910.5172
31. Bleszynski-Jayich, A.C., Shanks, W.E., Peaudecerf, B., Ginossar, E., von Oppen, F., Glazman, L., Harris, J.G.E.: Persistent currents in normal metal ring. Science **326**, 272 (2009)
32. Bluhm, H., Koshnick, N.C., Bert, J.A., Huber, M.E., Moler, K.A.: Persistent Currents in normal metal rings. Phys. Rev. Lett. **102**, 136802 (2009)
33. Astafiev, O., Zagoskin, A.M., Abdumalikov Jr, A.A., Pashkin, Y.A., Yamamoto, T., Inomata, K., Nakamura, Y., Tsai, J.S.: Resonance fluorescence of a single artificial atom. Science **327**, 840 (2010)
34. You, J.Q., Nori, F.: Atomic physics and quantum optics using superconducting circuits. Nature **474**, 589 (2011)
35. Lecocq, F., Pop, I.M., Matei, I., Dumur, E., Feofanov, A.K., Naud, C., Guichard, W., Buisson, O.: Coherent frequency conversion in a superconducting artificial atom with two internal degrees of freedom. Phys. Rev. Lett. **108**, 107001 (2012)

36. De Waele, AThAM, Kraan, W.H., De Bruynouboter, R., Taconis, K.W.: On the DC voltage across a double point contact between two superconductors at zero applied dc current in situations in which the junction is in the resistive region due to the circulating current of flux quantization. Physica **37**, 114 (1967)
37. Birge, N.O.: Sensing a small but persistent current. Science **326**, 244 (2009)
38. Nikulov, A.V., Zhilyaev, I.N.: The Little–Parks effect in an inhomogeneous superconducting ring. J. Low Temp. Phys. **112**, 227 (1998)
39. Nikulov, A.V.: The Meissner effect puzzle and the quantum force in superconductor. Phys. Lett. A **376**, 3392 (2012). arXiv:1211.0002
40. Nikulov, A.V.: Quantum force in superconductor. Phys. Rev. B **64**, 012505 (2001)
41. Hirsch, J.E.: Electromotive forces and the Meissner effect puzzle. J. Supercond. Novel Magn. **23**, 309 (2010)
42. Hirsch, J. E.: (2009). arXiv:0908.409
43. Cheung, H.-F., Gefen, Y., Riedel, E.K., Shih, W.-H.: Persistent currents in small one-dimensional metal rings. Phys. Rev. B **37**, 6050 (1988)
44. Gurtovoi, V.L., Nikulov, A.V.: Comment on vortices induced in a superconducting loop by asymmetric kinetic inductance and their detection in transport measurements. Phys. Rev. B **90**, 056501 (2014)
45. Burlakov A.A., Gurtovoi V.L., Dubonos S.V., Nikulov A.V., Tulin V.A.: Could two degenerate energy states be observed for a superconducting ring at $\Phi_0/2$? (2006). arXiv:cond-mat/0603005
46. Burlakov, A.V., Gurtovoi, V.L., Ilin, A.I., Nikulov, A.V., Tulin, V.A.: Experimental investigations of the change with magnetic flux of quantum number in superconducting ring. In: Proceedings of 19th International Symposium on ”NANOSTRUCTURES: Physics and Technology”. Ioffe Physical-Technical Institute, St. Petersburg, Russia, p. 128 (2011). arXiv:1103.3115
47. Gurtovoi, V.L., Burlakov, A.A., Nikulov, A.V., Tulin, V.A., Firsov, A.A., Antonov, V.N., Davis, R., Pelling, S.: Multiple current states of two phase-coupled superconducting rings. Zh. Eksp. Teor. Fiz. **140**, 777 (2011). arXiv:1111.6882
48. Tanaka, H., Sekine, Y., Saito, S., Takayanagi, H.: DC-SQUID readout for qubit. Phys. C **368**, 300 (2002)
49. Tanaka, H., Saito, S., Nakano, H., Semba, K., Ueda, M., Takayanagi, H.: Single-shot readout of macroscopic quantum superposition state in a superconducting flux qubit (2004). arXiv:cond-mat/0407299
50. Gurtovoi, V.L., Nikulov, A.V.: Energy of magnetic moment of superconducting current in magnetic field. Phys. C **516**, 50 (2015). arXiv:1501.00468
51. Landau, L.D., Lifshitz, E.M.: Course of Theoretical Physics. The Classical Theory of Fields, vol. 2. Butterworth-Heinenann, Oxford (1985)
52. Aharonov, Y., Bohm, D.: Significance of electromagnetic potentials in the quantum theory. Phys. Rev. **115**, 485 (1959)
53. Hess, K.: Einstein was Right!. Pan Stanford Publishing Pte Ltd, Singapore (2015)
54. Schrodinger, E.: Are there quantum jumps? Br. J. Philos. Sci. **3**, 233 (1952)
55. von Neumann, J.: Mathematical Foundations of Quantum Mechanics. Princeton University Press, Princeton (1955)
56. Heisenberg, W.: Physics and Philosophy. George Allen and Unwin Edition, London (1959)
57. Schrodinger, E.: Science and Humanism. Physics in Our Time. Cambridge University Press, New York (1952)
58. Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. **47**, 777 (1935)
59. Bell, J.S.: Bertlmann’s socks and the nature of reality. J. Phys. **42**, 41 (1981)
60. Conway, J., Kochen, S.: The Free Will theorem. Found. Phys. **36**, 1441 (2006)
61. ’t Hooft, G.: The Free-Will postulate in quantum mechanics. Her. Russ. Acad. Sci. **81**, 907 (2011)
62. ’t Hooft, G.: (2007). arXiv:quant-ph/0701097v1
63. Everett, H.: ’Relative state’ formulation of quantum mechanics. Rev. Mod. Phys. **29**, 454 (1957)
64. van Kampen, N.G.: Ten theorems about quantum mechanical measurements. Phys. A **153**, 97 (1988)
65. Bohr, N.: The quantum postulate and the recent development of atomic theory. Nature **121**, 580 (1928)
66. Heisenberg, W.: The physical content of quantum kinematics and mechanics. Zeil. Phys. **43**, 172 (1927)
67. Nikulov, A.V.: The quantum mechanics is a non-universal theory. The realistic Schrodinger’s and positivistic Born’s interpretation of the wave function (2013). arXiv:1311.4760
68. Schrodinger, E.: Discussion of probability relations between separated systems. Proc. Camb. Philos. Soc. **31**, 555 (1935)
69. Deutsch, D.: The Fabric of Reality. The Penguin Press, London (1997)
70. Bell, J.S.: On the impossible pilot wave. Found. Phys. **12**, 989–999 (1982)