Differences between application of some basic principles of quantum mechanics on atomic and mesoscopic levels

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Formalism of the quantum mechanics developed for microscopic (atomic) level comes into collision with some logical difficulties on mesoscopic level. Some fundamental differences between application of its basic principles on microscopic and mesoscopic levels are accentuated.

1. INTRODUCTION

Richard Feynman remarked: “I think I can safely say that nobody today understands quantum physics”. This remark may seem queer for people who studied and use quantum physics but some experts understand that in contrast to the theories of relativity, quantum mechanics is not yet based on a generally accepted conceptual foundation. Not only the collision of principles of quantum mechanics with macroscopic realism and the Einstein-Podolsky-Rosen paradox are indicative of our incomprehension of quantum physics. There are some quantum effects observed, first of all, on the mesoscopic level, strangeness of which is disregarded by most scientists who do not understand that nobody today understands quantum physics.

The experimental results corroborate for the present all principles of quantum physics, even in defiance of common sense. But the essence of these principles is not clear and is discussed now actively. The collision between quantum mechanics and macroscopic realism should be expected on the mesoscopic level. Therefore the consideration of differences between application of basic principles of quantum mechanics on atomic and mesoscopic levels is most urgent.

2. QUANTUM MECHANICS VERSUS MACROSCOPIC REALISM

One of the three “axes” along which, according to A.J. Leggett, it is not unreasonable to seek evidence of a breakdown of the quantum mechanics scheme of the physical world is the collision of it with our immediate experience of the “everyday” world. The obvious contradiction between the quantum mechanics and macroscopic realism was laid stress by Erwin Schrodinger already seventy years ago but only in the last years this problem is not only merely philosophical but it can be tested in experiment first of all on the mesoscopic level, i.e. between the microscopic (atomic) world and the Schrodinger cat. The formalism of the quantum mechanics, its Copenhagen interpretation, was developed first of all for the microscopic (atomic) level and it comes into collision with some logical difficulties on the mesoscopic level.

According to the formalism of the quantum mechanics a quantum system can be in a superposition of states but this superposition can not be observed because of its reduction to single state at measuring. The principle of the impossibility of noninvasive measurement seems admissible on the microscopic level when measuring device can not be smaller than measured object. But we can not assume that the Schrodinger cat can die or revive because of our look. The contradiction between quantum mechanics and the possibility of noninvasive measurability may come on the mesoscopic level.

3. QUANTIZATION OF THE MOMENTUM CIRCULATION

Other difficulty can be connected with the quantization of momentum circulation. According to the classical physics the momentum \( p = mv + qA \) of a particle with a charge \( q \) should maintain a constant value in absence of any force whereas the quantum number \( n \) in the relation for the momentum circulation

\[
\oint_{\text{l}} dp = \oint_{\text{l}} (mv + qA) = m \oint_{\text{l}} dv + q\Phi = n2\pi \hbar \quad (1)
\]

can change without any evident force. There is not problem on the microscopic realm, where electrons do not change their state of motion in the absence of an electromagnetic force but the problem is on the mesoscopic level. The mysterious change of state of electron motion without forces acting on the electrons can be both in superconductor and other (semiconductor and normal metal) mesoscopic structures with the quantization (1) of momentum circulation.

The quantization (1) takes place \( \oint_{\text{l}} dp = n2\pi \hbar \) when the wave function of a particle is closed in a two-connected mesoscopic loop and \( m \oint_{\text{l}} dv = n2\pi \hbar - q\Phi = 2\pi \hbar (n - \Phi/\Phi_0) \neq 0 \), i.e. the state with zero velocity \( v = 0 \) is forbidden, when the magnetic flux \( \Phi \) inside the loop is not divisible by the flux quantum \( \Phi_0 = 2\pi \hbar / q \). On the other hand the velocity can be zero \( v = 0 \) in the state with unclosed wave function when the quantization (1) is not valid. In this case the circular velocity of the particle should change, i.e. the particle should accelerate, from \( v = 0 \) to \( v = \oint_{\text{l}} dv/l = 2\pi \hbar (n - \Phi/\Phi_0) / l \) and the momentum circulation should change from \( q\Phi \) to \( n2\pi \hbar \).
at the closing of the wave function without any evident force.

There is important to accentuate a fundamental difference between atomic and mesoscopic levels. A switching between states with different connectivity of wave function can not be realized on atomic level whereas it can be enough easy made on mesoscopic level. For example it can be realized by switching of a segment $l_s$ of a loop $l$ between superconducting, i.e. with a density of superconducting pairs $n_s > 0$, and normal states with $n_s = 0$, whereas other segment $l_{scs} = l - l_s$ remaining all time in superconducting state with $n_s > 0$ [16, 17]. The quantization (1) should be along any closed path $l$ of the loop circumference when $n_s > 0$ along whole loop and the quantization (1) is not valid along $l$ when $n_s = 0$ in the $l_s$ segment. The velocity of superconducting pairs

$$\int_l dl v_s = \frac{2\pi h}{m} (n - \Phi/\Phi_0)$$  \hspace{1cm} (2)

and a density of the persistent current $j_p = 2en_sv_s \neq 0$ should be nonzero along $l$ in the closed superconducting state at $\Phi \neq n\Phi_0$ because of the quantization (1), whereas equilibrium velocity $v_s = 0$ and current $j_p = 0$ in the $l_{scs}$ segment when the $l_s$ segment is in the normal state with a non-zero resistance $R_{ls} > 0$. Thus, superconducting pairs in the $l_{scs}$ segment should accelerate without any force, in contradiction with the law of momentum conservation, at the switching of the $l_s$ segment from the normal $n_s = 0$ to superconducting $n_s > 0$ state. This change can be fixed experimentally by way of an observation of the appearance of the persistent current at closing of superconducting state.

The term “persistent current” was at first used for the current in superconducting state [18, 19, 20], i.e. at $T < T_c$. Under equilibrium conditions at $T < T_c$ the quantization (1) is valid during all time since coherence of wave function of superconducting pairs exists until the superconducting state exists. Above superconducting transition $T > T_c$ superconducting pairs exist because of thermal fluctuations [21] and coherence of their wave function along whole loop $l$ appears only at times. It is enough in order the persistent current, i.e. a direct circular current observed under equilibrium conditions, exists not only at $T < T_c$ but also in non-superconducting state at $T > T_c$ [22], when the resistance along $l$ is not zero $R_l > 0$. First experimental evidence of the persistent current at $R_l > 0$ in the fluctuation region $T > T_c$ is the Little-Parks oscillations of the resistance of cylinder [23] or loop [24] in magnetic field $R_l(\Phi/\Phi_0)$.

The observation of the circular persistent current $I_p$ at a constant magnetic field $\partial \Phi/\partial t = 0$ in a loop with a non-zero resistance $R_l > 0$ contradicts to the habitual knowledge according to which such current should disappear without the Faraday’s voltage $\oint_l dl E_F = -\partial \Phi/\partial t = 0$ because of dissipation, $R_l I_p \neq 0$, during the time of current relaxation $\tau_{RL} = L_l/R_l$. According to the explanation [17] the persistent current does not disappear at $R_l > 0$ since the velocity decrease because of the dissipation force is compensated by the velocity change because of the quantization (1) at closing of superconducting state at reiteration switching of the loop by thermal fluctuations between superconducting states with different connectivity. The explanation [17] of the observation of the persistent power $R_l I_p^2 \neq 0$ as a fluctuation phenomenon is natural since $I_p \neq 0$ at $R_l > 0$ is observed only in the fluctuation region near $T_c$, where the loop is switched by fluctuations between superconducting states with different connectivity. According to this explanation [17] the observation of the persistent current $I_p \neq 0$ at $R_l > 0$ in the fluctuation region of superconducting loop is experimental evidence of violation of the law of conservation of momentum circulation. Already the observation of the direct circular current $I_p$ at $d\Phi/\partial t = 0$ and $R_l > 0$ is challenge to this law since it is observed at $R_l > 0$, as well as a conventional circular current, but without the circular Faraday’s force $2eE_F$, $\oint_l dl 2eE_F = -2ed\Phi/\partial t = 0$.

The wave function not only superconducting pairs in the fluctuation region at $T > T_c$ but also of electrons in mesoscopic semiconductor and normal metal loops can become closed at times. I.O.Kulik predicted first the persistent current in normal metal mesoscopic structure [25] just after the consideration of this quantum phenomenon at $T > T_c$ in superconductor [22]. It is much more difficult to observed the persistent current of electron than superconducting pairs. Nevertheless the advancement of cryogenic and microfabrication technologies had allowed to make attempts to observe the persistent current in semiconductor [26, 27, 28] and normal metal [29, 30, 31] nanostructures. First it was made only in 1990, i.e. in 20 years after the prediction [25]. It may be therefore most authors refer to [32] as the first prediction of the persistent current in non-superconducting structures. The persistent current in non-superconducting loops also contradicts to the habitual knowledge since the resistance of these loop is not zero.

An additional, more obvious, experimental evidence of violation of the law of momentum conservation is the observation [33, 34] of the quantum oscillations of the dc voltage $V_{dc}(\Phi/\Phi_0)$ on segments of asymmetric superconducting loops predicted in [16, 17]. The potential difference $R_{ls} I_p$ should appear on the segment $l_s$ just after its switching in the normal state with $R_{ls} > 0$ if the persistent current in the loop $l$ was non-zero $I_p \neq 0$ before the switching. This potential difference $V(t) = R_{ls} I(t) = R_{ls} I_p \exp(-t/\tau_{RL})$, as well as the circular current $I(t) = I_p \exp(-t/\tau_{RL})$, are extinguished during a finite time of current relaxation $\tau_{RL} = L_l/R_{ls}$ because of a finite value of the loop inductance $L_l$. The time average of the $V(t)$ voltage during the time $t_n$ of a staying of the $l_s$ in the normal state $\overline{V}_{n} = t_n^{-1} \int_0^{t_n} V(t) = R_{ls} I_p t_n^{-1} \int_0^{t_n} \exp(-t/\tau_{RL})$ equals $\overline{V}_{n} \approx R_{ls} I_p t_n \approx R_{ls} I_p I_{sw} \int_0^{r_{sw}} \exp(-t/\tau_{RL})$ when $t_n \ll \tau_{RL}$ and $\overline{V}_{n} \approx L_l I_p / t_n$ at $t_n \gg \tau_{RL}$. The dc component of the voltage measured during a long time $T$, $V_{dc} = \Theta^{-1} \int_0^\Theta dV(t) = N_{sw}^{-1} \sum N_{sw} R_{ls} I_p \omega_{sw} t_n^{-1} \exp(-t/\tau_{RL})$ equals $V_{dc} \approx R_{ls} I_p t_n \omega_{sw}$ at $t_n \ll \tau_{RL}$ and $V_{dc} \approx L_l \omega_{sw} I_p$.
at $t_n \gg \tau_{RL}$ in the case of reiterate switching of the $l_s$ segment between superconducting and normal states with a frequency $\omega_{sw} = N_{sw}/\Theta$.

The switching of the $l_s$ with the frequency $\omega_{sw}$ means that during the long time $\Theta$ the loop $l$ is $N_{sw}$ times in the closed superconducting state and $N_{sw}$ times in the unclosed superconducting state. The density of the persistent current $j_p = 2e n_s v_s$ in each (from $N_{sw}$) closed superconducting state is determined by the $n_s$ value and the quantization of the velocity (2). The density $j_p$ is uniform across the narrow section $s \ll \lambda_L^2$ of the loops measured in $\textbf{16}$ $\textbf{L}$. Where $\lambda_L$ is the London penetration depth. The persistent current in the closed superconducting state of the loop equals $I_p = s j_p = 2e n_s v_s = (2\pi \hbar/m < (sn_s)^{-1}>) (n - \Phi/\Phi_0)$ because of the quantization (2) and since its value should be uniform along $l$ in the stationary state: $\int dl v_s = (I_p/2e) \int dl (sn_s)^{-1} = (I_p/2e)l < (sn_s)^{-1}>$. The quantum number $n$ can be any integer number in the closed superconducting state but with overwhelming probability $P_n \propto \exp(-E_n/k_BT)$ the loop switches in the permitted state with lowest energy $E_n$ since the energy difference $E_{n+1} - E_n$ between adjacent permitted states is much higher than the thermal energy $k_BT$. Therefore the average value $\bar{n} = \sum_{n=1}^{N_{sw}} N_{sw} n P_n$ is close to the integer number corresponding to the lowest $n \propto (n - \Phi/\Phi_0)^2$ value and $\bar{I}_p = \sum_{n=1}^{N_{sw}} N_{sw} I_p$ is not zero at $\Phi \neq n \Phi_0$ and $\Phi \neq (n+0.5)\Phi_0$. $\bar{I}_p = 0$ at $\Phi \neq (n+0.5)\Phi_0$ since two permitted states, $n - \Phi/\Phi_0 = 1/2$ and $n - \Phi/\Phi_0 = -1/2$, with opposite direction of the persistent current $I_p \propto n - \Phi/\Phi_0$ have the same energy $(n - \Phi/\Phi_0)^2 = (1/2)^2 = (-1/2)^2$ and therefore $\bar{n} - \Phi/\Phi_0 = 1/2 + (-1/2) = 0$ at $\Phi \neq (n+0.5)\Phi_0$.

Thus, the dc voltage $V_{dc} \propto \bar{I}_p \propto \bar{n} - \Phi/\Phi_0$, sign and value of which are periodical function of the magnetic flux $V_{dc}(\Phi/\Phi_0)$ should be observed on the $l_s$ segment at its reiterate switching between superconducting and normal states. Just such quantum oscillations of the dc voltage $V_{dc}(\Phi/\Phi_0)$ were observed in $\textbf{33}$ $\textbf{34}$. There is important that the dc potential difference $V_{dc}(\Phi/\Phi_0)$ is observed both on the switched segment $l_s$ and other one $l_{sca} = l - l_s$ remaining all time in superconducting state. The latter is possible since the acceleration of pair in the electric field $dp/dt = 2e \bar{I}_p = 2eV_{dc}/l_{sca}$ is equilibrated by the momentum change, i.e. by the acceleration in opposite direction $\bar{I}_p$, because of the quantization (1). The momentum circulation $\oint dl p$ of superconducting pair with the charge $q = 2e$ changes from $2e\Phi$ to $2n\pi \hbar$ at each closing of the wave function. The average value of this change $\sum_{n=1}^{N_{sw}} N_{sw} (2n\pi \hbar - 2e\Phi) = 2n\pi \hbar (\pi - \Phi/\Phi_0)$ depends periodically on magnetic flux as well as the dc voltage $V_{dc}(\Phi/\Phi_0) \propto (\pi - \Phi/\Phi_0)$ observed in $\textbf{33}$ $\textbf{34}$. The observation of the dc voltage on the $l_{sca}$ segment remaining all time in superconducting state contradicts to the law of momentum conservation. The quantum oscillation of the dc voltage $V_{dc}(\Phi/\Phi_0)$ may be expected also in semiconductor and normal metal asymmetric mesoscopic loops.

4. INTRINSIC BREACH OF SYMMETRY

The law of momentum conservation is connected with symmetry of space and the violation of this law at the closing of the wave function can be connected with the intrinsic breach of symmetry. The experimental evidence of the intrinsic breach of symmetry is even more obvious than violation to the law of momentum conservation. It is observed in $\textbf{33}$ $\textbf{34}$ that the potential electric field $E_p(\Phi/\Phi_0) = - \nabla V(\Phi/\Phi_0)$ has right or left direction which changes periodically with the value $\Phi/\Phi_0$ of the magnetic flux. For example, if the $E_p$ direction is right at $\Phi/\Phi_0 = 1/4$ then it is left at $\Phi/\Phi_0 = 3/4$. It is very strange that direction of a vector changes with a scalar value. We should ask: “Why can the dc electric field $E_p$ have right direction at $\Phi/\Phi_0 = 1/4$ and left one at $\Phi/\Phi_0 = 3/4$?” There can be only answer: “Because the loop is asymmetric, for example the lower half is more narrow than the upper one, see Fig.4 in $\textbf{34}$, and the circular persistent current has contra-clockwise direction at $\Phi/\Phi_0 = 1/4$ and clockwise one at $\Phi/\Phi_0 = 3/4$.”

It seems self-evident that any direct current has a direction. Nobody doubts that a conventional direct circular current $I = R^{-1} (-d\Phi/dt)$ (it is in the stationary regime at $t \gg L_4/R_4$) induced in a loop with a resistance $R_4$ by the Faraday’s voltage $\oint dl E = -d\Phi/dt$ has clockwise or contra-clockwise direction and this direction determines right or left direction of the potential electric field $E_p = - \nabla V$ observed on a loop segment $l_s$ the resistivity $R_{ls}/l_s$ of which differs from the one $R_4/l$ along whole loop $l$, when $V = (R_{ls}/l_s - R_4/l)l/I$. But it is no so obvious for the persistent current existing because of the Bohr’s quantization, as well as stable electron orbit in atom. There is important to accentuate the fundamental difference of the persistent current, as one of the mesoscopic quantum phenomena, from the conventional current, on the one hand, and from electron orbit in atom (1), on the other hand.

The direction of a conventional circular current is determined by the circular Faraday electric field $\oint dl E = -d\Phi/dt$. But the persistent current is observed at a constant magnetic flux $\Phi$ and, according to the experimental evidence $\textbf{33}$ $\textbf{34}$, its direction changes with a scalar value $\Phi/\Phi_0$ without any external vector factor, i.e. the $I_p$ can have different directions at the same direction of the magnetic flux $\Phi$ when the $\Phi$ values are different. The observation $\textbf{33}$ $\textbf{34}$ of a direction of the persistent current is experimental evidence of intrinsic breach of clockwise - counter-clockwise symmetry, since, in contrast to the conventional circular current, the $I_p$ direction is not determined by an external vector. The periodical dependence $I_p(\Phi/\Phi_0) \propto V_{dc}(\Phi/\Phi_0)$ of the direction of the persistent current with the period $\Phi_0 = 2\pi \hbar/q$ is indubitable evidence that this intrinsic breach of symmetry is consequence of the Bohr’s quantization (1).

Bohr postulated the quantization (1), $\oint dl p = \oint dl mv = n2\pi \hbar$ at $\Phi = 0$, in order to explain the stability of electron orbit in atom. There was a logical difficulty
in this model until electron considered as a particle having a velocity \( v \) since it was impossible to answer on the question: "What direction has the velocity of electron on stable atomic orbit?" The uncertainty relation \( \Delta p \Delta l \geq \hbar \) and the wave quantum mechanics have overcome this difficulty. Electron can not has a certain coordinate on stable atomic orbit with a certain momentum according to the uncertainty relation and therefore it can not have a velocity. It is a wave but not a particle in the case of the Bohr’s quantization on atomic orbit. Therefore the Bohr’s quantization does not break a symmetry on the atomic level. But we see that the breach of symmetry because of the Bohr’s quantization is observed on the mesoscopic level.

This intrinsic breach of symmetry is observed since the canonical momentum \( p = mv + qA \) includes not only velocity \( v \) but also a magnetic vector potential \( A \) and therefore sign and value of a circular velocity on the lowest permitted state (2) depend periodically on the \( \Phi/\Phi_0 \). It can be considered as the cause of the periodical changes of equilibrium magnetization \( M(\Phi/\Phi_0) \) of both superconductor and nonsuperconductor, semiconductor and normal metal loops, mesoscopic loops. It is very difficult to investigate experimentally a possibility of like oscillations on atomic level since the Bohr’s radius, a typical atomic size \( R_B \approx 0.053 \text{ nm} \), is much smaller than a radius \( R = 500 \text{ nm} \) of the mesoscopic loops. The very high magnetic field \( B > \Phi_0/\pi R_B^2 \approx 3 \times 10^6 \text{ T} \) is needed in order to observe the \( M(\Phi/\Phi_0) \) oscillations on atomic level. It is important to note that the \( M(\Phi/\Phi_0) \) oscillations is challenge to the law of momentum conservation since this periodical change is evidence of change of the quantum number \( n = \frac{1}{\hbar} \frac{d\Phi}{2\pi \hbar} \) determining the value of momentum circulation (1). One may assume that this change can be only at a breach of the coherency of wave function along \( l \).

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