

# Quantum mechanics vs relativity: an experimental test of the structure of spacetime

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We have performed an experimental test in which quantum mechanics predicts a nonlocal single-particle transport beyond the very paradigm of motion in three dimensions and therefore beyond the relativity. The test has shown that such transport does exist. This fact strongly challenges the relativistic concept of simultaneity giving rise to a renaissance of Newtonian concept of absolute time but in a combination with the multidimensional space which corresponds to the quantum-mechanical notion of configuration space. The test legitimates realistic interpretation of quantum mechanics insofar as the requirement of Lorentz invariance appears irrelevant to any version of quantum theory.

## 1. Introduction

Quantum phenomena cannot be described in terms of conventional three-dimensional space but only in terms of multidimensional configuration space. This fact was realized by the founders of quantum mechanics and was widely discussed in the fifth (1927) Solvay Conference [1]. At the Conference, both Lorentz and Einstein repeatedly urged participants to remain in the framework of three-dimensional space in their description of quantum phenomena. However, neither Schrödinger with his theory of wave mechanics nor de Broglie with his pilot-wave theory were able to follow this appeal. The reason for the general concern about the framework of quantum mechanics was certainly much deeper than merely a counter-intuitive character of quantum phenomena. The point is the very principle of locality appears at stake together with the relativistic concept of spacetime, which is largely based on the impossibility to synchronize remote clocks in a nonlocal way. Nevertheless, most participants, such as Bohr, Heisenberg, Dirac and Pauli, spoke in favour of fundamental impossibility to describe, for instance, interference in terms of three-dimensional space. The way to reconcile relativity with quantum mechanics they saw in rejection of realism of the

latter. As a result, their explicitly unrealistic (Copenhagen) interpretation of quantum mechanics received the most support at the Conference and today it remains the most widely studied [2-5]. However, as a reward for such preference, we have got the problem of philosophic inconsistency between macro- and microcosm together with the related problem of how to define a “point of switching” from realism of the former to mysticism of the latter. These issues were stressed by Einstein during the familiar Bohr-Einstein debates [6-8].

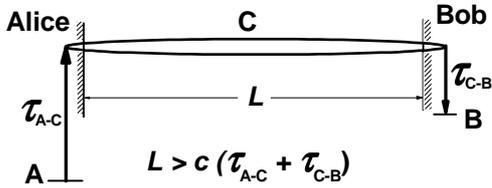
However, further course of events seems to confirm the preference made. It is the observation of nonlocal correlations under the conditions of Einstein-Podolsky-Rosen’s *gedanken* experiment which originally was conceived to demonstrate an incompleteness of quantum theory [9]. Actually, in the light of Bell’s theorem, EPR experiments play the role of a test which ultimately rules out any local hidden-variable theories and even some nonlocal realistic theories covered by the so-called Leggett theorem [10-13]. Moreover, even if a nonlocal realistic quantum theory, most notably the de-Broglie-Bohm theory, does not contradict any EPR experiments, it inevitably faces a truly formidable difficulty with the requirement of Lorentz invariance [14-20]. Although the orthodox quantum theory faces the same problem through the notion of wavefunction collapse, here the problem seems not so blatant just because of the mysticism of this theory. This circumstance is the basis of what today we call quantum dilemma which shortly reads as follows: either nonlocality or realism [21-23]. In the view of EPR experiments, the solution of the dilemma seems self-evident and therefore mysticism is still the philosophic foundation of microcosm [24-25].

The also significant fact is the EPR nonlocality cannot provide, even in principle, either a nonlocal transport or a nonlocal signaling. It is the subject of so-called no-communication theorem [26-28]. Today, this fact is generally regarded as being deeply fundamental because quantum mechanics appears thus completely safe for the relativistic concept of simultaneity and therefore for the relativistic concept of spacetime. Accordingly, the impossibility to describe quantum phenomena in terms of conventional spacetime is generally regarded as rather a descriptive problem which does not lead to any far-reaching consequences.

In this work, however, we carry out an experimental test in which quantum mechanics definitely predicts a nonlocal transport which is beyond the very paradigm of motion in three dimensions and could thus challenge the relativistic concept of spacetime.

## 2. *Gedanken* experiment

To clarify the core of the test, we start with a *gedanken* experiment shown schematically in Fig. 1. Suppose that there is a quantum system, the eigenstate of which is a macroscopic-scale one-dimensional circular orbit ( $C$ ). In the system, we can easily select two spatial domains such that both are crossed by the orbit  $C$  but remote from each other by a macroscopic distance  $L$ . Let in the first (Alice's) domain there is also a local level  $A$  while in the second (Bob's) domain there is a local level  $B$  together with a number of local scatterers capable to provide  $C \rightarrow B$  transition during a characteristic time ( $\tau_{C \rightarrow B}$ ).



**Fig. 1. *Gedanken* experiment to demonstrate a nonlocal single-particle quantum transport.**  $C$  – macroscopic-scale circular quantum orbit,  $L$  – the distance between Alice's and Bob's domains.  $A$  and  $B$  – local quantum levels belonged to Alice's and Bob's domain, respectively. Vertical arrows denote local quantum transitions.

Initially, only lowest level ( $A$ ) is occupied by an electron. However, if Alice exposes her domain to light capable to provide  $A \rightarrow C$  transition during a characteristic time ( $\tau_{A \rightarrow C}$ ), then the electron should appear in the level  $B$  during the time ( $\tau_{A \rightarrow C} + \tau_{C \rightarrow B}$ ) and this is nothing but the transport from  $A$  to  $B$ . The key point is the transport is *independent* of  $L$  but determined only by the above characteristic times which always can be shortened either through a more intense photo-excitation or through a higher concentration of scatterers. Moreover, to provide a nearly hundred-

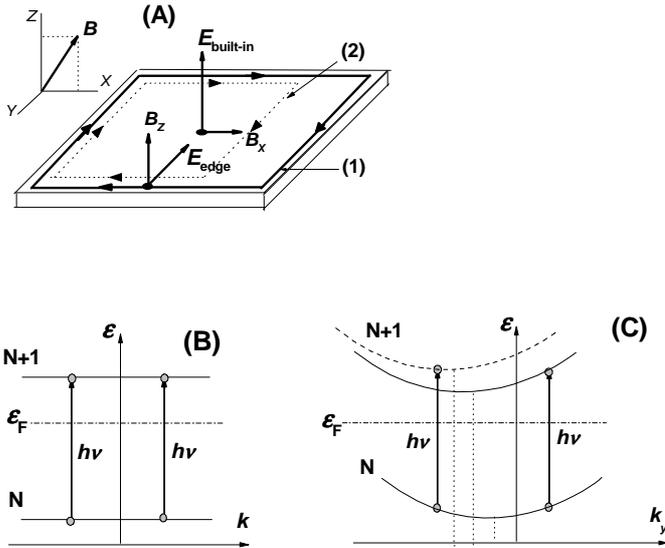
percent probability for the detection of at least one electron in Bob's domain, one can use a great number of spatially-separated quantum orbits of that kind. The "speed" of such transport ( $L/(\tau_{A \rightarrow C} + \tau_{C \rightarrow B})$ ) may well be higher than the speed of light without any conflict with relativity because both  $\tau_{A \rightarrow C}$  and  $\tau_{C \rightarrow B}$  have nothing to do with the time spent in overcoming the distance  $L$ . In other words, the transport is beyond the very paradigm of motion in conventional space as well as beyond the no-communication theorem. In terms of the orthodox quantum theory, it is based on the fundamental principle known as indeterminacy of the position of non-interacting particle in a quantum orbit.

### 3. The idea of how to realize

At first sight, our *gedanken* experiment seems fundamentally unrealisable because we used to think that quantum orbits are always microscopic and their size is uncontrollable. However, this is not exactly the case. To see that, consider a macroscopic quantum system known as the integer quantum Hall (IQH) system [29-30]. According to the generally-recognized Laughlin-Halperin's theory, any IQH system contains so-called current-carrying states extended along the perimeter of the system *regardless* of its size [31-32]. In the states, the electrons behave as spontaneous quasi-one-dimensional currents with a cross-section of the order of their microscopic cyclotron radius. Roughly, these states are originated from the external quantizing magnetic field crossed by the in-plane electric field which always occurs in the vicinity of system edges. In principle, these states are nothing but the quantum orbits and hence could be suitable to perform the experiment in Fig. 1. However, the problem is that in optical experiments, such as that one in Fig. 1, it is hard to distinguish the effect of a relatively small number of edging states on the effect of a gigantic number of localized states in the system interior. This fact is well known from the photo-conductivity measurements performed in IQH systems [33].

Nevertheless, the situation is not hopeless and we could try to make experimentally-accessible the Laughlin-Halperin-type states in two ways. The first way is to “construct” these states not only close to system edges but also in the interior. Indeed, if IQH system has a sharply asymmetric confining potential, then there should be the so-called built-in electric field and this field is an analogue of in-plane electric field near the system edges. Now if the external magnetic field has both in-plane and quantizing components, then the crossed electric and magnetic fields could occur not only close to system edges but also in the interior. Potentially, this could be the reason for Laughlin-Halperin-type states. Indirectly, this guess is supported by the theoretical calculations with a simplified model of infinite IQH-like system [34]. According to these calculations, if the system is asymmetric while the external magnetic field has both quantizing ( $Z$ ) and in-plane ( $X$ ) components, then Landau level degeneracy may be lifted so that the wavefunctions become Bloch-like with nonzero electrons’ in-plane velocities in the  $Y$ -direction:  $v_y(k_y) = \frac{1}{\hbar} \frac{\partial \varepsilon(k_y)}{\partial k_y} \neq 0$ . The energy spectrum consists thus of a series of Landau subbands shifted in  $k$ -space ( $\varepsilon(k_y) \neq \varepsilon(-k_y)$ ) and their shift depends on the Landau quantum number as well as on the so-called toroidal moment which is a cross product of the magnetic field and the electric field in the  $Z$ -direction [35-36]. In the  $X$ -direction, however, the wavefunctions remain strongly restricted within the electron cyclotron radius ( $r$ ) and the electrons’  $X$ -coordinates remain in a correlation with their wave vector like in the case of conventional IQH system ( $x_0 = -k_y r^2$ ). It follows that the electrons are spatially-separated one-dimensional spontaneous currents and they are thus strongly reminiscent the edging currents in the Laughlin-Halperin’s model. The only problem is they are not closed and *a-priori* it is not clear whether or not they exist in a system of finite size. It is still our guess that these currents do exist and they are closed through the system edges (Fig. 2A). However, if this guess will prove to be valid, we obtain a number of one-dimensional macroscopic orbits which differ in their spatial position, size, characteristic energy and velocity.

The second way is that we could try to find a type of optical measurements, which are sensitive only to delocalized states but insensitive to localized ones. In other words, these measurements should provide an output only if the energy spectrum of localized states (Fig. 2B) truly transforms into the energy spectrum of Laughlin-Halperin-type states (Fig. 2C). Fortunately, such measurements can be proposed. Indeed, in Fig. 2B the optical transitions between Landau levels cannot result in a measurable in-plane current because of zeroth in-plane electrons' velocities. By contrast, in Fig. 2C their in-plane velocities are nonzero and moreover they are not exactly the same at initial and final state of an optical transition. Therefore, in the latter case a net current could potentially emerge under the cyclotron resonance (CR) absorption even in *unbiased* IQH system and this current may well measurable. Phenomenologically, it would be the so-called photo-voltaic effect resulted from an inner spatial asymmetry of the excited system [37].



**Fig. 2. Schematic illustration of how long-range orbit-like quantum states could emerge in asymmetric IQH system and of how they could be detected.** (A) An unbiased IQH system with asymmetric confining potential in presence of tilted quantizing magnetic field: (1) true Laughlin-Halperin current-carrying states in the vicinity of system edges, (2) Laughlin-Halperin-type states originated from the crossed electric and magnetic fields in the system interior. (B) CR transitions in conventional IQH system (C) CR transitions under lifting of Landau level degeneracy in the  $Y$ -direction. The shift of Landau subbands is supposed to be a function of the toroidal moment as well as of the Landau quantum number.

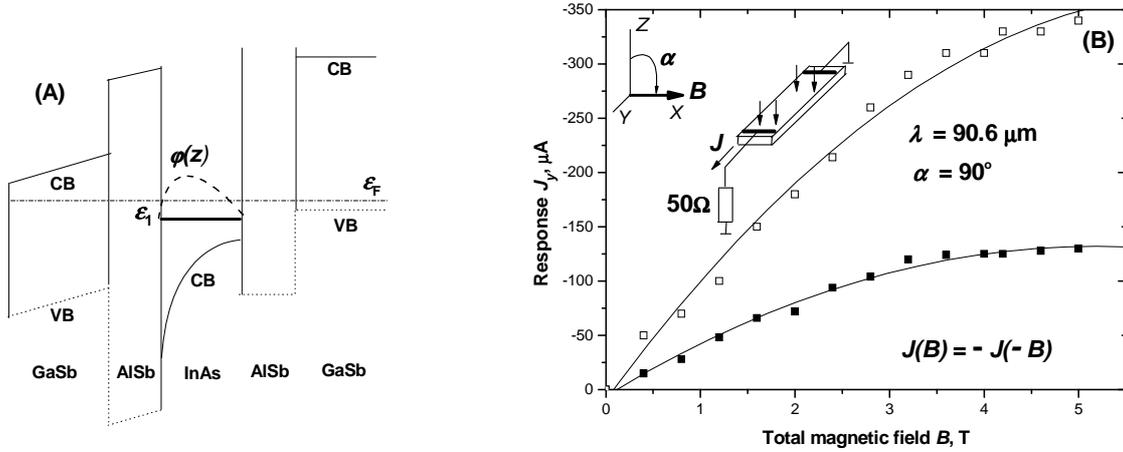
However, to be sure that the detected responses (if any) are truly related to the Laughlin-Halperin-type states, we need in a rigorous criterion that would allow us to distinguish these responses from the other possible ones. To find it, let us focus on the following remarkable thing. If the electrons'  $X$ -coordinates truly correlates with their wave vectors in accordance with the above-mentioned relation, then the electrons' velocities ( $v_y(k_y)$ ) appear spatially-ordered in the  $X$ -direction. Moreover, the ordering is of such kind that it does not imply any spatial periodicity because  $v_y$  is not a periodic function of  $k_y$ . If such ordering does exist, then we should observe quite different local responses at different  $X$ -coordinates because, as it is seen from Fig. 2C, the expected current should be a function of  $k_y$  and hence of  $x_0$ . The presence of such ordering is just the criterion we need. Returning to Fig. 2C, it is seen that CR conditions for electrons with positive velocities should be fulfilled at lower magnetic fields than those for electrons with negative velocity. This means that even CR position as well as CR lineshape may be sensitive to  $x_0$ , if the Landau subband broadening is not too high.

#### 4. Experimental details

In experiment, we use pulsed optically-pumped terahertz ammonia laser with the energy of light quanta of 13.7meV; pulse duration of about 50ns and the incident intensity of about 200W/cm<sup>2</sup> [38]. Spatially-uniform unpolarized radiation is incident normally onto the sample surface and does not thus induce any in-plane asymmetry. To provide nonzero toroidal moment, the external magnetic field (up to 6.5T) is tilted from the normal by about 15°. Sample temperature (1.9K) is much less than the energy of light quanta. High-speed in-plane responses are detected in short-circuit regime with a 50Ω load resistor.

The IQH system is based on the MBE-grown semimetallic single quantum well structures of type InAs-GaSb, for which CR is expected at magnetic fields of about 4.8T. In these structures, the

valance band of GaSb overlaps the conduction band of InAs by about 100 meV. Thus, to avoid a hybridization of these bands, a 15-nm-wide conducting layer of InAs is sandwiched between two 10-nm-wide AlSb barriers. Typical structure consists of a thick GaSb buffer layer followed by this sandwich and capped by a 20-nm-wide GaSb protecting layer. Under these conditions, Fermi level is well above the first quantum-size level but below the second level. Low-temperature electron sheet density is as high as  $1.4 \cdot 10^{12} \text{ cm}^{-2}$  with the mobility of about  $10^5 \text{ cm}^2/\text{Vs}$ .



**Fig. 3. Evidence for built-in electric field in the structures studied.** (A) The energy-band diagram of semimetallic InAs-GaSb single quantum well structure with two AlSb barriers. Dotted line shows schematically the electron density shifted toward more charged interface. (B) Test for the presence of built-in field. The inset shows the geometry. The outcome is shown for two samples with different growth parameters. Solid lines are a guide for the eye.

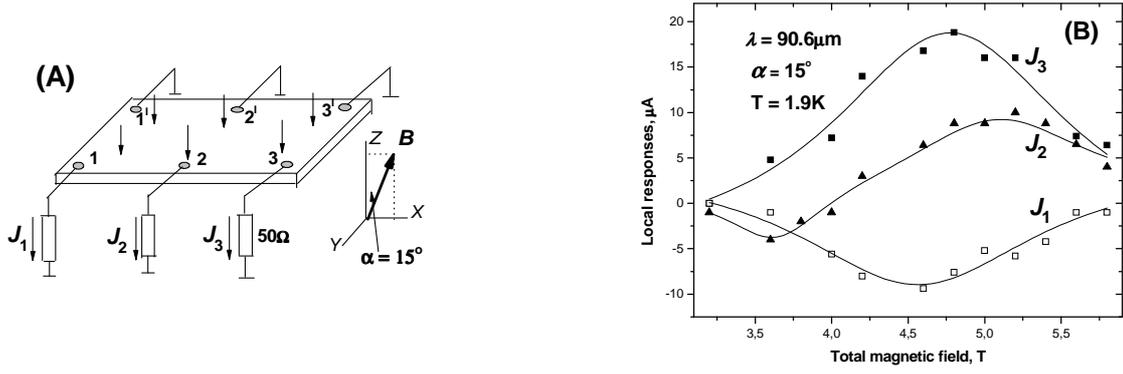
Schematically, the energy band diagram of the system is shown in Fig. 3A where the asymmetry of confining potential is supposed to be due to the penetration of surface potential into the well [39]. The potential profile across the well should be rather exponential than linear just because of the high electron density. As a result, the built-in electric field is most likely a sharp function of Z-coordinate. Therefore, if this field truly gives rise to delocalized states, then these states are most likely coexisting with the localized ones.

To be sure of the presence of built-in field in our structures, they were tested by the method shown in the inset of Fig. 3B. Actually, it is conventional photo-voltaic measurements in the classic

regime when the external magnetic field is non-quantizing. The test is based on the simple and reliable idea that in-plane magnetic field alone, as a pseudo-vector, cannot provide in-plane response which is a polar vector. However, the cross product of in-plane magnetic field and built-in electric field is indeed a polar vector, that is, the system toroidal moment. Therefore, in-plane response could occur, at least for symmetry reasons. In the test, we use the samples of  $5 \times 12 \text{ mm}^2$  with a single pair of ohmic contacts. Typical outcome is shown in the main graph of Fig. 3B. It is seen that in-plane response does occur. As expected, it increases with increasing of magnetic field and is sensitive to the MBE-growth parameters those alter the built-in field.

### 5. Test for the presence of macroscopic-scale quantum orbits

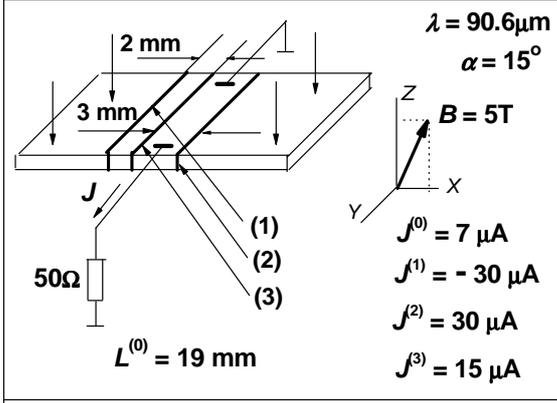
To test the availability of Laughlin-Halperin-type states in accordance with selected criterion, we take a relatively large sample ( $19 \times 12 \text{ mm}^2$ ) with three short contact pairs (1mm in length) belonged to different domains remote from each other at a distance of no less than 7mm (Fig. 4A). To avoid edging effects, each contact is remote from the closest edge by about 1mm and for the sake of convenience the pairs are numbered from left to right. Fig. 4B shows CR spectra obtained. It is clearly seen that despite of exactly the same experimental conditions, they indeed differ drastically from each other so that they have even opposite sign at the opposite sample ends. In the middle of the sample, CR has a hybrid bipolar lineshape. To be sure that we are truly dealing with the spatial ordering, we reverse magnetic field and repeat the measurements. The responses appear redistributed roughly in accordance with the following relations:  $J_1(-B) = -J_3(B)$ ;  $J_2(-B) = -J_2(B)$ ;  $J_3(-B) = -J_1(B)$ . That is just what one would expect because the reverse of magnetic field should result in the reversed shift of Landau subband in  $k$ -space (see Fig. 2C). Thus, the test strongly supports our guess regarding the existence of Laughlin-Halperin-type states in the system interior.



**Fig. 4. Evidence for Laughlin-Halperin-type states in the interior of an asymmetric IQH system.** (A) Scheme of the detection of local photo-responses from different sample domains. The contacts are identical and each one is 1mm in length. The distance between adjacent pairs is 7mm. The total sample length is 19mm. (B) CR spectra obtained from these pairs.

It should be noted that by definition we have realized a peculiar macroscopic quantum phase with the lack of translational symmetry because the local responses on the same excitation are not spatially periodic in the  $X$ -direction [40]. The new phase can thus be regarded as the result of a continuous quantum phase transition from the Quantum Hall state of matter and this transition is induced by system toroidal moment. The characteristic feature of the phase is that it has the lowest symmetry among all quantum phases known up to now. In a sense, a system in the phase is reminiscent a gigantic *single* atom rather than a solid state system with free electrons.

However, the lack of translational symmetry automatically implies that any local response should be extremely sensitive to the position of system edges *regardless* of their remoteness in the  $X$ -direction. Thus, the presence (or absence) of this effect would be a one more test to verify our guess. To perform the test, we take once more a large sample ( $19 \times 12 \text{ mm}^2$ ) but now with a single short contact pair (1mm long) centred in the  $X$ -direction (Fig. 5). At a fixed tilted magnetic field ( $B \approx 5\text{T}$ ), we measure photo-responses each time the sample has become shorter in the  $X$ -direction because of mechanical cuttings. Three sequenced cuttings have been made in such a way that each new edge is remote from the contacts at a macroscopic distance of no less than 1mm (see Fig. 5).



**Fig. 5. Evidence for a high sensitivity of local responses to the position of remote sample edges.** Responses from single short contact pair are measured after sequenced mechanical cuttings. The cutting lines are parallel to the  $Y$ -direction. Long arrows show their position with respect to the contact pair.

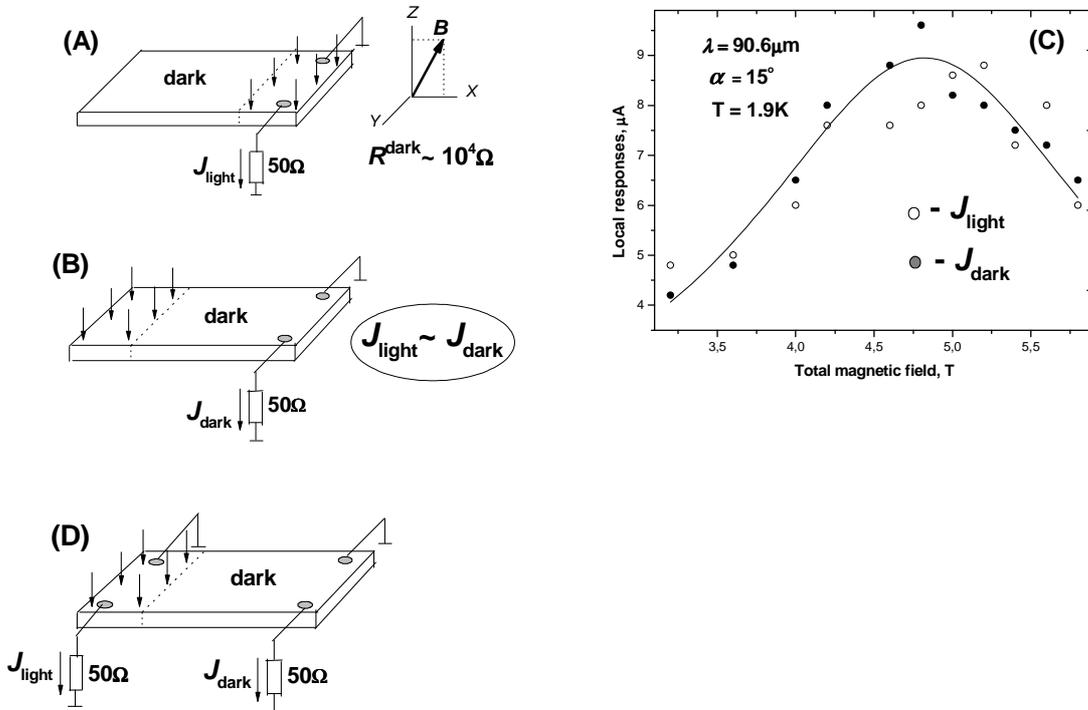
The outcome is presented in the right-hand corner of Fig. 5. Upper index denotes the number of cuttings before given measurement. It is clearly seen that each cutting does change drastically the response so that even the sign may become reversed. This fact cannot be interpreted in terms of any trivial effects depended on the sample length and therefore we are truly dealing with a phase in which Laughlin-Halperin-type states are responsible for the breaking of translational symmetry.

## 6. The main test

The apparent success of the test for the presence of macroscopic quantum orbits gives us the chance to realize the main test in accordance with the scheme in Fig. 1. Indeed, the role of  $A \rightarrow C$  transitions could play CR optical transitions while  $C \rightarrow B$  transitions are the intra-subband scattering-induced transitions. The characteristic time  $\tau_{C \rightarrow B}$  is thus the so-called quantum relaxation time which is of the order of  $0.3 \text{ ps}$  in typical structures and is always much shorter than the electron lifetime in higher Landau levels [41-42].

The idea of the main test is as follows. If the nonlocal quantum transport does exist, then the efficiency of Bob's detection should *not* depend on whether one excites his own domain or the

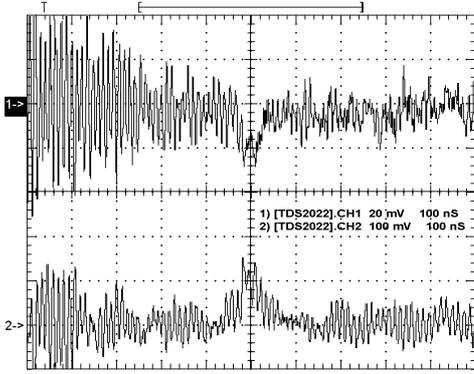
Alice's domain *independently* of the distance between these domains. Of course, in terms of everyday intuition this effect would seem even a bit crazy because no reasons for a transport between these domains, especially if the transport should not imply any substantial losses independently of the distance covered. So, the test consists of two experiments shown in Figs. 6A and 6B, respectively. In both cases, we use large samples ( $19 \times 12 \text{ mm}^2$ ) with a single short contact pair (1mm long) remote from the closest sample edge by about 1mm. Only one third of the sample is exposed to light but in the experiment 6A the contacts are inside the laser spot while in the experiment 6B they are remote from the laser spot at a distance of about 1cm.



**Fig. 6. Experimental test of nonlocal single-particle quantum transport.** (A) A one third of the sample is exposed to light and the contact pair is inside the laser spot. (B) The same experiment but now the contact pair is remote from the laser spot at a distance of 1cm. (C) CR spectra obtained in the experiments A and B. (D) The scheme of synchronous detection of the responses from both the illuminated pair and the pair in the dark.

Fig. 6C shows CR spectra obtained in both experiments. To be honest, this outcome exceeds even the most optimistic expectations. As expected, the responses are approximately the same despite the fact that a direct electric connection is impossible at least because the resistance of

unexposed domain is as high as about 10kOhm, i.e. more than two orders higher than the load resistance at which we measure the output. This means the nonlocal quantum transport does exist. Moreover we can roughly estimate the “speed” of such transport but bearing in mind that this “speed” has nothing to do with a motion throughout the sample. Under the high laser intensity, it seems a good approximation that the characteristic time necessary to “overcome” the distance of 1cm is the quantum relaxation time and we thus obtain the “speed” of the order of  $3 \times 10^{12}$  cm/s, i.e. two orders higher than the speed of light.



**Fig. 7. The outcome of synchronous detection.** Upper track – the signal from illuminated pair (20mV/div.); lower track – the signal from pair in the dark (100mV/div.). Timescale is 100ns/div.

To avoid any misinterpretation, we perform an additional experiment in which we use two contact pairs: inside and outside the laser spot (Fig. 6D). Fig. 7 shows typical tracks under the synchronous detection of both responses. It is clearly seen that the dark response is in a factor of five *higher* than the response in spotlit domain. This fact rules out the interpretation of the former in terms of a “secondary” effect with respect to the latter. Under reversed magnetic field the responses are redistributed as if the whole sample is still exposed to light:  $J_{dark} \approx -J_{light}$  ;  $J_{light} \approx -J_{dark}$  . It seems extremely hard for any alternative interpretation to explain the same dependence on the magnetic field in both cases. As it is also seen from the oscillogram, there is no delay between the responses with an accuracy of about 20ns. It follows that, to have a little chance to be relevant, any transport from laser spot must be of a ballistic character with a speed of no less than  $10^8$  cm/s and

with a mean free path of *more than 1cm*. This seems absolutely impossible because of a gigantic number of various scatterers. Finally, we repeat both experiments (6A and 6B) but in the classic regime when magnetic field has only X-component. No responses are observed in the experiment 6B despite the fact that the responses in the experiment 6A are as high as about 0.5mA, i.e. two orders higher than those in the quantum regime.

## **7. Fundamental consequences**

Although the nonlocal quantum transport is demonstrated at a relatively short distance, the very fact of such transport leads to truly fundamental consequences. The most prominent one is that *de-facto* we demonstrate a quasi-instantaneous procedure to synchronize remote clocks. The procedure naturally avoids relativistic causality paradoxes, such as Tolman's paradox [43-44], because they all suppose the relevance of Lorentz transformations. The procedure gives thus rise to a renaissance of Newtonian concept of absolute time in accordance with our intuitive perception of this notion. However, the concept of space appears conversely much more complicate than the Newton's concept: it is the concept of multidimensional space, which corresponds with the quantum-mechanical notion of configuration space. Perhaps that is just the concept responsible for the counter-intuitive character of quantum phenomena. Thus, in a broad sense, it may well be that the main news we have got from quantum mechanics is not a fundamental indeterminism or even mysticism of the world but rather its fundamental multidimensionality.

The also significant point that follows from our test is that the explicitly non-realistic orthodox quantum theory no longer has advances against the quantum realism which currently is embodied in the de Broglie-Bohm pilot-wave theory. It is a consequence of the fact that the quantum dilemma appears a fiction insofar as the quantum nonlocality cannot be contraposed to relativity and the requirement of Lorentz invariance appears thus inapplicable to any version of quantum theory. Moreover, the realistic quantum theory now looks even more attractive at least in the view of the

prospects to realize the Einstein's dream of unified philosophic foundations of physics. Accordingly, the insurmountable philosophic problem of the "switching" from the classic realism to the quantum mysticism is naturally transformed into rather a physical problem, that is, the "switching" from the classic three dimensions to the quantum multidimensionality.

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