Perspectives in Nanoscale Physics

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Abstract

This article provides a pedagogical introduction to the quantum transport in nanoscale systems. Nanoscale systems are at the boundary between the microscopic and macroscopic worlds. This gives rise to novel phenomena intrinsic to nanoscale systems, which are governed by fundamentally different physical principles.

INTRODUCTION

Common branches of physics such as atomic physics, plasma physics, and particle physics are named after the objects they are concerned of. Likewise, the nanoscale physics, or "nanophysics" as widely called, is the study of systems that have dimensions of several nanometers to hundreds of nanometers. However, it is rather an odd classification. It does not specify the state of the matter but only the size of the system. This may be a partial reason many fields in physics with completely different perspectives are called by the name of nanophysics. Apparently, nanoscale is the only metric scale that names a physics branch. Has anyone heard about picophysics or gigaphysics? What makes the scale of nanometers so special? Does the size of the system ever matter?

Let us first think of the question concerning an even more popular discipline "nanotechnology", which is no doubt closely related to the development of nanophysics under the ambitious interdisciplinary paradigm "nanoscale science and technology". The scale of nanometers put a technological (and eventually fundamental) barrier, for example, in the development of optical-or electron-beam based lithography for highly integrated circuits, and it has long been a technological challenge to overcome this barrier. This challenge brought a new strategy to build the ultra-small devices using the atoms and molecules as building blocks (socalled bottom-up approach) instead of fabricating the patterns (so-called top-down approach). This new approach implies the reliable manipulation of individual atoms or molecules with nanometer precision, and has become the basic paradigm in various fields of science and engineering. On this ground, nanoscale indeed has a special meaning for nanotechnology as a novel response to the technological challenge.

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However, challenging technological barriers may not attract so many physicists. The true reason that the nanoscale systems have opened a new branch of physics comes from the novel physical phenomena intrinsic to such systems governed by fundamentally different principles. Nanoscale is at the boundary between the microscopic and macroscopic world. Usually the microscopic world of individual atoms or molecules is well described by single-particle quantum mechanics. The macroscopic world of "bulk" systems is governed by the classical mechanics or the thermodynamic limit of statistical physics. Nanoscale systems are much larger than microscopic systems and should be described within the framework of many-body physics. Yet, they are far smaller than "bulk" systems; more precisely, they are comparable to or even smaller than the characteristic lengths of the physical effects in question. In principle, the characteristic lengths can be micrometers or even longer, and there is no particular reason to favor nanometers. Such an intermediate scale between microscopic and macroscopic scales is called the "mesoscopic" scale [1].

There are several unique features of the mesoscopic systems appearing as immediate consequences of the intermediate length scale. Firstly, the dynamics of the system is phase coherent and exhibit various interference phenomena. Secondly, the coherence however is not perfect. A mesoscopic system is inevitably coupled to the external world or "environment" (dynamic impurities, external controls, probes, etc.), the interaction with which causes dephasing of the wave function of the system. Thirdly, the nanoscale structures are typically low dimensional and the electron-electron interaction is strong. The interplay between the coherence and the strong interaction gives rise to many interesting effects. Fourthly, nanoscale systems allow us to tune the system parameters in a wide range to high accuracy. Nanoscale systems therefore provide a convenient test ground for fundamental theories as well as open a new era for information processing based on quantum theory. The purpose of this article is to show through a pedagogical review how novel phenomena intrinsic to nanoscale systems emerge and the fundamental principles of many-body quantum physics can be used to understand such effects.

The field of nanophysics is expanding very fast and now accommodates diverse subbranches. The perspectives of each sub-field are sometimes completely different from those of others. In this article, we only focus on the mesoscopic transport and related topics in nanoscale conductors.

CONDUCTANCE QUANTIZATION

It is well known that the electric conduction through a macroscopic conductor is governed by the Ohm's law

$$I = GV \tag{1}$$

where I is the current through the sample and V is the bias voltage applied across the sample. The conductance G is not an intrinsic quantity, and inversely proportional to the length L of the conductor. This seems natural because the number of impurities and hence the scattering of them will increase with L. However, this statistical argument is based on the assumption that there are sufficiently many impurities within the conductor. This argument does not apply any longer when there are only a few impurities, namely, when the length L is comparable to the mean free path ℓ_p of the electrons. Then in this limit, without scattering from impurities, would the conductance go to infnity? The truth is, as demonstrated experimentally, that the conductance in this limit ($L \lesssim \ell_p$) is finite and an integer multiples of the conductance quantum $G_0 = 2e^2/h$, where h is the Planck constant and e is the elementary charge. A natural question is, "Where does the finite resistance (inverse of the conductance) come from?" The conductor itself cannot cause the resistance since it has no scattering center inside. The finite resistance occurs at the interface of the conductor with the contact (or charge reservoir), which is made of different material [2]. Then why is the conductance quantized? The conductors in consideration has typically small size in the transverse directions, comparable to the de Broglie wavelength of the electrons. Therefore, according to quantum mechanics, the transverse motion is quantized. In other words, at a given energy, there are only finite number of transverse modes that can carry the electric conduction through the conductor. Each mode is capable of conductance of G_0 because of the .nite group velocity [3].

Another interesting difference between mesoscopic conductors and macroscopic conductors emerges when one considers more than one conductors connected in series. For example, the total conductance of the two macroscopic conductors with conductance G_1 and G_2, respectively, in series is given by

$$\frac{1}{G_{\text{total}}} = \frac{1}{G_1} + \frac{1}{G_2} \tag{2}$$

However, one can easily infer that this will breaks down for mesoscopic conductors. The transmitted wave through the two conductors has contributions from multiple reflections between the two scattering regions. The coherent sum of these contributions give rise to the Fabry-Pérot-type interference, whose consequence should be different from the incoherent sum in Eq. (2). Similar consideration shows that the macroscopic law of parallel resistors, $G_{\text{total}} = G_1 + G_2$, also breaks down in the mesoscopic regime.

These remarkably simple examples demonstrate clearly how the phase coherent motion of the electrons in nanoscale systems modify dramatically the macroscopic laws of transport. The conductance quantization is known as a basic phenomenon in mesoscopic physics.

Nevertheless, there is also a controversial issue: In a wide range of samples, they have observed an anomalous conductance plateau at $0.7G_0$ [4], which cannot be understood in a simple picture described above.

UNIVERSAL CONDUCTANCE FLUCTUATIONS

When describing disordered systems, the concept of impurity ensemble provides a very useful theoretical tools [5]. An impurity ensemble is the collection of systems that have the same macroscopic parameters (such as the average impurity concentration) but are different in the detailed configuration of the impurities. The average over the ensemble restores the symmetries, which otherwise will be lost due to presence of the impurities. This ensemble average is justified for a macroscopic system since the system size is much larger than the characteristic lengths and essentially the system itself is the same as the ensemble. However, this is not true any longer for mesoscopic systems, whose sizes are comparable to the characteristic lengths. Physical quantities of a mesoscopic sample with a given particular arrangement of the impurities can deviate significantly from the ensemble averaged ones. In particular, the conductance of different samples belonging to the same impurity ensemble varies from sample to sample. Such variation of conductance is the “fingerprint” of a particular mesoscopic system and of primary interest in mesoscopic physics.

Another interesting issue about the impurity ensemble and mesoscopic fluctuations is the distribution within an ensemble. A big surprise in mesoscopic physics was the finding that the distribution is “universal”. More precisely, the mean square fluctuations $\langle(\Delta G)\rangle^2 = \langle G^2\rangle - \langle G\rangle^2$ of the conductance G in an impurity ensemble is given by a universal constant which depends only on the effective dimensionality of the system and the general symmetry, but not on the conductance G itself nor on other microscopic details of the system or the impurities [6, 7].

COHERENCE AND MEASUREMENT

The motion of an isolated electron is coherent; the wave function of the electron has a definite phase. When the electron is, say, in a solid, its motion eventually becomes incoherent due to the coupling to various environments. This process of losing phase coherence is called *dephasing* and defines the characteristic dephasing length, over which the electron maintains its coherence. Since the dephasing length is typically at nanoscale, it is important to understand the dephasing mechanism.

The notion of dephasing is also related to the fundamental and intriguing issue in quantum mechanics: Why do macroscopic objects behave classically while microscopic world is governed by quantum mechanics? This issue dates back to Schrödinger’s cat paradox [8]. A very successful explanation has been provided in terms of dephasing [9]. A macroscopic object is inevitably exposed to various environments and loses quickly its phase coherence due to the interaction with the environments.

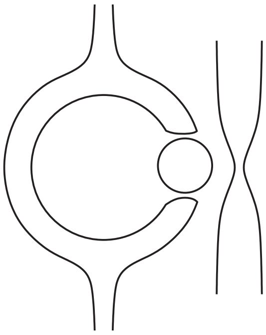

FIG. 1: A schematic of the “which-path experiment”. The electrons pass either through the left or right arm of the interferometer. Electrons passing through the right arm stay for a while on the quantum dot, and affect the current through the nearby quantum point contact. Which path of the two an electron takes can be detected by monitoring the current through the quantum point contact.

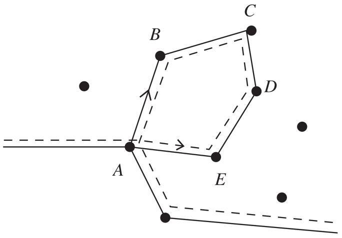

FIG. 2: Illustration of the weak localization effect. The paths following the solid and dashed lines, respectively, interfere always constructively.

But then how does an interaction with environments lead to dephasing? To examine this, let us consider a so-called “which-path experiment” (see Fig. 1 and Ref. [10]), a modified version of the double-slit experiment. The electrons pass either through the left or right arm of the interferometer. Electrons passing through the right arm stay for a while on the quantum dot, and affect the current through the nearby quantum point contact. Which path of the two an electron takes can thus be detected by monitoring the current through the quantum point contact. Therefore, in the presence of the quantum point contact the electrons will not interfere because interference appears “only if there is no way to know, even in principle, which path the particle took” [11]. Motivated from this experiment, we may regard the environment as a “detector”. In the presence of the coupling to the environment (detector), the electron cannot give rise to interference. This analogy can be generalized. In the which-path experiment, it was demonstrated that if the coupling between the quantum point contact and the quantum dot is week and the which-path information is not acquired enough, the electrons still exhibit partial interference. Likewise, one can infer that depending on the type of the coupling to the environment, if the coupling does not give enough information about the electron motion, the electron can still maintain (partial) phase coherence.

In realistic samples, there are a variety of dephasing sources. To understand the dephasing mechanism in a given system, we need to first measure the dephasing length accurately. The most convenient and powerful method has been provided by the theory of weak localization [2]. The weak localization is illustrated in Fig. 2. The paths following the solid and dashed lines, respectively, interfere always constructively (in the absence of external magnetic field). This implies that particles are localized near the impurities and enhances the resistance of the sample. Since this localization is essentially an interference effect, the extent of localization strongly depends on the dephasing length. Therefore, measuring the weak localization correction of the conductance of the sample, one can measure the dephasing length of the conductor.

COHERENCE AND CORRELATION

Among many other sources of dephasing, the electron-electron interaction is of primary interest. It exists in any sample, and without magnetic impurities it is the major source of dephasing at low temperatures. The dephasing time (length) due to the electron-electron interaction in disordered conductors has been investigated thoroughly by Altshuler et al. [12, 13] and Altshuler and Aronov [14]. It was shown that the dephasing time diverges as the temperature goes to zero. This theory had been confirmed by many experiments. However, very recently, it was challenged by experiments by Mohanty et al. [15] and Mohanty and Webb [16], where it was reported that the dephasing length is saturated in the limit of zero temperature. The controversy was heated even further by a new theory[17, 18], which predicts a finite dephasing length even at zero temperature. This controversy stimulated renewed interests in this fundamental issue and motivated many other experimental and theoretical works. In particular, recently the old and new theories have been re-investigated thoroughly in very detail. It predicts a divergent dephasing length at zero temperature and ascribes the experimental results reported by Mohanty et al. [15] and Mohanty and Webb [16] to very small concentration of magnetic impurities in the sample.

Apart from this fundamental issue, the interplay between the coherence and electron-electron correlation brings about many non-trivial effects. One interesting example is the effects of the interplay on the shot noise in superconducting single-electron transistor, viz, a small superconducting island tunnel coupled to two superconducting leads. This nanoscale structure and its noise characteristic are important since the the structure can be used as a fast charge detector with high precision, which is one of the essential parts for superconductor-based quantum information processor[19]. Since the de-coherence arises due to the interaction with the external world, the noise usually increases with the decoherence rate. However, in the superconducting single-electron transistor it turns out that the novel interplay between the coherent tunneling of Cooper pairs and the strong electron-electron interaction can reduce the shot noise significantly [20, 21].

Still another interesting effect of the interplay between coherence and correlation can be seen in Hanbury Brown-Twiss experiment [22, 23] on electron systems [24.26]. Suppose first that a beams of thermal electrons are incident on to an electron beam splitter (see Fig. 3). When one makes a coincidence measurement on the two output channels, the cross correlations of the measurement changes dramatically from bosons to fermions. While the bosons give positive cross correlations [22, 23], the fermions exhibit negative correlations [24, 25] because of the different statistics of the particles. Let us now consider two beams of electrons from independent sources incident on to two input channels of a beam splitter [26]. Since the input beams are independent and have no phase correlations among them, one cannot expect an interference at any of one output channels of the beam splitter. However, when one makes a coincidence measurement on both output channels, one restores the interference, which gives rise to the cross correlations of the particles detected on the output channels [26, 27].

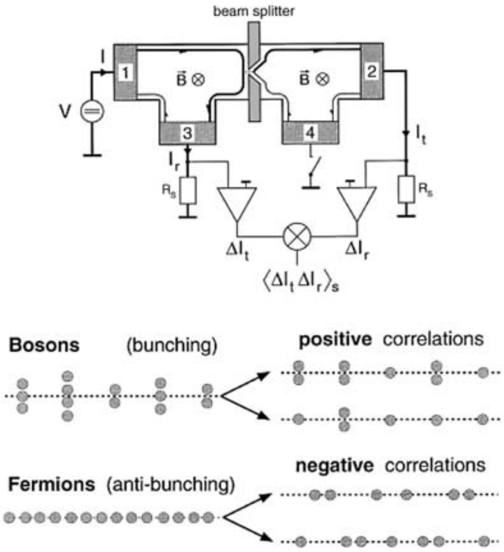

FIG. 3: Hanbury Brown-Twiss experiment on an electron system. Source: Ref. [25].

QUANTUM STATE MANIPULATION

The tunability to high precision in a wide range of parameters of nanoscale systems has opened a new era for information processing based on the fundamental principles of quantum mechanics. Quantum information processing is an effort to use the quantum states as logical states and to explore the full powers of the quantum mechanical principles. So far a vast number of theoretical proposals and experimental demonstrations have been made on semiconductor quantum dots [28, 29] and superconducting circuits [30.33] and many other nanoscale structures. The major advantage of these solid-state based quantum information processing is the scalability. Supported by the traditional lithography technology, the solid-state quantum bits (or qubits) are expected to be integrated to make a practical quantum computer. However, the obstacle to this direction is the relatively strong dephasing rate compared with, say, photon-based qubits.

CONCLUSION

We have reviewed the selected issues in nanophysics and showed how the novel phenomena intrinsic to nanoscale systems emerge at the boundary between the microscopic and macroscopic world. We have focused on the quantum transport through nanoscale systems and followed the perspectives of fundamental physics rather than device applications. This is a pedagogical introduction aimed for general audience. Those who are interested in more advanced study are referred to the text books by Datta [2] and Imry [5] and review articles by [34] and [35].

Acknowledgments

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