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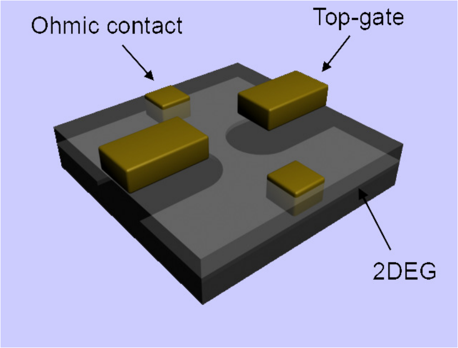

Kondo Effect and the 0.7 Anomaly in Quantum Point Contacts

Scientific Paper by:

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Abstract

An anomaly of the channel conductance of the quantum point contact *(QPC)* around the $0.7*2e^2/h$ has long been observed. The 0.7 anomaly shows many similar characteristics that have been found for quantum dots due to the presence of Kondo effect. From theoretical analysis, it seems that the possible localization in this open system cannot be like that which we observe in quantum dot. However, the localization in QPC may evolve at the edges and then merge at the centre. From simulation, this observation indicates that the possible Kondo effect in QPC is channel length dependant. This behaviour of localization indicates that the possible Kondo effect in QPC is not of the simple form to which we are familiar. But the Kondo effect may have more dynamical form. In order to understand the nature and form of the possible Kondo effect causing the 0.7 anomaly, it is important to study the channel length dependence of QPC.

Contents

Chapter 1

Introduction

A Quantum point contact (QPC) is a short channel that carries ballistic one-dimensional electron transport between two large electron reservoirs. QPC represents the simplest system in mesoscopic physics in many respects. By applying a voltage to the gate electrodes, the width of the constriction can be controlled and the conductance of a QPC as a function of channel width is *quantized*[1,2] in units of $G_0=2e^2/h$, where e is the electron charge and h Plank's constant. This interesting behaviour of quantized conductance can be understood with the simple non-interacting electron picture. After the discovery of quantized conductance[1,2], further investigations showed that the electron transport through a QPC is not as simple as expected. Other interesting behaviour of the QPC conductance was observed that *the conductance of QPC deviates from its quantized value* and an extra plateau around $0.7G_0$, known as *0.7 anomaly* was observed. This anomalous structure appears in the conductance due to the many-body effects among electrons. It is not possible to explain this conductance feature of QPC with the simple non-interacting picture of perfect quantization. This deviation of these clean systems from the perfect quantization has inspired a great deal of debate for more than a decade. Beenakker (University of Leiden) claims about the 0.7 anomaly "*It's the single most important problem in the field of the quantum ballistic transport*".

Although several candidates have been suggested to explain this anomaly, the *Kondo* and *spontaneous spin polarization* models are considered as the most plausible models among all. There are several indications that correlate 0.7 anomaly to the formation of self-consistent quasi-bound state that causes Kondo Physics to come into play. However, there are still some controversies about the nature of 0.7 anomaly and the possible Kondo phenomenon behind the 0.7 anomaly is not yet fully understood.

1.1 Research goal

Is it plausible that self-consistent quasi-bound state(s) and resulting Kondo effect is the correct explanation for the observed 0.7 anomaly in quantum point contact?

QPCs are the standard building blocks of sub-micrometer devices such as quantum dots and qubits that are proposed as a basic elements of quantum computers. A clear picture of this phenomenon is important for spintronics and quantum information proposals, where full control over the number and occupancy of energy states is required. During electron transport through the channel, possibly the spin state of the electron in QPC can be controlled due to the presence of the many-body effect that causes the 0.7 anomaly. However, it is important to understand the Physics behind 0.7 anomaly in order to transport an electron with a certain spin. Moreover, the understanding of complex physics of these simplest devices will open up the new doors of understanding of quantum mechanical effects in low-dimensional materials.

The present work is mainly devoted *to improve the understanding of "Kondo" many-body effect* by looking over the previous attempts that were made to explain 0.7 anomaly with the help of Kondo effect. Moreover, we want to find out *whether the Kondo effect resulting from spontaneous localization*[17, 3] is the *correct explanation* for 0.7 anomaly or not.

1.2 Outline of the report

The paper has been organized in the following way. ***Chapter 2*** gives theoretical concepts about the quantum point contact, 0.7 anomaly and Kondo effect in order to understand there possible relationships.

Chapter 3 consists of a brief *overview of the history* of the scientific efforts done to explain the 0.7 anomaly with the help of Kondo model. In order to fully understand the origin of the 0.7 anomaly, it is important to look over the previous efforts made in this field to reveal some insights about the nature (dependence on external parameters e.g. temperature) of 0.7 anomaly.

Chapter 4 lays out the theoretical and experimental dimensions of the research in order to understand that how the localization (which is the indispensable requirement for the Kondo effect) can possibly occur in an open quantum system.

Lastly, in ***Chapter 5***, we discuss the previous results critically and to find the conditions in which we should be able to fully understand the possible localization and the possible Kondo effect as an explanation for the 0.7 anomaly or not.

Chapter 2

Theoretical concepts

This chapter consists of a brief introduction about the theoretical concepts of quantum point contact (QPC), 0.7 anomaly and the Kondo effect in order to understand the possible relationships between them. This chapter also contains some insights about the nature of the 0.7 anomaly.

2.1 Layout of the quantum point contact (QPC)

A quantum point contact (QPC) is a small constriction between two large electron reservoirs in a two dimensional electron gas (2DEG), usually in a GaAs-AlGaAs heterostructure (see fig. 2.1, 2.2). Due to special stacking of layers in these heterostructures, the bottom of the conduction band only lies below the Fermi-energy at a specific boundary between two layers. At sufficiently low temperatures, the conduction electrons can only move in the plane of this boundary.

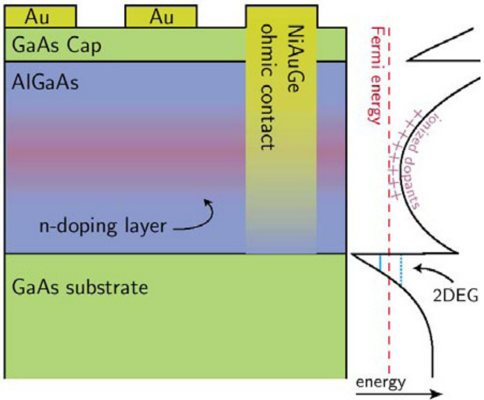


Figure 2.1: Semiconductor heterostructure containing a 2DEG from which electrons can be depleted locally with the application of negative voltages on top gates. On the right-side, the energy diagram for conduction band of the heterostructure is shown. (Figure adopted from thesis of S.M. Cronenwett[8]*).*

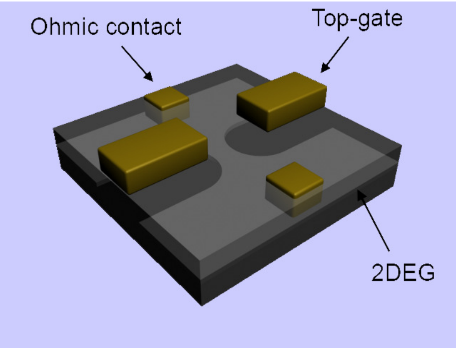


Figure 2.2: Schematic diagram of a QPC. (Figure adopted from C.H. van der Wal et al.)[4,5]

The constriction in a 2DEG can be made in different ways, for example by a split gate technique or by etching away the part of 2DEG. Ti/Au gates are usually patterned on the top of the GaAs-AlGaAs wafer, with a small gap between the gates. When a negative voltage is applied to the gates, the electrons are pushed out of the regions below the gates. The potential felt by the electrons is shown in fig.2.3c and is known as saddle potential. Such a saddle potential gives spin degenerate energy levels as shown schematically in fig.2.3b. Through the constriction, electrons can travel ballistically.

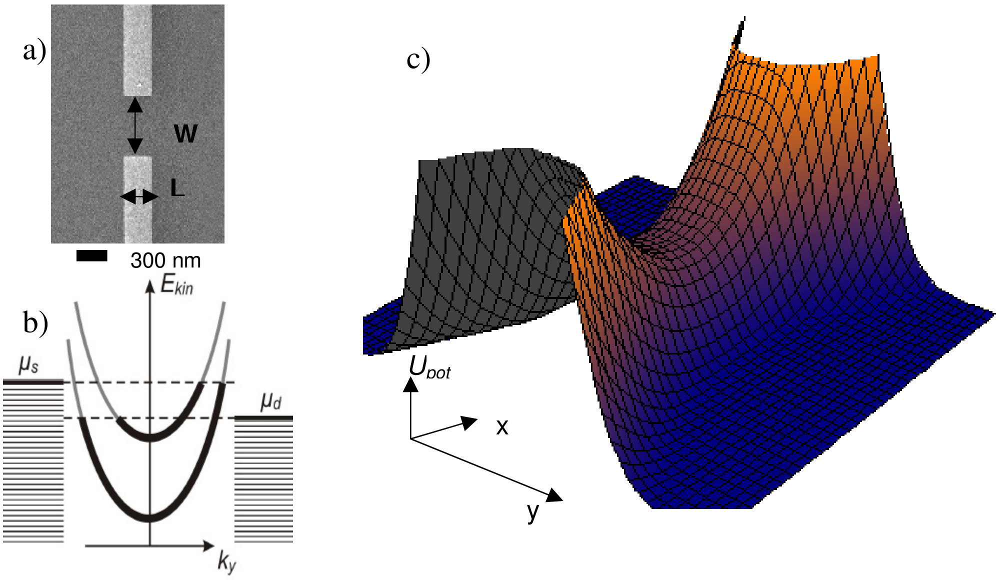


Figure 2.3: a) SEM image of a QPC, the center of the QPC considered as origin, L and W shows length and width respectively, b) the simple non-interacting picture of Fermi-level is shown, for the case of QPC tuned to $G=2(2e^2/h\ )$ c) Saddle potentials in QPC (Figure adopted from C.H. van der Wal et al.[4]).

When a sufficiently large negative gate voltage is applied, the constriction closed off completely. However, when the voltage is made less negative, the constriction begins to open up and the conductance through the QPC increases in steps of $G_0= 2e^2/h$ as a function of channel width[1,2].

The **origin of the quantized conductance** can be explained by using model of non-interacting electrons. In other words, the constriction lets through an integer number of transverse modes. The conductance modes of these electron states individually contribute one quantum of conductance $2e^2/h$ to the total electrical conductance; the additional factor of two arises from the spin degeneracy. The spin degenerate levels split in plateaus at integer steps of $0.5G_0$ (where $G_0=2e^2/h$) by applying a large magnetic field. The system-QPC thus provides a clear demonstration of ballistic transport in quantum systems. But the QPC has turned out to be more complicated systems than what this simple picture describes.

2.2 The 0.7 Anomaly

Due to the many-body effects of electrons, an extra plateau around $0.7G_0$ – known as 0.7 anomaly – is also observed[6, 11] in addition to the quantized conductance steps in QPC (see fig. 2.4). This anomalous structure cannot be explained with non-interacting picture of electrons. The 0.7 anomaly has been an attractive topic of theoretical and experimental study for more than one decade. Despite many attempts to explain this feature so far, its origin is controversial. Among many possible other explanations, origin of the 0.7 anomaly is attributed to the spontaneous spin splitting, the Wigner crystal and self-consistent bound state that give rise to Kondo effect. But the origin of 0.7 anomaly is not yet fully understood.

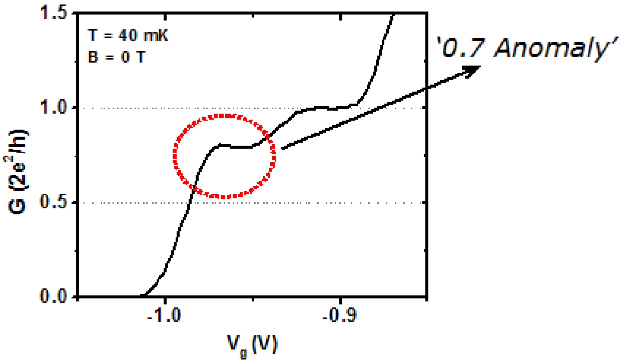


Figure 2.4: 0.7 structures are visible as a shoulder. (Figure adopted from research work of M. J. Iqbal et al.[4]*).*

2.3 The Kondo Effect

The Kondo effect is a well understood and widely studied phenomenon in condensed matter Physics. It is a many-body interaction effect. In the non-magnetic metals, the Kondo effect arises from a single magnetic impurity atom and many electrons. This effect causes the resistance of the system to increase upon lowering the temperature. In Quantum dots and low dimensional device structures, the unpaired spin (a single magnetic atom or an electron) couples to the electrons of the reservoirs and this coupling allow an extra mode of conductance through the dot (see fig. 2.5).

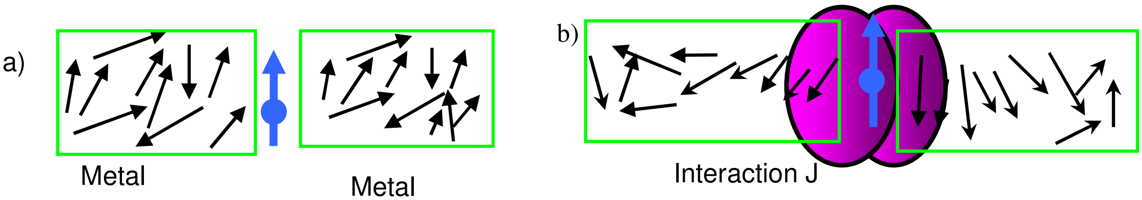


Figure 2.5: a) The unpaired magnetic spin (blue) exists near the reservoir (green) of electrons, b) an interaction J (pink) comes into play between the electrons of the metal (reservoir) and the unpaired magnetic spin. Due to this interaction, the magnetic moment (blue) screens by the conduction electrons of the reservoir resulting in the formation of quenched correlated spin state

For Quantum dot (QD) systems, the idea of formation of correlated spin state due to the Kondo effect is quite clear[7,8].However for Quantum wires (QWs) and Quantum point contacts (QPCs), the origin of formation of possible spin correlated states is not yet fully understood. The Kondo effect only arises when there is a net non-zero localized spin. The electrons forming the net localized spin state correlates with the mobile electrons in the reservoirs (host metal). In semiconductor quantum dot devices having a controllable number of electrons, a localized spin-correlated state between the metal leads via the magnetic impurity atom can be created. And the conductance measured between the reservoirs depends on the number of electrons confined in the dot. If the number of electrons in the dot is odd the conductance increases due to the Kondo effect at low temperatures. However, when the dot contains an even number of electrons with net spin zero, the Kondo effect does not occur and the conductance continuously decreases with decreasing the temperature (see fig 2.6).

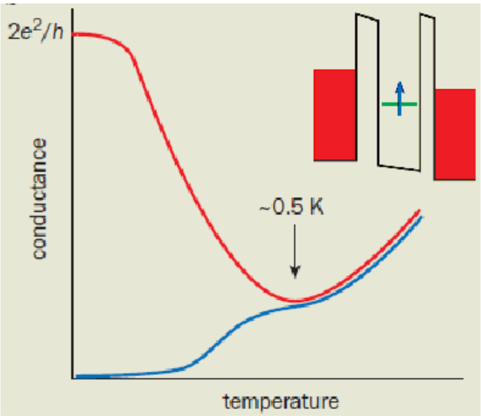


Figure 2.6: Conductance of the dot containing odd number of electrons (red curve) and for the dot with even number of electrons (blue curve). Inset shows schematic energy diagram (Figure adopted from L. P. Kouwenhoven et al.[9]).

As we discussed before that the Kondo effect is a many-body phenomenon, which concerns the spin interaction between the localized states (dot) and the surrounding sea (reservoirs) of the electrons. Now, let us consider, what happens when an electron is taken from the localized state and makes the transition from the localized state to the Fermi sea. Figure 2.7a shows a schematic energy diagram for a localized state between the metal leads with a net single spin. In this figure, it is clear that the transition from the localized state at the Fermi level for the electron is forbidden (shown as initial state in the fig 2.7). However, quantum mechanically, this transition is possible because the Heisenberg uncertainty principle allows such a transition for an effectively short period (shown as virtual state in the fig 2.7). Then another electron can tunnel from the Fermi sea through the energy barrier into the localized state because of the absence of the charging energy (shown as final state in the fig 2.7).

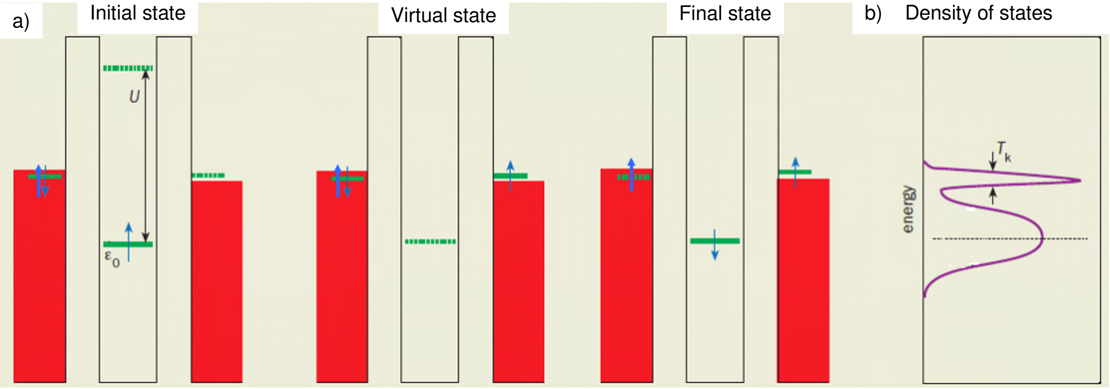


Figure 2.7: a) Transition between the localized state and the metal, the localized state is having one electron of energy ϵ_0 below the Fermi energy of the metal (red). b) Kondo resonance occurs at the Fermi level with a characteristic energy scale T_k (Figure adopted and modified from L. P. Kouwenhoven et al.[9]).

The spin exchange changes the energy spectrum of the system. It found that a new state, Kondo resonance is formed, resulting in an additional peak in density of states (DOS) at the Fermi energy. This process only occurs under a certain temperature called the Kondo temperature, T_k (see fig. 2.7 b).

Chapter 3

Review of the 0.7 anomaly in research

In 1991, N. K. Patel *et al.*[10] studied conduction versus gate voltage behaviour at different temperatures. They observed so called *0.7 anomaly*. However, Thomas *et al.*[6] firstly studied this anomalous feature in 1996. They suggested that this feature had a distinct physical origin rather than arising from the scattering events. They also suggested that it arises from a spontaneous spin polarization. Afterwards, several experiments have provided indications for the presence of 0.7 anomaly due to spin polarization or a breaking of spin degeneracy in QPCs at low electron density. These studies proved that this conductance feature is generic and sample impurities are not the reason for this extra structure. However, the origin of this anomaly is still controversial and there is no microscopic model that fully explains 0.7 anomaly.

Afterwards, the experimental[11] and theoretical[19] efforts attracted a lot of attention of the community towards the possibility of presence of Kondo effect. These studies revealed signatures of electron many-body effects, such as the universality Kondo scaling pointing[11], that indicate towards the presence of the simplest and interesting Kondo effect. However, there are still some controversies and the origin of 0.7 anomaly is not yet fully understood. In this chapter, we will discuss the scientific efforts done to explain the origin of the 0.7 anomaly with the help of Kondo effect. But, to understand the role of this interesting Kondo phenomenon in the occurrence of 0.7 anomaly, it is important to firstly consider the nature of the 0.7 anomaly i.e. the dependence of 0.7 anomaly on external parameters such as temperature, magnetic field etc.

3.1 Nature of the 0.7 anomaly

The 0.7 anomaly in QPC conductance has a characteristic dependence on external parameters such as temperature, magnetic field, bias voltage etc. We can define two conductance scales, Linear conductance G (Bias $eV \leq K_BT$ when $V_{sd}=0$) and other is nonlinear conductance as g (Bias $eV \geq K_BT$). The **non-linear conductance behaviour** is studied by determining the $g=dI/dV$ as a function of dc-source-drain bias voltage V_{sd}, with each trace taken at a fixed gate voltage (e.g. shown in the inset of fig. 3.3b).

3.1.1 In-plane magnetic field dependence:

The in-plane magnetic field to QPC splits the conductance plateau into spin dependent plateaus due to Zeeman splitting at integral multiples of e^2/h. The initial investigations[11,13,12] showed that the 0.7 anomaly which is already present at B=0 varies with the increase of in-plane magnetic field and finally attains exactly half integer value ($0.5*2e^2/h$) (see fig 3.1). The conversion of the 0.7 to 0.5 structure in magnetic field indicates that there is spontaneous spin splitting due to the many-body interactions[18].

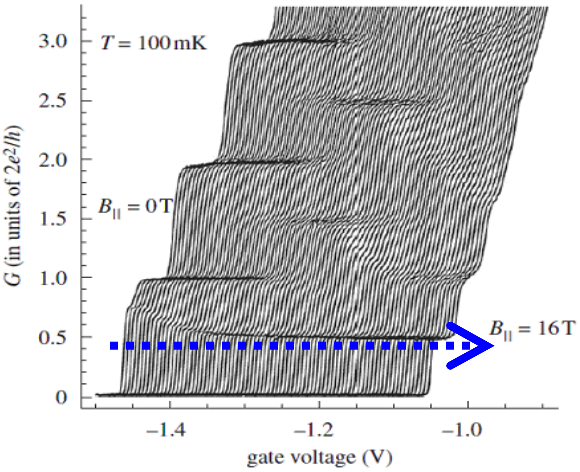


Figure 3.1: Linear conductance G of a QPC as a function of increasing magnetic field (from left to right). The spin degenerate plateaus resolve to spin split plateaus when a high magnetic field is applied and the trend is quite clear for 0.7 anomaly. The temperature of the measurement is 100 mK. The individual plots are moved along the voltage axis for clarity and the arrow is showing the evolution of 0.5 G_0 from 0.7 G_0 (Figure adopted from K.-F. Berggren et al.[13]).

The conversion of 0.7 feature to $0.5G_0$ at higher magnetic fields and the fact that it is never seen below $0.5G_0$, indicates that this feature is not a ground state property and does not arise from impurities or imperfections in point contacts[11]. Although the real position of the 0.7 feature can vary between $0.6G_0$ and $0.8G_0$. The connection between the 0.7 feature at zero magnetic field and spin polarization effects in higher magnetic field demonstrated the importance of spin-spin correlation effects in this feature[11,18].

3.1.2 Temperature dependence:

The 0.7 anomaly depends on the temperature. The anomaly appears more pronounced by increasing the temperature, whereas the integer conduction plateaus become blurred by thermal smearing[11] (see fig.3.2). When the temperature is sufficiently low, the anomaly disappears and it seems that the feature merge with the integer conductance plateau. This type of temperature dependent conductance behaviour is a Kondo signature that we will discuss in the next section.

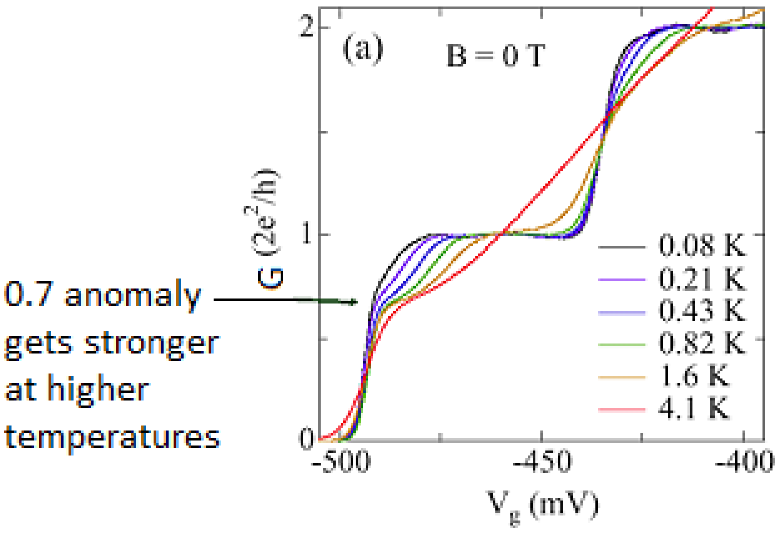

0.7 anomaly gets stronger at higher temperatures

Figure 3.2: Effect of temperature on 0.7 anomaly in zero magnetic field (Figure adopted from thesis of S.M. Cronenwett et al.[8]).

3.2 A kondo-like origin?

We discussed above the nature of the 0.7 anomaly observed by different experimental efforts. Now, firstly we will discuss *how Kondo effect came forward as the possible explanation for the 0.7 structure.*

In artificial systems like quantum dots, the Kondo effect involves the coupling of a localized spin with electrons of the reservoir and as a result of the Kondo effect conductance increases at low temperatures (for more definitions about the Kondo effect look over section 2.3).

Cronenwett *et al.* suggested[15] that like quantum dots, the Kondo-like correlation in point contacts (see discussion below) is a natural candidate to explain the origin of the enhanced conductance (0.7 anomaly) at low temperatures. Looking over the QPC data in detail, they noticed that the behaviour resembles to the Kondo behaviour of quantum dot.

When the experimental data is scaled by a gate-voltage-dependent parameter termed as the Kondo temperature T_k, the temperature dependence of the conductance in quantum dots falls nearly onto a single curve. The parameter T_k can be defined as the minimum temperature where the spins of localized electrons become correlated to the spins of the reservoirs and hence spin interactions start to become stronger at temperatures below T_k. They revealed that the temperature dependence of conductance of QPC (discussed in section 3.1.2) can be similarly scaled (see fig 3.3a). The collapse of data of the individual temperature dependent conductance curves on a single curve (see fig 3.3a) indicates that the QPC obeys the Kondo scaling and behaves like those systems in which localized state is present[14, 15, 16]. Moreover, this feature for QPC exhibits the same limit at zero temperature, namely the unitary conductance quantum.

They observed that at low temperatures, both systems (QPC and quantum dot) show a zero bias conductance peak (ZBA). The width of the ZBA is extracted from the non-linear conductance plot shown in the inset of the fig. 3.3b.

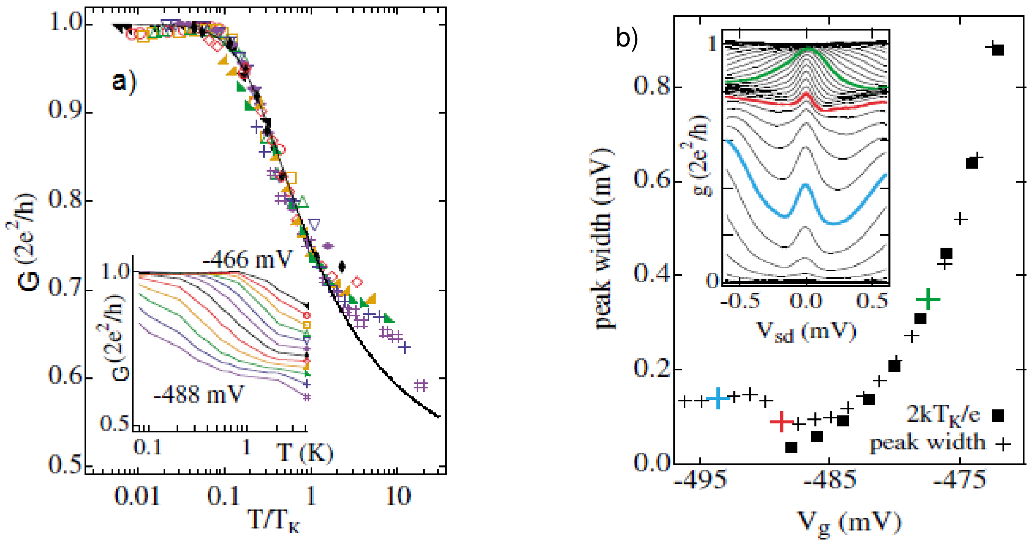


Figure 3.3: (a) Linear Conductance G as a function of scaled temperature T_k/T where T_k is the Kondo temperature and the inset: Linear conductance G as a function of unscaled temperature T for different gate voltages V_g, b) The inset shows non-linear conductance as a function of V_{sd}. In the plot, width of ZBA is represented with "+" and fitted with a scaling parameter T_k (Figure adopted and modified from S.M. Cronenwett et al.[8]).

Similar to quantum dots, if the Kondo temperature T_k defines the width of the ZBA in QPC then it should be possible to fit the ZBA with T_k (see fig 3.3b). Similar to quantum dots, QPCs also show a splitting of the zero-bias peak in a magnetic field and the amount of splitting is equal to twice the Zeeman energy.

These similarities between quantum point contact and quantum dot showed some indications for Kondo effect as a possible explanation for 0.7 anomaly.

But in addition to these similarities with the Kondo effect present in quantum dots, the point contacts also show some discrepancies and these discrepancies have raised some reservations about this conjecture.

Now, let's consider *what are the discrepancies due to which the possible Kondo-like origin of 0.7 anomaly is still not fully understood.* As discussed above that the data for QPC fits to a single curve-like in quantum dots. But the *empirical functional form* of this single curve has an *offset* (see fig 3.3a). If we look over the *fig. 3.3a* again, it becomes clear that the Kondo contribution to the conductance of QPC does not go to zero for high temperatures and the fit has a high temperature limit e^2/h rather than zero. The fact attributed to the empirical medication to their equation is that the QPC lacks a *Coulomb blockade* which is not fully understood yet. Anderson model played a crucial role in explaining this extra conductance. However, this perturbation theory failed in obtaining the low-temperature unitarity limit $2e^2/h$[12]. Another discrepancy appears when *in contrast to quantum dots*, the width of the ZBA obeys the scaling parameter just above the $0.7G_0$ anomaly. Below $0.7G_0$ the width of the ZBA in QPC does not correspond to the scaling parameter (see fig. 3.3b). Many theorists and experimentalists tried to solve this puzzle, but the debate over the nature of 0.7 structure is not settled, yet.

In order to understand the role of the possible Kondo effect in the occurrence of 0.7 anomaly, it is important to find whether the Kondo effect is present or not in QPC. As discussed before that Kondo effect involves the coupling of a localized magnetic spin with the electrons of adjoining reservoirs. In other words *localization is the indispensable requirement for the occurrence of Kondo effect*- if somewhere no localization, no Kondo phenomenon can occur there. Therefore, in the *next chapter* we will discuss *the possible localization in QPC* by looking over the scientific efforts done in this field.

Chapter 4

The localization (indispensable requirement for Kondo effect) in QPC

The presence of localization or formation of quasi-bound states in QPCs is an important issue in the Kondo scenario. Cronenwett *et al.*[11] build up very nicely the experimental basis for the explanation of 0.7 anomaly. They found indications for the Kondo effect caused by the electron spin localization in QPCs. Nevertheless, they did not fully explain the mechanism of localization behind the expected Kondo effect in QPC. In addition, the questions like how localization take place in an open quantum system like *QPC* remained uncovered.

Afterwards, many attempts were made to develop a nice theoretical explanation for the formation of a bound electron state at the centre of QPC[17, 18, 19]. They tried to explain the possible localization in the QPC by considering intuitive picture of the transport across a square barrier. They proposed that the successive reflections from the edges of the barrier in addition to the tunnelling states create quasi-bound particle states above the barrier itself. They support their argument with the help of the calculations made in spin-density-functional-theory (SDFT). Meir *et al.*[17] calculated the density of states (DOS) and self consistent barrier at the centre of the point contact for both spin up and spin down electrons by using SDFT (see fig 4.2). They defined self-consistent barrier as of bottom of the lowest 1D subband at temperature T=0.1K. They observed that the self-consistent barrier is high for spin-down electrons than spin-up electrons (see fig. 4.2a). They reported that *it is likely that a quasi-bound state formed in QPC results in a single net spin.*

In the above argument, it seems that the spin degeneracy is lifted. But it is not real removal of spin degeneracy; they deal with spin-up and spin down electrons separately just to calculate self consistent barrier. They considered a net spin at the centre of the QPC, but how they are defining the spin-up/down electrons is not clear.

Let's think about the quantum dot which contains single localized electron state at the centre. But in the case of quantum dot, at the centre there is no net spin, because the spin is correlated and it flips due to Kondo effect. As we cannot define a net spin in dot then how we can define a net spin in the QPC. If it is just a representation to explain the situation, then it is fine to say like this.

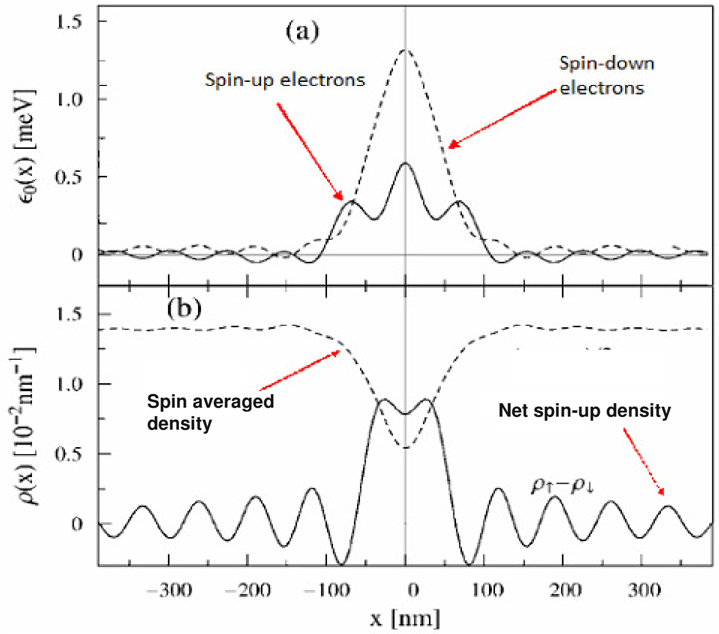


Figure 4.2: Results of SDFT: a) A self-consistent barrier for two spin types as a function of x in the direction of current flow through QPC. b) 1D electron density in QPC (Figure adopted and modified from Y. Meir[17]).

Kenji Hirose *et al.*[18] further explained the idea of possible localization in QPC. They proposed that the local moment found within SDFT results from self-consistent flattening of QPC barrier. In the low-density regime, the borders of the barrier screened less and the reflections results in formation of single quasi-bound state. They stated that the first resonance in the spin-up local density of states is clearly resolved showing a localized net spin of ½ at the QPC[18].

Afterwards, Meir *et al.*[19] suggested that near the pinch off, a regime emerges where a single bound electron state can exist in the centre of the QPC. They based their theoretical analysis on the spin-density-functional-theory (SDFT). This solid prediction sheds some light on the recent experiments. Their work gives strong support for the existence of such a single localized electron spin in QPC. The ideas presented in the paper are very difficult to understand and the language of the paper is quite confusing.

They calculated the spin densities of the 2DEG and charge distribution on the electrodes self-consistently. For the gate voltages corresponding to standard integer conductance plateaus, they found unique solution to their equations. These unique solutions indicate that there is no spin polarization at the plateaus. Between plateaus, however, additional lower-energy solutions appear that do exhibit spin polarization.

They classified these solutions in terms of spatial symmetry as symmetric and antisymmetric (see fig. 4.3).

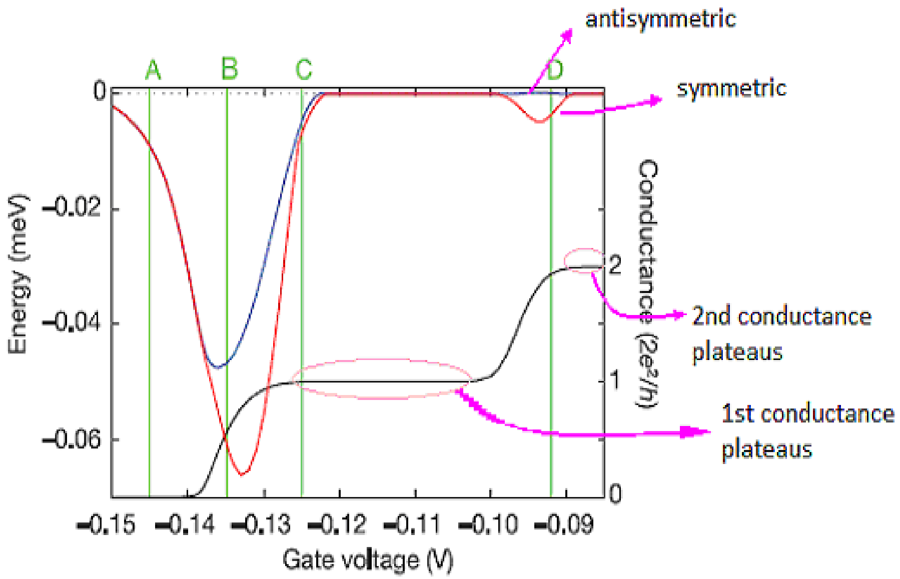
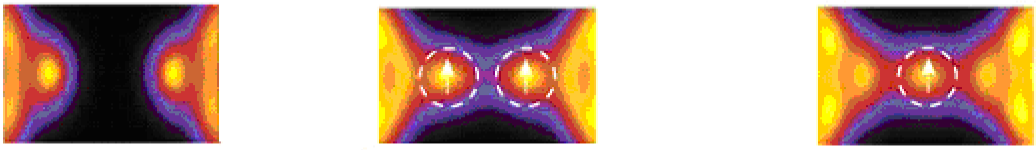


Figure 4.3: Energies of symmetric (red) and anti-symmetric (blue) spin-polarized solutions relative to the energy of un-polarized solution. Black curve is showing conductance of QPC versus gate voltage (Figure adopted and modified from T. Rejec et al.[19]*).*

Let us consider the symmetric solutions for spin-up electrons in the absence of field. When QPC is pinched-off (at point A), the density vanishes at the middle of the QPC in the constriction. The potential is high in the middle of QPC and it decreases towards the reservoirs. At some point near the reservoir, the potential crosses the Fermi-energy. The electron gas polarizes, here low density makes sure that the exchange energy dominates at low density is greater than the additional kinetic energy gained due to the polarization. Due to low density, the electron gas polarizes and the two regions on each side of QPC get polarized. When the gate voltage starts becoming less negative then these two regions starts overlapping (shown in fig. 4.3 and 4.4 as point B). For spin-up solution, the quasi-bound state of spin-1/2 moment is formed in the middle of the channel (shown in fig. 4.3 and 4.4 as point C). This bound state results in the maximum tunneling probability through the barrier and the conductance rises from zero. At certain gate voltage, the region in 2DEG again polarizes until again bound state is formed at point D.



Pinched-off state

Point A

Polarized regions start overlaping

Point B

Spin-1/2 magnetic moment formed

Point C

Figure 4.4: Evolution of spin densities for the symmetric solutions for spin up electrons of the two polarized solutions from point A (pinch-off) to point C (where the spin-1/2 magnetic moment is formed in the QPC), (Figure modified from T. Rejec et al.[19]*).*

They explained ideas about symmetric solutions of spin–up electrons in zero-magnetic field quite nicely. However, the ideas explained for symmetric solutions of spin-down electrons and anti-symmetric solutions are quite unclear. From fig. 4.3, it seems that the symmetric solutions are more stable and have higher probability than the anti-symmetric solutions; still anti-symmetric solutions are not negligible. Now, let us consider the point B in the figure 4.4, near the pinch off. *It seems that instead of one single localized state there are two localized states* (see in point B, on the two sides of the QPC in fig 4.4). And if we vary the gate voltage, *the two localizations starts to overlap resulting in the single localized state*. It is quite confusing that what situation we can see experimentally and what would be the probabilities for these qausi-bound states. They stated that the polarized regions at point B overlap and then after the rearrangement of electrons, we will have the single quasi-bond state shown as point C (see fig 4.4). They did these simulations for different lengths of the QPC, but they observed that the situation discussed above does not appear for all lengths. They proposed that the localizations in QPC couple with each other with the antiferromagnetically and this coupling may be dependant on the length of QPC. The concepts of the paper explained above are not clearly explained. To find this localization form they found by simulations is very difficult to visualize experimentally.

In 2006, Sablikov *et al.*[20] proposed that the quasi-bound states mainly caused by the Friedel oscillations of the density of higher subband of electrons which are not allowed to pass and hence are reflected back. These oscillations do not pass through the transition regions and are reflected. They proposed that these oscillations results in the backscattering of the electrons of open subbands and give rise to the formation of qausi-bound states. Several scientific efforts points towards the presence of the quasi-bound state in QPC due to the Friedel oscillations.[17, 21, 22] But the nature of this possible quasi-bound states and how the Kondo effect is causing the enhance conductance at $0.7G_0$ is not yet understood.

Chapter 5

Discussion

We discussed the possible localization (indispensable requirement for the Kondo effect) in chapter 4. As we have already seen that the situation of possible localization (indispensable requirement for the Kondo effect) in QPC is not as clear as in the case of quantum dots. As we discussed in the chapter 4 that *there are different configurations for the self-consistent localized states in the QPCs for the different gate voltage configurations (different channel lengths of QPC), there might be different types of Kondo Physics going on in the QPC that could not be explained by the simple models of Kondo effect*. It also shows that, in this open system the localization might be dependent on the *channel length*. The localization in QPC may be different in nature from that which we observe in quantum dot, which means it might be possible that the localization in QPC is not only confined at the centre as we observe in quantum dot. The localization in QPC may be evolving separately at the edges like two different Kondo systems and then overlap at the centre of the QPC at a specific channel length. Moreover from above discussion, it also seems that the Kondo effect may also not in its simple form that we observe in quantum dots but it may have more *dynamical form* due to the overlap of possible localized states in QPC. In order to understand the behaviour and form of the possible Kondo effect in QPC, it is important to study the channel length dependence of the QPC. As the QPC systems are sensitive for the remote impurities in the materials and the results obtained from different QPC systems fabricated for different length scales cannot be compared easily. To obtain further information on the characteristic properties of the 0.7 feature, a device with an *in-situ tunable effective length*, with fixed lithographic dimensions and impurity distribution should be investigated. In this way, the length 0.7 anomaly can be studied with the use of a single device.

Recently, Iqbal *et al.*[4] started investigating such a device in which the effective length of the 1D channel in the 2DEG can be tunned to different length scales by changing the relative gate voltages. The experimental design is quite motivating and it may help in looking over the true picture of 0.7 anomaly. To fully understand the nature and origin of 0.7 anomaly, a more dynamic form of possible Kondo effect should be considered. Moreover, it may help to consider the theoretical model in a different way instead of that which is used for the simple close conventional Kondo systems.

Conclusion

We critically reviewed various parallel efforts done to find out whether the Kondo effect is suitable candidate to explain the origin of 0.7 anomaly. We aimed at coming to a clear description of the emerging model that is consistent with the various publications and which removes sources of confusion in the used language. It is clear that the 0.7 anomaly emerges at low temperatures, and if the temperature is further reduced then the conductance began to rise from $0.7G_0$ to $1G_0$. The increase in the conductance points towards the Kondo effect as a possible explanation for the origin of 0.7 anomaly. We looked over the nature of the 0.7 anomaly and found that the behaviour is similar to the Kondo effect in quantum dots in many respects. Theoretical models and experimental results are in quite agreement with the presence of possible Kondo effect. But there are still some controversies. The ZBA is observed all the way from 0 to $1G_0$ but the conventional Kondo scaling is only in agreement from around 0.5 to $1G_0$. It is not yet clear why ZBA below $0.5G_0$ does not obey Kondo scaling. It might be possible that the Kondo effect appearing at the $0.5G_0$ is of a different form compared to the simple conventional Kondo effect. If we want to find the relation of the zero-bias peak and the 0.7 anomaly with the help of Kondo Physics then we have to find the nature and dynamics of Kondo effect below $0.5G_0$, because the possible Kondo effect causing 0.7 anomaly is of the different form than what we are familiar with. This kind of Kondo effect might be more dynamic than what we observe in quantum dot. As quantum dot is a close system but QPC is not. May be this is the reason due to which we are unable to fully define the origin of the 0.7 anomaly with Kondo effect. Still a detailed model is needed that should fully account for the Kondo-like behaviour as possible explanation for the origin of 0.7 anomaly.

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