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2008 J. Phys.: Condens. Matter 20 164213

(http://iopscience.iop.org/0953-8984/20/16/164213)

J. Phys.: Condens. Matter **20** (2008) 164213 (9pp) doi:10.1088/0953-8984/20/16/164213

Spin effects in one-dimensional systems

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Received 9 November 2007, in final form 7 December 2007
Published 1 April 2008
Online at stacks.iop.org/JPhysCM/20/164213

Abstract
We review the progress in the study of the 0.7 structure, a many-body spin effect observed in GaAs quantum wires. Electrical and thermal measurements show that the 0.7 structure is characterized by a spontaneous spin splitting which causes the spin-up subband to stay near the electrochemical potential as the channel is populated. The 0.7 structure is not an isolated phenomenon but is the first in a series of effects that occur whenever opposite spin subbands are degenerate in energy. Bias spectroscopy shows how the levels move with increasing source–drain bias as the 0.7 structure evolves into a structure near $0.85(2e^2/h)$. Our measurements do not support a Kondo effect from a single bound state in the channel as a possible explanation of the 0.7 structure.

1. Introduction

Early work on one-dimensional (1D) behaviour on split-gated devices in both Si [1] and GaAs [2] indicated that the observed electron transport behaviour could be described as strictly single-electron with no evidence of many-body interactions. The energy of the size quantized levels and their depopulation by a magnetic field could be calculated within this approximation [3], the only deviations being the observation of the Altshuler–Aronov interaction corrections, previously found in three and two dimensions in both Si and GaAs, and the Nyquist term in the phase-breaking rate [4].

At low temperatures the characteristics of ballistic quantum wires defined by split gates in GaAs heterostructures show excellent conductance plateaux in units of $2e^2/h$ [5, 6], and frequently an additional small structure just below $2e^2/h$. This structure was found to be reproducible on thermal cycling, suggesting that it was unlikely to be a universal conductance fluctuation (UCF) or a scattering event. However, it was overlooked for several years and thought to be a resonant structure. As high quality two-dimensional electron gases (2DEG) are routinely grown by molecular beam epitaxy, it is now possible to define split-gate devices that show nearly 30 quantized plateaux, indicating very little disorder scattering [7], and in addition, well-defined structure at or near $0.7(2e^2/h)$. Using such devices, Thomas *et al* [8] conducted the first detailed study of this latter feature, now known as the 0.7 structure, 0.7 anomaly, or 0.7 feature in the literature. In this work it was shown that applying a parallel magnetic field, $B_{\parallel}$, caused a spin splitting of the 1D energy levels, and surprisingly the 0.7 structure continuously decreased with field to evolve into the first spin-split plateau at e^2/h (figure 1(a)). The conclusion that the 0.7 structure is related to a spin polarization in the channel was reinforced by incipient spin splitting also observed just below the $4e^2/h$ plateau (1.7 structure) and an enhancement of the Landé g-factor value as the carrier concentration decreased. Whilst it was shown within mean-field theories that it is possible to have ferromagnetism at low densities in 1D [9, 10], it was pointed by others that spin polarization is forbidden in 1D due to the Lieb and Mattis theorem [11]. At present there is consensus this theorem is not appropriate to quantum wires used in practice [12], because the theorem assumes an infinite 1D subband energy level spacing and infinite length.

The 0.7 structure tended to disappear as the temperature decreased below 1 K and then the conductance increased smoothly to the $2e^2/h$ plateau. However the essential problem in explaining the 0.7 structure is that a complete spin polarization would produce a 0.5 structure at $0.5(2e^2/h)$ and a quantitative explanation of a higher fractional value is elusive. Significantly, later work [13] found that lowering the carrier concentration shifted the 0.7 structure towards $0.5(2e^2/h)$ and that, when this occurred, the application of a magnetic field strengthened the plateau without a change of value indicating a completely spin-polarized state. To date, a considerable number of experimental investigations have been performed on the 0.7 structure and salient points will be briefly summarized.

The effects of a finite source–drain bias, V_{sd}, on 1D subbands were investigated by Patel *et al* [14, 15], and they showed the first evidence of a bias-induced structure below

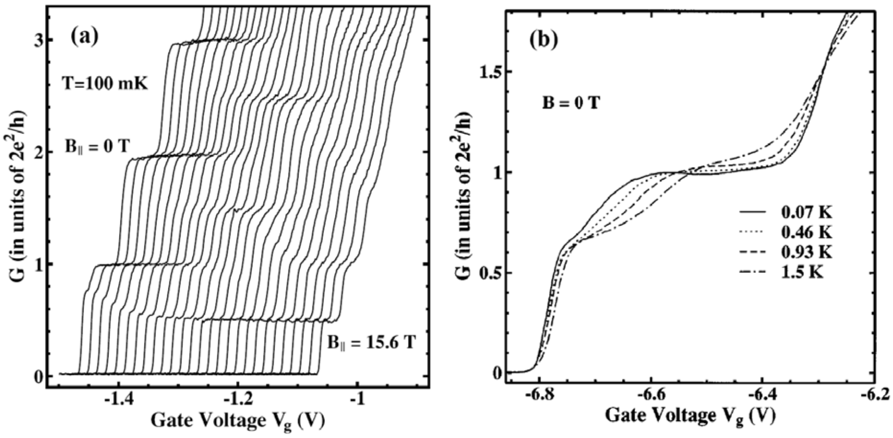

Figure 1. (a) Differential conductance, $G = \mathrm{d}I/\mathrm{d}V_{sd}$, traces where $B_{\parallel}$ is incremented in steps of 0.6 T. For clarity, successive traces are offset horizontally. The 0.7 structure evolves to the spin-split $0.5(2e^2/h)$ plateau. The 0.7 analogue can be observed to evolve from the $1.5(2e^2/h)$ plateau to the re-entrant $2e^2/h$ plateau at high magnetic fields. (b) Temperature dependence of the 0.7 structure in zero magnetic field compared to the quantized plateau $2e^2/h$. (Modified from [8].)

$2e^2/h$ plateau. This was not in agreement with the model of Glazman and Khaetskii [16], but is now known to evolve from the equilibrium 0.7 structure [17]. Increasing the source–drain voltage lifts the momentum degeneracy and splits each plateau in the differential conductance versus gate voltage into two. As bias increased to 1–3 mV the 0.7 structure increased smoothly to 0.8–$0.85(2e^2/h)$ and was then unaffected by lowering temperature. Application of $B_{\parallel}$ results in another splitting of each level into two. The source–drain bias serves as a reference and allows the extraction of the energy of the Zeeman splitting. Significantly, if a 0.7 structure is not clearly visible in the ohmic regime, the enhanced voltage brings out structure at 0.8–$0.85(2e^2/h)$. The exact form of the differential conductance, $\mathrm{d}I/\mathrm{d}V_{sd}$ with V_{sd} shows a zero-bias anomaly (ZBA) which has given rise to suggestions, initially by Lindelof [18] and Cronenwett *et al* [19], and subsequently Meir and colleagues [20, 21], that Kondo physics is responsible for this effect and there is a bound state in the channel.

Use of a wide channel enables an in-plane magnetic field to produce a spin splitting that exceeds the energy separation of the 1D levels. Consequently it is possible to obtain level crossings in $B_{\parallel}$ so that the first two or three occupied levels are all spin-down (↓, defined as spins with the lowest energy in magnetic field). Investigation of the manner in which opposite spin levels cross indicates that the crossing is not smooth but rather the levels merge and then the spin-up level (↑) jumps discontinuously to a higher energy as the channel widens. For example, at the crossing of spin 1↑ and spin 2↓ levels a structure emerges from the $1.5(2e^2/h)$ conductance plateau value and behaves rather like the 0.7 structure with increasing magnetic field and temperature [22–24]. Such 0.7 analogue structures imply that the zero-field 0.7 structure is the first in a series of spin instabilities whenever opposite spin levels become degenerate. Analysis of the behaviour as a function of V_{sd} shows that the spin ↓ levels drop abruptly in energy when starting to fill with electrons whereas the spin ↑ levels are pinned near the source chemical potential μ_s. A spin ↑ level does not fill until the spin ↓ level has dropped below both μ_s and μ_d [25].

It is relevant that when a 0.5 plateau is induced at low temperatures by a magnetic field then an increase in temperature increases the value to $0.7(2e^2/h)$. This might be a more general feature of a mixing of spin levels when the temperature is raised [26]. Further evidence that an incipient polarization occurs is provided by measurements of shot noise, which shows two channels propagating unequally, and thermopower which, as discussed later, points to an intrinsic spin splitting. The 0.7 structure has been observed in both heterostructures and quantum wells, the latter system having only a small out-of-plane electric field, eliminating Rashba spin–orbit coupling as a possible explanation [27]. In addition to modulation-doped GaAs split-gate and etched devices, the 0.7 structure has now been widely observed in 1D systems defined in induced GaAs electron [28] and hole gases [29, 30], Si [31], GaN [32], $In_{0.75}Ga_{0.25}As$ [33], and GaAs cleaved-edge-overgrowth structures [34, 35], proving the universal nature of this effect.

2. The 0.7 structure

Non-quantized conductance structures that may appear in the conductance characteristics of a ballistic quantum wire were generally ascribed to disorder or length resonance [36]. Therefore the 0.7 structure, though present in early experimental results, was not considered to be of significance. We conducted extensive investigations to rule out these possibilities in the case of the 0.7 structure. These involved shifting the channel sideways by unequally biasing the split gates, as well as measuring numerous samples, and the 0.7 structure was always found to be reproducible. With increasing $B_{\parallel}$, the 0.7 structure smoothly evolved to the spin-split e^2/h plateau. Another characteristic feature of the 0.7 structure is its temperature dependence: it evolves downwards from the $2e^2/h$ plateau as temperature increases (figure 1(b)), and strengthens with temperature. As the temperature

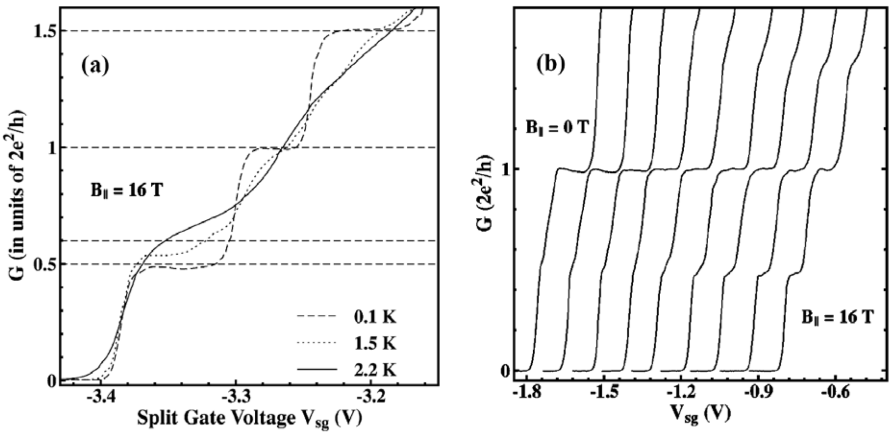

Figure 2. (a) Temperature dependence of the spin-split $0.5(2e^2/h)$ quantized plateau. (Modified from [26].) (b) The zero-field $0.5(2e^2/h)$ plateau lengthens and remains at $0.5(2e^2/h)$ as field is increased. (Modified from [13].)

is raised to 4.2 K, the 0.7 structure remains at around $0.62(2e^2/h)$ [26], whereas all quantized conductance plateaux may have disappeared. Detailed temperature dependence by Kristensen *et al* in etched 1D wires showed the structure appears thermally activated, suggesting it to be due to an excited state [37]. In addition to the 0.7 structure, we also observe structures at 1.7 and $2.7(2e^2/h)$ in low density samples, which evolve with magnetic field to 1.5 and $2.5(2e^2/h)$ plateaux [38]. See section 2.2 for an example of a zero-field $0.5(2e^2/h)$ plateau.

Disorder can create features at arbitrary conductance values. In general, the 0.7 structure can be identified from disorder effects by performing all three of the following tests:

(1) increasing temperature,
(2) increasing magnetic field, and
(3) laterally shifting the channel.

Raising the temperature will diminish structures caused by disorder. Increasing magnetic field will cause resonant structures to evolve in an arbitrary way, rather than into a quantized plateau at e^2/h as in the case of the 0.7 structure. Moving the conducting channel laterally by applying different voltages to each split gate in the pair will also cause resonant structures to evolve in an arbitrary way, and most likely evolve asymmetrically if the channel is moved to the right or to the left from the symmetric point $V_{\text{left}} = V_{\text{right}}$.

2.1. Temperature dependence in a magnetic field

Although much effort has been devoted to understanding the non-quantized 0.7 structure at zero magnetic field and the 0.7 analogues in high magnetic fields, spin effects occur in quantum wires at all magnetic fields. The region halfway between zero magnetic field and the first Zeeman crossing, where the spin-split subbands are spaced far apart in energy, is particularly illuminating because it allows the properties of the spin ↑ and spin ↓ subbands to be studied independently. For example, where we would expect a temperature-invariant point at the centre of each quantized plateau [39], we find, on the one hand, that plateaux associated with populating spin ↓ subbands do not show this. Instead, each such plateau rise with temperature in its entirety. On the other hand, plateaux due to populating spin ↑ subbands do show a temperature-invariant point at the centre of each plateau. Figure 2(a) shows that the $0.5(2e^2/h)$ plateau evolves to the 0.7 structure as temperature increases [26]. In quantum wires (either etched or split gate) with a large subband spacing, this can be observed in higher subbands as well [25, 39]. This can also be observed in high magnetic fields [22], for the $0.5(2e^2/h)$ and $1.0(2e^2/h)$ plateaux when they are due to the population of the 1↓ and 2↓ spin subbands. Self-consistent calculations with a saddle-point model and a density-dependent energy gap between spin subbands exhibit the same characteristics [39].

2.2. Zero-field 0.5 structure

There have been a few observations of a structure at $0.5(2e^2/h)$ in ballistic short wires and in long wires at low densities at zero magnetic field. We have measured a 0.5 structure in a short and wide 1D channel created in the lower 2DEG of a double-quantum-well structure. This 0.5 structure strengthened but remained at e^2/h with increasing magnetic field (see figure 2(b)). With increasing temperature, it gives way to a 0.7 structure (structure is found to stabilize at $0.62(2e^2/h)$ at $T \sim 4.2$ K) [13].

We also measured a 0.5 structure in a quantum wire, defined in a single heterostructure, by erasable electrostatic lithography (EEL) [40, 41]. In this case, the 0.5 structure was found to evolve from the 0.7 structure as the potential landscape at the exit and entrance were tuned by a biased scanning-probe tip. We observed that this 0.5 structure is crucially dependent on the symmetry of the device potential with respect to the saddle point. In most cases the symmetry is not perfectly achieved, and we observe a 0.7 structure. Further investigations are being carried out to understand the zero-field 0.5 structure. For this study we use wide geometries with a top gate. Preliminary measurements show a 0.5 structure in the wide channel limit as previously observed, but the relevance of this to the symmetry criterion [40] or an antiferromagnetic zig-zag Wigner crystal [42, 43] is being investigated.

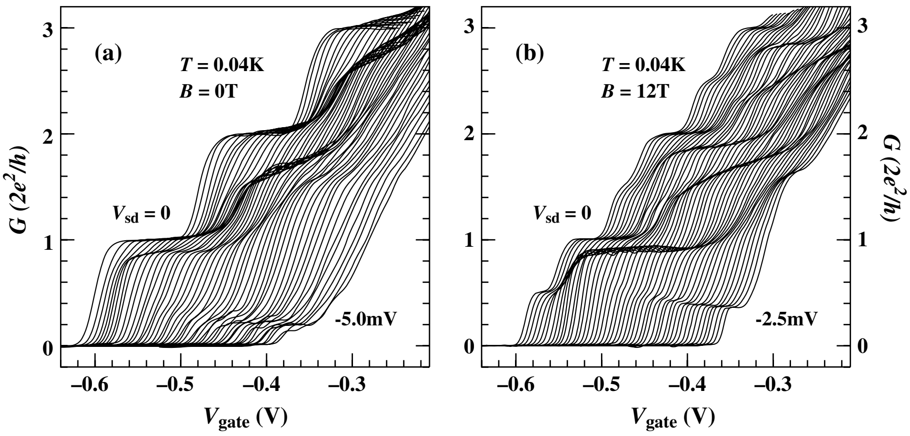

Figure 3. (a) Measured differential conductance in etched quantum wires in zero magnetic field (traces laterally offset) from $V_{sd} = 0$ to -5.0 mV. (b) Same as in (a), but at $B = 12$ T, from $V_{sd} = 0$ to -2.5 mV. Note how the bias-induced plateaux below $2e^2/h$ look identical in both panels.

It is of much significance to investigate the effect of the length of the wire on the 0.7 structure, particularly in the context of spin coherence over long distances in commercial applications. Reilly *et al* [44] reported that as length increases the 0.7 structure settles at $0.5(2e^2/h)$. However, cleaved-edge-overgrowth wires of 2 μm showed typical 0.7 structure [35]. We have measured wires longer that 2 μm [45, 46] and not observed any clear dependence of the 0.7 structure on wire length. In an induced 1D electron gas of length $L \leqslant 1$ μm, we reported [28] a 0.5 structure evolved from the usual 0.7 structure with decreasing as well as increasing 2D density.

2.3. Source–drain bias

Non-linear conductance measurements with a finite V_{sd} present interesting scenarios. Applying a V_{sd} selects different numbers of 1D channels transported from the source μ_s (left to right) and drain μ_d (right to left). This is expected to give rise to half-integer plateaux at zero magnetic field [16]. Half-integer plateaux were indeed observed for $G \geqslant 2e^2/h$ by Patel *et al* [14], but they also reported a plateau appearing at $0.85(2e^2/h)$ with increasing dc bias and another plateau appearing near $\sim 0.2(2e^2/h)$ at even higher biases. The $0.85(2e^2/h)$ plateau is known to evolve from the 0.7 structure [17]. Even if the 0.7 structure is not visible (such as in figure 3(a)) at low temperature, both the $0.85(2e^2/h)$ and $\sim 0.2(2e^2/h)$ plateaux can always be induced. The latter has been variously labelled as the $0.5(2e^2/h)$ plateau [19, 37, 47] or the $0.25(2e^2/h)$ plateau [48, 49].

In magnetic field, with well-resolved integer and half-integer plateaux at $N(2e^2/h)$ and $(N + 0.5)(2e^2/h)$, so-called 'quarter-integer' plateaux were observed for every subband [15] for $G \geqslant 2e^2/h$. For $G \leqslant 2e^2/h$, Thomas *et al* [17] noted how the $0.85(2e^2/h)$ and $\sim 0.2(2e^2/h)$ plateaux at $B = 0$ did not change at all under an increasing magnetic field (such as in figure 3(b)). This strongly suggests that these are quarter-integer plateaux, further strengthening spin-polarization theories at zero magnetic field. In $In_{0.75}Ga_{0.25}As$ quantum wires, plateaux at exactly $0.25(2e^2/h)$ and $0.75(2e^2/h)$ are observed in non-equilibrium transport [33].

Within a single-particle picture, we would expect both quarter-integer plateaux for a given subband to appear simultaneously at the same bias. For high-indexed subbands, experiments confirm this. However, we find that, as subband index N decreases, the $(N + 0.25)(2e^2/h)$ plateaux appear at increasingly higher biases than the $(N + 0.75)(2e^2/h)$ plateaux (figure 3(b)). Furthermore, the $(N + 0.75)(2e^2/h)$ plateaux drift to slightly higher conductance as subband index decreases. Self-consistent calculations with a saddle-point model and a density-dependent energy gap between spin subbands exhibit the same characteristics. Our measurements confirm that the zero-field $0.85(2e^2/h)$ and $\sim 0.2(2e^2/h)$ plateaux are spin-polarized quarter-integer plateaux [39].

Recently, we studied true DC-conductance [25], $G_{dc} = I/V_{sd}$. This contains important information not present in the differential conductance ($f < 1$ kHz) when a finite source–drain DC bias is applied. G_{dc} is given by $(\Delta E/eV_{sd})e^2/h$, where ΔE is the energy difference between the bottom of the subband and μ_s for $\Delta E \leqslant eV_{sd}$. This allows the Fermi energy to be extracted directly. By measuring ΔE as well as the differential conductance it is shown that in a magnetic field spin $\uparrow$ levels fill slowly as they populate in contrast to the spin $\downarrow$ levels, which drop sharply in energy. The $0.85(2e^2/h)$ plateau is due to the spin $1\uparrow$ subband moving slowly between μ_s and μ_d, while the spin $1\downarrow$ subband is below both chemical potentials. Furthermore, the $0.85(2e^2/h)$ plateau appears to be temperature-insensitive in the range 0.1–1 K. Since the $0.85(2e^2/h)$ feature evolves directly out of the 0.7 structure, this provides strong support for the hypothesis that spin $\uparrow$ subbands are pinned at the Fermi energy in the region of the 0.7 structure [60].

2.4. The zero-bias anomaly

A peak in the differential conductance of a quantum wire, called the zero-bias anomaly (ZBA), is observed for $G < 2e^2/h$ at very low temperatures [19]. The ZBA disappears

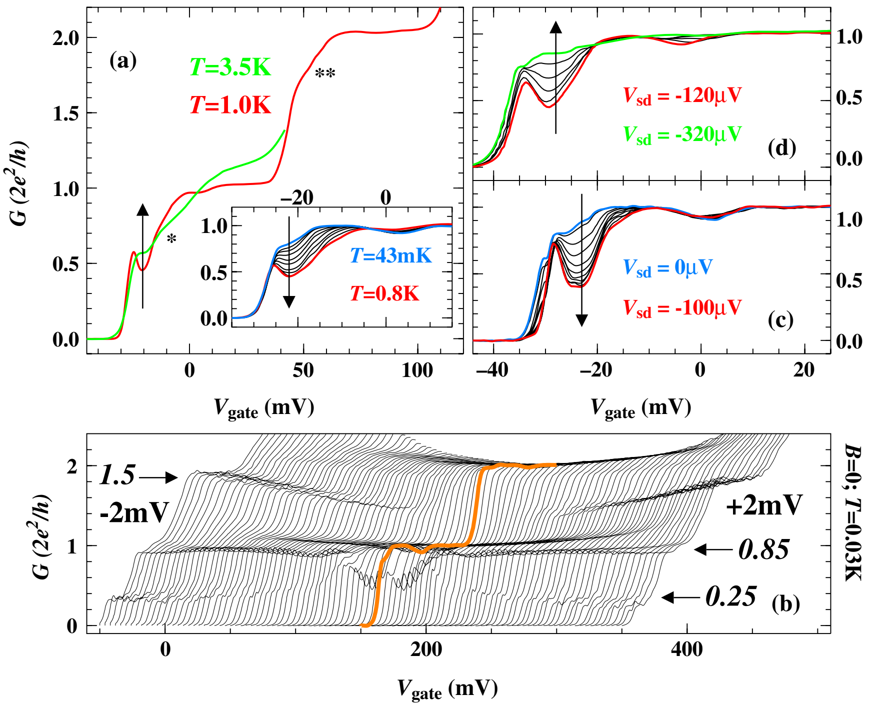

Figure 4. Focusing on the valley between the conductance peak and the $2e^2/h$ plateau, we observe: (a) the conductance increases with increasing temperature as the 0.7 and 1.7 structures begin to form (indicated by * and **), inset: the conductance decreases as temperature is increased, and is well described by the quantum dot Kondo formula $G = [1 + (2^{1/s} - 1)(T/T_K)^2]^{-s}$ [50], (b) the differential conductance as V_{sd} is varied from −2 to +2 mV in 40 μV steps (the orange trace shows $V_{sd} = 0$), (c) the Kondo effect is suppressed by an applied bias of 100 μV (conductance decreases as bias increases), and (d) the conductance increases with further increasing bias as the $0.85(2e^2/h)$ plateau begins to form. The formation of the $0.85(2e^2/h)$ plateau does not coincide with the suppression of the Kondo effect. The up and down arrows indicate the effect on conductance by the increase in V_{sd} or T. (Data taken from [51].)

with increasing temperature. With increasing magnetic field, the ZBA linearly splits into two peaks. Even in zero magnetic field, we have observed an asymmetric peak splitting, when the conducting channel is moved laterally [52]. The ZBA has been attributed to the Kondo effect [19–21], and was suggested to be intrinsically linked to the 0.7 structure. Within these models, all transport characteristics associated with the 0.7 structure result from the suppression of the Kondo-enhanced conductance above a spin-polarized $0.5(2e^2/h)$ plateau.

In order to understand the Kondo problem further we investigated etched quantum wires with a variable open quantum dot geometry that favours the formation of a bound state. These devices exhibit a strong Kondo-like effect. The 1D confinement in these devices is stronger than in split gates, thus increasing typical energy scales. This enabled us to observe that the suppression of the 1D Kondo effect did not coincide with the appearance of characteristics associated with the 0.7 structure: the two phenomena occurred at different energy scales. Thus, we propose that the Kondo effect in 1D channels and the 0.7 structure are separate and distinct effects [51].

Figure 4 shows that at low energy scales (<100 μeV), the Kondo effect is suppressed (transition from the blue to the red traces as either T or V_{sd} is increased). At higher energy scales (>100 μeV), the 0.7 structure and the $0.85(2e^2/h)$ plateau begin to form (transition from the red to the green traces as either T or V_{sd} is increased).

2.5. Thermopower

The Mott formula has had considerable success in describing the thermopower S in a variety of both degenerate and non-degenerate systems and is given by:

$$S = -\frac{\pi^2 k_B^2 T}{3e^2} \frac{1}{G} \frac{\partial G}{\partial E}\bigg|_{E=\mu}. \quad (1)$$

Appleyard *et al* [53–55] investigated the thermopower for a split-gate quantum wire, and, as seen in figure 5, the results agree with theoretical prediction of a zero in the thermopower when the conductance shows a quantized plateau. In a parallel investigation the thermopower was used as a thermometer of a 2D electron gas enabling good agreement to be found with theory for phonon emission.

However, from figure 5, it is quite clear that the thermopower rises and shows a small shoulder when the 0.7 plateau occurs. Either the Mott formula is not valid in this strongly interacting regime or else a straightforward interpretation suggests that there is not a true plateau in conductance but that the Fermi energy is pinned or moving slowly at the 0.7 structure. Application of a magnetic field converts the 0.7 structure to a spin-polarized $0.5(2e^2/h)$ plateau and is accompanied by a decline in the value of the thermopower to zero (see figure 5(c)). Analysis of the conductance behaviour indicates that in the region of the

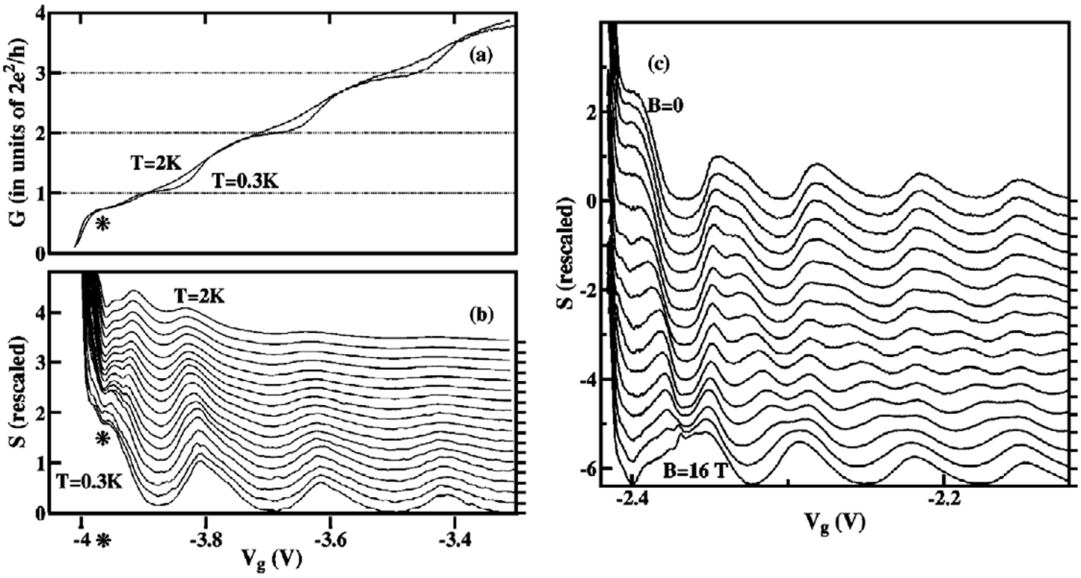

Figure 5. Temperature dependence of: (a) the conductance G, and (b) the thermopower S. (c) Thermopower when in-plane magnetic field $B_{\parallel}$ is incremented from 0 to 16 T in steps of 1 T. Lifting of spin degeneracy at high fields restores the zero in S that is predicted by single-particle theory. The traces in (b) and (c) are offset vertically. (Modified from [54].)

0.7 structure the first 1D subband is split with the spin $\downarrow$ subbands being transmitted and the other pinned near the chemical potential. Consequently this predicts two conduction mechanisms taking place in parallel, one spin subband is fully transmitted and hence contributes a quantized conductance of e^2/h and the other is only partially filled. Thus the observed finite thermopower is due to the partial transmission of the minority spin subband (spin $\uparrow$) and no contribution from the fully transmitted spin $\downarrow$ subband (zero thermopower results from a fully transmitted spin subband). The conventional semiconductor formula gives a temperature dependence of thermopower proportional to $\Delta E/k_B T$, where ΔE is the difference between the band edge and the Fermi energy. However the situation is not as simple as a conventional excitation across a gap in the density of states as spin-flip excitations across the spin gap can occur, giving a degenerate hopping type of thermopower with a linear temperature dependence (equation (1)). The results of the temperature dependence in figure 5 show that at the lowest temperatures there is a convergence with a slight increase in thermopower as the temperature decreases. The overall rise as carrier concentration decreases is consistent with an increase in the activation energy, but clearly the situation is complex when the magnetic field is applied until the completely spin-polarized conductance plateau is observed and the thermopower goes to zero.

2.6. Thermal conductance and shot noise measurements

The thermal conductance κ and the electrical conductance G of non-interacting electrons in quantum wires are related by the Wiedemann–Franz equation:

$$\kappa = -\frac{\pi^2 k_B^2 T}{3e^2} G. \qquad (2)$$

Consequently, as G is quantized in units of $2e^2/h$, so will the thermal conductance be quantized in units of $2\pi^2 k_B^2 T/3h$. At gate voltages near the 0.7 structure, a half-plateau at $0.5(2\pi^2 k_B^2 T/3h)$ is observed [56] in the thermal conductance κ. Below $2e^2/h$, the Wiedemann–Franz equation does not hold, which is possible evidence of strong electron–electron interactions.

Shot noise in a quantum wire vanishes at gate voltages corresponding to a quantized conductance plateau. A local minimum in shot noise was observed at gate voltages corresponding to the 0.7 structure in zero magnetic field and a full suppression in a finite magnetic field [57–59]. The interpretation of these results is that the two spin channels of the first 1D subband do not have the same transmission coefficients at gate voltages near the 0.7 structure.

3. 0.7 Analogues

In high magnetic field we induce Zeeman crossings of spin-split 1D subbands of different indices. We observed that at the crossing point, there is a spontaneous energy level splitting, giving rise to a conductance structure similar to the 0.7 structure [22–24] (see figure 6). Near the first Zeeman crossing (spin 1$\uparrow$ with spin 2$\downarrow$) a structure evolves from the quantized $1.5(2e^2/h)$ plateau, down to the re-entrant $2e^2/h$ with increasing field. Analogues are also produced at the second crossing of the spin 1$\uparrow$ subband with spin 3$\downarrow$. Mostly the splitting is observed on the spin $\uparrow$ branch and just after the crossing. Occasionally we observed the two split levels at the first crossing repel further in energy (gate voltage) giving rise to a lower 0.7 analogue structure named the 0.7 complement [60] starting from $2e^2/h$ and evolving into e^2/h. The temperature and bias dependences are similar to the 0.7 structure. This work underlines the fact that whenever there

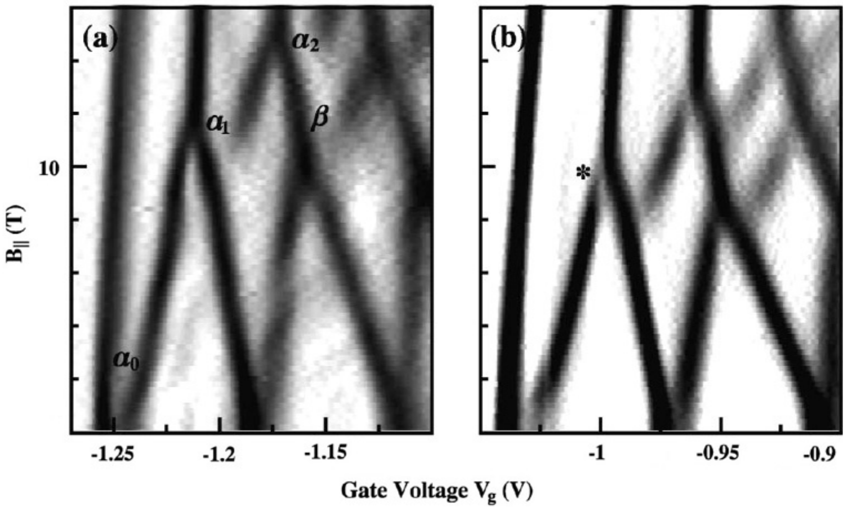

Figure 6. Greyscale plots of transconductance, dG/dV_g, as a function of V_g and $B_{\|}$ for two different quantum wires. (a) The labels α_1, α_2, and β show the 0.7 Analogues at the Zeeman crossing between spin levels 1↑ and 2↓, 1↑ and 3↓, and 2↑ and 3↓ respectively. (b) The label * shows a 0.7 complement. (Modified from [22].)

is a degeneracy occurring naturally, or created at Zeeman crossings, there is a spontaneous splitting of levels at low densities. Though it is simple to draw a picture of level splitting in this manner, the physics underlying the phenomenon may be complex [61]. The strongest analogues were observed in the Zeeman crossings due to the discontinuous jump of a spin ↑ energy level. DC bias spectroscopy was used to understand the analogues further which suggest pinning of the spin ↑ subbands near the source chemical potential [25, 60, 62]. This high-magnetic-field variant, known as the 0.7 analogue, shares the same dc bias, magnetic field and temperature dependences as the 0.7 structure—therefore, a full theoretical description of the 0.7 structure must also be valid for the 0.7 analogue as well as the 1.7 and 2.7 structures at zero-field.

4. Discussion

The earliest measurements of the 0.7 structure suggested the existence of a 'spin gap'. These were followed by calculations with the Hartree–Fock approximation that indeed at low densities exchange effects may give rise to a spontaneous spin polarization in 1D [9, 10]. Phenomenological models of Kristensen *et al* [37, 63] and Reilly *et al* [47, 64, 65], predict a density-dependent spin gap opening near the Fermi level as subbands populate. Calculations by Berggren *et al* [61] and Lassl *et al* [66] indicate that exchange–correlation effects could be the driving mechanism for the opening of a spin gap. With the discovery of the 0.7 analogues [22], the discontinuity in the energy spectrum of populating spin ↑ subbands could be probed below Zeeman crossings, a measurement not possible with the zero-field 0.7 structure.

Collectively, the 'spin gap' phenomenological models have been fairly successful at presenting a somewhat coherent explanation for many experimental results (the temperature, magnetic field, and bias dependences of the 0.7 structure and the 0.7 analogue; the density dependence of the 0.7 structure; the temperature and bias dependences of spin-split half-integer plateaux (away from Zeeman crossings or $B = 0$); the finite, local minimum in thermopower; and the finite, local minimum in shot noise). In order for a singly formulated model to reproduce the experiments above, three key features are required. The first is that the spin gap must depend on carrier density (i.e. be gate-voltage-dependent). Otherwise, an existing, static spin gap near pinch-off would lead to a quantized plateau at $0.5(2e^2/h)$, and not $\sim 0.7(2e^2/h)$. Second, both spin ↑ and ↓ subbands must be affected by the opening spin gap: the spin ↑ subbands are pushed to higher energies whilst the spin ↓ subbands are lowered in energy. Third, the spin ↑ subbands should remain near the chemical potential, as the spin gap changes whilst gate voltage increases. If only pinning were occurring for spin ↑ subbands without the spin ↓ subbands plunging abruptly in energy, then one would not observe the non-trivial temperature and bias dependences of the spin-split half-integer plateaux associated with populating spin ↓ subbands (see figures 2(a) and 3(b)).

None of the published spin-gap models have considered the zero-bias anomaly (ZBA). It has been suggested [18, 19] that Kondo physics is responsible for the ZBA in quantum wires. In [19], an empirical model was proposed where the bias-induced $0.85(2e^2/h)$ plateau, the magnetic field dependence and the temperature dependence of the 0.7 structure, all resulted from the suppression of Kondo-enhanced conductance above a spin-polarized $0.5(2e^2/h)$ plateau. This empirical model was soon followed by theoretical calculations [20, 21] supporting the concept of an exchange-induced quasi-bound state at the centre of the quantum wire. More recently, this exchange-induced quasi-bound state was suggested to survive high magnetic fields [67]. A key feature of the Kondo model described above is that the zero-field, high-temperature limit of the 0.7 structure is $0.5(2e^2/h)$.

The temperature dependence of the half-integer plateaux associated with populating spin ↓ subbands in finite field (see figure 2(a)) is not consistent with the above Kondo interpretation. Once the 0.7 structure has evolved into the spin-split $0.5(2e^2/h)$ plateau, Kondo interactions have been completely suppressed. The Kondo effect cannot be invoked to justify the rise in conductance of the spin-split $0.5(2e^2/h)$ plateau as temperature increases. Moreover, we find that the formation of the bias-induced $0.85(2e^2/h)$ plateau (see figure 4) does not result from the suppression of the Kondo effect. In clean quantum wires, it is difficult to reconcile a bound state still producing Kondo interactions at large source–drain biases (exceeding 1 meV) in the region of the $0.85(2e^2/h)$ plateau. We note that the thermal activation model [37] could fit the temperature dependence of the 0.7 structure to the same accuracy as a Kondo model [19, 68]. In our etched open quantum dot devices, despite a strong Kondo effect (the ZBA height reaches a maximum of e^2/h), the screening of the unpaired spin is incomplete in (a shoulder is still visible in the conductance in figure 4(a)). Yet, in quantum wires with a relatively much weaker Kondo effect (the maximum ZBA height ever reported in quantum wires only reaches $0.4e^2/h$), the 0.7 structure can disappear completely into the $2e^2/h$ plateau (such as the $V_{sd} = 0$ trace in figure 3(a)). This could imply that a mechanism other than Kondo interactions is involved in the temperature dependence of the 0.7 structure. A long and nearly-flat appearance of the 0.7 structure (such as in [54, 69]) is not consistent with a mechanism based only on Kondo physics. Thus, we find that the suppression of the Kondo effect from a single bound state in the 1D channel cannot account for the entire phenomenology of the 0.7 structure.

It is well known that electron–electron interactions are important in one-dimension. The standard model for an interacting 1D electron system is that of the Luttinger liquid. However a 1D Luttinger liquid joined to 2D Fermi liquid leads will exhibit perfectly quantized conductance for any strength of interactions, and would therefore not be able to explain the non-quantized 0.7 structure. Recently it has been pointed out that clean Luttinger liquids may actually exhibit temperature-dependent non-quantized conductance if they are in the spin-incoherent regime. At low electron densities, interactions between electrons are effectively much stronger, which will force the electrons to localize, thus creating a Wigner crystal. For particularly weak lateral confining potentials, however, these strong interactions between electrons may force a 1D string of electrons to overcome the lateral confinement and evolve into a quasi-1D zig-zag shape as density increases. Whereas a 1D Wigner crystal is found to be antiferromagnetic, as required by Lieb and Mattis, the zig-zag shaped electron chain has a ferromagnetic ground state [43].

With decreasing the 2D carrier densities using a back gate, we measured the 0.7 structure to fall further below $0.7(2e^2/h)$ and even approaching $0.5(2e^2/h)$ [38]. In wider split-gate geometries (width $\sim 1\ \mu$m) we used a midline gate to locally decrease the 1D carrier densities, in this case we observed a structure at e^2/h which upon application of a parallel magnetic field strengthened further indicating a zero-field spin splitting of the 1D subband [13]. Whether this can be described as ferromagnetism at low densities as suggested by mean-field calculations, or a result of spin-incoherent transport of strongly interacting 1D electrons which arrange into a zig-zag Wigner crystal [43] is being currently investigated [70].

In conclusion, many experimental observations have indicated that as a 1D channel is populated, a spontaneous lifting of the spin degeneracy occurs. This conclusion is supported by a range of thermal and electrical data as well as calculations of the energy of the spin subbands as they become progressively occupied. The 1D channel, which are relatively free from defects and scattering centres, is an outstanding laboratory of quantum transport and a variety of spin phases are becoming apparent.

Acknowledgments

We acknowledge useful discussions with K-F Berggren, N Cooper, C Barnes, C J B Ford, C-T Liang, T-M Chen, and W K Hew. We thank the Engineering and Physical Sciences Research Council (UK) for supporting this work. KJT acknowledges support from the Royal Society, UK.

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