行政院國家科學委員會專題研究計畫成果報告

中觀系統的量子傳輸：［一］中觀常態結構［二］中觀超導結構

Quantum transport in mesoscopic systems: [I] Mesoscopic normal structures [II] Mesoscopic superconducting structures

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一、中文摘要

在本計劃中，我們研究了中觀系統的量子傳輸，其中包括(一)常態結構(二)超導結構。

對於中觀常態結構，我們探討了一個有限範圍的縱向偏振時變電場作用在縮緊形結構的情形。我們發現：直流電導 G 表現出光抑制傳導的特性。這些即是准束縛態（QBS）特性，這是由於電子躍遷到次能帶底所產生的特性；此時，態密度具有發散性。這些 QBSs 為似谷形結構，而非似急降形結構；因此，這些 QBS 特性不同於一個時間調變電位作用在縮緊形結構的電導特性。另外，次能帶底向高能量移動，此移動的程度與電場的平方成正比而與頻率的平方成反比。此等效位疊源於向量位的平方，並導致有趣的且對電場敏感的 QBS 特性。

我們也探討了一個中觀環的傳導特性且環中心有一隨時間線性增加之磁通量。當環中只有彈性散射源而沒有非同調散射源時，我們發現平均電流為零。而在環中沒有彈性散射源而有非同調散射過程發生時，我們計算了環內的平均電流。我們發現一個令人驚訝的結果—平均電流的主要貢獻不是來自費米能階而是來自較低能之電子。對於這些發現我們給予了物理解釋。

對於中觀超導結構，我們探討了一個時變電場對 SNS 接頭電流的影響，其基本特性包含非彈性散射和 Andreev 反射的交互影響，在這個研究中，我們在接頭的常態部分引進振盪位場，並計算電流與相位（CPR）的關係，這裡相位ϕ是兩邊超導電極的相位差。在時變場作用下，原先分立 Andreev 能級變成會滲漏，因此對電流無直接貢獻，但藉由受激發出 n 個光子而暫陷入射準粒子，這些 Andreev 能級間接貢獻超導電流。每個準粒子的貢獻呈現尖峰和急降結構，這些結構取決於入射粒子能量和ϕ值。對於一個特定ϕ值，CPR 包含所有可能入射能量準粒子貢獻的積分，因此暫陷過程對於 CPR 有重大影響。我們詳細分析了這些暫陷特性的 CPR。

我們也探討了在一個彈性雙 SNS 接頭有限溫度的 CPR。我們發現中間超導相位具ϕ_2有多值，這對 CPR 形成的特性是關鍵。相對於有一個支系和 4π 週期的零溫 CPR，有限溫度不對稱接頭的 CPR 有兩個支系，每個支系週期為 2π，另外，有限溫

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度對稱接頭的 CPR 有兩個支系，一個支系週期為 4π，另一個為 2π，只有部分有限溫度的 CPR 與零溫 CPR 相類似，我們導出其差異的物理原因。

Abstract

We have studied the quantum transport in mesoscopic stystems, including [I] normal and [II] superconducting structures.

——For the mesoscopic normal structures, we have studied the situation when a finite-range longitudinally polarized time-dependent electric field acts upon a narrow constriction (NC). Our finding is that the dc conductance G exhibits suppressed features. These features are recognized as the quasi-bound-state (QBS) features associated with electrons making transitions to the vicinity of a subband bottom, of which the density of states is singular. However, these features, which are valley-like instead of dip-like, are different from the G characteristics when constrictions are acted upon by a time-modulated potential. In addition, the electric field is found to cause an effective static potential barrier which barrier height is proportional to the square of the electric field and to the inverse square of the frequency. The origin of this potential barrier is traced to the square of the vector potential and its role in giving rise to the interesting field-sensitive QBS features is analyzed in full detail.

We have also studied a mesoscopic ring threaded by a magnetic flux that is changing linearly in time. For the case when the ring has an elastic scatterer, and no incoherent processes, the dc current is found to be zero. For the case when the ring has incoherent processes and no elastic scatterers, the dc current is calculated. Furthermore , we find the surprising results that the contribution to the dc current is dominated not by electrons in the vicinity of the Fermi level but by lower energy electrons. A physical understanding is obtained for these findings.

For the mesoscopic superconducting struct-ures, we have studied the effects of a time-modulated potential on the supercurrent in a SNS junction. The essential feature involves the interplay between the inelastic scattering and the Andreev reflection. In this study, the oscillating potential is introduced in the normal region of the junction and the current-phase relation (CPR) is calculated. Here the phase ϕ is the phase difference between the two super-conducting electrodes. The originally discrete Andreev levels become leaky when acted upon by the time-modulated potential, and do not contribute to the supercurrent directly. Indirectly, however, these Andreev levels contribute to the suppercurrent by trapping incoming quasi-particles temporarily through the induced emission of $n\hbar\omega$. The contribution from each quasi-particle shows peak and dip structures which depend both on the energy of the incident quasi-particle and the values of ϕ. The CPR involves integrating, for a given ϕ, the contribution from quasiparticles of all possible incident energies, and thus the trapping processes have significant effects on the CPR. We have analyzed in detail these trapping features in the CPR.

We have also studied the finite-temperature CPR in a ballistic double SNS junction. It is found that the phase ϕ_2 of the middle superconductor is multivalued and it plays a crucial role in shaping the features of the CPR. In contrast with the zero-temperature CPR, which has one branch, and with a ϕ–period of 4π, the finite-temperature CPR for an asymmetric junction has two branches and each has a ϕ–period of 2π. On the other hand, the finite-temperature CPR for a symmetric junction has two branches, one with a ϕ–period of 4π and the other with a ϕ–period of 2π. Only part of the finite-temperature CPRs can be identified with the zero-temperature CPRs, and the physical reason for the differences is deduced.

Keywords: Quantum transport, mesoscopic normal junction, mesoscopic superconducting junction, time-dependent, quasi-bound state, magnetic flux, Andreev level tunneling.

二、Motivations and goals

[I] Normal structures:

A. A longitudinally polarized time-dependent electric field acting upon a NC

The influence of time-modulated fields on the quantum transport has received extensive interest recently due to the potential importance in future technological applications. The systems recently considered are primarily mesoscopic systems, such as narrow constrictions (NCs)[1-9]. The time-modulated fields can give rise to either inter-subband or intra-subband transitions. When the dimension of the time-modulated region is less than the incoherent length the scatterings are coherent inelastic scatterings. To understand the full effect of these time-modulated fields, we need to study systematically, and in great detail, each of these scatterings.

When a finite-range time-modulated field acts upon a NC, the inelastic scatterings involved are the intra-subband scatterings. Quasi-bound-state (QBS) features, which were not widely recognized, except for the work of Bagwell and Lake [10] who considered a time-dependent potential with a delta profile, were found also in the case when a finite-range time-modulated potential acts upon a NC that has a uniform widths.[8] The energy of this QBS is below, but close to, the band bottom of the one-dimensional structure. These QBS are associated with the singular density of states (DOS) at each subband bottom. These features are found also in NC that have varying widths [9]. Then it is legitimate to investigate how a longitudinally polarized time-dependent electric field influences the conductance G of a NC.

B. Mesoscopic 1D ring with a time-dependent magnetic flux

A small conducting 1-D ring threaded by a magnetic flux have been of interest to physicists because it provides a paradigm allowing issues of fundamental importance to be tested experi-mentally [11-13]. In the case when the magnetic flux is changing linearly with time, and the coherent ring has an elastic scatterer, a physical picture equivalent to the equation of motion concept in the semiconductors was proposed to describe the situation. Accordingly, the dc current was argued to be zero [12]. But later studies have applied a perturbative method to the same problem and concluded that the dc current is not zero [15]. This discrepancy is due to the lacking of a fully quantum mechanical time-dependent calculation that goes beyond finite-order perturbation. In this work we have developed a nonperturbative method for the system.

[II] Superconducting structures:

A. A time-modulated potential acting upon a SNS junction

Due to the progress of microtechnology, the nanostructures consisting of both normal metal (N) and superconductor (S) have caused renewed interests in the study of superconducting junctions. Numerous efforts, both theoretical and experimental, are devoted to explore such super-conducting mesoscopic systems [16], where not only the Cooper pairs in S regions but also the quasi-particles in N regions are coherent. The interplay between these two kinds of coherence induces peculiar transport properties in the mesoscopic regime [17-20].

Quantum transport in the presence of time-modulated fields in normal structures has been used by us [7-9] and by other researchers [1-10, 21-22]. Recently, there is interest in exploring the effect of an electromagnetic wave on the Josephson current through a mesoscopic SNS constriction [23]. The electromagnetic wave was supposed to induce transitions between the Andreev levels formed in the normal region. A resonant approximation has been used in the paper [23]. This motivates us to implement the exact time-dependent scattering method that we have developed for normal structures into this problem. The reason, based on our experience in mesoscopic transport, is that multiple inelastic scattering should be important even when resonant conditions are not met. We want to find the possible manifestations of the QBS features in a SNS junction

B. Finite-temperature effect on the CPR of a ballistic double SNS junction

Recently we have proposed a current-conserving condition to determine the current-phase relation (CPR) of a mesoscopic, and ballistic, double SNS junction [24-26]. Interesting results such as the cut-off features and the Andreev level tunneling features are found. In this work, we explore such features in the case of finite temperatures.

三、Results and discussions

[I] Normal structures

A. A longitudinally polarized time-dependent electric field acting upon a NC

In this work, our main finding is that the conductance G exhibits two types of suppressed features — the valley-like structures in the plateau regions and the suppressed features near each integral values of X. Here X represents a rescaled energy of an electron, and the integral value of X is the number of propagating channels.

The widths ΔX_V of both types of the suppressed features are the same in the G versus X curve. Both of the suppressed features are sensitive to the field amplitude E_0 and the field frequency ω. In particular, an explicit expression, $\Delta X_V = E_0^2/(2\omega^2\Delta\varepsilon)$, for the widths of these suppressed features is obtained. These findings for ΔX_V suggest that the widths for both of the suppressed features must have been caused by the same physical factor.

After careful analysis, a physical picture for the features in G is obtained and is summarized in the following. As the longitudinally polarized time-modulated electric field acts upon the constriction, an effective potential ΔX_V is induced in the time-modulated region, thus setting up an effective potential barrier. The effective potential barrier causes a transmitting N-th subband electron, with incident energy $N<X<N+\Delta X_V$, to transmit via direct tunnelling, or to transmit via assisted transmission by absorbing $m\Delta X$, where ΔX corresponds to an energy of $\hbar\omega$. The time-modulated region is very long so that transmission via direct tunneling is totally suppressed, leading to the large G suppression. For the assisted transmission, the electron must tunnel into the time-modulated region first before it can absorb the needed energy. When $\Delta X_V < \Delta X$, the minimum energy needed is ΔX. As X increases from N to $N+\Delta X_V$, the electron can tunnel deeper into the time-modulated region, so that the extent it get assisted is increased. Subsequently, G increases monotonically. The value of G saturates near $N+\Delta X_V$, showing that the saturated value of G, which increases with E_0, is a measure of the effectiveness of the assisted process. Similar understanding applies to the case when the electron can make transition to the QBS in the effective barrier region by emitting ΔX. These field-sensitive QBS features are interesting and is potentially important for applications such as detecting photons in the THz regime.

B. Mesoscopic 1D ring with a time-dependent magnetic flux

The magnetic flux is changing linearly in time. For the case when the ring has an elastic scatterer, and no incoherent processes, we have solved the Schrodinger equation for the wavefunction. It is shown explicitly that the dc current is zero. This result holds for any rate of change of the magnetic flux, including the regime when the semi-classical argument, the effective equation of motion argument, cannot be applied. For the case when the ring has incoherent processes and no elastic scatterers, the wavefunction is obtained exactly, using a model incoherent scatterer first proposed by Buttiker.. The advantage of the model is that the electrons that suffer incoherent are injected back into the system so that the current is conserved in the incoherent processes. We obtain an expression for the dc current. The analytic results allow us to show explicitly that the dc current is contributed by electrons in the lower energies rather than by those close to the Fermi energy.

[II] Superconducting structures:

A. A time-modulated potential acting upon a SNS junction

In this study, we have shown that the transmitting quasi-particles can be trapped in the normal region when it can make transition to an Andreev level by giving away $n\hbar\omega$. However, also because of the time-modulated potential in the normal region, the quasi-particle cannot be trapped forever. Since the Andreev levels are current-carrying states, this quasi-trapping processes show up in the CPR of the junction. The structures in the CPR that associated with these processes are identified and explained.

In a SNS junction, without impurities and ac fields, there is bound Andreev levels below the gap potential due to Andreev reflections at both S-N interfaces. In such case, the lifetime of discrete Andreev levels is infinite, and both discrete bound states and continuous scattering states can contribute to supercurrent [27-28]. But the lifetime of discrete levels becomes finite due to the oscillating potential, so that the current contribution from these discrete levels would not exist after long enough time. The continuous scattering current becomes the only component so that $I_\phi = I_{sca}(\phi)$. In a dc-biased SNS junction, the discrete Andreev levels are also leaky, and the scattering current is the only current too [29-31]. Although the discrete bound current is absent in the influence of the time-modulated potential, quasi-particles in the scattering states can be trapped near an original Andreev level by emitting one or several photons, and give rise to additional current.

A quasi-particle at energy $|E|>\Delta$ incident from one of the S sides may emanate in sidebands at energies $E+n\hbar\omega$, due to the ac field. We find sets of dips and peaks in the current that are contributed from one of such quasi-particles, which energy is $n\hbar\omega$ higher than the original Andreev levels E_b. When the strength of the ac field is small, the dips and peaks happen just at $E_b+ n\hbar\omega$. The time-modulated potential can induce the quasiparticles to emit $n\hbar\omega$ and be trapped temporarily in such a discrete Andreev level which is a carry current state. The current contributed from the same set of bound state decreases gradually with n. When the strength of the ac field is large enough, there is observable shift in the Andreev levels. It is found that the most important contribution comes from the trapping processes that occur in particles at incident energies close to the energy gap. We expect this trapping mechanism to remain important in general ac properties in mesoscopic superconducting structures.

B. Finite-temperature effect on the CPR of a ballistic double SNS junction

Our study shows that the finite-temperature CPR is interestingly different between a symmetric and an asymmetric mesoscopic ballistic double SNS structure. The difference is due to both the Andreev level tunneling and the special role played by the phase of the middle superconductor. These results suggest that the quantum transport in superconductor superlattice could have very interesting behavior.

四、Self-evaluation of project results

In this project, we have proposed a new time-dependent mode-matching method for solving the quantum transport in mesoscopic systems acted upon by external time-dependent fields, including both normal and super-conducting systems. New understandings have been obtained and various important processes identified. Part of these results have been presented in the 1997 annual meeting of the Physical Society of the Republic of China [32]. One paper has been submitted for publication in an international journal, and three papers are in preparation [33]. The issues studied are of current interest to the mesoscopic communities and the results obtained should have impacted their studies.

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[C1] C.S. Tang and C.S. Chu, "Quantum transport in narrow constrictions in a time-dependent electric field: longitudinally or transversely polarized."
Oral session: D'd3.

[C2] V.C.Y. Chang and C.S. Chu, "Critical current of a ballistic asymmetric double superconductor — normal-metal — superconductor junction."
Oral session: Ad5.

[33] *Published and submitted papers*:

[P1] C.S. Tang and C.S. Chu, 1998, "Quantum transport in the presence of a finite-range longitudinally polarized time-dependent field," (submitted).

[P2] C.S. Chu and M.J. Liu, 1998, "DC current induced by a linearly time-dependent magnetic flux in a mesoscopic ring with an incoherent scatterer," (in preparation).

[P3] H.C. Liang and C.S. Chu, 1998, "Suppercurrent in the presence of a time-modulated potential inside a SNS junction," (in preparation).

[P4] V.C.Y. Chang and C.S. Chu, 1998, "Finite-temperature effect on the current-phase relation of a ballistic double superconductor — normal-metal — superconductor junction," (in preparation).