論 文 の 内 容 の 要 旨

論文題目　Coherent Control and Phase Measurement in Electron Quantum Interferometer
(量子干渉計における電子のコヒーレント制御と位相測定)

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Recent advances in nano-fabrication and semiconductor technologies enable us to design and fabricate nano- and micro-structures, where a phase relaxation length is longer than the device size. Hence, a variety of quantum interference phenomena are within experimental reach. Quantum interferences in such mesoscopic systems are usually probed by means of electron transport or optics experiments. In transport experiments, we attach macro-scale contacts to a microscopic object and observe interference via currents flowing through the contacts.

A two-path interference is one of the simplest interferences. Numerous attempts at its realization have been made using an Aharonov-Bohm (AB) interferometer. However in a two-terminal AB ring, gauge invariance and time reversal symmetry between macro-scale contacts impose a boundary condition called *phase rigidity* for the electron transport, in which linear conductance is an even function of the magnetic field (Onsager's law). To satisfy this boundary condition, the two-path contribution is always accompanied by complicated multi-path interference, which scrambles the quantum phase difference between the two paths.

Although its realization has been difficult, observation of a two-path interference allows for a measurement of the relative transmission phase between the two paths. Transmission phase contains complementary information to conductance and gives a key ingredient in understanding various scattering problems. In particular transmission phase shift across a quantum dot (QD) attracts a considerable interest, where the phase behavior described by Friedel's sum rule and the one reflecting spin screening of the many-body singlet ground state in the Kondo regime are predicted. Pioneering experiments to study the transmission phase across a QD have been done by employing multi-terminal or multi-channel AB ring geometries. In most of the experimental works, lifting of the phase rigidity is confirmed by the observation of a smooth phase shift induced by a gate voltage, i.e. each conductance matrix element does not have to be an even function of the magnetic field.

The π-phase shift across a Coulomb peak in the Coulomb blockade regime as expected from Friedel's sum rule was observed by a group in Weizmann institute in Israel. However unexpected results were also reported: universal phase lapse in many-electron QD and the phase behavior

contradicting to the theoretical expectations in the Kondo regime. In these preceding experiments, the two-path contribution is properly extracted only for the appropriate tuning of an interferometer. Otherwise, multi-path contributions might smear the correct transmission phase, but which can indeed occur when gate voltages of the QD are changed during the measurement. This might have prevented correct extraction of the transmission phase. A new scheme for measuring the transmission phase across a QD, in which contributions from multiple paths are safely excluded, is therefore required.

In addition, once electrical control of the two-path interferometer becomes possible, it can be applied to the quantum information defining flying charge qubits of propagating electrons. A flying qubit is an architecture, where a quantum state is controlled during transfer, and hence it should be more suitable to create a non-local entangled state compared to static qubits. The solid-state realization of a non-local entanglement known as an essential quantum mechanical state, is not only attractive for understanding fundamentals of the quantum physics but also inevitable for constructing scalable semiconductor quantum information devices in which many qubits are manipulated.

In this thesis we realized a novel two-path interferometer that can also act as a flying qubit by combining an AB ring with two-channel wires, that is, parallel tunnel-coupled quantum wires that allow tunneling of an electron between the two paths. The device is defined by surface Schottky gates in a two-dimensional electron gas at the interface of a high-mobility GaAs/AlGaAs heterostructure. We define the two pseudo spin states $|\uparrow\rangle$ and $|\downarrow\rangle$, where $|\uparrow\rangle$ and $|\downarrow\rangle$ correspond to the state having an electron in the upper and lower path, respectively. In such a structure, any superposition state of $|\uparrow\rangle$ and $|\downarrow\rangle$ in the ring can transmit into the tunnel-coupled wire by being directly transformed into the superposition of the bonding and anti-bonding state in the tunnel-coupled wire, that is, $\psi_S = (1/\sqrt{2})(|\uparrow\rangle + |\downarrow\rangle)$ and $\psi_{AS} = (1/\sqrt{2})(|\uparrow\rangle - |\downarrow\rangle)$. This is in contrast with the conventional AB ring with only single wire leads, where only ψ_S is transmitted into the leads. Consequently, this new structure can work as a two-path interferometer for ballistic electrons, which does not suffer from paths encircling the AB ring due to the absence of backscattering at the entrance of the tunnel-coupled wire.

Experimentally the realization of a *pure* two-path interference is confirmed by observation of anti-phase oscillations of the two output currents as a function of the magnetic field, which are proportional to the square of the coefficients of $|\uparrow\rangle$ and $|\downarrow\rangle$ at the exit of the tunnel-coupled wire. Note in such a case, sum of the two output currents is independent with the magnetic field so that Onsager's law for the total current is satisfied. Pseudo spin is then defined as a flying qubit. We show that this flying qubit can be fully manipulated by combining quantum operations at the AB ring and the tunnel-coupled wires. The both operations are performed by means of electrostatic gate voltages, and high velocity of ballistic electrons allow for very short operation time of order of 10 ps. Furthermore, the relatively long coherence length (~ 86 μm @ 70 mK) compared to the

interferometer (~ 6 μm) was found from the temperature dependence of the AB oscillation amplitude. The only drawback of this flying qubit is the limited visibility of ~7 %, defined as the AB oscillation amplitude divided by double of the mean current. Because the coherence length is found to be long, decoherence is not the origin of this low visibility. The visibility is mainly limited by a contribution from several transmitting channels in each part of the tunnel-coupled wires and in each arm of the AB ring, while only one in each wire contributes to the main oscillation. If we reduce the number of transmitting channels to one, the screening effect is suppressed leading to enhancement of backscattering as a source of decoherence. One of promising remedies is to use electron transport by surface acoustic waves (SAWs), where electrons can be transferred one by one through a depleted quantum channel without backscattering being confined by large moving potential of SAWs.

We developed the techniques for electron transport by SAWs following the preceding experiments. As a first step to realize high fidelity flying qubit operations by combining a depleted AB ring with tunnel-coupled wires and electron transport by SAWs and to create a non-local entanglement, we demonstrated control of single electron charge states injected by SAWs into a depleted tunnel-coupled wire. We observed oscillation of an electron between the two wires as a function of tunnel-coupling energy, realizing a beam splitter operation. As expected, the visibility of the oscillation was improved up to ~40%. We also show another proof of coherent electron oscillations by changing the energy detuning between the two wires. The next step should be the flying qubit operation with yet higher fidelity, where the operations in the AB ring and the tunnel-coupled wire are combined.

As another application of the two-path interferometer, we measured transmission phase shift across a QD by embedding a QD in one arm of the AB ring and observing the interference pattern. Firstly we confirmed π-phase shift across a Coulomb peak expected from Friedel's sum rule as already observed in the preceding experiment. Then we focused on the phase behavior in the Kondo regime. The Kondo effect is one of the most intriguing and widely investigated electron correlations. It is characterized by a many-body singlet ground state often referred to the Kondo singlet state and occurs at temperatures lower than the Kondo temperature ($T \leq T_K$). Theoretically an electron is scattered by the Kondo singlet state into a single quasi-particle acquires a π/2-phase shift but without spin flip. This π/2-phase shift is consequence of the spin screening predicted for the low temperature limit, but interference experiment enables to observe it even at higher temperatures until $T \sim T_K$.

In the experiment we found that the total phase shift across the two Coulomb peaks (CPs) with the Kondo correlation in between is π and that the phase shift across each CP is π/2 for $T \leq T_K$. For $T \geq T_K$ the phase shift across each CP exceeds π/2, resulting in a *S*-shaped phase behavior in the valley. By further increasing the temperature compared to the Kondo temperature ($T >> T_K$), this *S*-shaped behavior was pronounced and became asymmetric about the valley center, approaching the one observed in the normal Coulomb blockade regime without the Kondo correlation. We also confirmed

that these features are well reproduced by numerical renormalization group (NRG) calculations.

Furthermore we found that the asymmetry of the phase behavior at $T >> T_K$ depends on the parity relation between the corresponding orbital of the Kondo correlation and those of the nearby CPs. From the theoretical expectation, this parity relation also determines existence of the phase lapse between Coulomb peaks. When the parity of the CPs is the same (opposite), the phase lapse appears (does not appear) in between. We determined the parity relations from the asymmetric phase behavior at $T >> T_K$ and confirmed that those parity relations are consistent with the phase lapse behavior expected from the theory.

Finally we investigated the transmission phase through a many electron QD, where universality of the phase lapse regardless of a QD parameters such as orbital parity relation as discussed above was reported in previous experiments for more than 14 electrons in the QD. Many theoretical works have been devoted to explain this observation, and the relation between the coupling energy Γ between the QD and the leads and the single level spacing δ are considered as key parameters. Γ becomes usually large for a large QD containing many electrons, whereas δ becomes small. Therefore $\Gamma > \delta$ was thought to be the condition for the universal phase lapse behavior. However there is no convincing theory, which can explain the phase lapse in the vast number of successive CPs.

In our experiments using a *true* two-path interferometer, we found valleys without phase lapse even in a many electron QD, which contains at least more than 20 electrons around the crossover region between $\Gamma < \delta$ and $\Gamma > \delta$. This observation is in contrast with the universal behavior observed in the previous experiments and suggests that orbital parity still plays an important role in the phase behavior in this regime.