Chapter 8
TUNNELING THROUGH MOVING NANOOBJECTS

Universally recognized parallels between real molecules and artificial complex quantum dots embrace electronic and spin properties of these few-electron systems included in tunneling electrical circuits. This analogy is not complete because the artificial nanoobjects do not possess vibrational eigenmodes which are integral part of excitation spectrum of natural molecular complexes. However, modern nanotechnologies are able to provide artificial atoms and molecules with mechanical degrees of freedom. As was mentioned in Section 3.6.4, mechanical motion of nanoisland may be induced by external electromotive or magnetomotive forces. For this sake the nanoisland may be mounted as an electromechanical pendulum formed by a gold clapper [97], silicon nanopillar [367, 368] or suspended silicon nitride string [229]. Nanostring itself [404] as well as a suspended carbon nanotube [172, 362, 376, 383] may be used as a nanomechanical oscillator.

Practical implication of moving nanoislands in fabrication of single-electron tunneling transistors, current standards, atomic force microscopy, etc encourages experimentalists to refine the electrical and nano-mechanical components of tunneling circuits in order to make the tunneling current more controllable and the parameters of devices more reproducible. Nanoisland oscillating between two “banks” (metallic electrodes) may catch up electrons from one electrode and eject them at another one, i.e. play part of a shuttle, which transports charge between two banks [143]. If the radius of the nanoisland is small enough, strong Coulomb blockade promotes one-by-one electron shuttling in NEMS-SET (nano-electro-mechanical shuttling - single-electron-tunneling) regime. Besides, the spin-flip cotunneling mechanism (Fig. 3.4) paves the way to spin shuttling in the Kondo regime [220].

Three basic configurations which may be used in electron shuttling by means of single and double quantum dots are presented in Fig. 8.1. We define these configura-
tions as "shuttle" (a), "pendulum" (b) and "turnstile" (c). Shuttling regime implies that the lead-dot tunneling is possible only when the shuttle "moors" to the bank, and dwells near it for a certain time $\tau_d$, while the tunneling contact is broken during the transportation time $T/2 - \tau_d$ where $T/2$ is a half period of the shuttling cycle.

In various experimental situations the contact may vary from sudden to adiabatic. In case of sudden contact the perturbation of the system due to switching on the tunneling channel results in various shake effects, including multielectron ionization of the dot, provided the electric field inducing mechanical motion is strong enough. This regime is practically beyond the reach of reliable theoretical description. In the opposite "smooth" regime the contact occurs adiabatically without inelastic excitations of the internal degrees of freedom of the shuttle and the electrodes. All intermediate regimes are also realizable. It is evident that the dynamical symmetries, which are in the center of our interest, manifest themselves in the adiabatic or nearly adiabatic regime, and we will consider below only the limit of smooth single or double electron shuttling (tunneling or cotunneling). Besides, from the point of view of time-dependent dynamical symmetries the complete interruption of the tunneling contact is not a decisive point, and all principal effects related to the time evolution of the dot spectrum may be observed if the tunneling rate changes from strong to exponentially weak coupling during the shuttling period but does not breaks completely. Having this in mind, we consider here the DQD and TQD in side geometries with moving side dot [Fig. 8.2(a,b)]. These geometries have been exploited above in the study of dephasing and decoherence in Kondo tunneling (Section 7.2), where the stochastic motion of the side dot have been considered. Here we will study the slow periodic motion regime and its influence on the Kondo effect.