Aharonov-Bohm Effect on Double Quantum Dot in AC Field

Miyu Umebayashi and Mikio Eto*

Faculty of Science and Technology, Keio University, Yokohama, Japan

*eto@rk.phys.keio.ac.jp

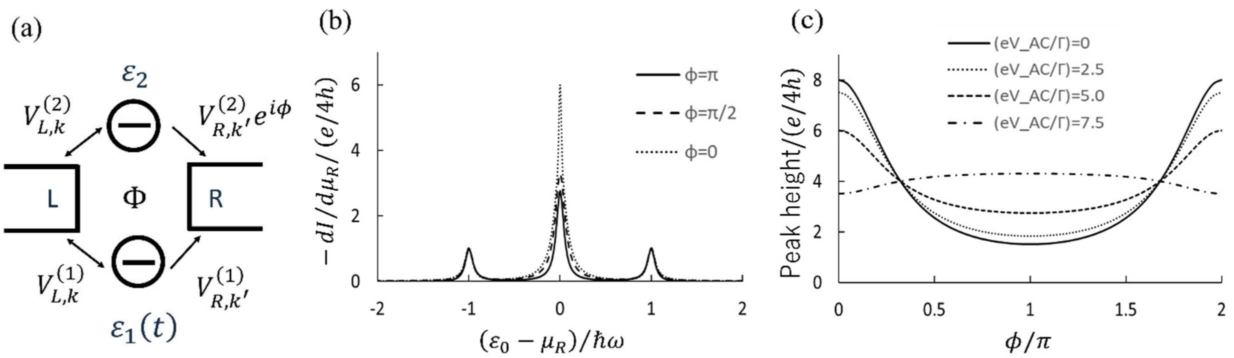
Photon-assisted tunneling (PAT) through a quantum dot (QD) has been intensively studied by both experimental and theoretical works [1-3]. A quantum dot irradiated by the AC field is modelled by the time-dependent energy level, $\varepsilon(t) = F_{\mathrm{AC}}(t) = \varepsilon_0 + eV_{\mathrm{AC}}\cos\omega t$, which results in "polariton states" of the energy levels, $\varepsilon_n = \varepsilon_0 + n\hbar\omega$ $(n = 0, \pm1, \pm2, \cdots)$, with the weight of Bessel functions $J_n(eV_{\mathrm{AC}}/\hbar\omega)$. This Tien-Gordon theory [4] explains the experimental results for the PAT in single-molecule transistors [5]. In this work, we formulate the PAT by solving the time-dependent Schrödinger equation exactly and calculate the transport through double quantum dot (DQD) in parallel to examine the Aharonov-Bohm (AB) effect in the AC field.

First, we formulate the PAT through a single QD with energy level $\varepsilon(t) = F_{\mathrm{AC}}(t)$, connected to two leads (L, R) by the tunnel Hamiltonian H_{T}. The tunnel couplings give rise to the level broadenings Γ_L and Γ_R $(\Gamma = \Gamma_L + \Gamma_R)$. The S-matrix is obtained to the infinite order in H_{T} using the scattering theory, assuming that the time scale $t \sim \hbar/\Gamma$ is much larger than the period of AC field $1/\omega$ $(\Gamma \ll \hbar\omega)$. We evaluate the electric current between the leads, which yields the differential conductance with respect to the Fermi level in lead R

$$-\frac{dI}{d\mu_R} = \frac{e}{h}\frac{4\Gamma_L\Gamma_R}{(\Gamma_L+\Gamma_R)^2}\sum_n \left[J_n\left(\frac{eV_{\mathrm{AC}}}{\hbar\omega}\right)\right]^2 \frac{(\Gamma/2)^2}{(\varepsilon_0 + n\hbar\omega - \mu_R)^2 + (\Gamma/2)^2}$$

at low temperatures of $k_B T \ll \Gamma$. This indicates the resonant tunneling through polariton states in accordance with the Tien-Gordon theory. This formula is also derived using the Keldysh Green's function method if the current is time-averaged over $1/\omega$ [6].

Second, we apply the scattering theory to the DQD with energy levels $\varepsilon_1(t) = F_{\mathrm{AC}}(t)$ in one QD and $\varepsilon_2 = \varepsilon_0$ in the other, as depicted in Fig. (a). The tunnel coupling to lead α is characterized by $\Gamma_{ij}^{\alpha} = 2\pi\sum_k V_{\alpha,k}^{(i)}V_{\alpha,k}^{(j)}\delta(\varepsilon-\varepsilon_k)$ at $\varepsilon \approx \varepsilon_{\mathrm{F}}$, with $V_{\alpha,k}^{(j)}$ being the tunnel amplitude between QD j and state k (energy ε_k) in lead α. Γ_{jj}^{α} is the level broadening in QD j, whereas the coherence between the QDs is determined by $p_\alpha = \Gamma_{12}^{\alpha}/\sqrt{\Gamma_{11}^{\alpha}\Gamma_{22}^{\alpha}}$ $(0 \le p_\alpha \le 1)$. The magnetic flux Φ is considered by the AB phase $\phi = 2\pi\,\Phi/(h/e)$. We formulate the conductance exactly and obtain its analytical expression to the second order in $eV_{\mathrm{AC}}/(2\hbar\omega)$. Figure (b) shows the differential conductance as a function of ε_0 for $\phi = 0$ (dotted line), $\phi = \pi/2$ (broken line), and $\phi = \pi$ (solid line) with $p_L = p_R = 0.9$. We observe subpeaks at $\mu_R = \varepsilon_0 \pm \hbar\omega$, which hardly depend on ϕ, in addition to the main peak at $\mu_R = \varepsilon_0$. The main peak shows the AB oscillation, as seen in Fig. (c) for $eV_{\mathrm{AC}}/\Gamma = 0$, 2.5, 5.0, and 7.5. The amplitude decreases with an increase in V_{AC} owing to the dephasing by the AC field.



[1] T. H. Oosterkamp *et al.*, Nature **395**, 873 (1998). [2] G. Platero and R. Aguado, Phys. Rep. **395**, 1 (2004). [3] S. Kohler, J. Lehmann, and P. Hänggi, Phys. Rep. **406**, 379 (2005). [4] P. K. Tien and J. P. Gordon, Phys. Rev. **129**, 647 (1963). [5] K. Yoshida, K. Shibata, and K. Hirakawa, Phys. Rev. Lett. **115**, 138302 (2015). [6] A.-P. Jauho, N. S. Wingreen, and Y. Meir, Phys. Rev. B **50**, 5528 (1994).