Switching the function of the quantum Otto cycle in non-Markovian dynamics: heat engine, heater and heat pump

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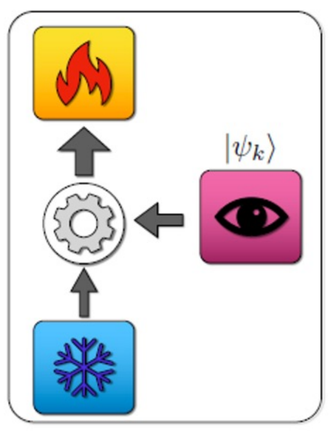
1. Background

- Many quantum heat engines are proposed using quantum resource (e.g. entanglement, quantum measurement)

  (e.g.)Making a refrigerator by measuring entangled two quits.
  [1] L. Buffoli, Phys. Rev. Lett. **122**, 070603 (2019)



- Conventional studies often assume that the system which absorbs and emits heat from the bath follows Markovian dynamics, under the GKSL master equation.
  Markov approximation assumes that the bath dynamics are faster than the system's dynamics.
- A previous study [2] which lets the system follow non-Markovian dynamics shows that there is an attractive interaction between the system and the bath.
  [2] Y. Shirai, K. Hashimoto, R. Tezuka, C. Uchiyama and N. Hatano, Phys. Rev. Research **3**, 023078 (2021).

2. Purpose

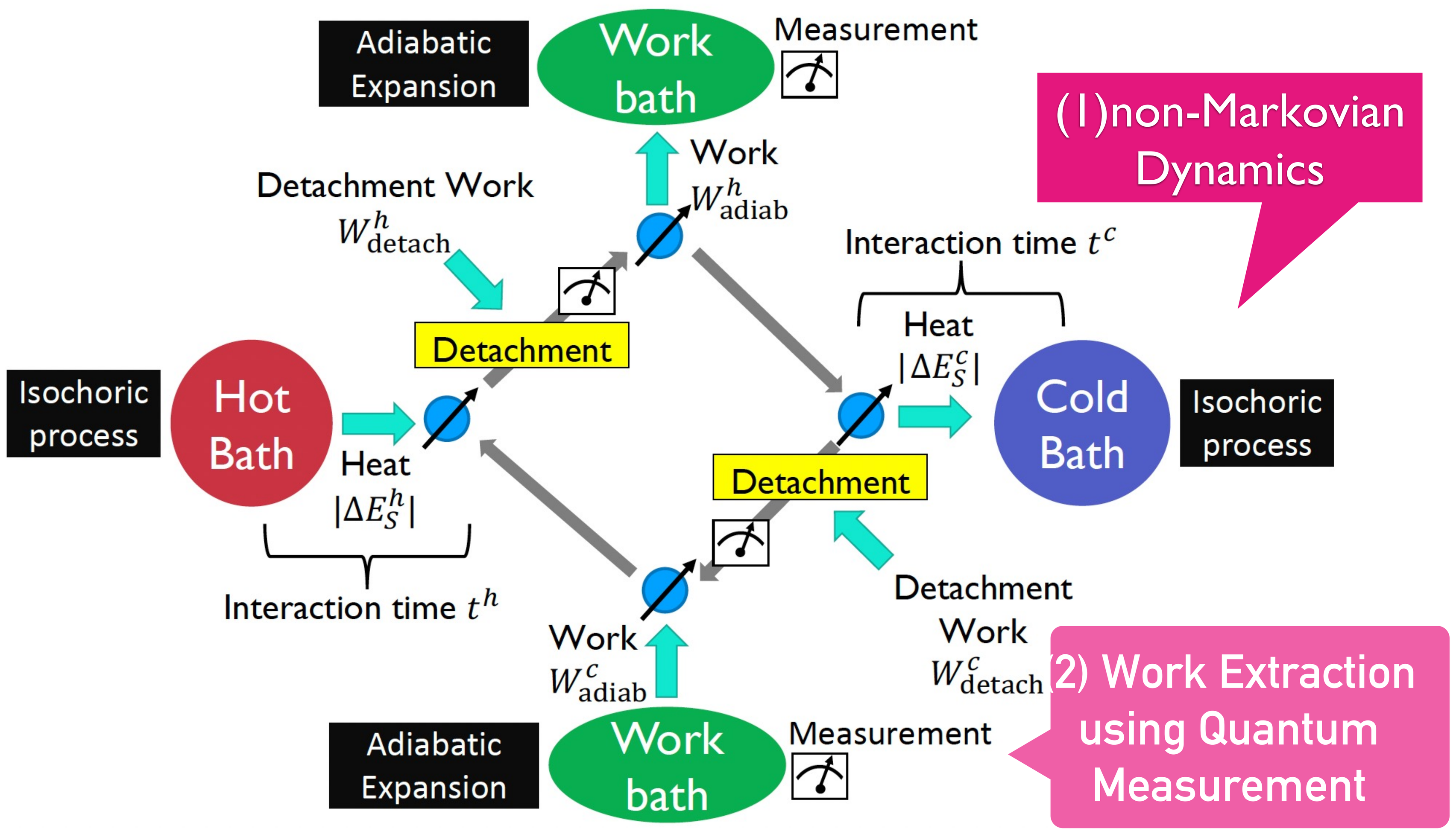
- Revealing essential features in the quantum thermodynamics; features of adiabatic and isochoric processes between microscopic and macroscopic systems.
- Describing the heat absorption and emission processes between microscopic and macroscopic systems in non-Markovian dynamics.
- Modeling the work extraction process from microscopic system to the macroscopic system.

3.Conclusion

- We can extract work from microscopic system to the macroscopic system using the work extraction process with quantum measurement.
- In the non-Markovian dynamics, an attractive force appears between the system and the bath. We calculate the work including the detachment work between the system and the bath.
- The qubit loses energy in this cycle, it has a possibility to cool the target qubit.
- A heater, a heat pump and an engine cycle appear, depending on the qubit's interaction time with the bath.

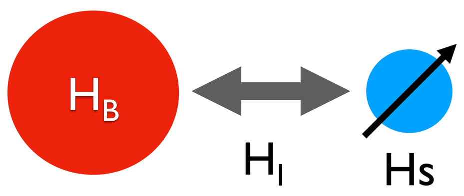
4. Method

Quantum Otto Cycle



1. non-Markovian heat absorption and emission process

■Hamiltonian



$$H^\mu = H_S^\mu + H_B^\mu + H_I^\mu$$

$$H_S^\mu = \frac{\omega_0^\mu(t)}{2}(\sigma_z + 1) \qquad H_B^\mu = \Sigma_k \epsilon_k^\mu b_k^\dagger b_k \qquad H_I^\mu = \sigma_x \otimes \Sigma_k (g_k^\mu b_k^\dagger + g_k^{\mu *} b_k)$$

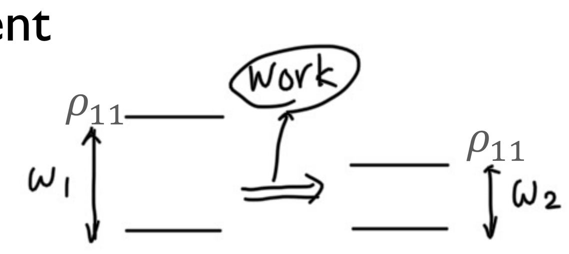
■TCL master equation (up to the second order of H_I)

$$\frac{d}{dt}\rho_S^\mu(t) = -i[H_S^\mu, \rho_S^\mu(t)] - v^2 \int_0^t d\tau Tr_B \left[H_I^\mu, [H_I^\mu(-\tau), \rho_S^\mu(t) \otimes \rho_B^{eq}]\right]$$

[2] Y. Shirai, K. Hashimoto, R. Tezuka, C. Uchiyama and N. Hatano, Phys. Rev. Research **3**, 023078 (2021).

2. Work Extraction with Quantum Measurement

■Hamiltonian



$$H = \omega_1 |1\rangle\langle 1| \otimes |0\rangle\langle 0| \otimes I + (\omega_1 - \omega_2) I \otimes I \otimes |1\rangle\langle 1|$$

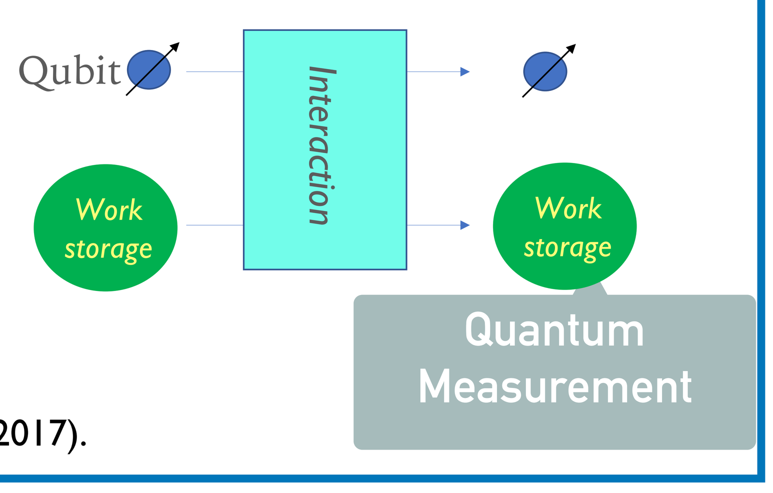
Qubit Clock Work storage

■Work extraction process

$$W(0) = (\rho_{11}|1\rangle\langle 1| + \rho_{00}|0\rangle\langle 0|) \otimes |0\rangle\langle 0| \otimes |0\rangle\langle 0|$$

↓ Unitary transformation U

$$W(t) = \rho_{11}|1\rangle\langle 1| \otimes |1\rangle\langle 1| \otimes |1\rangle\langle 1| + \rho_{00}|0\rangle\langle 0| \otimes |1\rangle\langle 1| \otimes |0\rangle\langle 0|$$



■Extracted work

$$W_1 = Tr[\rho dH] = P_1(\omega_1 - \omega_2)$$

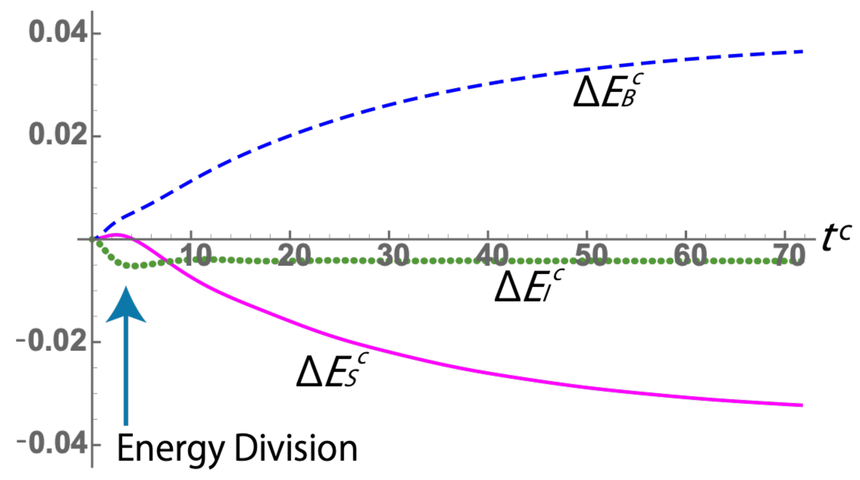
[3]M. Hayashi, H. Tajima, Phys. Rev. A. **95**, 032132 (2017).

5. Results / Consideration

1. Negative expectation value of the interaction energy

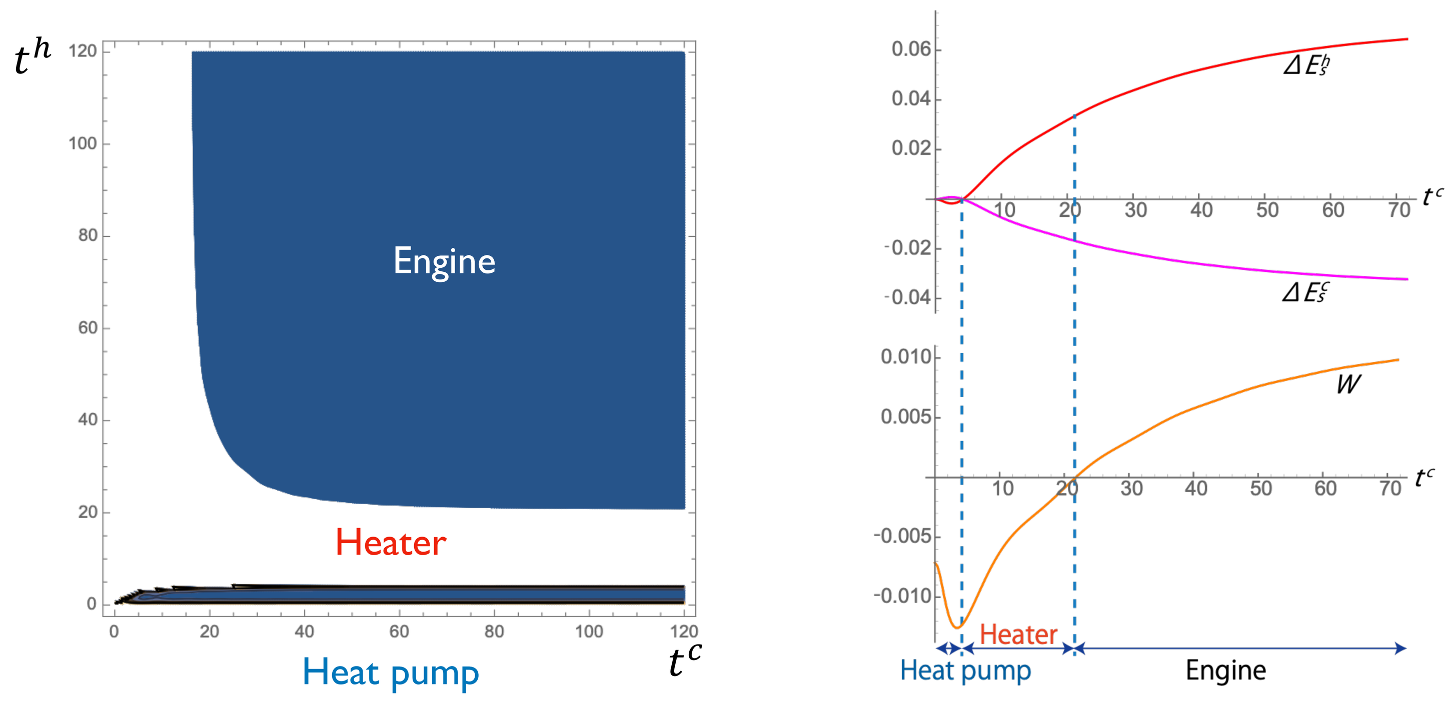
$$\Delta E_S^\mu = \mathrm{Tr}[H_S^\mu \rho(t)] - \mathrm{Tr}[H_S^\mu \rho(0)] = -\omega_0^\mu(\rho_{00}(t) - \rho_{00}(0))$$
$$\Delta E_B^\mu = \omega_0^\mu(\rho_{00}(t) - \rho_{00}(0)) + \int_0^t d\tau[(2\rho_{00}(\tau) - 1)D_1(\tau)\sin(\omega_0\tau) + D_2(\tau)\cos(\omega_0\tau)]$$
$$\Delta E_I^\mu = -\int_0^t d\tau[(2\rho_{00}(\tau) - 1)D_1(\tau)\sin(\omega_0\tau) + D_2(\tau)\cos(\omega_0\tau)]$$

$D_1(\tau)$: Noise term、$D_2(\tau)$: dissipation term



- The qubit's energy change is positive in the short-time region, which means the qubit absorbs heat.
- We need the detachment work between the qubit and the bath because the interaction energy becomes negative

2. Switching among an engine, a heater, and a heat pump
■Depending on the qubit's interaction time with the bath, a heater, a heat pump and an engine cycle appears.
■The sign of the qubit's energy change oscillates in the short-time region, which means the heat absorption and extraction processes appear alternately.



3. Cooling the target qubit

Total qubit's energy is negative in the heat pump region (i)
$\Delta E_S = \Delta E_S^c + \Delta E_S^h \leq 0$

→Possibility to cool the qubit by controlling the interaction time