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Quantum thermal transistor

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We demonstrate that a thermal transistor can be made up with a quantum system of 3 interacting sub-systems, coupled to a thermal reservoir each. This thermal transistor is analogous to an electronic bipolar one with the ability to control the thermal currents at the collector and at the emitter with the imposed thermal current at the base. This is achieved determining the heat fluxes by means of the strong-coupling formalism. For the case of 3 interacting spins, in which one of them is coupled to the other 2, that are not directly coupled, it is shown that high amplification can be obtained in a wide range of energy parameters and temperatures. The proposed quantum transistor could, in principle, be used to develop devices such as a thermal modulator and a thermal amplifier in nano systems.

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Managing and harvesting wasted heat in energy processes is becoming a big issue due to the limited energy resources and to the constraints of global warming. Heat can be transported by fluids and radiation, as well as guided in good conductors or devices, such as heat pipes. However, there exist no device that can manage the switching of heat amplification, as is the case in electricity.

In the XXth century, electricity management and its use for logical operations have been realized through the development of two components: the diode [1] and the transistor [2]. By analogy, one can, of course, envisage developing similar thermal devices that could make easier the thermal control in a passive way, without an external management. Thus, one of the goals of recent researches in thermal science has been focused on thermal rectifiers, i.e. components which exhibit an asymmetric flux when the temperatures at their ends are inverted. Thermal rectifiers have been designed for phononic [3–13] and electronic [12, 14] thermal transport, which has led to the conception and modeling of thermal transistors [15, 16]. In the framework of thermal radiation, rectifiers have been the subject of numerous theoretical works, both in near-field [17–19] and far-field [20–24]. The most efficient of these devices have involved phase change materials, such as thermochrome [25] materials like VO₂[26, 27]. This has led to the design of radiative thermal transistors based on phase change materials too[28, 29].

The last two decades have also seen the emergence of individual quantum systems, such as classical atoms [30, 31] or artificial ones, as is the case of quantum dots [32, 33], which have been proposed to develop photon rectifiers [34–36] and transistor [37, 38]. Moreover, given that quantum systems are always coupled to their environment, in particular to a thermal bath, the question of how heat is transferred through a set of quantum systems in interaction, naturally arises [39, 40] and have led to several studies reporting thermal rectification [41–44].

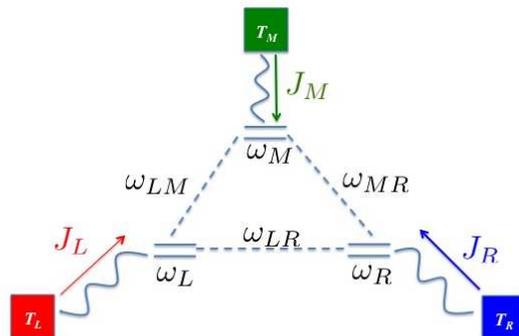


FIG. 1: Quantum system made up of 3 TLS coupled with each other and connected to a thermal bath.

The goal of this letter is to demonstrate that a quantum system composed of 3 two-level sub-systems (TLS) can be used as a thermal transistor equivalent to a bipolar electronic one with three entries: the base, the emitter, and the collector. Contrary to previous studies [45], each of the TLS is here connected to a thermal bath. It is shown that a thermal current imposed at the base equivalent, can drive the currents at the two other entries of the system. More importantly, we also show these currents perturbations imposed at the system entry can be amplified in such a device.

The system under consideration consists of 3 TLS coupled with each other, each of them being connected to a thermal bath, as is schematically described in Fig. 1. The three TLS are labelled with the letters L (left), M (medium) and R (right), as well as the temperature of the thermal bath they are related to. We generalized the strong-coupling formalism developed by Werlang et al. [43] to the system considered here. Indeed, strong-coupling formalism is required to catch thermal effects, such as thermal rectification that appear in a quantum system composed by two TLS [43]. Thermal transistor effects, that we want to emphasize in our study, are close

to rectification effects and we therefore chose to follow the same approach. TLS, in our present case are interacting spins that can be in the up state \uparrow or in the down one \downarrow . The Hamiltonian of the system is (in $\hbar = 1$ units)

$$H_S = \sum_{J=L,M,R} \frac{\omega_J}{2} \sigma_z^J + \sum_{J=L,M,R} \frac{\omega_{JJ+1}}{2} \sigma_z^J \sigma_z^{J+1} \quad (1)$$

where σ_z^J ($J = L, M, R$) is the Pauli matrix z , whose eigenstates for the system J are the states \uparrow and \downarrow . ω_J denotes the energy difference between the two spin states, whereas ω_{JJ+1} stands for the interaction between the spin coupled to the bath J and the spin coupled to the bath $J + 1$. H_S eigenstates are given by the tensorial product of the individual TLS states, so that we have 8 eigenstates labelled as $|1\rangle = |\uparrow\uparrow\uparrow\rangle$, $|2\rangle = |\uparrow\uparrow\downarrow\rangle$, $|3\rangle = |\uparrow\downarrow\uparrow\rangle$, $|4\rangle = |\uparrow\downarrow\downarrow\rangle$, $|5\rangle = |\downarrow\uparrow\uparrow\rangle$, $|6\rangle = |\downarrow\uparrow\downarrow\rangle$, $|7\rangle = |\downarrow\downarrow\uparrow\rangle$ and $|8\rangle = |\downarrow\downarrow\downarrow\rangle$. The coupling between the TLS and the thermal bath constituted of harmonic oscillators [46] is based on the spin-boson model in the x component $H_{TLS-Bath}^J = \sigma_x^J \sum_k g_k (a_k^J a_k^{J\dagger})$. The three reservoirs J have their hamiltonians equal to $H_{Bath}^J = \sum_k \omega_k a_k^J a_k^J$. This modelling implies that bathes can flip one spin at a time. This means that there are 12 authorized transitions. The left bath (L) induces the transitions $1 \leftrightarrow 5$, $2 \leftrightarrow 6$, $3 \leftrightarrow 7$ and $4 \leftrightarrow 8$, the middle one (M) drives the transitions $1 \leftrightarrow 3$, $2 \leftrightarrow 4$, $5 \leftrightarrow 7$ and $6 \leftrightarrow 8$. The right bath (R) triggers the transitions $1 \leftrightarrow 2$, $3 \leftrightarrow 4$, $5 \leftrightarrow 6$ and $7 \leftrightarrow 8$. All other transitions flipping more than one spin are forbidden.

The system state is described by a density matrix (8×8), which obeys a master equation driving its evolution. In the Born-Markov approximation, this master equation reads

$$\frac{d\rho}{dt} = -i[H_S, \rho] + \mathcal{L}_L[\rho] + \mathcal{L}_M[\rho] + \mathcal{L}_R[\rho]. \quad (2)$$

As in [43, 48], The Lindbladians $\mathcal{L}_J[\rho]$ are written for a ohmic bath according to classical textbooks [47, 48], so that we take expression (4) of [43]. We now solve the master equation in steady state ($\dot{\rho} = 0$). Averaging the master equation by multiplying by ρ and taking the trace, one defines $Tr(\rho \mathcal{L}_J[\rho]) = J_J$, the heat current injected by the bath J into the system. Noting also that the density matrix is diagonal in this situation, the sum of the three thermal currents is zero, in accordance to the conservation of energy

$$J_L + J_M + J_R = 0. \quad (3)$$

The master equation is a system of 8 equations on the diagonal elements ρ_{ii} . If we introduce the net decaying rate from state $|i\rangle$ to the state $|j\rangle$ due to the coupling with bath J : $\Gamma_{ij}^J = \omega_{ij} [(1 + n_\omega^J) \rho_{ii} - n_\omega^J \rho_{jj}] = -\Gamma_{ji}^J$, the master equation yields

$$\dot{\rho}_{11} = 0 = \Gamma_{51}^L + \Gamma_{31}^M + \Gamma_{21}^R,$$

$$\begin{aligned} \dot{\rho}_{22} &= 0 = \Gamma_{62}^L + \Gamma_{42}^M + \Gamma_{12}^R, \\ \dot{\rho}_{33} &= 0 = \Gamma_{73}^L + \Gamma_{13}^M + \Gamma_{43}^R, \\ \dot{\rho}_{44} &= 0 = \Gamma_{84}^L + \Gamma_{24}^M + \Gamma_{34}^R, \\ \dot{\rho}_{55} &= 0 = \Gamma_{15}^L + \Gamma_{75}^M + \Gamma_{65}^R, \\ \dot{\rho}_{66} &= 0 = \Gamma_{26}^L + \Gamma_{86}^M + \Gamma_{56}^R, \\ \dot{\rho}_{77} &= 0 = \Gamma_{37}^L + \Gamma_{57}^M + \Gamma_{87}^R, \\ \dot{\rho}_{88} &= 0 = \Gamma_{48}^L + \Gamma_{68}^M + \Gamma_{78}^R. \end{aligned} \quad (4)$$

These 8 equations are not independent since their sum is 0. In order to solve the system for the 8 ρ_{ii} , one adds the condition $Tr\rho = \sum_i \rho_{ii} = 1$. This system can be easily solved by any formal calculation software and its resolution gives access to all state occupation probabilities as well as to the currents J_J .

Let us now explicit what we call a thermal transistor, by making the analogy with an electronic one in which the current at the base controls the currents at the collector and at the emitter. The gain of the transistor is defined as the ratio of the current change at the collector or the emitter to the current variation applied at the base. Here, our goal is to show that it is similarly possible to control J_L or J_R by slightly changing J_M . We consider that the left and right TLS are both connected to thermal bathes, whose respective temperatures T_L and T_R are fixed. The third bath at temperature T_M control the fluxes J_L and J_R with the help of a current J_M injected in the system. If a small change in J_M makes a large change in J_L or J_R i.e if $|\alpha_{L,R}| = |\partial J_{L,R} / \partial J_M| > 1$, then a thermal transistor effect will be observed in the same way as a large collector-current change is present by applying a small electrical current at the base of a bipolar transistor. Note that this kind of amplification corresponds to an AC current amplification. This is the thermal current variation that is amplified and not the whole current itself.

We now focus on the conditions for which such a thermal transistor effect can be observed: a transistor will be characterized by the three TLS energies, the three coupling constants and the end temperatures T_L and T_R . The last temperature T_M , that is taken here between the two end temperatures, controls the transistor properties and is directly related to the current J_M through the energy conservation condition (3). A fine parametric study of the system solutions for the density matrix is difficult, due to the large number of parameters involved. To reduce this number and to focus on the physics involved, we restrict our analysis on a simple case for which the three TLS energies are set to 0 (i.e. interacting spins in the absence of magnetic fields), the coupling between the left and right bath is also set to $\omega_{RL} = 0$, whereas the two other couplings are equal $\omega_{LM} = \omega_{MR} = \Delta$. The operating temperature T_L is taken so that $e^{-\Delta/T_L} \ll 1$ ($T_L/\Delta \lesssim 4$) whereas $e^{-\Delta/T_R} \ll e^{-\Delta/T_L}$ ($T_R/\Delta \lesssim 8$).

Under these conditions, system states are degenerated two by two: $|1\rangle = |8\rangle$, $|2\rangle = |7\rangle$, $|3\rangle = |6\rangle$ and $|4\rangle = |5\rangle$.

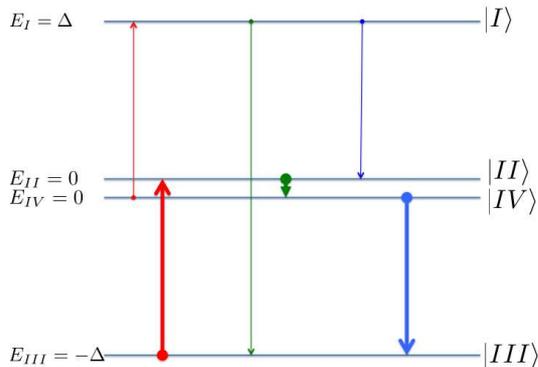


FIG. 2: Energy levels for $\omega_L = \omega_M = \omega_R = 0$, $\omega_{RL} = 0$ and $\omega_{LM} = \omega_{MR} = \Delta$. There are four states ($|I\rangle$, $|II\rangle$, $|III\rangle$ and $|IV\rangle$) but three energy levels since $E_{II} = E_{IV} = 0$. The arrows indicates the net decaying rate between the states due do bath L (Red), bath M (Green) and bath R (Blue) for $T_L = 0.2\Delta$, $T_R = 0.02\Delta$ and $T_M = 0.1\Delta$. The arrow direction give the sign of the decaying rate, which give a positive Γ_{JK} when the arrow direction is from J to K . The larger is the arrow thickness, the larger is the absolute value of the decaying rate.

Moreover, $E_1 = E_8 = \Delta$, $E_2 = E_4 = E_5 = E_7 = 0$ and $E_3 = E_6 = -\Delta$, so that there are only three energy levels (Fig. 2). We rename the states $|1\rangle$ and $|8\rangle$ as $|I\rangle$, $|2\rangle$ and $|7\rangle$ as $|II\rangle$, $|3\rangle$ and $|6\rangle$ as $|III\rangle$, $|4\rangle$ and $|5\rangle$ as $|IV\rangle$. We introduce the new density matrix elements, now reduced to 4, $\rho_I = \rho_{11} + \rho_{88}$, $\rho_{II} = \rho_{22} + \rho_{77}$, $\rho_{III} = \rho_{33} + \rho_{66}$ and $\rho_{IV} = \rho_{44} + \rho_{55}$. In a similar way, net decaying rates between these states are introduced and the three currents simply read

$$\begin{aligned} J_L &= -\Delta [\Gamma_{I-IV}^L + \Gamma_{II-III}^L] \\ J_M &= -2\Delta\Gamma_{I-III}^M + 0 \times \Gamma_{II-IV}^M \\ J_R &= -\Delta [\Gamma_{I-II}^R + \Gamma_{IV-III}^R] \end{aligned} \quad (5)$$

Note that the thermal currents are in units where $\hbar = k_b = 1$. Transitions between the different states are illustrated in Fig. 2, for $T_L/\Delta = 0.2$, $T_R/\Delta = 0.02$ and $T_M/\Delta = 0.1$. The arrow directions shows the transition direction whereas its width depends on the decay time. We see that energy exchanges are mainly dominated by the $III - II$ and $IV - III$ transitions. One therefore expects J_R and J_L to be larger than J_M . This is illustrated in Fig. 3, where J_L , J_M and J_R are represented versus T_M , for $T_L/\Delta = 0.2$ and $T_R/\Delta = 0.02$. The two currents J_L and J_R increase linearly with temperature T_M , at low temperature, and becomes sublinear as T_M approaches T_L . Note that over the whole range, J_M remains lower than J_L and J_R in accordance with what is expected from the analysis of the decay time. Thus, T_M will be controlled changing slightly the current J_M : a tiny change of J_M is therefore able to change significantly the values of J_L and J_R . Moreover, one sees that

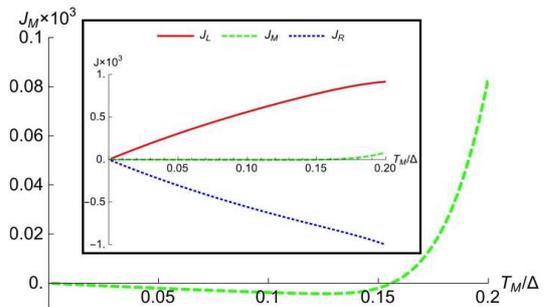


FIG. 3: Inset: thermal currents J_L , J_M and J_R versus T_M for $\omega_L = \omega_M = \omega_R = 0$, $\omega_{RL} = 0$, $\omega_{LM} = \omega_{MR} = \Delta$, $T_L = 0.2\Delta$ and $T_R = 0.02\Delta$. Main figure: thermal current J_M versus T_M .

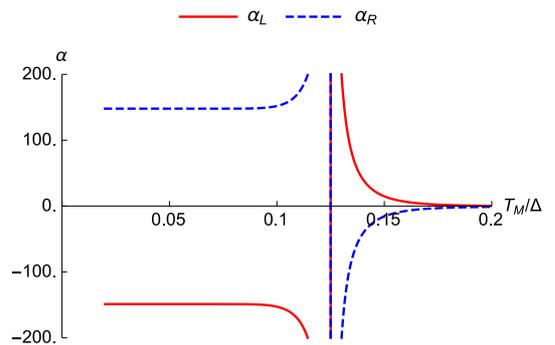


FIG. 4: Amplification factor α_L and α_R as a function of temperature T_M . Calculations were done for $\omega_L = \omega_M = \omega_R = 0$, $\omega_{RL} = 0$, $\omega_{LM} = \omega_{MR} = \Delta$, $T_L = 0.2\Delta$ and $T_R = 0.02\Delta$.

the J_M slope remains larger than the ones of J_L and J_R over a large part of the temperature range. Given the definition of the amplification factor, the comparison of the thermal currents slope is the key element to see if amplification is present.

In Fig. 4, we plot the two amplification coefficients α_L and α_R versus temperature T_M . Note that due to relation (3), one has $\alpha_R + \alpha_L = -1$. We see that at low T_M , α remains much larger than 1. One also note that α diverges for a certain value of the temperature for which J_M has a minimum. This occurs for $T_M \simeq 0.1251\Delta$. In these conditions, a infinitely small change in J_M makes a change in J_L and J_R . Of course, the infinite gain only exists for an infinitely small perturbation. When the perturbation is non zero, the gain will remain finite. As T_M is closer to T_L , the amplification factor drastically decreases to reach values below 1, i.e a regime where we cannot talk anymore of a transistor effet ($\alpha_L(T_M = T_L) = 0.26$). Note also that, in between, there exist a temperature where $J_M = 0$. This is the temperature for which the bath M is at thermal equilibrium with the system since it does not inject any thermal current in it. At this temperature

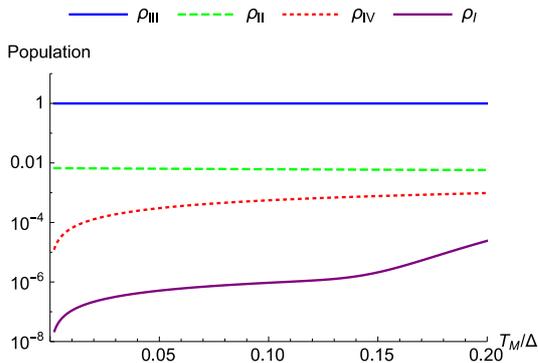


FIG. 5: Population variations with the temperature T_M for $\omega_L = \omega_M = \omega_R = 0$, $\omega_{RL} = 0$, $\omega_{LM} = \omega_{MR} = \Delta$, $T_L = 0.2\Delta$ and $T_R = 0.02\Delta$.

($T_M \simeq 0.156\Delta$), $J_L = -J_R = 7.97 \times 10^{-4}$. Amplification still occurs since $\alpha_L = 8.88$ and $\alpha_R = -9.88$.

All these observations can be explained by examining carefully populations and currents expressions. In the present case, if we limit the calculation to first order of approximations on $e^{-\Delta/T_L}$ and $e^{-\Delta/T_M}$, one can roughly estimate the populations by

$$\rho_I \simeq \frac{e^{-2\Delta/T_M}}{2} + \frac{T_M}{4\Delta + 8T_M} e^{-2\Delta/T_L}, \quad (6)$$

$$\rho_{II} \simeq \frac{\Delta + T_M}{\Delta + 2T_M} e^{-\Delta/T_L}, \quad (7)$$

$$\rho_{III} \simeq 1 - e^{-\Delta/T_L}, \quad (8)$$

$$\rho_{IV} \simeq \frac{T_M}{\Delta + 2T_M} e^{-\Delta/T_L}. \quad (9)$$

As shown in Fig. 5, ρ_{III} remains very close to 1 and ρ_{II} to 10^{-2} . ρ_I and ρ_{IV} keep much lower, but change by one to two orders of magnitude with temperature. Note that the sum of (6-9) is not 1, but we have verified that the error on ρ 's is less than 1% over the temperature range.

We now explicitly correlate the three thermal currents with temperature. Taking the same approximation as above, they read

$$J_L \simeq \frac{\Delta^2 T_M e^{-\Delta/T_L}}{\Delta + 2T_M}, \quad (10)$$

$$J_M \simeq \Delta^2 \left[2e^{-2\Delta/T_M} - \frac{T_M}{\Delta + 2T_M} e^{-2\Delta/T_L} \right], \quad (11)$$

$$J_R \simeq -\frac{\Delta^2 T_M e^{-\Delta/T_L}}{\Delta + 2T_M}. \quad (12)$$

Note here again that the sum of the three currents is not zero despite of the fact that expressions remain close to the exact solution. The largest error is on J_L and J_R around $T_M = T_L$ where it reaches 5%. These formula retrieve the linear dependance of the thermal currents for small values of T_M . One also note that, when we compare

with (9), J_L and J_R are driven by ρ_{IV} , i.e the state population at the intermediate energy ($E_{IV} = 0$). Looking at the authorized transitions, one expects that J_M is driven by the population of the most energetic state, i.e ρ_I . The main difference between ρ_{IV} and ρ_I is the temperature dependance, which is linear in one case and exponential ($e^{-2\Delta/T}$) in the other case. The result is that even when T_M is close to T_L , ρ_I remains low. Therefore, J_M keeps low values in the whole temperature range due to the low values of ρ_I . If we look more carefully at J_M , one notices that it is the sum of two terms. The first one is roughly linear on T_M . It is similar to the one that appears in ρ_{IV} . J_M depends on the population of state IV , which also influences the population of state I with the transition $|IV\rangle - |I\rangle$. The increase of ρ_{IV} with T_M makes easier the $|IV\rangle - |I\rangle$ transition, and raises ρ_I . This increases the decaying of state I through the $I - III$ transition. This corresponds to the second term in J_M which is negative and decreases as T_M increases. This can be seen as a negative differential resistance since a decreasing of J_M (cooling in M) corresponds to an increase of the temperature T_M . In this temperature range, it can easily be shown that the amplification factor $|\alpha_L| \approx |\alpha_R| \approx e^{\Delta/T_L}$. A second term in J_M , is the classical $e^{-\Delta/T_M}$ Boltzmann factor term, which makes the population of state I increase with T_M . J_M is a trade off between these two terms. At low temperature, the linear term is predominant. As T_M increases, the term $e^{-\Delta/T_M}$ takes over. As a consequence, there is a point where ρ_I increasing reverses the $I - IV$ transition, so that the $I - III$ transition competes with both $I - IV$ and $I - II$ transitions. $I - III$ is then reversed. With these two terms competing, there is a temperature for which J_M reaches a minimum and a second temperature where $J_M = 0$, as already described. These temperatures obey to the transcendental equations in T_M , $\partial J_M / \partial T_M = 0$ and $J_M = 0$ respectively.

Finally, one can summarize the conditions needed for the system to undergo a thermal transistor effect. Two baths (here L and R) induces transitions between 2 highly separated states with an intermediate energy level, whereas the third one (M) makes only a transition between the two extremes. This will first make J_M much smaller than J_L and J_R , and second, it will set a competition between a direct decay of the highest level to the ground level and a decay via the intermediate one. This competition between the two terms makes the thermal dependance of J_M with T_M slow enough to obtain a high amplification. As the temperature increases, the highest state I is more and more populated and the $I - III$ transition is finally favored over the others. J_M dependance on the temperature will be higher and the amplification disappears.

In conclusion, we have shown that it is possible to make a thermal transistor with 3 coupled TLS linked to 3 different thermal baths. One TLS is coupled to the 2 others, whereas the 2 other are not directly coupled. The TLS

related to the two other plays the same role as the base in a bipolar transistor, while the two other TLS can be seen as the emitter and the collector. We found a temperature regime where a thermal current variation imposed at the base generates an amplified variation at the emitter and the collector. This regime is typically such that temperature corresponds to an energy one order of magnitude smaller than the coupling energy between the TLS. This means that a transistor effect will be observed at ambient temperature for a coupling between the TLS with a typical frequency in the visible. With this kind of thermal transistor one can expect to modulate or amplify thermal fluxes in nanostructures made up of elementary quantum objects.

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