Thermalization process in bare and dressed coordinate approaches

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We consider a particle in the approximation of a harmonic oscillator, coupled linearly to a field modeling an environment. The field is described by an infinite set of harmonic oscillators, and the system (particle–field) is considered in a cavity at thermal equilibrium. We employ the notions of bare and dressed coordinates to study the time evolution of the occupation number. With dressed coordinates no renormalization procedure is required, leading directly to a finite result. In particular, for a large time, the occupation number of the particle becomes independent of its initial value. So we have a Markovian process, describing the particle thermalization with the environment.

A thermalization process occurs in some cases for a system of material particles coupled to an environment, in the sense that after an infinitely long time, the matter particles lose the memory of their initial states. This study is, not easy from a theoretical point of view, due to the complex non–linear character of the interactions between the matter particles and the environment. To get over these difficulties, linearized models have been adopted. An account on the subject of the evolution of quantum systems on general grounds can be found in [1, 2, 3, 4, 5, 6]. Besides, the main analytical method used to treat these systems at zero or finite temperature is, except for a few special cases, perturbation theory. In this framework, the perturbative approach is carried out by means of the introduction of bare, non–interacting objects (fields, to which are associated bare quanta), the interaction being introduced order by order in powers of the coupling constant.

In spite of the remarkable achievements of the perturbative methods, however, there are situations where they cannot be employed, or are of little use. These cases have led to attempts to improve non-perturbative analytical methods, in particular, where strong effective couplings are involved. Among these trials there are methods that perform resummations of perturbative series, even if they are divergent, which amounts in some cases to extending the weak-coupling regime to a strong-coupling domain. One of these methods is the Borel resummation of perturbative series [7, 8, 9, 10, 11, 12].

In this paper we follow a different non-perturbative approach: we investigate a simplified linear version of a particle–field or particle–environment system, where the particle, taken in the harmonic approximation, is coupled to the reservoir, modeled by independent harmonic oscillators [2, 3, 4]. We will employ, in particular, dressed states and renormalized coordinates. Using this method non-perturbative treatments can be considered for both weak and strong couplings. A linear model permits a better understanding of the need for non-perturbative analytical treatments of coupled systems, which is the basic problem underlying the idea of a dressed quantum mechanical system. Of course, the use of such an approach to a realistic non-linear system is an extremely hard task, while the linear model provides a good compromise between physical reality and mathematical reliability. The whole system is supposed to reside inside a spherical cavity of radius R in thermal equilibrium at temperature $T = \beta^{-1}$. In other words, we consider the spatially regularized theory (finite R) at finite temperature. The free space case is obtained by suppressing the
regulator, \((R \to \infty)\). For a detailed comparison between this procedure and the one considering an \textit{a priori} unbounded space, see [13].

I. THE MODEL

Let us start by considering a particle approximated by a harmonic oscillator, having bare frequency \(\omega_0\), linearly coupled to a set of \(N\) other harmonic oscillators, with frequencies \(\omega_k, k = 1, 2, \ldots, N\). The Hamiltonian for such a system is written in the form,

\[
H = \frac{1}{2} \left[ p_k^2 + \omega_0^2 q_0^2 + \sum_{k=1}^{N} \left( p_k^2 + \omega_k^2 q_k^2 \right) \right] - q_0 \sum_{k=1}^{N} c_k q_k,
\]

leading to the following equations of motion,

\[
\ddot{q}_0 + \omega_0^2 q_0 = \sum_{i=1}^{N} c_i q_i(t) \tag{2}
\]

\[
\ddot{q}_i + \omega_i^2 q_i = \sum_{k=1}^{N} c_k q_k(t). \tag{3}
\]

In the limit \(N \to \infty\), we recover our case of the particle coupled to the environment, after defining divergent quantities, in a manner analogous to mass renormalization in field theories. A Hamiltonian of the type (1) has been largely used in the literature, in particular to study the quantum Brownian motion with the path-integral formalism [1, 2]. It has also been employed to investigate the linear coupling of a particle to the scalar potential [13, 14, 15, 16, 17].

The Hamiltonian (1) is transformed to principal axis by means of a point transformation,

\[
q_\mu = \sum_{r=0}^{N} t_\mu^r Q_r, \quad p_\mu = \sum_{r=0}^{N} t_\mu^r P_r;
\]

\[
\mu = (0, \{k\}), \quad k = 1, 2, \ldots, N; \quad r = 0, \ldots, N,
\]

performed by an orthonormal matrix \(T = (t_\mu^r)\). The subscripts \(\mu = 0\) and \(\mu = k\) refer respectively to the particle and the harmonic modes of the reservoir and \(r\) refers to the normal modes. In terms of normal momenta and coordinates, the transformed Hamiltonian reads

\[
H = \frac{1}{2} \sum_{r=0}^{N} (P_r^2 + \Omega_r^2 Q_r^2), \tag{5}
\]

where the \(\Omega_r\)'s are the normal frequencies corresponding to the collective stable oscillation modes of the coupled system. Using the coordinate transformation (1) in the equations of motion and explicitly making use of the normalization of the matrix \((t_\mu^r)\), \(\sum_{\mu=0}^{N}(t_\mu^r)^2 = 1\), we get

\[
t_k^r = \frac{c_k}{\omega_k^2 - \Omega_r^2} t_0^r, \quad t_0^r = \left[ 1 + \sum_{k=1}^{N} \frac{c_k^2}{(\omega_k^2 - \Omega_r^2)^2} \right]^{-\frac{1}{2}}, \tag{6}
\]

with the condition

\[
\omega_0^2 - \Omega_r^2 = \sum_{k=1}^{N} \frac{c_k^2}{\omega_k^2 - \Omega_r^2}. \tag{7}
\]

We take \(c_k = \eta(\omega_k)^u\), where \(\eta\) is a constant independent of \(k\). In this case the environment is classified according to \(u > 1\), \(u = 1\), or \(u < 1\), respectively as supraohmic, ohmic or subohmic. This terminology has been used in studies of the quantum Brownian motion and of dissipative systems [2, 3, 4, 5, 6, 7]. For a subohmic environment the sum in Eq. (7) is convergent in the limit \(N \to \infty\) and the frequency \(\omega_0\) is well defined. For ohmic and supraohmic environments, this sum diverges for \(N \to \infty\). This makes the equation meaningless, unless a renormalization procedure is implemented. From now on we restrict ourselves to an ohmic system. In this case, Eq. (7) is written in the form

\[
\omega_0^2 - \delta \omega^2 - \Omega_r^2 = \eta^2 \Omega_r^2 \sum_{k=1}^{N} \frac{1}{\omega_k^2 - \Omega_r^2}, \tag{8}
\]
where we have defined the counterterm

\[ \delta \omega^2 = N \eta^2. \tag{9} \]

There are \( N + 1 \) solutions of \( \Omega_r \), corresponding to the \( N + 1 \) normal collective modes. Let us for a moment suppress the index \( r \) of \( \Omega^2_r \). If \( \omega^2_0 > \delta \omega^2 \), all possible solutions for \( \Omega^2 \) are positive, physically meaning that the system oscillates harmonically in all its modes. If \( \omega^2_0 < \delta \omega^2 \), then a single negative solution exists. In order to prove this let us define the function

\[ I(\Omega^2) = \omega^2_0 - \delta \omega^2 - \Omega^2 - \eta^2 \Omega^2 \sum_{k=1}^{N} \frac{1}{\omega^2_k - \Omega^2}, \tag{10} \]

so that Eq. (8) becomes \( I(\Omega^2) = 0 \). We find that

\[ I(\Omega^2) \to \infty \text{ as } \Omega^2 \to -\infty \text{ and } I(0) = \omega^2_0 - \delta \omega^2 < 0, \]

in the interval \((-\infty, 0]\). As \( I(\Omega^2) \) is a monotonically decreasing function in this interval, we conclude that \( I(\Omega^2) = 0 \) has a single negative solution in this case. This means that there is a mode whose amplitude grows or decays exponentially, so that no stationary configuration is allowed. Nevertheless, it should be remarked that in a different context, it is precisely this runaway solution that is related to the existence of a bound state in the Lee–Friedrichs model. This solution is considered in the framework of a model to describe qualitatively the existence of bound states in particle physics [18].

Considering the situation where all normal modes are harmonic, which corresponds to the first case above, \( \omega^2_0 > \delta \omega^2 \), we define the renormalized frequency

\[ \bar{\omega}^2 = \omega^2_0 - \delta \omega^2 = \lim_{N \to \infty} (\omega^2_0 - N \eta^2), \tag{11} \]

in terms of which Eq. (8) in the limit \( N \to \infty \) becomes,

\[ \bar{\omega}^2 - \Omega^2 = \eta^2 \sum_{k=1}^{\infty} \frac{\Omega^2}{\omega^2_k - \Omega^2}. \tag{12} \]

In this limit, the above procedure is exactly the analog of the mass renormalization in quantum field theory: the addition of a counterterm \( -\delta \omega^2 \eta^2 \) allows one to compensate the infinity of \( \omega^2_0 \) in such a way as to leave a finite, physically meaningful renormalized frequency \( \bar{\omega} \). This simple renormalization scheme has been introduced earlier [19]. Unless explicitly stated, the limit \( N \to \infty \) is understood in the following.

Let us define a constant \( g \), with dimension of frequency, by

\[ g = \frac{\eta^2}{2 \Delta \omega}, \tag{13} \]

where \( \Delta \omega = \pi c/R \). The environment frequencies \( \omega_k \) are given by,

\[ \omega_k = k \frac{\pi c}{R}, \quad k = 1, 2, \ldots, \tag{14} \]

where \( R \) is the radius of the cavity that contains the whole system. Then, using the identity

\[ \sum_{k=1}^{\infty} \frac{1}{k^2 - u^2} = \frac{1}{2} \left[ \frac{1}{u^2} - \frac{\pi}{u} \cot (\pi u) \right], \tag{15} \]

Eq. (12) can be written in a closed form:

\[ \cot \left( \frac{R \Omega}{c} \right) = \Omega \frac{\pi}{c g} + c \frac{R \bar{\omega}^2}{c \pi g c} \left( 1 - \frac{R \bar{\omega}^2}{c \pi g c} \right). \tag{16} \]

The solutions of the above equation with respect to \( \Omega \) give the spectrum of eigenfrequencies \( \Omega_r \) corresponding to the collective normal modes.
In terms of the physically meaningful quantities $\Omega_r$ and $\bar{\omega}$, the transformation matrix elements turning the particle–field system to the principal axis are obtained. They are

$$t_{0}^{r} = \frac{\eta \Omega_r}{\sqrt{(\Omega_r^2 - \bar{\omega}^2)^2 + \frac{\bar{\omega}^2}{2}(3\Omega_r^2 - \bar{\omega}^2) + \pi^2 g^2 \Omega_r^2}},$$

$$t_{k}^{r} = \frac{\eta \omega_k}{\omega_k^2 - \Omega_r^2} t_{0}^{r}.$$

These matrix elements play a central role in the quantities describing the system.

II. THE THERMALIZATION PROCESS IN BARE COORDINATES

We now consider the thermalization problem using bare coordinates. For the model described by Eq. (1) this problem was addressed in an alternative way in [20] with the canonical Liouville-von Neumann formalism. We consider the initial state described by the density operator,

$$\rho(t = 0) = \rho_0 \otimes \rho_\beta,$$

where $\rho_0$ is the density operator of the particle, that in principle can be in a pure or in a mixed state and $\rho_\beta$ is the density operator of the thermal bath, at a temperature $\beta^{-1}$, that is,

$$\rho_\beta = Z_\beta^{-1} \exp \left[ -\beta \sum_{k=1}^{\infty} \omega_k \left( a_k^\dagger a_k + \frac{1}{2} \right) \right],$$

with $Z_\beta = \prod_{k=1}^{N} z_k^\beta$ being the partition function of the reservoir, and

$$z_k^\beta = \text{Tr}_k \left[ e^{-\beta \omega_k (a_k^\dagger a_k + 1/2)} \right] = \frac{1}{2 \sinh (\beta \omega_k)};$$

The creation and annihilation operators given by

$$a_\mu = \sqrt{\frac{\omega_\mu}{2}} q_\mu + \frac{i}{\sqrt{2 \omega_\mu}} p_\mu,$$

$$a_\mu^\dagger = \sqrt{\frac{\omega_\mu}{2}} q_\mu - \frac{i}{\sqrt{2 \omega_\mu}} p_\mu,$$

where $\omega_\mu = (\bar{\omega}, \omega_k)$. The thermalization problem is addressed by investigating the time evolution of the state $\rho(t)$.

The thermalization problem concerns the time evolution of the initial state to thermal equilibrium. The subsystem corresponding to the particle oscillator is described by an arbitrary density operator $\rho_0$. As we will show, the expectation value of the number operator corresponding to particles will evolve in time to a value that is independent of the initial density operator $\rho_0$, the dependence will be exclusively on the mixed density operator corresponding to the thermal bath.

Our aim is to obtain expressions for the time evolution of the expectation values for the occupation number and in particular for the one corresponding to particles. We will solve the problem in the framework of the Heisenberg picture. It is to be understood that when a quantity appears without the time argument it means that such quantity is evaluated at $t = 0$. The Heisenberg equation of motion for the annihilation operator $a_\mu(t)$ is given by

$$\frac{\partial}{\partial t} a_\mu(t) = i \left[ \hat{H}, a_\mu(t) \right].$$

Due to the linear character of our problem, this equation is solved by writing $a_\mu(t)$ as

$$a_\mu(t) = \sum_{\nu=0}^{\infty} \left( \hat{B}_{\mu\nu}(t) \hat{q}_\nu + B_{\mu\nu}(t) \hat{p}_\nu \right).$$
where all the time dependence is in the c-number functions $B_{\nu\mu}(t)$. Then, Eq. (23) reduces to the following coupled equations for $B_{\nu\mu}(t)$:

$$\ddot{B}_{\nu\mu}(t) + \bar{\omega}^2 B_{\nu\mu}(t) - \sum_{k=1}^{\infty} \eta \omega_k B_{\nu k}(t) = 0,$$

$$\ddot{B}_{\nu k}(t) + \omega_k^2 B_{\nu k}(t) - B_{\nu 0}(t) \sum_{k=1}^{\infty} \eta \omega_k = 0.$$  \hfill (25) (26)

These equations are formally identical to the classical equations of motion, Eqs. (2) and (3), for the bare coordinates $q_\mu$. Then we decouple Eqs. (25) and (26) with the same matrix $\{t^r_\mu\}$ that diagonalizes the Hamiltonian Eq. (1). In an analogous manner, we write $B_{\nu\mu}(t)$ as

$$B_{\nu\mu}(t) = \sum_{r=0}^{\infty} t^r_\nu C^r_\mu(t),$$

such that from Eqs. (25) and (26), we obtain the following equations for the normal-axis functions $C^r_\mu(t)$,

$$\ddot{C}^r_\mu(t) + \Omega_r^2 C^r_\mu(t) = 0,$$

which gives the solution

$$C^r_\mu(t) = a^r_\mu e^{i\Omega_r t} + b^r_\mu e^{-i\Omega_r t}.$$  \hfill (28) \hfill (29)

Then substituting this expression into Eq. (27) we find

$$B_{\nu\mu}(t) = \sum_{r=0}^{\infty} t^r_\nu \left( a^r_\mu e^{i\Omega_r t} + b^r_\mu e^{-i\Omega_r t} \right).$$

The time independent coefficients $a^r_\mu, b^r_\mu$ are determined by the initial conditions at $t = 0$ for $B_{\nu\mu}(t)$ and $\dot{B}_{\nu\mu}(t)$. From Eqs. (21) and (24) we find that these initial conditions are given by

$$B_{\nu\mu} = \frac{i \delta_{\nu\mu}}{\sqrt{2 \bar{\omega}_\mu}},$$

$$\dot{B}_{\nu\mu} = \sqrt{\frac{\bar{\omega}_\mu}{2}} \delta_{\nu\mu}. $$

Using these equations, we obtain for $a^r_\mu$ and $b^r_\mu$,

$$a^r_\mu = \frac{i t^r_\mu}{\sqrt{8 \bar{\omega}_\mu}} \left( 1 - \frac{\bar{\omega}_\mu}{\Omega_r} \right),$$

$$b^r_\mu = \frac{i t^r_\mu}{\sqrt{8 \bar{\omega}_\mu}} \left( 1 + \frac{\bar{\omega}_\mu}{\Omega_r} \right).$$

We write $a_\mu(t)$ and $a^d_\mu(t)$ in terms of $a_\mu$ and $a^d_\mu$ using Eqs. (21), (22) and (24),

$$a_\mu(t) = \sum_{\nu=0}^{\infty} \left( a_{\mu\nu}(t) \hat{a}_\nu + \beta_{\mu\nu}(t) \hat{a}^d_\nu \right),$$

$$a^d_\mu(t) = \sum_{\nu=0}^{\infty} \left( \beta^*_{\mu\nu}(t) \hat{a}_\nu + a^*_{\mu\nu}(t) \hat{a}^d_\nu \right).$$
where \( \alpha_{\mu\nu}(t) \) and \( \beta_{\mu\nu}(t) \) are the Bogoliubov coefficients given by,

\[
\alpha_{\mu\nu}(t) = \frac{1}{\sqrt{2\omega_\nu}} \hat{B}_{\mu\nu}(t) - i \sqrt{\frac{\omega_\nu}{2}} B_{\mu\nu}(t)
\]  

(35)

and

\[
\beta_{\mu\nu}(t) = \frac{1}{\sqrt{2\omega_\nu}} \hat{B}_{\mu\nu}(t) + i \sqrt{\frac{\omega_\nu}{2}} B_{\mu\nu}(t) .
\]  

(36)

Using the definition of \( B_{\mu\nu}(t) \) we get

\[
\alpha_{\mu\nu}(t) = \sum_{\nu=0}^{\infty} \sqrt{\frac{\omega_\nu}{4\Omega_\nu}} \left\{ \frac{\Omega_\nu}{\omega_\nu} \left[ (\omega_\mu - \Omega_\nu)e^{i\Omega_\nu t} + (\omega_\mu + \Omega_\nu)e^{-i\Omega_\nu t} \right] 
+ \left[ (\Omega_\nu - \omega_\mu)e^{i\Omega_\nu t} + (\Omega_\nu + \omega_\mu)e^{-i\Omega_\nu t} \right] \right\}
\]  

(37)

and

\[
\beta_{\mu\nu}(t) = \sum_{\nu=0}^{\infty} \sqrt{\frac{\omega_\nu}{4\Omega_\nu}} \left\{ \frac{\Omega_\nu}{\omega_\nu} \left[ (\omega_\mu - \Omega_\nu)e^{i\Omega_\nu t} + (\omega_\mu + \Omega_\nu)e^{-i\Omega_\nu t} \right] 
- \left[ (\Omega_\nu - \omega_\mu)e^{i\Omega_\nu t} + (\Omega_\nu + \omega_\mu)e^{-i\Omega_\nu t} \right] \right\} .
\]  

(38)

Now we study the time evolution of \( n_\mu(t) \), the expectation value of the number operator \( N_\mu(t) = a_\mu^\dagger(t)a_\mu(t) \), that is,

\[
n_\mu(t) = \text{Tr} \left[ a_\mu^\dagger(t)a_\mu(t)\rho_0 \otimes \rho_\beta \right] .
\]  

(39)

Using the basis \( |n_0, n_1, n_2, \ldots n_N \rangle \) we obtain,

\[
n_\mu(t) = \sum_{\nu=0}^{\infty} \left[ |\alpha_{\mu\nu}(t)|^2 + |\beta_{\mu\nu}(t)|^2 \right] n_\nu + \sum_{\nu=0}^{\infty} |\beta_{\mu\nu}(t)|^2 ,
\]  

(40)

where

\[
n_0 = \sum_{n=0}^{\infty} n\langle n|\rho_0|n \rangle
\]  

(41)

is the expectation value of the number operator corresponding to the particle and the set \( \{ n_k \} \) stands for the thermal expectation values corresponding to the thermal bath oscillators, given by the Bose-Einstein distribution,

\[
n_k = \frac{1}{e^{\beta\omega_k - 1}} .
\]  

(42)

In Eq. (40) there appears a term that does not depend on the temperature of the thermal bath. This term has its origin in the instability of the initial bare vacuum state, \( |0, 0, \ldots, 0 \rangle \). To see this, we compute the expectation value of the time dependent number operator \( N_\mu(t) = a_\mu^\dagger(t)a_\mu(t) \) in this vacuum state. Thus all the terms containing operators different from the identity give a zero contribution. The only term, that gives a non-zero contribution comes from the normal ordering and is just the last one in Eq. (40). This term leads to the creation of excited states (particles, in a field theoretical language) from the initial unstable bare vacuum state.

We are interested in evaluating the expectation value of the number operator corresponding to particles. Thus taking \( \mu = 0 \) in Eq. (40) and using Eq. (42), we obtain

\[
n_0(t) = \left[ |\alpha_{00}(t)|^2 + |\beta_{00}(t)|^2 \right] n_0 + \sum_{k=1}^{\infty} \left[ |\alpha_{0k}(t)|^2 + |\beta_{0k}(t)|^2 \right] \frac{1}{e^{\beta\omega_k - 1}} + |\beta_{00}(t)|^2 + \sum_{k=1}^{\infty} |\beta_{0k}(t)|^2,
\]  

(43)
where the coefficients of this expression are \([20]\),

\[
\alpha_{00}(t) = \frac{e^{-\pi gt/2}}{16\omega_k} \left[ (2\bar{\omega} + 2\kappa - i\pi g)^2 e^{-i\omega t} - (2\bar{\omega} - 2\kappa - i\pi g)^2 e^{i\omega t} \right],
\]

\[
\beta_{00}(t) = \frac{\pi g e^{-\pi gt/2}}{8\omega_k} \left[ (\pi g + 2i\kappa) e^{-i\omega t} - (\pi g - 2i\kappa) e^{i\omega t} \right],
\]

\[
\alpha_{0k}(t) = \frac{\omega_k}{2\omega} \left[ \frac{(2\bar{\omega} + 2\kappa - i\pi g)}{(2\bar{\omega} - \omega^2 + i\pi g\omega_k)} + \frac{\omega_k}{4\kappa} \right]
\times \left[ (2\bar{\omega} + 2\kappa - i\pi g) e^{-i\omega t} + (2\bar{\omega} - 2\kappa - i\pi g) e^{i\omega t} \right] e^{-\pi gt/2},
\]

and

\[
\beta_{0k}(t) = \frac{\omega_k}{2\omega} \left[ \frac{(2\bar{\omega} + 2\kappa - i\pi g)}{(2\bar{\omega} - \omega^2 + i\pi g\omega_k)} + \frac{\omega_k}{4\kappa} \right]
\times \left[ (2\bar{\omega} + 2\kappa - i\pi g) e^{-i\omega t} + (2\bar{\omega} - 2\kappa - i\pi g) e^{i\omega t} \right] e^{-\pi gt/2},
\]

such that

\[\kappa = \sqrt{\bar{\omega}^2 - \pi^2 g^2/4}.\]

The parameter \(\kappa\) measures the intensity of the interaction: if \(\kappa^2 >> 0\), \(i.e. g << 2\bar{\omega}/\pi\), we are in the weak coupling regime. On the contrary if \(\kappa^2 << 0\), \(i.e. g >> 2\bar{\omega}/\pi\), the system is in the strong coupling regime. Here we will restrict ourselves to the weak coupling regime. This includes the important class of electromagnetic interactions, \(g = \alpha\bar{\omega}\), with \(\alpha\) being the fine structure constant \(\alpha = 1/137\) [4].

In the continuum limit \(\Delta \omega \to 0\), sums over \(k\) become integrations over a continuous variable \(\omega\) and we obtain for \(n_0(t)\),

\[
n_0(t) = \frac{e^{-\pi gt}}{\omega^2\kappa^2} \left[ \cos^4 + \frac{\pi^2 g^2}{8} (2\bar{\omega}^2 - \pi^2 g^2) \cos(2\kappa t) - \frac{\pi^3 g^3}{4} \sin(2\kappa t) \right] n_0
\]

\[
+ \frac{\pi^2 g^2 e^{-\pi gt}}{16\omega^2\kappa^2} \left[ 2\bar{\omega}^2 + (2\bar{\omega}^2 - \pi^2 g^2) \cos(2\kappa t) - 2\pi g\kappa \sin(2\kappa t) \right]
\]

\[
+ \frac{g}{2} \int_0^\infty d\omega \left[ \frac{F(\omega, \bar{\omega}, g, t)}{(e^{i\omega t} - 1)} + G(\omega, \bar{\omega}, g, t) \right],
\]

where

\[
F(\omega, \bar{\omega}, g, t) = \frac{\omega(\omega^2 + \bar{\omega}^2)}{[(\omega^2 - \omega^2)^2 + \pi^2 g^2\omega^2]} \left\{ 1 + \frac{e^{-\pi gt}}{4\kappa^2} \left[ 4\omega^2 - \pi^2 g^2 \cos(2\kappa t) \right]
\]

\[
- 2\pi g\kappa(\omega^2 + \bar{\omega}^2) \sin(2\kappa t) \right\} - \frac{e^{-\pi gt/2}}{\kappa} \left[ 2\kappa \cos(\omega t) \sin(\kappa t) \right]
\]

\[
+ \frac{4\omega\bar{\omega}^2}{(\omega^2 + \bar{\omega}^2)} \sin(\omega t) \sin(\kappa t) - \pi g \frac{(\omega^2 - \bar{\omega}^2)}{(\omega^2 + \bar{\omega}^2)} \cos(\omega t) \sin(\kappa t) \right\}
\]

\[
G(\omega, \bar{\omega}, g, t) = \frac{\omega(\omega - \bar{\omega})^2}{[(\omega^2 - \omega^2)^2 + \pi^2 g^2\omega^2]} \left\{ 1 + \frac{e^{-\pi gt}}{4\kappa^2} \left[ 4\omega^2 \frac{2\pi^2 g^2\omega^2}{(\omega - \bar{\omega})^2} + 2\pi^2 g^2\omega^2 \right]
\]

\[
- \pi g^2 \frac{(\omega^2 + \bar{\omega}^2)}{(\omega - \bar{\omega})^2} \cos(2\kappa t) - 2\pi g\kappa \frac{(\omega + \bar{\omega})}{(\omega - \bar{\omega})} \sin(2\kappa t) \right\}
\]
It is to be noted that the second and the third lines in Eq. (49) are independent of the initial distributions. Also the integral in the third line of $G(\omega, \bar{\omega}, g, t)$ is logarithmically divergent. We can understand the origin of this divergence in the following way: suppose that initially, in the absence of the linear interaction, we prepare the system in its ground state, that is, at $t = 0$ we have $|0, 0, \ldots, 0\rangle$. Then, we can compute, in the Heisenberg picture, the time evolution for the expectation value of the number operator corresponding to the particle, that is $\langle 0, 0, \ldots, 0 | \hat{a}_0^\dagger(t) \hat{a}_0(t) | 0, 0, \ldots, 0 \rangle$. Taking $\mu = 0$ we obtain,

$$\langle 0, 0, \ldots, 0 | \hat{a}_0^\dagger(t) \hat{a}_0(t) | 0, 0, \ldots, 0 \rangle = | \beta_0(t) |^2 + \sum_{k=1}^{\infty} | \beta_{0k}(t) |^2 ,$$

which in the continuum limit gives the second line of Eq. (49). Then, the origin of the divergence appearing in Eq. (49) is interpreted as the excitations produced from the unstable bare (vacuum) ground state, as a response to the linear interaction.

As we are interested in the thermal behavior of $n_0(t)$ only, the second line and the term $G(\omega, \bar{\omega}, g, t)$ in the third line of Eq. (49) can be neglected. This is a renormalization procedure. Thus we write the following renormalized expectation value for the particle number operator,

$$\bar{n}_0(t) = K(\bar{\omega}, g, t)n_0 + \frac{g}{\bar{\omega}} \int_0^\infty d\omega \frac{F(\omega, \bar{\omega}, g, t)}{(e^{\beta \omega} - 1)}$$

where

$$K(\bar{\omega}, g, t) = e^{-\frac{\pi g t}{2}} \left\{ \frac{\pi g^2}{2} (2\bar{\omega} - \pi^2 g^2) \cos(2\beta t) - \frac{\pi^3 g^3 \kappa}{4} \sin(\beta t) \right\}.$$

In the limit $t \to \infty$, $\bar{n}_0(t)$ has a well defined value, that is, the system reaches a final equilibrium state. Also, since $K(\bar{\omega}, g, t \to \infty) \to 0$, this final equilibrium state is independent of $n_0$. The equilibrium expectation value of the number operator corresponding to the particle is independent of its initial value, and the only dependence is on the initial distribution of the thermal bath, that is, the particle thermalizes with the environment. Before the interaction enters into play for $t < 0$, $n(t < 0) = n_0$, then we have that $K(\omega, \bar{\omega}, g, t < 0) = 1$. Taking $t = 0$ in Eq. (54) we obtain $K(\omega, \bar{\omega}, g, t = 0) = \bar{\omega}^2/\kappa^2 + \pi^2 g^2 (2\bar{\omega} - \pi^2 g^2) / (8\bar{\omega}^2 \kappa^2)$. Thus $K(\omega, \bar{\omega}, g, t)$ is a discontinuous function of $t$; the discontinuity appearing just at $t = 0$. From the physical standpoint this discontinuity can be viewed as a response to the sudden onset of the interaction between particles and the environment.

Although the integral in Eq. (53) cannot be computed analytically, we can perform numerical calculations, for example in Fig. II we display the time behavior for $n_0 = 1$, $\bar{\omega} = 1$, $\beta = 2$ and $g = 0.1$; ($t > 1$). In the next section we develop an alternative approach based on the notion of dressed particles. We will find that, in this new realm, no renormalization is needed.

### III. DRESSED COORDINATES AND DRESSED STATES

Let us start with the eigenstates of our system, $|n_0, n_1, n_2\ldots,\rangle$, represented by the normalized eigenfunctions in terms of the normal coordinates $\{Q_r\}$,

$$\phi_{n_0, n_1, n_2\ldots}(Q, t) = \prod_s \left\{ \frac{\Sigma_{n_s}}{n_s!} H_{n_s} \left( \sqrt{\frac{\Omega_s}{\hbar}} Q_s \right) \right\} \Gamma_0 e^{-\frac{i}{\hbar} \sum_s n_s \Omega_s t},$$

where $H_{n_s}$ stands for the $n_s$-th Hermite polynomial and $\Gamma_0$ is the normalized vacuum eigenfunction,

$$\Gamma_0 = N e^{-\frac{1}{\lambda} \sum_{s=0}^{\infty} \Omega_s^2 Q_s^2}.$$
FIG. 1: Time behavior for $\tilde{n}_0(t)$ given by Eq. (53) for $(t > 1)$, $n_0 = 1$, $\bar{\omega} = 1$, $\beta = 2$ and $g = 0.1$.

We introduce dressed or renormalized coordinates $q'_\mu$ and $\{q'_i\}$ for, respectively, the dressed particle and the dressed field, defined by,

$$\sqrt{\omega_\mu}q'_\mu = \sum_r t'_r \sqrt{\Omega_r}Q_r,$$

valid for arbitrary $R$ and where $\omega_\mu = \{\bar{\omega}, \omega_i\}$. In terms of dressed coordinates, we define for a fixed instant, $t = 0$, dressed states, $|\kappa_0, \kappa_1, \kappa_2...\rangle$ by means of the complete orthonormal set of functions

$$\psi_{\kappa_0\kappa_1...}(q') = \prod_\mu \left[ \frac{2^{\kappa_\mu}}{\kappa_\mu!} H_{\kappa_\mu} \left( \sqrt{\frac{\omega_\mu}{R}} q'_\mu \right) \right] \Gamma_0,$$

where $q'_\mu = \{q'_0, q'_i\}$, $\omega_\mu = \{\bar{\omega}, \omega_i\}$. Notice that the ground state $\Gamma_0$ in the above equation is the same as in Eq. (55). The invariance of the ground state is due to our definition of dressed coordinates given by Eq. (57). Each function $\psi_{\kappa_0\kappa_1...}(q')$ describes a state in which the dressed oscillator $q'_\mu$ is in its $\kappa_\mu$-th excited state.

It is worthwhile to note that our renormalized coordinates are new objects, different from both the bare coordinates, $q$, and the normal coordinates $Q$. In particular, the renormalized coordinates and dressed states, although both are collective objects, should not be confused with the normal coordinates $Q$, and the eigenstates Eq. (55). While the eigenstates $\phi$ are stable, the dressed states $\psi$ are all unstable, except for the ground state obtained by setting $\{\kappa_\mu = 0\}$ in Eq. (58). The idea is that the dressed states are physically meaningful states. This can be seen as an analog of the wave-function renormalization in quantum field theory, which justifies the denomination of renormalized to the new coordinates $q'$. Thus, the dressed state given by Eq. (58) describes the particle in its $\kappa_0$-th excited level and each mode $k$ of the cavity in the $\kappa_k$-th excited level. It should be noticed that the introduction of the renormalized coordinates guarantees the stability of the dressed vacuum state, since by definition it is identical to the ground state of the system. The fact that the definition given by Eq. (57) assures this requirement can be easily seen by replacing Eq. (57) in Eq. (58). We obtain $\Gamma_0(q') \propto \Gamma_0(Q)$, which shows that the dressed vacuum state given by Eq. (58) is the same ground state of the interacting Hamiltonian given by Eq. (5).

The necessity of introducing renormalized coordinates can be understood by considering what would happen if we write Eq. (58) in terms of the bare coordinates $q_\mu$. In the absence of interaction, the bare states are stable since they are eigenfunctions of the free Hamiltonian. But when we consider the interaction they all become unstable. The excited states are unstable, since we know this from experiment. On the other hand, we also know from experiment that the particle in its ground state is stable, in contradiction with what our simplified model for the system describes in terms of the bare coordinates. So, if we wish to have a nonperturbative approach in terms of our simplified
model something should be modified in order to remedy this problem. The solution is just the introduction of the renormalized coordinates $q'_\mu$ as the physically meaningful ones.

In terms of bare coordinates, the dressed coordinates are expressed as

$$q'_\mu = \sum_\nu \alpha_{\mu\nu} q_\nu,$$

where

$$\alpha_{\mu\nu} = \frac{1}{\sqrt{\bar{\omega}_\mu}} \sum_r t^{r}_\mu t^{r}_\nu \sqrt{\Omega_r}.$$

(60)

If we consider an arbitrarily large cavity ($R \to \infty$), the dressed coordinates reduce to

$$q'_0 = A_{00}(\bar{\omega}, g) q_0,$$

(61)

$$q'_i = q_i,$$

(62)

with $A_{00}(\bar{\omega}, g)$ given by,

$$A_{00}(\bar{\omega}, g) = \frac{1}{\sqrt{\bar{\omega}}} \int_0^\infty \frac{2 g \bar{\omega}^2 \sqrt{\bar{\Omega} \bar{\Omega}} \Omega}{(\bar{\Omega}^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \bar{\Omega}^2}.$$

(63)

In other words, in the limit $R \to \infty$, the particle is still dressed by the field, while for the field there remain bare modes.

Let us consider a particular dressed state $|\Gamma_1^\mu(0)\rangle$, represented by the wavefunction $\psi_{00...1(\mu)|0...}(q')$. It describes the configuration in which only the dressed oscillator $q'_\mu$ is in the first excited level. Then the following expression for its time evolution is valid [13]:

$$|\Gamma_1^\mu(t)\rangle = \sum_\nu f^{\mu\nu}(t) |\Gamma_1^\nu(0)\rangle$$

$$f^{\mu\nu}(t) = \sum_s t^s_\mu t^s_\nu e^{-i\Omega_s t}.$$

(64)

Moreover we find that

$$\sum_\nu |f^{\mu\nu}(t)|^2 = 1.$$

(65)

Then the coefficients $f^{\mu\nu}(t)$ are simply interpreted as probability amplitudes.

In approaching the thermalization process in this framework, we have to write the initial physical state in terms of dressed coordinates, or equivalently in terms of dressed annihilation and creation operators $a'^{\dagger}_\mu$ and $a'^{\dagger}_\mu$ instead of $a_\mu$ and $a_\mu^\dagger$. This means that the initial dressed density operator corresponding to the thermal bath is given by

$$\rho_\beta = Z^{-1}_\beta \exp \left[ -\beta \sum_{k=1}^\infty \omega_k \left( a^{\dagger}_k a'_k + \frac{1}{2} \right) \right],$$

(66)

where we define

$$a'_\mu = \sqrt{\frac{\bar{\omega}_\mu}{2}} q'_\mu + \frac{i}{\sqrt{2\bar{\omega}_\mu}} p'_\mu,$$

(67)

$$a^{\dagger'}_\mu = \sqrt{\frac{\bar{\omega}_\mu}{2}} q'_\mu - \frac{i}{\sqrt{2\bar{\omega}_\mu}} p'_\mu.$$
IV. THERMAL BEHAVIOR FOR A CAVITY OF ARBITRARY SIZE WITH DRESSED COORDINATES

The solution for the time-dependent annihilation and creation dressed operators follows similar steps as for the bare operators. The time evolution of the annihilation operator is given by,

$$\frac{d}{dt}a'_\mu(t) = i \left[ \hat{H}, a'_\mu(t) \right]$$

and a similar equation for $a'^*_\mu(t)$. We solve this equation with the initial condition at $t = 0$,

$$a'_\mu(0) = \sqrt{\frac{\omega_\mu}{2}} q'_\mu + \frac{i}{\sqrt{2\omega_\mu}} p'_\mu,$$

which, in terms of bare coordinates, becomes

$$a'_\mu(0) = \sum_{r,\nu=0}^{N} \left( \sqrt{\Omega_r} q'_\nu + \frac{i t'_\mu t'_r}{\sqrt{2\Omega_r}} p'_\nu \right).$$

We assume a solution for $a'_\mu(t)$ of the type

$$a'_\mu(t) = \sum_{\nu=0}^{\infty} \left( B'_\mu(t) q'_\nu + B'_\mu(t) p'_\nu \right).$$

Using Eq.(11) we find,

$$B'_\mu(t) = \sum_{r=0}^{\infty} t'_\nu \left( a'^*_r e^{i\Omega_r t} + b'^*_r e^{-i\Omega_r t} \right).$$

In the present case the time independent coefficients are different from those in the bare coordinate approach, Eq. (29). The initial conditions for $B'_{\mu\nu}(t)$ and $B^{'*}_{\mu\nu}(t)$ are obtained by setting $t = 0$ in Eq. (72) and comparing with Eq. (71); Then

$$B'_\mu(0) = i \sum_{r=0}^{\infty} \frac{t'_\nu t'_r}{\sqrt{2\Omega_r}} e^{-i\Omega_r t},$$

$$B^{'*}_\mu(0) = \sum_{r=0}^{\infty} \sqrt{\Omega_r} t'_\nu t'_r.$$

Using these initial conditions and the orthonormality of the matrix $\{t'_\nu\}$ we obtain $a'^*_r = 0, b'^*_r = it'_\mu/\sqrt{2\Omega_r}$. Replacing these values for $a'^*_r$ and $b'^*_r$ in Eq. (73) we get

$$B'_\mu(t) = i \sum_{r=0}^{\infty} \frac{t'_\nu t'_r}{\sqrt{2\Omega_r}} e^{-i\Omega_r t}. $$

We have

$$a'_\mu(t) = \sum_{r,\nu=0}^{N} t'_\nu t'_r \left( \sqrt{\frac{\Omega_r}{2}} q'_\nu + \frac{i}{\sqrt{2\Omega_r}} p'_\nu \right) e^{-i\Omega_r t}$$

and

$$a'_\mu(t) = \sum_{r,\nu=0}^{N} t'_\nu t'_r \left( \sqrt{\frac{\Omega_\nu}{2}} q'_\nu + \frac{i}{\sqrt{2\Omega_\nu}} p'_\nu \right) e^{-i\Omega_\nu t} = \sum_{\nu=0}^{\infty} f_{\mu\nu}(t) a'_\nu,$$

where

$$f_{\mu\nu}(t) = \sum_{r=0}^{\infty} t'_\nu t'_r e^{-i\Omega_r t}. $$
For the occupation number \( n'_\mu(t) = \langle a'^\dagger_\mu(t) a'_\mu(t) \rangle \) we get
\[
n'_\mu(t) = \text{Tr} (a'^\dagger_\mu(t) a'_\mu(t) \rho'_0 \otimes \rho'_\beta),
\]
(79)
where \( \rho'_0 \) is the density operator for the dressed particle and \( \rho'_\beta \) is the density operator for the thermal bath, which coincides with the corresponding operator for the bare thermal bath if the system is in free space (in the sense of an arbitrarily large cavity)\[13, 14].

To evaluate \( n'_\mu(t) \) we choose the basis \( |n_0, n_1, ..., n_N\rangle = \prod_{\mu=0}^\infty |n_\mu\rangle \), where \( |n_\mu\rangle \) are the eigenvectors of the number operators \( a'_\mu a'^\dagger_\mu \). From Eq. (77) we get
\[
a'^\dagger_\mu(t) a'_\mu(t) = \sum_{\nu, \rho=0}^\infty f^\ast_{\mu\nu}(t) f_{\mu\nu}(t) \hat{a}'_{\rho} \hat{a}'_{\nu}
\]
\[
= \sum_{\nu=0}^\infty |f_{\mu\nu}(t)|^2 \hat{a}'_{\nu} \hat{a}'_{\nu} + \sum_{\nu \neq \rho} f^\ast_{\mu\rho}(t) f_{\mu\nu}(t) \hat{a}'_{\nu} \hat{a}'_{\rho}. 
\]
(80)
In the basis \( |n_0, n_1, n_2, \cdots \rangle \) we obtain,
\[
n'_\mu(t) = \sum_{k=1}^\infty |f_{\mu k}(t)|^2 n'_k, 
\]
(81)
where \( n'_0 \) and \( n'_k \) are the expectation values of the initial number operators, respectively, for the dressed particle and dressed bath modes. We assume that, dressed field modes obey a Bose-Einstein distribution. This can be justified by remembering that in the free space limit, \( R \to \infty \), dressed field modes are identical to the bare ones, according to Eqs. (61) and (62). Now, no term independent of the temperature appears in the thermal bath. This should be expected since the dressed vacuum is stable, particle production from the vacuum is not possible. Setting \( \mu = 0 \) in Eq. (81) we obtain the time evolution for the occupation number of the particle,
\[
n'_0(t) = |f_{00}(t)|^2 n'_0 + \sum_{k=1}^\infty |f_{0k}(t)|^2 n'_k, 
\]
(82)

V. THE LIMIT OF ARBITRARILY LARGE CAVITY: UNBOUNDED SPACE

In a large cavity (free space) we must compute the quantities \( f_{00}(t) \) and \( f_{0k}(t) \) in the continuum limit to study the time evolution of the occupation number for the particle. Remember that in Eqs. (17), \( \omega_k = k \pi c/R, k = 1, 2, \ldots \) and \( \eta = \sqrt{2q \Delta \omega} \), with \( \Delta \omega = (\omega_{k+1} - \omega_k) = \pi c/R \). When \( R \to \infty \), we have \( \Delta \omega \to 0 \) and \( \Delta \Omega \to 0 \) and then, the sum in Eq. (78) becomes an integral. To calculate the quantities \( f_{\mu \nu}(t) \) we first note that, in the continuum limit, Eq. (17) becomes
\[
t_0' \to t_0^0 \sqrt{\Delta \Omega} \equiv \lim_{\Delta \Omega \to 0} \frac{\Omega \sqrt{2q \Delta \Omega}}{\sqrt{(\Omega^2 - \omega^2)^2 + \pi^2 q^2 \Omega^2}}, 
\]
(83)
\[
t_k' \to \frac{\omega' \sqrt{2q \Delta \omega}}{\omega^2 - \Omega^2} t_0^0 \sqrt{\Delta \Omega}. 
\]
(84)
In the following, we suppress the labels in the frequencies, since they are continuous quantities.

We start by defining a function \( W(z) \),
\[
W(z) = z^2 - \bar{\omega}^2 + \sum_{k=1}^\infty \frac{\eta^2 z^2}{\omega_k^2 - z^2}. 
\]
(85)
We find that the \( \Omega \)'s are the roots of \( W(z) \). Using \( \eta^2 = 2q \Delta \omega \), we have in the continuum limit,
\[
W(z) = z^2 - \bar{\omega}^2 + 2g z^2 \int_0^\infty \frac{d\omega}{\omega^2 - z^2}. 
\]
(86)
For complex values of $z$ the above integral is well defined and is evaluated by using Cauchy theorem, to be

$$W(z) = \begin{cases} z^2 + ig\pi z - \bar{\omega}^2, & \text{Im}(z) > 0 \\ z^2 - ig\pi z - \bar{\omega}^2, & \text{Im}(z) < 0. \end{cases}$$  \hspace{1cm} (87)$$

We now compute $f_{00}(t) = \sum_{\tau=0}^\infty (t_0^{\tau})^2 e^{-i\Omega \cdot t}$ which, in the continuum limit, is given by

$$f_{00}(t) = \int_0^\infty (t_0^{\tau})^2 e^{-i\Omega \cdot t} \, d\Omega.$$  \hspace{1cm} (88)$$

We find that,

$$(t_0^{\tau})^2 = \frac{1}{W(\Omega)},$$  \hspace{1cm} (89)$$

and since the $\Omega$’s are the roots of $W(z)$, we write Eq. (88) as

$$f_{00}(t) = \frac{1}{i\pi} \oint_C \frac{dz e^{-i\zeta t}}{W(z)},$$  \hspace{1cm} (90)$$

where $C$ is a counterclockwise contour in the $z$-plane that encircles the real positive roots of $W(z)$. Choosing a contour infinitesimally close to the positive real axis, that is $z = \alpha - i\epsilon$ below it and $z = \alpha + i\epsilon$ above it with $\alpha > 0$ and $\epsilon \to 0^+$, we obtain

$$f_{00}(t) = \frac{1}{i\pi} \int_0^\infty d\alpha e^{-i\alpha t} \left[ \frac{1}{W(\alpha - i\epsilon)} - \frac{1}{W(\alpha + i\epsilon)} \right].$$  \hspace{1cm} (91)$$

In the limit $\epsilon \to 0^+$, Eq. (87) gives $W(\alpha \pm i\epsilon) = \alpha^2 - \bar{\omega}^2 \pm i\pi\alpha$ which leads to

$$f_{00}(t) = C_1(t; \bar{\omega}, g) + iS_1(t; \bar{\omega}, g),$$  \hspace{1cm} (92)$$

where

$$C_1(t; \bar{\omega}, g) = 2g \int_0^\infty d\alpha \frac{\alpha^2 \cos(\alpha t)}{(\alpha^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \alpha^2},$$  \hspace{1cm} (93)$$

$$S_1(t; \bar{\omega}, g) = -2g \int_0^\infty d\alpha \frac{\alpha^2 \sin(\alpha t)}{(\alpha^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \alpha^2}.$$  \hspace{1cm} (94)$$

Notice that $C_1(t = 0; \bar{\omega}, g) = 1$ and $S_1(t = 0; \bar{\omega}, g) = 0$, so that $f_{00}(t = 0) = 1$ as expected from the orthonormality of the matrix $(t_0^{\tau})$. The real part of $f_{00}(t)$ is calculated using the residue theorem. For $\kappa^2 = \bar{\omega}^2 - \pi^2 g^2/\omega > 0$, which includes the weak coupling regime, one finds

$$C_1(t; \bar{\omega}, g) = e^{-\pi \kappa t/2} \left[ \cos(\kappa t) - \frac{\pi g}{2\kappa} \sin(\kappa t) \right] \quad (\kappa^2 > 0).$$  \hspace{1cm} (95)$$

Although $S_1(t; \bar{\omega}, g)$ cannot be analytically evaluated for all $t$, however for long times, i.e. $t \gg 1/\bar{\omega}$, we have

$$S_1(t; \bar{\omega}, g) \approx \frac{4g}{\bar{\omega}^4 t^3} \quad (t \gg \frac{1}{\bar{\omega}}).$$  \hspace{1cm} (96)$$

Thus, we get for large $t$

$$|f_{00}(t)|^2 \approx e^{-\pi \kappa t} \left[ \cos(\kappa t) - \frac{\pi g}{2\kappa} \sin(\kappa t) \right]^2 + \frac{16g^2}{\bar{\omega}^8 t^6}.$$  \hspace{1cm} (97)$$

Next we compute the quantity $f_{0k}(t) = \sum_{\tau=0}^\infty (t_0^{\tau} t_k^{\tau} e^{-i\Omega \cdot t}$ in the continuum limit. It is

$$f_{0m}(t) = \eta \omega \int_0^\infty \frac{(t_0^{\tau})^2 e^{-i\Omega t} \, d\Omega}{(\omega^2 - \Omega^2)} = \eta \omega \int_C \frac{dz e^{-i\zeta t}}{(\omega^2 - z^2)W(z)},$$  \hspace{1cm} (98)$$

where $\eta = \sqrt{2g\Delta \omega}$. Taking the same contour as that used to calculate $f_{00}(t)$, we obtain

$$f_{0m}(t) = -\frac{\eta \omega}{i\pi} \int_0^\infty d\alpha \left[ \frac{ae^{-i\alpha t}}{W(\alpha - i\epsilon)((\alpha - i\epsilon)^2 - \omega^2)} - \frac{ae^{-i\alpha t}}{W(\alpha + i\epsilon)((\alpha + i\epsilon)^2 - \omega^2)} \right].$$  \hspace{1cm} (99)$$
FIG. 2: Time behavior for \( n'_0(t) \) given by Eq. (105), for \( t > 1 \), \( n_0 = 1 \), \( \bar{\omega} = 1 \), \( \beta = 2 \) and \( g = 0.1 \).

Thus, taking \( \epsilon \to 0^+ \) \( f_{0\omega}(t) \) is written as

\[
f_{0\omega}(t) = \omega\sqrt{2\omega} \left[ C_2(\omega; t; \bar{\omega}, g) + iS_2(\omega; t; \bar{\omega}, g) \right],
\]

where

\[
C_2(\omega; t; \bar{\omega}, g) = (2g)^{3/2} \int_0^\infty \frac{\alpha^2 \cos(\alpha t)}{(\omega^2 - \alpha^2) \left((\alpha^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \alpha^2\right)} d\alpha,
\]

\[
S_2(\omega; t; \bar{\omega}, g) = -(2g)^{3/2} \int_0^\infty \frac{\alpha^2 \sin(\alpha t)}{(\omega^2 - \alpha^2) \left((\alpha^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \alpha^2\right)} d\alpha.
\]

Notice that the integrals defining the functions \( C_2 \) and \( S_2 \) are actually Cauchy principal values.

The function \( C_2 \) is calculated analytically using Cauchy theorem; we find

\[
C_2(\omega, t; \bar{\omega}, g) = \sqrt{2g} \left\{ e^{-\pi gt/2} \frac{\omega^2 - \bar{\omega}^2}{\left((\omega^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \omega^2\right)} \cos kt \\
- \frac{\pi g}{2\kappa} \frac{\omega^2 + \bar{\omega}^2}{\left((\omega^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \omega^2\right)} \sin kt \\
+ \frac{\pi g \omega}{(\omega^2 - \bar{\omega}^2)^2 + \pi^2 g^2 \omega^2} \sin \omega t \right\},
\]

The function \( S_2 \) cannot be evaluated analytically for all \( t \), it has to be calculated numerically. For long times, we have

\[
S_2(t; \bar{\omega}, g) \approx \frac{4\sqrt{2g} \sqrt{g}}{\omega^2 \bar{\omega}^2 t^3} \quad (t \gg \frac{1}{\bar{\omega}}).
\]

In the continuum limit, we get the average of the particle occupation number,

\[
n'_0(t) = \left[ C_1^2(t; \bar{\omega}, g) + S_1^2(t; \bar{\omega}, g) \right] n'_0 + \int_0^\infty d\omega \omega^2 \left[ C_2^2(\omega; t; \bar{\omega}, g) + S_2^2(\omega; t; \bar{\omega}, g) \right] n'(\omega),
\]

where \( n'(\omega) = 1/(e^{\beta\omega} - 1) \) is the density of occupation of the environment modes, the functions \( C_1 \) and \( C_2 \) are given by Eqs. (105) and (106) while the functions \( S_1 \) and \( S_2 \) are given by the integrals Eqs. (94) and (102), respectively. In Fig. 2 we display the behavior in time for \( n_0 = 1 \), \( \bar{\omega} = 1 \), \( \beta = 2 \) and \( g = 0.1 \); \( t > 1 \).

The important point, that is seen from Fig. 1 and Fig. 2 is that, for long times, both the bare and dressed occupation numbers of the particle approach smoothly to the same asymptotic value. Moreover this value is the one expected on
physical grounds, obtained from the Bose distribution at the final equilibrium temperature. In fact, taking $\beta = 2$ and $\bar{\omega} = 1$, as used in the plots, we get

$$n_\infty(\bar{\omega}) = 1/(e^{\beta \bar{\omega}} - 1) = 0.156$$

Therefore both methods, and in particular our dressed state formalism describes very precisely the thermalization process.

VI. FINAL REMARKS

We have considered a linearized version of a particle-environment system and we have carried out a non–perturbative treatment of the thermalization process. We have adopted the point of view of renouncing to an approach very close to the real behavior of a nonlinear system, to study instead a linear model. As a counterpart, an exact solution has been possible. This realises a good compromise between physical reality and mathematical reliability. We have presented an ohmic quantum system consisting of a particle, in the larger sense of a material body, an atom or a Brownian particle coupled to an environment modelled by non-interacting oscillators. We have used the formalism of dressed states to perform a non-perturbative study of the time evolution of the system, contained in a cavity or in free space. Distinctly to what happens in the bare coordinate approach, in the dressed coordinate approach no renormalization procedure is needed. Our renormalized coordinates contain in themselves the renormalization aspects. As far as the thermalization process is concerned from a physical viewpoint, both bare and dressed approaches are in agreement with what we expect for this process. For long times, all the information about the particle occupation numbers depends only on the environment. Both curves in Fig.1 and Fig.2 approach steadily to an asymptotic value of the bare and dressed occupation numbers of the particle, which is the physically expected one at the given temperature.

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