Quantum coherence of a circularly accelerated atom in a spacetime with a reflecting boundary

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We investigate, in the paradigm of open quantum systems, the dynamics of quantum coherence of a circularly accelerated atom coupled to a bath of vacuum fluctuating massless scalar field in a spacetime with a reflecting boundary. The master equation that governs the system evolution is derived. It is found that the quantum coherence diminishes to zero with increasing centripetal acceleration and evolution time in the case without a boundary. However, the presence of a boundary will modify the quantum fluctuations of the scalar field, which results in the enhancement of quantum coherence near the boundary compared with that for the unbounded case. Particularly, when the atom is very close to the boundary, although the atom still interacts with the environment, it behaves as if it were a closed system as a consequence of the presence of the boundary, and the quantum coherence can be shielded from the effect of the vacuum fluctuating scalar field.

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I. INTRODUCTION

Quantum coherence, introduced by the superposition principle of quantum states [1], plays the key role in quantum theory and quantum technology such as quantum optics [2, 3], quantum information [4], solid-state physics [5, 6] as well as biology systems [7–12], and so on. In this respect, several important works was proposed in order to develop a rigorous theory of coherence as a physical resource [13, 14] and put forward the necessary constraints to assess valid quantifiers of coherence [15]. Hence, in a recent work, Baumgratz *et al.* [16] proposed a rigorous framework to quantify quantum coherence such as l_1 norm of coherence and relative entropy of coherence. There also exist different works to quantify coherence as shown in Refs. [17, 18].

On the other hand, since every realistic system will unavoidably suffer from the decoherence and noise induced by the external environment, many ways were developed to enhance or protect the quantum resources, as the authors do when they analyze quantum correlation and metrology [19–24]. Therefore, in Refs. [25, 26] we discussed quantum coherence of a *inertial* atom coupled to the fluctuating electromagnetic field, and it can be protected with the presence of boundaries. Another example is related to investigations of quantum coherence for the *accelerated* atom immersed in electromagnetic field with a boundary [27]. This was also the subject of study by the author in Ref. [28]. Inspired by these works, we find that quantum coherence of atom moving with a more realistic trajectory is worth discussing, i.e., a atom moves in a uniform circular motion, since the very large acceleration which is required for experiments is easier to achieve in circular motion.

In the present paper, we plan to study the quantum coherence of a circularly accelerated atom coupled with the massless scalar field in analogy with the electric dipole interaction, as considered in Ref. [29]. It is worth mentioning that quantum coherence as a quantum resource decreases with the evolution time, which is due to the interaction between the atom and scalar field. Therefore, in order to enhance or even protect the quantum coherence, we would like to investigate the modification of the dynamics of quantum coherence by the presence of a boundary. In contrast to the case of without a boundary, our results show that as the atom gets closer and closer to the boundary, quantum coherence can be enhanced and may even be shielded from the influence of the external environment as if it were a closed system. The organization of the paper is as follows. In Sec. II, we introduce the way to quantify quantum coherence and derive the master equation that the system obeys. In Sec. III, we calculate in detail quantum coherence of a circularly accelerated atom interacting with the massless scalar field in the presence of a reflecting boundary and we also make a comparison between our results and those of the unbounded case. A summary is given in Sec. IV. In this paper we use units $\hbar = c = k_B = 1$.

II. PRELIMINARIES

In this approach taken in Ref. [16], quantum coherence can be measured in the reference basis which is due to the off-diagonal elements of a density matrix ρ, for instance, the intuitive l_1 norm of coherence. Mathematically, the

l_1 norm of coherence is defined as

$$C_{l_1}(\rho) = \sum_{\substack{i,j \\ i\neq j}} |\rho_{i,j}| \ , \tag{1}$$

where ρ indicates a state arbitrarily.

In quantum sense, any system should be regarded as an open system due to the interaction between the system and its surrounding environments. We consider the model which is consisted of a circularly accelerated atom interacting with a bath of fluctuating massless scalar field in the Minkowski vacuum. The total Hamiltonian of the atom-field system is

$$H = H_A + H_\Psi + H_I. \tag{2}$$

Here, $H_A = \frac{1}{2}\omega_0\sigma_z$ denotes the Hamiltonian of atom, with ω_0 being the energy-level spacing of the atom and σ_z being the Pauli matrix, and H_Ψ is the Hamiltonian of scalar field. We assume the the coupling between the detector and the massless scalar field is weak and their interaction Hamiltonian H_I, which is in analogy to the electric dipole interaction [30],

$$H_I = \mu(\sigma_+ + \sigma_-)\Psi(x(\tau)) \ , \tag{3}$$

with μ being the coupling constant that we assume to be small, σ_+ (σ_-) being the rasing (lowering) operator of the detector, and $\Psi(x(\tau))$ corresponding to the scalar field operator with τ being the detector's proper time.

At the beginning, the total density operator of the atom-field system can be represented as $\rho_{tot} = \rho_A(0) \otimes |0\rangle\langle 0|$, in which $\rho_A(0)$ is the initial reduced density matrix of the atom and $|0\rangle$ represents the vacuum for the massless scalar field. The equation of motion of the whole system in the interaction picture can be described by,

$$\frac{\partial\rho_{tot}(\tau)}{\partial\tau} = -i[H_I(\tau), \rho_{tot}(\tau)] \ . \tag{4}$$

With the help of $\rho_{tot}(\tau) = \rho_{tot}(0) - i\int_0^\tau ds[H_I(s), \rho_{tot}(s)]$, by taking the partial trace over the environmental degrees of freedom and $Tr_B[H_I(\tau), \rho_{tot}(0)] = 0$, the Eq. (4) can be rewritten as

$$\frac{\partial\rho_A(\tau)}{\partial\tau} = -\int_0^\tau ds Tr_B[H_I(\tau), [H_I(s), \rho_{tot}(s)]] \ . \tag{5}$$

Now, we assume that atom and field are weakly coupled (i.e., Born approximation [31]). This approximation is equivalent to assuming that the correlations established between atom and field are negligible at all times (initially zero), namely:

$$\rho_{tot}(s) \approx \rho_A(s) \otimes \rho_B \ . \tag{6}$$

Furthermore, we introduce the second approximation, the Markov approximation [31], which states that the bath has a very short correlation time τ_B. If $\tau \gg \tau_B$, we can replace $\rho_A(s)$ by $\rho_A(\tau)$, since the short "memory" of the bath correlation function causes it to keep track of events only within the short period $[0, \tau_B]$. Moreover, for the same reason we can extend the upper limit of the integral in Eq. (5) to infinity without changing the value of the integral. Therefore, with the help of Eq. (6), we have

$$\frac{\partial\rho_A(\tau)}{\partial\tau} = -\int_0^\infty ds\, Tr_B[H_I(\tau), [H_I(s), \rho_A(\tau) \otimes \rho_B]] \ . \tag{7}$$

Inserting Eq. (3) into Eq. (7), we can get the master equation in the Kossakowski-Lindblad form [32–34]

$$\begin{aligned}\frac{\partial\rho_A(\tau)}{\partial\tau} &= -i[H_{eff}, \rho_A(\tau)] \\ &\quad + \sum_{j=1}^{3}[2L_j\rho_A L_j^\dagger - L_j^\dagger L_j\rho_A - \rho_A L_j^\dagger L_j],\end{aligned} \tag{8}$$

where H_{eff} and L_j are given by

$$\begin{aligned}H_{eff} &= \frac{1}{2}\Omega\sigma_z = \frac{1}{2}\{\omega_0 + \mu^2\mathrm{Im}(\Gamma_+ + \Gamma_-)\}\sigma_z \ , \\ L_1 &= \sqrt{\frac{\gamma_-}{2}}\sigma_- \ , L_2 = \sqrt{\frac{\gamma_+}{2}}\sigma_+ \ , L_3 = \sqrt{\frac{\gamma_z}{2}}\sigma_z \ ,\end{aligned} \tag{9}$$

with

$$\begin{aligned}\gamma_\pm &= 2\mu^2\mathrm{Re}\Gamma_\pm = \mu^2\int_{-\infty}^{+\infty} e^{\mp i\omega_0\triangle\tau}G^+(s - i\epsilon)d\triangle\tau \ , \\ \gamma_z &= 0 \ ,\end{aligned} \tag{10}$$

in which $s = \tau - \tau'$, $G^+(x - x') = \langle 0|\Psi(x)\Psi(x')|0\rangle$ is the two-point correlation function of the massless scalar field with $x \equiv x(\tau)$ and $x' \equiv x(\tau')$ [35].

Assume that the initial state of two-level atom is a maximal coherent state $|\phi(0)\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$. Then, according to Eq. (8), the corresponding time-dependent reduced density matrix can be obtained as

$$\rho(\tau) = \frac{1}{2}\begin{pmatrix} 1 + \frac{\gamma_+ - \gamma_-}{\gamma_+ + \gamma_-}[1 - e^{-(\gamma_+ + \gamma_-)\tau}] & e^{-\frac{1}{2}(\gamma_+ + \gamma_-)\tau - i\Omega\tau} \\ e^{-\frac{1}{2}(\gamma_+ + \gamma_-)\tau + i\Omega\tau} & 1 - \frac{\gamma_+ - \gamma_-}{\gamma_+ + \gamma_-}[1 - e^{-(\gamma_+ + \gamma_-)\tau}] \end{pmatrix}. \tag{11}$$

In the above equation, we note that $\frac{1}{2}(\gamma_+ + \gamma_-)$ is the time scale for the off-diagonal elements of the density-matrix ("coherence") decay and $\gamma_+ + \gamma_-$ represents the time scale for atomic transition [36].

III. QUANTUM COHERENCE OF A CIRCULARLY ACCELERATED ATOM NEAR A CONDUCTING PLATE

We now investigate the quantum coherence of an atom rotating in the $x-y$ plate a distance z_0 from the boundary. The plate is located at $z = 0$. Our approach generalizes the method developed by Takagi [37] to the case when boundary conditions are present. In the Minkowski coordinate, the world line of the circular motion of radius R at a constant speed υ with centripetal acceleration $a = \frac{\gamma^2\upsilon^2}{R}$ is given by

$$\begin{aligned} t(\tau) &= \gamma\tau , \\ x(\tau) &= R\cos\omega\gamma\tau , \\ y(\tau) &= R\sin\omega\gamma\tau , \\ z(\tau) &= z_0 , \end{aligned} \tag{12}$$

where ω is the angular velocity

$$\omega = \upsilon/R, \tag{13}$$

and γ is the Lorentz factor

$$\gamma = (1 - \upsilon^2)^{-1/2}. \tag{14}$$

The parameter τ is the proper time as usual.

In order to obtain the quantum coherence of atom in the presence of a boundary, we first calculate the correlation function of the scalar field $G^+(x - x')$ consisted of a sum of two terms, i.e., an empty-space contribution $G^+(x-x')_0$ and a term $G^+(x-x')_R$ which is the correction induced by the presence of the plate with Dirichlet boundary conditions [35, 38]

$$G^+(x - x') = G^+(x - x')_0 + G^+(x - x')_R , \tag{15}$$

where

$$\begin{aligned} &G^+(x - x')_0 \\ &= \frac{1}{4\pi^2}\frac{1}{(x - x')^2 + (y - y')^2 + (z - z')^2 - (t - t' - i\epsilon)^2} , \end{aligned} \tag{16}$$

and

$$\begin{aligned} &G^+(x - x')_R \\ &= -\frac{1}{4\pi^2}\frac{1}{(x - x')^2 + (y - y')^2 + (z + z')^2 - (t - t' - i\epsilon)^2} . \end{aligned} \tag{17}$$

Applying the trajectories of the atom (12), one can easily get the correlation function as

$$\begin{aligned} G^+(x - x') = &-\frac{1}{4\pi^2}\frac{1}{\gamma^2(\triangle\tau - i\epsilon)^2 - (\frac{2\upsilon^2\gamma^2}{a})^2\sin^2(\frac{a\triangle\tau}{2\upsilon\gamma})} \\ &+\frac{1}{4\pi^2}\frac{1}{\gamma^2(\triangle\tau - i\epsilon)^2 - (\frac{2\upsilon^2\gamma^2}{a})^2\sin^2(\frac{a\triangle\tau}{2\upsilon\gamma}) - 4z_0^2} , \end{aligned} \tag{18}$$

which can be alternatively written as

$$\begin{aligned} G^+(x - x') \ = \ &-\frac{1}{4\pi^2}\frac{1}{(\triangle\tau - i\epsilon)^2[1 + f(\triangle\tau)]} \\ &+\frac{1}{4\pi^2}\frac{1}{(\triangle\tau - i\epsilon)^2[1 + f(\triangle\tau)] - 4z_0^2} , \end{aligned} \tag{19}$$

with

$$f(\triangle\tau) = \frac{a^2\triangle\tau^2}{12} - \frac{a^4\triangle\tau^4}{360\upsilon^2\gamma^2} + ... \tag{20}$$

Here, we expand $\sin^2(\frac{a\triangle\tau}{2\upsilon\gamma}) = \frac{a^2\triangle\tau^2}{4\upsilon^2\gamma^2} - \frac{a^4\triangle\tau^4}{48\upsilon^4\gamma^4} + \frac{a^6\triangle\tau^6}{1440\upsilon^6\gamma^6} +$ ... with $\triangle\tau = \tau - \tau'$. As is hard to find the explicit form of γ_+ and γ_-, we now consider the ultrarelativistic limit, i.e., $\gamma \gg 1$, shown in Ref. [39], so the field correlation function become

$$\begin{aligned} G^+(x - x') \ = \ &-\frac{1}{4\pi^2}\frac{1}{(\triangle\tau - i\epsilon)^2[1 + \frac{a^2\triangle\tau^2}{12}]} \\ &+\frac{1}{4\pi^2}\frac{1}{(\triangle\tau - i\epsilon)^2[1 + \frac{a^2\triangle\tau^2}{12}] - 4z_0^2} . \end{aligned} \tag{21}$$

Then, the Fourier transform of the field correlation function, which corresponds to the spontaneous emission rate, is given be

$$\gamma_- = \gamma_0\Bigg[1+\frac{a}{4\sqrt{3}}e^{-2\sqrt{3}\frac{\omega_0}{a}} - \frac{\sqrt{3}ae^{-\frac{\omega_0}{a}\sqrt{6+2\sqrt{9+12a^2z_0^2}}}}{2\sqrt{(3+\sqrt{9+12a^2z_0^2})(6+8a^2z_0^2)}\omega_0} - \frac{\sqrt{3}a\sin\left(\frac{\omega_0}{a}\sqrt{-6+2\sqrt{9+12a^2z_0^2}}\right)}{\sqrt{(-3+\sqrt{9+12a^2z_0^2})(6+8a^2z_0^2)}\omega_0}\Bigg], \tag{22}$$

where $\gamma_0 = \frac{\omega_0\mu^2}{2\pi}$ denotes the spontaneous emission rate for the atom coupled with scalar field without boundary. Similarly, the spontaneous excitation rate is given by

$$\gamma_+ = \gamma_0\Bigg[\frac{a}{4\sqrt{3}}e^{-2\sqrt{3}\frac{\omega_0}{a}} - \frac{\sqrt{3}ae^{-\frac{\omega_0}{a}\sqrt{6+2\sqrt{9+12a^2z_0^2}}}}{2\sqrt{(3+\sqrt{9+12a^2z_0^2})(6+8a^2z_0^2)}\omega_0}\Bigg], \tag{23}$$

Inserting Eqs. (22) and (23) into Eq. (11), the l_1 norm of coherence in Eq. (1) for the atom in the presence of a boundary is found to be

$$C_{l_1}(\tau) = e^{-\frac{1}{2}f(\omega_0,a,z_0)\gamma_0\tau}, \tag{24}$$

where

$$f(\omega_0,a,z_0) = 1+\frac{a}{2\sqrt{3}\omega_0}e^{-\frac{2\sqrt{3}\omega_0}{a}} - \frac{\sqrt{3}ae^{-\frac{\omega_0}{a}\sqrt{6+2\sqrt{9+12a^2z_0^2}}}}{\sqrt{(3+\sqrt{9+12a^2z_0^2})(6+8a^2z_0^2)}\omega_0} - \frac{\sqrt{3}a\sin\left(\frac{\omega_0}{a}\sqrt{-6+2\sqrt{9+12a^2z_0^2}}\right)}{\sqrt{(-3+\sqrt{9+12a^2z_0^2})(6+8a^2z_0^2)}\omega_0}. \tag{25}$$

Comparing the above result with Eq. (25) of Ref. [22], we can see that the function $f(\omega_0,a,z_0)$ gives the modification induced by the presence of the boundary. Here, $\gamma_R = f(\omega_0,a,z_0)\gamma_0$ represents the spontaneous emission rate for the circularly accelerated atom with a boundary. Note that for the centripetal acceleration $a/\omega_0 \to 0$, we have $f(\omega_0,a,z_0) = 1 - \frac{\sin 2\omega_0 z_0}{2\omega_0 z_0}$ and find that the transition rate recovers to that of an inertial atom interacting with the massless scalar field with a boundary [40].

Before the investigate of the whole evolution process, let us first examine that when evolving long enough time, i.e., $\tau \gg \frac{1}{\gamma_+ + \gamma_-}$ with $\frac{1}{\gamma_+ + \gamma_-}$ being the time scale for atomic transition, the system thermalizes to the steady state

$$\rho(\infty) = \frac{1}{\gamma_+ + \gamma_-}\begin{pmatrix} \gamma_+ & 0 \\ 0 & \gamma_- \end{pmatrix}. \tag{26}$$

Remark that the steady state in Eq. (26) is independent of the initial state, which the quantum coherence vanishes, that is $C_{l_1}(\infty) = 0$. This indicates that quantum coherence does not maintain for a long time under the effect of vacuum fluctuating scalar field.

Now let us examine the asymptotic behaviors of quantum coherence, i.e., when the atom is placed very close to the boundary ($\omega_0 z_0 \to 0$) or very far from it ($\omega_0 z_0 \to \infty$). When $\omega_0 z_0 \to 0$, $f(\omega_0,a,z_0) = 0$, one has $C_{l_1}(\tau) = 1$. This means that as the atom very closes to the boundary, quantum coherence is shield from the influence of the scalar field as if it were isolated. While for the case when $\omega_0 z_0 \to \infty$, $f(\omega_0,a,z_0) \to 1 + \frac{a}{2\sqrt{3}\omega_0}e^{-\frac{2\sqrt{3}\omega_0}{a}}$, our results reduce to those of the unbounded Minkowski space [22, 29] as expected. For the unbound case, as shown in Fig. 1, quantum coherence decreases with the evolution time, due to the fact that the decoherence is caused by the interaction between the atom and massless scalar field. Additionally, we find that as the centripetal acceleration a/ω_0 increases, which makes quantum coherence decay faster.

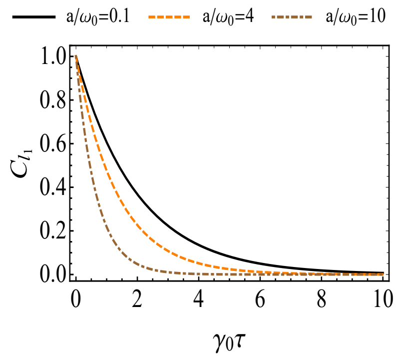

FIG. 1: (color online). Quantum coherence as a function of $\gamma_0\tau$ for different values of $a/\omega_0 = 0.1,\ 4,\ 10$ (solid, dashed, dotted-dashed), respectively, for the case without boundary.

For a generic case, the dynamics of quantum coherence are dependent on the evolution time, boundary effects and the centripetal acceleration. As shown in Figs. 2 and 3, we plot quantum coherence as a function of the atomic position $\omega_0 z_0$ (centripetal acceleration a/ω_0) with different centripetal acceleration (atomic position). Here, we take the fixed value $\gamma_0\tau = 1$. From Fig. 2, we find that quantum coherence saturates at different minimum values for different centripetal acceleration in the limit of infinite atomic position. However, we can see that for small centripetal acceleration, the quantum coherence fades to a stable value in an oscillatory manner. Also, in Fig. 2 we note that the maximal value of quantum coherence is obtained when $\omega_0 z_0 \to 0$, i.e., $C_{l_1}(\tau) = 1$, which implies that quantum coherence is immune to the external environment[refer to the case for the atom placed very close to the boundary]. Besides, Fig. 3 presents that quantum coherence decreases and reduces to zero in the limit of infinite centripetal acceleration. While for large atomic position, quantum coherence will increases for a while and starts to decrease to zero. This implies that quantum coherence can be enhanced by centripetal acceleration under some circumstances.

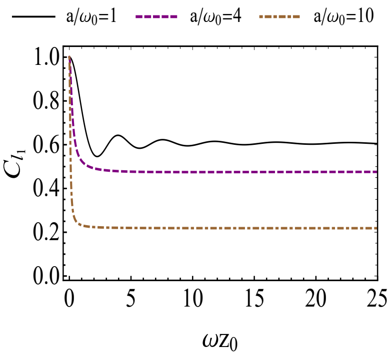

FIG. 2: (color online). $C_{l_1}(\tau)$ (24) as a function of $\omega_0 z_0$ for the fixed value $\gamma_0\tau = 1$ and three different values of centripetal acceleration, i.e., $a/\omega_0 = 0.1$ (solid line), $a/\omega_0 = 4$ (dashed line), $a/\omega_0 = 10$ (dotted-dashed line), respectively.

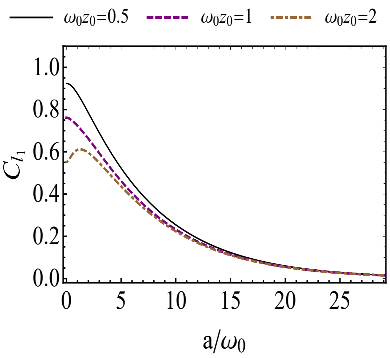

FIG. 3: (color online). $C_{l_1}(\tau)$ (24) as a function of a/ω_0 for the fixed value $\gamma_0\tau = 1$ and three different values of atomic position, i.e., $\omega_0 z_0 = 0.5$ (solid line), $\omega_0 z_0 = 1$ (dashed line), $\omega_0 z_0 = 2$ (dotted-dashed line), respectively.

More importantly, to compare quantum coherence of the atom with and without the presence of a boundary, we plot, in Fig. 4, quantum coherence with respect to evolution time and centripetal acceleration, for different values of atomic position, i.e., $\omega_0 z_0 \to 0$ and $\omega_0 z_0 = 1$ respectively. It is obvious that for the case of without a boundary, quantum coherence decreases by increasing the value of evolution time and centripetal acceleration. However, with the presence of a boundary, as we can see from Fig. 4(a), when the atom very close to the boundary, i.e., $\omega_0 z_0 \to 0$, quantum coherence always closes to 1. That is, quantum coherence is shielded from the influence of the vacuum fluctuations of the massless scalar field when the atom is close to the boundary. Besides, in Fig. 4(b), when $\omega_0 z_0 = 1$, despite of quantum coherence decreasing as the time and centripetal acceleration grow, while in contrast to the unbounded case, quantum coherence decays slowly in the case of a boundary. This means that quantum coherence can be enhanced in some degree with a boundary. As a result, we argue that as the atom gets closer and closer to the boundary, quantum coherence can be enhanced or even shielded from the influence of environment by the presence of boundary.

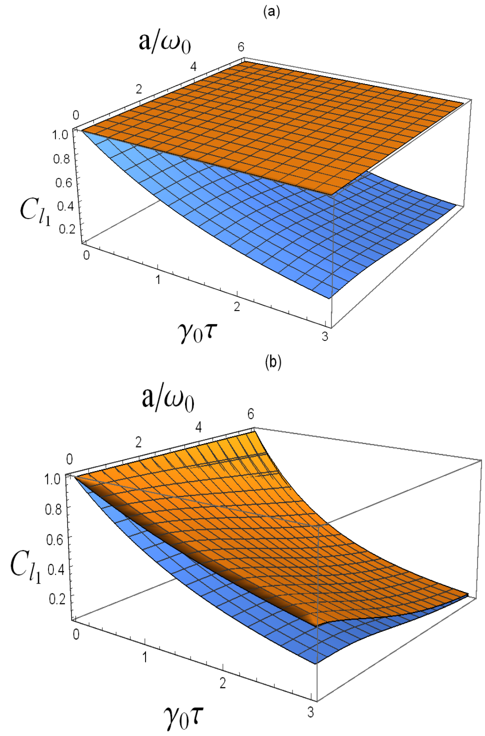

FIG. 4: (color online). Comparison between quantum coherence for the case of with the presence of boundary (the top yellow surface) and the case of without a boundary (the bottom blue surface), with (a) $\omega_0 z_0 \to 0$ and (b) $\omega_0 z_0 = 1$, respectively.

IV. CONCLUSION

In this letter, we studied, in the framework of open quantum systems, the dynamics of quantum coherence of a circularly accelerated two-level atom in a space with a reflecting boundary. Assuming a dipole-like interaction be- tween the atom and a scalar field, the master equation that describe the system evolution is derived. In the case of without a boundary, it is found that quantum coherence decreases with respect to the time, which result from the interaction between the atom and scalar field. Also, a decreasing quantum coherence is observed as centripetal acceleration increases. In the case of with a boundary, at distances far from the boundary $\omega_0 z_0 \to \infty$, the corrections induced by the presence of a boundary become negligible as one would expect, which means that the behaviors of quantum coherence recover to the result obtained for the case of without a boundary. However, when the atom close to the boundary, we found that quantum coherence decreases slowly, which implies that quantum coherence will be enhanced as compared to the case without any boundary. More remarkably, we are interested to note that very close to the boundary $\omega_0 z_0 \to 0$, the modifications induced by the presence of a boundary become so large that quantum coherence of the atom can be shielded from the influence of the vacuum fluctuating scalar field.

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Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon request.

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