Enhanced anti-Unruh effect by simulated light-matter interaction

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(Received 30 November 2022; accepted 15 March 2023; published 3 April 2023)

We investigate the transition of a two-level atom as the Unruh-Dewitt detector accelerated in the electromagnetic field in this paper. The enhancement of the transition probability is found for different field states under the conditions that the anti-Unruh effect appears. In particular, the enhancement is the most prominent when the field state takes the squeezed state. We also construct a new atomic trajectory to realize the effect of acceleration-induced transparency. Based on this, we show that the anti-Unruh effect still exists even at the specific atomic energy difference where acceleration-induced transparency happens.

DOI: 10.1103/PhysRevD.107.085001

I. INTRODUCTION

The Unruh effect [1,2] states that the uniformly accelerated observers can feel a thermal bath of particles in the Minkowski vacuum of a free quantum field. In the past few decades, it has been extensively investigated in many different situations (see the review [3] and references therein). An important application of the Unruh effect is connected with the Unruh-DeWitt (UDW) detector [4] which consists of a two-level atom accelerated in the vacuum. When such an atom is accelerated, it feels a thermal bath [5–12], which finally leads to a thermal balance between the accelerated atom and the vacuum field satisfying the Kubo-Martin-Schwinger (KMS) condition by the change of the probability distribution in two different energy levels of the accelerated detector [13–17]. However, the Unruh effect has not been observed directly in any experiments up to now due to the pretty low Unruh temperature, e.g., it requires an acceleration of 10^{20} m/s^2 to realize a thermal bath at 1 K.

A recent work [18] suggested a potentially strong enough method to detect the Unruh effect. In their method, the UDW detector is accelerated in the electromagnetic field instead of the vacuum. Thus, not only the conventional Unruh effect (the counterrotating terms) is activated but also the rotating-wave terms in the usual light-matter interaction [19] are also influenced by the acceleration. For the Fock state, the Unruh effect is enhanced by a factor of $n+1$ (n is the photon number) compared with the case that happened in the vacuum. But the enhancement can only be observed in some specific energy differences of the accelerated atom, in which the disturbance of rotating-wave terms is much suppressed and acceleration-induced transparency appears.

The recently found anti-Unruh effect [20,21] states that a particle detector in the uniform acceleration coupled to the vacuum can cool down with increasing acceleration under certain conditions, which is opposite to the celebrated Unruh effect. Under the situation of the anti-Unruh effect, some novel and interesting phenomena were found and studied [22–28]. Although the anti-Unruh effect can lead to different behaviors for the change of entanglement among many atoms from that led by the usual thermal effect [24], no feasible methods in the current technical conditions are found to detect it. An instant thought is whether the anti-Unruh effect could be enhanced by using the accelerated detector in the electromagnetic field along the line in Ref. [18]. However, the occurrence of this enhancement requires generating the acceleration-induced transparency for the accelerated atom in the electromagnetic field, which is dependent on the atomic energy difference as stated above. While the appearance of the anti-Unruh effect is also closely related to the energy difference of the accelerated atoms [21], it is unclear whether the anti-Unruh effect can appear when the acceleration-induced transparency happens for an accelerated atom in the electromagnetic field and should be investigated further. In this paper, we investigate this in detail. We consider the different field states, including the Fock state, the thermal state, the coherent state, and the squeezed state, and study whether the anti-Unruh effect can appear in these field states and whether the anti-Unruh effect and acceleration-induced transparency can appear under the same conditions.

This paper is organized as follows. In Sec. II, we describe the interaction between the UDW detector and the field, and compare the results for the accelerated detector in the vacuum with that in the electromagnetic field. We study the

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stimulated anti-Unruh effect for the different field states in Sec. III. This is followed in Sec. IV by choosing a specific accelerated trajectory to suppress the change of atomic state induced by the light-matter interaction. This is the effect of acceleration-induced transparency. We show that acceleration-induced transparency and the anti-Unruh effect can appear under the same conditions. Finally, we summarize and give the conclusion in Sec. V. In this paper, we use units with $c = \hbar = k_B = 1$.

II. THE MODEL

We start with the model of the UDW detector which is considered as a pointlike two-level atom in this paper. It has two different energy levels, described by the ground $|g\rangle$ and excited $|e\rangle$ states, respectively. The two energy levels are separated in the atomic rest frame by an energy gap Ω. When the atom is accelerated, the interaction Hamiltonian is expressed as [4,29]

$$H_I = \lambda\chi(\tau)\mu(\tau)\phi[x(\tau), t(\tau)], \tag{1}$$

where λ is the coupling constant between the accelerated atom and the field, $\mu(\tau) = e^{i\Omega\tau}\sigma^+ + e^{-i\Omega\tau}\sigma^-$ is the atomic monopole moment ($\sigma^\pm$ being SU(2) ladder operators), $\phi[x(\tau), t(\tau)]$ is the field operator in which $x(\tau)$, $t(\tau)$ represents the trajectory of the atom, and $\chi(\tau)$ is the switching function. In this paper, we choose $\chi(\tau)$ to be Gaussian function

$$\chi(\tau) = e^{-\frac{\tau^2}{2\varsigma^2}}, \tag{2}$$

where the parameter ς establishes the timescale of the interaction between the field and the detector. According to the earlier analyses [21,24], the interaction time will not affect the existence of the anti-Unruh effect. Thus, we can extend the interaction time to infinity, and the anti-Unruh phenomenon will still exist.

The time evolution operator under the Hamiltonian (1) is obtained by the following perturbative expansion,

$$\begin{aligned} U &= 1 - i\int d\tau H_I(\tau) + \mathcal{O}(\lambda^2) \\ &= 1 - i\lambda\sum_k [\eta_{(+,k)} a_k^\dagger \sigma^+ + \eta_{(-,k)} a_k \sigma^+ + \text{H.c.}] \end{aligned} \tag{3}$$

where $a_k^\dagger\sigma^+$ and $a_k\sigma^-$ are the counterrotating terms, while $a_k\sigma^+$ and $a_k^\dagger\sigma^-$ are the rotating-wave terms. $\sum_k$ represents the summation of all momentum modes in the $(1+1)$ dimensional spacetime. $\eta_{(\pm,k)} = \int \frac{\lambda d\tau}{\sqrt{(2\pi)^3 2\omega}} e^{i\Omega\tau \pm i k^\mu x_\mu - \frac{\tau^2}{2\sigma_\tau^2}}$ where $k^\mu x_\mu = \omega t(\tau) - kx(\tau)$ are related to the motion of the atom. The ladder operators $\sigma^\pm$ of the atom are defined by

$$\begin{aligned} \sigma^+|e\rangle &= 0, \qquad \sigma^+|g\rangle = |e\rangle, \\ \sigma^-|g\rangle &= 0, \qquad \sigma^-|e\rangle = |g\rangle. \end{aligned} \tag{4}$$

And the creation and annihilation operators of the field are defined by

$$\begin{aligned} a_k^\dagger|n\rangle_k &= \sqrt{n_k + 1}|n+1\rangle_k, \\ a_k|n\rangle_k &= \sqrt{n_k}|n-1\rangle_k. \end{aligned} \tag{5}$$

where $|n\rangle_k$ is the Fock state of the field and indicates that there are n photons in the k mode.

Hence the interaction between the accelerated atom and the field is described according to

$$\begin{aligned} U|g\rangle|n\rangle_k = |g\rangle|n\rangle_k - i\sqrt{n}\eta_{(-,k)}|e\rangle|n-1\rangle_k \\ - i\sqrt{n+1}\eta_{(+,k)}|e\rangle|n+1\rangle_k, \end{aligned} \tag{6}$$

$$\begin{aligned} U|e\rangle|n\rangle_k = |e\rangle|n\rangle_k - i\sqrt{n+1}\eta^*_{(-,k)}|g\rangle|n+1\rangle_k \\ - i\sqrt{n}\eta^*_{(+,k)}|g\rangle|n-1\rangle_k. \end{aligned} \tag{7}$$

In the two Eqs. (6) and (7), the second and third terms on the right side of each equation represent the rotating-wave and counter-rotating terms, respectively. For example, the second term on the right side of Eq. (6) indicates that the atom absorbs one photon in the field and jumps from the ground state to the excited state, which is also called the stimulated absorption term. The third term on the right side of Eq. (6) represents the contribution of the Unruh effect, which is generated by the accelerated motion of the atom in the electromagnetic field and is called the stimulated Unruh effect term. The Eq. (7) can be interpreted similarly.

At first, we take the field as the vacuum, i.e., there are no particles in the field, or $n_k = 0$ for any k mode. When the atom is accelerated in the vacuum with the trajectory [14,30],

$$x^\mu(\tau) = [\sinh(a\tau)/a, 0, 0, \cosh(a\tau)/a], \tag{8}$$

we have the transition probability P as

$$P \propto \frac{B}{e^{2\pi\Omega/a} - 1}, \tag{9}$$

where B is a coefficient related to the initial conditions of the atom. This represents a Bose-Einstein distribution at temperature $T = \frac{a}{2\pi}$, and indicates the uniformly accelerated detector in the vacuum perceives an apparently thermal field [31,32].

When the atom at the ground state is initially accelerated in the electromagnetic field, the atom will jump from the ground to the excited state in two different ways (i.e., the stimulated absorption and the stimulated Unruh effect). From Eq. (6), it is not hard to calculate the acceleration-induced transition probability as,

$$P_a \propto \frac{(n+1)B}{e^{2\pi\Omega/a}-1}, \tag{10}$$

where the field is taken as the single-mode Fock state $|n\rangle$. This result indicates that when the atom is accelerated in the n-photon field, its transition probability will be amplified by $n+1$ times compared with that accelerated in the vacuum.

III. STIMULATED ANTI-UNRUH EFFECT

In the previous section, it is shown that a detector accelerated in the electromagnetic field is more sensitive to acceleration-induced thermal effects than a detector accelerated in the vacuum field. It is mainly embodied in the amplification of the transition probability of the atom. Now we calculate the transition probability precisely and discuss its change with the acceleration.

Consider that an atom as the UDW detector is initially in the ground state $|g\rangle$. When the atom is accelerated in the k-mode photon field, according to Eq. (6), the probability of the transition to the excited state is calculated as

$$P_{|g\rangle\to|e\rangle} = n_k|\eta_{(-,k)}|^2 + (n_k+1)|\eta_{(+,k)}|^2, \tag{11}$$

where the first term on the right side is the contribution of the stimulated absorption term and the second term is the contribution of the stimulated Unruh effect term, as explained for the second and third terms on the right side of Eqs. (6) and (7).

In order to present the influence of the field on the detector, we choose a general initial state

$$\rho_{in} = |g\rangle\langle g| \otimes \sum_{n_k,n'_k} p_{n_k} p^*_{n'_k} |n_k\rangle\langle n'_k|, \tag{12}$$

where $\sum_{n_k,n'_k} p_{n_k} p^*_{n'_k} |n_k\rangle\langle n'_k|$ represents the state of the electromagnetic field, and p_{n_k} represents the number distribution in the k-mode. Thus, the transition probability becomes

$$\begin{aligned} P = &\sum_{n_k} |p_{n_k}|^2 n_k |\eta_{(-,k)}|^2 + \sum_{n_k} |p_{n_k}|^2 (n_k+1)|\eta_{(+,k)}|^2 \\ &+ \sum_{n_k} p^*_{n_k} p_{n_k+2} \sqrt{(n_k+1)(n_k+2)}\,\eta_{(-,k)}\eta^*_{(+,k)} \\ &+ \sum_{n_k} p_{n_k} p^*_{n_k+2} \sqrt{(n_k+1)(n_k+2)}\,\eta^*_{(-,k)}\eta_{(+,k)}. \end{aligned} \tag{13}$$

It is easily confirmed that the transition probability decays to the form in Eq. (11) when the field state is taken as the Fock state. Equation (13) is a more general result, with which we can study the influence of different field states. Note that some special states such as entangled states or squeezed states [23,33] can improve the accuracy of experimental measurements. Therefore, it is interesting to calculate the transition probability of the accelerated atom for the different field states, and in the following we will take the photon states as the coherent state, the thermal state, and the squeezed state, respectively.

When the field is taken as the single-mode coherent state [34],

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n_k=0}^{\infty} \frac{\alpha^{n_k}}{\sqrt{n_k!}} |n_k\rangle, \tag{14}$$

the transition probability in Eq. (13) is calculated as

$$\begin{aligned} P_{CS} = &|\alpha|^2|\eta_{(-,k)}|^2 + (|\alpha|^2+1)|\eta_{(+,k)}|^2 \\ &+ \alpha^2 \eta_{(-,k)}\eta^*_{(+,k)} + (\alpha^*)^2 \eta^*_{(-,k)}\eta_{(+,k)}. \end{aligned} \tag{15}$$

where $|\alpha|^2$ means the average number of photons.

When the field is taken as the thermal state, its expression is given as

$$\rho_k = \sum_{n_k} (1-e^{-\beta\omega_k}) e^{-n_k\beta\omega_k} |n_k\rangle\langle n_k|, \tag{16}$$

where $\beta = 1/T$ and T is the temperature of the thermal field. The evolution of the accelerated atom in such a field is similar to that studied earlier in Refs. [35,36], and the expected value of the particle number operator can be calculated as

$$\langle n_k\rangle = \mathrm{tr}(\rho_k n_k) = \frac{1}{e^{\beta\omega_k}-1}. \tag{17}$$

Substituting Eqs. (16) and (17) into Eq. (13), the transition probability becomes

$$P_{TS} = \frac{1}{e^{\beta\omega_k}-1}|\eta_{(-,k)}|^2 + \left(\frac{1}{e^{\beta\omega_k}-1}+1\right)|\eta_{(+,k)}|^2. \tag{18}$$

When the field is taken as a single-mode squeezed state [37,38], we have the expression

$$|S_k\rangle = \frac{1}{\sqrt{\cosh r_k}} \sum_{n_k=0}^{\infty} (-e^{i\phi}\tanh r_k)^{n_k} \frac{\sqrt{(2n_k)!}}{2^{n_k} n_k!} |2n_k\rangle. \tag{19}$$

Such a state can be generated by implementing the squeezing operator $S(\zeta) = \exp[\frac{1}{2}(\zeta^*\hat{a}_k^2 - \zeta\hat{a}_k^{\dagger 2})]$ on the vacuum state, $|S_k\rangle = S(\zeta)|0\rangle$, where $\zeta = re^{i\phi}$, r is squeezing parameter and ϕ is the spatially azimuthal angle. For simplicity, we take $\phi = 0$ in the following calculation. The average number of photons in this squeezed state is obtained as

$$\langle n_k\rangle_{S_k} = \sinh^2(r_k). \tag{20}$$

So the transition probability for the accelerated atom in such a field state is calculated as

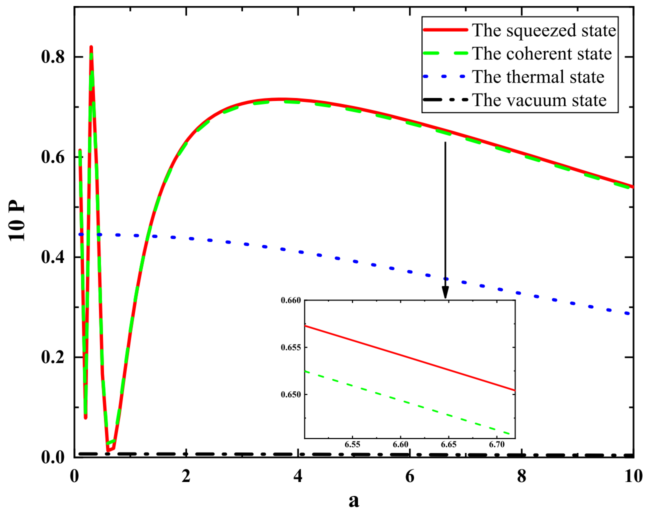

FIG. 1. The transition probability as a function of the acceleration a. The red solid line denotes the case that the field state is taken as a squeezed state. The green dashed line denotes the case that the field state is taken as the coherent state. The blue dotted line denotes the case that the field state is taken as the thermal state. The black dotted dashed line denotes the case that the field state is taken as the vacuum state. The model parameters employed are $\varsigma = 0.3$, $m = k = 1$, $\Omega = 1$, $\langle n \rangle = 29.1292$.

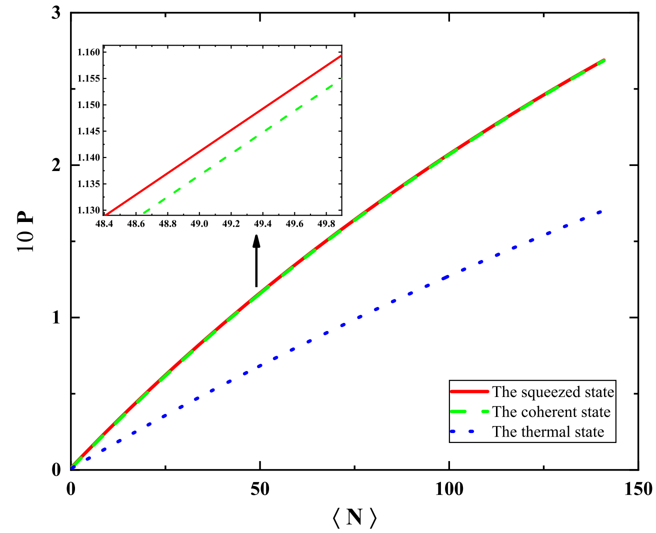

FIG. 2. The transition probability as a function of the number of particles. The acceleration takes $a = 4$, and the other parameters take the same values as in Fig. 1.

$$P_{SS} = \sinh^2(r_k)|\eta_{(-,k)}|^2 + [\sinh^2(r_k) + 1]|\eta_{(+,k)}|^2] + \sum_{n_k} Q_{n_k}[\eta_{(-,k)}\eta^*_{(+,k)} + \eta^*_{(-,k)}\eta_{(+,k)}], \tag{21}$$

where $Q_{n_k} = p^*_{n_k} p_{n_k+2}\sqrt{(n_k+1)(n_k+2)}$, and $p_{n_k} = \frac{1}{\sqrt{\cosh(r_k))}}[\tanh(r_k)]^n \frac{\sqrt{(2n_k)!}}{2^{n_k} n_k!}$ is the distribution of the single-mode squeezed state under the base of Fock states.

Figure 1 presents the change of different transition probabilities corresponding to different field states with the acceleration of the atom. It is found that the transition probability corresponding to every field state decreases when the acceleration is increased, which is an evident phenomenon that confirms the existence of the anti-Unruh effect [20,21]. The reason for the fluctuation at small acceleration in Fig. 1 is that the contribution from the light-matter interaction dominates and the acceleration-induced effect is small there. On the other hand, it is also evidently seen that the transition probability corresponding to the coherent, thermal or squeezed state is indeed enhanced compared with the case when the atom is accelerated in the vacuum. In particular, the enhanced effect for the squeezed state is better than that for any other state under the condition that the average atomic number is the same for every field state.

For the purpose of observation, we present the change of the transition probability with the average number of particles, as given in Fig. 2. It is seen that the amplification of the transition probability is more obvious for the squeezed state than that for any other state as the field state. The stimulated acceleration-induced effect can be detected via an accelerated low-mass two-level system [39]. When the field state is taken as the vacuum state, the spontaneous transition probability is only $P_0 \approx 10^{-18}$ which is obtained by considering the accelerated electrons in storage rings with the acceleration $a \approx 10^{17}$ ms^{-2} [40]. According to our calculation, the transition probability can increase about n times when the field is taken as the electromagnetic field, i.e., the transition probability becomes 2.34305×10^{-14} for the squeezed state as the field state, where $n = 1000$, other parameters take the same values as that in the acceleration of electrons [40], and all the physical constants such as the light velocity c, the reduced Planck constant $\hbar$, and the Boltzmann constant k_B are put into the Eq. (21). While in the actual experiment, the phonon number can reach 10^{15} [41,42], which implies that the possibility of observing the acceleration-induced effect under the present experimental conditions.

Moreover, from Eq. (13), it is noted that the acceleration affects not only the stimulated Unruh effect term but also the stimulated absorption term. So the phenomenon presented in Fig. 1 is not completely from the contribution of the acceleration, and the usual absorption of the atom from the field works in the process. We check the contribution of the stimulated absorption term for the transition of the atom from the ground to excited state with the proportional parameter, $\Lambda = \frac{\sum_{n_k} p_{n_k} n_k |\eta_{(-,k)}|^2}{P}$. It is found that the value of Λ for every field state decreases as the acceleration increases, and the contribution of the stimulated absorption terms to the transition probability is larger for the squeezed state than that for any other state. Although the influence of the stimulated absorption term is reduced by increasing the acceleration of the atom, the transition probability also decreases in the process. Thus, it cannot deduce directly that the contribution from the stimulated Unruh effect term decreases as the acceleration increases. So it requires a specific method in which the absorption term can be suppressed to confirm the existence of the anti-Unruh effect.

IV. ACCELERATION-INDUCED TRANSPARENCY

The recent study in Ref. [18] provides a method called acceleration-induced transparency, which can suppress the contribution of the stimulated absorption term for the transition of an accelerated atom in the electromagnetic field. In this section, we will discuss whether it is also feasible for the appearance of the anti-Unruh effect.

The acceleration-induced transparency means that in the process of interaction between the accelerated atom and the field, the rotating-wave term can be much suppressed, and the counterrotating term dominates in the transition of the atom [43–46]. This can be mathematically expressed as the condition that $\frac{|\eta_{(-,k)}|}{|\eta_{(+,k)}|} \ll 1$, where $\eta_{(-,k)}$ is related to the rotating-wave term and $\eta_{(+,k)}$ is related to the counterrotating term as given in Eq. (6) and (7). For an accelerated atom at the ground state initially, this condition means that the transition process of the atom is caused mainly by the stimulated Unruh effect term and the contribution from the stimulated absorption is much suppressed. In the following, we will discuss how to realize this condition. In order to present it clearly, we take the switching function as $\chi(\tau) = 1$.

Now we introduce a phase function $\alpha(\tau) = k^\mu x_\mu(\tau)$ determined by the atomic world line $x_\mu(\tau)$, and the transition amplitude can be rewritten as

$$\eta_{\pm,k} = \int q d\tau e^{i\Omega\tau \pm i\int_0^\tau \dot{\alpha}(\tau')d\tau'}, \tag{22}$$

where q is a coefficient determined by the initial detector settings and the field frequency [3]. For the conventional Unruh effect, the world line of a uniformly accelerated detector is given by Eq. (8) and $k^\mu = \{1, 0, 0, 1\}$ is taken for the excited particles associated with the uniformly accelerated detector in the vacuum without loss of generality [46,47]. Thus, we have, $\eta_{(+,\Omega)} = \frac{-iq}{4a\pi\sqrt{\pi}} e^{\frac{-i}{a}} e^{i\frac{\Omega}{a}\ln(\frac{-i}{a})}\Gamma(-i\Omega/a)$ where Γ is the complex Gamma function. For our purpose, a non-uniformly accelerated world line is required as,

$$\dot{\alpha}(\tau) \coloneqq k\begin{cases} v_0 & \tau < 0 \\ v_0 + a_1\tau & \tau \in [0, T_1) \\ v_1 + a_2(\tau - T_1) & \tau \in [T_1, T_2) \\ v_2 & \tau \geq T_2 \end{cases}, \tag{23}$$

as in Ref. [18].

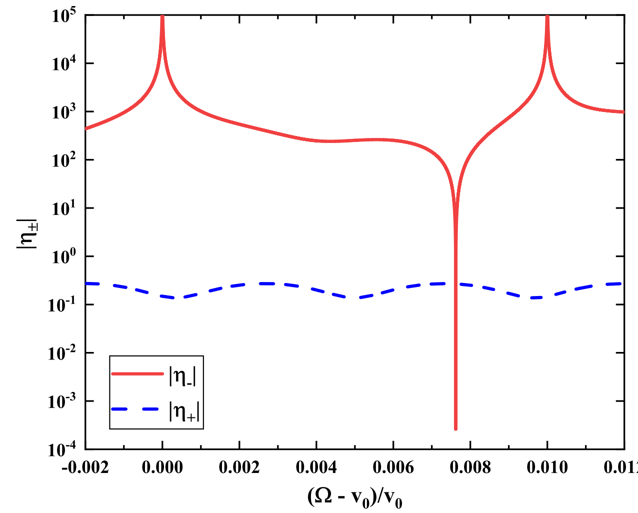

FIG. 3. The transition amplitude as a function of the atomic energy gap. The corresponding parameters are taken as $v_0 = 1.041$, $v_1 = 1.07$, $v_2 = 1.05141$, $T_1 = 9.7435$, $T_2 = 1305.412$, $\omega = k = 1$. The trajectory of the atom is given in Eq. (23).

From this expression in Eq. (23), it is seen that the atom moves inertially at velocity $\omega - v_0$ at the initial time. The first acceleration process is implemented with the acceleration $a_1 = (v_1 - v_0)/T_1$, where the velocity becomes $\omega - v_1$ at the end of this process. Then, the second acceleration process is started with the acceleration $a_2 = (v_2 - v_1)/(T_2 - T_1)$. Finally, the motion of the atom remains at the velocity of $\omega - v_2$. In Fig. 3, we plot $\eta_{\pm,k}$ for such a trajectory and obtain a similar result to that in Ref. [18]. It shows clearly that at some specific frequencies, the rotating-wave term represented by $\eta_{(-,k)}$ is much suppressed.

However, it is not easy to determine whether the anti-Unruh effect appears for the above process, since one requires checking the change of the transition probability with the acceleration (but there are two accelerations in the process described above) for the determination of the anti-Unruh effect. Thus, we have to choose another accelerated world line for the atom, given as,

$$\dot{\alpha}(\tau) \coloneqq k\begin{cases} v_0 & \tau < 0 \\ v_0 + a\tau & \tau \in [0, T) \\ v & \tau \geq T, \end{cases} \tag{24}$$

where $a = (v - v_0)/T$ represents the acceleration in the accelerated process.

With this accelerated world line (24), we study whether the stimulated absorption term can be suppressed. Figure 4 gives the corresponding results. It shows that the transition amplitude caused by the stimulated absorption term is highly suppressed by choosing a specific energy gap, e.g., it is $\Omega = 0.51$ as presented in Fig. 4. Thus, the phenomenon of acceleration-induced transparency occurs

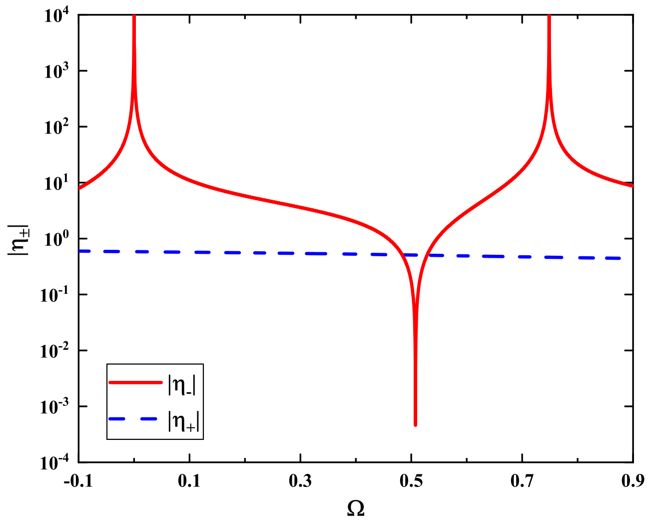

FIG. 4. The transition amplitude as a function of atomic energy gap. The corresponding parameters are taken as $v_0 = 1.03$, $T = 5.105$, $v = 1.801$, $\omega = k = 1$. The trajectory of the atom is given in Eq. (24).

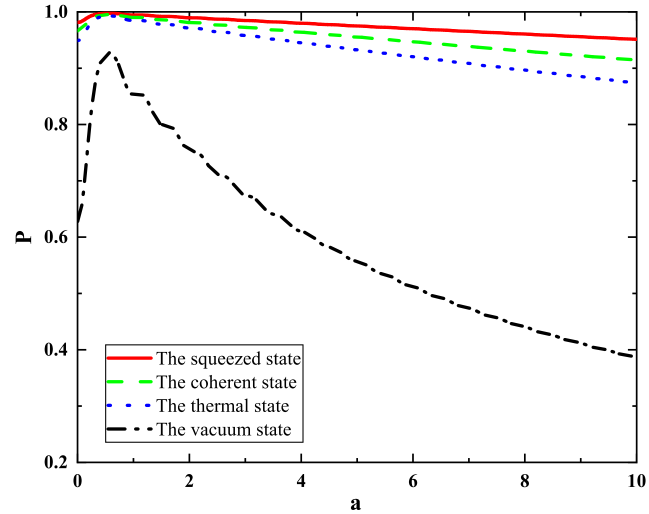

FIG. 5. The transition probability as a function of acceleration a for an accelerated atom with acceleration part of the world line (24). The corresponding parameters are taken as $v_0 = 1.03$, $T = 5.105$, $\Omega = 0.51$, $k = 1$, $\beta = 0.06728$, $\alpha = 4$, $r = 2.4$.

for the uniformly accelerated motion. Since the stimulated absorption term is suppressed and the stimulated Unruh effect term dominates for a specific energy gap of the atom, we can discuss whether the anti-Unruh effect exists with such an atomic energy gap. The expression of the transition probability in Eq. (13) is rewritten as

$$P = \sum_{n_k} |p_{n_k}|^2 (n_k + 1) |\eta_{(+,k)}|^2, \tag{25}$$

where $\eta_{(-,k)}$-related terms have infinitesimal values and are neglected here. Figure 5 presents the anti-Unruh effect for the different field states when the energy difference takes $\Omega = 0.51$ where the stimulated absorption term is suppressed. Note that the acceleration part of the detector's world line (24) is only considered here since the inertial parts will disturb the judgement on the existence of the anti-Unruh effect. In particular, the slight rising of the curve at the small acceleration in Fig. 5 is due to the integral of the finite time for calculating $\eta_{(+,k)}$. As we have checked, if the time for the integral in $\eta_{(+,k)}$ in expanded to infinity, the rising phenomena at the small acceleration in Fig. 5 will disappear. It is seen in Fig. 4 that the anti-Unruh effect can be enhanced by the stimulated interaction process under the condition that acceleration-induced transparency happens. According to our calculation, more enhancement is realized using the squeezed field states than any other field state. From Eq. (25), it is not hard to see that the transition probability is increased approximately n times when the atom is accelerated in the electromagnetic field, compared with the case in which the atom is accelerated in the vacuum. As the analyses made for Fig. 2, the observation is possible under the present experimental conditions, but it deserves further study about how to implement the experiment. For our discussion here, the anti-Unruh effect and the acceleration-induced transparency can appear at the same time, although each one of them requires a specific energy level gap to be realized.

V. CONCLUSION

In this paper, we investigate the transition process of a two-level atom as the UDW detector accelerated in the electromagnetic field. We calculate the transition probability of the accelerated atom initially at the ground state for different field states, including the Fock state, the coherent state, the thermal state, and the squeezed state. The transition probability is enhanced even when the anti-Unruh effect happens. Meanwhile, it is found that the enhancement phenomenon is more prominent by choosing the squeezed state than by choosing any other state as the field state. However, this enhancement includes the contribution from the stimulated Unruh effect term and the stimulated absorption term. The latter one can disturb the estimation for the existence of anti-Unruh effect. We select a specific trajectory for the accelerated atom to suppress the contribution to the transition probability from the stimulation absorption term. This is just the recently found acceleration-induced transparency if the stimulation absorption term can be much suppressed for the atoms with a specific energy difference. When the acceleration-induced transparency is realized, we find that the anti-Unruh effect still appears, which shows that the stimulated interaction between the accelerated atom and the field can enhance the possibility of observing the anti-Unruh effect experimentally. Since the anti-Unruh effect leads to some different phenomena (e.g., entanglement is increased with the increasing acceleration) from that caused by the

Unruh effect or the usual thermal effect [22–24], it is more advantageous to detect the anti-Unruh effect in the future feasible experiment using the squeezed state as the background field.

ACKNOWLEDGMENTS

This work is supported by Grant No. 11654001 of the National Natural Science Foundation of China (NSFC).

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