# The entanglement of two moving atoms interacting with a single-mode field via a three-photon process*

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In this paper, the entanglement of two moving atoms induced by a single-mode field via a three-photon process is investigated. It is shown that the entanglement is dependent on the category of the field, the average photon number $N$, the number $p$ of half-wave lengths of the field mode and the atomic initial state. Also, the sudden death and the sudden birth of the entanglement are detected in this model and the results show that the existence of the sudden death and the sudden birth depends on the parameter and the category of the mode field. In addition, the three-photon process is a higher order nonlinear process.

**Keywords:** induced entanglement, three-photon process, sudden death and sudden birth
**PACC:** 0367, 4250

## 1. Introduction

It is well known that entanglement plays an important role in quantum information theory. Quantum entanglement (QE) provides strong tests of quantum non-locality[1] and it is of great importance to create and manipulate an entangled state for quantum information application. Recently, this subject has become one theme of researches connected with the realization of many quantum information protocols, including quantum cryptograpy,[2] quantum teleportation[3] and quantum computations,[4] and so on. For future applications such as quantum networks and the quantum repeater,[5] it is crucial to achieve entanglement between separated quantum processors like atoms and photons which forms the interface between atomic quantum memories and photonic quantum communication channels.[6,7] The entanglement of two two-level atoms induced by a single-mode thermal field has been studied by Kim *et al.*,[8] and the same problem through a two-photon process with or without dipole–dipole interaction[9,10] has been studied. Considering the motion of the atoms, the T–C model with two moving atoms has been investigated[11] and the authors have shown the sudden death and sudden birth of entanglement called ESD and ESB,[12−18] have been also experimentally observed for entangled photon pairs[19] and atom ensembles.[20] In addition to the single-photon process and two-photon process, people are also interested in studying multi-photon treatment. Recently, in practical applications, three-photon transition in the hydrogen atom immersed in Debye plasmas has been investigated,[21] where the hydrogen atomic motion has been neglected. Considering the actual situation, our attention is mainly paid to the study of the QE of two moving atoms interacting with a single-mode field via a three-photon process.

The structure of this article is arranged as follows: the model is given in Section 2. Two cases of the single-mode field are discussed and the analysis of the induced atom-entanglement for different initial states of moving atoms and the parameters of the mode field are given. Also the ESD and ESB are investigated in Section 3. Finally, the conclusion is given in Section 4.

## 2. The model

In this model, we consider two identical moving atoms interacting with a single-mode field in the cavity through a three-photon process. In the rotating wave approximation, the Hamiltonian can be written

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as (set $\hbar$=1):

$$H = \omega a^{\dagger}a + \omega_0 \sum_{i=A,B} S_z^i + g \sum_{i=A,B} f_{(z_i)}(a^3 S_+^i + a^{\dagger 3} S_-^i), \quad (1)$$

where $a^{\dagger}$ and $a$ are the creation and annihilation operators of the field, $S_+^i$ and $S_-^i$ are the rising and lowering operators for the $i$-th atom. $\omega$, $\omega_0$ are the frequencies of the field and atom, respectively. Our discussion is focused on the resonant case ($\omega_0 = \omega$), $g$ is the atom–field coupling constant, and the atomic motion is restricted in the $z$-axis direction so that only the $z$-dependent field-mode function needs to be considered. $f(z_i)$ $(i = A, B)$ denotes the mode structure of the $i$-th atom, which can be specified as

$$f(z_i) \to f(v_i t) = \sin\left(\frac{p\pi v_i t}{L}\right), \quad (2)$$

where $p$ represents the half-wave number of the field in a cavity of length $L$, $v_i$ is the $i$-th atomic velocity. For simplicity, we consider that the two atoms have the same velocity, as a result, $f(z_A) = f(z_B)$.

Now let the density operator of the single-mode field be $\rho_f(0) = |\Psi_{fi}(0)\rangle\langle\Psi_{fi}(0)|$ and the two atoms enter the cavity with the state $|\Psi_{at}(0)\rangle$, so the initial density operator of the system is

$$\rho_{(f-a)}(0) = |\Psi_{at}(0)\rangle\langle\Psi_{at}(0)| \otimes \rho_f(0). \quad (3)$$

Using the Hamiltonian of Eq. (1) in the interacting picture and the standard techniques, we can obtain the exact time evolution operator $U_{\rm I}(t)$ for this system in the atomic basis $\{|ee\rangle, |eg\rangle, |ge\rangle, |gg\rangle\}$:

$$U_I(t) = \begin{pmatrix} u_{11} & u_{12} & u_{13} & u_{14} \\ u_{21} & u_{22} & u_{23} & u_{24} \\ u_{31} & u_{32} & u_{33} & u_{34} \\ u_{41} & u_{42} & u_{43} & u_{44} \end{pmatrix},$$

where

$$\begin{aligned}
&c_1(n) = 2[(a^{\dagger}a+6)(a^{\dagger}a+5)(a^{\dagger}a+4) + (a^{\dagger}a+3)(a^{\dagger}a+2)(a^{\dagger}a+1)],\\
&c_2(n) = 2[(a^{\dagger}a+3)(a^{\dagger}a+2)(a^{\dagger}a+1) + (a^{\dagger}a)(a^{\dagger}a-1)(a^{\dagger}a-2)],\\
&c_3(n) = 2[(a^{\dagger}a)(a^{\dagger}a-1)(a^{\dagger}a-2) + (a^{\dagger}a-3)(a^{\dagger}a-4)(a^{\dagger}a-5)],\\
&c_1(n-3) = c_2(n), \quad c_2(n-3) = c_3(n), \quad c_1(n-6) = c_3(n),\\
&u_{11} = 1 + \frac{2(a^{\dagger}a+3)(a^{\dagger}a+2)(a^{\dagger}a+1)}{c_1(n)}[-1 + \cos(g\Theta_{(t)}\sqrt{c_1(n)})],\\
&u_{12} = u_{13} = -\,\mathrm{i}\,\frac{1}{\sqrt{c_1(n)}}\sin(g\Theta_{(t)}\sqrt{c_{1(n)}})a^3, \qquad u_{14} = \frac{2}{c_1(n)}[-1 + \cos(g\Theta_{(t)}\sqrt{c_1(n)})]a^6,\\
&u_{21} = u_{31} = -\,\mathrm{i}\,\frac{1}{\sqrt{c_2(n)}}\sin(g\Theta_{(t)}\sqrt{c_2(n)})a^{\dagger 3}, \quad u_{22} = u_{33} = \frac{1}{2}[1 + \cos(g\Theta_{(t)}\sqrt{c_2(n)})],\\
&u_{23} = u_{32} = \frac{1}{2}[-1 + \cos(g\Theta_{(t)}\sqrt{c_2(n)})], \qquad u_{24} = u_{34} = -\,\mathrm{i}\,\frac{1}{\sqrt{c_2(n)}}\sin(g\Theta_{(t)}\sqrt{c_2(n)})a^3,\\
&u_{41} = \frac{2}{c_3(n)}[-1 + \cos(g\Theta_{(t)}\sqrt{c_3(n)})]a^{\dagger 6}, \quad u_{42} = u_{43} = -\,\mathrm{i}\,\frac{1}{\sqrt{c_3(n)}}\sin(g\Theta_{(t)}\sqrt{c_3(n)})a^{\dagger 3},\\
&u_{44} = 1 + \frac{2a^{\dagger}a(a^{\dagger}a-1)(a^{\dagger}a-2)}{c_3(n)}[-1 + \cos(g\Theta_{(t)}\sqrt{c_3(n)})] \qquad (4)
\end{aligned}$$

with

$$\Theta_{(t)} = \int_0^t f(v_i t')\mathrm{d}t' = \frac{L}{\pi p v}\left(1 - \cos\frac{\pi p v t}{L}\right). \quad (5)$$

Let the atomic velocity $v = gL/\pi$ (it can be realized in experiment), then $\Theta_{(t)}$ will become

$$\Theta_{(t)} = \frac{1}{pg}[1 - \cos(pgt)]. \quad (6)$$

The density operator of the atom–field system at time $t$ is

$$\rho_{(f-a)}(t) = U_I(t)(\rho_{(f-a)}(0))U_{\rm I}^{\dagger}(t). \quad (7)$$

In order to investigate the entanglement between these two moving atoms, we should obtain the atom–atom density operator and then trace over the field variables

$$\rho_a(t) = \mathrm{Tr}_f[\rho_{(f-a)}(t)] = \begin{pmatrix} \rho_{11}(t) & \rho_{12}(t) & \rho_{13}(t) & \rho_{14}(t) \\ \rho_{21}(t) & \rho_{22}(t) & \rho_{23}(t) & \rho_{24}(t) \\ \rho_{31}(t) & \rho_{32}(t) & \rho_{33}(t) & \rho_{34}(t) \\ \rho_{41}(t) & \rho_{42}(t) & \rho_{43}(t) & \rho_{44}(t) \end{pmatrix}. \quad (8)$$

A convenient measure of the entanglement for a two-qubit system is the concurrence $C$,[22] introduced by Wootters, and given by

$$C = \max\{0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\}, \quad (9)$$

where $\lambda_i$ are the positive eigenvalues, in a decreasing order, of the matrix $\rho(\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$, where $\rho$ is the density matrix of the atomic subsystem, $\rho = \rho_a(t)$, and $\sigma_y$ is the Pauli matrix.

# 3. Entanglement induced by a single-mode field

## 3.1. Entanglement induced by a thermal field

The cavity field is initially in a single-mode thermal state at temperature $T$, and its density operator is represented by

$$\rho_f(0) = \sum_n P_n |n\rangle\langle n|, \quad (10)$$

where

$$P_n = \frac{1}{1+\overline{n}} \left(\frac{\overline{n}}{1+\overline{n}}\right)^n,$$

and the mean photon number $\overline{n} = (\mathrm{e}^{\hbar\beta\omega} - 1)^{-1}, \beta = 1/(k_{\mathrm{B}}T)$, $k_{\mathrm{B}}$ is the Boltzmann constant.

If the atoms are initially in the atomic state $|ee\rangle$, $|eg\rangle$, $|ge\rangle$ or $|gg\rangle$, the density operator of the atoms can be expressed as

$$\rho_a(t) = \begin{pmatrix} \rho_{11}(t) & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \rho_{22}(t) & \rho_{23}(t) & \mathbf{0} \\ \mathbf{0} & \rho_{32}(t) & \rho_{33}(t) & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \rho_{44}(t) \end{pmatrix}. \quad (11)$$

For a atomic system described by the density matrix (11), the concurrence has a simple form

$$C = \max\{0, 2|\rho_{23}(t)| - 2\sqrt{\rho_{11}(t)\rho_{44}(t)}\}. \quad (12)$$

We present numerical results of the concurrence $C$ given by Eq. (12) for different parameters of this system in Fig. 1.

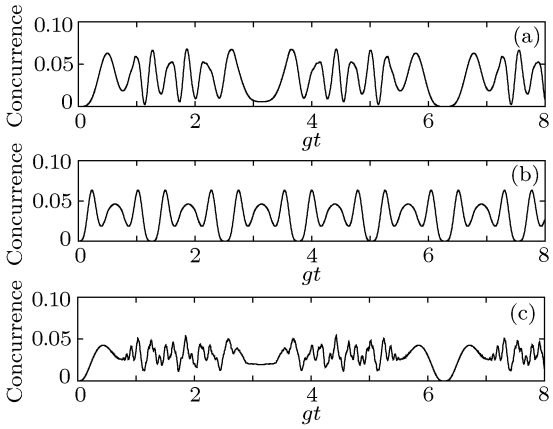



**Fig. 1.** The time evolution of the $C$ for the moving atom–atom entanglement with the initial atomic state $|eg\rangle$. (a) $\bar{n} = 1$, $p = 1$; (b) $\bar{n} = 1$, $p = 5$; (c) $\bar{n} = 10, p = 1$.

First, we discuss the influence of the half-wave number $p$ on the entanglement when the atomic state is initially in the $|eg\rangle$ state. As shown in Figs. 1(a) and 1(b), the concurrence evolves with the period of $T = 2\pi$ in Fig. 1(a) while it evolves with the period of $T = 2\pi/5$ in Fig. 1(b). This periodicity stems from the fact that, from Eq. (6), we have $g\Theta_{(t)} = (1/p)[1 - \cos(pgt)]$, it is observed that $g\Theta_{(t)}$ is a periodical function on the scaled time $gt$ with period $2\pi/p$. At the time $gt = mT$ $(m = 0, 1, 2\ldots)$, the concurrence is zero, otherwise the concurrence is not zero any more. The maximum of the concurrence is only 0.068 roughly, which means that the weakest entanglement is shown. The conclusions are given below: it is found that the atom–atom entanglement is substantially increased at some specific time, and the larger the $p$, the smaller the periodicity is. However the maximum values of the entanglement are almost the same.

The influence of the mean photon number $\bar{n}$ on the QE is displayed in Figs. 1(a) and 1(c). Compared Fig. 1(a) to Fig. 1(c), the evolution of the entanglement does not change greatly, it is similar to the above analysis. When $\bar{n}$ increases from 1 to 10, the maximum values of the entanglement change from 0.068 to 0.055, accompanied by the different number of average photon. That is to say, when the temperature of the thermal field becomes higher, the entanglement can also be induced at high temperature of this system.

Our numerical results show that, there is no entanglement when atomic initial state is $|ee\rangle$ or $|gg\rangle$. But in Ref. [9] the authors studied the two-photon process with static atoms and found the entanglement at some interval in the initial state $|gg\rangle$.

### 3.2. Entanglement induced by a coherent field

The cavity field is initially in the coherent mode field $|\Psi_{fi}(0)\rangle$

$$|\Psi_{fi}(0)\rangle = \sum_{n=0}^{\infty} f_n |n\rangle, \tag{13}$$

where

$$f_n = \exp\left(-\frac{N}{2}\right)\frac{N^{n/2}}{\sqrt{n!}}\exp(\mathrm{i}\,\Upsilon)\,,$$

and $N$ is the average photon number and $\Upsilon$ is the phase angle of the field, here, $\Upsilon = 0$. Then it is easy to get the elements of $\rho_a(t)$:

$$\begin{aligned}
\rho_{11}(t) &= \cos^2(r/2)\sum_n f_n^2 u_{11}|n\rangle\langle n|u_{11} + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{14}|n\rangle\langle n|u_{11} \\
&\quad + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{11}|n\rangle\langle n|u_{14}^* + \sin^2(r/2)\sum_n f_n^2 u_{14}|n\rangle\langle n|u_{14}^*, \\
\rho_{12}(t) &= \cos^2(r/2)\sum_n f_n^2 u_{11}|n\rangle\langle n|u_{21}^* + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{14}|n\rangle\langle n|u_{21}^* \\
&\quad + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{11}|n\rangle\langle n|u_{24}^* + \sin^2(r/2)\sum_n f_n^2 u_{14}|n\rangle\langle n|u_{24}^*, \\
\rho_{14}(t) &= \cos^2(r/2)\sum_n f_n^2 u_{11}|n\rangle\langle n|u_{41}^* + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{14}|n\rangle\langle n|u_{41}^* \\
&\quad + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{11}|n\rangle\langle n|u_{44}^* + \sin^2(r/2)\sum_n f_n^2 u_{14}|n\rangle\langle n|u_{44}^*, \\
\rho_{22}(t) &= \cos^2(r/2)\sum_n f_n^2 u_{21}|n\rangle\langle n|u_{21}^* + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{24}|n\rangle\langle n|u_{21}^* \\
&\quad + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{21}|n\rangle\langle n|u_{24}^* + \sin^2(r/2)\sum_n f_n^2 u_{24}|n\rangle\langle n|u_{24}^*, \\
\rho_{24}(t) &= \cos^2(r/2)\sum_n f_n^2 u_{21}|n\rangle\langle n|u_{41}^* + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{24}|n\rangle\langle n|u_{41}^* \\
&\quad + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{21}|n\rangle\langle n|u_{44}^* + \sin^2(r/2)\sum_n f_n^2 u_{24}|n\rangle\langle n|u_{44}^*, \\
\rho_{44}(t) &= \cos^2(r/2)\sum_n f_n^2 u_{41}|n\rangle\langle n|u_{41}^* + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{44}|n\rangle\langle n|u_{41}^* \\
&\quad + \cos(r/2)\sin(r/2)\sum_n f_n^2 u_{41}|n\rangle\langle n|u_{44}^* + \sin^2(r/2)\sum_n f_n^2 u_{44}|n\rangle\langle n|u_{44}^*, \\
&\rho_{13}(t) = \rho_{12}(t), \quad \rho_{21}(t) = \rho_{31}(t) = \rho_{12}^*(t), \quad \rho_{23}(t) = \rho_{32}(t) = \rho_{33}(t) = \rho_{22}(t), \\
&\rho_{34}(t) = \rho_{24}(t), \quad \rho_{42}(t) = \rho_{43}(t) = \rho_{24}^*(t), \quad \rho_{41}(t) = \rho_{14}^*(t).
\end{aligned} \tag{14}$$

The numerical results of the concurrence $C$ given by Eqs. (9) and (14) for different parameters of this system with different initial atomic states are presented in Fig. 2.

Compared with the above part, this part shows that the atom entanglement can be generated in the initial state with the coherent state of the cavity. As shown in Figs. 2(a) and 2(b), the atomic initial state is in the state $|ee\rangle$, the concurrence evolves with the period of $\tau = \pi$ in Fig. 2(a) while it evolves with the period of $\tau = 2\pi/5$ in Fig. 2(b). As the same to the above section, this periodicity stems from the fact that, we have $g\Theta_{(t)} = (1/p)[1 - \cos(pgt)]$, it is observed that $g\Theta_{(t)}$ is a periodical function of the scaled time $gt$ with period $2\pi/p$. The maximum values of the concurrence are 0.18 in Fig. 2(a) and 0.1 in Fig. 2(b), respectively. The results show that the larger the $p$ is, the smaller the maximum value of the concurrence is. Secondly, the time evolution of the concurrence with the initial state $|gg\rangle$ is shown in Figs. 2(c) and 2(d), the periodicity is also $2\pi/p$. The maximum of the concurrence is 0.33 in Fig. 2(c) and 0.22 in Fig. 2(d). It is

found that the maximum QE with the initial state $|gg\rangle$ is larger than that in $|ee\rangle$. Thirdly, in Fig. 2, it can be seen that no matter how the initial atomic state is, the concurrence of the entanglement is zero not only at $n(2\pi/p)$ $(n = 0, 1, 2\ldots)$ but also in some special continuous short-lived time, which means that there is no entanglement between the two moving atoms. Fourthly, the situation when the atoms initial state is $|eg\rangle$ is similar. We would like to emphasize that the atom–atom entanglement induced by coherent-mode field is larger than that induced by a thermal field, that is to say, the entanglement is dependent on the category of the field.

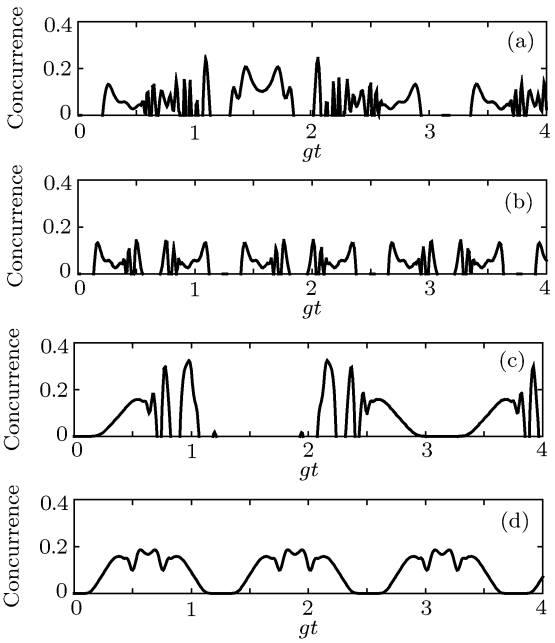



**Fig. 2.** The time evolution of the concurrence for the moving atom–atom entanglement with the initial atomic state $|\Psi_{at}(0)\rangle = \cos(r/2)|ee\rangle + \sin(r/2)|gg\rangle$ with $N = 5$ (a) $r = 0, p = 2$; (b) $r = 0, p = 5$; (c) $r = \pi, p = 2$; (d) $r = \pi, p = 5$.

In the above study, we have discussed a special case that the moving atomic system is in a direct product state. The study for the case of the atomic state being an entangled state is presented in Fig. 3. We can see the periodic death and birth of the entanglement between the atoms interacting with a coherent field, but we cannot see this phenomenon if the atoms interact with a thermal field.

The influence of the parameters $p$ and $N$ of the field on the entanglement between the moving atoms is shown in Fig. 3. In Fig. 3(a), when the two moving atoms are initially in the maximal entangled state, it is found that there are periodic death and periodic birth of the atom–atom entanglement when $N = 5$. However when $N = 2$, this phenomenon does not appear but the entanglement only gradually reduces and increases, as shown in Fig. 3(c). The numerical results of the concurrence $C$ also show that the ESB and ESD disappear when $N = 3$, as shown in Fig. 3(b). As a matter of fact, when $N \geq 5$, the periodic death and periodic birth of the atom–tom entanglement can be detected. Secondly, the periodicity stems from the fact that $g\Theta_{(t)}$ is a periodical function of the scaled time $gt$ with period $2\pi/p$, thus the period of death and birth becomes smaller when $p$ becomes larger.

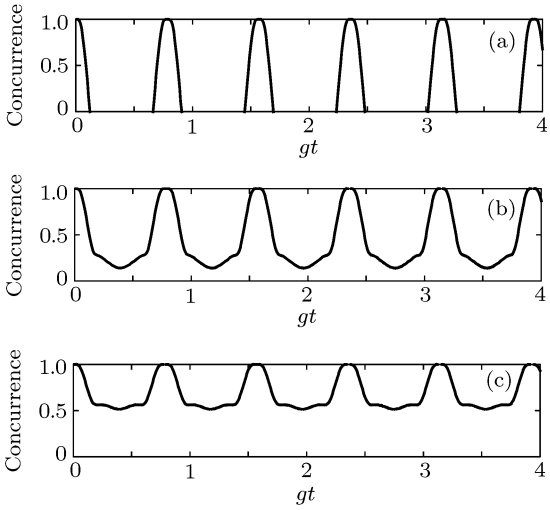



**Fig. 3.** The time evolution of the $C$ for the moving atom–atom entanglement with the initial atomic state $|\Psi_{at}(0)\rangle = (|ee\rangle + |gg\rangle)/\sqrt{2}$ with $p = 8$ (a) $N = 5$; (b) $N = 4$; (c) $N = 2$.

In Fig. 2, atom–atom entanglement induced by coherent-mode field, is also sudden reduce and increase in some special time, that is to say, there exist sudden death and sudden birth of the atom–atom entanglement. But in Fig. 1, atom–atom entanglement induced by thermal field is gradually reduce and increase (expect at some special time the concurrence is zero), that is to say, there are no sudden death or sudden birth.

Now let us pay attention to the essential differences between this paper and Ref. [11] in which the single-photon process was studied. The differences are the following: (i) the maximum QE with single-photon is bigger than that with three-photon. (ii) The oscillation of the concurrence in three-photon process is fiercer than that in single-photon process in a period, this situation stems from the fact that the three-photon process is a higher order nonlinear process.

Can three-photon process be realized? Yes. We let $E_f - E_g = 3\omega$, where $E_{\rm g}$ and $E_{\rm f}$ are energies of

initial state and final state, $\omega$ is the frequency of the field. three-photon transition in the hydrogen atom immersed in Debye plasmas has been investigated in Ref. [21] based on the condition that angular momentum channels are available for three-photon bound–bound transition of ground state with linearly polarized light as shown in Fig. 4, There are three possibilities for three photon processes (transitions), including 1S–P–D–nP, 1S–P–S–nP and 1S–P–D–nF, but three-photon processes cannot be easily realized.

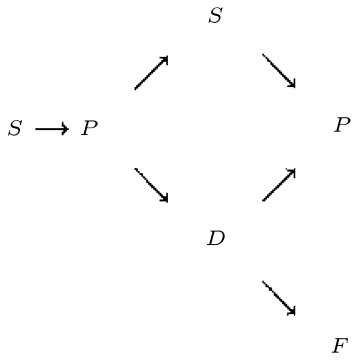



**Fig. 4.** Angular momentum channels for three-photon bound–bound transition.

## 4. Conclusions

The evolution of the entanglement between two moving atoms interacting with a single-mode field via a three-photon process is studied. The conclusions can be obtained as follows. i) As the same for the two-photon process, the three-photon process which shows nonlinear behaviour, is similar to the single-photon process that can induce atom entanglement. Moreover, we would like to emphasize that the atom–atom entanglement, induced by a coherent mode field, is larger than the entanglement induced by a thermal field. ii) In the case of the thermal field, there is no entanglement when the atomic initial state in $|ee\rangle$ or $|gg\rangle$ in a two-photon process with static atoms, the authors examined the entanglement in some interval in the initial state $|gg\rangle$; there is entanglement when atoms are initially in the state $|eg\rangle$, and it evolves periodically due to the atom motion. Furthermore, it is shown that the larger the $p$ is, the smaller the periodicity is. iii) In the case of the coherent field, there is entanglement whatever the atomic initial state in $|ee\rangle$, $|eg\rangle$ or $|gg\rangle$. The larger the $p$ is, the smaller the maximum value of concurrence is, and there is sudden death and sudden birth of the atom–atom entanglement. iv) If the atoms are in the entangled state initially, there are no ESD and ESB and the concurrence is increased or decreased continuously in the thermal field. However, in the case of the coherent field, there are ESD and ESB, and when $N \geq 5$, the ESD and ESB can be seen. It is also shown that the larger the $p$, the smaller the periodicity is. v) The three-photon process is a higher order nonlinear process.

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