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A.S.Shumovsky, Tran Quang\*

**RESONANCE FLUORESCENCE  
FROM ATOMS IN A CAVITY**

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\* Moscow State University, Moscow, USSR

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## I. Introduction

In recent years the Jaynes-Cummings and Tavis-Cummings models provide the basis for quantum optics and micromaser physics, see [1-4]. A number of interesting effects such as the enhancement and suppression of spontaneous emission [5-8], vacuum field Rabi oscillations [9-11], collapse and revival [12] have been observed experimentally. Recently, the spectrum for the fluorescence photons from one or two atoms in a cavity has been calculated [13-17].

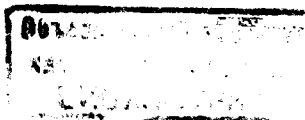
In this paper we discuss the spectral and statistical properties in the fluorescence field from  $N$  two-level atoms interacting with an intense cavity mode. The intensities and photon statistics of the spectrum components, cross-correlations between them and violation of the classical Cauchy-Schwarz (C-S) inequality are discussed. The novel results, quite different from collective resonance fluorescence in a free space have been obtained.

## II. Spectral properties of the fluorescence field

We consider a system of  $N$  two-level atoms interacting with a single cavity mode. Atoms are assumed to be placed in a cell of dimensions smaller than the wavelength of the field. In the case of an intense cavity mode, when it can be treated classically, the Hamiltonian of the system in the interaction representation has the following form

$$H = \frac{\delta}{2} (J_{12} - J_{11}) + G (J_{12} + J_{21}) \quad , \quad (1)$$

where  $\delta = \omega_{21} - \omega_L$  is the detuning of the cavity mode frequency  $\omega_L$  from the atomic resonance frequency  $\omega_{21}$ ;  $G$  is one half of



the resonance Rabi frequency describing the interaction of the intense cavity mode with the atomic system

$$J_{ij} = \sum_{k=1}^N |i\rangle_k \langle j| \quad (i, j=1, 2) \quad \text{are}$$

the collective operators for the atomic system. They satisfy the commutation relation

$$[J_{ij}, J_{i'j'}] = J_{ij} \delta_{j'i'} - J_{i'j'} \delta_{ij'} \quad (2)$$

Following previous works [18,19] we introduce the Schwinger representation for the collective atomic operators

$$J_{ij} = a_i^+ a_j \quad (i, j = 1, 2) \quad (3)$$

where the operators  $a_i$  and  $a_i^+$  obey the boson commutation relations

$$[a_i, a_j^+] = \delta_{ij}$$

and can be treated as the annihilation and creation operators for the atoms being populated in the level  $|i\rangle$

After performing the canonical (dressing) transformation

$$\begin{aligned} a_1 &= c_1 \cos \varphi + c_2 \sin \varphi \\ a_2 &= -c_1 \sin \varphi + c_2 \cos \varphi \end{aligned} \quad (4)$$

where

$$\tan 2\varphi = 2G/\delta \quad (5)$$

the Hamiltonian (1) reduces to the form

$$H = \Omega (c_2^+ c_2 - c_1^+ c_1) \quad (6)$$

where  $\Omega = (\frac{1}{4} \delta^2 + G^2)^{1/2}$

The equations of motion for the operators  $C_1(t)$  and  $C_2(t)$  are easily solved exactly and have the simple exponential form. By using the exact forms of the operators  $C_1(t)$ ,  $C_2(t)$  and canonical transformation (4) one can write the collective atomic operators  $J_{ij}(t)$  in the following form

$$J_{21}(t) = e^{2i\Omega t} S_1^+ + e^{-2i\Omega t} S_{-1}^+ + S_0 \quad (7)$$

$$J_{12}(t) = (J_{21}(t))^+ \quad (8)$$

where

$$S_0 = \sin \varphi \cos \varphi \{ \cos 2\varphi J_3 + \sin 2\varphi (J_{12} + J_{21}) \} \quad (9)$$

$$S_1^+ = \cos^2 \varphi \left\{ -\frac{1}{2} \sin 2\varphi J_3 + \cos^2 \varphi J_{21} - \sin^2 \varphi J_{12} \right\} \quad (10)$$

$$S_{-1}^+ = \sin^2 \varphi \left\{ \frac{1}{2} \sin 2\varphi J_3 + \sin^2 \varphi J_{21} - \cos^2 \varphi J_{12} \right\} \quad (11)$$

$$J_3 = J_{22} - J_{11} \quad (12)$$

Following refs. [13-15] we define the transient spectrum of the fluorescence in other modes as

$$S_F(\nu, \tau) = 2\Gamma \int_0^\tau dt_1 \int_0^\tau dt_2 e^{-(\Gamma-i\nu)(\tau-t_1) - (\Gamma+i\nu)(\tau-t_2)} \cdot \langle J_{21}(t_1) J_{12}(t_2) \rangle \cdot e^{-i\omega_L(t_2-t_1)} \quad (13)$$

where  $\Gamma$  is the bandwidth of the detector,  $T$  is the time at which the spectrum is evaluated. The  $\langle \dots \rangle$  stands for the average over the initial state of the atomic system.

By using the definition of fluorescence spectrum (13) and eqs. (7-8) we show that for the case of the intense cavity mode the terms in the fluorescence spectrum (13) which are proportional to  $\Omega^{-1}$  can be ignored (the secular approximation) and the operators  $S_{-1}$ ,  $S_0$  and  $S_{+1}$  can be considered as the operator-sources of the spectrum components at frequencies  $\omega_L - 2\Omega$ ,  $\omega_L$  and  $\omega_L + 2\Omega$ , respectively [19-21].

Let the atoms be initially in the state

$$S_a = |n_1, n_2\rangle \langle n_2, n_1|, \quad (14)$$

where

$$J_{22} |n_1, n_2\rangle = n_2 |n_1, n_2\rangle,$$

$$J_{11} |n_1, n_2\rangle = n_1 |n_1, n_2\rangle.$$

Then, the intensities of the spectrum components  $S_i$  ( $i = \pm 1, 0$ ) have the following form

$$\begin{aligned} I_+ &= \langle S_+^\dagger S_+ \rangle = \cos^4 \zeta \left\{ \frac{1}{4} \sin^2 2\zeta D^2 + \right. \\ &\quad \left. + \cos^4 \zeta B_+ + \sin^4 \zeta B_- \right\} \equiv \cos^4 \zeta \tilde{I}_+, \quad (15) \\ I_- &= \langle S_-^\dagger S_- \rangle = \sin^4 \zeta \left\{ \frac{1}{4} \sin^2 2\zeta D^2 + \right. \end{aligned}$$

$$\left. + \sin^4 \zeta B_+ + \cos^4 \zeta B_- \right\} \equiv \sin^4 \zeta \tilde{I}_-, \quad (16)$$

$$\begin{aligned} I_0 &= \langle S_0^\dagger S_0 \rangle = \frac{1}{4} \sin^2 2\zeta \left\{ \cos^2 2\zeta D^2 + \right. \\ &\quad \left. + \sin^2 2\zeta B \right\} = \frac{1}{4} \sin^2 2\zeta \tilde{I}_0, \quad (17) \end{aligned}$$

where

$$D = \langle J_3 \rangle = n_2 - n_1, \quad (18)$$

$$B_+ = \langle J_{21} J_{12} \rangle = \frac{1}{4} (N^2 - D^2 + 2N + 2D), \quad (19)$$

$$B_- = \langle J_{12} J_{21} \rangle = \frac{1}{4} (N^2 - D^2 + 2N - 2D), \quad (20)$$

$$B = B_+ + B_- = \frac{1}{2} (N^2 - D^2 + 2N). \quad (21)$$

One can show from eqs. (15)-(17) that in the off-resonance case

$\text{ctg}^2 \zeta \neq 1$  the intensities of all the three spectrum components  $S_0, S_{\pm 1}$  are proportional to  $N^2$  moreover  $I_+ \neq I_-$  without the case of  $D=0$  or  $\text{ctg}^2 \zeta = 1$  thus the fluorescence spectrum is nonsymmetric without the case of  $D=0$  (which is possible only for even  $N$ ) or  $\text{ctg}^2 \zeta = 1$  (the exact resonance). These properties are quite different from the collective resonance fluorescence in a free space [23] where for the case of an intense external field and off-resonance the intensities of the side-bands are proportional only to  $N$  and the fluorescence spectrum is symmetric ( $I_+ = I_-$ ).

For exact resonance  $\text{ctg}^2 \zeta = 1$  and  $D = \pm N$  eqs. (15)-(17) reduce to [24]

$$I_{+1} = I_{-1} = \frac{1}{16} (N^2 + N), \quad (22)$$

$$I_0 = \frac{1}{4} N. \quad (23)$$

It means that the intensities of the sidebands  $S_{\pm 1}$  are proportional to  $N$  while the intensity of the center component  $S_0$  is proportional to  $N$ . This result is also essentially different from the collective resonance fluorescence in the free space [22-23] where for the exact resonance the intensities of all the three spectrum components of the Molow triplet are proportional to the square of the number of atoms. For the case of  $ctg^2\zeta = 1$  and  $N=1$  the relations (22)-(23) are in agreement with the previous work [15].

### III. Statistical properties

In this section we discuss the photon statistics of spectrum components  $S_0$ ,  $S_{\pm 1}$  and generation of the sub-Poissonian light that has the potential application in the quantum nondemolition measurement [26] and detection of a gravitational wave [25]. We also discuss the correlation and anticorrelation between spectrum components and violation of the C-S inequality.

Following previous works [27] we define the degree of the second-order coherence of the fluorescence light to be

$$G_{i,j}^{(2)} = \frac{\langle S_i^+ S_j^+ S_j S_i \rangle}{\langle S_i^+ S_i \rangle \langle S_j^+ S_j \rangle} \quad i, j = 0, \pm 1 \quad (24)$$

The quantities  $G_{i,i}^{(2)}$  ( $i=0, \pm 1$ ) describe the photon statistics of the spectrum component  $S_i$  and the quantities  $G_{i,j}^{(2)}$  ( $i \neq j$ ) describe the cross-correlations between the spectrum components  $S_i$  and  $S_j$  ( $i, j = 0, \pm 1$ ).

Using the expressions (9)-(11) for the operator  $S_0$ ,  $S_{\pm 1}$  and atomic initial state (14) one can find

$$G_{0,0}^{(2)} = 1 + [\sin^4 2\zeta (B_+^2 + B_-^2 + D^2 - 2B) + 4 \sin^2 2\zeta \cos^2 2\zeta (D^2 B - 2D^2 + B)] / \tilde{I}_0^2, \quad (25)$$

$$G_{-1,-1}^{(2)} = \left[ \frac{1}{16} \sin^4 2\zeta (D^2 - B)^2 + \sin^6 \zeta (B_+^2 + DB_+ - 2B_+) + \cos^6 \zeta (B_-^2 - DB_- - 2B_-) + \sin^2 2\zeta \sin^4 \zeta \cdot (D^2 B_+ - 2DB_+ + B_+) + \sin^2 2\zeta \cos^4 \zeta (D^2 B_- + 2DB_- + B_-) \right] / \tilde{I}_{-1}^2, \quad (26)$$

$$G_{1,1}^{(2)} = G_{-1,-1}^{(2)} (\cos^2 \zeta \leftrightarrow \sin^2 \zeta), \quad (27)$$

where the quantities  $\tilde{I}_{\pm 1}$ ,  $\tilde{I}_0$ ,  $D$ ,  $B_{\pm}$  and  $B$  are found according to the relations (15)-(21).

For a single-atom case  $N=1$  the relations (25)-(27) reduce to

$$G_{0,0}^{(2)} = 1, \quad (28)$$

$$G_{1,1}^{(2)} = G_{-1,-1}^{(2)} = 0, \quad (29)$$

thus the center component  $S_0$  has the Poissonian statistics while the sidebands  $S_{\pm 1}$  have the sub-Poissonian statistics. The same photon statistics are obtained for the spectrum components of resonance fluorescence from one atom in a free space [20-21]. For the case of the exact resonance, i.e.  $ctg^2\zeta = 1$ , and  $D = \pm N$  the relations (25)-(27) reduce to [24]

$$G_{0,0}^{(2)} = 1 + 2 \frac{N-1}{N}, \quad (30)$$

$$G_{-1,-1}^{(2)} = G_{1,1}^{(2)} = 1 - 2 \frac{3N-1}{N(N+1)^2} \quad (31)$$

In this exact resonance case we have  $G_{0,0}^{(2)} > 1$  and  $G_{1,1}^{(2)} = G_{-1,-1}^{(2)} < 1$  for  $N > 1$ . It means that the center component  $S_0$  becomes the super-Poissonian light when the number of atoms is larger than unity while the two sidebands  $S_{-1}$  and  $S_{+1}$  have the same degree of the second-order coherence and remain the sub-Poissonian light for the collective case. This property is different from the collective resonance fluorescence in a free space [19] where the two sidebands have the sub-Poissonian statistics only for the case of several atoms.

For the general off-resonance case  $\text{ctg}^2 \mathcal{G} \neq 1$  one can show from eqs. (26)-(27) that the degrees of the second-order coherence  $G_{-1,-1}^{(2)}$  and  $G_{1,1}^{(2)}$  are nonequal except for the case of  $D=0$  or  $N=1$ , thus the two sidebands in the general case ( $\text{ctg}^2 \mathcal{G} \neq 1$ ,  $D \neq 0$ ,  $N > 1$ ) have various photon statistics for the same parameters of the system. This property is also different from collective resonance fluorescence in a free space [19] where the two sidebands have the identical photon statistics.

The behaviour of the quantities  $G_{0,0}^{(2)}$  and  $G_{-1,-1}^{(2)}$  as functions of the parameter  $\text{ctg}^2 \mathcal{G}$  for various numbers of atoms  $N$  and for  $D=-N$  (solid curves) and  $D=N$  (dashed curves) is plotted in fig. 1a,b. As is seen from fig. 1a for the collective case the center component  $S_0$  remains to obey the super-Poissonian statistics for off-resonance  $\text{ctg}^2 \mathcal{G} \neq 1$ . The two sidebands can have the sub-Poissonian or super-Poissonian statistics depending on the parameter  $\text{ctg}^2 \mathcal{G}$  (see fig. 1b).

Further, we discuss the cross-correlations between the spectrum components. Applying the expressions (9)-(11) and (14)

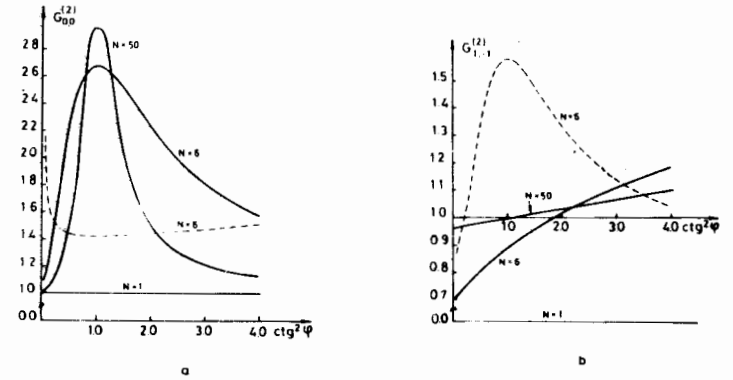


Fig. 1a-b The quantities  $G_{0,0}^{(2)}$  and  $G_{1,1}^{(2)}$  as functions of  $\text{ctg}^2 \mathcal{G}$  for  $D=-D$  (solid curves) and  $D=D$  (dashed curve).

one can find

$$G_{-1,-1}^{(2)} = \frac{1}{\tilde{I}_1 \tilde{I}_{-1}} \cdot \left\{ \left( \frac{1}{4} \sin^2 2\mathcal{G} D^2 + \cos^4 \mathcal{G} B_+ + \sin^4 \mathcal{G} B_- \right)^2 + \sin^4 \mathcal{G} \cos^4 \mathcal{G} (B_+^2 + B_-^2 + D^2 - 2B) + \frac{1}{4} \sin^2 2\mathcal{G} \cdot \left[ \cos^2 2\mathcal{G} D^2 B + 4 \sin^4 \mathcal{G} (DB_- + B_-) + 4 \cos^4 \mathcal{G} (B_+ - DB_+) + \sin^2 2\mathcal{G} D^2 \right] \right\} \quad (32)$$

$$G_{-1,1}^{(2)} = G_{1,-1}^{(2)} (\cos^2 \mathcal{G} \leftrightarrow \sin^2 \mathcal{G}) \quad (33)$$

$$G_{1,0}^{(2)} = \frac{1}{\tilde{I}_1 \tilde{I}_0} \cdot \left\{ \sin^2 2\mathcal{G} \left[ \left( -\frac{1}{2} \cos 2\mathcal{G} D^2 + \cos^2 \mathcal{G} B_+ - \sin^2 \mathcal{G} B_- \right)^2 + \cos^4 \mathcal{G} (B_+^2 + DB_+ - 2B_+) + \sin^4 \mathcal{G} (B_-^2 - DB_- - 2B_-) + \frac{1}{4} \sin^2 2\mathcal{G} D^2 B - \cos 2\mathcal{G} \cdot \cos^2 \mathcal{G} \cdot D(D-2) B_+ + \cos 2\mathcal{G} \sin^2 \mathcal{G} \cdot D(D+2) B_- \right] + \cos^2 2\mathcal{G} \left[ \cos^4 \mathcal{G} (D-2)^2 B_+ + \sin^4 \mathcal{G} (D+2)^2 B_- \right] \right\} \quad (34)$$

$$G_{-1,0}^{(2)} = G_{1,0}^{(2)} (\cos^2 \zeta \leftrightarrow \sin^2 \zeta) \quad (35)$$

$$G_{0,1}^{(2)} = \frac{1}{\tilde{I}_+ \tilde{I}_0} \left\{ \sin^2 2\zeta \left[ \left(-\frac{1}{2} \cos 2\zeta D^2 + \cos^2 \zeta B_+ + \sin^2 \zeta B_-\right)^2 + \cos^4 \zeta (B_+^2 + DB_+ - 2B_+) + \sin^4 \zeta (B_-^2 - DB_- - 2B_-) + \frac{1}{4} \sin^2 2\zeta (D-2)^2 B_+ + \frac{1}{4} \sin^2 2\zeta (D+2)^2 B_- - \cos^2 \zeta \cos 2\zeta D(D-2) B_+ + \sin^2 \zeta \cos 2\zeta D(D+2) B_- \right] + \cos^2 2\zeta [\cos^4 \zeta D^2 B_+ + \sin^4 \zeta D^2 B_-] \right\} \quad (36)$$

$$G_{0,-1}^{(2)} = G_{0,1}^{(2)} (\cos^2 \zeta \leftrightarrow \sin^2 \zeta) \quad (37)$$

where the quantities  $\tilde{I}_{\pm 1}$ ,  $\tilde{I}_0$ ,  $D$ ,  $B_{\pm}$  and  $B$  can be found in the relations (15)-(21).

In the case of one atom  $\tilde{u}=1$ ,  $\tilde{v}=\underline{1}$  the relations (32)-(37) reduce to

$$G_{1,0}^{(2)} = G_{0,1}^{(2)} = G_{-1,0}^{(2)} = G_{0,-1}^{(2)} = 1 \quad (38)$$

$$G_{1,-1}^{(2)} = \begin{cases} 1 + \text{tg}^2 \zeta & \text{if } D = -1 \\ 1 + \text{ctg}^2 \zeta & \text{if } D = 1 \end{cases} \quad (39)$$

$$G_{-1,1}^{(2)} = \begin{cases} 1 + \text{ctg}^2 \zeta & \text{if } D = -1 \\ 1 + \text{tg}^2 \zeta & \text{if } D = 1 \end{cases} \quad (40)$$

It means that in the single-atom case there is the correlation between the two sidebands and no correlation is between the side components and the central one.

Another picture follows for the collective case. The behaviour of the nondelayed correlation functions  $G_{1,-1}^{(2)}$ ,  $G_{1,0}^{(2)}$ ,  $G_{0,1}^{(2)}$  is plotted in fig.2a,b,c against the parameter  $\text{ctg}^2 \zeta$  for various

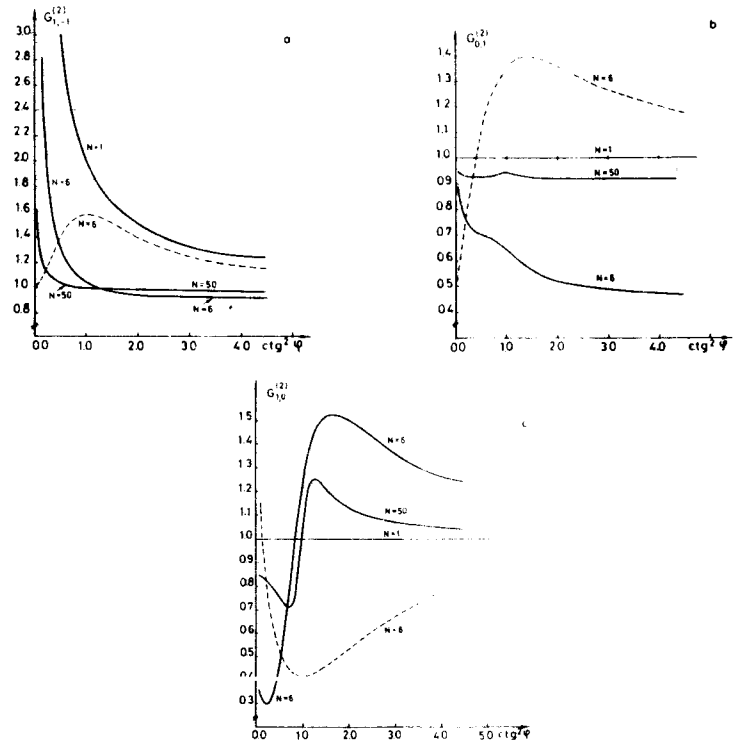


Fig.2a-c The quantities  $G_{1,-1}^{(2)}$ ,  $G_{1,0}^{(2)}$  and  $G_{0,1}^{(2)}$  as functions of  $\text{ctg}^2 \zeta$  for  $D = -N$  (solid curves) and  $D=0$  (dashed curve).

numbers of atoms  $N$  and for  $D = -N$ , i.e. for the atoms being initially in the ground state (solid curves) and for  $D=0$  (dashed curves).

As is seen from fig.2a-c for the case  $N > 1$ , the correlation ( $G_{i,j}^{(2)} > 1$ ) or anticorrelation ( $G_{i,j}^{(2)} < 1$ ) are present between any two spectrum components  $S_i$  and  $S_j$  ( $i \neq j$ ;  $1, j = 0, \pm 1$ ) in dependence on the system parameters  $D$  and  $\text{ctg}^2 \zeta$ . These results are different from the collective resonance fluorescence where the only correlation between side-

bands and the only anticorrelation between side components and central one are present [19].

Finally, we discuss the violation of the Cauchy-Schwarz (C-S) inequality for the correlation between spectrum components

The violation of the C-S inequality has been observed by Clauser [28] in the two-photon cascade emission in an optical double resonance experiment. This nonclassical effect has also been predicted in the two-photon laser [29], parametric amplifiers [30], the collective resonance fluorescence [31], and collective double optical resonance [32-33] and in the second-harmonic generation [34].

We see that the violation of the C-S inequality takes place for the correlation between spectral components  $S_i$  and  $S_j$  if the following condition is satisfied [27]

$$\left( G_{i,j}^{(2)} \right)^2 > G_{i,i}^{(2)} \cdot G_{j,j}^{(2)} \quad (i \neq j; i, j = 0, \pm 1) \quad (41)$$

For the single-atom case  $N=1$ , by using the relations (28)-(29) and (38)-(40) one can easily verify that the condition (41) is satisfied for any  $i \neq j$  and for all the parameters  $D$  and  $\text{ctg}^2 \zeta$ . It means that the C-S inequality is violated for any two spectrum components  $S_i, S_j$  ( $i \neq j$ ) from Mollow's triplet.

For the collective case  $N > 1$ , unlike the collective resonance fluorescence in a free space, where the C-S inequality is violated only for the correlation between the sidebands [31], one can show from relations (25)-(27) and (32)-(37) that the C-S inequality is violated for any two spectrum components  $S_i$  and  $S_j$  ( $i \neq j; i, j = 0, \pm 1$ ) under the proper choice of the parameters  $D$  and  $\text{ctg}^2 \zeta$ .

#### IV. Conclusions

We have considered the spectral and statistical properties in the fluorescence field from  $N$  two-level atoms interacting with an intense cavity mode.

It has been shown that in the case of the exact resonance  $\text{ctg}^2 \zeta = 1$  the intensity of the central spectrum components is only proportional to  $N$  and in the off-resonance case the fluorescence spectrum is nonsymmetric except for the case of  $D=0$ .

We also show that unlike the collective resonance fluorescence in a free space, the two sidebands have nonidentical photon statistics except for the case of  $D=0$  or  $\text{ctg}^2 \zeta = 1$ . Moreover, under the proper choice of the parameters  $D$  and  $\text{ctg}^2 \zeta$  the sub-Poissonian statistics of the sidebands is valid for the collective case  $N > 1$ . The correlation and anticorrelation between spectrum components are discussed. It is shown that the C-S inequality is violated for any two spectrum components from the Mollow triplet  $S_0, S_{\pm 1}$  for the single-atom case as well as for the collective case.

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Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1988

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The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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