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Interaction of Light with matter: nonclassical phenomenon

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Matter and light interaction has very important applications in classical as well as in nonclassical field. In classical mechanics charged particle interact with oscillating field. In quantum mechanics interaction of light is with quantum states. In this paper we focused on important nonclassical phenomenon, and their applications have been observed in last few years.

Keyword: Interaction of light with matter, coherent states, squeezing, antibunching, rabi oscillations, collapses and revivals.

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Introduction:

Light field has different nonclassical properties. These properties cannot be explained by classical theory, but they can be understood in the framework of quantum electrodynamics. For one beam of light, if its wavelets interfere each other, we say that this beam is a coherent light. LASER is a good monochromatic light source and field generated by it is a perfect coherent field. There are number of nonclassical phenomenon as a result of interaction of light with matter such as amplitude and higher order squeezing, sum and difference squeezing, atomic squeezing, polarization squeezing, spin squeezing, antibunching, collapses and revivals etc.

I. Squeezing of electromagnetic field

Quantum field have the different important characteristics, one of them is that the fluctuations of some operators describing the field may be squeezed [1].

A single mode electromagnetic field can be written in the form,

$$E(t) = E_0\hat{n}[a e^{-i(\omega t-kx)} + a^\dagger e^{-i(\omega t-kx)}] \tag{1}$$

where $E_0 = \sqrt{\frac{2\pi}{\omega}}$ is a constant, V is interaction volume, a and $a^\dagger$ are annihilation and creation operators for the quantum field respectively. These operators satisfy the commutation relation,

$$[a\, a^\dagger] = 1 \tag{2}$$

If we define two hermitian operators Z_1 and Z_2 to replace the operator a and $a^\dagger$,

$$Z_1 = \frac{1}{2}(a + a^\dagger);\ Z_2 = \frac{1}{2i}(a - a^\dagger), \tag{3}$$

in order to see the fluctuations of the quadrature amplitude of the field in the state $|\Phi\rangle$ we define the variance of the quadrature components Z_i (i=1, 2) as

$$\langle\Phi|(\Delta Z_i)^2|\Phi\rangle = \langle\Phi|{Z_i}^2|\Phi\rangle - [\langle\Phi|(Z_i)|\Phi\rangle]^2 \tag{4}$$

where $\Delta Z_i = Z_i - \langle\Phi|Z_i|\Phi\rangle$.

According to the Heisenberg Uncertainty relation, the product of their quantum uncertainties must satisfy,

$$(\Delta Z_1)^2(\Delta Z_2)^2 \geq \frac{1}{16} \tag{5}$$

A state whose fluctuations in Z_i are equal to the minimum value 1/4, called the minimum uncertainty state. Vacuum state |0> is a minimum uncertainty sate. The coherent states were first introduced by Schrodinger [2] and were studied by Klauder [3] and others [4]. Glauber [5] used these states to study the quantum coherence of optical fields. Glauber wrote that "If the singularities of $P^{(\alpha)}$ are of types stronger than those of delta function, e.g. derivatives of delta function, the field represented will have no classical analogue" on the basis of this statement the nonclassical states of electromagnetic field are defined as those for which the so called Glauber Sudarshan P-function is less well behaved than a probability density i.e. takes on negative values and becomes more singular than a delta function [5-7]. The thermal (chaotic) fields are classical since their *P* functions are positive probability distributions. All states whose *P* reorientations are nonnegative definite and more singular than a delta function are coherent sates, which is well behaved pure quantum state. The name coherent state was used by Glauber [8-9] and discussed in these papers [10-16]. L Mandel and E. Wolf [17] review the different coherent properties of optical fields. Coherence in spontaneous radiation process is studied by R.H Dicke [18]. Coherence at different process have also be studied.

There are different types of coherent states [19-20]. Coherent state $|\alpha\rangle$ of the field is defined as the eigen state of annihilation operator i.e., $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$. The eigen value α is in general a complex number since *a* is not a Hermitian operator. For a single mode field, coherent state is defined by

$$|\alpha\rangle = B_0 \sum_{n=0}^{\infty} \frac{\alpha^n}{(n!)^{1/2}} |n\rangle = n \sum_n B_n |n\rangle \qquad (6)$$

where B_0 is the normalization constant, and its value is $B_0 = exp\left(-\frac{1}{2}|\alpha|^2\right)$. The Eigen states $|n\rangle$ are called Fock states [21] or photon number state or eigen state of the number operator $N = a^\dagger a$ i.e., $N|n\rangle = n|n\rangle$ and these are defined as

$$|n\rangle = \frac{(a^\dagger)^n}{(n!)^{1/2}} |0\rangle \qquad (7)$$

They form a complete set of states, i.e.,

$$\sum_{n=0}^{\infty} |n\rangle \langle n| = 1$$

Coherent state can also be written as displaced vacuum state in the form,

$$|\alpha\rangle = D(\alpha)|0\rangle; \quad D(\alpha) = exp\,(\alpha\, a^\dagger - \alpha^* a) \qquad (8)$$

where $D(\alpha)$ is the displacement operator [6].

It is well known that the density operator of radiation can be written in the Sudarshan –Gluaber representation in the form,

$$\rho = \int d^2\alpha\; P(\alpha)\; |\alpha\rangle\langle\alpha| \qquad (9)$$

where $\alpha = (\alpha_r + i.\alpha_i)$is a complex number, $d^2\alpha \equiv d\alpha_r \,.\, d\alpha_i$ and $P(\alpha)$ is Glauber-Sudarshan *P* distribution [6-7]. Some other properties of density operators were also studied. Coherent state representation for the photon density operator was given by K.E. Cahil [10], density operator and quasi probability distribution was given by K.E. Cahil and R. J. Glauber [22].

It can be shown that for coherent state,

$$\langle\alpha|(\Delta Z_1)^2|\alpha\rangle = \langle\alpha|(\Delta Z_2)^2|\alpha\rangle = \frac{1}{4} \qquad (10)$$

i.e., coherent state is also a minimum uncertainty state (MUCS). The quantum fluctuations in a coherent state are equal to the zero-point vacuum fluctuations and are randomly distributed in phase.

In general, quantum fluctuations in both the quadratures are not necessarily equal. For such state the quantum fluctuations are no longer independent of phase. One quadrature phase may have reduced quantum fluctuations at the expense of increased quantum fluctuations in the other quadrature phase such that the product of the fluctuations still obeys Heisenberg's uncertainty relation. These states are called squeezed states [23] and this phenomenon is known squeezing of the field.

Mathematically for a squeezed state,

$$\langle\Phi|(\Delta Z_j)^2|\Phi\rangle < \frac{1}{4} (j = 1, or 2) \qquad (11)$$

Squeezed states have been considered as a general class of minimum uncertainty states. A squeezed state may in general have less noise in one quadrature than a coherent state. To satisfy the requirements of MUS, the noise in the other quadrature must be greater than that of a coherent state. Different type of squeezed states and different type of properties of squeezed state have studied, such as, squeezed vacuum state, squeezed optical solitons, phase variables, and squeezed states [24-26]. Another type of squeezing is also known as spin squeezing. M. Kitagawa and M Ueda gave the definition of spin squeezing. There are several applications of spin squeezing [27-29].

The concept of squeezing was introduced by Kennard [30] and detail study was initiate by Stoler and Yuen [31-33], Initially, importance of squeezing was in academic only, now it have several applications in optical communication and quantum information [34-35], in quantum teleportation [36-39], detection of gravitational field [40], dense coding [41], quantum cryptography [42], phase estimation [43], continuous variable quantum computing[44], quantum imaging[45], clock synchronization[46] etc. Squeezing of the electromagnetic field is now one of central topic in Quantum Optics and there are special issues of the journals [47-48] in which this and others nonclassical effects have been discussed in detail.

Squeezing has been studied in numerous cases such as different types of squeezing in parametric amplification [49-54], resonance fluorescence [55], harmonic generation [56-57], Jaynes Cumming model [58-59]. Recently some interesting work have been done in squeezing [60].

Different schemes for generating squeezed states were proposed such as multiphoton absorption, resonance fluorescence, parametric amplification, cavities, free electron laser, four wave mixing, harmonic generation. To detect and generate the squeezed states, first experiment was reported in 1985 [61]. Now so many experiments have been reported.

Higher order generation of single mode squeezing have also been proposed. Hong and Mandel [62-63] first demonstrated this type of squeezing. Hong and Mandel examined the expectation value of the 2*N*th power of the difference between a field quadrature component and its mean value.

If for a particular value this quantity is less than that the corresponding value for a coherent state, then the state is said to be squeezed to 2*N*th order i.e. the condition for a state $|\Phi\rangle$ to be *N*th order squeezed is

$$\langle\Phi|(\Delta Z_j)^m|\Phi\rangle < B^{m/2}(m-1)! \qquad j = 1,2,\ldots;\ B = \frac{1}{4}, \tag{12}$$

where $\Delta Z_j = Z_j - \langle\Phi|Z_j|\Phi\rangle$ and $m! = m(m-1)(m-2)$. The last term being 1 if *m* is odd and 2 if *m* is even.

Higher order squeezing exhibits larger percentage noise reduction than ordinary squeezing and it can be exploited in all those contexts where ordinary squeezing is useful. A second type of higher order squeezing is known as amplitude squared squeezing which has been proposed by Hillery [64-65]. This type of squeezing is present when the fluctuation in the square of the field amplitude is below a certain level that depends on the number of photons in the state. If we considered the operators,

$$\varkappa_1 = \frac{1}{2}(a^2 + a^{\dagger 2});\ \varkappa_2 = \frac{1}{2i}(a^2 - a^{\dagger 2}) \tag{13}$$

with commutation relation $[\varkappa_1\,\varkappa_2] = i\,(2N+1)$.

A state is said to be amplitude squared squeezed in the $\varkappa_j$ *(j=1, 2)* variable if

$$\langle\psi|(\Delta\varkappa_i)^2|\psi\rangle < [\langle\psi|N|\psi\rangle + \tfrac{1}{2}] \tag{14}$$

Amplitude squared squeezing is a nonclassical effect which occurs in a number of nonlinear optical process. Amplitude squared squeezing can be converted into normal squeezing by interaction in which the square of the field amplitude of one mode is coupled to the amplitude of a second mode, one example of this conversion is second harmonic generation. Amplitude squared squeezed states can be use in obtaining noise reduction in the output of certain nonlinear optical devices. Hillery [66] introduced another type of higher order multimode squeezing, called sum and difference squeezing. Both sum and difference two mode squeezing can be converted into normal single mode squeezing by the appropriate nonlinear optical process. Sum squeezing, becomes normal squeezing via sum frequency generation, and the second, deference squeezing becomes normal squeezing via difference frequency generation.

The author considered the operator for sum squeezing,

$$U_\Psi = (e^{i\Psi}\,a^\dagger b^\dagger + e^{-i\Psi}\,a\,b)/2 \tag{15}$$

and also the operators corresponding to $\Psi = 0$ and $\pi/2$ which are given by $U_1 = (a^\dagger b^\dagger + a\,b)/2$, $U_2 = i(a^\dagger b^\dagger - a\,b)/2$ respectively.

The operators obey the commutation relation,

$$[U_1\,U_2] = i/2\,(N_a + N_b + 1) \tag{16}$$

where $N_a = a^\dagger a$, $N_b = b^\dagger b$ are number operators for *a* and b mode, respectively.

A state is said to be sum squeezed if

$$(\Delta\,U_\Psi)^2 < \frac{1}{4}(N_a + N_b + 1) \tag{17}$$

for any Ψ.

The operator for difference frequency,

$$V_\Psi = (e^{i\Psi}\,ab^\dagger + e^{-i\Psi}\,a^\dagger\,b)/2, \tag{18}$$

and the operator

$$V_1 = (a\,b^\dagger + a^\dagger\,b)/2,\quad V_2 = i(a\,b^\dagger - a^\dagger b)/2$$

corresponding to $\Psi = 0$ and $\pi/2$ respectively.

These operator follows the commutation relation,

$$[V_1\,V_2] = i/2\,(N_a - N_b) \tag{19}$$

A state is said to difference squeezed if there is a Ψ such that

$$(\Delta V_\Psi)^2 < \frac{1}{4}(N_a - N_b) \tag{20}$$

In the case in which the A and B modes are the same, the operator U_1 and U_2 becomes $\varkappa_1 = \frac{1}{2}(a^2 + a^{\dagger 2});\ \varkappa_2 = \frac{1}{2i}(a^2 - a^{\dagger 2})$ so amplitude squared squeezing is the degenerate limit of sum squeezing. The author also reported the production of both kinds of squeezing in the case of uncorrelated modes, there is a connection between normal squeezing and sum and difference squeezing. But in the case of correlated mode higher order effects are, in general, independent of normal squeezing. Several authors have studied higher order squeezing, sum and difference squeezing, squeezing for M two level atoms, squeezing in four wave and six wave mixing process [67-70]. For very small number of photons in compared to atoms, one can obtain small squeezing for M two level atoms [71] as shown in fig. 1 and fig. 2.

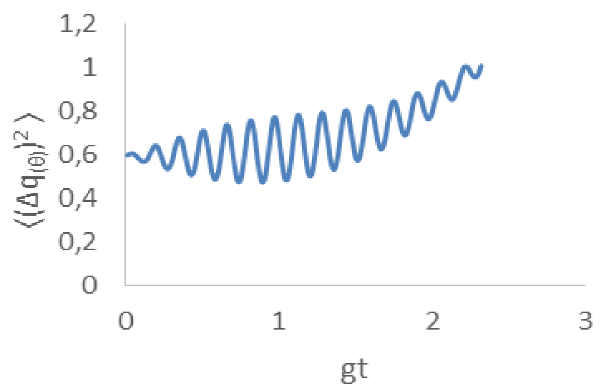

Fig. 1. Graph showing variation of variance ⟨(Δq(θ))2 ⟩min with gt for r = 6, m = 6, $\bar{n}$= 400 [71].

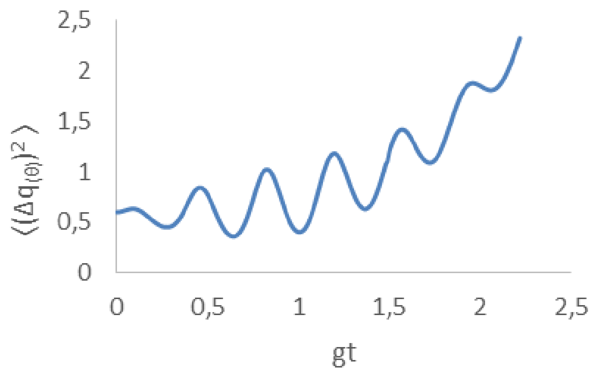

Fig. 2. Graph showing variation of variance ⟨(Δ$q_{(\theta)}$)² ⟩min with gt for r = 6, m = -6, $\bar{n}$= 400 [71].

A different type of squeezing of spin components known as atomic squeezing has been defined by number of authors. The earliest definition of atomic squeezing is given by Walls and Zoller [72]. Walls and Zoller wrote the condition for atomic squeezing in component S_x as $\left\langle (\Delta S_x)^2 \right\rangle < \frac{1}{2}|S_z|$ and in component S_y as $\left\langle (\Delta S_y)^2 \right\rangle < \frac{1}{2}|S_z|$. Here components S_x and S_y holds the commutation relation $\left[S_x, S_y\right] = iS_z$ and uncertainty relation $\left\langle (\Delta S_x)^2 \right\rangle \left\langle (\Delta S_y)^2 \right\rangle \geq \frac{1}{4}\langle S_z \rangle^2$. This definition was used by several authors. Later, atomic squeezing has been defined by number of authors in terms of squeezing parameter ξ as $\xi < 1$. Different authors defined differently the squeezing parameter ξ.

Recently number of papers have been published related to squeezing such as optimal squeezing, quantum teleportation and bright squeezed light, polarization squeezing, quantum cryptography and squeezing, squeezed- superpositions of coherent states, quadrature squeezed photons, bright squeezed vacuum, cw squeezed light, EPR entanglement from a single squeezed light source, squeezing in gravitational wave detection, sum squeezing, higher order squeezing, spin squeezing, low-frequency squeezing, squeezing in gravitational wave detection etc [73-100].

II. Antibunching or sub poissonian photon statistics

The other important nonclassical phenomenon is antibunching or sub poissonian photon statistics based on intensity fluctuations of optical field. The initial research on antibunching has been stated in 1966-1967 [101-102]. The first publication realizing a realistic source, which could exhibit the phenomenon of, antibunching was published in 1970 by Chandra and Prakash [103], followed by several other publications in this direction [103-107]. The first experimental evidence of antibunching of optical field was proposed by Kimble et al., in resonance fluorescence [108]. More recently higher order antibunching have been studied [109]. Antibunching can also be generated in different process such as harmonic generation, parametric amplification, and others. The antibunching is a phenomenon in which photon avoid to come in pairs and this show anticorrelation. The photon statistics of optical field in the state $|\psi\rangle$ was characterized by Mandel [110]. Mandel introduced a parameter Q based on intensity fluctuations of the field defined by

$$Q = \frac{\langle\Phi|\,(\Delta N)^2\Phi|\Phi\rangle - \langle\Phi|N|\Phi\rangle}{\langle\Phi|N|\Phi\rangle} \qquad (21)$$

where $\Delta N = N - [\langle\Phi|N|\Phi\rangle]$ *and* $N = a^{\dagger}a$. The value of the parameter Q characterizes departure of photon number distribution from poissonian photon statistics. When $0 < Q \leq -1$, the photon statistics is called sub poissonian and the field is called antibunched. The simplest example of this is a Fock state $|n\rangle$ for which $\left\langle (\Delta N)^2 \right\rangle = 0$ and $\langle N \rangle = n$ yielding Q = -1. When Q = 0, the photon statistics is called poissonian and when Q < 0 the photon statistics is called super poissonian. Some authors use the Fano factor defined by $F = Q$+1.

Most recently number of paper have been published on antibunching like optimal antibunching, antibunched photon-pair source, origin of antibunching in resonance fluorescence, photon-antibunching in the fluorescence, observation of photon antibunching with only one standard single-photon detector, quantum temporal imaging of antibunching, etc [111-120].

III. Collapses and Revivals

At low excitation intensities resonance fluorescence phenomenon occurs. For monochromatic excitation field an atom absorbs a photon at the excitation frequency and emitted photon have the same frequency. The emitted fluorescence has the same profile, and the same resonant field, nonlinear scattering occurs. The problem of intense beam of radiation with matter was an important issue of deal from a long time and now currently receiving much attention. In a multiphoton process, the atom can coherently interact many times with the laser field before spontaneously radiating a photon. It is important to obtain the exact quantum mechanical solution to this problem, since in general the atoms are multilevel, the radiation field is multimode, and the atomic transitions are homogeneous and in homogeneously broadened. It is not possible to treat even one atom's interaction with radiation exactly. The principal approximation used is that the radiation field is perfectly monochromatic and that it nearly coincides in frequency with one of the transition frequencies of the atoms. At this approximation, the effect of radiation field on the non-resonant atomic levels can be neglected and we can treat the atom as a two- level atom. The second important approximation is the rotating wave approximation (RWA), which accounts to neglecting the terms oscillating at twice the resonant frequency. So, the most natural assumption is that the atom has only two non-degenerate levels, which is usually interpret as two-level atom. When a two-level atom having transition frequency ω_0 interacts with a single mode radiation field with frequency $\omega \approx \omega_0$, the resonant transition occurs. The two-level atom plays a fundamental role in studying the interaction between atom and field. A two-level atom and a particle with spin ½ belong to the same kind of particles, so a two- level atom is defined as pseudo-spin particle with spin ½.

Dicke [18] deal first time with this problem and pointed out that owing to mutual interactions via a collection of atoms or molecule, the radiation field, radiating coherently must be treated as a single quantum mechanical system. Dicke found spontaneous emission rates for transitions between two energy levels and showed that under certain conditions, the rate of emission from n atoms may be proportional to n^2, and author defined it super radiant emission. These states for which the radiation rate is the large were called super radiant state. Author defined a Hamiltonian describe the atom-field coupling system under rotating wave approximation, given by

$$H_{RWA} = \hbar(\omega_0 R_z) + \hbar\left(\sum_n \omega_n a_n{}^{\dagger} a_n\right) + \sum_k g\left(a_n R_+ + a_n{}^{\dagger} R_-\right) \tag{22}$$

where ω_0 is the transition frequency, R_+, R_- and R_z are Dicke's operators, $a_n{}^{\dagger}$ and a_n are the annihilation and creation operators for nth mode, g is coupling constant. This Hamiltonian shows that the energy of the radiation field is the superposition of photons of infinite modes with wave vector k and angular frequency (ω_n). R_+, R_- and R_z can be represent two boson forms.

Study of interaction of an atom with its infinite number of states and a multilevel field is not easy problem. This problem is overcome by considering the case of a single two-level atom and a single mode field. This model is proposed by Jaynes and Cummings in 1963 and further [121]. This is an ideal model to describe the atom field coupling system and can be solved exactly except making the rotating wave approximation. A particular case of the Dicke model, when atoms interact with a single mode radiation field inside a cavity was considered by Tavis and Cummings [122].

A variety of non-classical phenomenon have been described by these models one of them is vacuum field Rabi oscillation. A lot of review articles, books and research papers are available emphasis these topics [123-134]. An atom of principal transition frequency ω_0 interacting with a coherent laser field at frequency ω_L is stimulated to emit and reabsorb photons. The rate at which transition are coherently induce between the two atomic levels is known as Rabi frequency and is proportional to the square root of the laser intensity. The quantum theory of the interaction of a single mode resonant radiation field with a two-level atomic system consisting of many identical atoms contained in a cavity which linear dimensions are much smaller than the radiation wavelength λ of the field.

One of the most interesting features of atom field interaction is the phenomenon of collapses and revivals of the Rabi oscillations, which manifests itself in the coherent state [135-140]. The shape of collapses and revivals is determined by the initial photon number distribution. For a sufficiently strong coherent field, the nonlinearity in the Rabi frequency seen and the system exhibits regular dynamics in the form of collapses and revivals of the oscillations. A number of authors have treated these problems. This interaction of multi two-level atoms which are interacting with a coherent radiation of single mode under different type of approximation is discussed in number of the paper [141-144]. Recently J. Rodríguez-Lima and L. M. Arévalo Aguilar studied the phenomenon of Collapses and revivals for entanglement in an optomechanical cavity[145].

Conclusions

In this article we focused on different nonclassical phenomenon of light as a result of interaction of light with matter. In the beginning we discussed about minimum uncertainty state, coherent state and Fock state and then very important Sudarshan –Gluaber representation of density operator of radiation. After that we discussed about squeezed states and different kind of squeezing. In the second section we discussed effect of intensity fluctuations of optical field in the form of sub poissonian photon statistics or antibunching. In third section we discussed about super radiant state. We also highlighted different Models to solve the problem of interaction of an atom with its infinite number of states. Very important Rabi frequency and collapses and revivals of the Rabi oscillations have also been discussed in this section.

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Взаємодія світла з речовиною: некласичний ефект

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Взаємодія речовини і світла має дуже важливе застосування як у класичній, так і в некласичній області. У класичній механіці заряджена частинка взаємодіє з коливальним полем. У квантовій механіці взаємодія світла відбувається із квантовими станами. У цій статті зосереджено увагу на важливому некласичному ефекті, а його застосування спостерігалося в останні кілька років.

Ключові слова: взаємодія світла з речовиною, когерентні стани, стискання, антигрупування, осциляції Рабі, колапсування та відновлення.