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TO TEST PHOTON STATISTICS BY ATOMIC BEAM DEFLECTION

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ABSTRACT

There exists a simple relation between the photon statistics in resonance fluorescence and the statistics of the momentum transferred to an atom by a plane travelling wave [1]. Using an atomic beam deflection by light pressure, we have observed sub-Poissonian statistics in resonance fluorescence of two level atoms.

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There has been growing interest in recent years in optical phenomena that exhibit purely quantum-mechanical features of radiation field[1-5]. Mandel's theory indicates that photon statistics of fluorescence of two-level atom is sub-Poissonian photon statistics, the narrowing of photon number distribution shows photon anti-bunching in time, and the photon anti-bunching in time can only occur in a quantized rediation field[2].

R.J. Cook first points out that there exists a simple relation between the photon statistics in resonance fluorescence and the statistics of the momentum transferred to an atom by a plane travelling wave[1]. This relation allows us to derive expressions for mean photon number $\langle n\rangle$ and variance $\langle(\Delta n)^2\rangle$ of the photon number from the theory of atomic motion in a travelling wave. From this theory we can obtain

$$\langle n\rangle = \frac{\beta\Omega^2 t}{2(\Delta^2+\beta^2+\frac{1}{2}\Omega^2)} \tag{1}$$

and

$$\langle(\Delta n)^2\rangle = \frac{\beta\Omega^2 t}{2(\Delta^2+\beta^2+\frac{1}{2}\Omega^2)}\left\{1-\frac{\Omega^2(3\beta^2-\Delta^2)}{2(\Delta^2+\beta^2+\frac{1}{2}\Omega^2)^2}\right\} \tag{2}$$

Here Ω is the Rabi frequency of two level atom in travelling wave, β is half the Einstein A-coefficient, and $\Delta=\omega-\omega_0$ is the detuning frequency. A natural measure of the departure of photon statistics from Poisson Law is Mandel's Q-parameter[1]

$$Q \equiv \frac{\langle(\Delta n)^2\rangle-\langle n\rangle}{\langle n\rangle} = -\frac{\Omega^2(3\beta^2-\Delta^2)}{2(\Delta^2+\beta^2+\frac{1}{2}\Omega^2)^2} \tag{3}$$

The Q-parameter is plotted as a function of Δ/β in Figure 1. For exact resonance Q is less than zero, $\langle(\Delta n)^2\rangle$ is less than $\langle n\rangle$, the photon statistics is sub-Poissonian. For certain off-ressonance cases Q may be greater than zero, the photon statistics is super-Poissonian. This result is of interest because it shows that sub-Poissonian photon statistics is not a necessary consequence of photon anti-bunching in time, which is always present in the radiation from a single two-level atom. Anti-bunching and sub-Poissonian statistics are distinct effects that need not necessarily occur together[5]. An experiment to verify this prediction is very valuable.

R. J. Cook suggested an atomic beam deflection experiment to demonstrate the non-Poissionian statistics. The atomic beam is transversely illuminated by a laser beam. In this case, the Q is expressed as

$$Q = \frac{M\langle 1/v^2\rangle}{\hbar k\langle 1/v^3\rangle} \times \frac{[\langle(\Delta\theta)^2\rangle - \langle(\Delta\theta)_0^2\rangle - S^2\langle\theta\rangle]}{\langle\theta\rangle} - \frac{7}{5} \qquad (4)$$

Here M is the mass of atom, V is the velocity in X-direction, $\hbar k$ is photon momentum, $\langle\theta\rangle$ is the mean deflection angle. $\langle(\Delta\theta)^2\rangle$ is the atomic beam spreading under laser beam illumination. $\langle(\Delta\theta)\rangle_0$ describes the initial beam divergence and $S^2\langle\theta\rangle^2$ is the contribution to the beam spreading resulting from the distribution of the atom's velocity. S^2 is expressed as $S^2=[\langle 1/v^4\rangle-\langle 1/v^2\rangle^2]/\langle 1/v^2\rangle^2$. For a thermal atomic beam, $\langle\theta\rangle^2S^2$ is quite large. To overcome this problem, S must be decreased by velocity selection, meanwhile the density of atomic beam decreased strongly. For a significant measurement $\langle(\Delta v)^2\rangle^{1/2}/\langle v\rangle$ must be less than 1/40[1].

We suggest a experiment of atomic beam deflection by the multiple laser beam to test photon statistics. The principle scheme of the experiment is shown in Figure 2. The idea is that the atomic beam travels across the multiple laser beam, which propagates forward and backward between two reflectors, the mean light forces cannot change the motion of the atoms, but due to

the quantum feature of radiation field, the momentum diffusion occurs, and the atomic beam spreads. In this case, the Q-parameter has been derived,

$$Q = \frac{2M^2(\Delta^2+\beta^2+\frac{1}{2}\Omega^2)\langle v^3\rangle}{Nd\,(\hbar k)^2\beta\,\Omega^2}\left[\langle(\Delta\theta)^2\rangle - \langle(\Delta\theta)_0^2\rangle\right] - \frac{7}{5} \qquad (5)$$

Here N is a number of laser beams, d is the diameter of laser beam. For resonance, $\Delta=0$ and the intensity of the laser beam is strong enough $\Omega^2 \gg \beta^2$, Q becomes

$$Q = \frac{M^2\langle v^3\rangle}{Nd\,(\hbar k)^2\beta}\left[\langle(\Delta\theta)^2\rangle - \langle(\Delta\theta)_0^2\rangle\right] - \frac{7}{5} \qquad (6)$$

All parameters in the expressions (5) and (6) are directly measured in the experiment.

This method has two advantages: First, the expressions (5) and (6) clearly show that the velocity distribution does not introduce any additional spreading of the atomic beam. The reason is that, in the multiple laser beam experiment, the average deflection $\langle\theta\rangle$ is zero, so that $S^2\langle\theta\rangle^2$ is zero. Second, in this experiment, atomic beam interact with the laser beam perpendicularly, all atoms will take part in the interaction, so that signal to noise ratio is much greater than that in the experiment using a velocity relected atomic beam.

An experiment on atomic beam deflection to test the non-Poissonian statistics is currently being carried out in our laboratory. The scheme of the experiment is a little different from that mentioned above. Fig.3 shows the scheme. The laser beam is incident at an oblique angle ϕ with the atomic beam. The laser frequency is tuned to near resonance of the atom, due to the Doppler frequency shift, only part of the atoms is resonant with the laser beam. In the case of $\phi \sim 84°$, the velocity distribution of the resonant atoms is very narrow, it is about $(\Delta v^2)^{1/2}/v_0 \sim 5\times10^{-2}$. The Q-parameter is expressed as

$$Q = \frac{2 v_0^3 M^2 (\beta^2 + \frac{1}{2}\Omega^2)}{N d (Kk) \sin^2\varphi} \left[\langle (\Delta\theta)^2 \rangle - \langle (\Delta\theta)_0^2 \rangle \right] - \frac{7}{5} \qquad (7)$$

Figure 4 is the experimental setup. The setup was described in [6]. When the laser beam 1 is interrupted the OMA records the intensity distribution of the fluorescence of the atomic beam, as shown in figure 5, which indicates the initial divergence of the atomic beam. When the laser beam is incident to the mirrors, the atomic beam is spread by the momentum diffusion, as shown in Figure 6. If the amplitude of the distribution is expressed by J, the $\langle(\Delta\theta)^2\rangle$ can be obtained as,

$$\langle (\Delta\theta)^2 \rangle = \frac{\sum_{i=1}^{N} (\Delta\theta_i)^2 J_i}{\sum_{i=1}^{N} J_i} \qquad (8)$$

From the experimental data, using the expression we have obtained $\langle(\Delta\theta)^2\rangle_0 = 2.15\times10^{-7}$ and $\langle(\Delta\theta)^2\rangle = 1\times10^{-6}$. The experimental parameters used are the following: the laser power P = 4.5mw, the source temperature T = 790K, the mean velocity $\langle V \rangle$ = 930m/s. and the saturation parameter G = 1.22, using expressing (6), we have obtained Q = -0.63. Using the expression (3) we have obtained the theoretical Q = -0.74. The difference between experimental and theoretical results is due to measurement error of laser power inside the vacuum chamber. The preliminary experiment shows that the photon statistics in resonance fluorescence of two-level atom is sub-Poissonian, the $\langle(\Delta n)^2\rangle$ is less than $\langle n \rangle$. We conclude that our results are consistent with QED theory of resonance fluorescence and the quantum theory of the motion of the atom.

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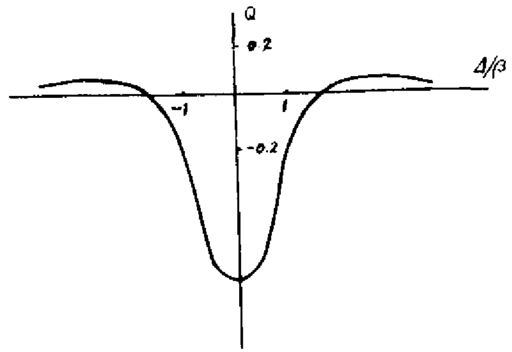

Fig.1. Q-parameter versus Δ/β for $\Omega=\sqrt{2}\beta$.

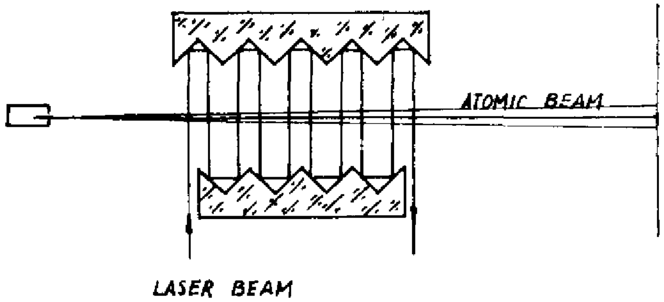

Fig.2. The principle scheme of the experiment.

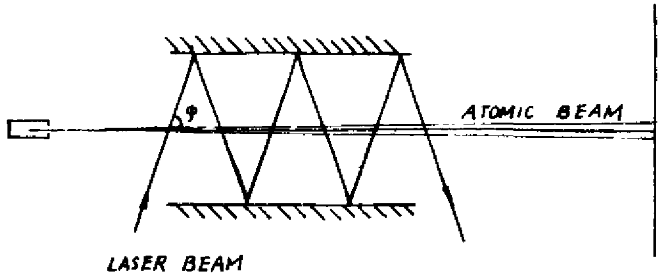

Fig.3. Another schematic diagram of the experiment

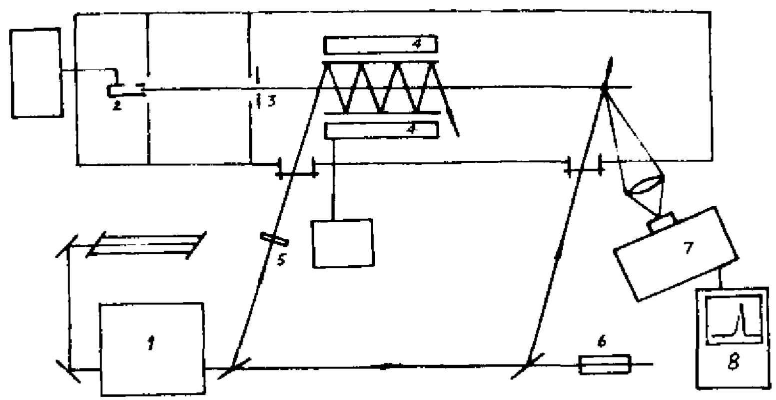

Fig.4. The schematic diagram of the experiment setup.
1-CW laser; 2-oven; 3-collimator; 4-D.C.magnet; 5-$\lambda/4$ plate; 6-Na absorption cell; 7-OMA; 8-oscilloscope.

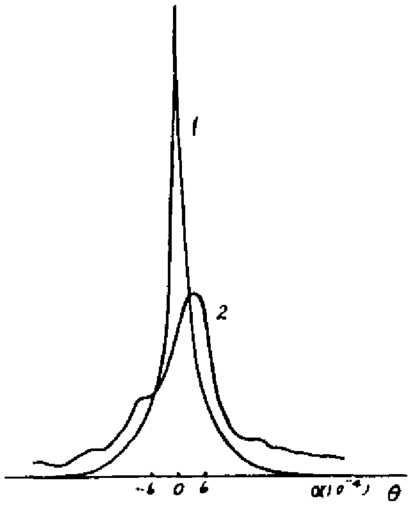

Fig. 5. The curves of the experimental results..
1-undiffused: 2-diffused.