news and views

Observation of photon antibunching

from Peter Knight

VERY few measurable optical effects require field quantisation and the idea of a photon for their explanation. One notable example of this rare class is photon antibunching in intensity correlation of resonance fluorescence (*Nature* **265**, 683; 1977), predicted by Carmichael and Walls (*J. Phys.* **B9**, L43; 1976; *J. Phys.* **B9**, 1199; 1976) and now observed by Kimble, Dagenais and Mandel (*Phys. Rev. Lett.* **39**, 691; 1977). Whereas most optical coherence and correlation experiments have an adequate semi-classical interpretation, antibunching requires quantisation of the emitted fluorescence and the idea of a 'quantum jump'.

The radiation emitted from the resonantly-excited atoms is collected, split into two, and imaged onto two photomultiplier tubes whose output is electronically correlated. The intensity correlation of interest is

$$g^{(2)}(\tau) = \frac{\langle \hat{I}(t+\tau)\hat{I}(t) \rangle}{\langle \hat{I}(t+\tau) \rangle \langle \hat{I}(t) \rangle}$$

where $g^{(2)}(0) = 2$ if the radiation was chaotic (this positive correlation, or bunching is the famous Hanbury Brown Twiss result) and $g^{(2)}(0) = 1$ for coherent light. Fully quantised and semiclassical approaches are here in agreement. However there are quantum states of the electromagnetic field which do not have a classical description, but the experimental realisation of such states has proved difficult. States exhibiting negative photoelectric correlation ($g^{(2)}(0) - 1 < 0$) or 'antibunching' are much-discussed examples of an effect requiring field quantisation: it is hard to visualise a function $I(t)$ representing the classical intensity whose mean square is less than the square of its mean. Carmichael and Walls showed that the resonance fluorescence radiated by a single two-level system driven by a coherent field possesses the required statistical properties to exhibit antibunching. This can be demonstrated easily since $g^{(2)}$ may be expressed in terms

of the two-level Pauli operators representing the atomic source fields as

$$g^{(2)}(\tau) \sim \langle \sigma_+(t)\sigma_+(t+\tau)\sigma_-(t+\tau)\sigma_-(t) \rangle$$

so that $g^{(2)}(0) \sim 0$. This behaviour at $\tau \sim 0$ is a strictly quantum feature: the atom emits a photon at time t and is unable to radiate again immediately after having made a quantum jump down to the lower state.

The measurement of $g^{(2)}$ consists of two parts: detection of the first photon (ensuring the de-excitation of the source atom) and a delay while the atom is re-excited by the resonant driving field for the subsequent re-emission of a second photon. So

$$g^{(2)}(\tau) \propto p(t, \tau)$$

where $p(t, \tau)$ is the probability of finding an atom, initially in its lower state at t , re-excited at τ . Cohen-Tannoudji (*Frontiers in laser spectroscopy*; Les Houches 27; North Holland, 1977) has stressed that the antibunching effect in resonance fluorescence is a striking example of wavepacket reduction in action. We expect first a lack of coincidence counts at short times τ , and further expect the Rabi nutational oscillation of $p(t, \tau)$ to be reflected in $g^{(2)}(\tau)$ which

should exhibit periodic bunching and antibunching as the driven atom undergoes Rabi oscillations. For a sufficiently intense resonant driving field for which the Rabi frequency Ω is much greater than the spontaneous decay rate β ,

$$g^{(2)}(\tau) = 1 - \exp(-3\beta\tau/2) \cos \Omega\tau$$

If there is more than one atom in the observation region the interpretation is a little harder and since fluorescence could then be produced by two or more atoms this would increase $g^{(2)}$ and obscure the antibunching.

The experimental arrangement of Mandel and coworkers resembles that used by earlier groups to study resonance fluorescence spectra. Sodium atoms in a well-collimated atomic beam are prepared by optical pumping to ensure a two-level transition and are driven by an intensity and frequency-stabilised CW dye laser at the $3^2S_{1/2} F=2, M_F=2$ to $3^2P_{3/2} F=3, M_F=3$ transition frequency. The fluorescence emitted at right angles to both atomic and laser beams is collected, divided by a beam splitter, imaged on to two photomultiplier tubes, and the correlation evaluated under computer control. The atomic beam current is designed to allow only one or two atoms to contribute to the collected fluorescence at the same time. The experiment shows direct evidence for antibunching of photoelectric pulses. After various corrections have been made for accidental pair correlations produced by background laser scatter, their results are shown in Fig. 1, where the broken curve shows the theoretical single atom prediction normalised to the same peak for $\Omega/\beta = 4$.

The observed $g^{(2)}(0)$ is approximately 0.4 rather than the zero predicted theoretically for a single atom. Mandel *et al.* estimate $g^{(2)}(0)$ to be 0.5 if the field were produced by two radiating atoms located at random positions. At large τ the atomic flight time through the photomultiplier field of view decreases $g^{(2)}(\tau)$. The overall result is as expected and plainly exhibits both bunching, and more importantly, for the first time antibunching. □

Fig. 1 Values of $g^{(2)}(\tau)$ derived from the data, demonstrating photon antibunching. The broken curve is the theoretical prediction, suitably normalised to the same peak.

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