Towards an improved test of Bose-Einstein statistics for photons

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Abstract. In this contribution we describe our current efforts at Berkeley to improve upon a limit on Bose-Einstein statistics violation for photons obtained earlier (D. P. DeMille, D. Budker, N. Derr, and E. Deveney, *Phys. Rev. Lett.* **83**(20), 1378 (1999)). The principle differences between the new and the previous experiments are the use of a narrow-band cw laser, an atomic beam, a different transition in atomic Ba, and possibly a different detection technique. We also discuss the ultimate limits that one can hope to obtain with this degenerate two-photon transition technique. Some potential conceptual difficulties with the interpretation of this experiment and the ways to avoid them are discussed as well.

I EXPERIMENTAL TECHNIQUE AND CHOICE OF THE TRANSITION

The principle of the technique and details of the earlier experiment [1] that used pulsed lasers and a barium vapor cell are discussed in D. P. DeMille's invited contribution in the current proceedings [2].

Our present choice of the two-photon transition is shown in Fig. 1. This scheme differs from that of Ref. [1] in its particular choice of levels, but is otherwise very similar to it. It offers a convenient excitation wavelength accessible to a dye laser, and a strong fluorescence decay channel at a sufficiently shorter wavelength, which is convenient for fluorescence detection. A slightly smaller energy defect Δ (93 cm^{-1} vs -163 cm^{-1} in Ref. [1]) enhances the two-photon rate. Note, however, that in addition to this blessing, a smaller Δ may also carry a curse of relatively high

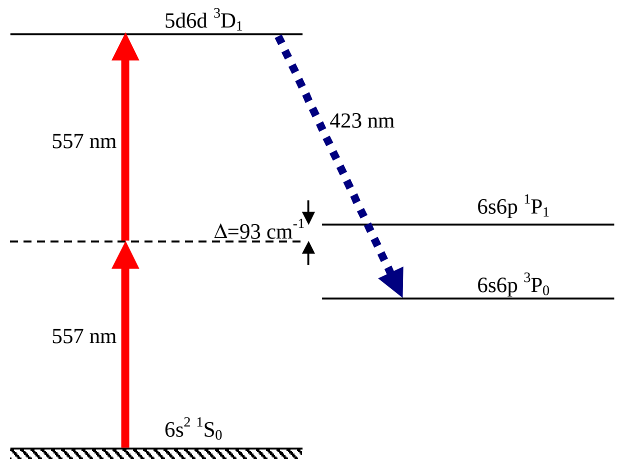

FIGURE 1. Selected levels and transitons in Ba I.

backgrounds, as discussed below. We emphasize that a variety of schemes involving $J = 0 \rightarrow J = 1$ two-photon transitions are available in Ba, Yb, and other atoms.

The schematic of the new experiment is shown in Fig. 2. Ba atoms are produced in a stainless steel source fitted with a multi-channel effusor constructed out of crinkled stainless steel foil. The atomic beam is further collimated with an external collimator constructed as a set of parallel, appropriately spaced thin metal foils. The atoms in the collimated beam interact with an intense light beam in a power build-up cavity. An unusual feature of the cavity is that there are intracavity quarter-wave plates in front of each mirror. The purpose of the waveplates is to ensure that light waves propagating in opposite directions have opposite polarizations.

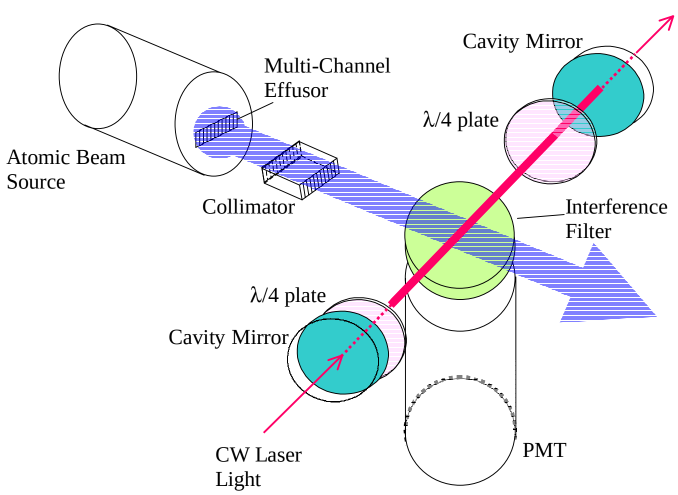

FIGURE 2. Experimental arrangement.

We introduce this feature in the experiment since in the absence of Bose-Einstein (BE) statistics violation and for photons of different energy, $J = 0 \rightarrow J = 1$ two-photon transitions are still forbidden if the photons are of the same polarization. (This point is further discussed below.) Fluorescence from the excitation region in appropriate decay channels is used to measure the excitation rate. In principle, more sophisticated detection techniques can be considered for future work (photon bursts, selective laser photoionization, etc.), that will provide higher detection efficiency and selectivity. However even with a straightforward detection system consisting of a cooled phototube installed near the interaction region and a light collection mirror (not shown in Fig. 2), the beam apparatus will provide considerable improvement in detection efficiency compared to that of Ref. [1]. In addition, collisional backgrounds present in the cell experiment [1] will be eliminated. Most importantly, small transverse Doppler width and the narrow bandwidth of the light reduce, by many orders of magnitude, the main limitations of the pulsed laser experiment [1] related to the two-photon transitions arising from the finite laser bandwidth ($\Delta\nu \approx 3$ GHz) and Doppler width (≈ 300 MHz).

It is a well known feature of two-photon transitions, in which two equal energy photons are picked up by an atom from counter-propagating light beams, that the first-order Doppler effect is absent [3]. However, the energies of the two photons are different as seen by the atom with a non-zero velocity component along the axis of the cavity. Consequently, the atomic beam has to be collimated to reduce the background due to the non-degenerate two-photon transitions. We are planning to collimate the beam so that $\Gamma_D \equiv 2k{\cdot}\Delta v_t \sim \Gamma_0$. Here k is the light wave number, Δv_t is the spread of the transverse velocities in the atomic beam, and $\Gamma_0 \approx 2\pi{\cdot}(6.9\text{ MHz})$ is the natural line width of the two-photon transition. Note that, as can be seen from the structure of the two-photon amplitudes (with expressions given in Refs. [1,2] amended in a straightforward manner by replacing $E_k \rightarrow E_k - i\Gamma_k/2$, where E_k and Γ_k are the energy and width of the state k), the finite level widths do not lift the ban on degenerate two-photon transitions. Thus, the non-degenerate two-photon background continues to decrease if the atomic beam is collimated even tighter, so that the Doppler width Γ_D becomes smaller than Γ_0. However, collimation to the level $\Gamma_D \sim \Gamma_0$ appears adequate for the projected level of sensitivity for the current version of the experiment (see estimates below). Future work may benefit from transverse laser cooling of the atomic beam or the use cold atomic samples where the Doppler width is negligible in place of the atomic beam.

II PARAMETER OPTIMIZATION

The number of two-photon transitions in the interaction region scales as

$$\frac{(\text{Light Power}, P)^2}{\text{Beam Area}, A}.$$

This scaling comes about because the transition rate per atom goes as the square of the light intensity, and the number of atoms in the interaction region is proportional to A. Thus, at first sight, in order to maximize the counting rate, one would need to increase light power as much as possible, and tightly focus the light beam. However, there exists a "parasitic" effect, the AC Stark shift, that limits possible gains to be achieved by following this route. For the scheme shown in Fig. 1, while both the upper and lower levels of the two-photon transition shift in the presence of the strong light field, the shift of the lower (ground) state is expected to be dominant because the energy defect is very small and the $6s^2\ ^1S_0 \rightarrow 6s6p\ ^1P_1$ transition is fully allowed (the $6s6p\ ^1P_1 \rightarrow 5d6d\ ^3D_1$ amplitude is suppressed by an order of magnitude). The ground state AC Stark shift can be estimated as:

$$\Delta_{AC} = -\frac{d_{gi}^2 E^2}{4\Delta} \approx -0.1MHz \cdot \frac{2P(W)}{A(mm^2)}.$$

Here $d_{gi} \approx 3.2\ e \cdot a$ is the dipole matrix element of the $^1S_0 \rightarrow ^1 P_1$ transition (known from the 8.4 ns lifetime of the $^1P_1$ state), E is the light electric field amplitude, and P is the power in each of the counter-propagating light waves. If all atoms were exposed to a uniform electric field, the AC Stark shift would not present much of a problem – it would simply shift the position of the two-photon resonance. However, since atoms passing through different regions of the light beam "see" different intensities this leads to a non-uniform AC Stark shift, and an effective inhomogeneous line broadening. Limiting this broadening at the level of the homogeneous width of the transition, sets a limit on the maximum ratio of P and A:

$$|\Delta_{AC}| = \Gamma_0 \Rightarrow \frac{P(W)}{A(mm^2)} \approx 30.$$

With this, we can now discuss the parameters of the power build-up cavity. Since the P/A ratio is fixed and the two-photon signal goes as P^2/A, it actually turns out beneficial to work with a large beam area. We are planning to employ a confocal cavity and use the degeneracy between transverse modes specific for this cavity configuration. This degeneracy allows one to excite multiple transverse modes simultaneously to obtain a large spot size and achieve transverse beam dimensions $\sim$1 mm ($A = 1$ mm^2; see e.g. [4] for a discussion of excitation of multiple transverse modes in a cavity). With $A = 1$ mm^2 and $\frac{P(W)}{A(mm^2)} = 30$, we need $P = 30$ W. The light power available from a dye laser system (Coherent CR-699 pumped by a Spectra Physics 2040 Ar-ion laser) is on the order of $P_{in} = 0.3$ W, thus the cavity should provide a build-up of $\frac{2P}{P_{in}} = 200$, corresponding to cavity finesse of $200 \cdot \pi/2 \approx 300$.

We now turn to estimating the two-photon rates. It will be convenient to introduce an allowed two-photon transition rate on resonance given by

$$W_{gf} \sim \frac{E_0^4}{\Gamma_0} \cdot \frac{d_{gi}^2 d_{if}^2}{\Delta^2} \sim 3 \cdot 10^2 \left(\frac{P(W)}{A(mm^2)}\right)\left(s^{-1}\right).$$

Here we used an estimated value $d_{if} = 0.1\ e \cdot a$. With the density of atoms in the interaction region $N \sim 10^{10}$ cm^{-3} and the length of the interaction region $l = 1$ cm, with $P = 30$ W and A=1 mm^2, we get $\sim 10^{13}$ allowed transition per second.

This estimate shows that if one is able to maintain high detection efficiency with no background counts for a time t, it will be possible to limit the relative probability of the forbidden transition at the level of $\nu \lesssim (10^{13} \cdot t(s))^{-1}$. Here ν corresponds to the relative fraction of the anti-symmetric photon pairs in our power build-up cavity out of all possible photon pairs (compare to $\nu \lesssim 10^{-7}$ obtained in Ref. [1]). This estimate shows a potential for high statistical sensitivity, and also indicates the necessity to ensure background-free operation. Note that if background counts are present, the limit on ν would only improve as $t^{-1/2}$ rather than as t^{-1} in the case of background-free operation.

III BACKGROUNDS AND CALIBRATION

Possible sources of background can be classified into *resonant* and *non-resonant* with respect to the detuning of the light frequency from the two-photon resonance. The dominant resonant background comes from the already mentioned two-photon transitions originating from the finite Doppler width. Inspection of the expressions for the BE-allowed transition rate (see e.g. Refs. [1,2]) shows that the *relative* background rate with respect to the allowed rate scales as $(\Gamma_D/\Delta)^2$ and comprises $\sim 10^{-11}$ with the chosen value $\Gamma_D \sim \Gamma_0$. We note that once the experiment using the current transition scheme becomes limited by this background, it may be beneficial to switch to a scheme with larger Δ. (Of course, the allowed two-photon rate itself scales $\propto \Delta^{-2}$, and will generally also be reduced for larger Δ. Another way to reduce the relative contribution of the background is to use $\Gamma_D < \Gamma_0$, see Section I.)

An example of non-resonant background is spontaneous hyper-Raman scattering which arises due to the population of virtual even parity states with $J = 0, 2$ followed by spontaneous emission at the detection wavelength. The relative rate for such process scales as

$$\frac{\Gamma_0 \cdot \Gamma(J \neq 1) \cdot B.R.}{\Delta_2^2} \cdot \left(\frac{d_{iJ\neq 1}}{d_{if}}\right)^2.$$

Here $\Gamma(J \neq 1)$ is the width of the corresponding even parity state, $B.R.$ is the branching ratio for the decay of this state into the final state of the detection transition, Δ_2 is the energy difference between the $J \neq 1$ state and the upper $J = 1$ state of the two-photon transition under investigation, and $d_{iJ\neq 1}$ is the appropriate matrix element. For the scheme used in Ref. [1], the relative rate for this process is $\sim 10^{-13}$, however, for the present scheme there is a further suppression $\sim \alpha^4$, where α is the fine structure constant, due to the fact that a $J = 2 \rightarrow J = 0$ decay can only go as a magnetic quadrupole transition (M2).

Another background process, hyperfine-interaction-induced two-photon transitions, is present only for Ba isotopes with non-zero nuclear spin (^{135}Ba, 6.6% natural abundance and ^{137}Ba, 11.2%, both with nuclear spin $I = 3/2$), and is negligible if one works near the resonance corresponding to the most abundant spin-less isotope (^{138}Ba, 71.7%), which is expected to be well separated in frequency due to isotope shift. However, the hyperfine-induced transition provide a convenient way of calibrating the apparatus. The relative rate for such a process contains a factor characterizing the admixture of the $J \neq 1$ states to the $J = 1$ upper state due to off-diagonal hyperfine interaction $\sim (\Delta_{\rm hfs}/\Delta_2)^2 \sim 10^{-8}$. Another way to calibrate the apparatus and to carry out initial measurements of the spectroscopic parameters of the two-photon transition (isotope shift, hyperfine structure, etc.) is to tilt the axis of the power build-up cavity, so it forms a large angle with the atomic beam. Such a geometry enhances the Doppler effect-induced transitions.

IV CURRENT STATUS

The laser system, the vacuum chamber, and the Ba beam source are all in place, and the first fluorescence signals (with one-photon excitation) have been observed. The external atomic beam collimator design has been successfully tested in another experiment carried out in our group which uses an atomic beam of Yb with similar parameters [5]. The optical cavity design is currently in progress.

V LIGHT POLARIZATION AND BOSE-EINSTEIN STATISTICS

The present experiment (as well as the earlier work [1]) is explicitly designed to ensure that we use a configuration where the two-photon transition is allowed for non-degenerate photons. To this effect, the polarizations of the two counter-propagating light waves are chosen orthogonal to each other. However, it is not obvious that this is necessary for the observation of BE-violating transitions. In fact, thinking naively in terms of classical fields, the two counter-propagating light waves of the same frequency form a standing wave, for which at each spatial location, there is *some* steady polarization. Since we are studying E1-E1 two-photon transition, the propagation direction would appear irrelevant, and the transitions would seem forbidden simply by a polarization argument, and not by BE-statistics. This is particularly clear for the case of two opposite circular polarizations. The resulting standing wave is locally linearly polarized at each point. The two-photon transition appears forbidden by the property of the Clebsch-Gordan coefficients (Fig. 3).

In our opinion, this example clearly illustrates the connection between BE statistics violation and light polarization. If BE statistics is violated, the naive polarization addition picture used in the above example must fail also. This highlights

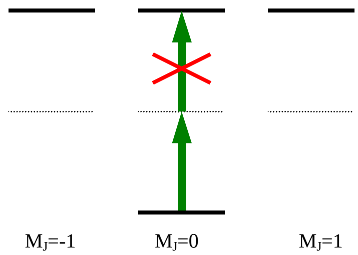

FIGURE 3. Why $J = 0 \rightarrow J = 1$ transitions are forbidden for linear light polarization (in the absence of BE-statistics violation).

a need for a theory that would incorporate possible small statistics violations for photons, and would generalize the usual electrodynamics and optics.

VI CONCLUSION

With the straightforward spectroscopic experiment now underway, it appears feasible to push the limit on Bose-Einstein statistics violation for photons to the level of $\nu \lesssim 10^{-11}$, with possible further improvements, perhaps by several orders of magnitude, down the road. However, certain basic questions concerning the nature, meaning and implications of statistics violation for photons remain open.

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