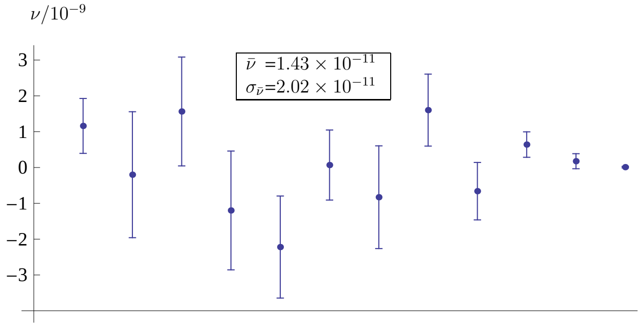

FIG. 7. (color online). ν from twelve runs. The error bars decrease over the lifetime of the experiment as improvements in excitation and detection efficiency were achieved.

rate, relative to an allowed transition (i.e., expressed in the same way as the limit parameter ν), is $\sim 10^{-8}$. This rate is 10^3 times larger than the present level of sensitivity, and the HFI-induced transitions are observed (e.g., in the right side of FIG. 6). To our knowledge, this is the first observation of HFI-enabled two-photon transitions. Fortunately, the peaks of the HFI-induced transitions, although close to the limit region, do not completely obscure it. As is also discussed in Ref. [14], magnetic fields can create a false-positive signal in a way similar to the HFI. A relatively large field (~10 gauss) would be necessary to generate a false-positive signal at the present level of sensitivity.

Another systematic effect, the one that limited the sensitivity in Ref. [12], is the non-zero spectral width of the lasers. Photons in opposite wings of the lasers' spectral profiles can together drive the nominally BE-statistics-forbidden transition at a relative rate $\sim (\Gamma_L/\Delta)^2 \sim 10^{-12}$, where the laser line width is $\Gamma_L \approx 2\pi \times 3$ MHz.

When two counter-propagating light beams drive a two-photon transition, the Doppler effect due to the motion of the atoms collinear with the light (i.e., the transverse motion in the atomic beam) shifts the frequencies, as seen by the atoms, of the two light fields in opposite directions. This leads to a nonzero allowed two-photon-transition amplitude. It is, however, largely suppressed in the case of a power-buildup cavity [10]. The residual effect has a relative rate $T^2\,\Gamma_D^2/\Delta^2 \sim 2\times 10^{-15}$, where T=10^{-2} is the PBC mirror transmission, and Γ_D=$2\pi\times 13$ MHz is the Doppler width of the two-photon transition.

At the limit point, the amplitudes that destructively interfere ($\mathscr{A}_{jk}$ in FIG. 1) proceed through magnetic sublevels (or orthogonal superpositions thereof) of the intermediate state. A disturbance of the degeneracy of these sublevels may alter the balance of the two amplitudes, preventing perfect cancelation, and generate a false-positive signal in a way similar to the HFI-splitting mentioned above. Considering only the states in FIG. 1, light shifts produce a difference in the intermediate state energies of $\delta_i = -\left(\mathcal{D}_{ng}^2 - \mathcal{D}_{en}^2\right)\left(E_1^2 - E_2^2\right)/4\hbar\Delta$, where E_1 and E_2 are the electric field intensities of the light. Notable is that both an imbalance in the light intensities and an imbalance in the dipole moments are necessary to make $\delta_i \neq 0$. There are, besides, additional atomic states in the region around $|e\rangle$ that make smaller but significant contributions to δ_i. Roughly calculated, the relative-rate due to light shifts is $(\delta_i/\Delta)^2 \sim 10^{-12}$, an order of magnitude below the present level of sensitivity.

The analysis of EQ. (1) and sequelae considered only E1E1 two-photon transitions. For the geometry of this experiment, where the light beams are collinear, the analysis still holds true for all multipole combinations [10]. However, misalignment of the laser beams permits certain higher-order multipole transitions [10]. The leading non-zero terms, E1M2 and E2M1 [9], roughly of the same magnitude, contribute a false-positive signal at a rate $\sim |\mathcal{D}_{M2}/\mathcal{D}_{E1}|^2 \sin^4\theta \sim 10^{-10}\theta^4 \sim 10^{-19}$, where $\mathcal{D}_{M2}$ and $\mathcal{D}_{E1}$ are the magnetic-quadrupole and electric-dipole reduced matrix elements of the transition, and $\theta \approx 0.3°$ is a conservative upper bound on the misalignment angle.

In conclusion, the reported experiment has improved the limit on possible Bose-Einstein statistics violation by photons by more than three orders of magnitude. Additionally, we have observed hyperfine-interaction induced two-photon transitions. In principle, further improvement by an order of magnitude or more is possible with this technique by improving laser-frequency lock which will allow longer statistics accumulation.

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[1] E. H. Wichmann, in *Art and Symmetry in Experimental Physics*, Vol. 596, edited by D. Budker, P. H. Bucksbaum, and S. J. Freedman (AIP, Melville, N.Y., 2001) p. 201.
[2] G. W. F. Drake and A. Dalgarno, Astrophys. J. **152**, L121 (1968).
[3] K. D. Bonin and T. J. McIlrath, J. Opt. Soc. Am. B **1**, 52 (1984).
[4] L. D. Landau, Dokl. Akad. Nauk **60**, 207 (1948).
[5] C. N. Yang, Phys. Rev. **77**, 242 (1950).
[6] M. Acciarri and et al., Phys. Lett. B **353**, 136 (1995).
[7] *Spin-statistics connection and commutation relations : experimental tests and theoretical implications*, edited by R. C. Hilborn and G. M. Tino, Vol. 545 (AIP, Melville, N.Y., 2000).
[8] S. P. Goldman and G. W. F. Drake, Phys. Rev. A **24**, 183 (1981).
[9] R. W. Dunford, Phys. Rev. A **69**, 062502 (2004).
[10] D. English, *A spectroscopic test of the Bose-Einstein statistics of photons*, Ph.D. thesis, University of California, Berkeley (2007).
[11] R. D. Amado and H. Primakoff, Phys. Rev. C **22**, 1338