Atomic Fock State Preparation Using Rydberg Blockade
Supplementary Material

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LIGHT-ASSISTED COLLISION RATE CALIBRATION

A quantitative analysis of the collective frequency enhancement requires an initial atom number measurement. In the absence of light-assisted collisions, the distribution of collected fluorescence counts s for N atoms after time t would be a Gaussian distribution $G_N(s, \bar{s})$ with a mean $\bar{s} = N\Gamma t$ and a standard deviation $\sigma_N = \sqrt{\bar{s}}$. Here Γ is the single-atom photon detection rate, typically 8-9 photons/ms, so that with > 3 ms of detection time the assumed Gaussian distribution is a good approximation to the actual Poisson distribution.

Interpretation of fluorescence measurements is complicated by significant two-body loss from light-assisted collisions over ms timescales. Since this loss rate is roughly proportional to N^2, large atom numbers will be significantly underestimated, as illustrated in Figure 1(a). To this end, we measure and account for the two-body losses.

The probability p_N of finding atom number N is given by the differential equation

$$\frac{dp_N}{dt} = \frac{\beta}{2}\left[(N+2)(N+1)p_{N+2}(t) - N(N-1)p_N(t)\right], \quad (1)$$

$$p_N(0) = P_{\bar{N}}(N) \quad (2)$$

where β is the two-body loss rate, and $P_{\bar{N}}(N)$ is the Poisson distribution at N with mean $\bar{N}$.

For large $\bar{N}$ such that after the exposure time there is a small probability of being left with the asymptotic values of 0 (even) or 1 (odd) samples, we use the simplified continuous model given by:

$$\frac{d\bar{N}(t)}{dt} = -\beta\bar{N}(t)\left(\bar{N}(t) - 1\right), \quad (3)$$

Then the mean camera signal, $\bar{s}$, generated by an initial mean $\bar{N}$ atoms, during an integration time t is given by:

$$\bar{s}(\bar{N}, t) = \frac{\Gamma}{\beta}\ln\left[1 + \left(e^{\beta t} - 1\right)\bar{N}\right], \quad (4)$$

By fitting the camera signal to Equation (4) we deduce β and $\bar{N}$. An example is shown in Figure 1(a).

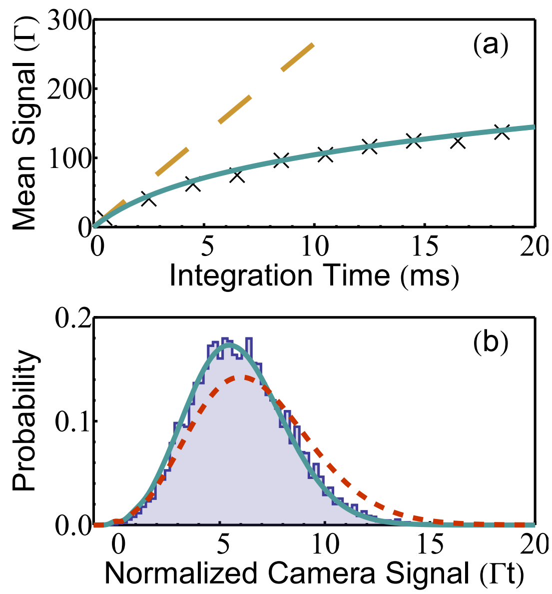

FIG. 1. (a) The integrated camera signal is shown along with the fit (solid green) to Eq. (4). The best fit parameters are $\bar{n} = 26.5$ and $\beta = 0.0170/$(atom ms). The camera signal in the ideal case of no two-body loss is shown as the dashed yellow line to demonstrate the magnitude of the light-assisted collision effect. (b) An example camera signal distribution is shown (blue bars), with a fit to Eq. (5) (solid green) using $\beta = 0.0158/$(atom ms) giving $\bar{N} = 6.68$ atoms, as compared to the expected distribution in the limit of no loss (dashed red).

MULTIATOM MEASUREMENTS

Once β is known, and assuming Poisson loading statistics, the mean atom number can be measured with a fixed camera integration time short enough so that $\bar{s}(N, t)$ is still close to linear in time. The resulting camera signal in bin s is a Poisson weighted sum of Gaussian distributions centered around the mean signals $\bar{s}(N, t)$ for N atoms:

$$\bar{S}(s) = \sum_{N=0}^{N=n_f} P_{\bar{N}}(N) G_N(s, \bar{s}(N, t)) \quad (5)$$

where σ_0 is the background signal standard deviation. For our normal 3 ms integration time $\sigma_0 = 0.188$ atoms and $\sigma_1 = 0.448$ atoms. The only free parameter in the fit is the Poisson mean $\bar{N}$. An example data set and fit are shown in Figure 1(b).

For longer exposure times, the signal distribution distorts from 2-body losses. This is important for $N < 3$ where long exposure times are needed to get sufficient

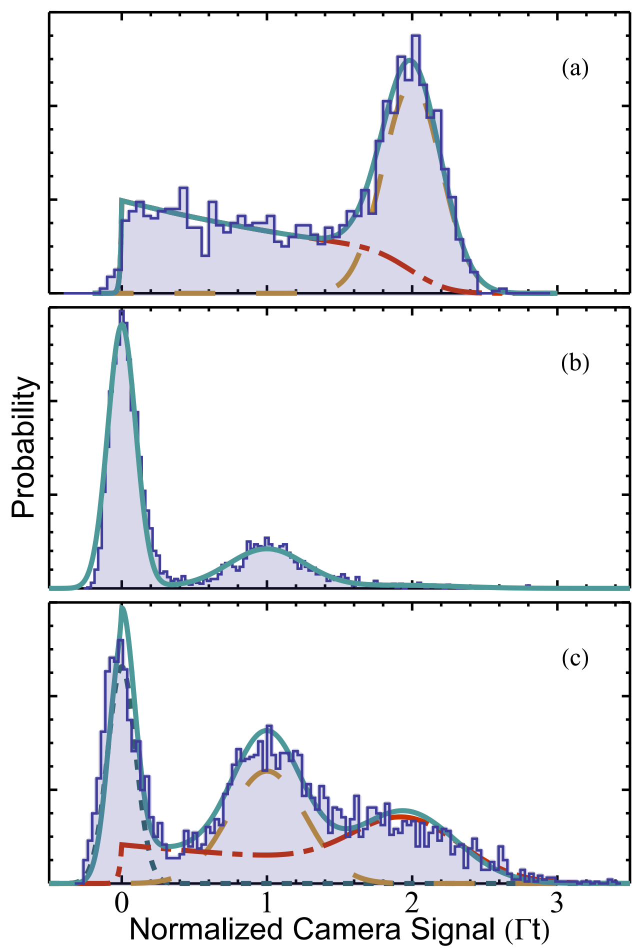

FIG. 2. (a) A Monte Carlo simulation of readout signals observed for a two-atom cloud, including two-body losses, and compared to our analytical model of Eq. (7). (b) A normal single atom readout with 10 ms exposure with minimal two atom signal. (c) An example of $\mathcal{N} = 2$ Fock State data with significant number of two atom occurances. The individual atom signal components are shown for comparison. Note that the gap between the background and 1 atom peaks is not preserved due to the "tail" of the 2 atom distribution from the two body loss.

signal. It is also important for small N to deduce the atom number distribution, as that allows us to isolate single-atom and two-atom Rabi flopping.

When $N = 0, 1$ there is no two-body loss so both signal distributions are Gaussian. When $N = 2$ there are two possible outcomes:

1. no collision occurs so both atoms scatter for the full readout time. This has a probability $e^{-2\beta t}$;

2. a two-body collision occurs and the atoms are ejected at time t' with a probability $e^{-2\beta t'} dt'$.

The signal due to no loss event is Gaussian, whereas for a loss event during the readout the two atoms scatter photons until the loss occurs. This gives a signal distribution

$$G_2^\star(s,t) = \int_0^t dt' e^{-2\beta t'} G_2(s, 2\Gamma t'). \tag{6}$$

We have neglected a small correction in $G_2^\star$ from the background counts, which slightly smear the data near $s = 0$, as seen in Fig. 2(a). The resulting model for the $N \leq 2$ camera distribution $S(s,t)$ is therefore

$$S(s,t) = p_0 G_0(s,0) + p_1 G_1(s, \Gamma t) + p_2 \left[e^{-2\beta t} G_2(s, 2\Gamma t) + (1 - e^{-2\beta t}) G_2^*(s,t) \right]. \tag{7}$$

To illustrate the effects of light-assisted collisions on the signals, we show in Fig. 2(a) a Monte Carlo simulation of a $p_2 = 1$ distribution, compared to the model. The observed signal distribution for the combined case of 0,1 and 2 atoms is shown in Fig. 2(c). An integration time of $t = 10$ ms was chosen to minimize the overlap integral between the single and double atom distributions. For this integration time, $\sigma_0 = 0.0883$ atoms, $\sigma_1 = 0.236$ atoms.