Black-body radiation induced facilitated excitation of Rydberg atoms in optical tweezers

Lorenzo Festa,1, 2 Nikolaus Lorenz,1, 2 Lea-Marina Steinert,1, 2, 3 Zaijun Chen,1, 2
Philip Osterholz,1, 2, 3 Robin Eberhard,1, 2, 3 and Christian Gross1, 2, 3

1 Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
2 Munich Center for Quantum Science and Technology (MCQST), 80799 München, Germany
3 Physikalisches Institut, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany
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Black-body radiation, omnipresent at room temperature, couples nearby Rydberg states. The resulting state mixture features strong dipolar interactions, which may induce dephasing in a Rydberg many-body system. Here we report on a single atom resolved study of this state contamination and the emerging pairwise interactions in optical tweezers. For near-resonant laser detuning we observe characteristic correlations with a length scale set by the dipolar interaction. Our study reveals the microscopic origin of avalanche excitation observed in previous experiments.

Tailored many-body systems can be engineered from atomic ensembles laser-coupled to Rydberg states. In combination with optical tweezers this forms a versatile platform for quantum simulation and computation [1–7]. Understanding decoherence channels is of prime importance for these emerging applications of Rydberg atoms. At room temperature, black-body radiation is known to incoherently drive transitions between nearby Rydberg states, a process often dominating the decay rate of a Rydberg state [8]. In a many-body setting, the resulting state contamination with Rydberg states of opposite parity opens extremely strong dipolar interaction channels. These uncontrolled interactions lead to dephasing, which may severely limit the coherence time for ensembles of Rydberg atoms. Previous works have observed and studied the presence of interaction induced dephasing and line broadening spectroscopically in a bulk setting [9–13]. A scaling analysis [9] and dynamic experiments [13] pointed towards black-body radiation induced state contamination to trigger an avalanche excitation process. Dipolar interactions cause level shifts, such that the normally off-resonant laser becomes resonant. This facilitated excitation results in quick population build up in the Rydberg state. Due to the high probability to undergo a black-body radiation induced state change, even more contaminant atoms are produced speeding up the facilitation process. Mean-field models have been employed to explain this effect, but they have shown large quantitative deviation from the data. This triggered a refined theoretical analysis pointing out the importance of correlations between the excited Rydberg atoms [15].

Here we report on a study of the state contamination induced interactions with neutral atoms individually trapped in a two-dimensional optical tweezer array. Similar to prior experiments in bulk, we near-resonantly laser-couple the atoms to a Rydberg state [9–14]. This realizes the setting of Rydberg dressing [16–20], a versatile strategy to realize complex Hamiltonians for the study of quantum magnets [21–25] and to prepare resource states for quantum metrology [17, 24–26]. Coherent evolution under Rydberg-induced interactions has been reported in small systems [27–30] or for relatively short times [31] and avalanche excitation has been observed as one limiting process [28, 29]. The single atom resolved tweezer system allows us to probe the excited Rydberg atoms one-by-one and to study the facilitation process in the pairwise limit outside of the avalanche regime. We extract the characteristic correlation length and directly show that this matches the length scale set by the dipolar interactions.

In our experiment we use Potassium-39 atoms initially prepared in the $|g\rangle = |4S_{1/2}, F = 2, m_F = 2\rangle$ ground state. We laser-couple the atoms to the $|r_0\rangle = |62P_{1/2}, m_J = -1/2\rangle$ Rydberg state by an ultraviolet laser at 286 nm with wave vector $k_{UV}$, Rabi frequency $\Omega$ and detuning $\Delta$ (see Fig. 1). The circular polarized Rydberg laser beam with a waist of 20 $\mu$m is propagating in x-direction, parallel to the magnetic field of 10 G. The ground state atoms are individually trapped in holographically generated two-dimensional optical tweezer arrangements using laser light at 1064 nm. In each experimental run about half of the tweezers are randomly loaded with a single atom and the occupation of the traps is detected using fluorescence imaging. A typical image is shown in Fig. 1c for a 3×16 array. In this work we vary the distance of the tweezers between $a = 5 \mu$m and $a = 40 \mu$m (for details of the setup see [32]). When the ground state atoms are excited to the Rydberg state, they receive a recoil kick $p_r = \hbar k_{UV}$, which together with the repulsive ponderomotive force due to the tweezers leads to efficient ejection out of the trap. We detect the lost atoms by comparison of two images, one before and one after the Rydberg laser illumination. The duration of the laser pulse is orders of magnitude shorter than the vacuum limited trap lifetime of about 80 s, such that lost atoms can be
identified with Rydberg excitations.

In the limit of a low excitation fraction, any interaction induced line broadening can be understood in a two-atom picture, in which the presence of a contaminating atom leads to a distance-dependent level shift for nearby atoms. The normally off resonant laser becomes resonant to the shifted atomic line if the interaction energy matches the detuning and the second atom is excited and subsequently lost from the trap. The line shifts may be rooted in van-der-Waals or dipolar interactions between two Rydberg atoms or in the electrostatic interaction between a Rydberg atom and an ion [34–35]. In all cases the process can lead to complex kinetically constrained dynamics [36–42], of which signatures have been observed by monitoring the bulk excitation dynamics of a Rydberg coupled gas [43–52]. The incoherent excitation is in contrast to a coherent two-photon excitation of the interacting pair, which becomes resonant at half the detuning. Facilitated excitation processes reduce the trap lifetime compared to the single atom expectation and imprint characteristic two-body correlations (see Fig. 1d, e) by which the underlying mechanism can be identified.

We measure the range of the induced two-point correlations on lost atoms \( g^{(2)}(d) = \langle (n_r - \langle n_r \rangle)(n_{r+d} - \langle n_{r+d} \rangle) \rangle \) versus detuning from the atomic resonance. Here, \( d = (d_x, d_y) \) is the distance vector connecting the two tweezer positions, \( n_r = \pm 1 \) encodes the occupation of the tweezer at position \( r \) and the averaging is over experimental runs and positions. We adjusted the Rabi frequency according to \( \Omega/\Delta = \Omega_m/\Delta_m \) with maximum Rabi frequency \( \Omega_m = 2\pi \cdot 0.4 \text{ MHz} \) at maximum detuning of \( \Delta_m = -2\pi \cdot 8 \text{ MHz} \), to limit the Rydberg state.

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**Figure 1.** a. Simplified level scheme with the atomic ground state \( |g\rangle \) and laser coupled Rydberg state \( |r_0\rangle = |62P_{3/2, m_J = -1/2}\rangle \) with Rabi frequency \( \Omega \) and detuning \( \Delta \). Black-body radiation couples to nearby Rydberg states \( |r_i\rangle \) with rate \( \Gamma_i \). b. Van der Waals and dipolar pair-potentials. The dipole-dipole potentials between \( |r_0\rangle \) and magnetic sub-states of the 13 GHz higher lying, strongest coupled states \( |61D_{3/2}\rangle \) and \( |61D_{5/2}\rangle \) are shown in gray. The shading is proportional to the laser coupling rate for a magnetic field of 10 G, which mixes the fine-structure states. In a black-body event, the energy difference between \( |r_0\rangle \) and \( |r_i\rangle \) is provided by the microwave photon, effectively collapsing all pair-potentials asymptotically (lower panel). The van der Waals potential between a pair of atoms in the state \( |r_0\rangle \) is highlighted in blue in the lower panel, illustrating its much shorter range. c. Single fluorescence image of ground state atoms in a 3×16 tweezer array with 5 μm spacing. The magnetic field direction is indicated by the gray and the UV laser direction by the purple arrow. d. Measurement of the trap lifetime in the 3×16 array at \( \Delta = -2\pi \cdot 4 \text{ MHz} \) and \( \Omega = 2\pi \cdot 430 \text{ kHz} \). The dark-red line shows an exponential fit to the data revealing a trap lifetime of 6.8(4) ms, much shorter than the laser phase noise limited trap lifetime of 21.4(1.3) ms measured for individual atoms (gray line) [32]. Error bars denote 1 s.e.m. e. Two body correlator \( g^{(2)} \) at different illumination times marked with the numbers in d, showing the growth of correlations over time.

**Figure 2.** Dipolar facilitation range. The figure shows the typical correlation distance \( d_c(\Delta) \) extracted from an exponential fit to \( g^{(2)}(d, \Delta) \) for a single line of atoms (light blue) and a 3×16 array (dark blue), both with spacing \( a = 5 \mu m \). Gray shaded lines are the asymptotically collapsed dipolar pair-potentials with the shading proportional to the expected logarithmic facilitation strength. The inset shows an example of the detected two-body correlations with the exponential fit \( g^{(2)}(d, \Delta) \propto \exp(\cdot d/d_c(\Delta)) \) to extract \( d_c(\Delta) \) for \( \Delta = -2\pi \cdot 5 \text{ MHz} \). Error bars denote 1 s.e.m. in the inset and the fit errors in the main panel.
population $p_0 = \alpha(\Delta)\Omega^2/4\Delta^2$, where $\alpha(\Delta)$ accounts for excess phase noise of the laser [32]. We confirmed, that the observed length scales are constant when decreasing $\Omega$ further. While the amplitude of $g^{(2)}$ is strongly dependent on the illumination time $\tau$, we found its spatial dependence to be insensitive to it. In order to assure comparability of the correlation amplitudes between different settings, we chose $\tau$ such that 60% of the initially loaded atoms remained in the array.

For correlations caused by black-body radiation induced state contamination, the length scale of the correlations $g^{(2)}(d)$ is expected to be set by the pairwise dipolar interaction potentials. To extract a typical correlation length scale $d_c(\Delta)$ we fit the data exponentially with $g^{(2)}(d, \Delta) \propto \exp(-d/d_c(\Delta))$. This empirical fit matches the data well (cf. inset of Fig. 2). The dipolar interaction potentials are approximately symmetric around the single atom resonance. In Fig. 2 we show that $d_c(\Delta)$ reproduces this approximate symmetry and we show that $d_c(\Delta)$ matches with the range of the dipolar pair-potentials. To illustrate this, we plot the relevant dipolar potentials of pair-eigenstates $\{\Psi_2\}$ asymptotically correlating to $|r_0, r_i\rangle$, with $|r_i\rangle$, the i-th state of opposite parity populated by black-body radiation with rate $\Gamma_0$. The energy difference $\hbar \Delta_{0i}$ is provided by the black-body photon and, hence, we plot all pair-states asymptotically at the same energy as $|r_0, r_0\rangle$. The pair-potentials are shaded according to the relative pair-potential strength. This is defined as the product $\langle \Psi_2 | r_{0r}, r_{i} \rangle \Gamma_{0i}/\Gamma_{0k}^{\text{max}}$ of the overlap of the pair state $|\Psi_2\rangle$ with $|r_{0r}, r_{i}\rangle$ and a normalized black-body coupling rate $\Gamma_{0i}/\Gamma_{0k}^{\text{max}}$. The normalization is performed to the strongest coupled state with rate $\Gamma_{0k}^{\text{max}}$. For the calculations the Pairinteraction [53] and ARC [54] software packages have been used.

While our analysis so far confirms that the length scale of the observed correlations is set by the dipolar-pair-potentials, our experiment fails to reproduce the short distance behavior expected in a picture of fixed atomic positions (see [32]). This discrepancy is resolved when considering moving Rydberg atoms with trajectories determined by the interplay of temperature, atomic recoil and the tweezer’s ponderomotive potential. The atomic recoil velocity $v_r = \hbar k_{UV}/m = 36 \text{ \mu m/ms}$ for potassium atoms of mass $m$, due to scattering of photons from the UV laser, is comparable to the typical velocity gained from the ponderomotive potential $v_U = \sqrt{2\Delta U/m} = 40 \text{ \mu m/ms}$, while the thermal velocity of $v_T = \sqrt{k_B T/m} = 0.5 \text{ \mu m/ms}$ for $T = 200 \text{ nK}$ is much smaller. This results in a directed motion of the atoms exited to Rydberg states (Fig. 3b). The decay to low lying states takes many hundred microseconds, in which the Rydberg atoms move by tens of micrometers, clearly invalidating a static picture [32]. The impact of this motion can be seen most directly when analysing the trap lifetime locally (Fig. 3d). Atoms in the first column of the array (counted with respect to the UV propagation direction) stay almost twice as long in the trap than atoms in the last column of the array. We attribute this to a lower effective facilitation rate as no facilitating atoms can approach from one direction. We confirmed, that the signal is absent without UV illumination. To probe for the effect of this motion on the nearest-neighbor correlations we prepare arrays of different spacing $a$ and compare the strength of $g^{(2)}_{nm}(a)$ for two different detunings $\Delta = -2\pi \cdot 2 \text{ MHz}$ and $\Delta = -2\pi \cdot 5 \text{ MHz}$ (see Fig. 3e). For those detunings, the dipolar potential range differs by almost a factor of two, but the observed distance dependence of $g^{(2)}_{nm}(a)$ is indistinguishable. This demonstrates that the sampling of all positions in flight is hiding the dependence of the dipolar pair-potentials entirely. The correlations feature...
a plateau for short distances, which we attribute to the typical flight distance of the Rydberg atoms within their electronic lifetime [32].

This result seems to be in contradiction to our observations reported in Fig. 2, which is resolved when taking into account the presence of other tweezers in the system. The recoil energy is about $3 \mu K$, comparable to the ponderomotive potential height of $3.7 \mu K$ of the individual tweezers, resulting in a “shielding” effect for the next-nearest-neighbors. To support this interpretation we performed classical simulations, which clearly confirm this effect (see Fig. 3b,c). In Fig. 3f we show the strength of two-point correlations $g^{(2)}(d)$ for three distances $d$. For each distance, we compare the correlation amplitude of nearest-neighbor setting (zero potential barriers in between) to a setting of one or more potential barriers in between. In all cases, the setting without barriers in between shows strong and almost distance independent correlations. In contrast, when at least one potential barrier is present, the correlation amplitude decreases with distance and the effect is stronger for the larger detuning, for which the dipolar range is smaller. Note that in a static picture no dependence on the presence of empty traps in between the two positions is expected.

So far we have focused on the low excitation fraction regime, in which avalanche facilitation is small. The avalanche effect arises, when an already facilitated atom is transferred to a state $|\bar{f}\rangle$ by black-body radiation and itself facilitates the excitation of further atoms. To test for the avalanche mechanism we measure the two-point correlations in the $3 \times 16$ geometry with $a = 5 \mu m$ for increasing Rabi frequency while fixing the total fraction of lost atoms. Fig. 4a shows that both, range and amplitude of two-point correlations increase with higher Rabi frequency. For the strongest driving, the amplitude of correlation between the two ends of the array (almost $80 \mu m$ apart) is of comparable strength to the nearest-neighbor correlation for the weakest drive. The local measurements reveal, that the strong increase of the $g^{(2)}(d)$ signal is accompanied by an emergence and subsequent increase of higher order correlations. In Fig. 4b we show the connected $k$-point correlator at shortest possible distance ($k$ subsequent tweezers along the UV beam) $g^{(k)}_{n\ldots n} = \langle \prod_{j=0}^{k} (n_{x+j+a} - \langle n_{x+j+a} \rangle) \rangle$. Remarkably, all higher order correlators increase simultaneously underlying the avalanche character of the process. This is further supported by a strong broadening of the distribution of lost atoms [32], which is a precursor of the observed bimodality in higher density settings [23, 53].

In this work we microscopically explored correlations emerging in atomic samples near-resonantly coupled to Rydberg states. We identified dipolar interactions due to black-body radiation induced state contamination as the underlying process. Furthermore, we have shown that the recoil triggered, directed motion of the Rydberg atoms is governing the facilitation process at nearest-neighbor distance. By increasing the driving strength, our observations seamlessly connect to previous studies, which concentrated on the avalanche regime in bulk systems [9, 14]. The possibility to control the Rydberg motion by repulsive trapping potentials suggests a new possibility to circumvent catastrophic avalanche dephasing in one- or two-dimensional Rydberg-dressed systems: With realistic experimental parameters a light-sheet potential at wavelengths chosen to trap the ground state but to repel the contaminant atoms can be implemented. This method works also in combination with tailored trapping wavelengths, which allow one to trap the ground state and only one particular Rydberg state [50, 57]. It is compatible with future two-dimensional Rydberg quantum processors and simulators and, in particular, it paves the way to utilize Rydberg dressing for the design of atomic Hamiltonians for the study of various quantum spin models [21, 23] or to generate useful states for quantum metrology [24, 26].

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Figure 4. Avalanche facilitation. a. Two-point correlations $g^{(2)}$ vs. distance for different coupling strength in a $5 \mu m$-spaced $3 \times 16$ array. The Rabi frequency increases from light to dark blue as $\Omega = 2\pi \cdot (6, 25, 102, 410)$ kHz and the pulse time was adjusted to fix the fraction of lost atoms to $60\%$. Exponential fits are shown as solid lines. b. Multi-point correlations vs. coupling strength. The shortest distance connected multi point correlations $g^{(k)}_{n\ldots n}$ in $x$-direction are shown for $k = 2$ (blue), $k = 3$ (light green) and $k = 4$ (dark green). Error bars, where larger than the point size, denote 1 s.e.m.
SUPPLEMENTAL INFORMATION

Experimental setting

We load the potassium-39 atoms from an optical molasses into the tweezer array and subsequently cool them near the motional ground state using Raman sideband cooling. We then ramp the optical tweezers down to 0.5% of their initial power (corresponding to a trap depth of 3.7 $\mu$K). This reduces the inhomogeneities between different tweezers to less than 50 kHz. Simultaneously, the atoms are adiabatically “cooled” to 200 nK, reducing the Doppler broadening to $2\pi \cdot 50$ kHz. This preparation of the atomic sample in the tweezer array is further detailed in reference [33].

Single-atom trap lifetime and laser phase noise

Spectral components of the laser phase noise that match the detuning resonantly increase the Rydberg population. The phase noise contribution often dominates the population, in particular, near the resonance. The impact of the phase noise alone can be conveniently revealed by measuring the single-atom trap lifetime, because any Rydberg excitation is efficiently ejected from the tweezer. In the main text we characterize this phase noise by an enhancement $\alpha(\Delta)$ of the Rydberg population w.r.t. the noise free value. The enhancement factor $\alpha(\Delta) = \tau_{id}/\tau$ follows from the ratio of the measured trap lifetime $\tau$ and the ideal trap lifetime $\tau_{id} = \tau_{r} \cdot \Omega^2 / \Delta^2$ for a noise-free laser. The latter is only limited by the electronic lifetime $\tau_{r}$ of the Rydberg state. Here we assumed $\Delta \gg \Omega$. In the tweezer array, isolated atoms can be realized by placing them far away from each other. We use distances of 30 $\mu$m and 40 $\mu$m and confirm that interactions can be neglected in this setting by checking for the absence of correlations in the losses.

Figure S1 shows the result of a measurement of the trap lifetime for a Rabi frequency of $\Omega = 2\pi \cdot 266$ kHz and a detuning of $\Delta = -2\pi \cdot 4$ MHz. From the exponential fit we extract a lifetime of $\tau = 49.3$ ms ± 1.1 ms, resulting in a factor $\alpha = 2.9$. The single-atom prediction shown in figure 1d of the main text includes this factor. In figure S1b we show $\alpha(\Delta)$, summarizing the results of all our noise characterization measurements.

Electronic decay of the Rydberg state

Figure S2 shows the decay rates of the chosen Rydberg state $62P_{1/2}$ into all states of different principal quantum number for 0 K and for 300 K. These numbers have been calculated with the ARC software package [54]. At 300 K the majority of decays are to nearby Rydberg states. When defining $n = 30$ as a boundary between low and high lying states, of which the latter emerge only due to black-body radiation, the ratio of the decay rates is $\sum_{n<30} \Gamma_{0,n} / \sum_{n\geq30} \Gamma_{0,n} = \frac{2\pi \cdot 0.16 \text{ kHz}}{2\pi \cdot 0.8 \text{ kHz}} \approx \frac{1}{5}$. Atoms, which make a black-body radiation induced transition from the $62P_{1/2}$ to a state of $s$- or $d$-orbital symmetry interact via dipolar interactions with atoms in the $62P_{1/2}$ state. This shifts the transition frequency and is the mechanism behind the facilitated excitation we observe. For the effects of the moving Rydberg atoms and for the avalanche processes at higher driving strength, the time the atoms stay in any Rydberg state is a fundamentally important parameter. This time can be approximated by the zero temperature lifetime, where all decays are to the low lying states. In the vicinity of $n = 60$,
the 0 K-lifetime is about 250 μs for s-states, 800 μs for p-states and 500 μs for d-states. Including black-body radiation, none of the states live for more than about 150 μs. When assuming a lifetime of 150 μs to roughly estimate the time in which facilitation can take place, the atoms move about 13 μm. Note that this is a crude simplification since the atoms may change their Rydberg state several times before decaying to the ground state.

**Dipolar facilitation for fixed atomic positions**

The resonant rate of dipolar facilitation $\gamma_i$ due to the i-th pair-potential can be readily calculated in the low excitation fraction regime. It follows from $\gamma_i = \Gamma_{\text{eff}}p_0\Omega^2\sigma^2 \bar{r}^2$ with an effective rate $\Gamma_{\text{eff}} = \langle \Psi_2 | r_0, \bar{r}_i \rangle \Gamma_{0,i}$, taking into account the pair-state overlap $\langle \Psi_2 | r_0, \bar{r}_i \rangle$ and the black-body coupling rate $\Gamma_{0,i}$. The probability for the atom to be in state $| r_0 \rangle$ is given by $p_0 = \alpha(\Delta)\Omega^2/4\Delta^2$ and includes the laser phase noise factor $\alpha(\Delta)$. The electronic lifetime of the Rydberg state is $\tau_r$. The expected facilitation rate $\gamma_{\text{fac}}$ shown in Figure S3 for two detunings takes the rates $\gamma_i$ of all pair-potentials into account, which become resonant at a certain distance. Additionally, it includes a convolution with a Gaussian of standard deviation $\sigma = 0.58 \mu m$ to include the thermal extend of the spatial wavefunction in the individual tweezers. The expected spatial dependence is clearly non-exponential in contradiction to our measurements. We interpret this as a further indication for the changing positions of the Rydberg atoms.

**Atom loss distributions at different Rabi frequency and density**

Previous experiments have reported a bimodality in the distribution of lost atoms and interpreted this as a signature of avalanche facilitation triggered by black-body induced state contamination [28, 55]. In Figure S4 we show the distribution of lost atoms for different settings. It increases strongly in width with increasing Rabi frequency and even more when post-selecting the high Rabi frequency data to the high density sector of more than 26 atoms (54% of the tweezers) loaded. This matches the observation in previous experiments, in which the atomic density was even higher and the avalanche regime was fully realized.

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*christian.gross@uni-tuebingen.de*

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