An echo experiment in a strongly interacting Rydberg gas

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When ground state atoms are excited to a Rydberg state, van der Waals interactions among them can lead to a strong suppression of the excitation. Despite the strong interactions the evolution can still be reversed by a simple phase shift in the excitation laser field. We experimentally prove the coherence of the excitation in the strong blockade regime by applying an ‘optical rotary echo’ technique to a sample of magnetically trapped ultracold atoms, analogous to a method known from nuclear magnetic resonance. We additionally measured the dephasing time due to the interaction between the Rydberg atoms.

Interactions are often characterized by a length scale \(a\). In the case of strong interaction \(a\) is much larger than the mean distance \(r\) between two particles \(r \sim n^{-1/3}\), where \(n\) is the particle density. Contrary to dilute systems, where \(na^3 \ll 1\), strongly interacting systems are dominated by correlations that make mean field descriptions inaccurate or even misleading.

Strongly correlated ground states of ultracold fermionic quantum systems are currently studied in the BEC-BCS crossover regime [1]. Here, the length scale for the interaction, the s-wave scattering length \(a\) is increased by means of a Feshbach resonance. Superfluid behavior has been observed even in the strongly interacting regime [2]. Likewise, the Mott insulator state is a strongly correlated state of matter which is studied using ultracold gases in optical lattices [3].

Excited states can also be correlated by strong interactions, leading to collective states and blockade phenomena. Several proposals have been made on how to use this blockade mechanism for the implementation of fast quantum gates for thermally frozen neutral atoms [4, 5]. In the case of the excitation of gaseous atoms to a Rydberg state by a laser with a small linewidth, a length scale for the interaction among them can be found by equating the mutual interaction energy with the power broadened transition linewidth \(\hbar \Omega\), where \(\Omega\) is the Rabi frequency. For the purpose of this paper it can be assumed that the Rydberg–Rydberg interaction is dominated by the van der Waals interaction \(V(r) = -C_6/r^6\). Strong blockade effects are expected, if the resulting blockade radius \(a_{\text{block}} \propto \sqrt[3]{C_6/\hbar \Omega}\) is much larger than the mean distance of the ground state atoms, given by the density of ground state atoms \(n_g^{-1/3}\). Such blockade effects have been studied for the van der Waals interaction and for resonant dipolar interactions between Rydberg atoms [6, 7, 8, 9]. These experiments were done in a regime where \(n_g a_{\text{block}}^3\) is on the order of 10 or less and the blockade effect can be understood in a mean field model, where the interactions tune the Rydberg state out of the laser resonance [7, 10].

In the strong blockade regime, where \(n_g a_{\text{block}}^3 \gg 1\), the system can be described as two-level atoms and beyond mean field effects have been predicted for samples smaller than \(a_{\text{block}}[5, 10]\). The excitation is then limited to a single excitation into a Rydberg state, delocalized over all \(N\) members of a blockade sphere with radius \(a_{\text{block}}\). The corresponding collective transition matrix element between the ground state and the state carrying a single excitation is given by \(\sqrt{N} \Omega_0[5]\), where \(\Omega_0\) is the single atom Rabi frequency. These objects are sometimes called ‘superatoms’ [11] as the \(N\) members of the ensemble resemble a two-level system with the enhanced collective Rabi frequency \(\sqrt{N} \Omega_0\).

In previous experiments conducted in the strong blockade regime, we have confirmed the collective coherent scaling of the excitation rates with \(\sqrt{N} \Omega_0[12]\). This letter aims at a direct demonstration of the coherence of the excitation and the measurement of the dephasing times in a strongly interacting Rydberg gas, where \(n_g a_{\text{block}}^3\) is a few thousand.

For a thermal atomic cloud, trapped in a harmonic potential, the density \(n_g\) has a Gaussian distribution over the position in the sample. Thus, the atom number \(N\) and, consequently, the collective Rabi frequency \(\sqrt{N} \Omega_0\) is inhomogeneously distributed. This leads to the fact that Rabi oscillations cannot be observed directly, because an integrated signal over all Rabi frequencies is detected. Echo techniques, such as the rotary echo sequence [13], have been developed in nuclear magnetic resonance physics to overcome these inhomogeneity effects.

In frozen Rydberg gases the center of mass motion of the atoms can be neglected. If the narrowband excitation laser is tuned to resonance, the Hamilton operator can be written using the Pauli matrices \(\sigma_x\) and \(\sigma_z[10]\) as:

\[
\mathcal{H} = \sum_j \Omega_0 (\sigma_x)_j + \sum_{j<k} V_{jk} \frac{1}{2} (\mathbb{1} + \sigma_z)_j \frac{1}{2} (\mathbb{1} + \sigma_z)_k, \tag{1}
\]

where \(V_{jk}\) is the pair interaction between two Rydberg atoms \(j\) and \(k\). This model assumes for single atoms a two-level system consisting of a ground and a Rydberg state at site \(j\).

In a rotary echo [13] sequence an atom is excited and after a certain time \(\tau_p\) the sign of the excitation amplitude \(\Omega\) is reversed. Independent of the magnitude of \(\Omega\,
the state of the system evolves back to the electronic ground state at time $2\tau_p$, unless dephasing occurs, e.g., due to the interaction $V_{jk}$.

Strong interactions $V_{jk}$ also strongly suppress the excitation and build up spatial correlations in the distribution of Rydberg states [10]. Therefore a mean field model is not expected to lead to a correct description of the dephasing. Spatial correlations are taken into account in a model that is based on the collective superatom states. Such an approach is more appropriate although of course not complete. A superatom model would predict a coherent evolution with reduced dephasing compared to a mean field model as the spatial correlations prevent short distances between Rydberg atoms. Therefore, even in the case of strong suppression of excitation an echo signal is expected.

To measure the dephasing in the excitation of a strongly interacting Rydberg gas, a sample of Rubidium atoms in a magnetic trap is prepared (Fig. 1 and [14]). The atoms are cooled to a temperature of 3.8 µK at a peak density of ground state atoms $n_g$ of $5.2 \times 10^{19}$ m$^{-3}$. For a systematic variation of the density, a Landau-Zener sweep is used [15]. A microwave sweep of 6.8 GHz couples the two hyperfine ground states of $^{87}$Rb and, depending on the sweep time, a fraction of the atoms are transferred from the initial $5S_{1/2}, F = 2$, $m_F = 2$ state into the untrapped $F = 1$, $m_F = 1$ state (Fig. 1(a)). The size of the sample depends only on the temperature and the trap frequencies, which are held constant for all data presented here. The sample therefore has a constant size and is fully characterized by either the number of ground state atoms $N_g$ or the peak density $n_g$ and $T$. The number of ground state atoms $N_g$ in the trap was varied between $1.1 \times 10^7$ and $1.0 \times 10^6$ atoms without a significant change in temperature $T$.

Afterwards, the atoms are excited by a resonant two-photon transition into the $43S_{1/2}$ Rydberg state, using 480 nm and 780 nm light, which is detuned by $2\pi \times 472$ MHz from the $5P_{3/2}$ intermediate state (Fig. 1(a) and [14]). A value for the two-photon Rabi frequency $\Omega_0$ of $2\pi \times 90.5$ kHz is found using a calculation of the dipole matrix element between the $5P_{3/2}$ and the $43S_{1/2}$ state and a value for $\Omega_r$ (Fig. 1(a)) of 8.7 MHz. The obtained value is in excellent agreement with values from independent calculations [16]. The Rabi frequency can be treated as constant over the atomic cloud, as the cloud is smaller than the waists of the exciting lasers. The two laser beams are superimposed along the $z$-direction of the magnetic trap, i.e., the long axis of the cigar shaped atomic cloud (Fig. 1(b)). The magnetic offset field in $z$-direction defines the quantization axis, so that, by choosing $\sigma^+$ for the 780 nm and $\sigma^-$ light for the 480 nm laser, the atoms are selectively excited into the $43S_{1/2}, m_J = +1/2$ state, which has the same Zeeman energy shift as the ground state. In order to exclude the effects of ions, an electric field of 200 V/m is applied during the excitation [12]. Subsequent to the excitation, the Rydberg atoms are field ionized and pushed towards a micro channel plate by applying an electric field of 20 kV/m. Temperature and density of the atomic ensemble are obtained from absorption images of the remaining ground state atoms.

A typical excitation curve is shown in Fig. 2(a). Such excitation curves were systematically studied in our previous work [12]. For the purpose of this work, a constant pulse with a duration $\tau$ is applied and the number of Rydberg atoms for different numbers of ground state atoms in the sample is investigated. For the measurements in Fig. 2(b), 3, 4 the time $\tau$ was held constant at 478 ns. The pulse duration $\tau$ was chosen to be short compared to the time scale of the saturation, which is on the order of microseconds (Fig. 2(a)). Figure 2(b) shows that the experiments are performed in the strong interaction regime: Without interaction one would expect Rydberg atom numbers $N_R$ depicted by the two solid lines. The upper bound is given by $N_R = N_g \sin^2(\Omega_0 \tau/2) = 0.02 N_g$. Taking a statistically distributed laser detuning with an experimentally determined width of $2\pi \times 1.5$ MHz into account, the number of Rydberg atoms would decrease to the value $N_R = 0.01 N_g$. In both cases the Rydberg atom number scales linearly with the number of ground state atoms $N_g$. In comparison, our data show significantly less excitation and an increase of $N_R$, which scales only like $N_g^{0.43 \pm 0.03}$. Thus, a strong suppression of the Rydberg atom number due to the van der Waals interaction is observed. This clearly indicates that the following experiments are done in the strong blockade regime, where strong interactions among the Rydberg atoms suppress...
we show the dependence of the visibility on the interaction strength among the sample ensembles have been prepared and the time $\tau_p$ has been scanned from 0 to $\tau$ in 10 steps within every sample. The excitation was resonant with the two-photon transition $V_{12}$ for all measurements. The laser frequency has a Gaussian distribution with a width of $2\tau \times 130$ kHz on the time scale on which $\tau_p$ is scanned and a width of $2\tau \times 1.5$ MHz on the long time scale, i.e., between the preparation of two samples. The data in Fig. 4 has been fitted with a parabolic function to guide the eye and to obtain the visibility

$$V = \frac{N_R(\tau_p = 0) - N_R(\tau_p = \tau/2)}{N_R(\tau_p = 0) + N_R(\tau_p = \tau/2)}$$

of the rotary echo signal. The visibilities are $(47 \pm 8)$ %, $(48 \pm 5)$ % and $(29 \pm 6)$ % in Fig. 4(a)-(c), respectively. This echo signal is a clear for the coherence of the excitation, despite strong interactions among the excited atoms.

In Fig. 5 we show the dependence of the visibility on the density of ground state atoms for three different pulse lengths. The data was fitted with a simple exponential decay to guide the eye. From the data the tendency of the visibility on the interaction strength among the sample can be obtained: The higher the density and the longer the pulse length, the smaller the visibility. Assuming an exponential decay for the dependence of the visibility on the pulse time, a dephasing time of 860 ns is obtained for a density $n_g = 7.2 \times 10^{18}$ m$^{-3}$. Note that the effect due to the radiative lifetime of the Rydberg state is on the order of 100 $\mu$s and, thus, can be safely neglected.
To conclude, we have prepared a cold sample of ground state atoms, from which a few thousand atoms are excited into a strongly interacting Rydberg state. It was shown that even for pulse lengths, short compared to the time scale on which the interaction leads to a full blockade of the Rydberg signal, the excitation was strongly suppressed in comparison to the non-interacting case. The excitation into the Rydberg state was shown to be phase stable for the whole inhomogeneous sample with respect to the exciting laser field. The phase stability was proven by a so called optical rotary echo technique, where the excitation laser field was phase shifted by $\pi$ during the pulse leading to a coherent de-excitation. The rotary echo signal shows dephasing times of several $100\,\text{ns}$, while the rotary echo signal shows dephasing times of several $100\,\text{ns}$, during the pulse leading to a coherent de-excitation. The rotary echo signal obtained are $47\pm8\%$ with $N_g = 1.0 \times 10^9$ in (a), $48\pm5\%$ with $N_g = 3.3 \times 10^7$ in (b) and $29\pm6\%$ with $N_g = 1.0 \times 10^7$ in (c). The error bar indicates the statistical fluctuation of the Rydberg atom number over five independent experiments.

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