Coherent control of processes that break the dipole blockade

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We experimentally study state mixing during Rydberg excitation near Förster resonance. By varying the excitation pulse duration or Rabi frequency, we can controllably change the dominant process causing the mixing. This results in exciting either predominantly two- or three-atom mixed states. We use an optical rotary echo technique to prove the coherence of the excitation to three-atom states. We find good agreement between our data and a model for excitation in a three-atom basis.

Neutral atoms are good candidates to implement quantum technologies because of weak couplings with each other and with the environment [1]. However, to do something useful, one must make the atoms interact at the right time. This problem is often solved by exciting atoms to strongly-interacting Rydberg states.

A key ingredient in most proposals is the dipole blockade, or the interaction-induced suppression of excitation [2, 3]. If atoms can be individually addressed in optical lattices or tweezer traps, then one atom in a Rydberg state can block the excitation of adjacent atoms. Rydberg-Rydberg interactions shift the energy levels of the neighboring atoms out of resonance with the laser. This has been used to create neutral atom quantum gates [4, 5] and flexible quantum simulators [6–21]. If single atoms cannot be isolated and addressed, then dipole-dole interactions lead to an unequal ladder of energies of the collective states of the system. If states with \( \geq 2 \) shared excitations shift by more than the excitation laser linewidth, one will excite a “superatom” where many atoms coherently share a single excitation. This has enabled the creation of controllable entanglement [22–27], strongly correlated systems [28–31], single photon sources [32, 33], single photon switches and transistors [34, 35], optical nonlinearities [36, 42], and coherent effects in room-temperature vapors [30, 32, 43–45].

One might expect that adding more atoms in the vicinity of a close pair would increase the efficiency of the blockade. However, it has been shown that adding even one additional atom to strongly blockaded pair can dramatically reduce the efficiency of the blockade [40]. Consider Rydberg excitation of three atoms from a ground state, \(|g⟩\), to a target state, \(|d⟩\), via a resonant optical pulse. Near Förster resonance, the \(|d⟩\) state is coupled to nearby product states \(|p⟩\) and \(|f⟩\), and the energy defect \( \Delta E = 2 \times E_d - (E_p + E_f) \approx 0 \). This near-resonance leads to enhanced interactions, which should lead to a better blockade [47]. However, an optical pulse can drive transitions between the three-atom ground state \(|ggg⟩\) and a triply-excited mixed state, \(|M_3⟩\), through virtual levels whose populations adiabatically follow the pulse envelope. This state has zero energy shift, and has the form

\[
|M_3⟩ = c_1|dpf⟩ + c_2|dfp⟩ + c_3|pdf⟩ + c_4|fdp⟩ + c_5|pdf⟩ + c_6|fpd⟩,
\]

where \( c_i \) are probability amplitudes. Given appropriate values for the pair-state detuning, pulse duration, and Rabi frequency, \(|M_3⟩\) can be excited with high probability [46]. Creation of this state ruins a perfect blockade.

Recently, we studied excitation of \( ^{85}\text{Rb} \) atoms to \( nD_{5/2} \) Rydberg states \(|⟨d⟩| \) in the vicinity of the Förster resonance at \( n = 43 \): \( 2 \times nD_{5/2} + (n-2)F_{7/2} + (n+2)F_{3/2} \) [50]. In this case, atoms are detected in \(|nD_{5/2}⟩ \) and \(|(n-2)F_{7/2}⟩ \) with high probability immediately after excitation [50, 53–55]. For the experimental conditions of Ref. [50], the state-mixing mechanism was consistent with the excitation of two-body mixed states, \(|M_2⟩ = a_1|dd⟩ + a_2|pf⟩ + |fp⟩⟩ \) for \( n = 43 \). For values just off resonance, atoms were detected in \(|p⟩ \) and \(|f⟩ \) states with slightly lower probability. However, the mechanism was consistent with excitation of triply-excited states, \(|M_3⟩\).

![FIG. 1. Rydberg excitation sequence. (a) Two-step excitation scheme for \(^{85}\text{Rb}\). (b) Optical pulses of duration \( \tau \) are created by amplitude modulating RF signals driving acousto-optic modulators (AOMs). At time \( t' \), the phase of the RF signal driving the upper transition AOM is shifted by \( \pi \), and the effective Rabi frequency switches from \( \Omega \) to \( -\Omega \), where \( \Omega = \Omega_L \Omega_U / 2\Delta \).](image)
make it break down $\text{[15, 17]}$. In the present work, we see evidence of coherent excitation into triply excited states, $|M_3\rangle$, as we vary excitation pulse duration or Rabi frequency. We employ an optical rotary echo technique $\text{[51, 48, 54, 58]}$ to demonstrate coherence, and we find good agreement between our data and the model of Ref. $\text{[46]}$. This implies that the excitation of $|M_3\rangle$ can be coherently controlled, or avoided altogether, through careful choice of experimental parameters. It is striking that the coherent signal remains so strong when exciting multiple excitation domains with a spatially inhomogeneous laser, in an inhomogeneous density distribution. Thus, our results suggest that the states $|M_3\rangle$ might be useful as a resource in quantum information, in situations with non-ideal control over experimental parameters.

Our experimental setup is described elsewhere $\text{[50]}$. Briefly, we collect ultracold $^{87}\text{Rb}$ atoms in an optical dipole trap. We control the ground state atom density by turning off the dipole trap beam and allowing the atoms to freely expand before they are excited to Rydberg states $\text{[54]}$. We use a relatively low density: $\rho \sim 5 \times 10^{10} \text{ cm}^{-3}$. The excitation scheme is shown in Fig. $\text{[1]}$. We apply coincident pulses of duration $\tau$ to drive the $5S_{1/2} \rightarrow 6P_{3/2} \rightarrow 42D_{5/2}$ transitions, with an intermediate state detuning $\Delta = 50 \text{ MHz}$. Since $\tau \leq 2 \mu\text{s}$, the atoms are effectively frozen during Rydberg excitation. The $\pi^+$ polarized lower transition beam is derived from a MOGLabs external cavity diode laser. The $\pi$ polarized upper transition beam is derived from a MOGLabs cavity laser that is frequency stabilized to a pressure-tunable Fabry–Pérot cavity $\text{[59]}$. The beams are perpendicular to each other and to the long axis of our dipole trap. Pulses are created by amplitude modulating the radiofrequency (RF) signal driving acousto optic modulators (AOMs) in each beam.

We detect atoms using state selective field ionization spectroscopy. A high voltage ramp is applied to electrodes above and below the atom cloud 50 ns after each excitation sequence. Atoms with different binding energies will ionize at different electric fields, and the liberated electrons are detected by a dual stage microchannel plate detector. For each of 1001 shots of our experiment, we use a pulse counter to record the number of excitations in each of two independent timing gates. The “P Gate” counts atoms in $44P_{3/2}$, or $|p\rangle$, while the “T Gate” counts all Rydberg atoms. From this data, we construct a “sorted graph,” or a 2D histogram of the total number of excitations as a function of the number in $|p\rangle$. We fit each sorted graph to a linear function. The slope tells us how many additional Rydberg excitations are created each time an atom is detected in the $|p\rangle$ state. A larger value of the slope indicates the presence of three-atom mixed states of the type $|M_3\rangle$ $\text{[50]}$. A transition from a low value of the slope to a high value indicates a change in the dominant mechanism causing state mixing.

Example sorted graphs are shown in Fig. $\text{[2]}$ for fixed Rabi frequency $\Omega = \Omega_L\mu_d/2\Delta = 1 \text{ MHz}$. In panels (i) through (iii) the pulse duration, $\tau$, is increased from 200 ns to 500 ns to 2000 ns. The slope of the sorted graphs clearly increase and then decrease. This suggests that the dominant mechanism causing state mixing events near Förster resonance is highly sensitive to pulse duration. To explore further, we measured the slopes of the sorted graphs as a function of $\tau$ for fixed $\Omega$ and as a function of $\Omega$ for fixed $\tau$. The results are shown as black diamonds in the top two panels of Fig. $\text{[3]}$. We also plot two other quantities: the Mandel $Q$ parameter and the mixing fraction. The Mandel $Q$ parameter represents the width of the distribution of number of excitations. It is defined as $Q = \sigma^2/N - 1$, where $\sigma^2$ is the dispersion and $N$ is the mean. The mixing fraction is defined as the fraction of Rydberg excitations found in $|p\rangle$ and $|f\rangle$ states. While this fraction increases monotonically with pulse duration or Rabi frequency, the slopes of the sorted graphs and the Mandel $Q$ parameter go through clear relative maxima.

To test the coherence of the process causing this change, we implemented an optical rotary echo technique $\text{[51, 48, 54, 58]}$. The sequence, shown schematically in Fig. $\text{[1]b}$, is similar to the rotary spin echo of nuclear magnetic resonance $\text{[57]}$. At a variable time, $t'$, within our upper transition excitation pulse, we reverse the phase of the RF signal driving an AOM. This reverses the sign of the excitation Rabi frequency, $\Omega$. Independent
of the value of $\Omega$, the system should undergo reverse evolution and arrive back to its ground state at a time $2\tau'$, unless some dephasing occurs. The plots of slope, Mandel $Q$, and mixing fraction with phase flip at half the pulse duration ($\tau' = \tau/2$) are shown in Fig. 3 as purple circles. A raw sorted graph with phase flip at the same time is shown in panel (iv) of Fig. 2. In both Figs. 2 and 3 it is clear that, while the phase flip does not significantly change the fraction of atoms excited into product states, it dramatically reverses the evolution into multiparticle states that feature large slope and $Q$. Thus, we conclude that the excitation of these multiply excited states is coherent over most of the range of $x$-axis values.

To determine the nature of the multiply-excited states, we compare the measured values of the slopes of our sorted graphs with the results of a Monte Carlo simulation. We model the effects of non-unity detector efficiency and shot-to-shot fluctuations in excitation number on the slopes (see Ref. 50 for more details). Figure 4 shows the data from Figs. 3a and d, along with the predictions of our Monte Carlo model. For no phase flip, our data is consistent with the excitation of doubly-excited states ($|M_2\rangle$) for small $\tau$ and $\Omega$, triply-excited states ($|M_3\rangle$) as $\tau$ and $\Omega$ increase, and doubly-excited states ($|M_2\rangle$) for long $\tau$ or large $\Omega$. In the case of a phase flip at $\tau/2$, our data is consistent with the excitation of doubly-excited states, except over narrow regions of the graph. Note that, since the Mandel $Q$ and mixing fraction are inputs to our model, it cannot predict changes in the slope, it merely indicates whether the measured values of slope are consistent with a two- or three-body model for the mixing.

We conclude that the dominant mechanism causing mixing into product states near Förster resonance is excitation of close pairs into unshifted levels in the complex manifold of molecular potential states [49, 50]. However, for a range of parameter space, we can reversibly excite triply-excited states, $|M_3\rangle$, as shown by the relative maxima in the slopes in Figs. 3b and d. The presence of a phase flip at $\tau' = \tau/2$ almost entirely undoes the evolution into these triply-excited states.

To further explore the coherence of the evolution into $|M_3\rangle$, we vary the echo time, $\tau'$, for fixed $\Omega = 1$ MHz and $\tau = 500$ ns. Thus, we should excite $|M_3\rangle$ for a time $\tau'$ and reverse the evolution for a time $\tau - \tau'$. The slopes of the sorted graphs and the Mandel $Q$ are shown in Fig. 5. The clear relative minimum gives strong evidence of the reversibility of the evolution. Note that in this graph, as in the previous graphs, the Mandel $Q$ closely follows the behavior of the slopes of the sorted graphs. As we transition from exciting predominantly two-body excited states to three-body excited states, the fluctuations in excitation number increase. Each excitation event that does

FIG. 3. Slopes of the sorted graphs, Mandel $Q$, and mixing fraction for atoms excited to the $42D_{3/2}$ state. In panels (a)-(c) $\Omega = 1$ MHz, and $\tau$ is varied. In panels (d)-(f) $\tau = 400$ ns, and $\Omega$ is varied. The black diamonds are for excitation without upper transition phase flip. The purple circles are for excitation with a phase flip at $t' = \tau/2$.

FIG. 4. Slopes of the sorted graphs from Fig. 3 along with the results of a Monte Carlo model. In panels (a) and (b) $\Omega = 1$ MHz, and $\tau$ is varied and in panels (c) and (d) $\tau = 400$ ns, and $\Omega$ is varied. The black diamonds correspond to excitation with no upper transition phase flip. Purple circles correspond to an upper transition phase flip at $t' = \tau/2$. The results of a Monte Carlo model are shown with open red triangles (three-body model for state mixing) and open green diamonds (two-body model for state mixing).
not produce a single superatom goes from producing two additional Rydberg excitations to three additional Rydberg excitations. This broadens the excitation number distributions.

To fully understand our data, we implemented the model described in Ref. [46] for excitation in a three particle basis, which we modified by adding always resonant “hopping” couplings $|d\rangle \leftrightarrow |f\rangle$ and $|d\rangle \leftrightarrow |p\rangle$. We numerically solved the time-dependent Schrödinger equation (TDSE) for various coupling strengths $V_{i,j}$ (or distances $r_{i,j}$), where $\{i,j\} \in \{1,2,3\}$. We first placed the atoms on an equilateral triangle and did not calculate the maximum probability to find the system in a state with only one atom each in $d$, $p$, and $f$. The probability to create triply-excited mixed states is a sharply peaked function of the triangle’s side length, $r$, with a maximum value at $r_{\text{max}} = 3.25$ µm and full width at half maximum (FWHM) 1.07 µm for $\Omega = 1$ MHz. We then solved the TDSE, averaging over random atom placements within the experimental distribution of Rabi frequencies. We placed the atoms inside a shell of radius $r_{\text{max}}$ and width equal to the FWHM. This is the volume inside of which the excitation of triply-excited mixed states will be most probable. We recorded the probability to detect one atom each in $d$, $p$, and $f$. For $\Omega = 1$ MHz there are, on average, about 8 atoms inside of the shell. We accounted for the fact that there are $N = \binom{3}{3}$ possible triples which could be excited within this volume. Since each of these excitation channels is independent and do not interfere, we multiplied the triple excitation probability by the appropriate value of $N$ for each Rabi frequency.

The results of the calculation are shown in Fig. 4. The black curves are for no Rabi frequency inversion and the purple dashed curves are for an inversion at $t' = \tau/2$. It is notable that the Rabi oscillation shows only moderate damping, in spite of the fact that we average over many random placements in an inhomogeneous intensity distribution. For no rotary echo, the maximum probability occurs at approximately the same pulse duration (panel a) as the data in Fig. 3a, but at a larger Rabi frequency (panel b) than the data in Fig. 3b. For Rabi frequency inversion at $t' = \tau/2$ the calculated maxima occur at even longer times (panel a) and higher Rabi frequencies (panel b). In Figs. 4d and d we see the beginnings of these delayed maxima; however, the dominant mixing mechanism transitions to two-body before the slope can reach its full maximum. The disagreements between theory and experiment have a common source. Whenever we drive our atoms strongly (long pulses or large Rabi frequency), incoherent excitation of doubly-excited states dominates over the coherent excitation of $|M_3\rangle$. We increase the probability of exciting close pairs into unshifted branches of the molecular potentials $|\|\|50\rangle$. This is true both with and without a rotary echo phase flip, and it causes the slope and Mandel $Q$ to decrease.

Interestingly, if we repeat the experiments described in this paper when exciting to 43$D_{5/2}$ states, the slopes of the sorted graphs are consistent with the excitation of two-body states, $|M_2\rangle$, for any value of pulse duration, Rabi frequency, or phase flip time we used. Since the magnitude of the Förster defect is much smaller for $n = 43$ than for $n = 42$ (-11 vs. -97 MHz), we would expect a higher probability to excite $|M_3\rangle$. However, this is not the case. The reason is that, for $n = 43$, molecular potential branches cross zero at much larger separations, and with larger overlap with the asymptotic state $50\rangle$. These unfavorable molecular potential curves dominate the dynamics, no matter our choice of experimental parameters.

In conclusion, we have demonstrated coherent excitation of three-atom mixed states near Förster resonance. Coherence was proven using an optical rotary echo technique. We used a Monte Carlo method to demonstrate a transition in the dominant state-mixing mechanism from two- to three-body. Finally, we showed that our data agrees with the model of Ref. [46]. The robustness of the state $|M_3\rangle$ to decoherence suggests that it might find use in quantum technologies, in situations where experimental conditions cannot be carefully controlled.

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FIG. 5. Slopes of the sorted graphs (a) and Mandel $Q$ (b) with fixed $\Omega = 1$ MHz and $\tau = 500$ ns. The time, $t'$, of the upper transition phase inversion is varied.

FIG. 6. Calculated probability to excite a state with one atom each in $|d\rangle$, $|p\rangle$, and $|f\rangle$, using the model in Ref. [46]. The black solid line is for no phase flip and the purple dashed line is for a phase flip at $t' = \tau/2$. Panel (a) is for $\Omega = 1$ MHz and panel (b) is for a pulse duration of 400 ns.

"Slope (b) as the data in Fig. 3a, but at a larger Rabi fre-"}

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[1] Quantum information with Rydberg atoms. M. Saffman, T. G. Walker, and K. Molmer. Rev. Mod. Phys. 82, 2313 (2010).

[2] D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, Fast Quantum Gates for Neutral Atoms, Phys. Rev. Lett. 85, 2208 (2000).

[3] M. D. Lukin, M. Fleischhauer, R. Côté, L. M. Duan, D. Jaksch, J. I. Cirac, and P. Zoller., Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles, Phys. Rev. Lett. 87, 037901 (2001).

[4] D. Tong, S. M. Farooqi, J. Stanojevic, S. Krishnan, Y. P. Zhang, R. Côté, E. E. Eyler, and P. L. Gould., Local Blockade of Rydberg Excitation in an Ultracold Gas, Phys. Rev. Lett., 93 063001 (2004).

[5] T. Cubel Liebisch, A. Reinhard, P. R. Berman, and G. Raithel, Atom Counting Statistics in Ensembles of Interacting Rydberg Atoms, Phys. Rev. Lett. 95, 253002 (2005).

[6] E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman, Observation of Rydberg blockade between two atoms, Nature Physics 5, 110 (2009).

[7] L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, and M. Saffman, Demonstration of a Neutral Atom Controlled-NOT Quantum Gate, Phys. Rev. Lett. 104, 010503 (2010).

[8] K. M. Maller, M. T. Lichtman, T. Xia, Y. Sun, M. J. Piotrowicz, A. W. Carr, L. Isenhower, and M. Saffman, Rydberg-blockade controlled-not gate and entanglement in a two-dimensional array of neutral-atom qubits, Phys. Rev. A 92, 022336 (2015).

[9] J. Phys. B: At. Mol. Opt. Phys, Quantum computing with atomic qubits and Rydberg interactions: progress and challenges, 49, 202001 October (2016).

[10] Harry Levine, Alexander Keesling, Ahmed Omran, Hannes Bernien, Sylvain Schwartz, Alexander S. Zibrov, Manuel Endres, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin, High-fidelity control and entanglement of Rydberg-atom qubits. Phys. Rev. Lett. 121 123603, (2018).

[11] Harry Levine, Alexander Keesling, Giulia Semeghini, Ahmed Omran, Tout T. Wang, Sepehr Ebadi, Hannes Bernien, Markus Greiner, Vladan Vuletić, Hannes Pichler, and Mikhail D. Lukin, Parallel Implementation of High-Fidelity Multiqubit Gates with Neutral Atoms, Phys. Rev. Lett. 123, 170503 (2019).

[12] T. M. Graham, M. Kwon, B. Grinkemeyer, Z. Marra, X. Jiang, M. T. Lichtman, Y. Sun, M. Ebert, and M. Saffman. Rydberg-mediated entanglement in a two-dimensional neutral atom qubit array, Phys. Rev. Lett. 123, 230501 (2019).

[13] Dolev Bluvstein, Harry Levine, Giulia Semeghini, Tout T. Wang, Sepehr Ebadi, Marcin Kalinowski, Alexander Keesling, Nishad Maskara, Hannes Pichler, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin, A quantum processor based on coherent transport of entangled atom arrays, Nature 604, 451 (2022).

[14] Shuo Ma, Alex P. Burgers, Genyue Liu, Jack Wilson, Bichen Zhang, and Jeff D. Thompson, Universal Gate Operations on Nuclear Spin Qubits in an Optical Tweezer Array of $^{171}$Yb Atoms, Phys. Rev. X 12, 021028 (2022).

[15] Henning Labuhn, Daniel Barredo, Sylvain Ravets, Sylvain de Léséleuc, Tommaso Macrì, Thierry Lahaye, and Antoine Browaeys, Tunable two-dimensional arrays of single Rydberg atoms for realizing quantum Ising models, Nature 534, 667 (2016).

[16] Hannes Bernien, Sylvain Schwartz, Alexander Keesling, Harry Levine, Ahmed Omran, Hannes Pichler, Soonwon Choi, Alexander S. Zibrov, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin, Probing many-body dynamics on a 51-atom quantum simulator, Nature 551, 579 (2017).

[17] Sylvain de Léséleuc, Sebastian Weber, Vincent Lienhard, Daniel Barredo, Hans Peter Büchler, Thierry Lahaye, and Antoine Browaeys, Accurate Mapping of Multilevel Rydberg Atoms on Interacting Spin-1/2 Particles for the Quantum Simulation of Ising Models, Phys. Rev. Lett. 120, 113602 (2018).

[18] Alexander Keesling, Ahmed Omran, Harry Levine, Hannes Bernien, Hannes Pichler, Soonwon Choi, Rhine Samajdar, Sylvain Schwartz, Pietro Silvi, Subir Sachdev, Peter Zoller, Manuel Endres, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin, Quantum Kibble Zurek mechanism and critical dynamics on a programmable Rydberg simulator, Nature 568 207 (2019).

[19] A. Browaeys and T. Lahaye, Many-body physics with individually controlled Rydberg atoms, Nature Phys. 16, 132 (2020).

[20] Sepehr Ebadi, Tout T.Wang, Harry Levine, Alexander Keesling, Giulia Semeghini, Ahmed Omran, Dolev Bluvstein, Rhine Samajdar, Hannes Pichler, Wen Wei Ho, Soonwon Choi, Subir Sachdev, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin, Quantum phases of matter on a 256-atom programmable quantum simulator, Nature 595, 227 (2021).

[21] Pascal Scholl, Michael Schuler, Hannah J. Williams, Alexander A. Eberharter, Daniel Barredo, Kai-Niklas Schymik, Vincent Lienhard, Louis-Paul Henry, Thomas C. Lang, Thierry Lahaye, Andreas M. Läuchli, and Antoine Browaeys, Quantum simulation of 2d antiferromagnets with hundreds of Rydberg atoms, Nature 595, 233 (2021).

[22] Alpha Gaëtan, Yevhen Miroshnychenko, Tatjana Wilk, Amosden Chotia, Matthieu Viteau, Daniel Comparat, Pierre Pillet, Antoine Browaeys, and Philippe Grangier, Observation of collective excitation of two individual atoms in the Rydberg blockade regime, Nature Physics 5, 115 (2009).

[23] T. Wilk, A. Gaëtan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, and A. Browaeys, Entanglement of Two Individual Neutral Atoms Using Rydberg Blockade, Phys. Rev. Lett. 104, 010502 (2010).

[24] Y. O. Dudin, L. Li, F. Bariani, and A. Kuzmich, Observation of coherent many-body Rabi oscillations, Nature Physics 8, 790 (2012).

[25] L. Li, Y. O. Dudin, and A. Kuzmich, Entanglement between light and an optical atomic excitation, Nature 498, 466 (2013).
with Anisotropic Interactions, Phys. Rev. Lett., 112, 183002 (2014).

[27] M. Ebert, M. Kwon, T. G. Walker, and M. Saffman, Coherence and Rydberg Blockade of Atomic Ensemble Qubits, Phys. Rev. Lett. 115, 093601 (2015).

[28] A. Schwarzkopf, R. E. Sapiro, and G. Raithel, Imaging spatial correlations of Rydberg excitations in cold atom clouds, Phys. Rev. Lett., 107: 103001 (2011).

[29] Peter Schauß, Marc Cheneau, Manuel Endres, Takeshi Fukuhara, Sebastian Hild, Ahmed Omran, Thomas Pohl, Christian Gross, Stefan Kuhr, and Immanuel Bloch, Observation of spatially ordered structures in a two dimensional Rydberg gas, Nature 491, 87 (2012).

[30] A. Urvoy, F. Ripka, I. Lesanovsky, D. Booth, J. P. Shaffer, T. Pfau, and R. Löw, Strongly correlated growth of Rydberg aggregates in a vapor cell, Phys. Rev. Lett. 114, 203002 (2015).

[31] N. Thaicharoen, A. Schwarzkopf, and G. Raithel, Control of spatial correlations between Rydberg excitations using rotary echo, Phys. Rev. Lett., 118, 133401 (2017).

[32] Y. O. Dudin and A. Kuzmich, Strongly interacting Rydberg excitations of a cold atomic gas, Science, 336 887 (2012).

[33] Fabian Ripka, Harald Kübler, Robert Löw, and Tilman Pfau. A room-temperature single-photon source based on strongly interacting Rydberg atoms, Science, 362, 446 (2018).

[34] Simon Baur, Daniel Tiarks, Gerhard Rempe, and Stephan Dür, Single-photon switch based on Rydberg blockade, Phys. Rev. Lett. 112, 073901 (2014).

[35] Daniel Tiarks, Simon Baur, Katharina Schneider, Stephan Dür, and Gerhard Rempe, Single photon transistor using a Förster resonance, Phys. Rev. Lett. 113, 053602 (2014).

[36] J. D. Pritchard, D. Maxwell, A. Gauguet, K. J. Weatherill, M. P. A. Jones, and C. S. Adams, Cooperative atom-light interaction in a blocked Rydberg ensemble, Phys. Rev. Lett. 105, 193603 (2010).

[37] Q.-Y. Liang S. Hofferberth A. V. Gorshkov T. Pohl M. D. Lukin V. Vuletić T. Peyronel, and O. Firstenberg, Quantum nonlinear optics with single photons enabled by strongly interacting atoms, Nature 488, 57 (2012).

[38] C. S. Hofmann, G. Günter, H. Schempp, M. Robert-de Saint-Vincent, M. Gärttner, J. Evers, S. Whitlock, and M. Weidemüller, Sub-Poissonian statistics of Rydberg-interacting dark-state polaritons, Phys. Rev. Lett. 110, 203601 (2013).

[39] D. Maxwell, D. J. Szew, D. Paredes-Barato, H. Busche, J. D. Pritchard, A. Gauguet, K. J. Weatherill, M. P. A. Jones, and C. S. Adams, Storage and control of optical photons using Rydberg polaritons, Phys. Rev. Lett. 110 103001 (2013).

[40] O. Firstenberg, C. S. Adams, and S. Hofferberth. Nonlinear quantum optics mediated by Rydberg interactions, J. Phys. B: At. Mol. Opt. Phys. 49, 152003 (2016).

[41] Hannes Busche, Paul Huillery, Simon W. Ball, Teodora Ilieava, Matthew P. A. Jones, and Charles Adams, Contactless nonlinear optics mediated by long-range Rydberg interactions, Nature 13, 655 (2017).

[42] Qi-Yu Liang, Aditya V. Venkatramani, Sergio H. Cantu, Travis L. Nicholson, Michael J. Gullans, Alexey V. Gorshkov, Jeff D. Thompson, Cheng Chin, Mikhail D. Lukin, and Vladan Vuletić, Observation of three-photon bound states in a quantum nonlinear medium, Science 359 783, (2018).

[43] H. Kübler, J. P. Shaffer, T. Baluktsian, R. Löw, and T. Pfau, Coherent excitation of Rydberg atoms in micrometre-sized atomic vapour cells, Nature Photonics 4, 112, (2010).

[44] T. Baluktsian, B. Huber, R. Löw, and T. Pfau, Evidence for strong van der Waals type Rydberg-Rydberg interaction in a thermal vapor, Phys. Rev. Lett. 110, 123001 (2013).

[45] Fabian Ripka, Yi-Hsin Chen, Robert Löw, and Tilman Pfau, Rydberg polaritons in a thermal vapor, Phys. Rev. A, 93, 053429 (2016).

[46] T. Pohl and P. R. Berman, Breaking the Dipole Blockade: Nearly Resonant Dipole Interactions in Few-Atom Systems, Phys. Rev. Lett. 102, 013004 (2009).

[47] A. Reinhard, T. Cubel Liebsch, B. Knuffman, and G. Raithel, Level shifts of rubidium Rydberg states due to binary interactions, Phys. Rev. A 75, 032712 (2007).

[48] Ulrich Raitzsch, Vera Bendkowsky, Rolf Heidemann, Björn Butscher, Robert Löw, and Tilman Pfau, Echo experiments in a strongly interacting Rydberg gas, Phys. Rev. Lett. 100, 013002 (2008).

[49] Andrei Derevianko, Peter Kómar, Turker Topcu, Ronen M. Kroeze, and Mikhail D. Lukin, Effects of molecular resonances on Rydberg blockade, Phys. Rev. A 92, 063419 (2015).

[50] Milo Eder, Andrew Lesak, Abigail Plone, Tomohisa Yoda, Michael Highman, and Aaron Reinhard, Quantifying the impact of state mixing on the Rydberg excitation blockade Phys. Rev. Res. 2, 023234 (2020).

[51] Wenchao Xu, Aditya V. Venkatramani, Sergio H. Cantú, Tamara Sumarac, Valentin Klüser, Mikhail D. Lukin, and Vladan Vuletić, Fast Preparation and Detection of a Rydberg Qubit Using Atomic Ensembles, Phys. Rev. Lett. 127, 050501 (2021).

[52] Nicholas L. R. Spong, Yuechun Jiao, Oliver D.W. Hughes, Kevin J. Weatherill, Igor Lesanovsky, and Charles S. Adams, Collectively encoded Rydberg qubit, Phys. Rev. Lett. 127 063604, (2021).

[53] A. Reinhard, T. Cubel Liebsch, K. C. Younge, P. R. Berman, and G. Raithel, Rydberg-Rydberg Collisions: Resonant Enhancement of State Mixing and Penning Ionization, Phys. Rev. Lett. 100, 123007 (2008).

[54] K. C. Younge, A. Reinhard, T. Pohl, P. R. Berman, and G. Raithel, Mesoscopic Rydberg ensembles: Beyond the pairwise-interaction approximation, Phys. Rev. A 79, 043420 (2009).

[55] Jorge M. Kondo, Luis F. Goncalves, Jonathan Tallant, and Luis G. Marcassa, Two-body resonant Enhancement of State Mixing and Penning Ionization, Phys. Rev. Lett. 100, 123007 (2008).

[56] I. Solomon, Rotary Spin Echoes, Phys. Rev. Lett. 2, 301 (1959).

[57] Kelly Cooper Younge and Georg Raithel, Rotary echo tests of coherence in Rydberg-atom excitation, New J. Phys. 11, 043006 (2009).

[58] J. V. Hernández and F Robicheaux, Simulations using echo sequences to observe coherence in a cold Rydberg gas, J. Phys. B: At. Mol. Opt. Phys. 41, 195301 (2008).

[59] Keegan Orr, Ian George, and Aaron Reinhard, A pressure-tuned Fabry Pérot interferometer for laser frequency stabilization and tuning, Rev. of Sci. Inst. 89, 093107 (2018).