Quantum Computing, Excitation Blockade, and Many-body Physics in Ultracold Rydberg Gases

J. Stanojevic, R. Côté, D. Tong, S. Farooqi, E. Eyler and P. Gould

Department of Physics, University of Connecticut, Storrs, CT

In recent years, experiments involving ultracold Rydberg gases and plasmas [1, 2] have attracted a lot of attention. For example, in a pair of atoms with one Rydberg excitation, the existence of long-range molecular bound states with very complex wave functions – the so-called "trilobite" states [3] – or bound molecular states with two highly-excited atoms – the so-called "macrodimers" [4] – have been predicted. Although such molecules have not yet been detected, molecular resonances caused by Rydberg-Rydberg interactions have been observed [5]. The effect of interactions between Rydberg atoms can also lead to density-dependent line broadening of resonances [6, 7].

The unique combination of properties of ultracold Rydberg atoms has led to proposals for using them to implement fast quantum gates [8, 9]. Some of those schemes exploit a "dipole blockade", i.e. a strong suppression of Rydberg excitation in a confined gas, to realize elements for quantum computation between atoms [8] or in mesoscopic ensembles [9]. Recently, large inhibitions of Rydberg excitation have been observed [6, 7], and a similar effect, labeled a "van der Waals blockade" has been reported [6].

Here, we review how quantum information processing could be achieved using Rydberg atoms, especially the so-called *phase gate*. We also explore the behavior of macroscopic atomic samples under conditions where the laser excitation of ultracold atoms to high-lying Rydberg states are dramatically suppressed by their strong long-range interactions, leading to a local blockade effect, *i e.* the excitation of one atom prevents excitation of its neighbors. For pairs of atoms excited in the same *np* state, the long-range interaction takes the form $V(R) \sim -C_5 / R^5 - C_6 / R^6 - C_8 / R^8$ [4, 10], and because the leading term arises from the large C_6 coefficient, the blockade mechanism is labeled "van der Waals blockade" [6]. We discuss a mean-field model that defines local blockade domains and agrees well with the experimental observations. In addition, many-body effects will be investigated. Such effects have been explored in diffusion of excitations [2], and in a N-atom mesoscopic sample under perfect blockade condition, where the single excitation is described by a many-body Rabi frequency, *i.e.* $\sin^2(\sqrt{N}\,\Omega\tau)$ [9]. Here, we explore if this result can be generalized to a macroscopic sample with several "domains" containing effectively N_{eff} atoms, *i.e.* if the number of excited atoms is given by

$$N_{\text{exc}} \sim \sum_{\text{domain}} \sin^2(\sqrt{N_{\text{eff}}}\,\Omega\tau) \ . \tag{1}$$

References

[1] W.R. Anderson, J.R. Veale and T.F. Gallagher, Phys. Rev. Lett. **80**, 249 (1998).

[2] I. Mourachko, D. Comparat, F. de Tomasi, A. Fioretti, P. Nosbaum, V.M. Akulin, and P. Pillet, Phys. Rev. Lett. **80**, 253 (1998).

[3] C.H. Greene, A.S. Dickinson, and H.R. Sadeghpour, Phys. Rev. Lett. **85**, 2458 (2001).

[4] C. Boisseau, I. Simbotin, and R. Côté, Phys. Rev. Lett. **88**, 133004 (2002).

[5] S.M. Farooqi, D. Tong, S. Krishnan, J. Stanojevic, Y.P. Zhang, J.R. Ensher, A.S. Estrin, C. Boisseau, R. Côté, E.E. Eyler, and P.L. Gould, Phys. Rev. Lett. **91**, 183002 (2003).

[6] D. Tong, S.M. Farooqi, J. Stanojevi, S. Krishnan, Y.P. Zhang, R. Côté, E.E. Eyler, and P.L. Gould, Phys. Rev. Lett. **93**, 063001 (2004).

[7] K. Singer, M. Reetz-Lamour, T. Amthor, L.G. Marcassa, and M. Weidemüller, Phys. Rev. Lett **93**, 163001 (2004).

[8] D. Jaksch, J.I. Cirac, P. Zoller, S.L. Rolston, R. Côté, and M.D. Lukin, Phys. Rev. Lett. **85**, 2208 (2000).

[9] M.D. Lukin, M. Fleischhauer, R. Côté, L.M. Duan, D. Jaksch, J.I. Cirac, and P. Zoller, Phys. Rev. Lett. **87**, 037901 (2001).

[10] K. Singer, J. Stanojevic, M. Weidemüller, and R. Côté, J. Phys. B **38**, S295-S307 (2005).