1 ESF Travel Grant Final Report

This is a short report, detailing the work done by Rick van Bijnen, during his visit of the group of Dr. Thomas Pohl at the Max Planck Institute for Complex Systems, in the period of july 1, 2012, until september 7th, 2012. An ESF travel grant was awarded for this visit.

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Project topic:	Rydberg Crystals
Project duration:	2 months

2 Purpose of the visit

The purpose of the visit has been twofold. Firstly, from a scientific point of view the purpose was to investigate the possibility of using Rydberg atoms for the experimental study of strongly correlated quantum systems, and to use them as quantum simulators for complicated condensed matter systems. Secondly, the visit has provided the grant recipient with valuable working experience, networking contacts, and started a new collaboration between the groups of dr. Pohl and dr. Kokkelmans.

3 Work carried out during visit

Rydberg atoms are atoms which are excited to a very high principal quantum number n, e.g. $n = 30 - 100$. Typically, experimental and theoretical research efforts have focused on atoms excited to a single Rydberg S-state. This state, together with the ground state, can be thought of forming two internal states of a (pseudo)spin 1/2 particle. When excited to the Rydberg state, the interaction between atoms is of the Van der Waals type, i.e. the potential decays with the sixth power of the interparticle distance. Moreover, the strength of the interaction scales with the principal quantum number n as n^{11}, leading to very strong interactions which can be significant over interparticle distances of many micrometers, which is very large by atomic standards. The excitation laser competes with this interaction energy, resulting in a rich phase structure and an intricate dynamical behaviour. In the absence of laser driving the Hamiltonian reduces to that of a classical spin system, which cannot support quantum correlations between atoms and whose phases can be understood from classical statistical mechanics.

In contrast, we investigated a system in which the atoms can be excited to either one of *two* possible Rydberg states $|1\rangle, |2\rangle$, distinguished by their principal quantum numbers n_1 and n_2, respectively. Together with the ground state level $|0\rangle$, the system is described by a spin-1 Hamiltonian, whose physics is known to be vastly different from that of spin-1/2 systems. In particular, non-classical ground states such as a spin liquid phase can arise even in the absence of excitation lasers. Such non-classical phases are a consequence of the appearance of a novel Van der Waals *hopping* interaction, where two particles in states $|1\rangle, |2\rangle$ (respectively) swap internal states, such that after an interaction the particles are in the states $|2\rangle, |1\rangle$ (respectively).

The main work carried out during the visit consisted of accurately calculating the interaction coefficients between atoms in the Rydberg states $|1\rangle$ and $|2\rangle$, and calculating the strength of the Van der Waals hopping interaction. In addition, the effect upon the interactions of adding a static electric field and/or microwave radiation was also investigated. These external fields would allow experimentalists to tune the interaction strengths, and provide an experimental knob to tune the system in and out a spin liquid phase.

Finally, a numerical simulation has been written during the visit with which the dynamics of the spin-1 system can be simulated. This is useful for the experimental preparation of the system by means of adiabatic chirping of laser intensity and detuning.

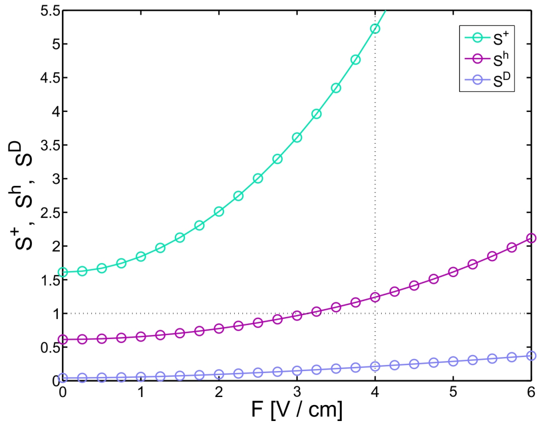

Figure 1: *Effective spin-1 interaction coefficients, as a function of electric field strength F. The spin liquid phase transition occurs around $F = 3V/cm$.*

4 Main results obtained

A many body Rydberg system as described in the previous section has a Hamiltonian governing the internal states of the atoms, which is of the following form:

$$\hat{H} = -\frac{1}{2}\sum_i \left(\Delta_-^S \hat{J}_z^{(i)} + \Delta_+^S \left(\hat{J}_z^{(i)}\right)^2\right) + \sum_{i<j} \frac{1}{|i-j|^6}\left[-S^I \hat{J}_z^{(i)}\hat{J}_z^{(j)} + S^D \hat{J}_z^{(i)}\hat{J}_z^{(j)}\left(\hat{J}_z^{(i)} + \hat{J}_z^{(j)}\right) + S^+\left(\hat{J}_z^{(i)}\right)^2\left(\hat{J}_z^{(j)}\right)^2 + S^h \hat{A}\right]. \quad (1)$$

The $\hat{J}_z^{(i)}$ are 3×3 spin-1 matrices operating on the i-th particle, $\Delta_\pm$ are parameters determined by the laser detuning, and the operator $\hat{A} = \hat{J}_+^{(i)}\hat{J}_+^{(i)}\hat{J}_-^{(j)}\hat{J}_-^{(j)} + \hat{J}_-^{(i)}\hat{J}_-^{(i)}\hat{J}_+^{(j)}\hat{J}_+^{(j)}$. Among the interaction terms S^I, S^D, S^+, and S^h, the term S^I is the classical Ising type. The only quantum perturbation is the hopping term S^h. When the hopping strength exceeds the Ising interactions, a spin liquid is expected to appear.

Figure 1 shows experimentally attainable spin interaction strengths as a function of applied electric field strength F. The values of these interaction strengths are the main result obtained during the project. The spin liquid transition is expected to appear at $F = 3V/cm$. The numbers we obtained are realistic and within current experimental reach.

5 Future collaborations with host institution

In the weeks following the project close contact with the host institution is maintained to finish the final publication. In the future, both parties (grantee and host) are open to filling in a possible postdoc position at the Max Planck institute, after the grantee has completed his PhD. An oral areement to this effect has been reached.

6 Projected publications resulting from grant

At least one publication is expected, in a high profile journal such as Physical Review Letters.