Phases and dynamics of Rydberg atoms in presence of dissipation

Subhasis Sinha

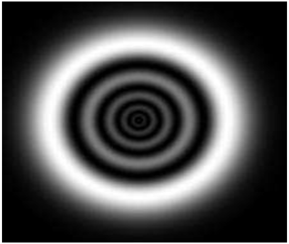
Department of Physical Sciences
Indian Institute of Science Education and Research, Kolkata

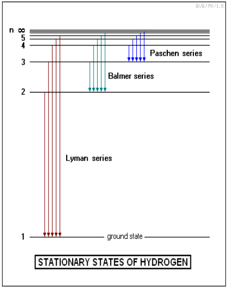
collaboration with: Sayak Ray, K. Saha, Krishnendu Sengupta

Outline

- Rydberg atoms
- Hubbard model for Rydberg atoms in lattice
- Phase diagram and excitations
- Frozen Rydberg atoms with dissipation(decay)
- SF-MI transition in presence of dissipation
- Quench dynamics
- Outlook

Rydberg atom

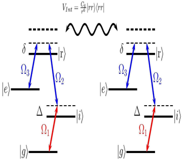




Rydberg formula: $\frac{1}{\lambda} = R(\frac{1}{n_1^2} - \frac{1}{n_2^2})$

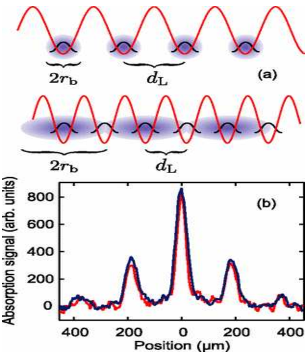
Rydberg atom scaling laws

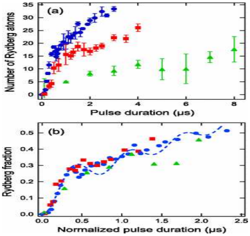
- Radius $\sim n^2$ $\quad R \sim 0.3\mu m$
- Dipole moment $\sim n^2$ $\quad \sim 10^4 ea_0$

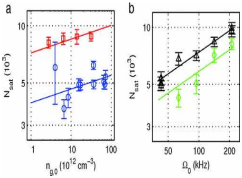


- strong Van der Waals interaction $\sim \frac{C_6}{r^6}$, with $C_6 \sim n^1 1$.
- Rydberg blockade radius $r_b \sim (C_6/\hbar\Omega)^{1/6} \sim 5 - 15\mu m$
- Lifetime $\tau \sim n^{3-4.5}$, $\sim 600\mu s$

Ultracold Rydberg atoms







M. Viteau et. al. PRL, 107, 060402 (2011), R. Heldemann et. al. PRL, 99, 163601 (2007)

The Model

$$
\begin{aligned}
H_0 &= \Omega \sum_i (a_i^\dagger b_i + \mathrm{h.c}) - \mu \sum_i \hat{n}_i + \Delta \sum_i \hat{n}_i^b \\
&+ U \sum_i \hat{n}_i^a (\hat{n}_i^a - 1) + \lambda U \sum_i \hat{n}_i^a \hat{n}_i^b, \\
H_1 &= -J/2 \sum_{\langle ij \rangle} (a_i^\dagger a_j + \eta b_i^\dagger b_j + \mathrm{h.c.}) \\
H_2 &= V_{\mathrm{di}}/2 \sum_{ij} (\hat{n}_i^b \hat{n}_j^b)/|i-j|^6.
\end{aligned}
$$

$|g\rangle = a^\dagger|0\rangle$, and $|ex\rangle = b^\dagger|0\rangle$. For Rydberg blockade $b^{\dagger 2}|0\rangle = 0$

K. Saha, S. Sinha, K. Sengupta, PRA 89, 023618 (2014)

Gutzwiller's wavefunction

$|\psi\rangle = \prod_i |\psi\rangle_i$.

$|\psi\rangle_i = \sum_{n_i^a, n_i^b} f^i_{n_i^a, n_i^b} |n_i^a, n_i^b\rangle_i$

$f^i_{n_i^a, n_i^b}$ are the Gutzwiller coefficients on site i.

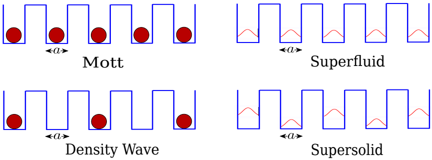
$E[\{f^i_{n_i^a, n_i^b}\}] = \langle\Psi|H - \mu\hat{N}|\Psi\rangle$.

Energy is minimized with respect to the variational parameters f^i.

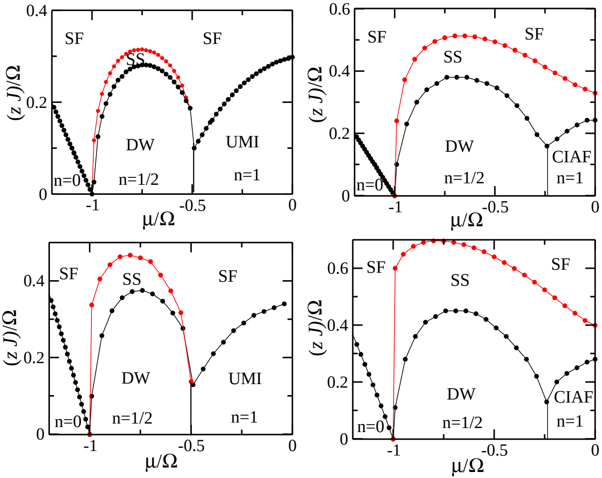
Insulating phases

By increasing μ, insulating phases with filling $n = 0, 1/2, 1, 3/2....$ appears.

- Uniform Mott insulator (MI): $|\Psi\rangle = \prod_i (\cos\theta|n_0, 0\rangle + \sin\theta|n_0 - 1, 1\rangle)$.
- Density wave (DW): Because of near-neighbor interactions lattice translational symmetry breaks. Wavefunction of DW state with $n_0 = 1/2$: $|\Psi\rangle = \prod|\Psi_A\rangle \prod|\Psi_B\rangle$, where $|\Psi_A\rangle = (\cos\theta|1, 0\rangle + \sin\theta|0, 1\rangle)$, and $|\Psi_B\rangle = |0\rangle$.



Equilibrium Phase diagram



- Multicritical points where the boundaries of SS,DW,SF and boundaries of MI,DW,SF meet.

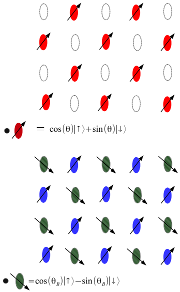
Effective spin-model of M.I with filling n_0

$$H = \Omega \sum_i [|\uparrow\rangle\langle\downarrow|_i + |\downarrow\rangle\langle\uparrow|_i] + \sum_{\langle ij\rangle} P_i V_{ij} P_j + \Delta \sum_i |\uparrow\rangle\langle\uparrow|_i$$

where: $|\downarrow\rangle = |n_0, 0\rangle$, $|\uparrow\rangle = |n_0 - 1, 1\rangle$, and $P = |\uparrow\rangle\langle\uparrow|$.

$$H_{spin} = \Omega \sum_i S_i^x + \sum_{<i,j>} S_i^z V_{ij} S_j^z \,.$$

- Canted Ising Antiferomagnetic phase (CIAF): uniform filling but two sublattice spin orientation with a canting angle.



MI-SF transition in presence of dissipation

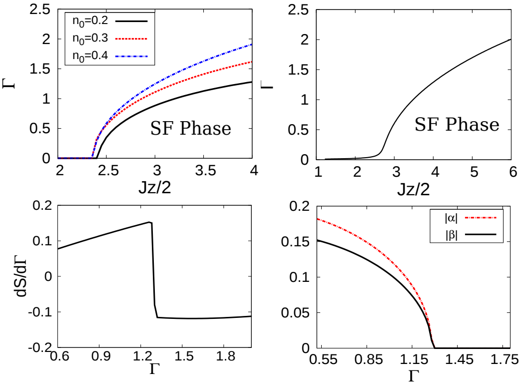
- Within MF: $\rho = \prod_i \rho_i$.
- Master equation in Lindblad form:

$$\partial_t \rho_i = -i[H_i^{MF}, \rho_i] + L_i \rho_i L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho_i\}$$

- Dissipator: $L_i = \sqrt{\Gamma} a_i^\dagger b_i$, where Γ is the decay rate

S. Ray, S. Sinha, K. Sengupta, Phys. Rev. A 93, 033627 (2016)

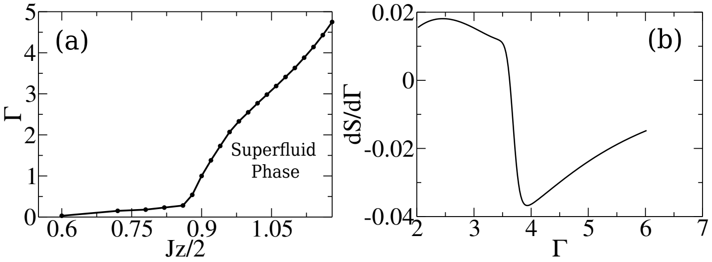
Phase diagram of hardcore bosons



- Superfluid orders: $\langle a \rangle = |\alpha| e^{i\theta_1}, \;\; \langle b \rangle = |\beta| e^{i\theta_2}$. Relative phase $\theta_1 - \theta_2$ is fixed.
- Entropy: $S = -\mathrm{Tr}\rho\log\rho$

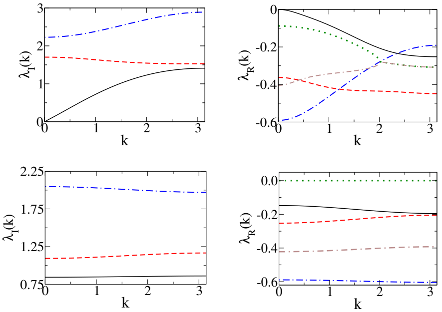
Phase diagram for finite U

- Initial density matrix: $\rho = |G\rangle\langle G|$.



Stability analysis and collective modes

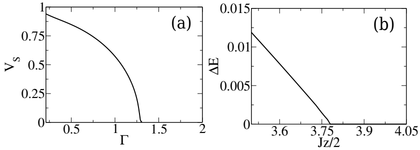
- Fluctuations around the steady states: $\rho^{ab}(t) = \rho_s^{ab} + e^{\lambda t}\delta\rho_i^{ab}$. $\lambda = \lambda_R + i\lambda_I$.
- Stability of phase $\lambda_R(k) \leq 0$
- collective modes: $\lambda_I(k)$.



upper panel: SF, lower panel: M.I

Nature of the transition

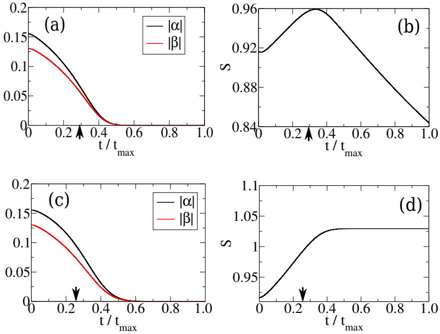
- Continuous transition with a jump in S.



- At SF-MI boundary: sound velocity v_s vanishes and energy gap Δ vanishes linearly.
  dynamic critical exponent $z = 2$.

Non-equilibrium quench dynamics : SF to MI

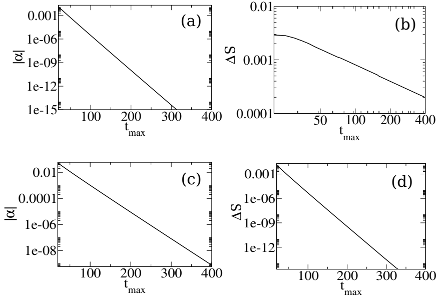
- Linear quench in J (a-b): $J(t) = J_i + (J_f - J_i)t/t_{\max}$; Linear quench in Γ(c-d): $\Gamma(t) = \Gamma_i + (\Gamma_f - \Gamma_i)t/t_{\max}$.



- Entropy S changes with faster rate for quench in Γ.

Change in entropy S and scaling with quench rate

- Deviation of S from the steady state value: $\Delta S = S(t_{\rm max}) - S_0$.



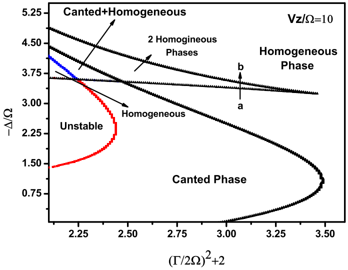
upper panel: quench in J, lower panel: quench in Γ

- For quench in Γ: $\Delta S \sim 1/t_{\rm max}^{\kappa}$. with $\kappa \simeq 1$, analogous to Kibble-Zurek mechanism.

Non-Equilibrium translational symmetry broken phases of ‘frozen’ Rydberg atoms

Lindblad master equation: $\partial_t \rho_i = -i[H_i^{spin}, \rho_i] + \mathcal{L}(\rho_i)$.

Dissipator: $L = \sqrt{\Gamma} S_-$



Summary and outlook

- Due to the Van der Waals interaction translational symmetry broken phases appear.
- ’Roton’ excitation in SS phase
- longer range interaction can form various DW phases with lower filling
- Symmetry broken phases particularly Supersolid phase in presence of dissipation
- Entropy generation and quench dynamics in presence of dissipation.