A3 Inhomogeneous Quantum Phases and Dynamics in Ultracold Gases and Hybrid Atom-ion Systems

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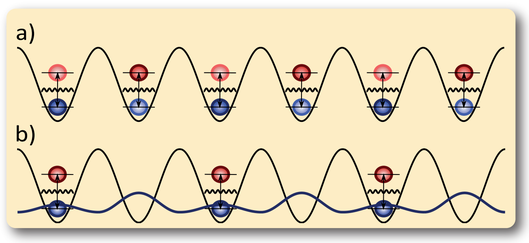
Goals

Rydberg-dressed bosons

Emergence of long-range crystalline and magnetic order in interacting ^{87}Rb Rydberg gases (beyond “dressed“ and “frozen“ limits)

Many-body quantum phases A5 A9

- investigate crystalline, supersolid and magnetically ordered states and their formation dynamics
- tunable long-range interactions
- combined (semi-) analytical variational treatment and bosonic real space DMFT



canted Ising antiferromagnet a) and supersolid order b) in a Rydberg lattice gas

- theoretical description: **extended two-species Bose-Hubbard model**

$$\hat{H} = \hat{H}_0 + \hat{H}_{kin} + \hat{H}_{vdW}$$

- local part includes Rabi driving in rotating wave approximation

$$\hat{H}_0 = \frac{\Omega}{2}\sum_i(\hat{b}^\dagger_{g,i}\hat{b}_{e,i}+\text{h.c.})-\Delta\sum_i\hat{n}^e_i+U\sum_i\left(\frac{\hat{n}^g_i}{2}(\hat{n}^g_i-1)+\lambda\hat{n}^g_i\hat{n}^e_i+\tilde{\lambda}\frac{\hat{n}^e_i}{2}(\hat{n}^e_i-1)\right)$$

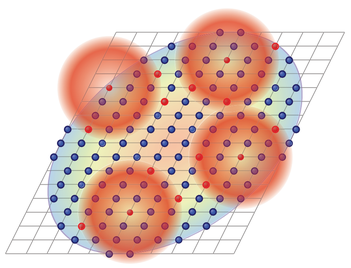
- we allow for different kinetic energy of ground and excited state

$$\hat{H}_{kin} = -t\sum_{\langle i,j\rangle}(\hat{b}^\dagger_{g,i}\hat{b}_{g,j}+\eta\hat{b}^\dagger_{e,i}\hat{b}_{e,j}+\text{h.c.})$$

- strong correlations due to Rydberg-Rydberg van der Waals coupling

$$\hat{H}_{vdW} = \frac{V_{vdW}}{2}\sum_{i\neq j}\frac{\hat{n}^e_i\hat{n}^e_j}{|\mathbf{r}_i-\mathbf{r}_j|^6} \quad \text{with} \quad V_{vdW}=\frac{C_6}{a^6}$$

Real time excitation and crystallization dynamics A5 A9



facilitation effect of Rydberg excitations in a trapped lattice gas

- design of quench protocols to accomplish optimal crystallization of Rydberg atoms
- influence of initial state and finite size
- include (Markovian) dissipation by master equation combined with Gutzwiller theory
- real-space dynamical correlations to be measured in SEM (project A9)

$$g^{(2)}(x_1,t_1;x_2,t_2)=\frac{\langle\hat{a}^\dagger(x_1,t_1)\hat{a}^\dagger(x_2,t_2)\hat{a}(x_2,t_2)\hat{a}(x_1,t_1)\rangle}{\langle\hat{n}(x_1,t_1)\rangle\langle\hat{n}(x_2,t_2)\rangle}$$

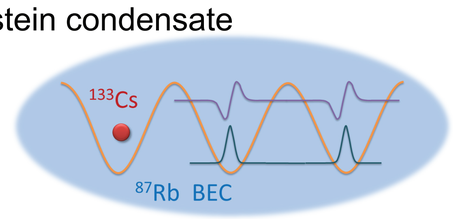
second order coherence

Polarons and impurity dynamics

Investigate polaron formation and impurity dynamics in mixtures and hybrid atom-ion quantum systems

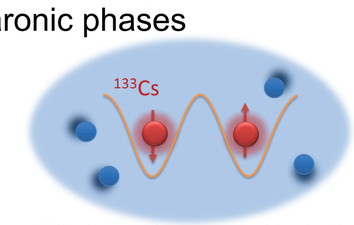
Atomic impurities in a BEC A12

- ^{133}Cs atoms immersed into a ^{87}Rb Bose-Einstein condensate
  → detection of polaron by RF spectroscopy
- multiband physics in tilted lattices
  → damped Bloch oscillations and Landau-Zener tunneling



^{133}Cs impurity in a ^{87}Rb BEC

- effective interactions and long-range ordered polaronic phases
- impurity spin dynamics: dynamical synchronization of Rabi oscillations
- **effective two-band polaron Hamiltonian** after variational Lang-Firsov transformation



two ^{133}Cs impurities coupled by bath

$$H_{\rm P} = -\sum_{\langle i,j\rangle}\sum_\alpha \tilde{J}_\alpha\hat{a}^{\alpha\dagger}_i\hat{a}^\alpha_j+\sum_{i,\alpha}\tilde{\varepsilon}_\alpha\hat{a}^{\alpha\dagger}_i\hat{a}^\alpha_i+\sum_{\mathbf{s}}\omega_{\mathbf{s}}\hat{b}^\dagger_{\mathbf{s}}\hat{b}_{\mathbf{s}}+\sum_{i,j,\alpha,\beta}V^{\alpha\beta}_{i,j}\hat{n}^\alpha_i\hat{n}^\beta_j$$

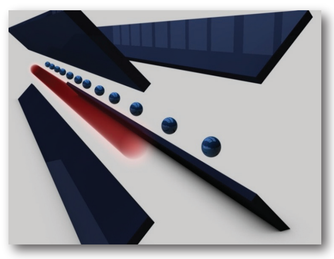
- combine DMFT and Lindblad equation

$$\frac{d\rho_{\rm P}}{dt} = -i[H_P,\rho_{\rm P}]+\mathcal{L}[\rho_{\rm P}]$$

- complementary theory work in A5

Hybrid atom-ion quantum simulator A10

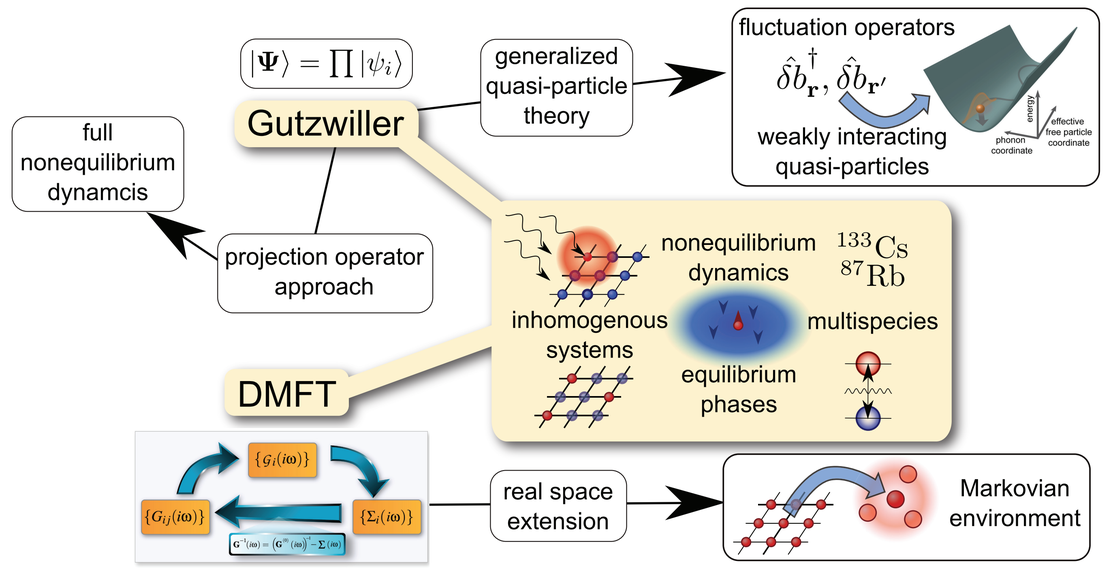
quantum simulator composed of ultracold atoms and trapped ions



- characteristic phonon dispersion
- discretized modes due to finite system size
- heating and decoherence due to ionic micromotion will be addressed by Floquet theory
- describe collective modes and instabilities for strongly correlated bosonic atoms + ions by generalized quasiparticle theory

U. Bissbort, et al, arXiv: 1401.4466

Methods



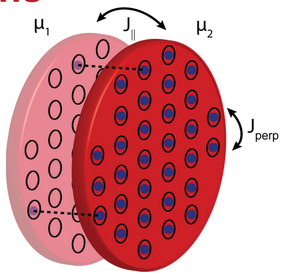
Bosonic quench dynamics

Investigate dynamics of interacting bosons after a Hamiltonian quench and related many-body cooling mechanisms

Initial state expansion, transport and dynamical arrest of interacting bosons A9

- clarify microscopic mechanism of arrest
- effect of gravity and spin degrees of freedom on the expansion
- possible negative differential conductance in mass transport
- include quantum fluctuations by projection operator technique

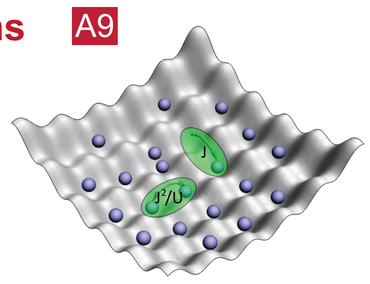
C. Trefzger et al, PRL **106**, 095702 (2011)



strongly correlated mass transport figure from project A9

Many-body cooling mechanisms A9

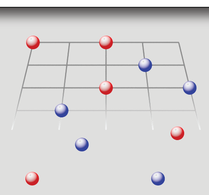
- design optimized lattice ramp protocols for fully adiabatic time-evolution
- reduce temperature of final state
- Pomeranchuk effect due to residual spin entropy
- novel low-temperature, spin-correlated Mott insulators in frustrated optical lattices
- related studies on itinerant electronic antiferromagnetism on triangular lattices (e.g. in $Cs_2CuCl_{4-x}Br_x$) in project B1 and B4



dynamical arrest of an interacting bosonic cloud

Role within the SFB/TR 49

- Provide quantitative theory for strong correlation phenomena and dynamics in ultracold gases and hybrid quantum systems.
- We will closely collaborate with the experimental project A9 on the formation of long-range crystalline and magnetic order in interacting Rydberg gases and on the dynamics and transport of interacting bosons after quantum quenches.
- Together with project A12 we will investigate polaron formation and impurity dynamics of atomic ^{133}Cs defects in a ^{87}Rb BEC.
- In continued collaboration with project A10 we will investigate polaronic quasi-particles and collective modes in hybrid quantum systems of ultracold atoms and trapped ions.
- There will be close interaction with project A5, where complementary theory on interacting Rydberg gases and polaronic dynamics in lower dimensions is developed, as well as with B3 regarding frustrated spin systems, and with A8 regarding nonequilibrium bosonic dynamics.
- Our studies on many-body cooling and magnetism on frustrated lattices will continue to be of high relevance for the solid-state quantum spin systems studied in B1 and B4.



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