Molecules of bosons and Zeno effect in lattices

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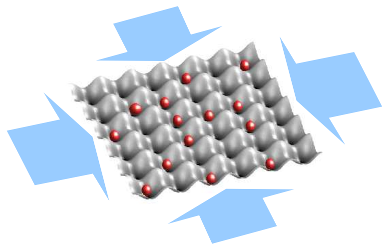
Overview

- We have studied molecules of bosonic atoms in a 1D optical lattice, combining analyitical results with accurate numerical simulations based on Matrix Product States.
- First we have analyzed the creation of molecules through a Feschbach resonance
  - How correlations are transferred to molecule
  - What are the time-scales in the process
  - How does motion of atoms affect the process
  - Can this be used to "measure" things
- Next we have studied the dynamics of molecules alone, considering both the hopping, the interaction and the two-body losses of molecules.
  - Strong dissipation ⇒ Zeno effect
  - Dissipation equivalent to strong interaction
  - Molecules form a Tonks gas
  - Experimentally realizable & observable

The system

- Six lasers create a periodic potential which confines bosons in a quasi-1D regular setup



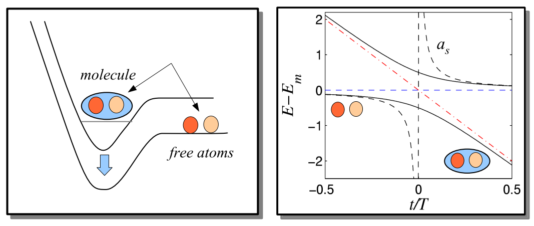
- Atoms have two internal states ($\sigma = \uparrow, \downarrow$) may tunnel to neighboring sites (J)

$$H = -J \sum_{\langle i,j\rangle,\sigma} a^\dagger_{i\sigma} a_{j\sigma} + \sum_i \frac{U_{\sigma\sigma'}}{2} a^\dagger_{i\sigma} a^\dagger_{i\sigma} a_{i\sigma} a_{i\sigma}$$

- Strongly interacting limit, $J \ll U_{\uparrow\uparrow}, U_{\downarrow\downarrow}$, similar to the Tonks-gas experiments [1].
- Depending on the inter-species interaction, can have impenetrable gases or BCS transition.

Feschbach ramp

- We couple the atoms to a molecular level



- Moving through the resonance transfer atoms to the molecular state and viceversa. This is modeled with a conservative coupling

$$H_{am} = \sum_i \left\{ (E_m + U_m n_i^{(a)}) n_i^{(m)} + \Omega [b_i^\dagger a_{i\uparrow} a_{i\downarrow} + \text{H.c.}] \right\}$$

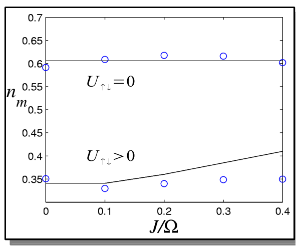
- The final correlations should ideally be related to those of original atomic cloud

$$\begin{aligned} \langle m_k^\dagger m_k \rangle_{t=T} &\sim \langle n_{k\uparrow} n_{k\downarrow} \rangle_{t=0}, \\ \langle a_k^\dagger a_k \rangle_{t=T} &\sim \langle a_k^\dagger a_k \rangle_{t=0} - \langle n_{k\uparrow} n_{k\downarrow} \rangle_{t=0}. \end{aligned} \quad (1)$$

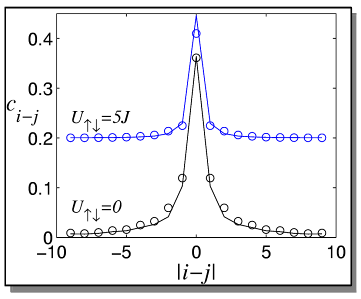
Molecules probe correlations in the atomic cloud.

Molecule creation

- The efficiency in the conversion process is slightly decreased because of the atoms moving



- Molecules do not form a "condensate"



- But the correlations of the molecules agree with those derived from the initial Tonks gas by Eq. (1)

Molecular gas

- We assume that atoms have been removed from the trap, either artificially or by three-body losses.
- The dynamics of the remaining molecules is modeled with a master equation

$$\frac{\partial}{\partial t}\rho := -i[H,\rho] + \mathcal{L}_\gamma \rho$$

$$H = -J_m \sum_{\langle i,j\rangle} b_i^\dagger b_j + U_m \sum_i b_i^\dagger b_i^\dagger b_i b_i$$

$$\mathcal{L}_\gamma \rho := \sum_k \frac{\gamma}{2} \left[2 b_k b_k \rho b_k^\dagger b_k^\dagger - b_k^\dagger b_k^\dagger b_k b_k \rho - \rho b_k^\dagger b_k^\dagger b_k b_k \right]$$

- We lose molecules due to two-body processes, measured by γ, and since we consider longer times, we include molecule hopping and interaction.
- We want to compute the evolution in the regime of strong losses

$$U_m \sim \gamma \gg J_m$$

which is physically relevant [3].

Zeno effect

- Strong dissipation in Eq. (), effectively projects onto states of singly-occupied sites. We can expand the solution in powers of J/γ around this subspace.
- The effective model is a Tonks-gas Hamiltonian for the molecules, where now $b_i^2 = 0$

$$H_{\text{eff}} = -J_m \sum_{\langle i,j\rangle} b_i^\dagger b_j$$

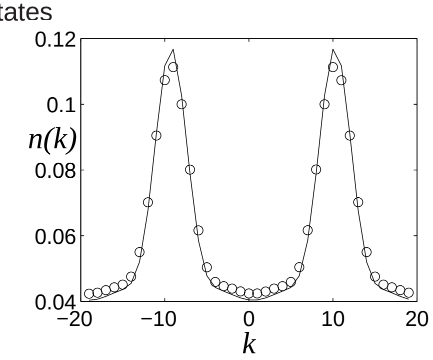
plus a Linblad operator that contains reduced losses and three-site hopping

$$\begin{aligned} \mathcal{L}_\gamma \tilde\rho &= \sum_k \left[(z+\bar z) C_k \tilde\rho C_k^\dagger - z C_k^\dagger C_k \tilde\rho - \bar z \tilde\rho C_k^\dagger C_k \right] \\ C_i &:= b_i (b_{i+1} + b_{i-1}), \\ z &:= \frac{2J^2}{\gamma + iU} \end{aligned}$$

- Now the losses happen in a longer time-scale, $\gamma/J_m \gg J_m$, which can observed in current experiments.

Dynamics

- We consider as initial state a Mott insulator of molecules and no atoms.
- Hopping is raised slowly to a finite value and the molecules expand like a Tonks gas in the lattice.
- We simulate the whole problem using Matrix Product States



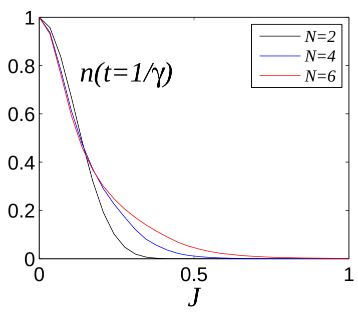
The two peak represent the momenta of the expanding atoms in 1D.

- Good agreement with the Tonks gas model (solid) for $J/\gamma \leq 0.05$ (In experiments $\gamma/J \sim 40$).

Decay of molecules

- For short times we can study just two molecules in two sites, affected by the Zeno effect. The decay of the molecules is ruled by

$$\frac{d}{dt} N = -4 \frac{J^2}{\gamma} \frac{\gamma^2}{\gamma^2 + U^2} N$$



- Losses slow down as holes are created, but for short times it can be approximated by

$$n(t) = 1 - \beta(J) t$$

where $\beta(J)$ is a quadratic function of J.

Conclusions

- When passing through a Feschbach resonance, hopping decreases number of molecules produced.
- Molecule correlations are related to higher order correlators in the atoms even for stronger hoppings.
- Strong molecular decay induces a Zeno effect on the system, which becomes equivalent to a Tonks gas with losses.
- This effect observable in reduced molecular decay.

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- **[1]** B. Paredes, A. Widera, V. Murg, O. Mandel, S. Fölling, I. Cirac, G. V. Shlyapnikov, T. W. Hänsch, and I. Bloch, Nature 429, 277 (2004).
- **[2]** T. Volz, N. Syassen, D. M. Bauer, E. Hansis, S. Dürr, G. Rempe, arXiv:cond-mat/0605184
- **[3]** J. J. García-Ripoll, arXive:cond-mat/0602305