Two distinguishable impurities interacting with a few one-dimensional lattice bosons

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Background

The study of **optical lattices** with **two impurities** and a **bosonic bath** has received increased theoretical attention in the past few years [1-5]. On one side, the consideration of two impurities enables the study of the formation of bound **bipolarons**, which have been predicted to form in BECs [6]. On the other hand, optical lattices offer an unique setting to study impurity physics due to the onset of lattice-specific phases such as **Mott insulators** [7].

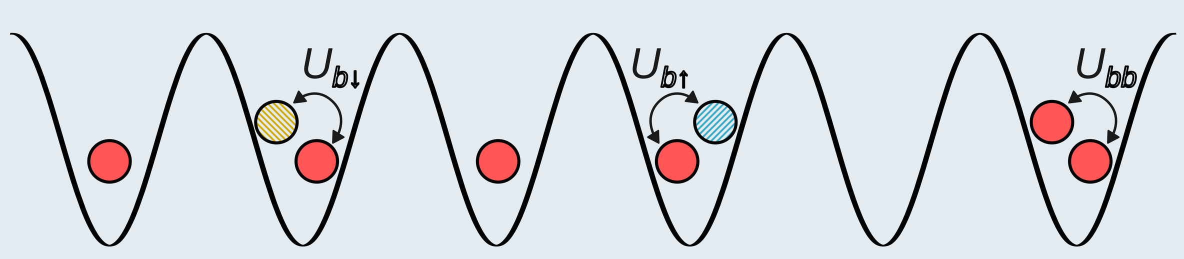


Illustration of the system in consideration. A one-dimensional lattice is filled with a bath of bosons (red circles) and two distinguishable impurities (blue and yellow cross-hatched circles).

In this work, we study **ground-state** properties of a **one-dimensional lattice** filled with **two distinguishable mobile impurities** and a **bosonic bath** at **unity filling** (see figure). We examine the general scenario where **both impurities can interact differently with the bath**, as has been recently considered in one-dimensional traps [8]. We examine **bipolaron energies** and **average distances** between atoms.

Model

We model the system with a **three-component Bose-Hubbard Hamiltonian**

$$\hat{H} = -t \sum_i \sum_{\sigma=b,\uparrow,\downarrow} \left(\hat{a}^\dagger_{i,\sigma} \hat{a}_{i+1,\sigma} + \text{h.c.} \right) + \frac{U_{bb}}{2} \sum_i \hat{n}_{i,b}(\hat{n}_{i,b}-1) + \sum_{\sigma=\uparrow,\downarrow} U_{b\sigma} \hat{n}_{i,b} \hat{n}_{i,\sigma} \,,$$

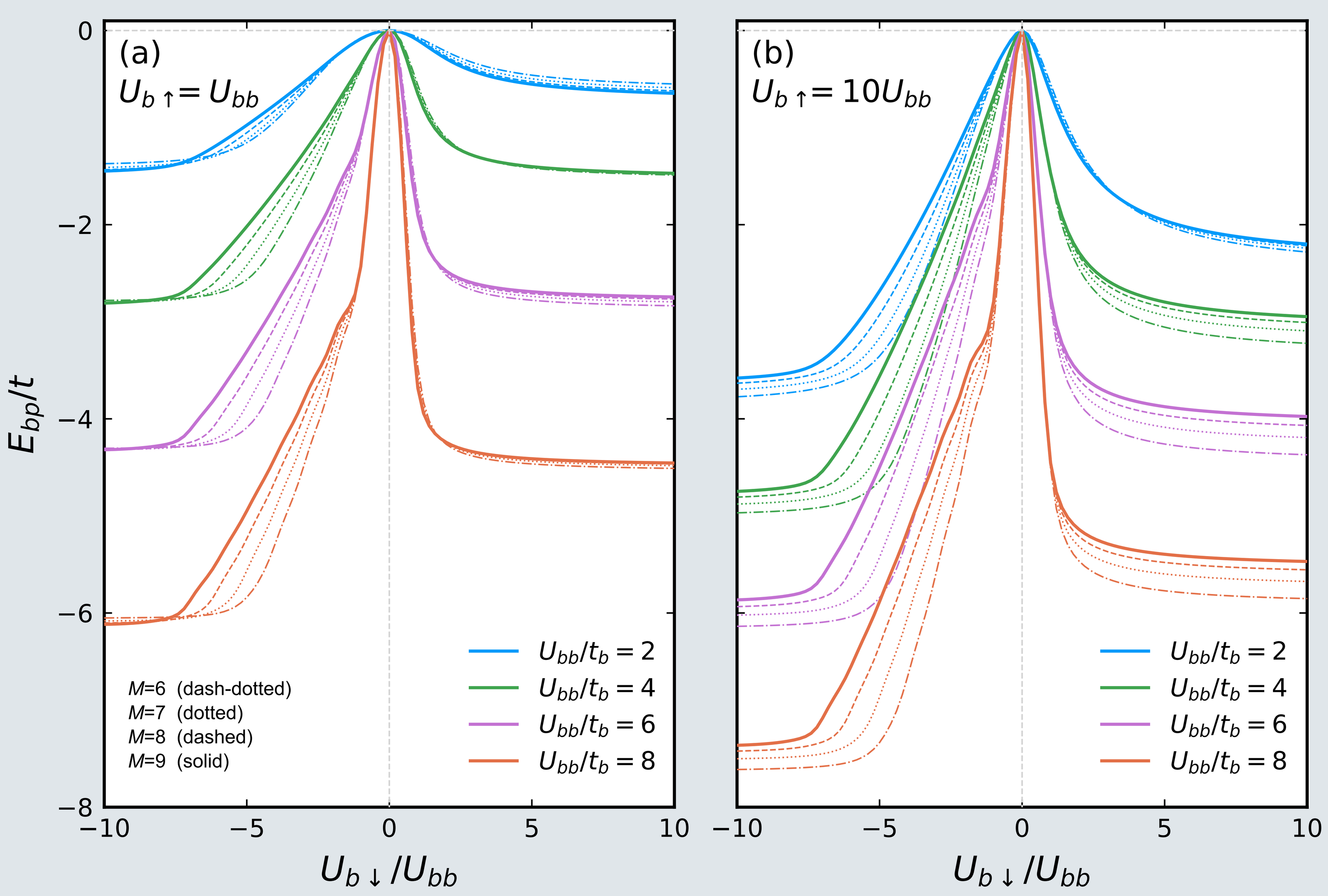
where b denotes the bath's bosons, while ↑ and ↓ denote the two impurities. To study this system we employ the **exact diagonalisation** method [9], and consider **periodic lattices** with a small number M of sites. We consider M bath's bosons (unity filling), and **one impurity of each species**.

Bipolaron energy

We examine the **bipolaron energy** of the system [6,8]

$$E_{bp} = E_2(U_{b\uparrow}, U_{b\downarrow}; U_{bb}) - E_1(U_{b\uparrow}; U_{bb}) - E_1(U_{b\downarrow}; U_{bb}) + E_0(U_{bb}) \,,$$

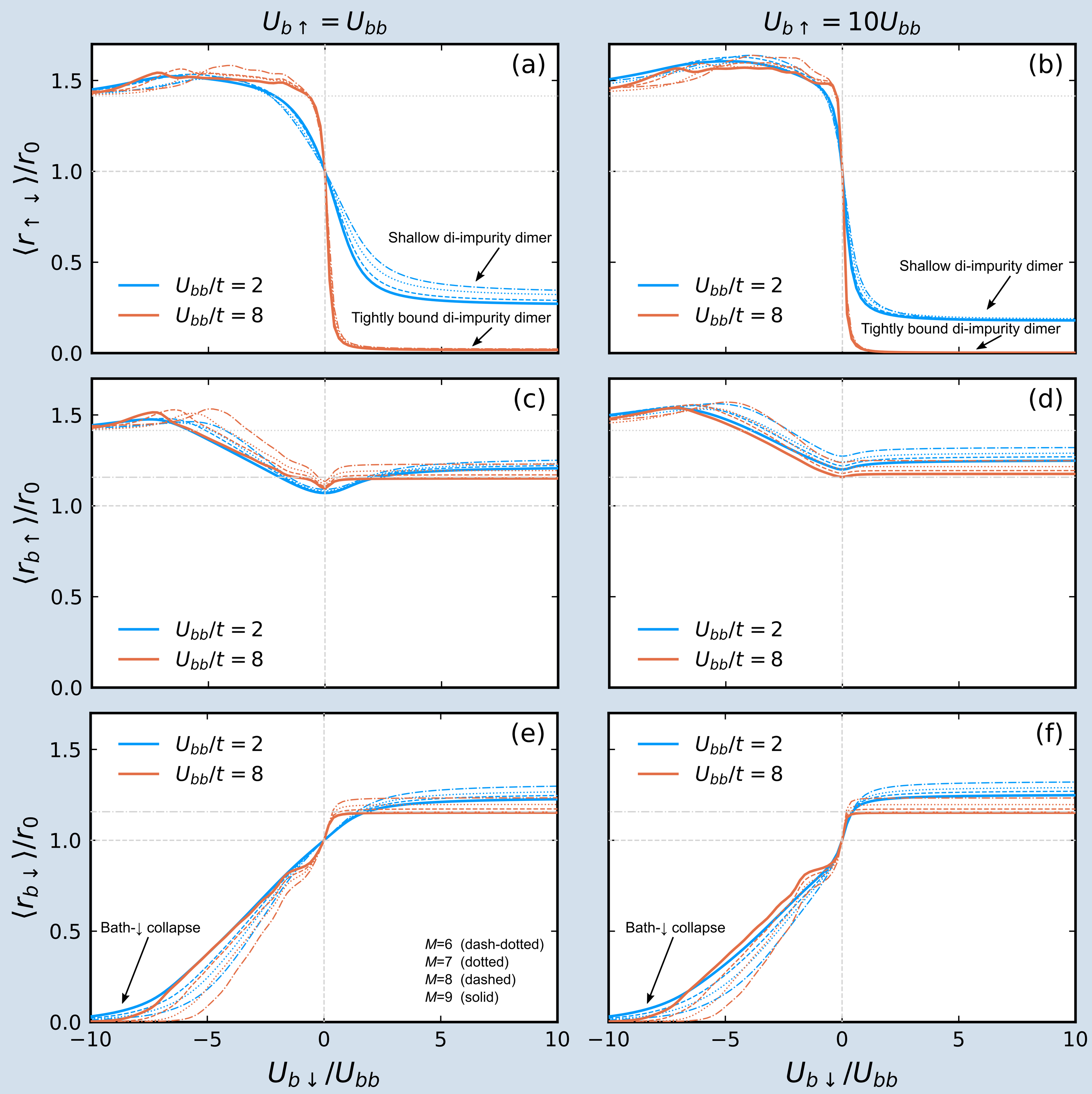
where E_2, E_1, and E_0 are the energy of the system with two, one, and zero impurities, respectively.



In all cases E_{bp}<0. Furthermore, E_{bp} **satures to finite values** when at least **one boson-impurity interaction is strong**, signalling the **phase separation** of the impurities with the bath when $U_{b\downarrow} \gg U_{bb}$, and the **bath's collapse** to the ↓-impurity's site when $-U_{b\downarrow} \gg U_{bb}$.

Average distance between atoms

To further understand the physical behaviour of the system, we examine the **average distance between atoms** $\langle r_{\sigma\sigma'} \rangle$ [5].



The average distance between atoms depends strongly on the interaction strengths. In particular, $\langle r_{\uparrow\downarrow} \rangle$ shows the mentioned formation of **di-impurity dimers for strongly repulsive bath-impurity interactions**. In contrast, a **strong bath-↓ attraction collapses the bath**, as shown by $\langle r_{b\downarrow} \rangle$. In the latter case, the bath-↓ complex and the ↑-impurity behave as two fermions of the same spin. We illustrate these limits in the following illustrations.

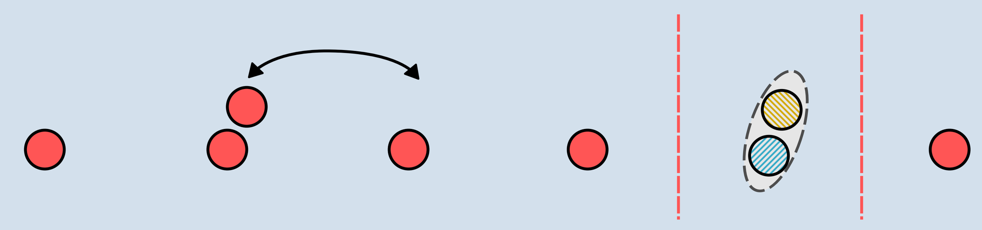


Illustration of the limit $U_{b\downarrow} \gg U_{bb}$ for $U_{b\uparrow}$>0 and $U_{bb} \gg t$. The two impurities form a dimer which is phase-separated from the bath.

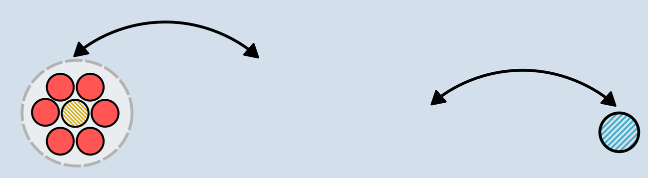


Illustration of the limit $-U_{b\downarrow} \gg U_{bb}$ for $U_{b\uparrow}$>0. The attractive impurity collapses the bath to one site.

Outlook

We have studied **two distinguishable impurities** immersed in a small **one-dimensional lattice Bose bath**. We have characterised the behaviour of the impurities in different limits, including the formation of **di-impurity dimers** and the **impurity-bath collapse**.

Current and future work include a more comprehensive examination of more properties, such as **correlations**, as well as the examination of **excited states** and **quench dynamics**. Future work will include studies of similar systems with other techniques.

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