Magnetic properties of commensurate Bose-Bose mixtures in one-dimensional optical lattices

M. Dalmonte\textsuperscript{1,2}, E. Ercolessi\textsuperscript{1}, M. Mattioli\textsuperscript{1}, F. Ortolani\textsuperscript{1}, and D. Vodola\textsuperscript{1}

\textsuperscript{1}Dipartimento di Fisica dell’Università di Bologna and INFN, via Irnerio 46, 40126 Bologna, Italy
\textsuperscript{2}Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria

Received 12 October 2012 / Received in final form 15 January 2013
Published online 11 March 2013

Abstract. We investigate magnetic properties of strongly interacting bosonic mixtures confined in one dimensional geometries, focusing on recently realized \textsuperscript{87}Rb-\textsuperscript{41}K gases with tunable interspecies interactions. By combining analytical perturbation theory results with density-matrix-renormalization group calculations, we provide quantitative estimates of the ground state phase diagram as a function of the relevant microscopic quantities, identifying the more favorable experimental regimes in order to access the various magnetic phases. Finally, we qualitatively discuss the observability of such phases in realistic setups when finite temperature effects have to be considered.

1 Introduction

Experimental advances in the preparation and manipulation of cold atoms and molecules trapped in optical lattices \cite{1,2} have revived the theoretical interest towards models and problems that in the past played a fundamental role for the description of possible new states of matter, but lacked physical realization in solid state setups. Indeed, thanks to the possibility of using both fermionic and bosonic type of atoms and to the high tunability of the interaction shape and parameters, the phenomena that one can access with these systems are the most varied, ranging from standard superfluidity to BEC-BCS cross-over, to Mott physics and dynamical processes \cite{2–5}.

Among the various advantages in dealing with cold atoms, it is worth mentioning the possibility of trapping them in highly anisotropic optical lattices, thus realizing systems with different geometries and dimensions. In particular, strongly anisotropic lattices allow to realize systems in which the atoms are forced to live in one-dimensional (1D) lattices, i.e. on a chain \cite{2,6}. From a theoretical point of view, physics in 1D is of particular interest not only because it may realize toy models for higher dimensional problems, but also because some physical effects, such as quantum ones, are much stronger and give rise to new phenomena and new states
of matter [7,8]. Analytically, one can use powerful low-energy field theories to describe fermionic, bosonic, and spin models in terms of collective bosonic degrees of freedom [7,8]. Also, under suitable hypothesis, one can establish an equivalence between fermionic and spin degrees of freedom. Theoreticians have long been studying models by switching from a bosonic to a fermionic representation, from a fermion to a spin one, or vice versa. These mappings allow to see how new phases of matter may stabilize for certain values of the coefficients appearing in the Hamiltonian. This is the case, for example, of the emergence of magnetic ordered phases in fermionic and in bosonic models, a problem that was studied long ago in the seminal work by Mott. It was first demonstrated that an insulating antiferromagnetic phase may arise in an apparently simple fermionic model such as the Hubbard one (see [9,10] for reviews). The analysis has then been extended to more complicated systems, such as mixtures of fermionic species described by the two-species Hubbard model, where also more exotic phenomena may appear (singlet superconductivity, FFLO phase, super-counter-flow, etc.) (see Refs. [2,6,11] for a complete review). As for the bosonic case, it was first in Refs. [12,13] that it was shown that the Bose-Hubbard model could admit a quantum phase transition from superfluid to an insulating magnetic Mott-like phase. Since then, much attention has been devoted to understand the features of this transition in arbitrary dimensions or in more complex models describing for example mixtures of bosonic species [14–24].

In recent years, these theoretical predictions have become accessible to experimental checks in cold atoms experiments. Starting from the breakthrough demonstration of Mott-insulator to superfluid transition in a gas of $^8$Rb atoms [25], strongly correlated regimes have been systematically accessed in ultracold gas experiments, prominent examples being the realization of Tonks-Girardeau [26,27] and super-Tonks gases [28], the observation of 1D Mott [29] and Berezinskii-Kosterlitz-Thouless transitions [30], and various dynamical processes [2,31].

Even more intriguing is the possibility of investigating magnetism in such controllable setups, as recently shown in the case of the Ising model in Ref. [32]. In particular, two-species bosonic and fermionic gases represent ideal setups for the search of strongly correlated magnetic states of matter, since once the charge degrees of freedom are gapped in a Mott insulating region, the many-body dynamics is dominated by pseudo-spin degrees of freedom [14,15,17], as in the case of the aforementioned Hubbard model [10].

In this work, motivated by impressive experimental achievements in tuning and controlling low-dimensional heteronuclear bosonic mixtures [33,34], we present a systematic and quantitative investigation for the realization of magnetic phases in a feasible setup of a Bose-Bose mixture of cold atoms trapped in one-dimensional optical lattices. In Sect. 2, we will describe how to model the system via a two-species Bose-Hubbard Hamiltonian, whose effective parameters are determined by microscopic properties, such as the depth of the lattice potential and the Feshbach resonance scattering length. We will discuss this relationship in details for Rb-K mixtures which, thanks to their high tunability [33], allow to span a wide range for both the hopping and the interaction coefficients.

In Sect. 3, we will discuss the theoretical background to study the emergence of magnetic phases in such a system. To describe the physics deep inside the insulating Mott regions, where the single site density is fixed to integer values, we will study the two species Bose-Hubbard Hamiltonian in the strong coupling regime via a perturbative scheme which is a generalization of the Schrieffer-Wolff transformation [35]. At integer fillings, the so obtained effective Hamiltonian can then be mapped onto a spin model, which turns out to be the spin-1/2 $XXZ$-chain for filling one particle per site and the $\lambda - D$ spin-1 Hamiltonian for filling two. Both these models are paradigmatic for the description of many body systems that display quantum phase