ULTRACOLD ATOMS WITH ADDITIONAL DEGREE OF FREEDOM. SPIN-ORBITAL VIEW

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Experimental research of ultracold atoms in optical lattices have expanded the possibilities of quantum many-body physics simulation. Moreover, ultracold atoms open the path to the parameter range that is hardly possible to achieve in the natural condensed matter systems. The typical example is the system of vector bosons. This case corresponds to Bose–Hubbard model that is absent in the standard solid state theory. The situation becomes even more intriguing, when the problem implies additional nontrivial parameters. In our case, we have multiple vector boson species.

Vector two-species bosons in optical lattices are characterized by the following parameters: hopping amplitudes t_α, where $\alpha = 1, 2$ labels different bosons, $U_{\alpha,\alpha'}$ – on-site interactions and spin-channel interaction parameters U_s. In Ref. [1] we have considered the limiting case of nearly identical bosons in the Mott insulating state: $U_{12} \simeq U_{11} \simeq U_{22} = U_0$ and $t_1 \simeq t_2 \ll U_0$. This model differs from the case of perfectly identical bosons by the absence of tunneling with the change of boson identity. It has been shown in that the model can be reduced to the Kugel–Khomskii type spin-1–pseudospin-1/2 model model (pseudospin labels different bosons). The assumption about perfectly identical bosons have lead to simple and intuitively expected phase diagram with one quantum phase transition near $U_s = 0$ (note, that the picture is inverse to spin-1/2–pseudospin-1/2 case, Ref. [2])

Here investigate two species of cold vector bosons in an optical lattice and trace the evolution of the phase diagram with the increase in the "degree of atomic nonidentity" (manifesting itself in the difference of tunneling amplitudes and on-site Coulomb interactions), starting from nearly identical atoms. We show that nature of the ground states and the set of quantum phase transitions of sufficiently distinct atoms are qualitatively different from those in the case of (nearly) identical atoms.

For distinct bosons in the strong correlation Mott insulating limit ($U_{\alpha,\alpha'} \gg |t_\alpha|$) the initial Hamiltonian can also be reduced to the Kugel–Khomskii type spin-1–pseudospin-1/2 model, though rather bulky on this case, Ref. [3].

Within the mean-field approximation, we neglect any correlations between spin and *p*-spin degrees of freedom. Two states are possible in the *p*-spin space — ferromagnetic (FM, domain) and antiferromagnetic (AFM). In the spin space we take for trial wave functions the usual FM, AFM, and nematic (NEM) states. So six different phases are possible.

We show that all this phases are realized in a particular regions of parameters. Moreover, one can find quantum phase transitions nearly between all the possible phases, there are also several reentrant phase transitions. The example of phase diagram evolution for the case $U_{12}/U_{11} = 0$ is presented in Fig. 1, where different colors correspond to different phases. We also note the evolution of the artistic image of the phase diagrams. Namely, at small $\xi_{12} = U_{12}/U_{11} = 0$ their style resembles the J. Miró paintings, while at large ξ_{12} — those of K. Malewicz.

To conclude, we have investigated the evolution of the quantum state of vector two-species bosons in optical lattices with the "degree of atomic nonidentity" that drives the cascade of quantum phase

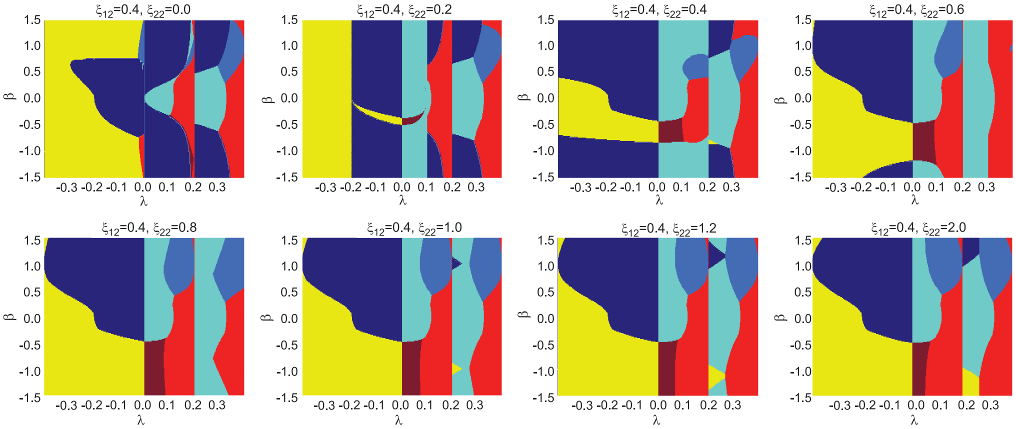

Figure 1. Phase diagrams for $\xi_{12} = U_{12}/U_{11} = 0.4$. Here $\beta = t_2/t_1$, $\xi_{22} = U_{22}/U_{11}$ and $\lambda = U_s/U_{11}$. Different colors correspond to different phases. Brown — *p*-spin AFM, spin NEM; red — *p*-spin AFM, spin AFM; yellow — *p*-spin AFM, spin FM; light blue — *p*-spin FM, spin NEM; middle blue — *p*-spin FM, spin AFM; dark blue — *p*-spin FM, spin FM

transitions. We have transferred the initial general Hamiltonian for vector bosons to the anisotropic spin-pseudospin model of the Kugel–Khomskii type that served as the effective Hamiltonian. The variational approach have been used to uncover the phase diagram of the system in hand. We have investigated also limiting cases of the effective Hamiltonian and demonstrated the relation of our rather complicated Hamiltonian to the well known results.

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