Bose mixtures : magnetic and condensation phenomena

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Bose mixtures are one of the most active research directions in the field of ultracold atoms. They are realized with a two-component bosonic gas, either two atomic species or two hyperfine states of the same atomic species, where both components are brought to quantum degeneracy below the Bose-Einstein transition temperature. Atoms of different components can attract or repel each other realizing attractive or repulsive mixtures.

The ground state of such mixtures is fairly well understood using the standard Gross-Pitaevskii description: repulsive mixtures can undergo a phase separation transition from miscible to immiscible states which shares many analogies with the magnetic transition in spin ½ ferromagnets. Attractive mixtures, instead, can enter a regime where colapse is prevented by beyond mean-field correlations and self bound quantum droplets are formed. Experiments have clearly evidenced both the magnetic and the quantum condensation features exhibited by Bose mixtures as a function of the interspecies coupling.

At finite temperature, though, the situation is less well understood. Perturbative approaches based on Bogoliubov theory at finite temperature predict instabilities of the mixed phase driven by temperature in repulsive mixtures or fail completely when one tries to apply them to attractive mixtures in the regime where droplets are formed at zero temperature. At present no reliable simple theoretical picture can describe the magnetic behavior nor the gas to liquid condensation transition in quantum mixtures at finite temperature.

I will review recent works on the study of both repulsive and attractive Bose mixtures at finite temperature using exact path-integral quantum Monte-Carlo numerical methods. For repulsive mixtures in the quantum degenerate regime we rule out predictions of perturbative theories and find a first-order ferromagnetic transition as a function of the interspecies coupling constant. For attractive mixtures we investigate the gas to liquid transition and the region where the two phases coexist and droplets appear in equilibrium. A similar behavior is observed both in 3D and 2D geometries. In particular, the transition to the superfluid state occurs in a discontinuous way as the density jumps from the gas to the liquid phase. Furthermore, in 3D, the line of first-order transition terminates at a tricritical point and in 2D a relevant role in the gas-liquid transition is played by the quantum scale anomaly. The experimental relevance of these findings is also discussed.

REFERENCES
[1] Phase separation in binary Bose mixtures at finite temperature, G. Spada, L. Parisi, G. Pascual, N. G. Parker, T. P. Billam, S. Pilati, J. Boronat and S. Giorgini, SciPost Phys. **15**, 171 (2023).
[2] Attractive solution of binary Bose mixtures: liquid-vapour coexistence and critical point, G. Spada, S. Pilati and S. Giorgini, Phys. Rev. Lett. **131**, 173404 (2023).
[3] Quantum droplets in two-dimensional Bose mixtures at finite temperature, G. Spada, S. Pilati and S. Giorgini, Phys. Rev. Lett. **133**, 083401 (2024).