3D Bose-Einstein condensates from first principles

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In this research topic, we focus on first-principles calculations (both numerical and analytical) of the many-body quantum dynamics of BEC. The numerical work includes 3D dynamical simulations of colliding condensates and of the formation of BEC via the evaporative cooling process. Inspired by the completely quantum-mechanical regimes predicted by the simulations, the analytic work includes the formulation of the robust, generalised BEC criteria, and calculations of the fundamental noise limits on the centre-of-mass degrees of freedom. The numerical simulations are performed by means of the $+P$ stochastic phase-space method, which can be applied to a range of cold-atom systems, sometimes involving over $10^{1,000,000}$ quantum states.

Firstly, we simulate[1] the quantum dynamics of macroscopic colliding Bose-Einstein condensates[3] with 150,000 interacting atoms. Measurable two-body correlations[2] and velocity distributions are found for experimentally accessible parameters and evolution times. Preliminary experimental measurements from Aspect's group (Orsay) with He* agree qualitatively with the theoretical predictions.

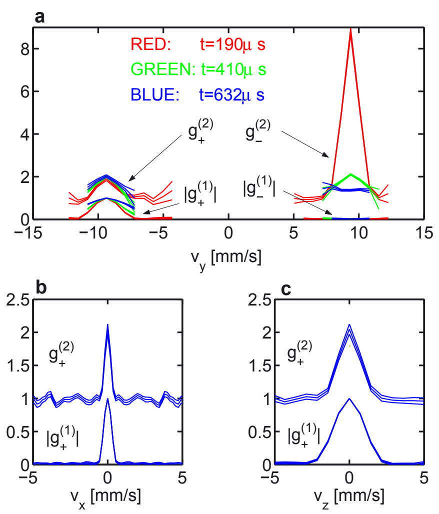

Figure: Correlations between scattered atoms for parameters corresponding to a sodium BEC in a cigar-shaped trap similar to the MIT experiment[3], but at lower densities. Correlations $g^{(1)}$ (coherence) and $g^{(2)}$ (density correlations) shown are in velocity space between a point on the shell of scattered atoms (where $v_y = -9.37\text{mm/s}$, and $v_x = v_z = 0$) and the second velocity shown along the horizontal axis. Top panel **a** – correlations in a direction perpendicular to the collision direction and radial with respect to the shell of scattered atoms; panel **b** correlations along the collision direction; panel **c** correlations perpendicular to the collision direction but tangential to the scattered shell. Details in [1]. Triple lines are 1σ error bars.

Secondly, we simulate the formation of BEC via evaporative cooling[4], to extend earlier predictions[5] of residual centre-of-mass oscillations. Statistical uncertainty in the phase of the oscillations causes the atoms to spontaneously condense into different single-particle states in each realisation. In this situation, the Penrose-Onsager criterion for BEC fails to predict presence of the condensate. Thus, we are evaluating various higher-order correlation functions as alternative criteria for condensation.

Finally, we have calculated [6] the fundamental limits that quantum noise places on the accuracy of mean position (centre of mass) measurements for small low-temperature bosonic and fermionic systems. We have identified a standard quantum limit for such measurements and show that this limit can be exceeded by diffusion of the centre of mass wavepacket.

References

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