Quantum effects and entanglement in Bose-Einstein condensates

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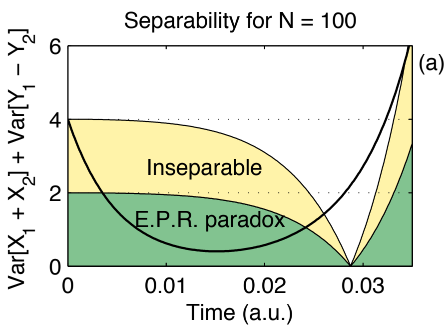
This project considers situations in which beyond mean-field effects are important in the dynamics of Bose gases even at zero temperature. Typically we make use of the truncated Wigner method for solving the quantum evolution of a Bose-condensed gas [1]. The inclusion of initial quantum noise means the technique can represent quantum corrections to the classical field equations of motion.

1. We have identified that the reduction in density fluctuations due to interactions in a Bose-Einstein condensate at zero temperature implies that there is relative number squeezing between the left and right hand sides of the system. We have performed calculations of this using Bogoliubov theory, and also studied how this is affected by time-of-flight expansion and imaging. The ANU He BEC experiment has provided us with a set of data that is being analyzed to determine if this is experimentally observable. Related to this, we have begun work with the Obethaler group at the University of Heidelberg on calculating the theoretical relative number squeezing that they would expect in their double-well BEC experiment as a function of temperature and barrier height.

3. We have been interested in the effect of quantum noise in the collapse of Bose-Einstein condensates as the interaction strength is manipulated with a Feshbach resonance from positive to negative. A paper on quantum effects in the Bosenova was published at the start of the year [2], and we are now studying an experiment that observed the formation of 3D solitons after a collapse [3]. We have found that although these solitons appear to be repulsive, this has more to do with the effects of quantum noise rather than the relative phase of the components.

4. We have continued studying degenerate four-wave mixing of a BEC in a moving 1D optical lattice, where atoms from a mother condensate form two entangled daughter condensates with differing momenta. A simplified three-mode model showed that significant continuous variable entanglement could be generated [4], and we have extended this to an inhomogenous multimode model. In order to prove entanglement between atomic beams, we need to be able to make phase-sensitive homodyne measurements of the atomic fields. We have adapted criteria used in quantum optics and shown how their usage is slightly different with atoms as in the figure to the right. This is largely due to the difficulty in obtaining a phase reference condensate many orders of magnitude larger than that which is being measured.



Adapted Duan and EPR measurements for a three-mode model of four wave mixing in an optical lattice. The yellow shaded area shows where the two modes are inseparable and the green shaded area shows the limits for demonstration of the EPR paradox.

5. We have analysed an experiment performed in Utrecht [5] which exhibited superradiant scattering of laser light from a Bose-Einstein condensate, and which potentially can generate entanglement between light and atoms.

6. Finally, our work on dynamical instabilities in a BEC in an optical lattice was published [6].

References

[1] M.J. Steel *et al.*, Phys. Rev. A **58**, 4824 (1998).
[2] S. Wüster *et al.*, Phys. Rev. A **75**, 043611 (2007).
[3] S.L. Cornish, S.T. Thompson and C.E. Wieman, Phys. Rev. Lett. **96**, 170401 (2006).
[4] M.K. Olsen and M.J. Davis, Phys. Rev. A **73**, 063618 (2006).
[5] R. van der Stam, Ph.D thesis, Universiteit Utrecht (2006).
[6] A.J. Ferris, M.J. Davis, R.W. Geursen, P.B. Blakie and A.C. Wilson, Phys. Rev. A **77**, 012712 (2008).