Theory of Continuous Atom Lasers

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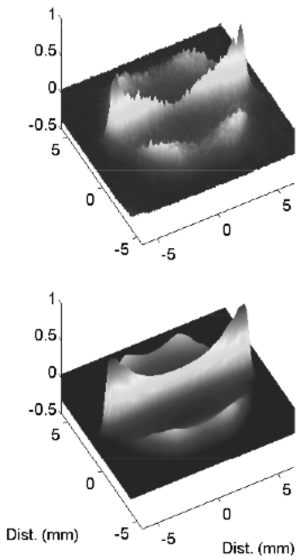
When the Bose-Einstein condensation (BEC) of dilute atomic gases became feasible in the last decade, one of the most exciting prospects was the possibility of producing an atom laser. Atom lasers are formed from output coupling from a Bose-Einstein condensate (BEC), and the spatial properties and quantum statistics of the resulting beam are strongly dependent on those of the source field. This talk will focus on the specific advantages of providing a continuous pumping scheme for the atom laser. Pumped atom lasers offer the promise of an atomic source with dramatically narrow linewidth, high coherence, and a high atomic flux. While experiments demonstrating continuous loading of atom lasers are in their infancy, there are still many unanswered questions about the correct design of such a device. This talk will give an overview of theoretical and experimental progress towards this goal.

Early first principles calculations suggested that BECs might commonly be formed in an excited state. This possibility is consistent with current experiments, where examining the atom laser output often gives the most sensitive measure of the state of the condensate. Simple models of pumping for Bose-Einstein condensates suggest that spatially independent pumping also leads to excitations in the spatial modes, except potentially in the presence of very large nonlinearities. While this instability can be reduced with spatially selective pumping, such processes are difficult to produce experimentally. Large nonlinearities create another problem, in that the phase diffusion of the BEC mode becomes extremely large on the other energy scales of the problem, and this creates an output laser beam with broad linewidth even when the BEC is in a single spatial mode. In practice, therefore, atom lasers will operate best in an intermediate regime.

To date, BEC numbers have been maintained experimentally by preparation of multiple condensates and creating an irreversible coupling from one condensate to another. When this is done without the use of a Bose-enhanced process, the phase diffusion is maximal. When a Bose-enhanced process is used, the phase diffusion of a Poisson pumping process is minimal. When this is achieved by an optical emission stimulated by the existence of the target BEC, the coupling from one condensate to another is restricted to a narrow spread of atomic momenta. A broader momentum resonance can be achieved with continuous evaporation from a thermal source, but there is obviously a balance between the pumping and heating effects.



Comparison of experiment and theory for the transverse spatial profile of a metastable helium atom laser.

To provide a highly coherent atomic source, both the spatial and statistical properties of the lasing mode of an atom laser must be controlled. One way to do this is with active measurement-based feedback control. Feedback control of quantum systems is comparatively undeveloped compared to classical control engineering, but most of the concepts from classical control can be applied directly to atom lasers. Simulating the resulting highly multimode conditional master equations requires the development of new methods, however. In fact, even in the absence of feedback control, simulating these systems in all their multimode complexity is a very difficult process that can be achieved using stochastic techniques. We demonstrate how these techniques have been applied to model atom laser experiments quantitatively and also show how they can be extended for conditional systems.