Universiteit van Amsterdam

1000 Times Closer To A Continuous Atom Laser: Steady-State Strontium With Unity Phase-Space Density

S.P. Bennetts

Summary

Since antiquity, humanity has strived for ever greater control of the world around us. In 1960 we first demonstrated ultimate control over light in the form of the first laser and a year later a steady-state laser made this control eternal. It took another 35 years to extend this to matter. With the first achievement of a pure Bose-Einstein Condensate (BEC) in 1995 we realised for the first time a pure quantum mechanical state of matter and shortly after, a matter-wave laser. This new ability to control matter sparked the revolution in ultracold physics that we see today with applications ranging from time standards to quantum simulation to quantum information and sensing. But 25 years on, these states remain fleeting. They survive at most a few minutes before they dissipate and are lost from our world. Yet the physics says there should be a way to provide stimulated gain, to replenish losses, to make these states eternal. The goal of our research is to try to realise this, to make a steady-state BEC, and with it, a steady-state matter-wave laser.

To make a BEC you first need to laser cool a sample of atoms as cold as possible, then you turn off all resonant light and finally you evaporatively cool them to reach degeneracy. The incorporation of these two incompatible steps, laser cooling and evaporation, is what made BEC possible in a practical sense, but it also made it very hard to make a steady-state system. In 2012 our group demonstrated a "cloak of invisibility" for a BEC. Using Stark shifts, a BEC was made transparent, showing it is possible for a BEC to coexist and form in the presence of small intensities of resonant cooling light. With this in hand we set about trying to make the first steady-state BEC.

The measure of how close you are to forming a BEC is the phase-space density (PSD). This describes how cold and dense your sample is. For values above 2.6 a BEC can form. When we started, the highest steady-state phase-space density demonstrated was a sample of one hundred thousand chromium atoms with a PSD of 0.0004. We now have a PSD around 1, just a heartbeat away from the critical value of 2.6. But this thesis is about much more than just one number.

This thesis will describe, the Strontium Continuous Atom Laser (SrCAL) machine that we built and the many lessons we learned. The path to a steady-state BEC is uncharted. To navigate us there we designed and built a unique and flexible strontium quantum gas machine, a machine designed from the beginning to be a steady-state device. Few non-alkali

quantum gas machines have ever been built and only a handful of them are for strontium, so making a new quantum gas machine is always a challenge. Learning how to build such a machine is not something you will learn in class, or from the literature. The best resources we have are the theses of those who came before us so an important part of this thesis is to document some of that hard won knowledge, to aid future builders in the construction of both pulsed and steady-state degenerate gas machines. I also describe the technical detail needed for future users of SrCAL to wield this tool with mastery.

The result was a unique ability to make steady-state ultracold gases. Using a steady-state magneto-optical trap (MOT) on the narrow 7.4 kHz red transition we achieved a phase space density of 1×10^{-3}. This improved the state of the art phase-space density for steady-state MOTs by more than two orders of magnitude, an unusual event given that MOTs have now been around for more than 30 years.

New ways to protect a BEC from resonant light were developed and demonstrated. This allowed BECs to survive for the first time even within MOT beams with lifetimes of around 1 s. The ability to protect a BEC from the strong blue transition of strontium was also demonstrated for the first time, validating our baffled twin chamber design. We produced a BEC surrounded by a reservoir of thermal atoms designed to replenish it. We were able to hold and protect this BEC within 2 mm of a steady-state red MOT and in full view of the MOT light, but we were not able to couple fresh atoms from our MOT to the reservoir without melting the BEC. For this reason we developed a second approach towards steady-state BEC.

A new architecture was developed and demonstrated for constructing guided atomic beams. It produced the highest phase-space density ever achieved in a continuous ultracold beam experiment, improving the state of the art by around three orders of magnitude. Our steady-state guided atomic beam of ^{88}Sr attained a peak PSD of $1.5(4) \times 10^{-4}$, a flux of $3.3(3) \times 10^{7}\,\mathrm{s}^{-1}$ and radial temperatures as low as $0.89(8)\,\mu\mathrm{K}$. Furthermore, by demonstrating on the order of 30% conversion efficiency from the flux captured by the MOT into a high PSD beam, we showed the practicality of our approach for future steady-state beam sources. This could have important implications for ultracold beam generation in applications from ion beams, to sympathetic cooling, to atom lasers. It could also be the ideal source for an active optical clock based on a steady-state superradiant laser.

We used this beam to continuously transport atoms from a steady-state red MOT to a protected dark trap accumulating and cooling them there. Here, in a protected dipole trap we produced a steady-state sample with a PSD approaching degeneracy, 1.7 ± 1.1. This result is another three orders of magnitude beyond the already record phase-space density produced by our red MOT. In fact, from this steady-state sample a BEC can form within 250 ms simply by turning off the slower laser beam that loads new atoms into the protected trap. We believe this tantalizingly close result was limited primarily by the lifetime of atoms in the this trap.

Finally, we developed and demonstrated a new Sisyphus type slowing and cooling technique. The Sisyphus Optical Lattice Decelerator (SOLD) uses Sisyphus cooling within an excited state lattice to slow and cool atoms without using radiation pressure. This approach can be more photon efficient than radiation pressure based techniques and it eliminates the need for counter-propagating resonant beams. It has other applications from molecule cooling to slowing and trapping anti-hydrogen.

Our system is now being upgraded to use a SOLD decelerator to slow and cool atoms from our atomic beam. It is hoped that this will extend the lifetime of atoms in our reservoir trap. Together with a new dark-state free transparency transition at 487 nm, we are hoping to tip our system into steady-state quantum degeneracy.

Five years ago the highest steady-state phase-space densities were on the order of 4×10^{-4}. We are now at 1, just a heartbeat away from the critical value of 2.6 needed to make a steady-state BEC. Along the way, new records were demonstrated for steady-state MOTs and ultracold beams. We developed new ways to slow, to cool and to protect atoms from resonant light and we now stand at the dawn of a new era in which eternally existing states of pure matter become reality.