A step closer to atom lasers that stay on

Continuous amplification of coherent matter waves has been demonstrated, allowing an exotic state of matter called a Bose–Einstein condensate to be maintained indefinitely. This set-up is the matter-wave analogue of an optical laser enclosed by fully reflective mirrors, and it could have uses in both applied and fundamental physics.

The problem

About a quarter of a century ago, scientists created the first Bose–Einstein condensates (BECs) – collections of indistinguishable atoms that behave like a single coherent matter wave1,2. This work enabled the production of the first pulsed atom lasers: atomic equivalents of optical lasers that emit coherent matter waves, as opposed to coherent light waves. But whereas continuous-wave optical lasers were demonstrated around six months after their pulsed counterparts3, continuous-wave atom lasers have remained elusive. This enduring difficulty can be attributed mainly to a conundrum: BECs are extremely fragile and are rapidly destroyed by radiation known as resonant light, yet resonant light is essential for the laser-cooling steps needed to create these states of matter. As a result, BECs have been restricted to fleeting bursts produced by sequences of steps involving both laser cooling and evaporative cooling, with no way to sustain them indefinitely.

The solution

The key to sustaining a BEC is achieving continuous amplification of coherent matter waves. This requires two ingredients: a constant supply of dense, ultracold atomic gas, and a gain mechanism that produces the amplification. We obtained the first ingredient using a series of cooling stages separated in space instead of time. Crucially, this approach needed resonant light to be in close proximity to the BEC and, therefore, required a way to protect the BEC from this light. Our solution was to locally shift the frequencies of atomic transitions4, creating a region in which the BEC could form safely. We achieved the second ingredient – the gain mechanism – using collisions between the atoms. By ensuring that the atomic gas remained sufficiently cold and dense, we created sustained matter-wave amplification.

Observing the BEC was destructive, so we verified the state’s presence through many independent observations over a timescale much longer than the system’s lifetime (Fig. 1). Once established, the BEC was maintained in a steady state indefinitely, with continuous matter-wave amplification counteracting atom losses, which were caused mostly by the formation of molecules. This system is the matter-wave analogue of a continuous-wave optical laser surrounded by fully reflective mirrors. Theoretical modelling of the system suggests that it gains about 240,000 atoms per second through matter-wave amplification, indicating that the addition of an output coupler – a way to extract the BEC atoms from their confining trap – could produce a strong continuous-wave atom laser.

Future directions

The demonstrated gain mechanism for continuous matter-wave amplification could provide a fresh approach for exploring ultracold physics, one that is not limited to sequences of measurements separated in time. Furthermore, by analogy with continuous-wave optical lasers, such amplification might make it possible to remove fundamental limits on the coherence of atom lasers imposed by the lifetime and atom number of a single BEC5. Eventually, quantum sensors based on continuous matter waves could revolutionize atom interferometry, quantum sensing and atomtronics – the atomic equivalent of electronics. However, two main practical challenges must be overcome before this vision can be realized. First, many applications require a continuous-wave atom laser, for which the BEC atoms would need to be transferred from their trap. Second, the coherence in this proof-of-principle experiment is probably very limited and will need to be improved. This drawback results mainly from the fact that the gain mechanism was implemented by directly immersing the BEC in a cloud of thermal (non-condensed) atoms, such that the BEC was inherently strongly coupled to this thermal cloud. Nevertheless, such a system might provide opportunities for fundamental studies of open, non-equilibrium quantum systems.

For future work, reducing the temperature of the thermal cloud is the key to increasing the purity and coherence of the BEC. This step could be achieved by improved cooling of the thermal cloud through, for example, evaporative cooling or a technique called Raman side-band cooling. Guided evaporative cooling offers the tantalizing prospect of producing a pure BEC that operates continuously.

Shayne Bennetts and Chun-Chia Chen are at the University of Amsterdam, Amsterdam, the Netherlands.

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The creation of a continuous Bose–Einstein condensate constitutes a real milestone in atomic, molecular and optical physics, and is the outcome of an incredible experimental effort. This result is a key step towards the realization of continuous-wave atom lasers, which in turn will pave the road to intriguing follow-up applications in quantum sensing, such as the continuous-wave super-radiant clock.” (CC-BY 4.0)

Andrea Bertoldi is at the Institut d’Optique, Talence, France.

REFERENCES


In 2012, our group developed a technique that allowed a BEC to be protected from resonant laser-cooling light, enabling creation of this state using only laser cooling4. Although this was a crucial first step towards the goal of constructing a continuous-wave atom laser, it was clear that a dedicated experiment would be needed to take the research further. On moving to Amsterdam in 2013, we began this effort with a leap of faith, borrowed funds, an empty room and a team entirely funded by personal grants. Six years later, in the early hours of Christmas morning 2019, the experiment was finally on the verge of working. We had the idea of adding an extra laser beam to the set-up, which lowered the temperature of the atoms. Instantly, every image we took showed the long-sought continuously sustained BEC.

C.-C.C.

Figure 1 | A continuously sustained Bose–Einstein condensate. Density profiles are plotted for the atomic gas after the confining trap was removed and the gas began to expand as a function of the time, $t_{\text{hold}}$, since the system formed. In the initial 3.5 seconds (A–F), a Bose–Einstein condensate (BEC) emerged and reached a steady state. The BEC atoms produced a peak (purple shading) in the density profiles because they came from the lowest energy state of the trap and therefore collectively expanded very little. During the subsequent minute (G–J), the BEC was continuously sustained by matter-wave amplification. Chen, C.-C. et al./Nature (CC BY 4.0).

BEHIND THE PAPER

FROM THE EDITOR

This work stands out because it demonstrates that it is possible to overcome a fundamental limitation of any experiment that relies on atomic BECs: the need to operate in a pulsed fashion. The availability of a continuously sustained sample of Bose–Einstein condensed atoms could be transformative for many applications in fundamental and applied physics.

Federico Levi, Senior Editor and Team Manager, Nature