A fundamental limit to how fast coherence can spread

An ultracold atomic gas can sync into a single quantum state. Researchers uncovered a speed limit for the process that has implications for quantum computing and the evolution of the early universe.

By **Laura Fattaruso**

The transition of a system from a nonequilibrium to an equilibrium state is of interest across a broad range of research areas. Relevant questions include not only how the transition proceeds but also how long it takes.

Zoran Hadzibabic and his team at the University of Cambridge's Cavendish Laboratory have been studying that transition in a confined cloud of weakly interacting potassium-39 atoms using the setup shown in figure 1. Cooled to temperatures that are orders of magnitude colder than the vacuum of space, the atoms condense into a single, quantum state known as a Bose–Einstein condensate (BEC).

Starting with that equilibrium state, the Cavendish team pushed the atoms into a low-energy incoherent state far from equilibrium and then observed how they condensed back into the coherent ground state. When he examined the results, Gevorg Martirosyan, a PhD student at the time, found something surprising: Regardless of the initial nonequilibrium state, the clouds of atoms would reach a common intermediate state, as shown in figure 2, and then evolve in the same exact way toward the condensed equilibrium state.

Taking the observations a step further, the group used magnetic fields to tweak the strength of interactions between the particles. Common sense dictates that particles with stronger interactions evolve toward equilibrium faster. And to a certain extent, observations bore that out, but only until the cloud of atoms reached that common intermediate state. After that, systems with comparatively weak and strong particle interactions evolved the same way. "We realized the strength of interactions is just a detail," says Hadzibabic.

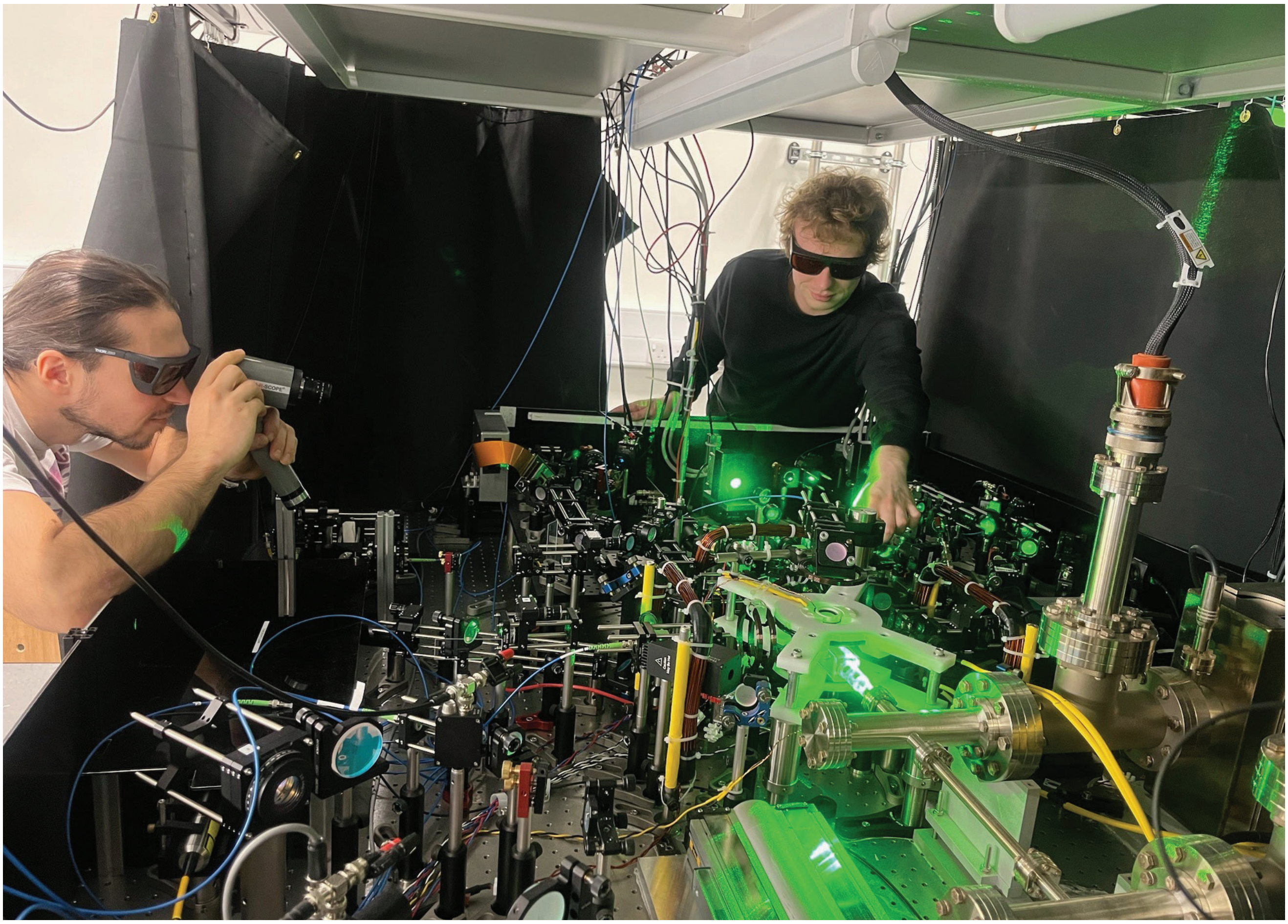
The researchers had found a universal speed limit for the spread of coherence as the atoms condensed into the BEC ground state.[1] The limit depends on just the ratio of two fundamental parameters—the reduced Planck's constant $\hbar$ divided by particle mass m—multiplied by a factor of 3.4. And the underlying physics should apply to fields well beyond cold-atom experiments, including high-energy physics and cosmology.

A long ride

A rough analogy can be drawn between the speed limit on the spread of coherence and the speed limit when traveling by car. Over short distances, like a morning commute, various factors, such as local traffic and the performance of your vehicle, can have a large impact on your arrival time. If you embark on a long journey—such as a cross-country trip across the US—those factors become less important, and the speed limits of the highway exert greater control over your travel time.

Similarly, the initial conditions of the atom clouds affect how quickly they reach the maximum speed for the spreading of coherence, but they all reach the same maximum speed limit that exerts control over how fast they can condense. Measuring the spread of coherence, though, poses a greater challenge than estimating your travel time from Washington, DC, to Santa Barbara, California.

One key breakthrough enabling the Cavendish experiment was the development of the box trap. For almost two decades, from the first demonstration of ideal-gas BECs in 1995 (see the *PT* story "Gaseous Bose–Einstein condensate finally observed") until 2013, the traps used to isolate and cool atoms to form BECs had harmonic-shaped potential-energy wells. That trap shape, unsurprisingly, produces a corresponding harmonic distribution of particle positions and energies that obscures observation of homogeneous-system behavior. In 2013, Hadzibabic and colleagues in the Cavendish Lab announced that they had developed a cylindrical optical trap that could confine a BEC in a region with nearly uniform potential in all directions,[2]



▲ **Figure 1.** Gevorg Martirosyan (left) and Martin Gazo (right) make adjustments to the tabletop apparatus they use to make and measure Bose–Einstein condensates of potassium-39 atoms. Tens of thousands of experiments lasting about 30 seconds each led to the finding that there is a universal speed limit on the spreading of coherence and the formation of the condensates. (Photo courtesy of Simon Fischer.)

akin to the textbook example of putting a particle in a box. That set the stage for producing nearly uniform BECs that are much more theoretically tractable.

Generally, when making a BEC, researchers rapidly cool atoms to very low temperatures using lasers and then evaporatively cool them down to the nanokelvin temperatures needed for the atoms to form a coherent quantum state. That works well for forming a condensate, but it doesn't provide ideal conditions for observing the transition from incoherent, nonequilibrium phases to coherent phases. By first forming a BEC and then using magnetic fields to manipulate it, the Cavendish researchers found that they could create low -energy, nonequilibrium states with varied momentum distributions,[3] such as the ones shown in figure 2. From there, they could quantitatively track the transition to a BEC.

A final crucial advance came from a study of 2D BECs earlier this year by Martin Gazo, Hadzibabic's PhD student, and colleagues. In that work, the researchers devised a way to separate out the initial state-dependent evolution of the trapped gas from the universal behavior that later emerged as it condensed into a BEC.[4]

Determining the speed limit of coherence in the quantum system required repeatedly returning to the same starting point and going a little bit further in time for each iteration. In the road trip analogy, figuring out your maximum speed on a trip from DC to Santa Barbara in a similar fashion would involve restarting the trip from DC for every time and distance measurement collected along the route—and doing so without knowing if a limit exists at all.

"It's a quantum system, so when we measure it, we destroy it," says postdoc Christoph Eigen, a coauthor on the new work. So, in the analogy, it's actually as though you are rebuilding the car for every measurement. Fortunately, each experimental run lasted about 30 seconds.

Driving forward

The universal nature of the speed limit means that it should have relevance across many fields—it's now in

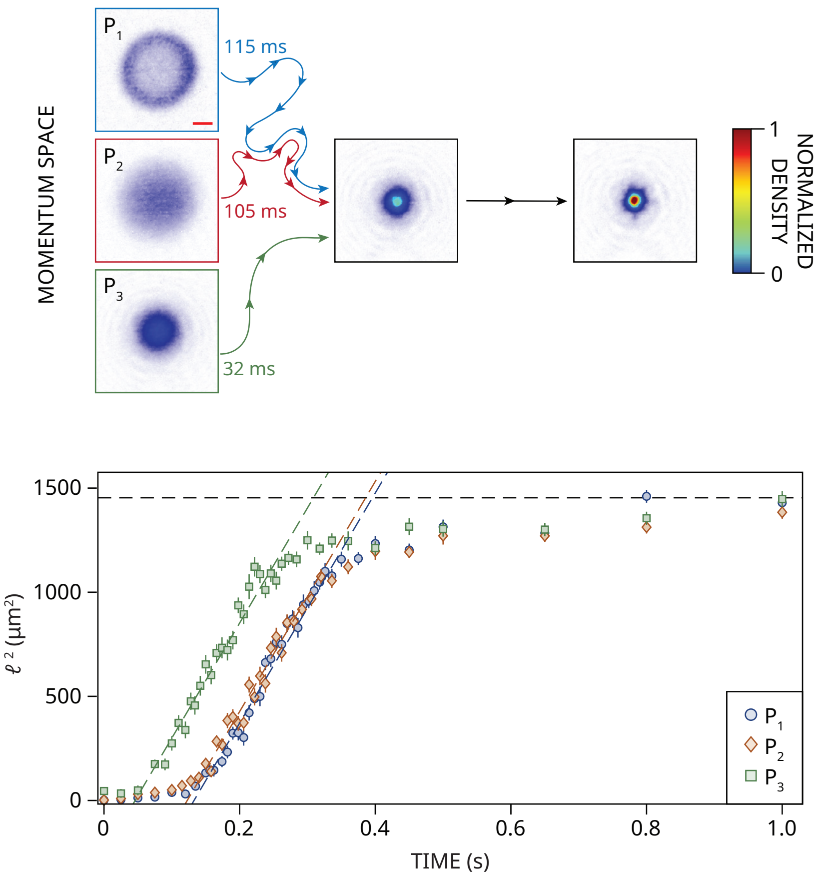


Figure 2. Researchers induced several distinct far-from-equilibrium states (P_1, P_2, P_3) in isolated atomic gases, each of which had a different momentum distribution, shown in the top left, but the same total energy. The red scale bar in the P_1 box corresponds to 1 μm^{-1}. Though the initial state affected the early stages of relaxation toward equilibrium, all systems eventually reached the same intermediate state. After reaching that state, the coherence length ℓ in all of the systems increased at the same maximum rate (indicated by the dashed lines on the graph), 3.4 $\hbar/m$, where m is the atomic mass. (Figure adapted from ref. 1.)

the hands of theorists to determine what the implications might be.

"The entire universe is, in principle, a closed quantum system," says Immanuel Bloch, scientific director at the Max Planck Institute of Quantum Optics. "So if you have the Big Bang and you ask how thermal equilibrium is established in parts of our universe, these are questions that pertain from very small to very large scales," he says. "To find universal behavior in relaxation dynamics is very important; I think it might help us find universal laws that govern out-of-equilibrium evolution."

The Cavendish team found the value of the speed limit to be surprisingly slow, which has possible implications for coherence in macroscopic systems: Calculations show that forming a BEC more than 1 cm across would take hours.

The finding also has implications for quantum computing. "There's a limitation imposed by the interactions of the system, and that's relevant now in an era of using and spreading quantum information," says Vanderlei Bagnato, a physicist at Texas A&M University and the University of São Paulo.

The ratio $\hbar/m$, which determines the coherence speed limit, also corresponds to the circulation of velocity around a quantum vortex. That similarity hints that vortices may play a role in the spreading of coherence. Simulations of low-energy atomic gases have suggested that ordering into a coherent BEC involves movement from a turbulent state to a spaghettilike tangle of vortices. "The ultimate process of ordering is about relaxing the tangle of vortices," says Boris Svistunov, a physicist at the University of Massachusetts Amherst. For the future, the researchers hope to use direct imaging to explore the roles of vortices and waves in the relaxation process. PT

References

1. G. Martirosyan et al., "A universal speed limit for spreading of coherence," *Nature* **647**, 608 (2025).
2. A. L. Gaunt et al., "Bose–Einstein condensation of atoms in a uniform potential," *Phys. Rev. Lett.* **110**, 200406 (2013).
3. G. Martirosyan et al., "Observation of subdiffusive dynamic scaling in a driven and disordered Bose gas," *Phys. Rev. Lett.* **132**, 113401 (2024).
4. M. Gazo et al., "Universal coarsening in a homogeneous two-dimensional Bose gas," *Science* **389**, 802 (2025).