QUANTUM ENTANGLEMENT

Split, but still attached

Entanglement survives between spatially separated atoms of an atomic cloud after it expands

By **Daniel Cavalcanti**

Recent years have witnessed the beginning of the second quantum revolution, in which an impressive degree of control over quantum systems has led to several applications in quantum communication, computation, and sensing, along with new host materials reaching commercial success. A key driver behind many of these applications is entanglement, a form of correlation that can develop between quantum systems that is stronger than any type of correlation that can exist between the macroscopic systems we deal with in our everyday life. The creation, manipulation, storage, and detection of entanglement have posed some of the biggest challenges to quantum physicists. On pages 409, 413, and 416 of this issue, Fadel *et al.* (*1*), Kunkel *et al.* (*2*), and Lange *et al.* (*3*), respectively, describe three independent experiments in which entanglement is observed in a system composed of thousands of ultracold atoms. More importantly, the entanglement is observed between atoms occupying different spatial regions, which paves the way to new applications of these systems.

Entanglement is a very fragile property. Generating it requires highly precise operations and very low levels of noise. There are generally two approaches for entangling particles. The first requires the ability to control each particle and to entangle them one by one by generating suitable interactions. Using this strategy, physicists have managed, for example, to produce entangled states of up to 10 photons (*4*) and 20 ions (*5*). The second approach involves confining the particles and applying controlled global operations in order to make them interact collectively and evolve into an entangled state. This idea has been used to entangle thousands of atoms in Bose-Einstein condensates (BECs), a state of matter at such extremely low temperatures that all atoms behave collectively (*6*). Although this method has been used to entangle a huge number of particles, the lack of control over individual particles means that these systems are not applicable to the majority of quantum-information tasks (see the figure, top).

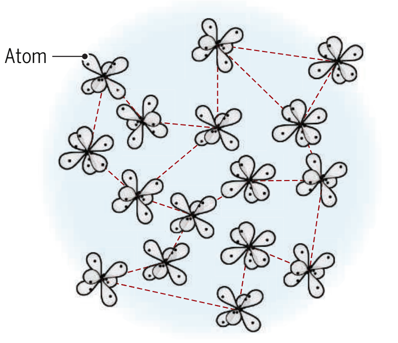
The three studies in this issue used the second approach and demonstrated an important step toward having more control over the generated entanglement (see the figure, bottom). They generated ultracold atomic clouds and split them into different spatial regions, where they could then perform measurements. By making observations of local properties of each separated region, they demonstrate the existence of entanglement between the atoms belonging to these separated cloud regions. In order to prove the existence of entanglement in their systems, each group of authors developed their own strategy, based on two key concepts of quantum mechanics—namely, the uncertainty principle and quantum steering.

Ultracold atom entanglement

It is difficult to address and control individual atoms in Bose-Einstein condensates. Fadel *et al.*, Kunkel *et al.*, and Lange *et al.* show that entanglement is preserved between atoms when these atomic clouds are split up.

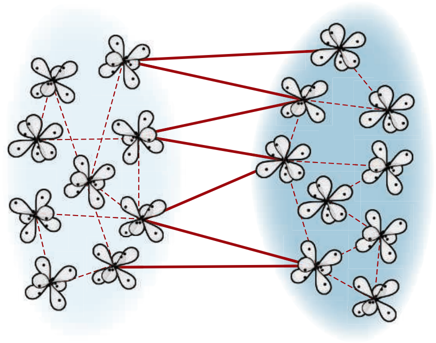
The whole cloud

Previous experiments on entanglement were global measurements on the entire atomic cloud that could not address individual atoms.



The cloud split

Local measurements on atomic clouds that were split demonstrate the existence of entanglement and quantum steering between separated atoms.



GRAPHIC: C. BICKEL/SCIENCE

The uncertainty principle states that there are pairs of quantum observables O_1 and O_2 that cannot be determined simultaneously with arbitrary precision, no matter how sophisticated the implemented experimental setup is. The standard Heisenberg uncertainty relation states that $\Delta O_1 \times \Delta O_2 \geq k$, where ΔO quantifies the uncertainty one has in the measurement of O and k is a constant that depends on the observables in question. Examples of such pairs are the position and momentum of a particle, or different spin directions of an electron.

For systems composed of many parties (here, the different atomic cloud regions), there are relations between the uncertainties of observables applied to each party that are satisfied by all nonentangled states (*7*, *8*). Lange *et al.* showed that measurements of spin observables applied on the spatially separated atomic clouds violate one of these relations, proving that the two clouds are entangled.

Fadel *et al.* and Kunkel *et al.* also make use of the uncertainty principle but combine it with yet another interesting property of quantum mechanics, that of quantum steering. This concept was first discussed by Schrödinger in 1935 (*9*) and more recently has emerged as a new form of quantum nonlocality with interesting properties (*10*, *11*). Schrödinger noticed that if two observers—say, Alice and Bob—share a system of two spin-½ particles in a maximally entangled state $|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle$, and Alice projects her system into the state $a|\uparrow\rangle + b|\downarrow\rangle$, Bob's system immediately collapses to $a^*|\uparrow\rangle + b^*|\downarrow\rangle$, where * stands for complex conjugation. This result implies that by adjusting the coefficients a and b, Alice can prepare different states on Bob's system; that is, she can steer it.

In order to understand how steering and the uncertainty principle can be used to detect entanglement, consider this particular example. Suppose that in every run of an experiment, Alice and Bob share a maximally entangled spin system $|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle$. In each round, they will both either measure their spins along the x or z directions. According to the uncertainty principle, after averaging over all runs, Bob will observe that the uncertainties of his two measurements satisfy $\Delta x \times \Delta z \geq 1$. Notice, however, that because of steering, when Alice measures z and observes that the spin direction is $|\uparrow\rangle$, she knows for sure that the result of the z

Institut de Ciències Fotòniques (ICFO), The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain. Email: daniel.cavalcanti@icfo.eu

measurement on Bob's system is also $|\uparrow\rangle$ (the same certainty is achieved if she observes $|\downarrow\rangle$ instead). Equivalently, if Alice measures x and observes spin direction $|\rightarrow\rangle = |\uparrow\rangle + |\downarrow\rangle$, she knows that Bob's x measurement will also provide $|\rightarrow\rangle$ (similarly for $|\leftarrow\rangle$).

Thus, from Alice's perspective, there is no uncertainty in Bob's measurements because she knows exactly what Bob's outcome will be, given that he applies the same measurement as hers. This example illustrates how steering allows for an apparent violation of the uncertainty principle that can only happen if Alice and Bob share an entangled state. This basic idea was used by Fadel *et al.* and Kunkel *et al.*, although in a more complex fashion. They demonstrated how spin measurements on the atoms residing on one side of the cloud led to a reduction in the uncertainty of measurements applied to the other side.

The articles by Fadel *et al.*, Kunkel *et al.*, and Lange *et al.* address an important requirement for several applications in quantum information and sensing: namely, addressability. The three papers demonstrate the flexibility of BECs in the generation and detection of entanglement by dealing with different system sizes (from a few hundred to a few thousand atoms), using different entanglement criteria to detect entanglement, and showing entanglement between different regions of the atomic cloud. Besides the foundational aspects of these results, the techniques developed could lead to future applications, such as the estimation of local properties of BECs or quantum steering–based tasks (*11*). ■

> ***"...they demonstrate the existence of entanglement between the atoms belonging to these separated cloud regions."***

REFERENCES

1. M. Fadel, T. Zibold, B. Décamps, P. Treutlein, *Science* **360**, 409 (2018).
2. P. Kunkel *et al.*, *Science* **360**, 413 (2018).
3. K. Lange *et al.*, *Science* **360**, 416 (2018).
4. X.-L. Wang *et al.*, *Phys. Rev. Lett.* **117**, 210502 (2016).
5. N. Friis *et al.*, arXiv:1711.11092 [quant-ph] (2017).
6. L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, P. Treutlein, arXiv:1609.01609v2 [quant-ph] (2017).
7. L.-M. Duan, G. Giedke, J. I. Cirac, P. Zoller, *Phys. Rev. Lett.* **84**, 2722 (2000).
8. R. Simon, *Phys. Rev. Lett.* **84**, 2726 (2000).
9. E. Schrödinger, *Math. Proc. Camb. Phil. Soc.* **31**, 555 (1935).
10. H. M. Wiseman, S. J. Jones, A. C. Doherty, *Phys. Rev. Lett.* **98**, 140402 (2007).
11. D. Cavalcanti, P. Skrzypczyk, *Rep. Prog. Phys.* **80**, 024001 (2017).

10.1126/science.aat4590

IMMUNITY

Disrupting metabolism to treat autoimmunity

Dimethyl fumarate, a treatment for multiple sclerosis, inhibits Warburg metabolism

By **Mai Matsushita**[1] *and* **Edward J. Pearce**[1,2]

Autoimmune and inflammatory diseases are diverse conditions caused by inappropriate and prolonged activation of immune cells with associated ongoing production of inflammatory mediators that cause tissue damage. In 2013, dimethyl fumarate (DMF), a methyl ester of fumaric acid used to treat psoriasis (an autoimmune skin condition), was approved for the treatment of multiple sclerosis (MS), a demyelinating autoimmune disease (*1*). Although this drug is now first-line treatment for relapsing remitting MS, its mechanism of action is elusive (*1*, *2*). On page 449 of this issue, Kornberg *et al.* (*3*) provide evidence that the beneficial effects of DMF are related to its ability to inhibit glyceraldehyde-3-phosphate dehydrogenase (GAPDH)—a central enzyme in glucose metabolism (glycolysis)—and, in so doing, inhibit the development and function of inflammatory immune cells, highlighting the promise of targeting metabolism to modulate immune responses.

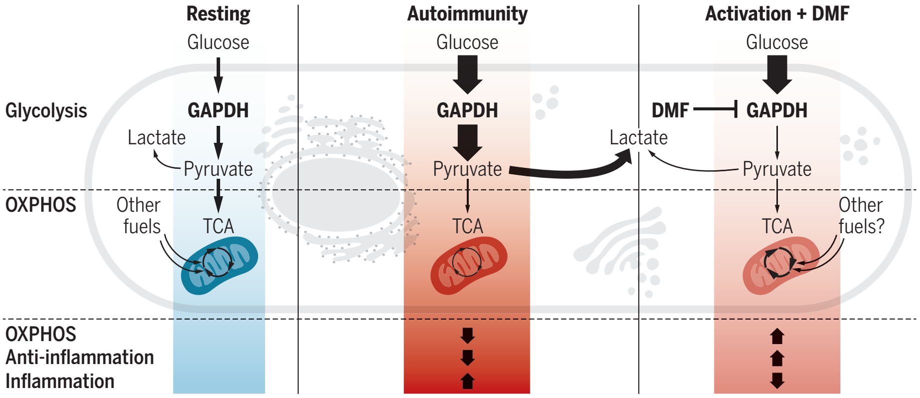
When activated, immune cells undergo profound alterations in metabolism that are integral to their changing bioenergetic and biosynthetic needs. Increases in glycolysis are widely acknowledged to be a hallmark of immune cell activation (*4*). Targeting this pathway with small-molecule inhibitors, such as 2-deoxyglucose, has indicated that enhanced glycolysis is required for cellular functions that occur upon activation (*4*, *5*). Glycolysis serves numerous functions in cellular biology. Pyruvate, produced from glucose by glycolysis, can feed the tricarboxylic acid (TCA) cycle, and therefore mitochondrial oxidative phosphorylation (OXPHOS) (see the figure), which together couple adenosine triphosphate (ATP) production with redox balance. However, glucose is uniquely capable of additionally supporting Warburg metabolism (or aerobic glycolysis), in which pyruvate is converted to lactate through a process that is coupled to ATP production in the cytoplasm. Warburg metabolism is a mark of immune cells that have the potential to cause inflammation (*4*, *5*). Various glycolysis intermediates upstream of pyruvate provide the initiating molecules for ancillary pathways that assume greater importance as cells move from quiescence into growth, proliferative, migratory, and/or

---

[1]Max Planck Institute of Immunobiology and Epigenetics, Freiburg, Germany. [2]Faculty of Biology, University of Freiburg, Freiburg, Germany. Email: pearceed@ie-freiburg.mpg.de

Inhibition of GAPDH blocks inflammation

Resting immune cells depend on mitochondrial respiration to produce ATP. In autoimmunity, Warburg metabolism is increased, supporting the inappropriate production of inflammatory mediators that fight infection and cancer. DMF inhibits GAPDH and thus Warburg metabolism, increasing OXPHOS and inhibiting inflammatory cytokine production, allowing the emergence of cells with anti-inflammatory properties.



GRAPHIC: A. KITTERMAN/SCIENCE

Published by AAAS

Science

Split, but still attached

Daniel Cavalcanti

Science **360** (6387), 376-377.
DOI: 10.1126/science.aat4590
