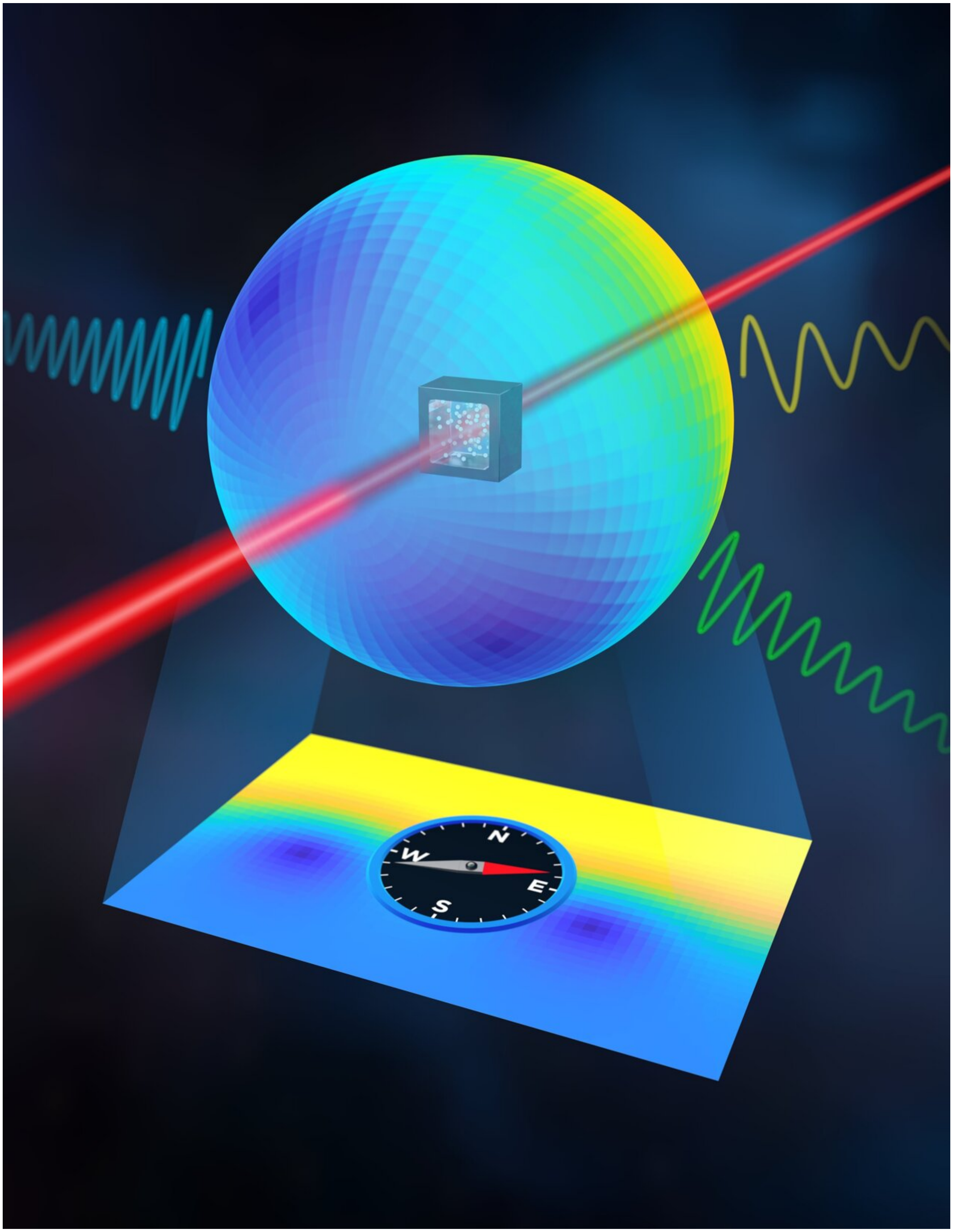
Atoms that measure magnetic fields could lead to new quantum sensors

January 30 2025



Artist's depiction of a new strategy for measuring the direction of magnetic fields by exposing a cell containing roughly a hundred billion rubidium atoms to a microwave signal. Credit: Steven Burrows/JILA

A team of physicists and engineers at the University of Colorado Boulder has discovered a new way to measure the orientation of magnetic fields using what may be the tiniest compasses around—atoms.

The group's findings could one day lead to a host of new quantum sensors, from devices that map out the activity of the human brain to others that could help airplanes navigate the globe. The new study, published in the journal *Optica*, stems from a collaboration between physicist Cindy Regal and quantum engineer Svenja Knappe.

It reveals the versatility of atoms trapped as vapors, said Regal, professor of physics and fellow at JILA, a joint research institute between CU Boulder and the National Institute of Standards and Technology (NIST).

"Atoms can tell you a lot," she said. "We're data mining them to glean simultaneously whether magnetic fields are changing by extremely small amounts and what direction those fields point."

These fields are all around us, even if you never see them. Earth's iron-rich core, for example, generates a powerful magnetic field that surrounds the planet. Your own brain also emits tiny pulses of magnetic energy every time a neuron fires.

But measuring what direction those fields are pointing, for precise atomic sensors in particular, can get tricky. In the current study, Regal and her colleagues set out to do just that—with the aid of a small chamber containing about a hundred billion rubidium atoms in vapor form. The researchers hit the chamber with a magnetic field, causing the atoms inside to experience shifts in energy. They then used a laser to precisely measure those shifts.

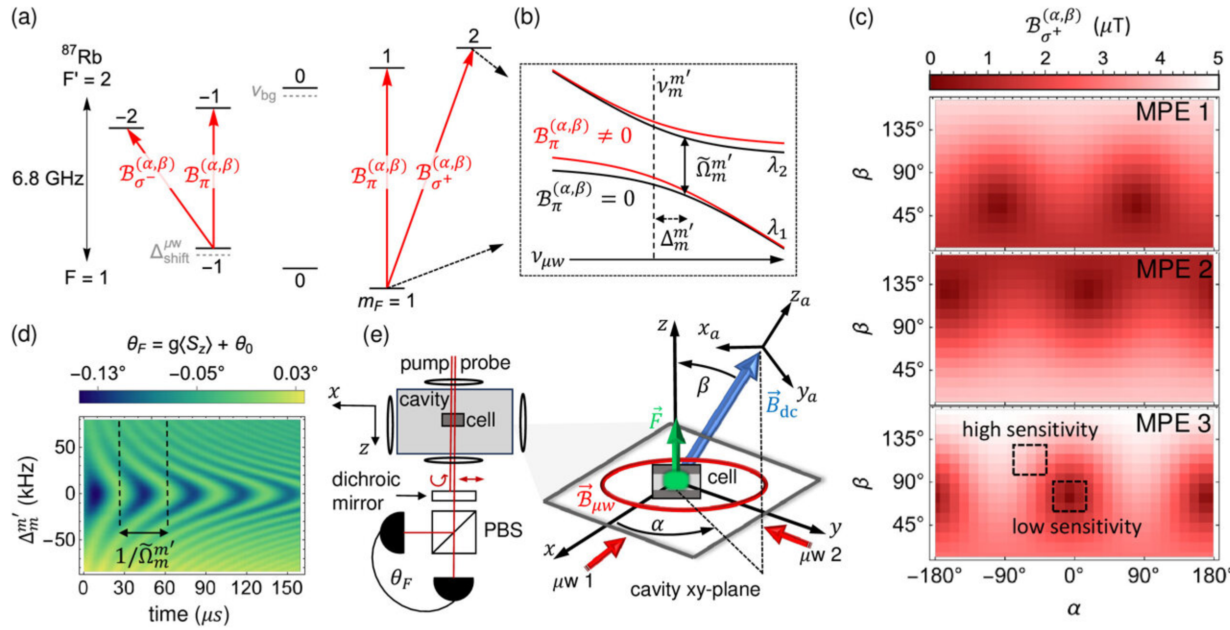
"You can think of each atom as a compass needle," said Dawson Hewatt, a graduate student in Regal's lab at JILA. "And we have a billion compass needles, which could make for really precise measurement devices."

Magnetic world

The research emerges, in part, from Knappe's long-running goal to explore the magnetic environment surrounding us.

"What magnetic imaging allows us to do is measure sources that are buried in dense and optically opaque structures," said Knappe, research professor in the Paul M. Rady Department of Mechanical Engineering. "They're underwater. They're buried under concrete. They're inside your head, behind your skull."

In 2017, for example, Knappe co-founded the company FieldLine Inc. that manufactures atomic vapor magnetic sensors, also called optically pumped magnetometers (OPMs). The company builds integrated sensors the size of a sugar cube and fits them into helmets that can map out the activity of human brains.



Vector magnetometry using Rabi oscillation frequencies referenced to multiple microwave polarization ellipses (MPEs). Credit: *Optica* (2024). DOI: 10.1364/OPTICA.542502

These OPMs also have a major limitation: They only perform well enough to measure minute changes in magnetic fields in environments shielded from outside magnetic forces. A different set of OPMs can be used outside these rooms, but they are only adept at measuring how strong magnetic fields are. They can't, on their own, record what direction those fields are pointing. That's important information for understanding changes brains may undergo due to various neurological conditions.

To extract that kind of information, engineers typically calibrate their sensors using reference magnetic fields, which have a known direction, as guides of a sort. They compare data from sensors with and without the reference magnetic fields applied to gauge how those sensors are responding. In most cases, those references are small metal coils, which, Knappe said, can warp or degrade over time.

Regal and her team had a different idea: They would use a microwave antenna as a reference, which would allow them to rely on the behavior of atoms themselves to correct for any changes of the reference over time.

Study co-authors included Christopher Kiehl, a former graduate student at JILA; Tobias Thiele, a former postdoctoral researcher at JILA; and Thanmay Menon, a graduate student at JILA.

Atoms guide the way

Regal explained that atoms behave a bit like tiny magnets. If you zap one of the team's atoms with a microwave signal, its internal structure will wiggle—a sort of atomic dance that can tell physicists a lot.

"Ultimately, we can read out those wiggles, which tell us about the strength of the energy transitions the atoms are undergoing, which then tells us about the direction of the magnetic field," Regal said.

In the current study, the team was able to use that atomic dancing to pinpoint the orientation of a magnetic field to an accuracy of nearly one-hundredth of a degree. Some other kinds of sensors can also reach this level with careful calibration, but the researchers see atoms as having significant potential with further development.

Unlike mechanical devices with internal parts that can morph, "atoms are always the same," Regal said.

The team still has to improve the precision of its tiny compasses before bringing them out into the real world. But the researchers hope that, one day, airplane pilots could use atoms to fly around the globe, following local changes in Earth's magnetic field, much like migratory birds using their own biological magnetic sensors.

"It's now a question of: 'How far can we push these atomic systems?'" Knappe said.

More information: Christopher Kiehl et al, Accurate vector optically pumped magnetometer with microwave-driven Rabi frequency measurements, *Optica* (2024). DOI: 10.1364/OPTICA.542502

Provided by University of Colorado at Boulder