Atomic Physics: Neutral atoms put in charge

ATOMIC PHYSICS

Neutral atoms put in charge

Martin Zwierlein

An elegant experiment shows that atoms subjected to a pair of laser beams can behave like electrons in a magnetic field, as demonstrated by the appearance of quantized vortices in a neutral superfluid.

Ultracold gases of atoms — a million times thinner than air and a million times colder than interstellar space — allow the observation and control of many-body quantum physics at macroscopic scales. They can thus serve as model materials[1] for condensed-matter systems where such quantum behaviour dominates. From frictionless flow in superfluids to inhibited transport in insulators and from weakly to strongly interacting systems, an extreme variety of fundamental states of matter can be realized in ultracold atomic gases in real time and with the precision of atomic physics. But there seems to be one obvious limitation: atoms are neutral, a fact that in principle precludes the observation of a wealth of phenomena tied to the behaviour of charged particles, for example their behaviour in a magnetic field. On page 000 of this issue, Lin *et al.*[2] get round this problem and demonstrate in a striking fashion their ability to create synthetic magnetic fields for a neutral ultracold atomic system – A collective state of matter termed a Bose-Einstein condensate develops mini-tornadoes known as quantized vortices.

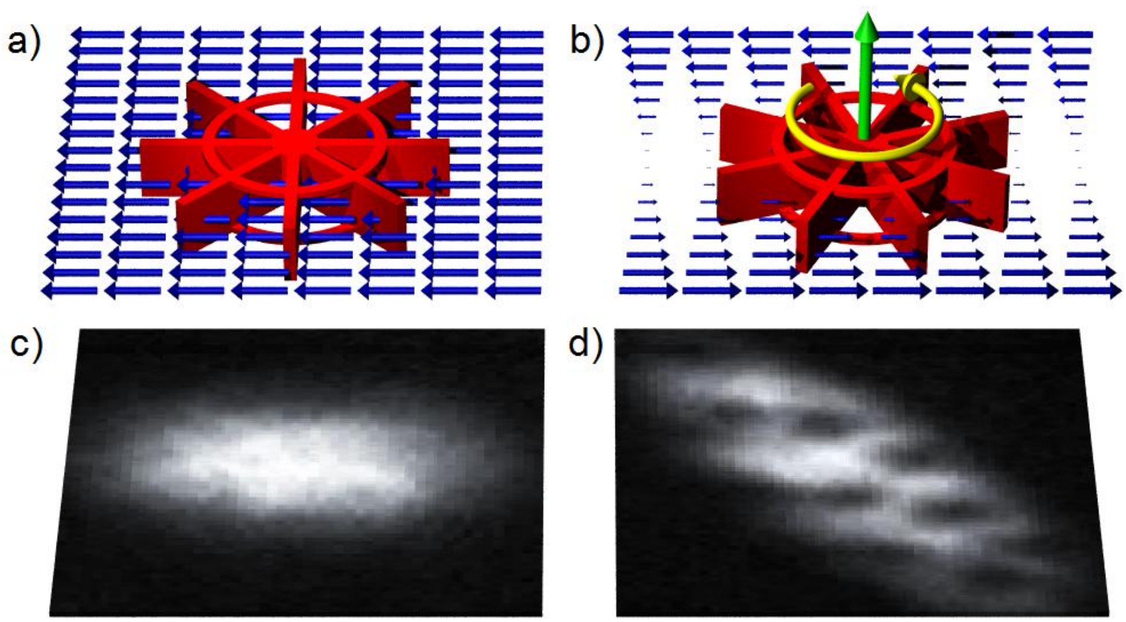

Figure 1 Paddle-wheel analogy for magnetic fields. a, A paddle wheel placed in water flowing with uniform velocity (blue arrows) does not rotate. b, If the water flows non-uniformly and in a different direction on one side of the paddle wheel from that on the other, the wheel rotates (green arrow). The flow pattern is analogous to the 'vector potential' created in Lin and colleagues' experiment[2] to generate a synthetic magnetic field for an ultracold cloud of atoms known as a Bose–Einstein condensate. The rotation axis (purple arrow) and the speed with which the paddle wheel rotates correspond respectively to the direction and strength of the magnetic field. c, d, Images of the Bose–Einstein condensate before (c) and after (d) application of the synthetic magnetic field. The appearance of quantized vortices (d) is a direct demonstration of a synthetic magnetic field.

Magnetic fields are directly tied to the rotational motion of charged particles: an electron placed in a uniform magnetic field rotates about the field axis. One way to mimic the effect of a magnetic field on a cloud of neutral atoms is thus to set it under rotation. But this approach comes with limitations. To achieve a large effective magnetic field requires fast rotation, which causes atoms to fly apart. Also, the method necessitates extremely round confinement and cannot be applied to atoms trapped in a static optical lattice - an artificial crystal of light used to model solid state systems[1]. A more direct implementation of effective magnetic fields should thus not be restricted to certain geometries. To get a picture of what is needed, consider what happens to a paddle wheel placed in a river (Fig. 1). If the river flows with uniform velocity across the paddle wheel, it will not rotate. But if the water on one side of the paddle wheel flows faster or even in a different direction than on the other side of it, or if there is a swirl (vortex) in the flow, the paddle wheel will rotate. In this analogy, the axis and speed of rotation represents the direction and strength of the magnetic field, and the flow pattern is called a vector potential. Just like the paddle wheel rotates in the presence of vortices in the flow, a cloud of atoms will experience a magnetic field if one manages to imprint a vector potential that carries vorticity.

This is precisely what Lin and colleagues[2] achieved in their ingenious experimental set-up, which is an inspired realization of earlier proposals[3–6]. Using a pair of laser beams, they first imprinted the equivalent of a river's uniform flow — a uniform vector potential — on their ultracold cloud of atoms[7,8]. Next, by judiciously tuning the lasers in a spatially dependent way, they endowed the vector potential with a swirl: atoms across different sides of the cloud experienced a different vector potential. This non-uniform flow created a synthetic magnetic field.

Quantum mechanics predicts a wide range of peculiar effects for systems subjected to magnetic fields. One dramatic example, the Meissner effect, is found in superconductors, in which currents of electron pairs flow without resistance. In this effect, a superconductor placed in a magnetic field expels it from its interior. But beyond a certain critical field strength, many superconductors, termed Type II, allow magnetic flux to pierce their interior in the form of tiny quantized vortices or flux tubes. This is a direct consequence of the fact that superconductors can be described by one collective macroscopic wavefunction shared among all their constituent electron pairs. Such quantized vortices are the only way such a wavefunction can circulate. Flux quantization is the principle behind the working of SQUIDs (Superconducting quantum interference devices), the extremely accurate magnetometers used to measure small magnetic fields.

Superconductors are nothing else than charged superfluids, fluids that flow without friction. The behaviour of superconductors in magnetic fields is thus directly analogous to that of neutral superfluids under rotation. Observations of a rotating lattice of vortices in Bose–Einstein condensates[9] and gases of fermionic atoms[10] (particles with half-integer spin, just like electrons) have in fact served as direct proofs of their superfluidity. Such neutral superfluids thus provided the ideal test case for Lin *et al.*'s novel effective magnetic field that does *not* require rotation. When they applied their synthetic magnetic field on a Bose-Einstein condensate, a striking array of vortices appeared in the atom cloud, the smoking gun for quantized circulation. This is the first time that a stable, long-lived, non-rotating array of vortices has been formed in a neutral superfluid.

Many intriguing magnetic phenomena observed in charged systems arise at large magnetic fields. One example is given by fractional Quantum Hall States, collective states of matter in which electrons behave as if the elementary charge is only a fraction of their actual charge. Reaching the required field strengths in neutral systems is likely out of reach for experiments that rely on rotation to mimic the effect of such fields. Lin and colleagues' experiment[2] offers a new approach to generate synthetic fields and might point the way towards observing the fractional quantum Hall effect and other exotic states of matter in neutral systems. Of course, the task of extending the authors' technique to strong magnetic fields won't be an easy one. Their technique also comes with shortcomings, for example the finite lifetime of the atomic cloud in the presence of the laser beams, a limit on the highest vector potential possible, and the not-so-immediate applicability to fermionic systems. That said, the challenges that accompany the authors' technique might be easier to tackle than those that plague the rotational approach.

Lin and colleagues' spectacular demonstration[2] of a synthetic magnetic field for neutral atoms signals the advent of synthetic electrodynamics to the field of ultracold atomic gases. Future applications of their method might include the measurement of the superfluid fraction in ultracold atomic gases[11] and the realization of unusual quantum states in two-dimensional optical lattices at high effective fields[5]. The demonstration of quantum Hall physics in such lattices[6] using the authors' approach might also be within reach. Thus, this work opens up exciting new avenues for the realization of novel many-body quantum systems.

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